# AUTOMOBILE IN TRANSITION? AN ECONOMIC AND ENVIRONMENTAL ANALYSIS OF POLICIES FOR REDUCING $CO_2$ EMISSIONS FROM TRANSPORT

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# Contents

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# Introduction

Transport is a means of helping people obtain access to the goods and services they need. Transport sustains energy and resource flows within society, and between the social system and the ecological system in support of economic activities. Heavily dependent on fossil fuels, transport raises concerns about environmental impacts, centring on climate change, local air pollution, and energy security.

Transport is an increasingly significant greenhouse gas (GHG) emitter. Emissions from all transport modes are growing rapidly, but emissions from road transport, especially motorized vehicles, represent the bulk of the total GHG emissions from transport. Climate change mitigation calls for a transition to low-emission transport. Therefore, transport policies for climate change have become one of the main drivers for the innovation and adoption of low-emission vehicle and fuel technologies. The present dissertation is an attempt to better understand the influences of recent environmental transport policies on the markets for motorized vehicles (i.e. passenger cars and other light-duty vehicles) and GHG emission reductions, such as $CO_2$ emissions. Other aspects are considered, such as local air pollution (e.g. $NO_x$, $SO_2$), noise, and congestion.

A transition to low-emission transport requires addressing a number of complications. For example, which vehicle technologies should be used to achieve the ambitions of $CO_2$ emission reductions from transport? What are the economic feasibility, social acceptance, and environmental impacts of the deployment of vehicle technologies? The history of cars shows patterns of inventing new technologies. Before the internal combustion engines, there were vehicles powered by steam — an external combustion process. Even earlier, wind-powered vehicles were designed. Nowadays, car manufacturing provides various options of low-emission vehicles in the market. We can improve the current internal combustion engines, for example, by blending gasoline with biofuel, or we can choose more environmentally friendly vehicles without internal combustion engines, such as electric vehicles.

One of the challenges with low-emission vehicles is that their vehicle fuel economy is often underestimated by consumers in the trade-offs with other attributes, such as engine power and vehicle size. Vehicle fuel economy — in litres per vehicle kilometre — is basically the same as the $CO_2$ emission rate (grams per vehicle kilometre), once fuel type is given. Therefore, the underestimation of vehicle fuel economy leads to consumers' relatively low willingness to pay for vehicles with low $CO_2$ emission rates. On the other hand, the prices of low-emission vehicles, such as electric vehicles, are higher than those of gasoline/diesel vehicles with similar characteristics. One of the main reasons is that the health and environmental damage costs of emissions from fuel combustion are not internalized in the costs of owning and driving vehicles without governmental interventions. This is known as market failure. Neo-classical economics indicates that government policies should be implemented to correct the externalities. Among countries, especially in Europe, environmental transport policies recently have tended to be based on the $CO_2$ emission rate as $CO_2$ emissions are regarded as a useful proxy for a car's wider environmental impacts. Those policies target three key factors that are used to measure the total $CO_2$ emissions from vehicles.

1) Vehicle fuel economy/$CO_2$ emission rate

The largest potential and most cost-effective $CO_2$ abatement opportunities in transport lie in improvements of vehicle fuel economy/$CO_2$ emission rate. The most frequently used policies for improving vehicle fuel economy/$CO_2$ emission rate are mandatory standards (i.e. Corporate Average Fuel Economy Standard in the US and $CO_2$ emission standards in the EU), vehicle taxes or subsidies based on vehicle fuel economy, or $CO_2$ emission rate. To bring down further the average $CO_2$ emission rate of a new car fleet, fiscal incentives are provided for adoption of electric vehicles. The influences of policies on vehicles sales and $CO_2$ emissions are explored in Chapter 1 with regard to an unorthodox and forceful $CO_2$-based Norwegian vehicle registration tax and in Chapter 2 for tax incentives that promote sales of battery electric vehicles in Europe.

2) Carbon intensity of automotive fuels

Reducing the carbon intensity of automotive fuels can also achieve $CO_2$ emission reductions from transport. This approach aims to decouple the vehicle $CO_2$ emission rate from fuel consumption, either by switching to fossil fuels with a lower carbon-to-hydrogen ratio or by replacing fossil fuels with renewable energy (i.e. hydrogen and biofuel). Although relevant policies are implemented, such as carbon taxes, biofuel blending mandates, and volumetric subsidies for biofuel, alternative automobile fuels face many challenges, such as technology limits, indirect emission sources, high production costs, and competition with food. In Chapter 3, we shed light on these issues by assessing ethanol tax credits and corn ethanol production in the US.

3) Vehicle kilometres travelled

Only a few government initiatives aim to reduce the total travel demand for $CO_2$ emission reductions, such as fuel tax, road pricing, and regulatory bans. For example, London has low-emission zones where access by high-emission vehicles is restricted while Beijing bans highly polluting old cars from being driven whenever air-quality alerts are issued in the city or neighbouring regions. In addition, there are policies to reduce unnecessary transport activities resulting from inefficient routing of vehicles, such as supplementing road signs or information technologies for routing guidance. These policies affect the travel demands of different drivers and consequently, have impacts on vehicle purchase decisions. In Chapter 4, we use a logistic company to illustrate the impacts of policies for electric vehicles on the company's decisions about vehicle purchases and routing plans in the context of urban freight transport.

The individual chapters of this dissertation address common issues in environmental economics for evaluating policy instruments to reduce $CO_2$ emissions from transport. However, the chapters rely on different methods — econometrics (fixed effects and instrumental variables), cost-estimation methods, life cycle analysis, economic modelling and optimization models. My graduate studies have taught me that flexibility and resourcefulness are among the most vital components of the modern researcher's toolkit. The mix of methods allows my PhD research to explore the influences of climate-related transport policies on vehicle sales and $CO_2$ emission reductions from different perspectives. The economic modelling reveals the mechanism behind the influences of policies on vehicle and transport-related markets, while the econometric methods provide tools to estimate the responses of the vehicle markets to the policies. The market responses to the policies can be explored further by using optimization models that simulate optimal decisions of individuals. Last, the cost-estimation methods and life-cycle analysis value the environmental impacts of market behaviour and their changes which are caused by policies.

# Summary

### Chapter 1: Greening the Vehicle Fleet: Evidence from Norway's $CO_2$ Differentiated Registration Tax

Chapter 1 estimates the responsiveness of new vehicle registrations (sales) to a $CO_2$ differentiated vehicle registration tax that aims to promote low-emission vehicles and reduce $CO_2$ emissions from transport.

The $CO_2$ element in Norway's vehicle registration tax was introduced in January 2007. Later, the $CO_2$ differentiated tax started rising. Since 2009, the vehicle registration tax has been adapted into a feebate form by giving rebates to relatively low-emission vehicles. Our study of Norway's forceful and unorthodox tax experiment carries important lessons.

In this chapter, we are interested in the responsiveness of new vehicle registrations — by vehicle type — to the vehicle registration tax. To identify the tax effect on vehicle registrations, both vehicle fixed effects and model-year-quarter fixed effects are used to control for vehicle characteristics and exogenous shocks to demand and supply. We analyse tax effects in different vehicle groups, and how vehicle registrations respond to taxes through vehicle prices, using instrumental variables. We also analyse alternative models in order to be well informed of the limitations and interpretations of our estimation techniques and results. Lastly, to provide useful policy implications, we use the tax coefficient estimates to investigate the response of the average $CO_2$ intensity in new vehicle sales.

We make use of the quasi-experimental nature of a string of sequential tax reforms from 2006 to 2014. We find that a 1000-NOK tax increment is associated with sales reduction of 1.13–1.58%. The estimated tax effect explains most of the reduced $CO_2$ intensity and yields an elasticity of average $CO_2$ intensity to the $CO_2$ price of -0.06. With pass-through to car prices of 88%, the tax yields a $CO_2$ elasticity to an average car's price of -0.53. An intuitive model with shifts between 'all' car types applies fairly well, as high-emitting segments lose market share and become $CO_2$ leaner, while low-emitting segments gain market share. The policy is costly, but shifts vehicles toward greater fuel efficiency.

## Chapter 2: The Economic and Environmental Impacts of Tax Incentives for Battery Electric Vehicles in Europe

Chapter 2 examines the role of tax incentives for battery electric vehicles (BEVs) in reducing the total ownership cost of BEVs, increasing sales of BEVs and therefore, reducing environmental externalities — $CO_2$ emissions and local air pollution. The tax incentives could be exemptions of vehicle taxes (vehicle registration taxes or annual circulation taxes) or subsidies for BEVs or higher vehicle taxes for internal combustion electric vehicles (ICEVs).

In our study, we compose comparable pairs of BEV–ICEV. Within each pair, BEVs and ICEVs have similar characteristics. Based on the vehicle pairs, we carry out cost benefit analyses and ordinary least square (OLS) regressions to assess the tax incentives for BEVs. First, we calculate total ownership costs of ICEVs and BEVs. The total tax incentive for a BEV is represented by the difference between the total vehicle taxes for a BEV and its ICEV counterpart. In light of heterogeneity in tax incentives, we compare the vehicle costs in three dimensions: cross-country, cross-(car) model, and cross-driver. Second, to estimate the influence of tax incentives on BEV adoption, we regress sales shares of BEVs on the total tax incentives for BEVs, controlling for country and (car) model-level differences. Lastly, from an environmental perspective, we compare the total tax incentives to the total reductions of $CO_2$ emissions and the total reductions of external costs when switching from an ICEV to a BEV.

Our assembly data cover 10 pairs of BEV–ICEV in 28 European countries from 2012 to 2014. The study offers a critical perspective to inform international debates on both the role of transport electrification and associated policy instruments. The results show that tax incentives, especially registration tax exemptions, significantly reduce total ownership costs of BEVs. Strong tax incentives can lower the requirements of annual distance travelled to achieve equal total ownership costs of ICEVs and BEVs. Furthermore, for larger vehicles, BEVs have much lower relative costs compared to their ICEV counterparts. Resulting from the cost reduction, a 10% increase of the total tax incentive is associated with an estimated 3–4% increase in the sales share of BEVs. Finally, the environmental benefits of switching to BEVs vary across countries. However, it is still costly to use tax incentives to reduce $CO_2$ emissions and other externalities through transport electrification, despite recent improvements in greening electricity generation and lowering battery costs.

## Chapter 3: How to measure greenhouse gas emissions by fuel type for binary sustainability standards: Average or marginal emissions? An example of fertilizer use and corn ethanol

Chapter 3 proposes a modelling framework to evaluate the interactions between energy and agricultural markets and calculate the greenhouse gas (GHG) emissions from biofuel production, considering the exogenous changes in energy prices and the Volumetric Ethanol Excise Tax Credit.

The increase in biomass production for biofuel (e.g. corn ethanol) is usually realized through an increase in the cultivated area or higher corn yield per unit of area. The latter is often proposed as a promising strategy to avoid undesirable indirect land-use change effects. The indirect land-use change is always accompanied by increases in GHG emissions and damage to biodiversity. These high yields are very likely to be realized by applying higher fertilizer application rates, which lead to higher GHG emissions per unit of corn. Therefore, higher crop yield might have similar GHG emission effects to indirect land-use change. To evaluate such emission effects from applying high fertilizer application rates, we establish a framework that consists of two parts: economic analysis of output–input relations in terms of market interactions between oil, natural gas, gasoline, ethanol, corn, and fertilizers, and life cycle analysis of emissions from the four main stages of a corn ethanol production chain — corn cultivation, corn transportation, ethanol production, and ethanol distribution.

We apply the framework to the case of corn ethanol production and nitrogen fertilizer in the US. The results show that, the increases of oil price and the implementation of the Volumetric Ethanol Excise Tax Credit stimulate corn-based ethanol production and increase corn yields by encouraging profit-maximizing farmers to increase their application rate of nitrogen fertilizers. The effect of the increases of oil price and the implementation of the tax credit is that, on average, GHG emissions per unit of corn ethanol remain almost constant, while marginal GHG emissions per additional unit of ethanol production vary from 96,97 to 157,53 $g$ $CO_2eq./MJ$. Although on average there are GHG emission savings of corn ethanol compared to conventional gasoline, the savings are negative when based on the marginal GHG emissions from corn ethanol production. An interesting implication is that the effectiveness of the Volumetric Ethanol Excise Tax Credit aimed at reducing GHG emissions might be questionable.

### Chapter 4: A framework to evaluate policy options for supporting electric vehicles in urban freight transport

Chapter 4 establishes a framework combining an optimization model with an economic analysis to evaluate the effects of policies for electric vehicles in the context of urban freight transport. This framework contributes to exploring the relationships among 1) policy measures, 2) an individual company's likely actions in response to the measures, 3) the effects on operational (routing) costs, and 4) the resulting changes to environmental impacts and welfare.

We consider three policies: purchase subsidy for electric vehicles; limited access (zone fee) to a congestion/low-emission zone with exemptions for electric vehicles; and vehicle taxes with exemptions for electric vehicles. In our framework, the optimization model is used to simulate a logistics company's cost-minimizing responses to the policies for electric vehicles. The responses are presented as the company's optimal decisions on vehicle fleet composition and routing plan. Based on the decisions, we calculate the external costs resulting from $CO_2$ emissions, local air pollution, and congestion. The marginal external costs vary, depending on the vehicle types (Electric Vehicle, EV or Internal Combustion Engine Vehicle, ICEV) and locations (inside or outside the zone). Last, we calculate the changes of social welfare resulting from the changes of the company's decisions when different policies are implemented.

Our results from the numerical experiments show that the purchase subsidy, zone fee, and vehicle taxes increase the electric vehicle share in the vehicle fleet, decrease the distances travelled by ICEVs, reduce external costs, and improve social welfare. Among the policies, the zone fee leads to the largest reduction in external costs, because it significantly reduces the distances travelled by ICEVs inside the congestion/low-emission zone where the marginal external costs of congestion and local air pollutants are higher. Although the vehicle taxes and subsidy have almost the same influences on the company and society, they perform differently at low tax/subsidy rates due to the different effects of tax and subsidy on vehicle routing plans. Finally, local factors at the company and city levels, such as vehicle type and transport network, are important for designing effective policies that support electric vehicles for urban freight transport.

# Chapter 1

# Greening the Vehicle Fleet: Evidence from Norway's $CO_2$-Differentiated Registration Tax

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## Abstract

Unorthodox but forceful fiscal policy reforms in Norway enable detailed inference about improving vehicle fuel efficiency and reducing $CO_2$ emissions. Since 2007, Norway has linked its vehicle registration tax to $CO_2$ intensities that on average have declined faster than elsewhere in Europe. Based on econometric analysis of data from 2006 to 2014, a 1000-NOK tax increment is associated with sales reduction of 1.13–1.58%. The estimated tax effect explains most of the reduced $CO_2$ intensity and yields an elasticity of average $CO_2$ intensity to the $CO_2$ price of -0.06. With pass-through to car prices of 88%, the tax yields a $CO_2$ elasticity to an average car's price of -0.53. An intuitive model with shifts between 'all' car types applies fairly well, as high-emitting segments lose market share and become $CO_2$ leaner, while low-emitting segments gain market share. The Norwegian policy is costly, but shifts vehicles toward greater fuel efficiency.

**Keywords**: $CO_2$ intensity, new vehicle, vehicle registration tax, fuel cost, green tax reform, greenhouse gas emission reductions

## 1.1 Introduction

Research on vehicle choice and use is relevant for policy objectives, such as energy security and greenhouse gas (GHG) emission abatement. We study how the selection of new vehicles sold — especially their $CO_2$ intensity and fuel efficiency — responds to rather forceful changes in taxation and fuel price[1].

Standards for fuel economy or GHG emissions are used for passenger vehicles and light commercial vehicles/light trucks in many countries (Atabani et al., 2011). The European Union first introduced mandatory $CO_2$ standards for new passenger cars in 2009, and by 2013, reached agreement regarding an emission target of 95 $CO_2$ $g/km$ averaged over all manufacturers (Mock, 2014). Many countries also use fiscal policy instruments, such as fuel taxes and vehicle taxes based on $CO_2$ intensity. From 2005 to 2010, the number of countries which adopted fiscal policy instruments to reduce vehicle $CO_2$ emissions (or fuel consumption) increased from 9 to 17 (He and Bandivadekar, 2011). At the same time, sales-weighted average $CO_2$ intensity of new vehicles in Europe has fallen steadily (Figure 1.1).

Norway has had a $CO_2$ element in its fuel taxes since 1991, while the $CO_2$ element in its vehicle registration tax was introduced in January 2007 with the explicit objective to reduce $CO_2$ emissions. Before that, the vehicle registration tax consisted of three elements: weight, engine power, and engine size[2]. In 2007, engine size was replaced by an element taxing $CO_2$ intensity, as reported in the registration document[3]. Later, the $CO_2$-differentiated tax has been rising per gram while other parts of the registration tax have declined. Since 2009, the vehicle registration tax has been adapted to a feebate form by giving rebates to relatively low-emission vehicles. Such a vehicle registration tax is a powerful climate policy instrument (Fridstrøm and

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[1] $CO_2$ intensity, in grams per vehicle kilometre, is basically the same as fuel efficiency (litres per vehicle kilometre), once fuel type is given (Smokers et al., 2009). We consider 'fuel efficiency', '$CO_2$ emission rate', and '$CO_2$ intensity' as equivalent. We do not include in our study other greenhouse gases nor any pollutant other than $CO_2$. Greenhouse gases other than $CO_2$ are generally not important in transport, except when natural gas is important.

[2] The weight/engine power/engine size/$CO_2$-differentiated taxes are progressive, based on those vehicle characteristics.

[3] The vehicle's official vehicle $CO_2$ intensity measure is determined by laboratory tests. The gaps between on-the-road and official $CO_2$ measures have been increasing over time (Tietge et al., 2015). Our present study merely takes these $CO_2$ intensity values as given, although we note that these questions raise demands both for improved laboratory measurements and for emphasis on complementary fuel taxation. The issue of improved tests is less critical for $CO_2$ than for air pollution species, such as $NO_x$, highlighted in the cases of Volkswagen and other makes.

Østli, 2017). Figure 1.1 shows Norway's declining sales-weighted average $CO_2$ intensity in new vehicles. Our study of the country's forceful and unorthodox tax experiment carries important lessons.

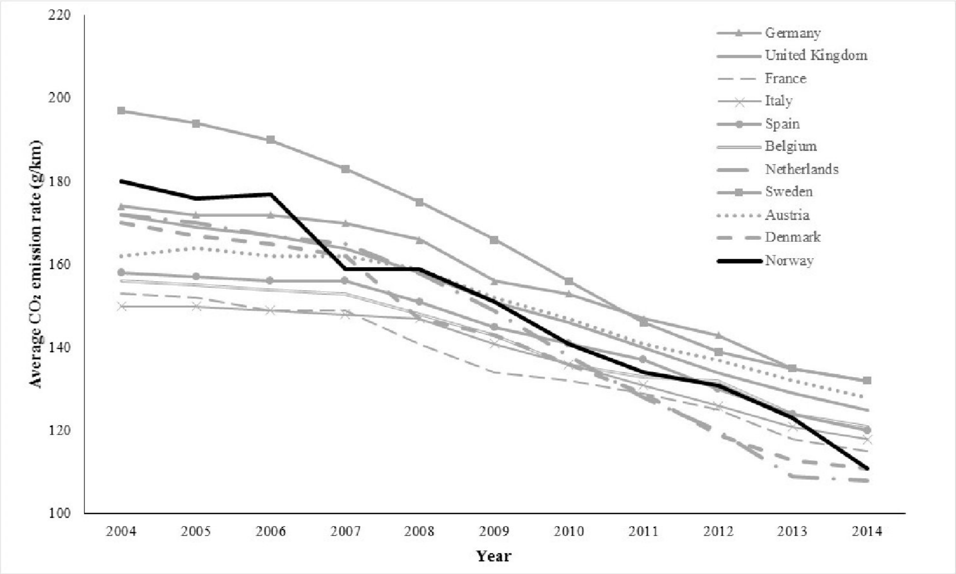

Figure 1.1: Average $CO_2$ intensity of new vehicles in selected European countries, 2004–2014.

Although there has been much research on fuel economy standards, few studies have contributed empirical ex-post analysis of $CO_2$-differentiated vehicle taxation. Examples of discrete choice models/multinomial logit models are Germany (Adamou et al., 2012a), Ireland (Giblin and McNabola, 2009), France (d'Haultfoeuille et al., 2014), Sweden (Huse and Lucinda, 2014), Norway (Østli et al., 2017), and Greece (Adamou et al., 2012b). Another econometric technique includes single equation methods (Ryan et al., 2009; Klier and Linn, 2015; Michielsen et al., 2015; Rivers and Schaufele, 2016; Alberini and Bareit, 2017). Ryan et al. (2009) and Michielsen et al. (2015) estimate the impact of a $CO_2$-differentiated vehicle tax on average $CO_2$ intensities across countries in the EU. Klier and Linn (2015), Rivers and Schaufele (2016), and Alberini and Bareit (2017) focus on the tax effects on registrations of vehicles with different emission rates in France, Canada, and Switzerland, respectively. Differently, an ex-ante assessment of the potential design and benefits of the $CO_2$-based feebate program is undertaken in a comprehensive study for California by Bunch et al. (2011).

In this study, we are interested in the responsiveness of new vehicle registrations — by vehicle type — to the vehicle registration tax. To identify the tax effect on vehicle registrations, both vehicle fixed effects and model-year-quarter fixed effects are used to control for vehicle characteristics and exogenous shocks to demand and supply. We analyse tax effects in different vehicle groups, and how vehicle registrations respond to taxes through vehicle prices, using instrumental variables (IVs). Lastly, we use the tax coefficient estimates to investigate the response of the average $CO_2$ intensity in new vehicle sales.

This study contributes to the literature in three ways. First, we provide insights into the structure of the $CO_2$-differentiated vehicle tax for questions of interest in policy decision making. Previous empirical research on this tax in Norway was conducted using a difference-in-difference approach; Ciccone (2014) studied changes in $CO_2$ intensity (and the shares of diesel cars and high-emission cars) by treating the introduction of the tax in 2007 as a one-time uniform incident for all vehicles. By contrast, we study how the tax reforms yield different tax liabilities to vehicles with different characteristics. We make use of the quasi-experimental nature of a string of sequential tax reforms from 2006 to 2014 as follows: (i) the tax is based on $CO_2$ intensity and other vehicle characteristics, (ii) time variation through the reforms on tax design and structure, and (iii) notches created by threshold values of vehicle characteristics. This enables detailed evaluations and identifies a reduced-form purchase response without many of the problems (e.g. unobserved heterogeneity issues) that can influence more structural vehicle choice models. Second, for robustness analysis, we analyse alternative models in order to be well informed of the limitations and interpretations of our estimation techniques and results. We include an IV approach to introduce vehicle price information in the evaluation of tax effects (at the cost of fewer observations). Third, for a better interpretation of the results, we explain economic concepts for the empirical estimations and perform counterfactual analyses for policy purposes.

Our main findings are based on data for private passenger vehicle registrations from 2006 to 2011. We observe a consistent reduction in the sales-weighted average $CO_2$ intensity of new vehicles, from around 177 $g/km$ in 2006 to 134 $g/km$ in 2011. We identify the part of this reduction that is associated with the changes in Norwegian new vehicle taxes, while we admit that emission intensities are affected by other factors (e.g. changes in income, technological change, and EU policies).

Our econometric results show that an average vehicle's sales (or registration of new vehicles) fall by an average 1.13–1.58% for a 1000-NOK (125-USD) tax increase. We find that the introduction of the $CO_2$-differentiated tax in 2007 explains the majority (79%) of the average $CO_2$ intensity reductions from 2006 to 2007. The estimated elasticity of $CO_2$ intensity to the $CO_2$ price is -0.06. This might sound like very tiny responsiveness, but is actually not considering that the effect works through car prices, and that the $CO_2$ tax is a moderate contributor to average car costs. With pass-through to car prices of 88%, the tax results in an elasticity of $CO_2$ intensity to car prices of -0.53.

An important expected feature is that high-emitting segments lose in share and become $CO_2$ leaner, while low-emitting segments (small and light cars) gain in share and do not become $CO_2$ leaner owing to the substitutions from larger and heavier vehicles. We find both moves between and within nine predefined segments to be important in lowering the average $CO_2$ intensity in new vehicle sales.

The rest of this chapter is organized as follows. Section 1.2 introduces the Norwegian new vehicle registration tax and vehicle market in Norway. Section 1.3 presents some economic concepts, and in Section 1.4, empirical approaches are proposed. In Section 1.5, we present the results from estimation models as well as robustness analysis. Section 1.6 provides counterfactual analysis to highlight policy implications, and Section 1.7 concludes.

## 1.2 The new vehicle registration tax and market in Norway

Our data on vehicle registrations and taxes extend from 2006 to 2014, but we highlight data for gasoline and diesel cars from 2006 to 2011. This is primarily because from 2012, a $NO_x$ fee and other policy instruments supporting EVs were introduced (e.g. privileges in bus lanes and tolls) that we can incorporate or represent only poorly.

### 1.2.1 The $CO_2$-differentiated vehicle registration tax

Figure 1.2 presents the $CO_2$ tax schedule by year, visualizing the changes of the vehicle registration tax on new vehicles. As a progressive tax based on $CO_2$ intensity, the tax features discrete jumps in tax rates at cut-offs (or pivot points), represented by the kinks on each line. The second main reform took place in 2009, when a subsidy ('rebate') was introduced to yield a ‘feebate’ form, shown below the X-axis. Apart from these two main reforms, the vehicle registration tax is subject to policy adjustments every year by January 1. The reforms have changed tax rates and pivot points for $CO_2$ as well as other tax components (not shown) affecting vehicles with different $CO_2$ intensities and other vehicle characteristics. As shown in Figure 1.2, from 2006 to 2011, the slopes become steeper, since the tax gap between low-emission and high-emission vehicles is extended.

As the Norwegian $CO_2$-differentiated vehicle registration tax is smooth and continuous, it sends a tax/price signal for all steps in $CO_2$ intensity. Among the schemes of other European countries, the Netherland’s scheme is based on vehicle characteristics and prices. The French system has fixed taxes or subsidies for emission groups without being continuous in $CO_2$ intensity. Some other countries (e.g. Sweden and Germany), have implemented $CO_2$-differentiated annual circulation taxes.

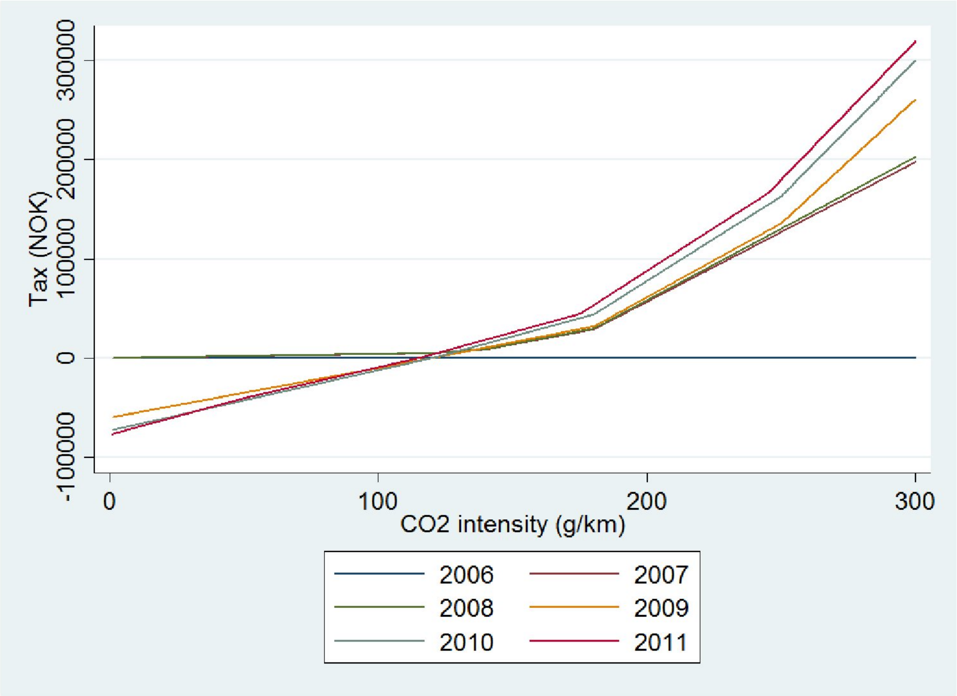

Figure 1.2: $CO_2$-differentiated registration tax in Norway.

### 1.2.2 The Norwegian new vehicle market

In Norway, about 100000 new private passenger vehicles are registered annually. We focus on new vehicle registrations: there is no vehicle manufacturing in Norway, and only smaller numbers of used cars are imported, often privately. The car importers pay a depreciated version of the new vehicle registration tax. The number of annual vehicles purchased is reasonably stable, but is subject to variations, including income shocks, as is often the case for consumer durables. The number of annual vehicles purchased decreased during the financial crisis in 2008 and 2009. Such phenomena, including seasonality, are picked up in our econometric analysis.

Figure 1.3 shows a downward trend in the sales-weighted average $CO_2$ intensity for new passenger vehicles from 2006 to 2011. In November and December 2006, average $CO_2$ intensity increased dramatically, reflecting that tax changes are typically announced through budget negotiations in parliament in autumn, while the introduction in 2007 of a $CO_2$ tax was proposed in a report and hearing even earlier. These end-year peaks reflecting purchases of high-emission vehicles are observed every year before annual tax adjustments.

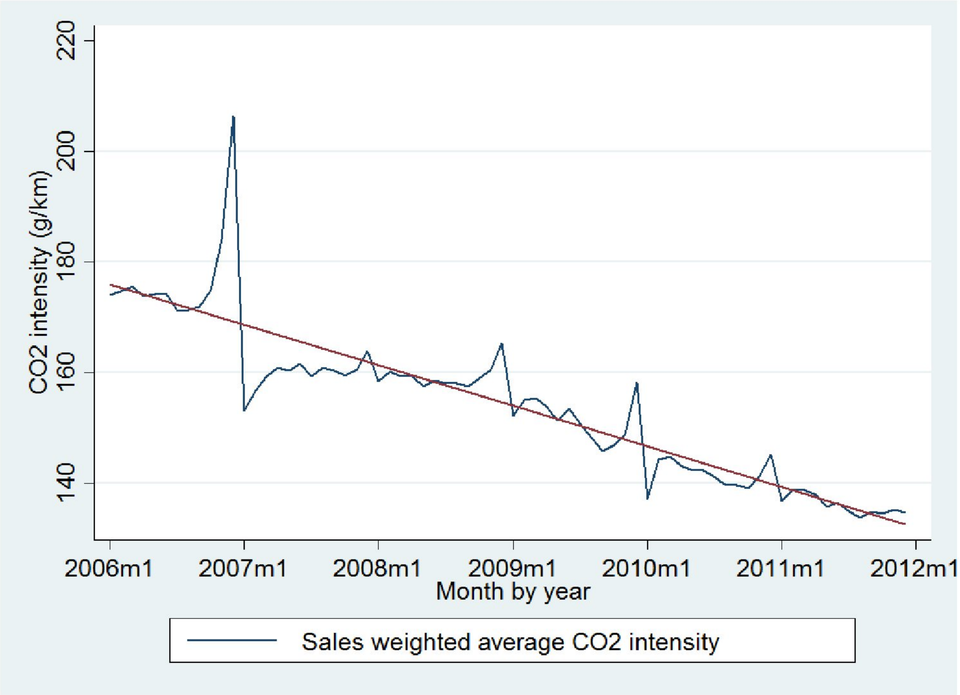

Figure 1.3: Monthly sales-weighted average $CO_2$ intensity of new vehicles in Norway, 2006–2011.

Beyond these averages, Figure 1.4 displays the shifting distributions of new car sales over emission groups from 2006 to 2007. The introduction of the new tax in 2007 raised sales of vehicles with intensity less than 180 $g/km$ and reduced sales of vehicles with more than 180 $g/km$, reducing the average $CO_2$ intensity by about 10%, from 177 $g/km$ to 159 $g/km$. Over the longer term to 2011, the intensity has fallen by about 26%. Similar shifts are observed in more narrowly defined groups, for instance, between types chosen of Volkswagen's Golf model.

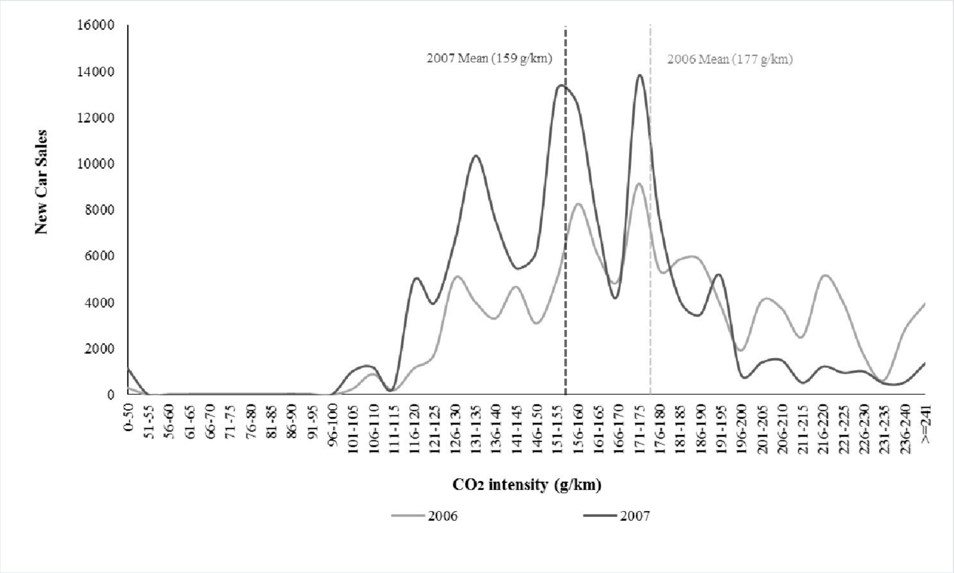

Figure 1.4: Distribution of new passenger vehicles by $CO_2$ intensity in Norway.

Although these graphs (Figure 1.2, 1.3, and 1.4) tell an important story, many factors might lie behind these movements, motivating our econometric model to identify the response to the Norwegian registration tax changes. A further study of Figure 1.4 reveals that thresholds of the $CO_2$ tax do not create 'bunching' of $CO_2$ intensities by calculating the ratio of sales below and above but near the thresholds (plus and minus 2 grams). This might be attributed to the continuity of the tax and to the minor role of Norway in vehicle markets.

Other important aspects behind the continuously decreasing trend in average $CO_2$ intensity can illustrate our demand analysis. First, since diesel vehicles deliver the same driving with lower $CO_2$ emissions, the share of diesel vehicles increases from 48% in 2006 to 76% in 2011. Second, in the short term, small changes can be made in vehicle materials, styling, and weight to improve the fuel economy of a vehicle, while in the long term, technical improvements might allow the same vehicle weight and engine power with a lower emission rate. Our study needs to take account of the possibility that these changes occur for reasons independent of Norwegian policies.

## 1.3 Economic concepts

From a welfare economic perspective, coordination of behaviour for the purposes of providing a 'global public good' involves a tax (or tradable quotas) on $CO_2$ emissions, equivalent to taxes on each fuel differentiated by their $CO_2$ content. Thus, a $CO_2$-differentiated tax on the sale of new cars is at best 'second best'. This might be regarded pragmatically as a sensible strategy in a transition phase, or a way to instigate transformation of the stock of 'polluting durables' (cars) and technology to make the economy less dependent on $CO_2$. Unlike a Pigouvian tax that is placed on the quantity of $CO_2$ emissions, this $CO_2$-differentiated registration tax aims to influence car choice but not car usage.

The registration tax might encourage consumers to buy smaller cars with relatively low emissions. The idea of taxing the $CO_2$ emission rate is that there might be many ways — not only being smaller — that a car with lower emissions can suit certain preferences. Similarly, since taxing emitted $CO_2$ itself would allow incentives to an even wider range of responses (e.g. driving less or ridesharing), we should notice that the responses studied here are part of what is needed to evaluate broader combinations of policy instruments.

King (2007) estimates that choosing the lowest $CO_2$ emitters in any car market segment can make a difference of about 25% to fuel efficiency and $CO_2$ intensity. To convey and discuss the underlying intuition of the vehicle registration tax, we take a representative consumer approach for the new vehicle market. We restrict attention to the demand side, since the Norwegian market is too small to influence car manufacturers, and the incidence of tax falls predominantly on the buyer. In a simple model with two car types, the representative consumer chooses the quantities of high-emission vehicles $Q_H$ and low-emission vehicles $Q_L$ with utility given by:

$$U = U(Q_L, Q_H) \tag{1.1}$$

The consumer maximizes utility subject to a budget constraint:

$$M = C_L Q_L + C_H Q_H \tag{1.2}$$

where $C_i$ ($i = H$ or $L$) is the lifetime ownership cost[4].

A constant elasticity of substitution (CES) utility function could illustrate how the responsiveness to a $CO_2$-differentiated vehicle tax depends on the substitutability between the high-emission vehicle and its 'substitute'. Abstracting from income effects and focusing on inter-vehicle substitution in this simple two-good case, we would expect

$$\frac{\partial Q_H}{\partial T_c} < 0 < \frac{\partial Q_L}{\partial T_c} \tag{1.3}$$

Taxing high-emission vehicles more than low-emission vehicles (a feebate could be used to tax high-emission vehicles while subsidizing low-emission vehicles) raises sales of low-emission vehicles, but reduces sales of high-emission vehicles. High sales change reflects high elasticity of substitution, so that when carbon is taxed more heavily, there are substantially higher sales of light vehicles, but substantially lower sales of heavy vehicles. It is possible that both types of vehicles experience reductions in sales with a relatively smaller reduction by low-emission vehicles; this would be when substitutability between cars is low but car demand as a whole is fairly elastic (e.g. when bicycles are an alternative).

Our case with multiple vehicle types is different. This is best observed as we shift focus from the consumer to vehicle types. For a rising $CO_2$-based tax, most vehicle types will lose demand to lower-emission vehicles, but also gain demand from higher-emission vehicles. Indeed, one special case for the response is that all types lose as much demand as they gain, except the most high-emission type, which only loses demand and the most low-emission vehicles, which only gain demand. In fact, from an environmental perspective, what matters is the total effect on average $CO_2$ intensity. Most importantly, the logic we take from this simplistic case is that a heterogeneous range of vehicles might have many 'substitutes'. For most vehicle types, we can imagine substitutes that are more highly emitting, equally emitting, or less emitting. We cannot say in advance that we know which vehicle types are the substitutes of a given vehicle type, even though we might have some ideas. This, of course, influences our strategy when we

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[4] $C_i = (P_{i,t_0} + T_{i,t_0}) + \sum_{t=0}^{T_i} \frac{M_{it} + act_{it} + (fp_t + ft_t) fe_i D_{it}}{(1+\rho)^t}$. $P_{i,t_0}$ is the price of a vehicle before vehicle registration tax at purchasing moment $t_0$. $T_{i,t_0}$ is the vehicle registration tax liability of a vehicle $i$ at purchasing moment $t_0$. $(P_{i,t_0} + vrt_{i,t_0})$ is the price the consumer pays for a car. Mit is the maintenance cost. $act_{it}$ is the annual circulation tax. $D_{it}$ is the total distance driven $\rho$ is the discount rate. $fp_t$ is the pre-tax fuel price and $ft_t$ is the fuel tax. $fe_i$ is the fuel economy of a vehicle $i$.

attempt to estimate responsiveness to the $CO_2$ tax reforms.

## 1.4 Econometric approach

This research aims to estimate the effect of the vehicle registration tax on the composition of new car sales (registrations) in Norway. Cars represent a heterogeneous range of products that are differentiated in many quality dimensions. When $CO_2$ intensity becomes more expensive, some of the quality dimensions become more expensive to deliver, leading consumers to make sacrifices, either by shifting to other vehicle types (e.g. with less horsepower) or to accept the higher purchase cost.

Our task is to establish a model of this responsiveness in car demand. In doing so, we admit that when a product is differentiated in many dimensions, we might lack prior ideas of which product types are close substitutes to others. In line with the literature and industry terminology, we could use industry defined ‘segments’. As an example, vehicle types within the segment ‘subcompacts’ might be close substitutes to each other. In addition, ‘subcompacts’ might be closer substitutes to vehicles in the ‘small car’ segment than in the ‘large car’ or ‘sports utility vehicle’ segments. In addition, within the more narrowly defined category of ‘model’ (e.g. Volkswagen Golf), we could assume that vehicle types with certain similar characteristics (e.g. engine sizes) are close substitutes. Finally, one idea that we exploit is that substitutes are found in a vehicle type’s ‘neighbourhood’ in the $CO_2$ intensity dimension. As $CO_2$ intensity is itself associated with quality dimensions, ‘$CO_2$ neighbourhoods’ might indicate substitutability. If a vehicle type emitting 120 $g/km$ increases in price, then less $CO_2$-intensive vehicles (e.g. 118 $g/km$) might benefit from this with increased demand, while a vehicle with 122 $g/km$ might lose demand. This assumption is not typical in the literature, but is worth checking for us because of the policy experiment in relative prices and its motivation. Importantly, we exploit the fact that we have very finely defined product types in our dataset. This implies that if we study changes in demand by vehicle type without limiting ourselves to specific assumptions of demand systems — making generous use of fixed effects — we can still recover important features of the responsiveness we seek.

Our data cover a period in which the $CO_2$-differentiated registration tax varies in a way that affects all new vehicles. Therefore, a difference-in-difference approach would not be able to identify tax effects on new vehicle demand appropriately. Similarly, methods making specific assumptions of substitution and grouping, such as by segment, multinomial logit, or nested CES, would be difficult to justify because of the assumptions regarding preference structures that would then discard information we want to use in our study.

Apart from the concept of 'segment', we use two concepts to categorize cars as follows. A car 'model' is a family of car types delivered by a manufacturer that sells several such families (e.g Golf from Volkswagen; and Avensis from Toyota). Such a 'model' then has many family members, and we use the term 'type' for each such car specified in fairly narrow detail (e.g. Golf, horsepower, and five doors).

To focus on the demand effects of tax changes and avoid the hazards of assumptions regarding substitution between vehicle types, we use a linear equation for vehicle sales in Equation 1.4. Later, we relax the linearity assumption in Equation 1.5. Our approach is tailored to fit the policy context as well as the available data. In particular, our approach controls for contemporaneous shocks in demand and supply with the help of fixed effects. The approach is informed by and in the spirit of Klier and Linn (2015) and Chandra et al. (2010).

$$\ln Q_{it} = \alpha T_{it} + \beta FC_{it} + \gamma_{jt} + \delta_i + \varepsilon_{it} \tag{1.4}$$

where the dependent variable, $Q_{it}$ is the number of new vehicles of type $i$ registered at time $t$. The registration tax $T_{it}$ is the prime interest in this research. $FC_{it}$ represents fuel costs. $\gamma_{jt}$ is a model-year-quarter fixed effect ($j$ represents car model), while $\delta_i$ is a vehicle type fixed effect. $\varepsilon_{it}$ is an error term.

Equation 1.4 uses the log form of new vehicle sales, since sales changes in the percentage form can be an appropriate formulation when we consider changes over time associated with tax changes. The tax would be less appropriate in the log form due to its non-positive values and non-linear relationship between log price and log tax.

Vehicle type $i$ is defined more narrowly than a unique car model, by including fuel type (gasoline or diesel), engine power, engine size, weight, and $CO_2$ intensity. Vehicle type is constructed from the original data (Table 1.1). Around 100000 new vehicles are sold and registered annually, distributed over about 2800 vehicle types that belong to about 240 vehicle models. The national level of aggregation matches the national level application of the vehicle registration tax.

Table 1.1: Number of observations by aggregation level.

| | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** |
|---|---|---|---|---|---|---|
| **Car model** | 243 | 247 | 251 | 256 | 253 | 239 |
| **Vehicle type** | 2758 | 2666 | 2777 | 2792 | 2826 | 2658 |

Time $j$ is defined by year and quarter in our main estimations. During the period from 2006 to 2011, no other relevant national polices were introduced[5]. The quarter as time unit allows us to control for policy pre-announcement effects and to include independent variation in the prices of vehicle fuels as well as other shocks[6]. Robustness checks are undertaken in Section 1.5.2, including variations around Equation 1.4.

$T_{it}$, the total vehicle registration tax, is the sum product of the value of vehicle characteristics and corresponding tax rates. The tax consists of three parts — weight-based tax, engine power-based, tax and engine size-based tax, with the latter shifting to a $CO_2$-based tax by January 2007. The changes of the $CO_2$-based tax account for the majority of the total vehicle registration tax changes. Our focus on the sum of the taxes is mainly motivated by the policy experiment, which does not provide alternative shocks to the various elements in the tax changes. As for the high correlations among vehicle characteristics that the taxes are based on, the sales response of a given specific vehicle type to a tax change should be the same irrespective of its ‘origin’. According to Norwegian marketing laws, listed prices include taxes, and buyers are not informed about or interested in the various tax components.

The tax effect on sales that we estimate subsumes the impact of market responses caused by changes in the new vehicle registration tax and omitted price effect. While we explore the tax effect through prices later in Equations 1.6 and 1.7, we notice here that the tax change might be incompletely passed through to consumers.

Fuel prices affect vehicle purchases (Kahn, 1986; Eskeland and Feyzioğlu, 1997; Klier and Linn,

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[5] Instruments supporting electric vehicles include free tolls and bus lanes, and thus, comprise local variations in policy. Electric vehicles started being important from 2012, which is one reason we emphasize the data before 2012 in our analysis.

[6] The pre-announcement effects refer to consumers responding to the future tax change. In the last quarter of each year (2006 in particular), average $CO_2$ intensity has a peak (Figure 1.3).

2013). Equation 1.4 includes fuel cost per kilometre, $FC_{it}$, which is not just of interest in itself, but also helpful in identifying the effects of the vehicle registration tax[7]. Fuel cost per kilometre is calculated by fuel price ($NOK/liter$) and fuel consumption ($liters/km$), using the fuel price when the vehicle is purchased as a proxy for expected fuel prices. Other costs are not included. They would anyway be about invariant for car specifications within the same model, and thereby are captured by fixed effects.

Two fixed effects are included. A time-invariant fixed effect $\delta_i$ is defined at the level of vehicle type. The model-year-quarter fixed effect, $\gamma_{jt}$ is defined by the interaction between a unique model $j$ and year-quarter $t$. $\delta_i$ controls for all characteristics of vehicle types that do not vary over time. $\gamma_{jt}$ controls for shocks at the model level, both to demand and supply, such as economic crisis in 2008 or exchange rate movements, policy pre-announcement effects, and changes of unobserved vehicle model characteristics, including technological change, policies in Europe. These fixed effects enable us to control for preferences for particular car models over time. They pick up such broad phenomena as model shifts due to the effect of income growth.

Our approach allows us to take account of observable and unobservable aspects of policies, model changes, and changes within models. An individual car model might be produced for a decade or more, while the manufacturer tends to redesign passenger vehicles and introduce new versions at the start of the calendar year in Europe (Klier and Linn, 2015). As we control for vehicle make, model, fuel type, fuel economy, weight, and engine characteristics, other year-to-year physical changes of vehicles are minor. However, these changes are picked up by our 'vehicle type' definition in our characteristics, or otherwise by fixed effects. As an example of how our approach accounts for exogenous shocks and developments, Norway does not have a fuel economy standard. Within the EU, however, a $CO_2$ emission standard is implemented on vehicle manufacturers[8]. The standard as well as other drivers of technological change and car supply might affect the fuel economy/$CO_2$ intensity of new vehicles supplied to the Norwegian market. In our approach, both the standard and other drivers are captured by the fixed effects for the model that includes quarters. The responsiveness to tax changes in Norway is estimated by controlling for such exogenous developments.

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[7] Collinearity between registration tax and fuel cost is avoided, as the latter includes quarterly fuel price, whereas the vehicle registration tax changes only by year (in January).

[8] The 2009 regulation set a 2015 target of 130 $g/km$ for the fleet average of all manufacturers combined (similar in principle to the US corporate average fuel economy standard, CAFÉ). Individual manufacturers are allowed a higher $CO_2$ emission value, depending on the average vehicle weight of their fleets (Mock, 2014).

Although the model-year-quarter fixed effects are useful for identifying the tax effect, they absorb some of the data variation and thus, leave only the within-model (between vehicle types) variations to identify our demand responsiveness parameter, $\alpha$. These within-model variations account for a significant share of the overall consumer purchase response. Vehicle types vary a lot within car model (Table 1.1). On average, there are 11–15 type specifications within one vehicle model.

In our main formulation in Equation 1.4, the coefficient $\alpha$ represents the percentage change in vehicle type sales with respect to its tax change. For robustness, we use broader segment-year-quarter fixed effects. These allow more of the total variation for identification, since there are nine segments, compared to about 240 car models. We also test broader groups and 'neighbourhood' in the $CO_2$-intensity dimension in our fixed effects. Compared to segments and groups, such as '$CO_2$ neighbourhood', car model is naturally grouped by physical features and the manufacturers' production strategies. As a preamble to our discussion in the results section, the model-year-quarter fixed effects in our view represents a balance between controlling for demand/supply shocks and retaining sufficient variation for estimation. Other formulations for robustness checks, including relative tax effects, are discussed below.

In Equation 1.5, an interaction term is included to allow a difference in slope $\alpha$, either for each vehicle segment $k$, or similarly for different vehicle groupings, or simply with a quadratic term for the tax.

$$\ln Q_{it} = \alpha_1 T_{it} + \alpha_2 T_{it} g_k + \beta_1 FC_{it} + \gamma_{jt} + \delta_i + \varepsilon^*_{it} \tag{1.5}$$

An important additional inquiry is how the effect of the tax is conveyed through market prices to vehicle sales. A reason we do not allow this as our main analysis is that the price data have weaknesses. First, the price data are incomplete and reduce the number of observations, largely due to mismatches between the vehicle registration and price data. Second, the price data represent list prices, and therefore, might suffer from endogeneity bias as well as inaccurately reflect actual transaction prices. An increase in demand might cause a vehicle price increase, resulting in spurious correlation between the price and regression error, and could bias estimates.

Our IV approach in Equations 1.6 and 1.7 regresses vehicle registrations $Q_{it}$ on vehicle prices $P_{it}$.

This addresses the endogeneity issue, as the registration tax is used as an IV for the price[9]. The vehicle registration tax accounts for a significant part of the vehicle type's sales price variation, and thus, with type fixed effects, is highly predictive of vehicle prices. The vehicle registration tax is independent of vehicle demand. Therefore, we adopt a two-stage least squares method for the IV estimation: First stage:

$$\ln P_{it} = \pi_1 T_{it} + \lambda_1 FC_{it} + \gamma_{jt} + \delta_i + \mu_{it} \tag{1.6}$$

Second stage:

$$\ln Q_{it} = \pi_2 P_{it} + \lambda_2 FC_{it} + \gamma_{jt} + \delta_i + \upsilon_{it} \tag{1.7}$$

As a result, the responsiveness of vehicle sales to the tax is $\pi_1 \times \pi_2$. We use this approach to discuss our main results from Equation 1.4. This IV approach has an important advantage (discussed by Gavrilova et al. (2015)) in interpreting the estimated tax effect. For instance, if there is no response to tax changes in vehicle sales, our reduced-form approach in Equation 1.4 cannot distinguish between 'no pass through of the tax to the price' and 'no price responsiveness in demand'. Further interpretations require discussions in light of the fixed effects and the limitations of the price dataset. Pricing decisions are made separately by car companies while the tax reforms are instituted uniformly. Our model-year-quarter fixed effects fit the estimation of the tax effect rather than the price effect.

## 1.5 Results and discussions

### 1.5.1 Results from main specifications

Table 1.2 reports the estimated coefficients of the registration tax and vehicle fuel cost from Equation 1.4. The first row presents the tax coefficients, followed by robust standard errors. The tax coefficients are statistically significant and with expected sign, and so are the fuel cost coefficients (second row). Summary statistics are presented in Appendix Table 1.8.

The tax coefficient in Model 1 indicates that a tax increase of 1000 NOK (about USD 125)

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[9] There is a tradition to instrument for gasoline prices using gasoline taxes in order to estimate the responsiveness of gasoline consumption (Coglianese et al., 2017). Our IV approach is inspired by this.

reduces a vehicle's sales by 1.26%[10] . The sales weighted average Norwegian vehicle registration tax is around 101374 NOK, so our estimated coefficient implies a demand elasticity with respect to the tax is of -1.28 at sample means. With highly 'tax-sensitive demands', the coefficient indicates that in general any vehicle type has close substitutes.

The fuel cost coefficient in Model 1 indicates that an increase of 1 NOK in cost per vehicle kilometre (about 112000 NOK per year) would reduce demand by 94%. To compare the fuel cost sensitivity parameter with the tax sensitivity parameter, we use an annual cost increase of 15000 NOK (15000 vehicle kilometres per year is the Norwegian car average) and discount it at 10% over 12 years of expected lifetime to arrive at an upfront cost. Then, the estimated fuel cost sensitivity translates into about 75% of the tax sensitivity, indicating that buyers discount future fuel costs at a higher discount rate or a lower expected lifetime, which are both plausible in light of earlier literature.

Based on vehicle registration data from 2006 to 2011, Table 1.4 shows four model specifications, all of which include vehicle type fixed effects that account for characteristics and preferences that are constant for a vehicle type. In addition to vehicle type fixed effects, the first specification includes the model-year-quarter fixed effects. These pick up and eliminate shocks down to each quarter and every model. In Model 2, we replace type-year-quarter fixed effects with segment-year-quarter fixed effects, which are less finely disaggregated. In Model 3, we leave behind such specifications as model and segment, and rather include fixed effects for a close 'neighbourhood' of vehicle types in terms of $CO_2$ intensities. In Model 4, we disaggregate observations to Norway's 20 counties and include county fixed effects.

An increase in the vehicle registration tax reduces vehicle registrations significantly in all specifications. Except for Model 2, the tax coefficients are about the same, varying around -0.0126 from -0.014 to -0.011. In Model 2, the tax effect on vehicle registration is smaller, but in light of Model 4, we interpret this to reflect that the broader segment-fixed effects control insufficiently for exogenous demand and supply shocks. As one of the stepwise tests with fixed effects, an original regression without controlling for any exogenous shocks shows an even smaller tax effect (-0.009). In conclusion, we prefer the first specification (Model 1), which includes the

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[10] Our estimate is around 0.101, corresponding to a tax increase of 1000 Euros. It is within the range of the tax coefficients estimated by Klier and Linn (2015) where log vehicle registrations are reduced by 0.561 (France), 0.18 (Germany) to 0.008 (Sweden). The various tax coefficients possibly can be explained by the differences in tax structure.

model-year-quarter fixed effects, as explained in Section 1.4. In addition, Model 1 has the best fit in terms of $R^2$.

Table 1.2: Estimates of the registration tax effects on registrations of new vehicles in Norway.

| | **Model 1** | **Model 2** | **Model 3** | **Model 4** |
|---|---|---|---|---|
| **Tax** | -0.0126*** | -0.0055*** | -0.0142*** | -0.0106*** |
| | (0.0012) | (0.0008) | (0.0031) | (0.0004) |
| **Fuel cost** | -0.9448* | -1.2653 *** | -1.3929 | -1.0530*** |
| | (0.4346) | (0.3617) | (0.7869) | (0.1381) |
| **Vehicle type FEs** | Yes | Yes | Yes | Yes |
| **County-model FEs** | | | | Yes |
| **Model-year-quarter FEs** | Yes | | | Yes |
| **Segment-year-quarter FEs** | | Yes | | |
| $CO_2$**-neighbourhood-year-quarter FEs** | | | Yes | |
| **Number of observations** | 34552 | 35585 | 33295 | 197887 |
| **Adjusted** $R^2$ | 0.65 | 0.62 | 0.63 | 0.53 |

Note: *$p<0.05$, **$p<0.01$, ***$p<0.001$. For readability, tax is divided by 1000.

### *Estimating more detailed tax effects for different vehicle groups*

In Table 1.3, we introduce variations allowing the tax effect to vary across the range of vehicles. In Model 1, we give the tax itself a possibly non-linear role by introducing a quadratic term. In Model 2, vehicles are grouped according to brackets of the $CO_2$ intensities[11] . In Model 3, the vehicles are grouped into segments from the original dataset (nine segments from 'mini' through 'SUV'). For Models 2 and 3, the coefficient estimates represent a tax coefficient additive to the tax coefficient in the top row. All three models allow more details than the overall average tax effect estimated in Table 1.2, and a pattern is that the marginal effect of a 1000-NOK tax change is lower for heavier vehicles. This is plausible, since for high-emission vehicles, a given tax increase represents on average a smaller share of the vehicle's tax and price.

### *Exploring how the tax works through vehicle price with two-stage least squares*

The registration tax with its $CO_2$ element has its effect on vehicle registrations through its influences on the vehicle's tax-inclusive price. Here, we ask how the tax influences the vehicle

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[11] Emission groups: (0–50 $g/km$), (51–120 $g/km$), (121–140 $g/km$), (141–160 $g/km$), (161–180 $g/km$), (181–200 $g/km$), (201–220 $g/km$), (221–250 $g/km$), and (>251 $g/km$)

price and how the price influences demand. Table 1.4 presents the results for Equations 1.6 and 1.7 using IVs. The first column (First stage) shows an estimated effect of a tax increase on the vehicle's price of 0.8846 with a small standard error 0.0163. This indicates that 88% of tax variations are passed on to buyers[12] . In other words, a small part of the tax change (11%) is borne by manufacturers. The second column shows that the estimated effect of the vehicle's price on demand is -0.0179 with a standard error 0.0025[13]. Combining the two columns, the effect of the tax on vehicle registrations is the product of the coefficients for tax and price, which is 0.0158. This is quite close to the estimated coefficients we obtained in the direct approaches of Table 1.2 for Equation 1.4, indicating that our reduced sample for the IV model does not involve important bias.

The IV approach has the advantage of being more economically intuitive and meaningful, and addresses endogeneity. However, in the end, we are mostly interested in the tax effect, and are concerned about the reductions in observations and the quality of the price data. For these reasons, in our further analysis, we concentrate on direct estimates, not the two-stage (IV) ones[14].

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[12] Simply regressing prices changes on tax changes without model-year-quarter fixed effects, we get similar estimate for the tax coefficient.

[13] The price effect seems to be large. But it is explained in the light of fixed effects in the section 1.4.

[14] For policy, the tax change share not passed through works against the registration tax's objective of enticing demand substitution toward less carbon emissions, might also give incentives to manufacturers to find ways to deliver cars with less $CO_2$.

Table 1.3: Estimation of tax effects: different vehicle groups.

| | **Model 1** | **Model 2** | **Model 3** |
|---|---|---|---|
| | Tax groups | $CO_2$ groups | Segments |
| **Tax** | -0.0222*** | -0.0668*** | -0.1399*** |
| | (0.0018) | (0.0085) | (0.0286) |
| **Fuel cost** | -1.0778* | -0.8899*** | -0.9940* |
| | (0.4332) | (0.4325) | (0.4336) |
| **Tax_squared** | 0.00001*** | | |
| | (0.0000) | | |
| **Group 2** | | 0.0344*** | 0.0978*** |
| | | (0.0098) | (0.0302) |
| **Group 3** | | 0.0316*** | 0.1268*** |
| | | (0.0094) | (0.0288) |
| **Group 4** | | 0.0441*** | 0.1222*** |
| | | (0.0108) | (0.0287) |
| **Group 5** | | 0.0402*** | 0.1233*** |
| | | (0.0095) | (0.0287) |
| **Group 6** | | 0.05828*** | 0.1341*** |
| | | (0.0089) | (0.0286) |
| **Group 7** | | 0.0578*** | 0.1408*** |
| | | (0.0087) | (0.0294) |
| **Group 8** | | 0.0616*** | 0.1416*** |
| | | (0.0087) | (0.0290) |
| **Group 9** | | 0.0645*** | 0.1428*** |
| | | (0.0086) | (0.0287) |
| **Observations** | 34552 | 34552 | 34552 |
| **Adjusted $R^2$** | 0.65 | 0.65 | 0.65 |

Note: The first group in each division serves as the base group.

Table 1.4: Estimation of tax effects: instrumental variable.

| | **First stage** | **Second stage** |
|---|---|---|
| **Tax** | 0.8846*** | |
| | (0.0163) | |
| **Fuel cost** | -4.4678 | -1.3773* |
| | (3.8363) | (0.6473) |
| **Price** | | -0.0179*** |
| | | (0.0025) |
| **Observations** | 15425 | 15425 |
| **Adjusted $R^2$** | 0.99 | 0.81 |

Note: *p<0.05, **p<0.01, ***p<0.001. For readability, tax is divided by 1000.

### 1.5.2 Robustness analysis

#### Aggregation

Using annual rather than quarterly observations, Model 1 in Table 1.5 shows the results for Equation 1.4. The estimated coefficient for the tax, -0.0158, reflects a slightly greater responsiveness than our main result (-0.0126) in Table 1.2. To control especially for shocks and effects, such as pre-announcement effects and fuel costs, as well as to include more data variation, we prefer to focus on the quarterly formulation.

Table 1.5: Data aggregation.

| | **Yearly** | **Detailed car specification** | **All years** |
|---|---|---|---|
| | Model 1 | Model 2 | Model 3 |
| **Tax** | -0.015*** | -0.013*** | -0.016*** |
| | (0.002) | (0.001) | (0.001) |
| **Fuel cost** | -2.780* | -0.942* | -1.18*** |
| | (1.378) | (0.432) | (0.370) |
| **Adjusted $R^2$** | 0.56 | 0.65 | 0.66 |
| **Observations** | 11980 | 35002 | 54963 |

Model 2 in Table 1.5 shows the results for Equation 1.4 allowing vehicle types to be defined by additional characteristics, such as body, transmission, and number of doors. With greater number of observations resulting from more detailed car specifications, standard errors are reduced. The coefficient estimate is similar to the results in the Table 1.2.

In Model 3 in Table 1.5, we include all years, from 2006 to 2014. Our main regressions do not use 2012 through 2014, because our data enable us to control very well the effects of the 2012 $NO_x$ tax, and the increase in sales of electric vehicles and their incentives. The boom of electric vehicles contributes significantly to declining average $CO_2$ intensity. In Model 3, the estimated tax coefficient is a little larger in absolute value than that in Table 1.2. This might reflect bias due to omitted coverage of the additional incentives for electric vehicles.

### Alternative specifications

Here, robustness is assessed by re-specifying dependent as well as independent variables. The first model in Table 1.6 addresses the size of new vehicle market, modelling the vehicle type's share in the market rather than the number of vehicles sold. The tax coefficient is almost the same as in Table 1.2, which is plausible, since our finely defined car types imply small sales shares.

We check the relevance of tax changes relative to close substitutes in Model 2, Table 1.6, by including two additional independent variables: tax_left is the average registration tax for all vehicles that are, at most, 2 $g/km$ less $CO_2$ intensive than the vehicle type in question, and tax_right is the average registration tax for all vehicles that are at most 2 $g/km$ more $CO_2$ intensive. The estimated relative tax coefficients are small and not significant. More importantly, the estimated own tax coefficient is unchanged. The relative tax change between cars and own tax change is closely related to comparable vehicles, since they are under the same tax structure based on vehicle characteristics. Therefore, and in light of our practical research objectives, using the more straightforward approach of fixed effects, rather than relying on assumptions of substitutes (as through '$CO_2$ neighbourhood'), is supported.

Third, preferences for vehicle characteristics can change over time. Model 3 in Table 1.6 includes a trend variable interacting with fuel type (diesel and gasoline) and Model 4 for engine power. Both can be considered to represent a trend in consumer preferences or technological change. In the latter case, if we allow a trend in power (wealth and preferences might make us want more horsepower), then responsiveness to the tax in absolute value is estimated to be higher.

Lastly, the registration tax rate makes discontinuous jumps at the cut-offs at $120g/km$, $140g/km$, $180g/km$, and $250g/km$ (Figure 1.2). Consumers have stronger economic incentives to shift their purchases from vehicles just around the cut-offs. Based on Equation 1.4, an regression using only observations near cut-offs yields estimated tax coefficients almost three times larger in absolute value than the one (1.26%) in Table 1.2. However, when we drop the observations near the cut-offs (within ± $2g/km$), we can observe in Model 5 of Table 1.6 that the tax coefficient is close to that in Table 1.2, indicating that the small share of vehicles around the cut-offs do not bias our results.

Table 1.6: Omitted variables.

| | **Sales share** | **Relative taxes** | **Fuel type** | **Engine power** | **Cut-offs excluded** |
|---|---|---|---|---|---|
| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
| **Tax** | -0.013*** | -0.013*** | -0.012*** | -0.019*** | -0.012*** |
| | (0.001) | (0.001) | (0.012) | (0.001) | (0.003) |
| **Fuel cost** | -0.945* | -0.959* | -1.579*** | -1.132** | -1.041* |
| | (0.435) | (0.434) | (0.444) | (0.378) | (0.456) |
| **Tax_left** | | 0.002 | | | |
| | | (0.001) | | | |
| **Tax_right** | | -0.002 | | | |
| | | (0.001) | | | |
| **Adjusted $R^2$** | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 |
| **Observations** | 34552 | 34552 | 34552 | 34552 | 30883 |

## 1.6 Implications

In this section, we analyse the implications of our quantitative findings. First, we disentangle the reductions in $CO_2$ intensities. Second, we estimate reductions in $CO_2$ intensities when the whole demand system — across all car types — is exposed to realistic reforms. For this purpose, we use the tax coefficient (-0.0126) from Model 1 in Table 1.2. We believe it is close to the true tax effect in light of our robustness analysis and discussion above, but we reach similar conclusions when using the estimates from Table 1.3.

### 1.6.1 Disentangling the role of the tax reform in the declining $CO_2$ intensities historically

We use the estimated model to calculate vehicle sales changes corresponding to changes of the $CO_2$-differentiated registration tax, keeping other factors unchanged. The average $CO_2$ intensity of new vehicle sales was 177.76 $g/km$ in 2006 and 159.63 $g/km$ in 2007, while for 2007 the projected mean (due only to the $CO_2$ tax reform) was 163.37 $g/km$. Thus, 14.39 grams of the 18.14 grams reduction, or 79%, was due to the $CO_2$ tax change. Other factors, such as income changes, preferences, European and other standards, and technological changes, account for the remaining 21%, and thus, the $CO_2$ tax explains a large part of the reduction in $CO_2$ intensity.

### 1.6.2 A $CO_2$ elasticity estimate for new vehicle sales

We investigate the response in $CO_2$ intensity to changes of $CO_2$ price that is indicated by the $CO_2$ tax. Using a $CO_2$ price allows us to combine fees and rebates. Choosing 2009 (mid-sample and first year of the feebate form) as a baseline, we simulate a rise in the $CO_2$ price by 50% and calculate the changes in tax, sales, and thereby emission intensities. The results are listed by segments of increasing intensity in Table 1.7. The sales-weighted average $CO_2$ intensity is reduced by 2.74%, and the sales-weighted average $CO_2$ price is increased by 48.41%, and thus, the estimated elasticity of $CO_2$ intensity with respect to the $CO_2$ price is -0.06, or minus 6%. This result is close to the estimates by Michielsen et al. (2015) based on average $CO_2$ intensities by country in Europe. Our results are based on the distribution of sales over detailed car types. Furthermore, we notice that the overall reduction is about equally shared by within-segment reductions and between-segment changes (Table 1.7). Comparing the lower two rows, the elasticity of -2.74% is the average of the elasticities within segments, while the elasticity of -6% includes the role of sales changes between segments.

An elasticity of $CO_2$ intensities with respect to $CO_2$ price of -0.06 might appear small. However, it appears reasonable if we notice that the $CO_2$ tax is a small share (about 10%) of the vehicle price for a 'mean' vehicle. Using a pass-through of 88%, the car price change is about 8.8 percentage points of the $CO_2$ price increase. Thus, the elasticity of $CO_2$ intensities with respect to car prices is about -0.53 (= -0.06 × 10 × 0.88). This means that a $CO_2$ price increase of 10% that passes through car prices reduces average emission intensities by about 5.3%.

Table 1.7: The elasticity of average $CO_2$ intensity to average $CO_2$-based registration tax by segments.

| **Segment** | **Growth rate of $CO_2$ intensity** | **Growth rate of $CO_2$ price** | **Elasticity** |
|---|---|---|---|
| **Mini** | -0.0033 | 0.4999 | -0.01 |
| **Small** | -0.0064 | 0.4996 | -0.01 |
| **Compact** | -0.0125 | 0.4979 | -0.03 |
| **Medium** | -0.0102 | 0.4962 | -0.02 |
| **Sports** | -0.0160 | 0.4830 | -0.03 |
| **Large** | -0.0187 | 0.4805 | -0.04 |
| **Multi-purpose** | -0.0193 | 0.4764 | -0.04 |
| **SUV** | -0.0189 | 0.4723 | -0.04 |
| **Luxury** | -0.0238 | 0.4499 | -0.05 |
| **Others** | -0.0653 | 0.3918 | -0.17 |
| **Average** | 0.0133 | 0.4901 | -0.03 |
| **Total fleet** | -0.0274 | 0.4841 | -0.06 |

Note: The sales-weighted average elasticity of all segments is -0.028 based on vehicle sales before the tax change. If we use the vehicle sales data after the tax change to calculate the average value, it is -0.026.

In Figure 1.5, we present the reductions in emission intensities within segments with the changes in demand between segments in the direction of arrows from grey points (before the tax change) to corresponding black points (after the tax change). Important changes, such as exogenous technological change, are eliminated, and thus, Figure 1.5 shows only the changes that are due to the $CO_2$ tax changes[15]. Heavy and large vehicles, such as SUVs and luxury cars, have the highest $CO_2$ intensity. Buyers of such vehicles can respond to higher $CO_2$ taxes either by choosing less-emission cars in the original heavy segment or by shifting purchases to vehicles in lighter segments. Buyers of cars in the middle segments reduce their emission intensities within the segments, and when the sales in these segments are about unchanged, an interpretation is that these segments win about as much sales from heavier segments as they lose to lighter segments. Lighter segments experience rising sales and modest $CO_2$ intensity reductions. Light

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[15] Our commitment to simplicity, even in Table 1.7 and Figure 1.5, might be surprising. Our elasticity estimates from Column 2, Table 1.3, lead to similar results.

segments, such as mini, small, compact, and midsize, increase their sales, as indicated by Equation 1.3, as purchases shift from high-emission to low-emission vehicles.

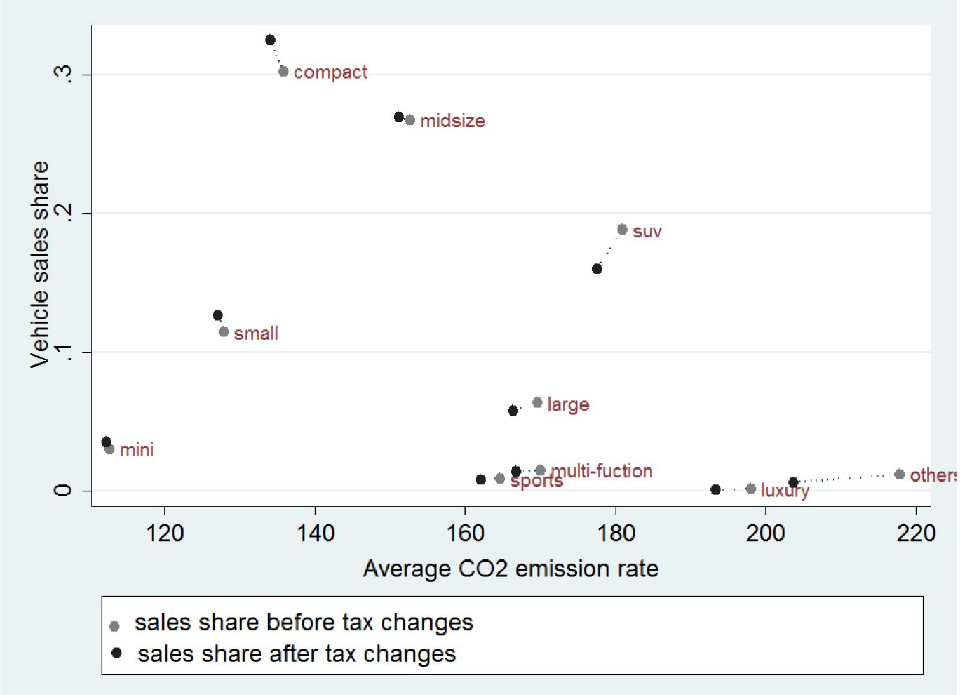

Figure 1.5: Average $CO_2$ intensity and vehicle sales share by segments before and after tax changes.

## 1.7 Conclusion

There are good a priori reasons that a fuel tax is the first best instrument for $CO_2$ emission reductions. In light of this principle, fuel economy standards (e.g. those in the EU, or CAFE in the US) and $CO_2$-based vehicle taxes applied to cars are not obvious policy recommendations.

Nevertheless, policy makers might want a policy instrument that works on $CO_2$ intensities in the vehicle stock via new car sales, and thus, might look to standards, tradable quotas, or taxes that favour vehicles with lower $CO_2$ intensities. The Norwegian vehicle registration tax on $CO_2$ intensity provides political experiments worth studying. The responsiveness of car purchases and the $CO_2$ intensities in the car fleet are of interest from the perspectives of emission reductions as well as energy security.

More generally, we can think about reductions in emissions or energy use in settings in which the composition of assets (vehicles) and their use represent separate windows for policy intervention. There are good reasons to assume that a first best instrument, such as fuel taxes, would cost-effectively both modify the car fleet through new car sales and economize on driving. It is clear that if instruments such as a $CO_2$-based new car tax were used to influence fleet composition, there would also be a need for user-cost instruments, such as fuel taxes to influence the use of cars[16].

This research analyses the effects of the $CO_2$-differentiated vehicle registration tax on vehicle registration (new car sales) and especially on the average $CO_2$ intensity of Norway's new vehicle fleet. The econometric analysis includes vehicle-type fixed effects and model-quarter fixed effects to control for potential confounding effects, such as vehicle characteristics, time effects, policy pre-announcement effects, macro-economic developments, exchange rate shocks, technological change, and consumer preferences. We perform numerous reformulations to examine alternative functional forms, variable inclusion, and aggregations. We use a simple model for the practical purpose of quantifying the effects of prospective policies on average $CO_2$ intensities.

Our estimates imply that a 1000-NOK (125-USD) tax increase for one vehicle type is associated with a sales reduction of 1.26% to 1.58%. We conclude that a large part of the reduction in the sales-weighted average $CO_2$ intensity in Norway since 2006 is attributed to the $CO_2$-differentiated registration tax. Viewing the rising tax as an increasing $CO_2$ price, a 1% increase in the $CO_2$ price is associated with a 0.06% reduction of average $CO_2$ intensity. Translating this effect to new car prices implies a $CO_2$ elasticity with respect to new car prices of about -0.53 (when the car price changes due to the $CO_2$ price). Another finding worth mentioning is that even with the high taxation of $CO_2$ in Norway, car buyers remain sensitive to fuel costs, even in a setting in which the government has given consumers fairly strong other reasons to seek fuel-efficient vehicles.

Our analysis finds that declining average $CO_2$ intensity represents a consistent and significant purchase shift toward low-emission vehicles, which are the majority cars driven in Norway as a result of the government's introduction and raising of a $CO_2$-differentiated registration tax.

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[16] A series of arguments has been made in favour of sensible policy instrument combinations (Manski, 1983; Kahn, 1986; Eskeland and Mideksa, 2008). As argued by Eskeland and Mideksa (2008), the role of standards might be a greater commitment in policy, and might influence car purchase decisions if buyers are ill informed or myopic. Accelerating asset renewal could play a role in political economy, since resistance to fuel taxes is reduced as the fuel economy embodied in the stock of assets (cars) rises.

Norway is a small country without a car industry, and thus, this instrument use might be viewed not as influencing car-makers but as affecting how Norwegian buyers choose from internationally available vehicle types. If world car markets were (expected) to apply consistent pressure on $CO_2$ reductions — albeit lower reductions — there would be good reason to expect car-makers to display additional responsiveness in their inventiveness and efforts, resulting in a lower cost for global emission reductions.

Notably, total emissions depend also on the total number of vehicles and on kilometres driven. Vehicle sales might rise for many reasons — and so might driving — but driving will also be stimulated by the fact that people are induced to own cars with lower user cost (higher fuel efficiency). In Norway, policies related to driving include fuel taxes (including a $CO_2$ element) and should also include geographical and time dependent factors, such as congestion and local air pollution (to some extent they do already, with toll rings in such cities as Oslo and Bergen).

Important issues that we have not looked into here are life cycle assessments and other questions of indirect emissions. Emissions in the transport sector are addressed at the emitting source only, which is not unusual and entails consideration of strengths and weaknesses. Such an approach considers a vehicle as zero emitting both locally and globally if its tailpipe is clean. Thus, it abstracts from pre-tailpipe emissions in the energy carrier, which is entirely justified in the case of electricity in Europe, where an emission cap places responsibility for emissions in power generation with the power generator[17]. Finally, we should note there are gaps between emission intensities on-road and from official laboratory tests. This fact argues against excessive use of vehicle taxes based on measured emission intensities, and in favour of both improved measurement and emission taxes in fuel taxes. Much analysis has been undertaken in these areas but much remains to be done.

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[17] Relevant arguments are made by Eskeland (2012), in favour of drawing this cut-off at the tailpipe both in analysis and in policy. If electrification of a vehicle appears attractive under such policies and analysis, it means that electricity generators live more easily with their own $CO_2$ emission constraints than do cars. Of course, if for electricity in Europe one can argue that a cap applies to emissions from coal-based electricity generation in Denmark, then a similar argument would not necessarily apply to emissions involved in producing an electric car's battery. Solving global problems requires global solutions and with rising mitigation costs, is increasingly inescapable.

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# Appendix

## Data description

The monthly registration data of new passenger vehicles from 2006 to 2014 in Norway are provided by the Norwegian Road Federation (OFVAS). The data arte structured by brand, model, segment, body, engine fuel type, engine power, engine size, transmission type, number of doors, fuel economy, weight, municipality, and county. The yearly vehicle sales price, including taxes, is provided by the OFVAS. The dataset also contains detailed vehicle characteristics. The monthly fuel prices, including fuel taxes for both diesel and gasoline, are collected from Statistics Norway (SSB). The characteristics-based vehicle registration tax rates for new passenger cars are collected from the National Budget (2006–2014) by the Norwegian Ministry of Finance.

Table 1.8: Summary statistics for regression data.

| **Variable** | **N** | **Mean** | **Std.Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|
| **Vehicle sales** | 59722 | 18.4531 | 47.9542 | 1 | 1283 |
| $CO_2$ | 59722 | 159.1456 | 39.96228 | 49 | 448 |
| **Weight** | 59722 | 1457.342 | 302.1256 | 530 | 4700 |
| **Engine power** | 59722 | 104.3725 | 41.56085 | 33 | 486 |
| **Engine size** | 59722 | 1905.208 | 564.2025 | 698 | 7011 |
| $CO_2$**-based registration tax** | 59722 | 30.63235 | 42.61158 | -49.806 | 631.97 |
| **Total vehicle registration tax** | 59722 | 140.4071 | 121.5291 | 8.517067 | 1378.867 |
| **Fuel cost (NOK/km)** | 59722 | 0.783585 | 0.2022 | 0.29908 | 2.314158 |
| **Vehicle price** | 26691 | 353.0122 | 211.6225 | 90.17626 | 3446.852 |

Note: Prices and taxes are in a unit of 1000 NOK for readability. For all variables except vehicle price, N is the number of vehicle types (specification) with non-zero registrations. For prices, N report the numbers of matched vehicle types in both the registration dataset and the price dataset.

# Chapter 2

## The Economic and Environmental Impacts of Tax Incentives for Battery Electric Vehicles in Europe

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### Abstract

Vehicle taxes and purchase subsidies have been used by many European countries to provide incentives for electric vehicle adoption and $CO_2$ emission reduction. To examine the role of the incentives in reducing total ownership costs of electric vehicles, increasing electric vehicles sales, and obtaining environmental benefits from switching to electric vehicles, we carry out cost benefit analyses and ordinary least square regressions. The results are based on a dataset of electric vehicles sales, vehicle costs, and socio-economic variables that we assemble for 10 pairs of battery electric vehicles (BEVs) and their internal combustion engine vehicle (ICEV) counterparts in 28 European countries from 2012 to 2014. The results show that the tax incentives, especially registration tax exemptions, significantly reduce total ownership costs of BEVs. For larger vehicles, BEVs have much lower relative costs, compared to their ICEV counterparts. Due to the cost-reduction effect, a 10% increase of the total tax incentive is associated with an estimated 3–4% increase in the sales share of BEVs. This estimation reflects a BEV price elasticity of -1.3 for the sample mean. Finally, the environmental benefits of switching to BEVs vary across countries. However, it is still costly to use the tax incentives to reduce $CO_2$ emissions and other externalities through transport electrification, despite recent improvements in greening electricity generation and lowering battery costs.

**Keywords**: battery electric vehicle, tax incentive, purchase subsidy, vehicle tax, vehicle cost, vehicle sales

## 2.1 Introduction

Electric vehicles, such as battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), are regarded as key alternatives to internal combustion engine vehicles (ICEVs) for improving energy efficiency, mitigating local air pollution, and reducing carbon dioxide ($CO_2$) emissions in the transport sector. Many governments have established interim goals for market shares of electric vehicles in the relatively near-term timeframe of 2020–2025 in order to spur the vehicle market and promote a long-term shift to an economy that is consistent with climate stabilization (Weeda et al., 2012; Mock and Yang, 2014; IEA, 2015b).

To achieve these goals, various concrete policies have been implemented to benefit the production and sales of electric vehicles. Fuel economy standards, information labelling, and research and development (R&D) support are used to promote the development of electric vehicle technology. Moreover, in conjunction with complementary policies (e.g. low electricity prices, development of charging infrastructure, access to bus lanes, and free parking spots), national tax incentives have been provided directly to induce consumers to adopt innovative low-emission vehicle technologies. The tax incentives work by reducing the costs of electric vehicles relative to ICEVs. First, tax incentives could be in the forms of tax exemptions or subsidies for electric vehicles at the purchase stage or use stage. Second, incentives could be implemented in the form of higher vehicle registration taxes or annual circulation taxes for ICEVs. Such incentives offer an important and powerful mechanism to reduce the total ownership costs of electric vehicles and therefore, to promote the adoption of electric vehicles[1] (Eppstein et al., 2011; Hidrue et al., 2011; Trigg et al., 2013; Jin et al., 2014; Mock and Yang, 2014; Sierzchula et al., 2014; Cazzola and Gorner, 2016).

Among all electric vehicles, BEVs have the most disadvantages over ICEVs[2]. The adoption of BEVs is more likely to rely on national tax incentives. The different designs of vehicle taxes and subsidies create different levels of incentives for BEVs and PHEVs. For example, compared

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[1] Diamond (2009) find that fuel prices, not tax incentives, have a strong relationship with sales of electric vehicles in the US. However in fact, from 2015 to 2016, with lower fuel prices, EVs still experienced a large sales increase in new vehicle markets globally.

[2] The disadvantages include high purchase prices, limited travel range, long charging time, limited availability of models, limited availability of charging stations, and uncertainty regarding new technology (Stephens, 2013).

to the Netherlands, Norway provides higher cost reductions for BEVs than PHEVs (Kley et al., 2012). This difference reflects the fact that Norway and the Netherlands have relatively high sales of BEVs and PHEVs, respectively. However, the removal of the internal combustion engine system gives BEVs an increasingly important role in climate change mitigation, especially with greener electricity and decreasing battery costs, from about 1000 $\$/kWh$ in 2008 to 268 $\$/kWh$ in 2015 (Cazzola and Gorner, 2016). Hence, we are motivated to focus our research on BEVs and explore answers to the significant research questions — to what extent the tax incentives for BEVs i) reduce the total ownership costs of BEV; ii) induce purchases of BEVs; and thereby iii) reduce environmental externalities — $CO_2$ emissions, local air pollution, and noise from driving.

Research on detailed calculations for total ownership costs of electric vehicles was conducted in the 1990s and early 2000s (Chapman et al., 1994; Lave et al., 1995; Kazimi, 1997; Vyas et al., 1998; Funk and Rabl, 1999; Delucchi and Lipman, 2001; Carlsson and Johansson-Stenman, 2003). However, with developments in battery and vehicle technologies, integration of renewable energy in power generation and particularly recent reforms of vehicle taxes/subsidies, there is a need to re-evaluate the costs and benefits of electric vehicles, especially BEVs. Recent studies (Crist, 2012; Prud'homme and Koning, 2012; Piao et al., 2014) have undertaken cost benefit analysis for individual BEV, PHEV, and ICEV within a single country. Quantitative cross-country comparisons of electric vehicles are presently limited to single areas of electricity production (Doucette and McCulloch, 2011; Wu et al., 2012; Buekers et al., 2014) or taxation (Kley et al., 2012; Mock and Yang, 2014). An integrated cost benefit analysis across countries and across car models could contribute to the evaluation of the impacts of tax incentives for electric vehicles.

Previous empirical research has mainly focused on sales of PHEVs, including BEVs. Three types of methods have been frequently used: discrete choice models (Brownstone et al., 2000; Bolduc et al., 2008; Axsen et al., 2009; Axsen and Kurani, 2013), cross-sectional and time-series models (Diamond, 2009; Chandra et al., 2010; Beresteanu and Li, 2011; Gallagher and Muehlegger, 2011; Jenn et al., 2013), and simulated models (Mau et al., 2008; de Haan et al., 2009; Eppstein et al., 2011). To evaluate impacts of policies on electric vehicle adoption, previous research mainly has used cross-sectional and time-series models. Although the tax responsiveness of consumers for BEVs and PHEVs might vary, little research has studied BEVs separately. In recent years, BEVs have experienced huge sales increases in different countries, which presents a good research opportunity. For example, Mersky et al. (2016) conducts research on BEVs in Norway, where variables have limited variations and tax incentives are uniform within the country. We believe that the use of variation from a larger dataset across countries, years, and vehicle models leads to more precise estimation of tax incentive impacts than previously, and adds to the understanding of BEV adoption.

In our study, we compose comparable pairs of BEV–ICEV. Within each pair, BEVs and ICEVs have similar characteristics. The total tax incentive for a BEV is represented by the difference between the total taxes (vehicle registration, annual circulation tax, and subsidy) for a BEV and its ICEV counterpart. To assess the tax incentives for BEVs, we carry out cost benefit analyses and ordinary least square (OLS) regressions. First, we calculate the vehicle total ownership costs, including the taxes, and the net benefit of switching from an ICEV to a BEV. In light of heterogeneity in tax incentives, we compare the vehicle costs in three dimensions: cross-country, cross-(car) model, and cross-driver. Second, to estimate the influence of tax incentives on BEV adoption, we regress sales shares of BEVs by country, (car) model, and year on the total tax incentive for specific electric vehicles, controlling for country and (car) model-level differences. For robustness, we conduct regressions with alternative specifications. Lastly, from an environmental perspective, we compare the total tax incentives to the total reductions of $CO_2$ emissions and the total reductions of external costs when switching from an ICEV to a BEV in different countries.

Thus, we provide a comprehensive evaluation of recent vehicle tax incentives for BEVs by applying cost benefit analyses and OLS regressions. In addition, part of our contribution to the literature is our development of a panel dataset with substantial variation not only in tax differences but also in different electricity generation mix and local environmental factors (e.g. local marginal benefits of pollutants), covering 10 pairs of BEV–ICEV in 28 European countries from 2012 to 2014. The applications of methods on 10 pairs of BEV–ICEV provide a creative and robust approach to evaluate tax incentives for BEVs. Last, the international comparisons of results offer a critical perspective to inform global debates on both the role of transport electrification and associated policy instruments.

The results of the cross-country comparisons of vehicle costs show that tax incentives and energy cost savings together significantly reduce the relative costs of BEVs. The cross-(car) model comparisons indicate that for larger vehicles, BEVs have much lower relative costs compared to their ICEV counterparts. Both comparisons show that with a high registration exemption or a purchase subsidy, BEVs are more likely to have lower total ownership costs compared to ICEVs. Lastly, as shown in the cross-driver comparisons, strong tax incentives can lower the requirements of annual distance travelled to achieve equal total ownership costs of ICEVs and BEVs.

Owing to the cost-reduction effect, a 10% increase of the total tax incentive is estimated to be associated with a 3–4% increase in BEV sales share. This estimation reflects a price elasticity of -1.3, using the percentage of tax incentive to BEV price of 15% for the sample mean. Finally, the environmental benefits of driving BEVs vary considerably across countries. However, it is still costly to use the tax incentives to reduce $CO_2$ emissions and other externalities through transport electrification, despite recent improvements in greening electricity generation and lowering battery costs.

The rest of this chapter proceeds as follow. Section 2.2 presents the features of tax incentives for electric vehicles in Europe. Section 2.3 shows the methods for analysing tax incentives. Section 2.4 describes our data. The results and discussion are presented in Section 2.5 and the conclusion in Section 2.6.

## 2.2 Tax incentives for electric vehicles in Europe

In this section, we summarize and introduce different national tax incentives[3] for BEVs in Europe. Three main types of tax incentives have been implemented in Europe – exemptions from vehicle registration tax, exemptions from annual circulation tax, and different forms of subsidy (ACEA, 2014a,b).

The tax incentives work through exemptions or reduction of taxes for BEVs and higher taxes on ICEVs. There are different types of vehicle tax duties imposed and numerous different bases of tax assessment and tax schedules across European countries, leading to substantial variation

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[3] We limit our focus to national fiscal incentives. We do not consider local incentives, such as free parking or access to bus lanes in Norway. We list only the incentives from the perspective of BEVs. Some tax exemptions do not apply to PHEVs, for example in Denmark.

in tax incentives for BEVs. In recent years, $CO_2$ emission rates[4] have been frequently used as a base for vehicle taxes to promote fuel-efficient car purchases. These $CO_2$-based vehicle taxes in practice give maximum advantage to BEVs, which are considered to have zero tailpipe $CO_2$ emissions. Therefore, these taxes strongly incentivize the purchase and use of BEVs, even though, in many cases, they also differentiate support between PHEVs and between ICEVs.

***Exemptions from vehicle registration tax***

A vehicle registration tax is a one-off payment for registration with a government authority when purchasing a new vehicle. It directly influences the price signal given to vehicle purchasers as well as suppliers. In 2014, 20 out of 28 European countries had implemented a vehicle registration tax. Across countries, more than 10 vehicle characteristics (e.g. price, weight, $CO_2$ emission rate, engine power, and engine size) serve as the base for the registration tax in different ways. In most countries, BEVs are exempt from vehicle registration tax regardless of car model.

For example, Ireland has a step-wise vehicle registration tax that fully depends on $CO_2$ emission rate. Vehicles with $CO_2$ intensity from 0 to 120 $g/km$ are taxed at 14% of their purchase prices, while vehicles with a $CO_2$ emission rate from 121 to 140 $g/km$, from 141 to 155 $g/km$, from 156 to 170 $g/km$, from 171 to 190 $g/km$, from 191 to 255 $g/km$, and 226 $g/km$ and over face a rate of 16%, 20%, 24%, 28%, 32%, and 36%, respectively. In the Irish tax system, with the same price, ICEVs with $CO_2$ intensity of 121 $g/km$ and with 140 $g/km$ pay the exact same amount of taxes, while BEVs are exempt from registration tax. On the other hand, under a continuous $CO_2$-based registration tax structure, such as in Norway, each increment of $CO_2$ ($g/km$) in $CO_2$ intensity of vehicles is charged. ICEVs with $CO_2$ intensity of 140 $g/km$ pay higher tax than ICEVs with $CO_2$ intensity of 121 $g/km$, which offers a stronger incentive for higher-emitting vehicles (normally with higher configurations) to be replaced by BEVs. In addition, the registration tax in Norway includes weight-based tax, engine power-based tax, and $NO_x$-based tax. Since all three characteristics are related to $CO_2$ emissions, the registration tax can be considered as a partially $CO_2$-based tax.

***Exemptions from annual circulation tax***

An annual circulation tax is a yearly payment for using a vehicle on the road. Of 28 European

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[4] $CO_2$ emission rates, sometimes also called $CO_2$ intensity, in grams per vehicle kilometres, is basically the same as fuel efficiency, once fuel type is given.

countries, 21 charged annual circulation taxes on cars in 2014. In addition, BEVs are incentivized by tax exemption in many countries. In Ireland, the annual circulation tax is based on the $CO_2$ emission rate. Vehicles with 0 $g/km$ emission rate, including BEVs, have to pay annual circulation tax of 120 €. Vehicles with an emission rate of 1 to 80 $g/km$ have to pay 170 €in annual circulation tax. Electric vehicles are not exempt from annual circulation tax in Ireland, but Germany and some other countries offer annual circulation tax exemption. From the perspective of vehicle lifetime, annual circulation taxes can give the same incentives in purchase decisions for ICEV versus BEV as vehicle registration taxes. However, such equivalence depends on consumers' preferences and how they discount future costs.

***Subsidies***

A subsidy is given directly and reduces the purchase price of a car. It can be coupled with a requirement to buy a specific car and might apply to different vehicle classes. The direct subsidies for BEVs are relatively easy to identify and to compare across different countries. For example, the UK does not have a vehicle registration tax but uniformly subsidizes electric vehicles with a grant of 5000 pounds, which is deducted from the purchase price.

A special instrument combining tax and subsidy is the so-called 'feebate'. This subsidizes low-emission vehicles and penalizes high-emission vehicles with tax. The feebate is usually combined with or integrated into vehicle taxes. In Austria, the vehicle registration tax (or fuel consumption tax) is levied on the purchase price (net) or the commercial leasing fee of new passenger cars. The tax rate is based on fuel consumption and fuel type. In addition, a feebate (or bonus/malus system) is included to account for emissions of $CO_2$ (and $NO_x$/particulate matter).

## 2.3 Method

In this section, by applying cost benefit analysis, we calculate the total ownership cost of vehicles, the net benefits of switching from an ICEV to a BEV, and the tax incentives for BEVs. The cost comparisons provide insight into the cost-reduction effects of the tax incentives. Furthermore, we explore the influence of the tax incentives on sales with regression analysis. Lastly, we evaluate the environmental benefits of switching BEVs due to reductions in $CO_2$

emissions, local air pollution, and noise from driving.

### 2.3.1 Calculating vehicle costs and tax incentives

We perform a cost benefit analysis to calculate the total ownership costs of an ICEV and a BEV. $TC_i^v$, ($v = icev$ or $bev$), the total ownership cost of a vehicle through its lifetime, is expressed as the sum of investment cost (purchase prices and registration taxes), operation cost (annual circulation taxes and energy costs), and maintenance costs, as follows.

$$TC_i^v = p_i^v + vrt_i^v + \sum_{t=0}^{l} \frac{act_{it}^v}{(1+\rho)^t} + \sum_{t=0}^{l} \frac{(ep_{it}^v + et_{it}^v) \times ee^v \times d_{it}}{(1+\rho)^t} + \sum_{t=0}^{l} \frac{mc_{it}^v}{(1+\rho)^t} \tag{2.1}$$

where $p_i^v$ ($v = icev$ or $bev$) is vehicle price[5] in country $i$, including VAT and a one-off payment for purchasing the battery if the vehicle is a BEV. $vrt_i^v$ is the vehicle registration tax. $l$ is the vehicle lifetime. $mc_{it}^v$ is annual maintenance cost[6] in country $i$ and year $t$. $act_{it}^v$ is annual circulation tax. $d_{it}$ is annual driving distance. $ep_{it}^v$ is pre-tax price of energy (gasoline/diesel if $v = icev$ or electricity if $v = bev$) and $et_{it}^v$ is the sum of VAT on energy price and energy exercise tax. $ee^v$ is vehicle energy efficiency. Specifically, it is kilowatt-hours of electricity consumed per kilometre for BEVs and litres of gasoline/diesel consumed per kilometre for ICEVs. $\rho$ is the discount rate for future costs. $NB_i$, the net benefit of switching from an ICEV to a BEV, is calculated as the difference between total ownership costs of a BEV and its ICEV counterpart, $TC_i^{icev} - TC_i^{bev}$. The difference consists of five parts: price change, vehicle registration tax change, annual circulation tax change, energy cost change (including both energy prices and taxes), and maintenance cost change, as shown in Equation 2.2.

$$NB_i = \Delta p_i^v + \Delta vrt_i^v + \Delta \sum_{t=0}^{l} \frac{act_{it}^v}{(1+\rho)^t} + \Delta \sum_{t=0}^{l} \frac{(ep_{it}^v + et_{it}^v) \times ee^v \times d_{it}}{(1+\rho)^t} + \Delta \sum_{t=0}^{l} \frac{mc_{it}^v}{(1+\rho)^t} \tag{2.2}$$

---

[5] We do not deduct salvage value from price. Vehicles have almost no positive salvage value at scrappage and even if they did, it would occur so far in the future that it would be discounted to nearly zero.

[6] The maintenance cost of a BEV is lower than that of its ICEV counterpart, because the drive-train of a BEV contains no gear box, transmission, and other moving components that are liable to wear. Regular ICEV maintenance, such as the replacement of oil and filters, is not needed for BEVs. In addition, as with maintenance costs, insurance costs depend strongly on driver behaviour. However, insurance costs do not systematically relate to choice of power train. Therefore, we do not consider insurance costs.

$inc_i$, the total tax incentive for BEVs, consists of three types of measures – exemptions from vehicle registration tax, exemptions from annual circulation tax, and subsidies, as outlined in Section 2.2. The tax exemptions require the calculation of the total tax incentive for a BEV to rely on the comparison with an ICEV that the BEV replaces. Since the tax incentives are uniform for all BEVs, the magnitude of incentives for different BEVs is mostly determined by the stringency and design of the vehicle registration taxes and annual circulation taxes on ICEVs. In addition, subsidies are counted as vehicle registration tax exemptions or annual circulation tax exemptions, depending on the implementation stage. The total tax incentive for BEVs, as one part of Equation 2.2, is presented separately as follows.

$$inc_i = (vrt_i^{icev} + \sum_{t=0}^{l} \frac{act_{it}^{icev}}{(1+\rho)^t}) - (vrt_i^{ev} + \sum_{t=0}^{l} \frac{act_{it}^{ev}}{(1+\rho)^t}) \tag{2.3}$$

### 2.3.2 Estimating influences of tax incentives on BEV adoption

To estimate the influence of the tax incentives on BEV sales, we regress the national sales share of BEVs on the total tax incentives, fuel cost savings, and fixed effects for identification. The basic premise of the method is based on the behavioural utility function for automobile demand given by Berry et al. (1995). The model specification reduces to an objective function of relating vehicle market share to a number of socio-economic and policy variables. The choice of log–log specification provides a better fit to the data, as indicated by the adjusted $R^2$. It is also useful because it enables the interpretation of the regression coefficient as the elasticity of market share with respect to those predictors.

Indexing country, (car) model, and year as $i$, $m$, and $t$, respectively, the regression specification is given as follows.

$$\ln s_{imt} = \ln inc_{imt} + \ln fuel_{imt} + \alpha_{ct} + \theta_{mt} + \varepsilon_{imt} \tag{2.4}$$

where $s_{imt}$ is the market share of a BEV, $m$, in country $i$ and year $t$. It is assumed that a 1-year period for each market share observation is long enough to smooth out the effects of waiting lists and backlogs that might have occurred on a monthly basis. $inc_{imt}$ is the total tax incentive for BEVs. $\varepsilon_{imt}$ is the mean zero error term. $fuel_{imt}$ is the fuel cost savings from driving a BEV instead of an ICEV.

The total tax incentive for a BEV, $inc_{imt}$, is based on the calculation of tax incentives in Equation 2.3 with extension to different years and vehicle models. Notably, tax incentives might be not fully passed on through vehicle price to consumers, which might cause potential bias. The incentives are split in an unobserved ratio between dealer and consumers, through either endogenous deal incentives or negotiation. According to previous research (Sallee et al., 2008; Yan and Eskeland, 2016), a vehicle registration tax is largely passed on through price. Thus, it is important to note that our tax coefficient estimates the equilibrium effect of tax incentives on BEV sales.

Fuel cost savings, $fuel_{imt}$, are the difference between gasoline/diesel cost per kilometre for an ICEV and electricity cost per kilometre for a BEV. Fuel cost savings are calculated by using energy efficiency and energy price when the vehicle is purchased.

The identification in our empirical specification is based on the considerable variation from different designs in tax exemptions/subsidies and taxes across countries. A relatively small part of the variation comes from tax variation within the countries over the years, due to different implementation times or changes of incentives or adjustments of tax rates. For further identification of the impacts of tax incentives, we make use of variations from different electric vehicle models within a given country and year, which helps to isolate and separate the policy and economic determinants of BEV adoption.

Model-year fixed effect, $\theta_{mt}$, flexibly controls country-invariant trends in sales, national production constraints, and the timing of each model's introduction. In addition, the model-year fixed effect captures model-specific attributes (e.g. engine power, fuel economy, and special model preference) and country-invariant components of the omitted pre-tax sales price. Country-specific taxes and subsidies are considered in the tax incentives. Therefore, it is reasonable to omit the listed or transacted prices of different models. Country-year fixed effect, $\alpha_c t$, controls the country-specific factors affecting supply and demand in a country, allowing for a certain level of year variation. The disadvantages of this approach (Equation 2.4) are that we are not able to estimate the effects of country-level socio-economic factors that are all absorbed by our country-year fixed effects[7].

### 2.3.3 Environmental benefits

From a lifetime perspective, the environmental benefit of a BEV, $EB_i$, is calculated as the total reduction in external costs when switching from an ICEV to a BEV in Equation 2.5. $EC_{it}^v$, (v=icev or bev) is the external cost for a vehicle, $i$. As shown in Equation 2.6, the external cost results from three sources: emissions from vehicle manufacture ($ecm_it^v$), emissions from energy consumption (fuel combustion or electricity production, ($ece_{it}^v$), and noise during driving ($ecn_{it}^v$).

$$EB_i = EC_i^{icev} - EC_i^{bev} \tag{2.5}$$

$$EC_i^v = \sum_{t=0}^{l} \frac{(ecm_{it}^v + ece_{it}^v \times ee^v \times d_{it} + ecn_{it}^v \times d_{it})}{(1+\rho)^t} \tag{2.6}$$

#### Vehicle manufacture

Production impacts are more significant for BEVs than for conventional cars (Hawkins et al., 2013). BEV production emits more $CO_2$ than ICEV production does. The global warming potential (GWP) of BEVs is almost twice the impact of that of ICEVs owing to the higher impacts of battery-related and electronic component manufacturing. Vehicles with the same brand/model have constant $CO_2$-equivalent emissions from manufacturing, regardless of country of production and sales.

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[7] For further exploration of the impacts of socio-economic factors on BEV sales, we simply regress national total BEV sales share on incentives, fuel cost savings, income, charging station, annual distance travelled, BEV producer information, and environmental performance index, following previous research on PHEVs/HEVs (Diamond, 2009; Sierzchula et al., 2014). This is conducted at the national level by year with a representative average BEV and ICEV. The main disadvantages of this approach are limited variation, strong correlation between independent variables, and possible endogeneity problems. However, the coefficient of tax incentives from this regression is close to our main results. Further details are shown in Appendix B.

### Electricity production and fuel combustion

From the perspective of life cycle analysis, electric vehicles do not run cleanly. BEVs consume electricity, the production of which emits pollutants, such as $NO_x$, $NH_3$, $SO_2$, $PM_{2.5}$, $NMVOC$, and $CO_2$, from high stacks at the site of power plants, mostly outside of cities. For ICEVs, fuel combustion emits pollutants, such as $NO_x$, $SO_2$, $PM_{2.5}$, $VOCs$, and $CO_2$. The external costs of electricity production and fuel combustion are country specific. They depend on meteorology, natural landscape, and relative geographical position of countries (Friedrich et al., 2001). The costs include negative impacts on human health and environment (Buekers et al., 2014; Parry et al., 2014). Within one country, externalities from electricity production are less dependent on local population density whereas externalities from fuel combustion are strongly site specific (Maibach et al., 2008; Ayalon et al., 2013). The external cost per unit of electricity or per unit of fuel is calculated as follows:

$$ece_i^v = \sum_j r_{ij}^v + c_{ij}^v \tag{2.7}$$

where $r_{ij}^v$ ($v = icev$ or $bev$) represents the following two sets of emission factors. 1) For BEVs, $r_{ij}^{bev}$ represents production-weighted average emission factors of pollutant $j$ in country $i$ from electricity generation from different local energy sources. 2) For ICEVs, $r_{ij}^{icev}$ represents emission factors of pollutant $j$ from fuel (gasoline/diesel) combustion in country $i$. $c_{ij}^v$ ($v = icev$ or $bev$) represents two sets of marginal social costs for emissions resulting from driving BEVs or ICEVs.

### Noise

The amount of noise from driving BEVs is less than that from driving ICEVs at most speed levels, since BEVs do not have combustion engines and create noise only from tyres when driving fast. The effects of noise depend on vehicle speed and whether driving in a rural or urban area. The marginal social cost of noise, $ecn_{it}^v$, is expressed in units of monetary values per kilometre.

## 2.4 Data

We construct a dataset for the 10 most popular BEV models in 28 European countries, including countries in the EU and Norway, across 3 years, 2012–2014. The BEV models belong to different segments from mini/small cars to sports cars. We compose BEV–ICEV pairs with similar vehicle characteristics, which are listed in Table 2.6 in the Appendix. The cost benefit analysis is based on the year 2014, while the OLS regression makes use of information from 2012 to 2014. Summary statistics are provided in Table 2.5 in the Appendix.

We assume that pre-tax basic prices for vehicles are the same for all countries in order to focus on evaluating designs of tax incentives in the cost benefit analysis. In addition, we assume that consumers use the current prices of fuel and electricity as a best estimate of future fuel prices. A vehicle average lifetime is assumed to be 10 years with a discount rate of 5%. Average annual travelled distance is 15000 $km$ for both vehicles [8] according to the European Automobile Manufacturer Association. Other variables are listed in Table 2.1 with data sources.

Table 2.1: Data sources of variables used in the cost benefit analysis and OLS regression.

| **Variables** | **Data source** |
|---|---|
| **Vehicle registration tax** | ACEA (2012, 2013, 2014b,a, 2015b,a); National government websites |
| **Annual circulation tax** | ACEA (2012, 2013, 2014b,a, 2015b,a); National government websites |
| **Value-added tax** | ACEA (2012, 2013, 2014b,a) |
| **Annual maintenance cost** | Piao et al. (2014) |
| **Fuel price and tax** | EU (2015); IEA (2015a) |
| **Electricity price and tax** | EU (2015); IEA (2015a) |
| **Emission factors of pollutants from power generation** | Buekers et al. (2014) |
| **Emission factors of pollutants from fuel combustion** | Parry et al. (2014) |
| **Marginal costs of pollutants from power generation** | Markandya et al. (2011) |
| **Marginal costs of pollutants from fuel combustion** | Parry et al. (2014) |
| **Marginal costs of pollutants from vehicle manufacture** | Wilson (2013) |
| **Marginal costs of noise from driving** | Litman (2009) |
| **Sales share of BEVs** | EEA (2016) |

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[8] We leave aside the rebound effect associated with improvements of fuel efficiency and range limitation of BEVs

## 2.5 Results

### 2.5.1 Reduction in relative costs of BEVs

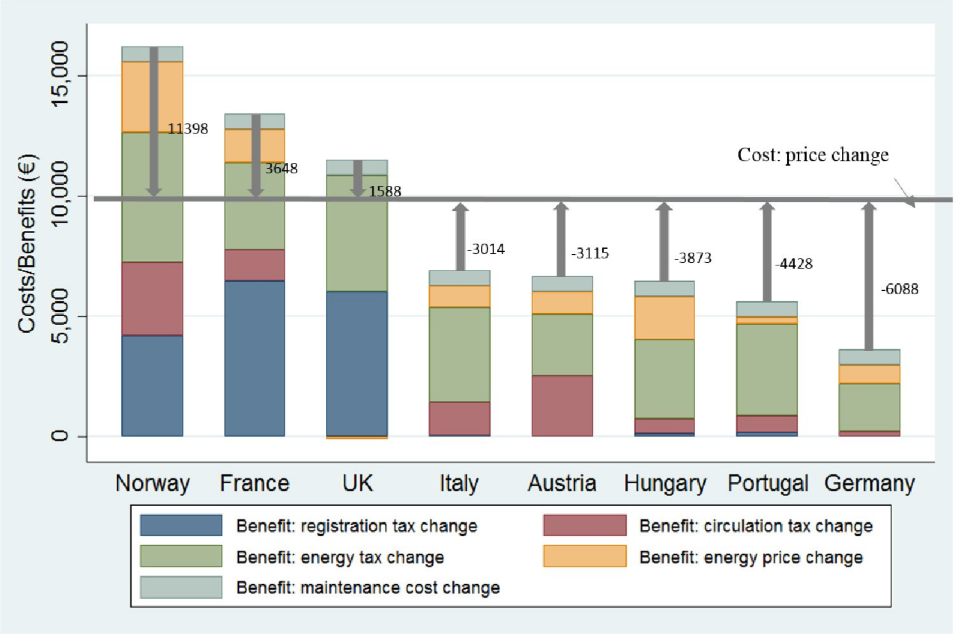

Figure 2.1: Costs and benefits of switching from an ICEV to a BEV.

Figure 2.1 presents the costs and benefits of switching from an ICEV (Renault Clio, gasoline) to a BEV (Renault Zoe, electric[9]) in eight selected countries[10]. The countries are ranked in descending order from left to right according to net benefits of switching to a BEV, varying from 11398 €in Norway to -6088[11] €in Germany. In addition, switching vehicles provides benefits (stacked bars) in that BEVs have lower vehicle registration tax, lower annual circulation tax, lower maintenance cost, lower energy tax, and lower energy price. However, the figure shows

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[9] The Renault Zoe is a representative BEV, accounting for about 13% of all electric vehicle sales in Europe in 2013. The Zoe is available only in an electric version. Its combustion engine counterpart is the Renault Clio, a vehicle from the small-car segment. The Clio is Europe's fourth most popular passenger car Mock and Yang (2014).

[10] We perform the calculation for all 28 countries in the sample. However, owing to space constraints, only eight countries are selected to represent the illustration, based on the type of tax incentives, size of the vehicle market, BEV sales, energy mix, and regional development.

[11] The net benefit reflects only the magnitude of the tax incentives for the vehicle pair with similar characteristics. In fact, the negative sign does not necessarily mean that a BEV is more expensive than all gasoline/diesel vehicles. The replacement of a luxury ICEV (e.g. Audi A3) with a small BEV (e.g. Renault Zoe) results in a positive net benefit but such replacement is more likely to be induced by both tax incentives and other factors, such as consumer preferences or environmental awareness.

that the switch from an ICEV to a BEV causes an additional cost in price (horizontal grey line), since BEVs have higher prices than their ICEV counterparts do, regardless of taxes/subsidies.

The variation in costs and benefits of vehicles reflects heterogeneity in the role of tax incentives in three dimensions: cross-country, cross-(car) model, and cross-driver.

*Cross-country comparison*

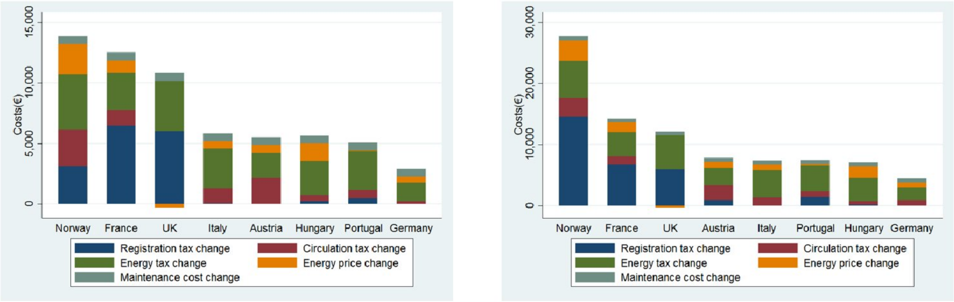
Figure 2.1 illustrates the positive net benefit of switching to a BEV in France, Norway, and the UK in 2014. These countries offer an incentive of more than 6000 €for BEVs in the form of vehicle registration tax exemptions and purchase subsidies. In addition, BEVs are fully exempt from annual circulation taxes in Norway and the UK. In other countries, excluding Norway, the UK, and France, the registration tax is not reduced or is reduced slightly when switching from an ICEV to a BEV. In Italy, BEVs are not exempt from registration taxes but are exempt from annual circulation tax for 5 years. In Austria, Hungary, and Portugal, BEVs are exempt from both vehicle taxes but their ICEV counterparts have very small vehicle registration taxes. Germany ranks very low in terms of the net benefit of switching to a BEV, since it has no registration taxes for any vehicles and small amounts of annual circulation taxes on the ICEV counterparts. Instead of providing tax incentives for consumers, Germany invests substantially in R&D and market demonstration projects.

Apart from tax incentives, the reduction of energy cost contributes significantly to the total net benefit when switching to a BEV. For these countries in the sample, excluding Norway, the UK, and France, the total ownership cost of a BEV is 10–20% higher than the cost of an ICEV. The cost gap has been reduced compared to the results (30–40%) from earlier research (Funk and Rabl, 1999; Delucchi and Lipman, 2001). The reduction of the gap has resulted not just from a reduction in the production costs of BEVs but also from an increase in financial support for BEVs and taxation for ICEVs.

*Cross-(car) model comparison*

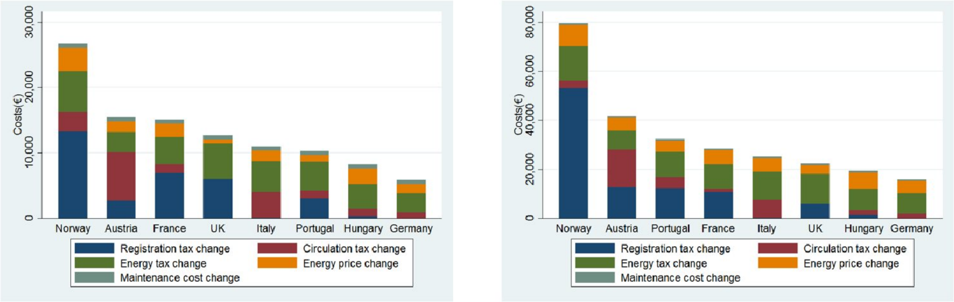
We calculate the costs and benefits of switching to other BEV models, such as Nissan Leaf (compact car), BMW i3 (midsize car), and Tesla Model S (sports car). The results (Figure 2.2) identify the important role of registration tax exemption in reducing the relative costs of BEVs. In particular, for larger vehicles, BEVs have much lower relative costs, compared to their

ICEV counterparts. With regard to the net benefits of switching to a BEV in different vehicle segments, the ranking of the countries is slightly different, because tax designs in different countries favour BEVs in different vehicle segments.



(a) Mitsubishi i-MiEV (mini)

(b) Nissan Leaf (compact)



(c) BMW i3 (midsize)

(d) Tesla (sports)

Figure 2.2: Benefits of switching from an ICEV to a BEV by car model.

*Cross-driver comparison*

The net benefits of switching to a BEV vary with drivers who travel different distances annually. Table 2.2 presents the requirements of annual distance travelled to achieve breakeven conditions in which the total ownership costs of BEVs and ICEVs are equal. Drivers with higher annual distance travelled are more likely to buy BEVs, because more energy costs will be saved by switching from an ICEV to a BEV. In addition, travelling longer distances means lower purchase cost of a BEV per kilometre. In Norway, France, and the UK, where huge tax incentives are provided, drivers can benefit from switching to BEVs within a normal range of annual distance travelled. Other countries require drivers to have an extremely high annual distance travelled in order to benefit from driving BEVs. However, owing to technical limitations, BEVs are not able to fulfil the necessary annual distance travelled sufficiently. In fact, this conflict leads to low sales of BEVs.

Table 2.2: Breakeven requirements of annual distance travelled for equal vehicle costs by country.

| | **Norway** | **France** | **UK** | **Italy** | **Hungary** | **Austria** | **Portugal** | **Germany** |
|---|---|---|---|---|---|---|---|---|
| **Annual distance travelled ($km$)** | 0 | 4054 | 9946 | 24325 | 26419 | 28439 | 31332 | 48273 |

### 2.5.2 Increase in BEV sales

The tax incentives reduce the total ownership costs of electric vehicles and therefore, induce the purchase of electric vehicles. In Table 2.3, the estimated coefficients illustrate to what extent the tax incentives influence BEV sales. There are 240 observations in total. Observations with zero value variables are omitted due to the log forms.

We run five specifications. In our main specification (Model 1), we regress BEV sales share on the tax incentives and two main fixed effects — model-year fixed effects and country-year fixed effects. In Model 2, we add an additional variable, fuel cost savings (€/$km$). The estimated coefficient for fuel cost savings is not significant, partly because fuel costs include energy prices, which are highly correlated with country-year fixed effects, but possibly also because annual national average prices do not reflect the observation and expectation of fuel prices when consumers decide to purchase BEVs. In Model 3, we divide the total tax incentives into two independent variables: the amounts of registration tax exemption and annual circulation tax exemption. The result shows that the registration tax exemption has similar coefficients to the total incentives while the annual circulation tax exemption has no significant influence on BEV purchases. In Model 4, instead of a discount rate of 5%, we perform the regression with a discount rate of 10%. Model 5 replaces the country-year fixed effects by country-segments fixed effects that control preferences of country to car segments, apart from the country-invariant characteristics.

In Table 2.3, the estimated coefficients of tax incentives are positive and significant, ranging from 0.319 to 0.397. This means an increase of tax incentive by 10% is associated with a 3.19–3.97% increase in market share of BEV sales. By using the mean values in the summary statistics, we are able to convert our results and compare them with the estimates of the impacts of tax incentives on HEV sales by Diamond (2009), Chandra et al. (2010), and Gallagher and Muehlegger (2011). The estimated effect of tax incentives in our study is smaller. This is reasonable, considering that BEVs have bigger disadvantages over ICEVs than PHEVs do. Consumers are more unfamiliar with BEVs, which creates uncertainty about future costs, benefits, reliability, convenience, and/or required adaptations (Stephens, 2013). The uncertainty leads to lower responsiveness of sales to the tax incentives. In addition, the actual observed market share is a result of complex interactions between tax exemptions/rebates, energy prices, development of infrastructure, consumer preferences and other socio-economic factors[12]. Furthermore, if the average (sample mean) percentage of tax incentive to BEV price is 15%, BEV price elasticity of -1.3 is obtained, which is close to the BEV price elasticity of -1.8 estimated by DeShazo et al. (2017) and the new vehicle sales price elasticity of -1.6 by Hess (1977).

Table 2.3: Fixed-effect regression results: model specifications.

| | **Model 1** | **Model 2** | **Model 3** | **Model 4** | **Model 5** |
|---|---|---|---|---|---|
| | Main | Fuel savings | Separate tax | Discounting | Fixed effects |
| **Incentives** | 0.342** | 0.319* | | 0.326* | 0.397* |
| | (0.151) | (0.163) | | (2.220) | (0.203) |
| **Registration tax** | | | 0.359*** | | |
| | | | (0.125) | | |
| **Circulation tax** | | | 0.208 | | |
| | | | (-0.176) | | |
| **Fuel savings** | | 0.404 | | | |
| | | (-1.094) | | | |
| **Country × Year** | YES | YES | YES | YES | |
| **Model × Year** | YES | YES | YES | YES | YES |
| **Country × Segment** | | | | | YES |
| **Constant** | -11.839*** | -15.103*** | -12.732*** | -11.657*** | -13.921*** |
| | (1.549) | (8.971) | (1.667) | (1.507) | (1.921) |
| **N** | 240 | 240 | 155 | 240 | 240 |
| $R^2$ | 0.811 | 0.811 | 0.865 | 0.811 | 0.872 |
| **Adjusted** $R^2$ | 0.721 | 0.720 | 0.761 | 0.721 | 0.791 |

Note: *p<0.01, **p<0.05, ***p<0.1.

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[12] As the regression in Appendix B shows, the influence of charging stations, vehicle kilometres travelled, and income are consistently and significantly associated with BEV sales.

### 2.5.3 Environmental benefits

Green taxes are implemented to internalize externalities. The main purpose of the tax incentives for BEVs is to mitigate climate change. In this subsection, we investigate whether the size of emission reductions from switching from an ICEV to a BEV is reasonable in light of the corresponding total tax incentives. Table 2.4 presents the ratio of total $CO_2$ emission reduction to total tax incentive for BEVs, varying from 0.07 to 0.754. The table shows the final cost governments pay to reduce 1 $kg$ of $CO_2$ from switching to a BEV. Compared to the European Union Emissions Trading System $CO_2$ price, around 0.006 €/$kg$ in 2014, the emission reductions are very expensive.

Table 2.4: Comparison of tax incentives for switching to BEVs in terms of cost efficiency.

| | **Austria** | **France** | **Germany** | **Hungary** | **Italy** | **Norway** | **Portugal** | **UK** |
|---|---|---|---|---|---|---|---|---|
| **Cost efficiency:**<br>**tax** $/CO_2$ **(€/$kg$)** | 0.198 | 0.513 | 0.267 | 0.07 | 0.178 | 0.480 | 0.100 | 0.754 |

Moreover, apart from $CO_2$ emissions, we consider two other important externalities: local pollution and noise for calculating the total external cost of switching to a BEV. In Figure 2.3, we present the tax incentives for BEVs and corresponding environmental benefits (reductions of the total external costs) of switching to a BEV in different countries in 2014. The line connects dots in which the total tax incentive is equal to the environmental benefit. Countries above the line would gain more environmental benefit than loss of tax revenue when switching from ICEVs to BEVs.

Higher tax incentives make it more likely to switch from driving an ICEV to driving a BEV. For such vehicle replacement, Slovakia, Hungary, and Czech Republic achieve very high environmental benefits while Greece, Ireland, and the UK gain relatively low environmental benefits. The reasons vary across countries. For example, in Hungary, the environmental benefits of switching to a BEV are high, since the marginal damage cost of pollutants from road transport is much higher than that in the other countries. On the contrary, the UK has low environmental benefits from such a switch, since fossil fuels, especially coal, accounted for a large part of its electricity production in 2014. Importantly, in most countries (e.g. Denmark, Norway, France, and the UK), especially those in which BEVs are heavily subsidized, the tax incentives are much higher than the estimated environmental benefits. Criticism of heavy subsidization for BEVs emerges when we compare the total tax incentives[13] with the total $CO_2$ emission reduction and the total environmental benefits. However, arguments in favour of subsidization point to the benefits of promoting battery technology progress and cultivating a new market in the long run. Nevertheless, it remains to be determined how much the tax incentives can contribute to BEV sales.

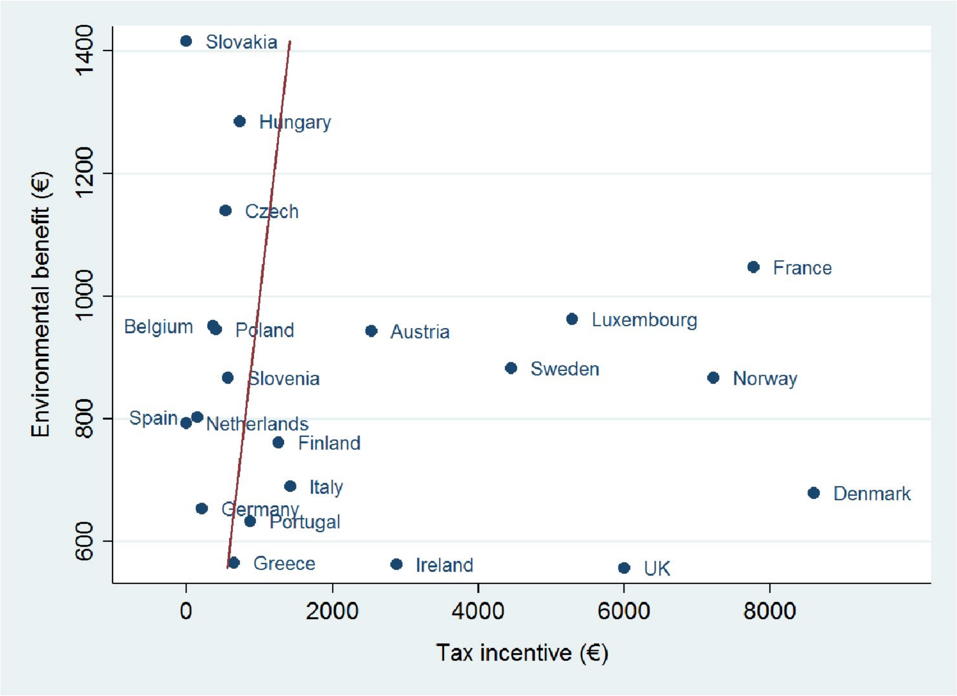

Figure 2.3: Environmental benefits and tax incentives for switching from an ICEV to a BEV.

## 2.6 Conclusion

Various tax incentives are used by many European countries to promote fuel-efficient/low-emission vehicles, such as BEV. The tax incentives are in the form of tax exemptions or subsidies for electric vehicles or in the form of higher vehicle registration taxes or annual circulation taxes for ICEVs. Policy-making must be well informed to ensure that the most effective measures are to put in place to achieve desired outcomes. In this thesis, we apply cost benefit analyses and OLS regressions to study the role of the tax incentives in reducing the total ownership cost of

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[13] We do not consider fuel taxes. Here, we focus on the vehicle tax incentives that mainly induce sales of BEVs. By considering fuel taxes in the total tax incentives, the excess of tax incentives over environmental benefits would be larger.

BEVs, increasing sales of new BEVs and therefore, yielding environmental benefits. The study is based on a dataset covering 10 pairs of the best-selling BEVs and their ICEV counterparts in 28 European countries across 3 years, 2012–2014.

The total ownership cost calculation of vehicles contributes to the understanding of interactions between tax incentives and BEV sales. The calculation is based on individual switches from an ICEV to a BEV. We find that the tax incentives, especially registration tax exemption, significantly lower the relative costs of BEVs. For larger vehicles, BEVs have much lower relative costs, compared to their ICEV counterparts. Moreover, strong tax incentives can lower the requirements of annual distance travelled to achieve equal total ownership costs of ICEVs and BEVs.

Apart from the total ownership costs, many other socio-economic factors (e.g. environmental awareness, income, the number of BEV charging stations, travel demand, maximum travel range of BEVs, and consumer preferences) also have important influences on the adoption of BEVs. We control these factors with different fixed effects in order to identify the effects of the tax incentives on BEV sales. Our OLS regression shows that a 10% increase in the tax incentives is associated with a 3–4% increase in sales share of BEVs. This implies a BEV vehicle price elasticity of -1.3 for the sample mean. In addition, we attempt to explore the effects of the socio-economic factors on BEV sales in a simple regression in the Appendix. Although the coefficient for the effect of tax incentives is close to the coefficient in our main regression, independent variables are highly correlated and the precision of estimations is limited due to the limited data variation. To estimate the effects of the socio-economic factors on BEV sales, further research calls for larger datasets with sufficient variations for implementing advanced econometric approaches.

Our research is motivated not only by the recent vehicle tax reforms with exemptions for BEVs and various options of BEVs in the current market but also by the increasing share of clean electricity generation and continuous reductions in production costs in recent years. In spite of the improvements, it is still costly to use the tax incentives to reduce $CO_2$ emissions and other externalities through transport electrification. However, the inefficiency of the tax incentives can be justified as long-term policy instruments for breaking market barriers and promoting new technologies. The question then is to what extent the BEV tax incentives contribute to the development of new vehicle/battery technology that already receives strong financial support. It might be more efficient to provide incentives for the development of vehicle/battery technologies than for purchase behaviour. Notably, we do not discourage policy support for switching to BEVs. It is important to point out that key prerequisites for the success of BEV adoption are the availability of clean electricity and the significant reduction of BEV production costs. Furthermore, future research on the deployment of new vehicle technology (e.g. BEVs) needs to take into account local incentives (e.g. regional distributions of charging stations, commuting routes, access to bus lane, and free parking for electric vehicles) in order to better assess their specific merits relative to alternative vehicle options (e.g. ICEVs).

## Acknowledgement

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# Appendix A

Table 2.5: Summary statistics.

| **Variable** | **Observation** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|
| **BEV sales number** | 746 | 128.2386 | 513.4582 | 0 | 5970 |
| **BEV sales share** | 746 | 0.000463 | 0.002614 | 0 | 0.033155 |
| **Incentive (5% discount rate)** | 746 | 3811.982 | 10373.92 | 0 | 128947.7 |
| **Incentive (10% discount rate)** | 746 | 3699.247 | 10278.77 | 0 | 127761.5 |
| **Vehicle registration tax** | 746 | 3128.461 | 9886.945 | 0 | 121963.5 |
| **Annual circulation tax** | 746 | 84.10644 | 190.4441 | 0 | 1899 |
| **Fuel saving** | 746 | 6319.933 | 3598.464 | 2091.94 | 19438.61 |

Table 2.6: Vehicle pairs of BEV and ICEV models.

| BEV | Nissan Leaf | Renault Fluence Z.E. | Renault Zoe | Tesla Model S | BMW i3 | Mitsubishi i-MiEV | Citroën C-Zero | Peugeot iOn | Smart Fortwo EV | Volkswagen e-up! | Average EV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Basic price | 26400 | 28784 | 24000 | 44925 | 31013 | 18000 | 18000 | 18000 | 18750 | 22500 | 25422 |
| Engine power | 80 | 70 | 66 | 260 | 125 | 47 | 47 | 47 | 55 | 60 | 86 |
| Energy efficiency | 0.173 | 0.14 | 0.146 | 0.181 | 0.129 | 0.135 | 0.135 | 0.135 | 0.151 | 0.117 | 0.144 |
| Weight | 1521 | 1543 | 1468 | 2090 | 1195 | 1080 | 1080 | 1080 | 900 | 1214 | 1317 |
| ICEV | Nissan Note | Renault Fluence Z.E. | Renault Clio | BMW 740i | BMW Series1 | Mitsubishi Imirage | Mitsubishi Imirage | Mitsubishi Imirage | Smart Fortwo ICE | Volkswagen up | Average ICEV |
| Basic price | 12000 | 20000 | 13000 | 58000 | 28000 | 10400 | 10400 | 10400 | 10000 | 15000 | 22000 |
| Engine power | 64 | 82 | 66 | 235 | 125 | 59 | 59 | 59 | 52 | 66 | 89 |
| Engine size | 1198 | 1598 | 898 | 2979 | 1598 | 1193 | 1193 | 1193 | 999 | 999 | 1642 |
| Energy efficiency | 0.049 | 0.068 | 0.043 | 0.106 | 0.048 | 0.037 | 0.037 | 0.037 | 0.043 | 0.045 | 0.054 |
| Weight | 1546 | 1747 | 1009 | 1825 | 1315 | 845 | 845 | 845 | 780 | 929 | 1864 |
| CO2 intensity | 139 | 155 | 99 | 184 | 137 | 96 | 96 | 96 | 97 | 101 | 133 |

# Appendix B

We estimate the influence of socio-economics factors on BEV adoption by country and year.

$$\ln s_{it} = \ln inc_{it} + \ln X_{it} + pro_i + year_t + \epsilon_{it} \tag{2.8}$$

where $s_{it}$ is the market share of total BEV sales in country $i$ and year $t$. $inc_{it}$ represents the tax incentives for BEVs. $X_{it}$ is a bundle of socio-economic factors, such as annual vehicle kilometres travelled, average household income, charging station per capita, fuel cost saving, and an environmental performance index. $pro_i$ is the dummy for whether a BEV manufacturer exists in country $i$. $year_t$ is the year fixed effects. $\epsilon_{it}$ is a mean zero term. The dummy $pro_i$ controls the tendency of policy-making and vehicle purchases due to domestic vehicle industry support, which might increase domestic BEV sales. The year fixed effect controls for the time-variant variables that are indifferent among countries, such as the development of battery technology.

Table 2.7: OLS regression results with socio-economic factors.

| | **Model - Fuel saving** |
|---|---|
| **Incentives** | 0.276* |
| | (0.157) |
| **Charging station per capita** | 0.335*** |
| | (0.103) |
| **Vehicle kilometre travelled** | -1.431*** |
| | (0.350) |
| **Income** | 1.160*** |
| | (0.388) |
| **Fuel saving** | 0.111 |
| | (0.954) |
| **Environmental performance index** | 2.646 |
| | (0.315) |
| **(constant)** | -38.609*** |
| | (10.149) |
| **Producer** | 0.627** |
| | (0.309) |
| **Year fixed effect** | YES |
| **N** | 46 |
| $R^2$ | 0.794 |
| **Adjusted** $R^2$ | 0.730 |

# Chapter 3

# How to Measure Greenhouse Gas Emissions by Fuel Type for Binary Sustainability Standards: Average or Marginal Emissions? An Example of Fertilizer Use and Corn Ethanol

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## Abstract

This study proposes a modelling framework which addresses various issues, such as decreasing marginal yield of corn with respect to fertilizer use in biofuel production and the resulting greenhouse gas emissions. In particular, the framework considers exogenous changes, including oil price development and biofuel policy, through market interactions of different inputs and outputs in biofuel production. We numerically apply a modelling framework using an example of corn ethanol production in the US to illustrate how the economics of fertilizer use could impact GHG emissions based on both average and marginal emissions. The results show that, the increases of oil price and the implementation of the Volumetric Ethanol Excise Tax Credit stimulate corn-based ethanol production and increase corn yields by encouraging profit-maximizing farmers to increase their application rate of nitrogen fertilizers. The effect of the increases of oil price and the implementation of the tax credit is that, on average, GHG emissions per unit of corn ethanol remain almost constant, while marginal GHG emissions per additional unit of ethanol production vary from 96,97 to 157,53 $g\ CO_2 - eq./MJ$. Although on average there are GHG emission savings of corn ethanol compared to conventional gasoline, the savings are negative when based on the marginal GHG emissions from corn ethanol production. An interesting implication is that the effectiveness of the Volumetric Ethanol Excise Tax Credit aimed at reducing GHG emissions might be questionable.

**Keywords**: oil price, ethanol, corn, nitrogen fertilizer, greenhouse gas emissions, ethanol tax credit

## 3.1 Introduction

More than 50 countries globally have implemented legislative instruments to promote the use of biofuels, such as the mandatory use of biofuels and tax exemptions for them, while many more countries are considering introducing similar policies (Sorda et al., 2010; IEA, 2011; Le et al., 2013a,b). As a result, the use of biofuels has increased rapidly in recent years; biofuels currently account for about 3.4% of worldwide energy use in road transport (Martinot et al., 2013).

The US has an ambitious biofuel policy, which started with the implementation of the Energy Policy Act in 2005. The Energy Policy Act included targets for the mandatory use of biofuels in the US's transport fuel supply. The Energy Independence and Security Act of 2007 expanded the biofuel blend mandates to 9 billion US gallons of biofuels in 2008, and to 36 billion gallons in 2022. This legislation is referred to as the Renewable Fuel Standard 2 (RFS 2). In the RFS 2, the use of corn ethanol is capped at 15 billion gallons. These policies resulted in an increase in the use of biofuels from 4.2 billion gallons in 2005 to 13.8 billion gallons in 2013. A key objective of the RFS 2 is to reduce the US's dependency on fossil oil imports, to increase energy security, and to increase resilience to price fluctuations of fossil oil. The prerequisite for the use of biofuels is that it contributes to reducing greenhouse gas (GHG) emissions, that is, a 20% threshold reduction of GHG emissions (compared to conventional gasoline produced from fossil oil) for biofuel-producing facilities whose construction started after December 2007. Similarly, in Europe, GHG savings of 35% have been proposed for implementation of biofuels by the Renewable Energy Directive (EC, 2010).

In this context, an important task is how to evaluate the GHG emissions from biofuel production. According to the annotated example of a GHG calculation (Alberici and Hamelinck, 2010), a comprehensive assessment of environmental impacts over the life cycle of a biofuel, that is, a life cycle analysis, is involved to calculate the average emissions of GHG per unit of biofuel (e.g.$kg\mathrm{CO}_2 - eq./MJ$ ethanol). Life cycle analyses have been used for evaluating the effectiveness of biofuel policies in reducing GHG emissions, that is, the GHG savings of a biofuel by comparing its GHG emissions with those of gasoline (e.g. (Le et al., 2013b)). Life cycle analyses take into account the emissions from the production chain of a biofuel measured across the entire life cycle, including biomass production, processing, and distribution. Life cycle analyses calculate the emissions for a functional unit, such as one $MJ$ or one tonne of a biofuel. Thus, the final conclusion on emission savings is based on the average emissions of a biofuel. In conventional life cycle analyses, a linear relationship between emissions and direct inputs is assumed without considering the external effects of the use of biofuels. In particular, indirect effects, diminishing marginal productivity of a biomass (e.g. corn) with respect to fertilizer input, and interrelations in the energy and agricultural markets are not well considered. Examples of these indirect effects are the impact of biofuel production on indirect land-use change and on energy use (Hochman et al., 2010; Laborde, 2011; Rajagopal et al., 2011; Le et al., 2013b; Kavallari et al., 2014; Smeets et al., 2014). These effects might have a large impact on the overall GHG savings of biofuels (Plevin et al., 2014).

Apart from the increase in the cultivated area, the increase in biomass production for biofuels is usually realized through higher corn yields per unit of area. Higher crop yields are often proposed as a promising strategy to avoid undesirable indirect land-use change effects of biofuel production and thereby undesirable effects on GHG emissions and biodiversity. These higher yields are partially realized by higher fertilizer application rates. However, higher application rates are probably related to higher GHG emissions per unit of corn, because of a concave yield response function. Kim and Dale (2008) investigates the economically and environmentally optimal nitrogen application rates of corn production in the US. The authors' results show that the GHG emissions associated with per unit corn production decrease as the nitrogen application rates increase, until a minimum GHG emission level is reached. Further increasing the nitrogen application rate increases GHG emissions, due to decreasing marginal productivity gains of fertilizer use. In other words, there is a U-shaped relationship between the nitrogen application rate and the GHG emission intensity of corn production. In addition, the results of Kim and Dale (2008) indicate that the economically optimal application rates of fertilizers are higher than those at which the GHG emissions per unit of corn are lowest. Stehfest et al. (2010) suggest that merely increasing the quantity of nitrogen fertilizer — probably the simplest way to produce higher yields — could lead to additional emissions of up to 150 $kg$ $CO_2 - eq./GJ$ biofuel, which is more than the 91 $kg$ $CO_2 - eq./GJ$ of conventional gasoline. This shows that higher crop yields might have similar GHG emission effects as indirect land-use change, if higher corn yields are realized through higher application rates of fertilizers under conditions of decreasing marginal productivity gains of fertilizer use. Therefore, there is a need to calculate the marginal emissions of a biofuel (e.g. emissions from the last unit of biofuel produced from the last unit of corn) for evaluation of emission savings.

Furthermore, the biofuel sector is closely connected to other economic sectors. There is a close economic linkage between the inputs of corn ethanol (e.g. natural gas) through commodity markets and government policies (Tyner et al., 2012; Babcock, 2013). Price changes in the oil market have a direct impact on the demand for ethanol and the price of gasoline through energy markets (Tyner and Taheripour, 2007; Serra et al., 2011), which influences the use of inputs for ethanol production (corn and fertilizers) and thereby GHG emissions. Current biofuel policies (e.g. tax for fossil fuels and tax credits for biofuels) change the economic incentives of economic agents to choose their energy products, which have impacts on GHG emissions.

The aim of the research presented in this chapter is to develop a modelling framework for evaluating the impact of the economics of nitrogen fertilizer use on GHG emissions, based on average and marginal GHG emissions, considering the interactions of energy and agricultural markets. The model is applied to the case of corn ethanol production in the US, and it particularly concerns the impacts of oil price developments and ethanol policies, especially the Volumetric Ethanol Excise Tax Credit (VEETC), on average and marginal GHG emissions. The novelty of this research is that we are able to calculate both average and marginal GHG emissions of biofuels, which can be compared to those of fossil fuels, and provide useful insights on the actual emission savings of biofuels.

The rest of this chapter is structured as follows. Section 3.2 presents an analytical framework for calculating the average and marginal GHG emissions of corn ethanol, taking into account energy and agricultural market interactions. The framework consists of an economic model that links the oil price to the prices of gasoline, corn ethanol, and corn, the price of fertilizers used for the production of corn, and the price of natural gas for the production of corn ethanol. GHG emissions from corn production depend, among others, on the application rate of fertilizers. An economically maximized rate was recommended in the Corn Belt in the US (Sawyer et al., 2006). Therefore, we determine the economically optimal nitrogen application rate based on profit maximization. To calculate the average and marginal emissions of corn ethanol, the economic model is combined with the data on the GHG balance of corn ethanol from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) life cycle analysis model (CARB, 2009). In Section 3.3, we use corn ethanol production in the US as an example to illustrate how the model can be applied. We report the data for the model parameters and the range of the oil prices used in the calculations, as well as information on GHG emissions from the production of conventional gasoline from oil sands. The main results concerning the GHG emissions from corn ethanol production under different oil prices are presented for two scenarios, namely, with and without VEETC. Sensitivity analyses are presented for the yield–fertilizer response curve and the fertilizer type. Finally, in Section 3.4, we present conclusions and discuss implications for policy and research.

## 3.2 The Analytical Framework

To calculate GHG emissions, we develop an analytical framework based on the four main stages of a corn ethanol production chain: corn cultivation, corn transport, ethanol production (corn–to-ethanol conversion), and ethanol distribution (including transport of ethanol and blending with gasoline). The framework consists of two parts: an economic analysis and the calculation of GHG emissions. The economic analysis deals with the interactions between inputs and outputs in different stages, particularly the market interactions between oil, natural gas, gasoline, ethanol, and fertilizers, which impact the use of fertilizers in corn cultivation. The emission part calculates the particular outputs, that is, the emissions of $CO_2$ and $N_2O$ from the ethanol chain, based on an environmental life cycle analysis. In this way, the framework combines the economic analysis of the inputs and outputs with the life cycle analysis to calculate the GHG emissions from corn ethanol production. Thus, it allows for capturing the impact of external changes — such as changes in oil price or a biofuel policy — on the GHG emissions from corn ethanol production through the market interactions of inputs and outputs, particularly the change in fertilizer use in corn cultivation (see Figure 3.1).

GHGs are emitted in all stages of the ethanol production chain. In the corn cultivation stage, we use the economically optimal nitrogen application rate to achieve the maximum economic return from corn production. This economically optimal nitrogen application rate is based on profit maximization, despite the possible overuse of fertilizers by farmers in most developed countries owing to risk aversion. The nitrogen application rate depends on the relative price of nitrogen fertilizers to corn and the corn yield response function. Any change in inputs or outputs in this stage influences the nitrogen application rate, which definitely impacts the GHG emissions from corn cultivation. In the stage of ethanol production, in which corn is converted to ethanol, natural gas is the second important input after corn. Therefore, any exogenous forces which influence the price of natural gas and thus, the cost of production of corn (e.g. a change in oil price) impact the price of ethanol. This has a feedback effect on corn production and fertilizer use in the first stage, and thereby results in changes in GHG emissions. In the stage of blending with gasoline, exogenous changes (e.g. oil price changes) have implications for the price of gasoline and ethanol through the energy market. This again has a feedback effect on the production of corn as well as fertilizer use, and influences final GHG emissions. Below, we present the quantitative relationships that describe the optimal application rate of nitrogen and the market interactions of inputs and outputs, which finally determine the GHG emissions of corn ethanol.

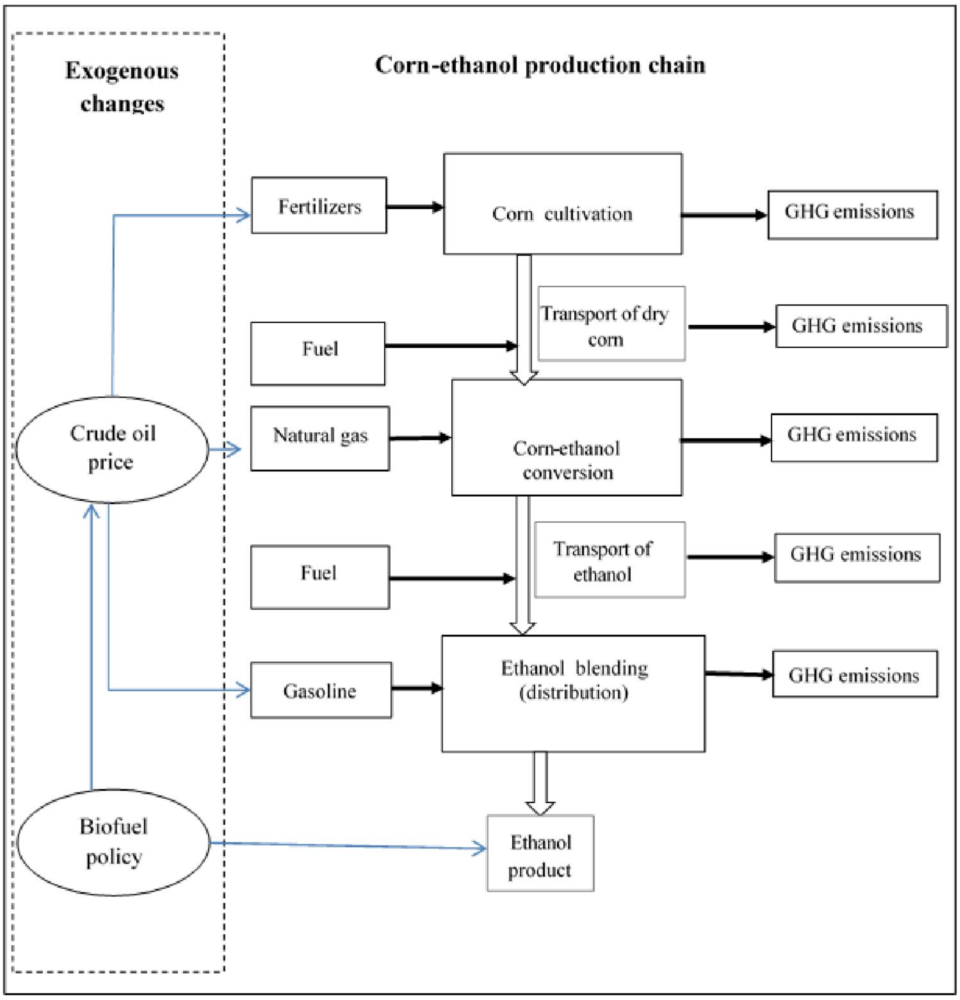

Figure 3.1: The analytical framework for calculating GHG emissions from corn ethanol production.

### 3.2.1 Economic analysis

In this subsection, we elaborate in a mathematical model the optimal application rate of nitrogen fertilizer in corn cultivation, the price relationship of inputs and outputs in ethanol production, and the price relationship between ethanol and gasoline under biofuel policies. The optimal application rate of nitrogen fertilizers is determined by the profit maximization of corn farmers, taking into account the yield response to the nitrogen input. The price relationship of corn, natural gas as an input, and ethanol as an output in ethanol production is determined by the equilibrium condition in which no positive profit of ethanol production is earned under constant-return-to-scale technology. As for the price relationship of ethanol and gasoline, energy efficiency is considered in vehicle engines for the same distance travelled. Biofuel policies, such as a gasoline tax or a biofuel subsidy, influence the consumer prices of ethanol and gasoline.

***Economically optimal application rate of nitrogen in corn cultivation***

We pay special attention to the economically maximized application rate based on the yield response function, which is currently recommended by agronomists. The problem can be represented as follows. A corn farmer maximizes his or her profit by choosing the application rate of nitrogen fertilizers, subject to the yield–nitrogen response function. Since the response function is based on the nitrogen content, the application rate and the price of fertilizers in the following calculations are also determined by nitrogen content ($kgN/ha$ or $\$/kgN$, respectively). The unit-area profit function can be written as

$$\pi_{corn} = Q_{corn}P_{corn} - NP_{nitrogen} - C_{other} \tag{3.1}$$

where $Q_{corn}$ is the corn yield or the corn output per unit of land ($kg/ha$), $P_{corn}$ and $P_{nitrogen}$ are the price of corn ($\$/kg$) and nitrogen ($\$/kgN$), respectively, $N$ is the application rate of fertilizer in nitrogen content ($kgN/ha$), and $C_{other}$ represents the costs of other inputs per unit of land for corn production ($\$/ha$). The price of nitrogen is based on the price of nitrogen fertilizers (ammonia is used as a reference fertilizer) and the nitrogen content. Following Cerrato and Blackmer (1990), the yield response function can be expressed as a quadratic function of the application rate of nitrogen, indicating a positive relationship between nitrogen input and corn output with diminishing marginal productivity. In other words,

$$Q_{corn} = m + n \times N - kN^2 \tag{3.2}$$

where $m$, $n$, and $k$ are parameters and $N$ is the same as above. Plugging Equation 3.2 into Equation 3.1 yields

$$\pi_{corn} = mP_{corn} + (nP_{corn} - P_{nitrogen}) \times N - kP_{corn}N^2 - C_{other} \tag{3.3}$$

Similar to Sawyer et al. (2006), assuming fixed costs of other inputs, we take the derivative of

Equation 3.3 with respect to $N$ and set it to zero to obtain the economically optimal application rate of nitrogen and corn yield:

$$N = [(P_{nitrogen}/P_{corn}) - n]/(-2k) \tag{3.4}$$

$$Q_{corn} = [4mk + (P_{nitrogen}/P_{corn})^2 - n^2]/(-4k) \tag{3.5}$$

***Price relationship between corn, ethanol, and natural gas in ethanol production***

Ethanol production (see Figure 3.1) needs corn and natural gas as inputs. Following Tyner and Taheripour (2007), the production technology of ethanol production based on the dry mill process follows a linear relationship between inputs and outputs, including the co-product of dried distillers' grains with solubles (DDGS). The profit derived from ethanol production includes the revenue from selling ethanol and the DDGS, minus the various costs, including those of corn and natural gas. Due to fixed technical coefficients of inputs and outputs (i.e. a constant–return-to-scale production technology), the unit profit of the ethanol producer ($\$/m^3$) can be expressed as

$$\pi_{ethanol} = \beta P_{ethanol} - \alpha P_{corn} - \gamma P_{naturalgas} + \delta P_{DDGS} - c_0 \tag{3.6}$$

where $P_{ethanol}$ is the price of ethanol ($\$/m^3$), $P_{corn}$ is the price of corn ($\$/kg$), $P_{natural}$ gas is the price of natural gas ($\$/m^3$), $P_{DDGS}$ is the price of DDGS ($\$/kg$), and $c_0$ represents other costs, including the capital costs per unit of ethanol production. Parameters $\beta$, $\alpha$, $\gamma$, and $\delta$ are the technical coefficients, that is, $\gamma$ $m^3$ of natural gas and $\alpha$ $kg$ of corn can produce $\beta$ $m^3$ of ethanol and $\delta$ $kg$ of DDGS for one $m^3$ of ethanol production (CARB, 2009). Since the co-product DDGS can be used as a substitute for corn and soybean meal in animal feed, its price is correlated with the corn price (Tyner et al., 2012). This can be expressed as $P_{DDGS} = xP_{corn}$, where $x$ is the price ratio of DDGS to corn. As a result, the unit profit function can be written as

$$\pi_{ethanol} = \beta P_{ethanol} - (\alpha - \delta x)P_{corn} - \gamma P_{naturalgas} - c_0 \tag{3.7}$$

In a competitive market, if the profit under constant-return-to-scale technology is positive, the producer will continue to increase his or her production by demanding more corn inputs. This results in a higher price of corn and a lower price of ethanol. The producer will continue to increase his or her production until the profit becomes zero or an equilibrium is reached. Therefore, at the equilibrium, the following price relationship exists:

$$P_{corn} = (\beta P_{ethanol} - \gamma P_{naturalgas} - c_0)/(\alpha - \delta x) \tag{3.8}$$

It can be observed that Equation 3.8 is consistent with Equation (2.1) of De Gorter et al. (2015) when $\alpha$=1, which is the case for Leontief technology.

***Ethanol and gasoline prices under biofuel policies***

We follow De Gorter et al. (2015) to derive the ethanol and gasoline price relationsships under the volume tax and volume tax credit policies. For fuel users, the willingness to pay for a certain fuel depends not only on the fuel price, but also on the energy efficiency of the fuel for travelling a given distance. Due to its lower energy content, one unit (e.g. one $m^3$) of ethanol will power a vehicle over a shorter distance than the same amount of gasoline, assuming the combustion efficiency of the two fuels is equal. Assuming that gasoline and ethanol are perfect substitutes for fuel users, the willingness to pay for ethanol and gasoline for travelling the same distance should be equal. If the ratio of distance (e.g. $km$) made by 1 $m^3$ of ethanol to that of gasoline is denoted as $\lambda$ ($0< \lambda< 1$), the price relationship between ethanol and gasoline in a competitive market is $P_{ethanol}$=$\lambda$ $P_{gasoline}$ (De Gorter and Just, 2010). If a volumetric consumption tax for any fuel is used, the price relationship between gasoline and ethanol becomes

$$P_{ethanol} = \lambda(P_{gasoline} + t) - t \tag{3.9}$$

where $P_{ethanol}$ and $P_{gasoline}$ are the prices of ethanol ($\$/m^3$) and gasoline ($\$/m^3$), respectively, $\lambda$ is the ratio of travel kilometres incurred by one $m^3$ of ethanol relative to the same amount of gasoline, and $t$ is the volumetric fuel tax ($\$/m^3$).

Furthermore, the VEETC (i.e. the subsidy for ethanol blenders) was implemented in the US to promote the blending of ethanol with gasoline. For each unit of ethanol blended with gasoline, the ethanol blender obtains a certain credit, which changes the price relationship as follows:

$$P_{ethanol} = \lambda P_{gasoline} - (1 - \lambda)t + t_c \tag{3.10}$$

where $t_c$ is the tax credits, including state and federal subsidies, for each unit of ethanol blended ($\$/m^3$).

***Price relationship of fossil fuels and nitrogen fertilizers***

The prices of crude oil, natural gas, and gasoline are closely related (Serra and Zilberman, 2013). Based on some historical data on these prices, the following correlations [1] are identified using the linear regression analysis of Tyner and Taheripour (2007):

$$P_{naturalgas} = a_1 + a_2 P_{crudeoil} \tag{3.11}$$

$$P_{gasoline} = b_1 + b_2 P_{crudeoil} \tag{3.12}$$

where $P_{naturalgas}$, $P_{gasoline}$, and $P_{crudeoil}$ are the prices of natural gas, gasoline, and crude oil ($\$/m^3$), respectively, and $a_1$, $a_2$, $b_1$, and $b_2$ are the estimated parameters.

For the production of nitrogen fertilizers, around 80% of the production cost is attributed to the use of natural gas (GAO, 2003). Owing to the close relationship between the prices of natural gas and crude oil, a statistically significant price relationship between fertilizer and crude oil can be established (Chen et al., 2012), that is,

$$P_{fertilizer} = c_1 + c_2 P_{crudeoil} \tag{3.13}$$

---

[1] Caution is needed in the use of the price correlation between natural gas and crude oil, because after 2005, their prices are not always strongly correlated.

where $c_1$ and $c_2$ are estimated parameters (EIA, 2013; USDA, 2013). Equations 3.1–3.13 form the economic part of the framework for determining the optimal application rate of nitrogen and yield in corn production as well as the price relationships between corn, ethanol, gasoline, natural gas, fertilizers, and crude oil. In the following subsection, we explain how we calculate the GHG emissions from corn ethanol.

### 3.2.2 Calculation of greenhouse gas emissions

The GHG emissions of corn ethanol production are calculated using data from the GREET model (CARB, 2009). The GREET model provides data on inputs and outputs at different stages of the production chain of corn ethanol: corn cultivation, corn transport, corn-to-ethanol conversion, and ethanol distribution, including transport and blending (see Figure 3.1 and Table 3.1). Estimated emissions of nitrous oxide from nitrogen fertilizer use in the GREET model are based on the national GHG inventories by the International Panel on Climate Change (IPCC, 2006). These emissions include both direct emissions from the field on which fertilizers are applied, and indirect emissions from nitrogen lost through runoff and leaching. The emissions are converted into $CO_2$ equivalent. Table 3.1 shows the average GHG emissions per $MJ$ of ethanol production and the marginal emissions per additional $MJ$ in terms of $CO_2$ equivalent based on the GREET model.

We use the GREET model to calculate the GHG emissions of corn ethanol production under different application rates of nitrogen. Dry corn milling of ethanol conversion is used in the calculations, because it accounts for 85% of the ethanol production (CARB, 2009). This assumption results in a conservative estimate of GHG emissions, since wet milling results in 10% higher emissions (CARB, 2009). In addition, note that emissions from indirect land-use change, which might be substantial, are not considered in this study. For example, Hertel et al. (2010) estimates the GHG emissions of corn ethanol produced in the US at 27 $g\ CO_2 - eq./MJ$ due to indirect land-use change. The impact of biofuel use on energy markets can greatly reduce the GHG-saving effect of biofuels (Smeets et al., 2014).

#### ***Average GHG emissions of corn ethanol***

The GHG emissions of corn ethanol are calculated based on the emissions from each phase of the production chain: $E_{cc}$ in the cultivation stage, $E_{ct}$ for corn transport, $E_{ep}$ for corn-to-ethanol

Table 3.1: GHG emissions of dry mill corn ethanol production.

| **Stages** | **Main activities and inputs** | **GHG** ( $g$ $CO_2 - eq./MJ$) |
|---|---|---|
| **Corn cultivation** | Corn farming | 5.65 |
| | Agricultural chemicals excluding nitrogen fertilizers | 7.88 |
| | Nitrogen fertilizer $N_2O$ in field | 15.91 |
| | Production of nitrogen fertilizers | 6.40 |
| **Corn transport** | | 2.22 |
| **Corn-to-ethanol conversion** | Corn-to-ethanol conversion, excluding DDGS | 38.30 |
| | DDGS | -11.51 |
| **Ethanol distribution** | Ethanol transport and blending | 2.70 |
| **Total** | | 67.55 |

Source: CARB (2009).

conversion, and $E_{et}$ for ethanol transport. The units for calculation are modified to SI units. As indicated, $\alpha$ $kg$ of corn can produce $\beta/m^3$ of ethanol. The following equation yields the relationship between the corn yield in $kg/ha$ and ethanol in $m^3/ha$:

$$Q_{corn} = \frac{\alpha}{\beta} Q_{ethanol} \tag{3.14}$$

The total GHG emissions from ethanol production per unit area ($ha$) can be written as

$$TE(N, Q_{ethanol}) = E_{cc}(N, \frac{\alpha}{\beta} Q_{ethanol}) + E_{ct}(\frac{\alpha}{\beta} Q_{ethanol}) + E_{ep}(Q_{ethanol}) + E_{et}(Q_{ethanol}) \tag{3.15}$$

The average GHG emissions per $m^3$ of ethanol production ($E_{average}$) are calculated as

$$E_{average} = \frac{TE(N, Q_{ethanol})}{Q_{ethanol}} \tag{3.16}$$

In order to calculate the GHG savings of corn ethanol, we take the difference between the average GHG emissions of corn ethanol and those of conventional gasoline. In order to compare the environmental impact of corn ethanol with that of fossil fuels, we further convert $m^3$ to $MJ$ in calculating the average and marginal emissions for consistency with the literature.

### *Marginal GHG emissions of corn ethanol*

The marginal GHG emissions are defined as the change in emissions for an additional unit of ethanol production. According to the relationship between the total GHG emissions ($TE$) and production quantity ($Q_{ethanol}$) in Equation 3.15, marginal emissions are mathematically the derivative of $TE$ with respect to $Q_{ethanol}$. However, we do not have an explicit function for $TE$ as a function of $Q_{ethanol}$ in Equation 3.15. Therefore, the marginal emissions are dealt with numerically. Consider that the last unit of ethanol production can be achieved by using more fertilizers and there is a non-linear yield response function. If the nitrogen application rate increases by a small amount $\Delta N$, that is, from $N$ to $N^*$ ($= N + \Delta N$), and the corn yield increases to $Q_{corn}(= Q_{corn} + \Delta Q_{corn})$, then the production of ethanol increases to $Q_{ethanol}(= Q_{ethanol} + \Delta Q_{ethanol})$. This leads to total GHG emissions $TE^*$, a function of $N^*$ and $Q_{ethanol^*}$ (see Equations 3.14 and 3.15). Then, the marginal GHG emissions of ethanol or the emissions of the last unit of ethanol ($E_{margainl}$) can be calculated as

$$E_{marginal} = \frac{\Delta TE(N, Q_{ethanol})}{\Delta Q_{ethanol}} \approx \frac{TE^*(N^*, Q^*_{ethanol}) - TE(N, Q_{ethanol})}{Q^*_{ethanol} - Q_{ethanol}} \tag{3.17}$$

## 3.3 A Numerical Example

### 3.3.1 Input Data

This section summarizes the data needed for calculation. The parameter values used in the economic analysis are presented in Table 3.2. The base year is 2007 with an application rate of 136 $lb$ nitrogen per acre or 152 $kg$ nitrogen from ammonia per hectare.

For the price of crude oil ($P_{crudeoil}$), we consider a plausible increase range from 30 to 120 $\$/barrel$, because corn ethanol becomes attractive only above this level when it can compete with gasoline under scenarios with poor weather (low yields) and good weather (high yields) (Good et al., 2011). An upper limit of 120 $\$/barrel$ is considered to account for the variability in the near future (IEA, 2012).

To calculate emission savings, we use average GHG emissions of 91.0 $g$ $\mathrm{CO_2} - eq./MJ$ (or 4.31 $GJ/m^3$) for gasoline sold in the US provided by Lattanzio (2015). About 9% of the oil products consumed in the US are currently made from oil sands (Lattanzio, 2015). The use of oil sands from Canada will increase as a result of the Keystone pipeline system. Therefore, we consider GHG emissions from the gasoline produced from Canadian oil sands, which are on average 14–20% higher than the average of 91.0 $g$ $CO_2 - eq./MJ$, or 104–109 $g$ $CO_2 - eq./MJ$, which is equal to 4.93–5.31 $GJ/m^3$ (Lattanzio, 2015). Therefore, in this study, we use 106.5 $g$ $CO_2 - eq./MJ$, or 5.05 $GJ/m^3$ for the marginal emissions of gasoline produced from oil sands.

Table 3.2: Parameter values used in calculations based on the analytical framework.

| **Parameter** | **Value** | **Units** | **Sources** |
|---|---|---|---|
| $m$ | 93.739 | Not applicable | Vanotti and Bundy (1994) and Havlin and Benson (2006) |
| $n$ | 0.58443 | Not applicable | Vanotti and Bundy (1994) and Havlin and Benson (2006) |
| $k$ | 0.001495 | Not applicable | Vanotti and Bundy (1994) and Havlin and Benson (2006) |
| $\gamma$ | 87937.6 | $Btu$ | CARB (2009) |
| $\alpha$ | 1 | $bushel$ | CARB (2009) |
| $\beta$ | 2.72 | $gallon$ | CARB (2009) |
| $\delta$ | 14.52 | $lb.$ | CARB (2009) |
| $c_0$ | 1.22 | $\$/bushel$ | Mallory et al. (2012) |
| $x$ | 91 | % | Anderson et al. (2008) |
| $\lambda$ | 0.7 | Not applicable | De Gorter and Just (2010) |
| $t$ | 0.48 | $\$/gallon$ | API (2013) |
| $t_c$ | 0.52 | $\$/gallon$ | Koplow (2007) |
| $a_1$ | 2.1748 | Not applicable | EIA (2014) |
| $a_2$ | 0.04 | Not applicable | EIA (2014) |
| $b_1$ | 0.3693 | Not applicable | EIA (2014) |
| $b_2$ | 0.0278 | Not applicable | EIA (2014) |
| $c_1$ | 0.0826 | Not applicable | EIA (2014) and EIA (2013) |
| $c_2$ | 0.003 | Not applicable | EIA (2014) and EIA (2013) |

Note: Units in the table are given according to the original sources.

### 3.3.2 Numerical Results

We use the framework developed in Section 3.2 and the data in Subsection 3.3.1 to calculate how changes in oil prices and tax credits influence the economic variables and GHG emissions. We then calculate the emission savings compared to conventional gasoline from oil sands. We also conduct sensitivity analyses particularly for the parameter values in the yield response function and the type of fertilizers.

Table 3.3 shows the impacts of changes in the price of crude oil and of the VEETC on the prices of ethanol, corn, and nitrogen, the yield of corn, the nitrogen application rate, the economic return to nitrogen, and ethanol production per hectare. The impacts on the average and marginal GHG emissions of corn ethanol are also shown in Table 3.3.

Table 3.3: Impacts of oil prices on economic variables and emissions, with and without VEETC.

| | **With VEETC** | | | | **Without VEETC** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Crude oil price** ($\$/barrel$) | | | | **Crude oil price** ($\$/barrel$) | | | |
| | 30 | 60 | 90 | 120 | 30 | 60 | 90 | 120 |
| **Prices** | | | | | | | | |
| Ethanol ($\$/m^3$) | 322 | 476 | 630 | 785 | 184 | 339 | 493 | 647 |
| Corn ($\$/kg$) | 0.09 | 0.17 | 0.25 | 0.32 | 0.02 | 0.10 | 0.17 | 0.25 |
| Nitrogen ($\$/kgN$) | 0.46 | 0.71 | 0.95 | 1.19 | 0.46 | 0.71 | 0.95 | 1.19 |
| **Corn and ethanol production** | | | | | | | | |
| Nitrogen application rate ($kgN/ha$) | 186 | 191 | 193 | 194 | 61 | 170 | 182 | 187 |
| Corn yield ($kg/ha$) | 9384 | 9410 | 9418 | 9423 | 7605 | 9288 | 9367 | 9392 |
| Economic return to nitrogen ($\$/ha$) | 782 | 1455 | 2129 | 2802 | 121 | 773 | 1444 | 2116 |
| Ethanol yield ($MJ/ha$) | 80384 | 80604 | 80677 | 80713 | 65147 | 79558 | 80239 | 80450 |
| **Emissions** | | | | | | | | |
| Average emissions ($g$ $CO_2 - eq./MJ$) | 69.20 | 69.57 | 69.72 | 69.79 | 61.03 | 68.17 | 68.98 | 69.30 |
| Marginal emissions ($g$ $CO_2 - eq./MJ$) | 148.54 | 154.06 | 156.31 | 157.53 | 96.97 | 135.98 | 145.65 | 150.03 |

### Price and production effects

We first examine the price and production effects of an increase in oil price from 30 $\$/barrel$ to 120$\$/barrel$, which partially reflects the past and future expected development of oil prices. An increase in oil price results in an increase in the price of gasoline (see Equation 3.12; not shown in Table 3.3) and ethanol (Equation 3.10). The increase in oil price from 30 to 120$\$/barrel$ increases the price of ethanol from 322 to 785 $\$/m^3$ if VEETC is implemented, or from 184 to 647 $\$/m^3$ if VEETC is not implemented.

The price of nitrogen fertilizers is strongly correlated with the price of natural gas and oil, because the price of natural gas is strongly correlated with the price of oil (see Equation 3.11) and because of the high share of natural gas in the production costs of nitrogen fertilizers. The increase in oil price from 30 to 120 $\$/barrel$ leads to a 159% increase in the nitrogen price from 0.46 to 1.19 $\$/kg$, which is the same in both scenarios (see Equation 3.13).

An increase in the price of ethanol induces an increase in the production of ethanol, which depends on the price of corn and the costs of other inputs (Equations 3.6–3.8). Especially important is the price of natural gas, which is used for distilling corn ethanol and is correlated with the price of oil, as well as the price of DDGS, which is correlated with the price of corn. The net effect is an increase in the price of corn, which is greater if the price of ethanol is higher. The price of corn increases from 0.09 to 0.32 $\$/kg$ in the case that VEETC is considered and from 0.02 to 0.25 $\$/kg$ without VEETC.

The increasing corn price triggers an increase in the production of corn as a result of the profit-maximizing behaviour of farmers (Equations 3.1–3.5). An increase in corn production is partially realized via an increase in fertilizer use, despite the higher costs of nitrogen fertilizer, which follow from the assumed increase in oil prices.

As a result of the higher prices of corn and ethanol, the nitrogen application rate and corn production effects are greater when VEETC is implemented. Consequently, the economic returns to nitrogen fertilizers are higher in the case with VEETC (i.e. 782–2802 $\$/ha$) than in the case without VEETC (i.e. 121–2116 $\$/ha$).

The net effect of an increase in oil price is that both the corn yield per hectare and the yield of corn ethanol per hectare increase. However, the impact on yields and on the nitrogen application rate is limited. Corn yields per additional kilogram of nitrogen fertilizers decline with the increase in the oil price. This shows that the marginal productivity of fertilizer use is declining (see Equation 3.2 and Figure 3.2).

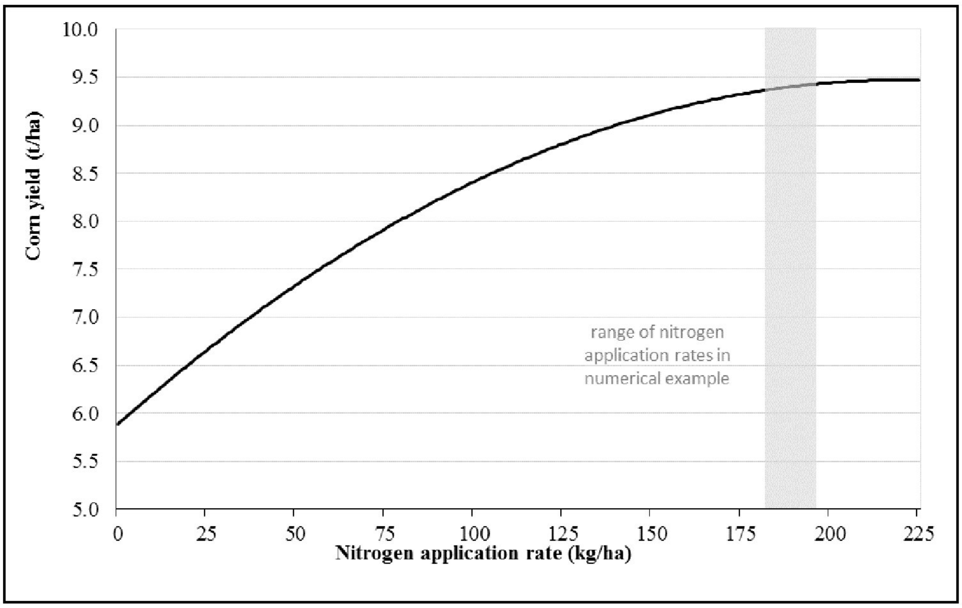

Figure 3.2: Correlation between fertilizer use and corn yield.

Figure 3.2 shows the link between nitrogen application rates and the corn yield response curve, which is concave. It is important to note the relatively limited response of corn yields for the range of nitrogen application rates of 186–194 *kg* of nitrogen per hectare considered in this study (see Table 3.3). This suggests that the corn yield in the US is currently close to the maximum yield. By comparison, the average nitrogen application rate in the US in 2010, when the oil price was 80 $\$/barrel$, was 157 $kg/hectare$ (USDA, 2013).

The results presented above show that the nitrogen application rate is determined by the price of nitrogen fertilizers and especially by the price of corn. The results also show that the price of corn is significantly influenced by the oil and ethanol markets and indirectly through the RFS 2 biofuel policy (i.e. the blender tax credit).

Table 3.3 also shows the relationship between the price of oil and the application rate of nitrogen, which is positive but at a decreasing rate with the oil price. This relationship is graphically represented in a stylized form in Figure 3.3. The vertical axis shows the price ratio of nitrogen to corn. A higher oil price reduces the nitrogen-to-corn price ratio. This means that the increase in the price of nitrogen is less than the increase in the price of corn. This effect is reduced when the price of oil increases. According to Equation 3.4, the price ratio has a negative and linear relationship with the (economically optimal) nitrogen application rate. The relationships are examined by a series of continuous calculations in the application of the analytical framework. We show the outcomes of our calculations for the range of oil prices between 30 and 120 $\$/barrel$ in Figure 3.3.

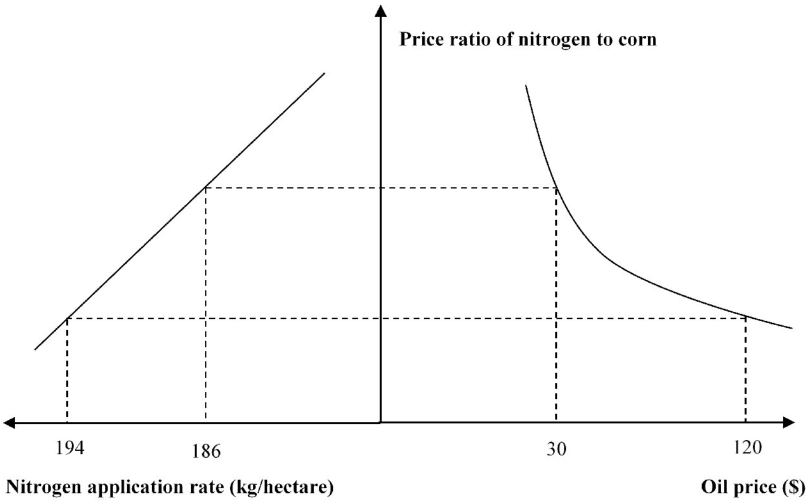

Figure 3.3: Relations between oil price and nitrogen application rate.

The results in Table 3.3 show that both the average and marginal emissions of corn ethanol increase with the oil price. The increase in average emissions is negligible, whereas the increase in the marginal emissions is 6.0% or 54.7% for oil price increases from 30 to 120$\$/barrel$, depending on whether the VEETC is implemented. Furthermore, we can analyse the impacts of a price fall in crude oil, such as from 60 to 30 $\$/barrel$, which reflects recent oil market development. This result shows a stronger impact of oil price change on marginal emissions than on average emissions of ethanol production.

### Savings of greenhouse gas emissions of corn ethanol compared to gasoline

The results presented in the previous subsection show that it is profitable for farmers to increase their production of corn through higher fertilizer application rates when the oil price increases. These changes influence the GHG emissions of corn and corn ethanol. In the research presented in this chapter, a distinction is made between the effect on average emissions and marginal emissions of corn ethanol. GHG emission savings are defined as the percentage reduction in GHG emissions from the production of corn ethanol compared to conventional gasoline. For example, a 24% GHG emission saving of ethanol means that the substitution of one energy unit of ethanol for gasoline reduces GHG emissions by 24%.

The results in terms of emission savings are presented in Figure 3.4, showing the average and marginal GHG emission saving effects of substituting ethanol for gasoline under the range of oil prices considered for the scenarios with and without tax credits. The average emissions are hardly affected by the change in oil price; thus, the GHG emission savings based on the average GHG emission saving of corn ethanol and gasoline are nearly constant at 25% to 35%.

However, our calculation of the marginal GHG emissions from ethanol production is much higher than the marginal emissions of conventional gasoline. The comparison of the two along the range of oil prices considered shows that the marginal GHG saving is negative, and becomes more negative as oil prices increase. This means that each unit of additional ethanol production results in an increase in emissions above the marginal emissions of gasoline produced from oil sands, which are 106.5 $g$ $\mathrm{CO_2} - eq./MJ$. The increase in marginal GHG emissions of corn ethanol is the result of the higher application rate of fertilizers and the decreasing marginal productivity of fertilizer use. It is interesting that the blender tax credits lead to higher (average and marginal) emissions, but also reduce the emission-increasing effect of higher oil prices.

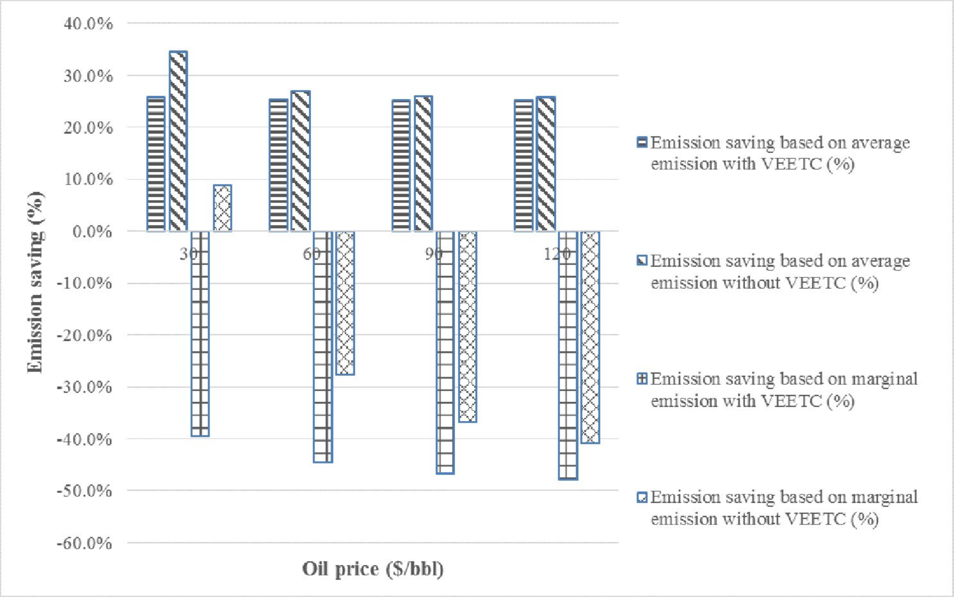

Figure 3.4: Average and marginal emission savings of corn ethanol with and without VEETC.

### Sensitivity analyses

The analytical framework presented in Section 3.2 is based on a set of assumptions concerning the dynamics of energy markets and the agricultural production of corn. In this subsection, the robustness of the model results is illustrated by sensitivity analyses in which two key sets of parameters are adjusted: the corn yield response function (Equation 3.2), which determines the decreasing marginal yields of fertilizer use; and the type of fertilizers (Equation 3.13), which is an important factor for determining the optimal application rate. The sensitivity analyses are carried out under the 'with a blender tax credit' scenario. The results are presented in Table 3.4.

### Sensitivity analysis 1: yield response curve

Together with the price of corn and nitrogen, the yield response function determines the economically optimal application rate of nitrogen at a given oil price level. The reference results presented in Table 3.3 are based on an empirical yield response function (see Subsection 3.2.1 for the values of the relevant parameters). However, Vanotti and Bundy (1994) refer to a lower-yield function variant that depends on soil quality, crop management, and cultivation technology. Therefore, we take their (lower) values for an alternative yield function (Equation 3.2): 61.265, 0.50653, and 0.0012038 for parameters $m$, $n$, and $k$, respectively. Our calculation (see Table 3.4) shows that this alternative yield function is less responsive to the oil price changes and the optimal nitrogen application rates are around 5.5% higher, while corn yields are about 24% lower compared to the results in Table 3.3. This leads to about 8% higher average emissions per unit of corn ethanol, and slightly lower marginal emissions per additional unit of corn ethanol. We conclude that the results are rather robust for changes in the fertilizer yield response curve.

### Sensitivity analysis 2: fertilizer type

The most important types of nitrogen fertilizer used in corn cultivation are ammonia, urea, and ammonium nitrate. In Subsection 3.3.2, we use ammonia as a reference. However, different types of fertilizers have different prices, which have implications for their use. For urea fertilizer, different correlations between the oil price and fertilizer price are identified. According to USDA (2013) and EIA (2013), parameters $c_1$ and $c_2$ are lower for urea than for ammonia, which are

0.0754 and 0.0021, respectively. We use these values for the sensitivity analysis of the fertilizer type.

The use of urea leads to higher nitrogen prices and thus, lower optimal application rates. Compared to ammonia, the production of urea requires more energy. In addition, urea contains carbon, which can be released in the soil as $CO_2$. Therefore, average emissions are higher when urea is used as a fertilizer for corn cultivation than when ammonia is used. However, the marginal emissions per additional unit of ethanol are lower compared to ammonia fertilizer. A lower nitrogen application rate corresponds to a higher corn production level, which indicates higher ethanol production with fewer emissions. The marginal emissions of corn ethanol are, however, still well above the marginal emissions of gasoline produced from oil sands.

Table 3.4: Sensitivity of the yield response function and fertilizer type to the results.

| | **Yield response function** | | | | **Fertilizer type** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Crude oil price** $(\$/barrel)$ | | | | **Crude oil price** $(\$/barrel)$ | | | |
| | 30 | 60 | 90 | 120 | 30 | 60 | 90 | 120 |
| **Prices** | | | | | | | | |
| **Ethanol** $(\$/m^3)$ | 322 | 476 | 630 | 785 | 322 | 476 | 630 | 785 |
| **Corn** $(\$/kg)$ | 0.09 | 0.17 | 0.25 | 0.32 | 0.09 | 0.17 | 0.25 | 0.32 |
| **Nitrogen** $(\$/kgN)$ | 0.46 | 0.71 | 0.95 | 1.19 | 0.46 | 0.71 | 0.95 | 1.19 |
| **Corn and ethanol production** | | | | | | | | |
| **Nitrogen application rate** $(kgN/ha)$ | 194 | 201 | 204 | 205 | 171 | 181 | 185 | 186 |
| **Corn yield** $(kg/ha)$ | 7086 | 7118 | 7128 | 7133 | 9296 | 9359 | 9379 | 9389 |
| **Ethanol yield** $(MJ/ha)$ | 60696 | 60969 | 61060 | 61104 | 79632 | 80169 | 80340 | 80423 |
| **Emissions** | | | | | | | | |
| **Average emissions** $(g\ CO_2-eq./MJ)$ | 74.52 | 75.11 | 75.34 | 75.46 | 68.25 | 68.89 | 69.13 | 69.26 |
| **Emission savings on average emissions** (%) | 20.13 | 19.50 | 19.25 | 19.12 | 26.85 | 26.17 | 25.91 | 25.77 |
| **Marginal emissions** $(g\ CO_2-eq./MJ)$ | 235.7 | 233.06 | 232.9 | 233.0 | 136.8 | 144.4 | 147.6 | 149.4 |
| **Emission savings on marginal emissions** (%) | -121.3 | -118.8 | -118.7 | -118.8 | -28.48 | -35.58 | -38.62 | -40.3 |

## 3.4 Discussion and conclusions

This paper attempted to provide a modeling framework to evaluate the greenhouse emissions from biofuel production. Particular attention has been paid to how diminishing productivity of corn with respect to the fertilizer inputs, and the market interactions of energy and agricultural products may impact the GHG emissions of biofuels, considering oil price changes and the implementation of VEETC.

The use of biofuels leads to fundamental changes in the economic linkages between energy and agricultural markets. The economics of fertilizer is especially important for the GHG emission-saving potential of biofuels. For example, the production and use of nitrogen fertilizers accounts for one-third or more of the GHG emissions of corn ethanol production in the US. Thus, changes in fertilizer use can have a large impact on the GHG-saving potential of corn ethanol. Therefore, we apply the modelling framework developed to evaluate the impact of the correlation between oil markets and the markets for ethanol and corn in the US on nitrogen fertilizer use and on the GHG emissions of corn ethanol.

The results show that a higher oil price results in higher gasoline, ethanol, and corn prices. The profit-maximizing behaviour of farmers results in an increase in the use of fertilizers to increase the production of corn. The effect is that the average GHG emissions per unit of corn ethanol remain fairly constant, but that the marginal emissions increase somewhat (5%), mainly as a result of decreasing marginal yield with respect to fertilizer use. The conclusion is that although higher corn yields result in higher GHG emissions, increasing corn ethanol production for fuel reduces GHG emissions on average compared to the alternative of increasing gasoline production.

It should be noted that our analysis is based on an economically optimal application rate of fertilizers. In reality, risk-averse farmers might overuse fertilizers owing to lack of knowledge about decreasing marginal yields with respect to nitrogen fertilizers. Thus, our calculation based on economically optimal application rates might underestimate real emissions. Next, we do not include the other indirect effects of ethanol production, such as land-use change. Hence, our numerical results on the marginal emissions reflect only the lower bound of real emissions related to the last unit of ethanol production. Furthermore, the use of a linear relationship for the market interactions of energy and agricultural products based on historical data before 2007, without considering the recent development of shale gas, might lead to overestimation of the economic response of higher oil prices. The objective of the exercise presented in this chapter is not to produce a thorough calculation of GHG emissions of corn ethanol production in the US, which requires estimating the actual application rates in different regions. Rather, the modelling framework presented in this chapter aims to illustrate how different effects can be taken into account when calculating emissions. The novelty is that the diminishing productivity of corn with respect to nitrogen fertilizers can have profound impacts on the marginal emissions of biofuels. The results show that the marginal emissions of corn ethanol production in the US can be substantially higher than average emissions, thereby questioning the efficiency and effectiveness of biofuel policies to reduce GHG emissions.

An important limitation of the modelling framework applied in this study is that it represents only short-term economic correlations. Our numerical example takes the relationship between oil price and natural gas based on historical data before 2007. Therefore, we should be aware that the huge increase in shale gas supplies in recent years might have changed this quantitative relationship. Increasing the use of fertilizers is, in the short term, a logical and simple way to increase yields and to optimize economic returns in response to higher corn prices. In the long run, higher corn prices might induce higher corn yields through technological changes, such as the development and use of improved seeds and the increased use of irrigation and agricultural machinery. In that case, the increase in GHG emissions will be reduced owing to the use of improved corn production technologies and higher corn yields.

Another limitation of the research is that the numerical example for applying the modelling framework does not include other indirect effects, although the market interactions of inputs and outputs are considered. However, we can calculate the marginal emissions of corn ethanol, which provides useful insights for environmental management. Economic instruments, such as emission tax, are based on marginal emissions in order to determine the optimal production level. Therefore, identifying marginal emissions creates the basis for policy intervention.

Moreover, the prices of oil, natural gas, and agricultural commodities (including corn) have fluctuated substantially during the timeframe of this study. This means that the empirically observed correlations and parameter values considered in this study are partially uncertain. More detailed analyses that consider longer timeframes are needed to improve the accuracy of the parameters used in our modelling framework. Further research is also encouraged to model the economic interactions between oil, ethanol, and corn markets in more detail. Therefore, this study should be regarded as a first-order assessment that, despite its uncertainties, clearly shows the potential impact of the economic correlations between energy and agricultural markets on the average and marginal GHG emissions of corn ethanol. To include other indirect effects of

GHG emissions from ethanol production would be an interesting future research direction.

# Chapter 4

# A Framework to Evaluate Policy Options for Supporting Electric Vehicles in Urban Freight Transport

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## Abstract

Electric vehicles (EVs) are considered as a feasible alternative to gasoline/diesel vehicles. Few studies have addressed the impacts of policies for EVs in urban freight transport. To cast light on this topic, we established a framework combining an optimization model with economic analysis to determine the optimal behavior of an individual delivery service provider company and social impacts (e.g., externalities and welfare) in response to policies for supporting EVs, such as purchase subsidy, limited access (zone fee) to congestion/low-emission zones with exemptions for EVs, and vehicle taxes with exemptions for EVs. Numerical experiments showed that the zone fee can increase the company's total costs but improve the social welfare. It greatly reduced the external cost inside the congestion/low-emission zone with a high population, dense pollution, and heavy traffic. Although the vehicle taxes and subsidy have almost the same influences on the company and society, they perform differently at low tax/subsidy rates due to their different effects on vehicle routing plans. Finally, we performed sensitivity analyses, which shows that local factors at the company and city levels (e.g., types of vehicle and transport network) are important to designing efficient policies for supporting EVs in the urban freight transport.

**Keywords**: electric vehicle, social welfare, congestion/low-emission zone, urban freight transport, logistics, heterogeneous vehicle routing problem

## 4.1 Introduction

Urban freight transport that serves trading activity is fundamental to sustain current lifestyles. The logistic costs of freight transport have a direct bearing on economic efficiency and social welfare. Heavy freight vehicles cause more severe environmental and health problems than passenger vehicles. Russo and Comi (2012) noted that urban freight vehicles account for about 6%-18% of total urban transport but for about 19% of energy use and for about 21% of $CO_2$ emissions. Urban freight vehicles are also responsible for a large part of local transport-based pollution (IEA, 2013) such as nitrogen oxides ($NO_x$), sulfur dioxide ($SO_2$), and particulate matter (PM). Cities clearly need to reduce pollution-intensive freight traffic by managing logistic processes more efficiently and switching to low emission vehicles. Electric vehicles (EVs) are being considered to replace internal combustion engine vehicles (ICEVs) in order to mitigate the pollution caused by urban freight transport owing to the former's zero tailpipe emissions, although introducing EVs to the market will increase emissions at the site of the power plants. A long-term shift to an economy that is compatible with climate stabilization will require a vehicle fleet that is predominantly powered by electric drives in the 2040-2050 timeframe (Mock and Yang, 2014).

The main challenges with EVs in real-life urban freight transport are their high acquisition cost, long recharging time, low capacity, and limited driving range. As for the urban freight transport, these influence the vehicle purchase and routing decisions of logistics companies. Various national and local policies have been implemented to provide fiscal incentives for encouraging the purchase and use of EVs in both passenger and freight transport, mostly light-duty vehicles (Taefi et al., 2016). Several examples of the measures[1] are given below.

- Purchase subsidy on EV: Direct subsidy is given to reduce the EV purchase price.
- Limited access (zone fee) to congestion/low-emission zone: For the purpose of generality, we define the term *limited zone* as representing a *low-emission zone* or *congestion zone* with restricted entry for high-emission or heavy vehicles (e.g., a fee charge or other

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[1] The measures are commonly used in European cities for promoting EVs. With a focus on vehicle specific measures, we choose purchase subsidy for EVs, free access to the limited zone (congestion/low-emission zone) for EVs and vehicle taxes with exemptions for EVs for evaluation purpose. In terms of providing free access for EVs and imposing limitations for ICEVs, the concept of "limited zone" can be further generalized as parking lots/bus lanes/low-noise zones/pedestrian zones/areas with toll.

deterrent) in order to reduce emissions or congestion.

- Vehicle taxes with exemptions for EVs: There are two main types of vehicle taxes. The vehicle registration tax is paid for the first registration. The annual circulation tax is paid to use the vehicle on the road. With an appropriate discount rate, these two taxes can be designed to work in the same way. EVs can be exempted from at least one of the vehicle taxes.

In this study, we consider an individual logistics company that provides delivery services for its customers. In response to these policies, the logistics company would adapt its vehicle fleet composition and vehicle routing plan in order to minimize the total logistic costs. This can have an influence on changes in the external costs resulted from $CO_2$ emission, local air pollution and congestion, and the overall social welfare.

Despite growing research interest in urban freight transport, few studies have addressed the impacts of EV-supporting policies on logistics and society. As we discuss in the literature review in Section 4.2, research is needed to explore the relationships between 1) policy measures, 2) individual company's likely actions in response to the measures, 3) the effect on operational (routing) costs, and 4) the resulting changes to environmental impacts and welfare. As a contribution to cover this gap, we establish a framework that combines an optimization model with economic analysis to evaluate the potential operational, financial, and environmental effects of using EVs in urban freight operations. The framework focuses on obtaining an individual company's expected response to policies and corresponding changes in externalities and welfare. Previous empirical economic studies on relevant policy evaluation have usually focused on upfront purchase cost and assumed fixed annual routing costs (in other words, annual distance travelled) for vehicles. Differently, to assess the impacts of EV-supporting policies, the optimization model provides an opportunity to study how the policies can affect a logistics company's decisions on both EV purchase and routing.

We develop different scenarios in which logistics companies are exposed to policy options that support EVs: The purchase subsidy for EVs, vehicle taxes with exemptions for EVs, and limited access (zone fee) to the limited zone with exemptions for EVs. We establish an optimization model to determine the optimal fleet and routing for a logistics company while minimizing the fixed usage costs, routing costs, and entrance fees of vehicles to the congestion/low-emission zone. Such a company transports the given demands of a single product from multiple central depots to a known set of customers located in or outside a congestion/low-emission zone using two types of vehicles: EVs and ICEVs. The two types of vehicles differ in driving range, capacity, acquisition cost, energy cost, and emission rates of pollutants. The locations (in or outside a congestion/low-emission zone) differ in marginal external costs of pollutants and entrance fees to congestion/low-emission zones. Based on the results of solving the optimization model, we calculate the changes in all taxes, changes in the externalities produced by EVs and ICEVs and changes in the total welfare under different policy scenarios. At last, the influences of EV-supporting policies are evaluated.

We tested the proposed general framework with numerical experiments. The data are generated for a transport network under different scenarios. Based on the results from our numerical experiments, the purchase subsidy, zone fee, and vehicle taxes were found to increase the EV share in the vehicle fleet composition of the logistics company, decrease the distances traveled by ICEVs, and reduce externalities (i.e., $CO_2$ emission, local air pollution, and congestion ) and improve social welfare. In the numerical experiments, the zone fee had a larger impact on improving social welfare. This is because the zone fee significantly reduces the external cost by preventing emissions and congestion inside a zone with higher marginal external costs from a high population, dense pollution, and heavy traffic. However, in some of the sensitivity analyses, the zone fee may increase external costs by forcing ICEVs to travel around the zone to reach customers on the other side of the zone, which may lead to more emissions from fuel combustion or congestion. Although the vehicle taxes and subsidy have almost the same influences on the company and society, they perform differently at low tax/subsidy rates due to the different effects of tax and subsidy on vehicle routing plans. Finally, we performed sensitivity analyses, which shows that local factors at the company and city levels (e.g., types of vehicle and transport network) are important to designing efficient policies for supporting EVs in the urban freight transport.

The rest of this paper is organized as follows. Section 4.2 reviews the related literature. Section 4.3 proposes a framework for evaluating urban freight policies. Section 4.4 presents the numerical experiments. The conclusions are presented in Section 4.5.

## 4.2 Literature review

In this section, we review relevant research on both economic and logistics research for the use and evaluation of EV policies in the context of urban freight transport.

Traditionally, evaluation of transport policies in urban freight transport involves social and economic issues (Lagorio et al., 2016). For example, Hosoya et al. (2003), Anderson et al. (2005), Quak and De Koster (2006), and Holguin-Verasand et al. (2010) performed general assessments of policies that affect urban freight transport. Hosoya et al. (2003) studied Tokyo and used a survey to evaluate a number of freight policies: bans on large trucks, road pricing, and the construction of logistic centers. Anderson et al. (2005) provided an ex ante assessment of regulation measures in UK cities, including time windows and charging. Quak and De Koster (2006) addressed regulations based on time windows. They reviewed practices in Dutch cities and assessed possible changes to current policy. Holguin-Verasand et al. (2010) evaluated the impacts of policy incentives for encouraging off-hour deliveries on carriers, receivers and society. In particular, they used the Discrete Choice Model and the Comprehensive Modal Emissions Model with GPS based data to simulate the consumer choice of delivering time and changes of emissions.

However, this is still an evolving field of research because of the greater sensitivity to environmental issues, new policy measures, and introduction of new technologies. In the case of promoting the purchase and use of EVs, several types of policies are involved (e.g., access to low-emission zones, exemptions from vehicle taxes, and purchase subsidy). Taefi et al. (2016) reviewed policy measures directed at emission-free urban road freight transport. They assessed and compared policies against other prospective options by multi-criteria analysis. In the previous economic research, evaluation of EV-supporting policies mainly focused on ex post analysis based on empirical data and econometric approaches, such as the consumer choice model (Lee et al., 2016; Greene et al., 2014), the fixed effect model (Chandra et al., 2010; Gallagher and Muehlegger, 2011), and other ordinary least squares models (Sierzchula et al., 2014; Diamond, 2009; Jenn et al., 2013; Jiménez et al., 2016; Yan and Eskeland, 2016).

From the perspective of logistics, the literature on urban freight transport does not yet provide an ample discussion of specific policy measures to support EVs in urban freight transport. The main focus is on the use of EVs in the context of *heterogeneous vehicle routing problems.* Survey papers on *heterogeneous vehicle routing problems* are provided by Hoff et al. (2010); Baldacci et al. (2008); Koç et al. (2016). The *heterogeneous vehicle routing problem* generally considers a limited or unlimited fleet of vehicles with different attributes (e.g., capacity, fixed cost, and driving range) in order to serve a set of customers with given demand. The objective is to decide the vehicle fleet composition and routes while minimizing the vehicle routing and usage costs. Juan et al. (2014) extended the heterogeneous vehicle routing problem to consider multiple driving ranges for vehicles. The multiple driving range variant implies that the total distance traveled by each type of vehicle is limited and is not necessarily the same for all vehicles. This problem arises in routing of EVs (Schneider et al., 2014; Goeke and Schneider, 2015) and hybrid electric vehicles for which the driving range is limited due to limited capacity of batteries. Sassi et al. (2014) introduced a new real-life heterogeneous vehicle routing problem where the mixed fleet consists of ICEVs and heterogeneous EVs with different battery capacities (i.e., driving range limit) and fixed costs. Partial recharging for EVs at available recharging stations during trips is allowed, as well as intermittent recharging at the depot. The main challenges facing use of EVs are their limited driving range and considerably long charging time. The limited driving range will probably remain the main obstacle to using EVs in the medium term as long as there is no global infrastructure for replacing batteries or direct power induction to EVs during their trip.[2]

Although the driving range limit of EVs makes them less practical for use in real life, advantages such as free or cheap access to a congestion zone, provide an incentive to use them as an alternative fleet. The zone-dependency aspect of the problem that we discuss in this paper, is similar to *site dependency* in the *site-dependent vehicle routing problem* introduced by Nag et al. (1988). In their problem, different types of vehicles could only visit their preassigned customers; that is, no vehicle traveled from one customer to another customer unless both customers were assigned to the same type of vehicle. The difference between the *site-dependent vehicle routing problem* and our problem is that, in the latter, the customers are not preassigned to each type of vehicle. There are two types of customers with regard to their geographic location: inside or outside congestion/low-emission zones. ICEVs are charged a zone fee when they cross the congestion/low-emission zone. Hence, customers of both types can be potentially visited by

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[2] http://www.isoe.de/english/projects/futurefleet.htm

each type of vehicle.

In contrast to empirical economic research focusing on national or household data, optimization models, used in the logistic problems, provide a chance to study the economic impacts of EV-supporting policies on freight transport at the company level. The literature has scarcely addressed research that explores the relationships between 1) policy measures, 2) individual company's likely actions in response to the measures, 3) effects on operational (routing) costs, and 4) changes to the environmental impact and welfare. The present study establishes a framework for evaluating EV-supporting policies and investigating these relationships.

## 4.3 A framework for policy evaluation

To evaluate the impacts of different EV-supporting policy options on the logistic costs of the company and welfare, we propose a framework that combines an optimization model with economic analysis. First, we develop scenarios for comparison based on policies that support the purchase and use of EVs: The purchase subsidy for EV, limited access (zone fee) to congestion/low-emission zones with exemptions for EVs, and vehicle taxes with exemptions for EVs. Second, we evaluate policy implementations and adjustments for their effects on a company's decision on vehicle fleet composition and routing. Finally, we evaluate the influences of the company's optimal decisions on the tax revenue of the government, customer and producer surpluses, and externalities such as emissions and congestion. Then, we calculate the total change in welfare in order to evaluate the impacts of policies on society.

### 4.3.1 Scenarios

Owing to their comparable efficiencies and social feasibility for supporting EV adoption (Taefi et al., 2016), we consider three policies: purchase subsidy for EVs, limited access (zone fee) to congestion/low-emission zones with exemptions for EVs, and vehicle taxes with exemptions for EVs. A baseline scenario and three primary scenarios are established, as presented below.

- Baseline: no purchase subsidy, no vehicle taxes, and no zone fees charged for both EVs and ICEVs.

- Scenario 1: implementation of purchase subsidy on vehicle prices for EVs.
- Scenario 2: implementation of a zone fee with exemptions for EVs.
- Scenario 3: implementation of vehicle taxes with exemptions for EVs.

### 4.3.2 Optimization Model

In this section, we describe a company's logistic problem and provide an optimization model. We consider an individual logistics company[3] that provides delivery service for a single product within a single-echelon distribution system. The distribution system consists of two levels. The first level consists of depots, and the second level consists of customers. Each customer is visited once. Each customer is given a deterministic delivery demand, and the splitting of demands is not permitted. The depots are uncapacitated. Each vehicle visits the customers in a tour starting and ending at the same depot.

The mixed fleet of vehicles consists of EVs and ICEVs. The two types of vehicles differ regarding the driving range, cargo capacity, acquisition cost, energy cost, and zone fee to access the limited zone. We assume that both types of vehicles move at a constant speed that is the same for both inside and outside the limited zone. The EVs are fully charged at depots. We did not consider EV recharging during a daily delivery service because the EVs are being used by a logistics company for short-distance deliveries in an urban area.

The urban area in the problem is divided into two areas: outside and inside the limited zone. The marginal external cost is higher for driving vehicles inside the limited zone than outside owing to the high-density population, heavy traffic, and urban landscape.

The aim of the problem is to decide the vehicles routes and fleet size for EVs and ICEVs while minimizing the vehicle routing costs, purchasing costs, and entrance fee to the limited zone. This problem is called the zone-dependent vehicle routing problem with a mixed fleet.

Below, we present an arc-based mixed-integer linear programming (MILP) formulation for the zone-dependent vehicle routing problem with a mixed fleet. The time frame of the optimization model is set to one day. The problem is defined on a directed graph $G(V, A)$, where $V$ represents

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[3] We focus on a logistics company that provides delivery service for products such as milk or newspapers, where the vehicle routing plan is the same everyday.

the set of nodes and $A$ is the set of arcs. $V = D \cup J$, where $D$ is the set of depots and $J$ is the set of customers. $V^O$ is the subset of nodes $i \in V$ located outside the limited zone. The set of arcs $A$ includes arcs between node $i \in V$ and node $j \in V$, excluding the arcs between node $i$ and $j$, $\forall i, j \in D$. It is defined as $A = \{(i,j)|i,j \in V \setminus \{(i,j)|i,j \in D\}\}$. $d_{ij}$ is the traveling distance for traversing arc $(i,j)$, $\forall(i,j) \in A$. $A^Z \subset A$ is the subset of arcs $(i,j) \in A$ that connect two nodes $i, j \in V^O$ without crossing the limited zone. $\alpha_{ij}$ is the proportion of arc $(i,j) \in A$ that is located inside the zone.

$\mathcal{D}_j$ is the given demand of customer $j \in J$. $K_{EV}$ is the set of EVs. $K_{ICEV}$ is the set of ICEVs. $\mathcal{Q}_k$ is the capacity of vehicle $k \in K_t, t \in \{EV, ICEV\}$. A fixed acquisition cost $f_k$ including vehicle registration tax is assigned to vehicle $k \in K_t, t \in \{EV, ICEV\}$. A purchase subsidy $S_k$ is assigned to vehicle $k \in K_t, t \in \{EV, ICEV\}$. A fixed annual circulation tax $\mathcal{C}_k$ is assigned to vehicle $k \in K_t, t \in \{EV, ICEV\}$. $\mathcal{P}_k$ is the energy price, and $\mathcal{T}_k$ is the energy tax per liter for ICEVs and per watt-hour for EVs for vehicle $k \in K_t, t \in \{EV, ICEV\}$. $\mathcal{E}_k$ is the energy efficiency (in $Wh/km$ for EVs and $L/km$ for ICEVs) for vehicle $k \in K_t, t \in \{EV, ICEV\}$. $\mathcal{F}_k$ is the entrance fee paid by vehicle $k \in K_{ICEV}$ if it crosses the limited zone at least once (i.e., if the trip for vehicle $k \in K_{ICEV}$ includes at least one arc $(i,j) \in A \setminus A^Z$). $\mathcal{F}_k$ is paid by the ICEV only for its first entrance to the limited zone. Each vehicle $k \in K_{EV}$ has a limited driving range $R_k$.

The decision variables are as follows. $x_{ijk} \in \{0,1\}$ is the routing variable. It is equal to unity if arc $(i,j)$ is traversed by vehicle $k, \forall k \in K, (i,j) \in A$ and zero otherwise. Binary variable $y_k \in \{0,1\}$ is defined as equal to unity if the route performed by vehicle $k \in K$ consists of at least one arc crossing the zone and zero otherwise.

The sets, parameters, and decision variables are summarized in Table 4.1.

Table 4.1: Sets, parameters, and variables used in the MILP model for the zone-dependent vehicle routing problem with a mixed fleet.

| **Sets and parameters** | **Description** |
|---|---|
| $D$ | set of depots |
| $J$ | set of customers |
| $V = D \cup J$ | set of all nodes |
| $V^O$ | subset of nodes $i \in V$ located outside the limited zone |
| $A$ | set of arcs |
| $A^Z \subset A$ | subset of arcs $(i,j) \in A$ that connect two nodes $i, j \in V^O$ without crossing the limited zone |
| $\mathcal{D}_j$ | demand of customer $j$, $\forall j \in J$ |
| $d_{ij}$ | traveling distance for traversing arc $(i,j)$, $\forall (i,j) \in A$ |
| $\alpha_{ij}$ | proportion of arc $(i,j)$ located inside the zone, $\forall (i,j) \in A$ |
| $K_{EV}$ | set of EVs |
| $K_{ICEV}$ | set of ICEVs |
| $K = K_{EV} \cup K_{ICEV}$ | set of all vehicles |
| $\mathcal{Q}_k$ | capacity of vehicle $k \in K_t, t \in \{EV, ICEV\}$ |
| $f_k$ | acquisition cost of vehicle including vehicle registration tax, $k \in K_t, t \in \{EV, ICEV\}$ |
| $S_k$ | subsidy on purchase price of vehicle, $k \in K_t, t \in \{EV, ICEV\}$ |
| $\mathcal{C}_k$ | annual circulation tax of vehicle $k \in K_t, t \in \{EV, ICEV\}$ |
| $\mathcal{F}_k$ | entrance fee paid by vehicle $k \in K_{ICEV}$ entering the limited zone |
| $R_k$ | driving range limit for vehicle $k \in K_{EV}$ |
| $\mathcal{P}_k$ | energy price per liter for ICEV and per watt-hour for EV for vehicle $k \in K_t, t \in \{EV, ICEV\}$ |
| $\mathcal{T}_k$ | energy tax per liter for ICEV and per watt-hour for EV for vehicle $k \in K_t, t \in \{EV, ICEV\}$ |
| $\mathcal{E}_k$ | energy efficiency for vehicle $k \in K_t, t \in \{EV, ICEV\}$ |
| $M$ | a sufficiently large number |
| **Variable** | **Description** |
| $x_{ijk} \in \{0,1\}$ | binary variable equal to 1 if arc $(i,j)$ is traversed by vehicle $k$, $\forall k \in K, (i,j) \in A$, 0 otherwise |
| $y_k \in \{0,1\}$ | binary variable equal to 1 if the route performed by vehicle $k \in K$ consists of at least one arc crossing the zone, 0 otherwise |

$$\min \sum_{k\in K} \sum_{(i,j)\in A} (\mathcal{P}_k + \mathcal{T}_k)\mathcal{E}_k d_{ij} x_{ijk} + \sum_{k\in K}\sum_{i\in D}\sum_{j\in J}(f_k + \mathcal{C}_k - S_k)x_{ijk} + \sum_{k\in K_{ICEV}} \mathcal{F}_k y_k \tag{4.1}$$

The objective function (4.1) consists of three components: the routing costs, fixed costs of vehicles, and sum of entrance fees to the limited zone for ICEVs. The costs in the objective function are calculated on daily basis.

The constraints can be classified as follows: routing constraints, vehicle capacity, vehicle range, and vehicle symmetry removal.

**Constraints**

$$\sum_{i\in D}\sum_{j\in J} x_{ijk} \leq 1 \quad \forall k \in K \tag{4.2}$$

$$\sum_{i\in V}\sum_{k\in K} x_{ijk} = 1 \quad \forall j \in J \tag{4.3}$$

$$\sum_{i\in V} x_{ijk} = \sum_{i\in V} x_{jik} \quad \forall j \in V, k \in K \tag{4.4}$$

$$\sum_{i\in \mathcal{S}}\sum_{j\in \mathcal{S}} x_{ijk} \leq |\mathcal{S}| - 1 \quad \forall \mathcal{S} \subseteq J, k \in K \tag{4.5}$$

Constraints (4.2), (4.3), (4.4), and (4.5) are routing constraints. Constraints (4.2) impose that no vehicle starts from more than one depot. Constraints (4.3) state that each customer is visited by exactly one vehicle.

Constraints (4.4) state that, if a vehicle enters node $j \in V$, it must exit from it. Constraints (4.5) eliminate sub-tours.

$$\sum_{(i,j)\in A\setminus A^Z} x_{ijk} \leq My_k \quad \forall k \in K \tag{4.6}$$

Constraints (4.6) calculate the number of entries by vehicle $k \in K$ into the limited zone.

$$\sum_{i\in V}\sum_{j\in J} \mathcal{D}_j x_{ijk} \leq \mathcal{Q}_k \quad \forall k \in K \tag{4.7}$$

Constraints (4.7) ensure that the demand volumes of customers must respect the vehicle capacity.

$$\sum_{(i,j)\in A} d_{ij} x_{ijk} \leq R_k \quad \forall k \in K_{EV} \tag{4.8}$$

Constraints (4.8) limit the vehicle range and ensure that the total duration of a tour performed by an EV must respect its driving range limit.

$$\sum_{i\in D}\sum_{j\in V} x_{ijk} \leq \sum_{i\in D}\sum_{j\in V} x_{ijk-1} \quad \forall k \in K_t \neq K_t^1, t \in \{EV, ICEV\} \tag{4.9}$$

Constraints (4.9) avoid vehicle symmetry. These constraints are valid because the fleet of vehicles for each type is identical. Constraints (4.9) state that vehicle $k$ can only be dispatched if vehicle $k-1$ has already been dispatched. $K_t^1$ is the first element of $K_t, t \in \{EV, ICEV\}$.

$$x_{ijk} \in \{0,1\} \quad \forall (i,j) \in A, k \in K; \quad y_k \in \{0,1\} \quad \forall k \in K \tag{4.10}$$

Finally, constraints (4.10) define the nature of the variables.

### 4.3.3 Economic analysis

Following the least cost principle, the optimal decisions of an individual logistics company regarding vehicle fleet composition and routes with a mixed fleet of EVs and ICEVs are determined in response to different EV-supporting policy options. The proposed optimization model provides rational decisions of an individual company regardless of unobserved factors, such as personal preferences of the decision makers. The optimal decisions of a company may change according to policy adjustments under different policy scenarios in Section 4.3.1. Together with changes in the vehicle fleet composition and routing plan, such decisions change the total cost of the company (i.e., surplus), tax revenue of the government, energy consumption, and thus the emissions of different pollutants. Such responsiveness changes the social welfare as given in the following expression:

$$\Delta W = \Delta S + \Delta R - \Delta EC \tag{4.11}$$

$\Delta W$ is the change in social welfare that is induced by policy changes and the company's responses. $\Delta S$ is the sum of changes in the customer surplus $\Delta CS$ and producer surplus $\Delta PS$ in terms of the delivery service.

$$\Delta S = \Delta CS + \Delta PS \tag{4.12}$$

The customer surplus is the total difference between the willingness to pay $WP$ and service price for all customers $P_c$.

$$\Delta CS = \Delta WP - \Delta P_c \tag{4.13}$$

The producer surplus is the difference between the service price for the producer $P_p$ and the total delivery cost $TC$ (i.e., value of the objective function in the optimization model) for the logistics company.

$$\Delta PS = \Delta P_p - \Delta TC \tag{4.14}$$

In order to focus on the company side, we assumed that the price that the customer pays and price that the producer receives are the same: $P_c$=$P_p$. Any taxes imposed by the government are treated as an internal business cost for the company in the short run. Therefore, the service price does not change. The customer's willingness to pay does not change either in the short run. Finally, we obtain the change in the total surplus as the company's total delivery cost.

$$\Delta S = -\Delta TC \tag{4.15}$$

$\Delta R$ is the change in government tax revenues, including changes in the vehicle purchase subsidy $\Delta PS$, vehicle taxes $\Delta VT$, fuel tax $\Delta FT$, and zone fee for getting access to the limited zone $\Delta LEZ$.

$$\Delta R = \Delta PS + \Delta VT + \Delta FT + \Delta LEZ \tag{4.16}$$

The proposed optimization model is based on a daily calculation. The purchase subsidy and vehicle taxes are converted to a daily cost with a discount rate of 0.05 and lifetime of $10 \times 365$ days. The zone fee and fuel tax are daily costs for using EVs and ICEVs.

$$\begin{align}
\Delta PS &= \Delta \sum_{k\in K}\sum_{i\in D}\sum_{j\in J} -S_k x_{ijk} \tag{4.17}\\
\Delta VT &= \Delta \sum_{k\in K}\sum_{i\in D}\sum_{j\in J} (f_k + \mathcal{C}_k) x_{ijk} \tag{4.18}\\
\Delta FT &= \Delta \sum_{k\in K}\sum_{(i,j)\in A} \mathcal{T}_k \mathcal{E}_k d_{ij} x_{ijk} \tag{4.19}\\
\Delta LEZ &= \Delta \sum_{k\in K} \mathcal{F}_k y_k \tag{4.20}
\end{align}$$

$\Delta EC$ is the change in the total external cost of climate change, local air pollution and congestion. $e_k^j, \forall k \in K_t, t \in \{EV, ICEV\}, j \in \{I, O\}$ is the marginal external cost per liter of fuel for an ICEV or per watt-hour of electricity for an EV, where $I$ stands for inside the limited zone and $O$ stands for outside the limited zone. $\alpha_{ij}$ is the proportion of arc $(i,j) \in A$ located inside the zone. $\mathcal{E}_k$ is the energy efficiency for vehicle $k \in K_t, t \in \{EV, ICEV\}$. Based on the optimization model parameters, the following is obtained:

$$\Delta EC = \Delta \sum_{k \in K} \sum_{(i,j) \in A} \alpha_{ij} e_k^I \mathcal{E}_k d_{ij} x_{ijk} + \Delta \sum_{k \in K} \sum_{(i,j) \in A} (1 - \alpha_{ij}) e_k^O \mathcal{E}_k d_{ij} x_{ijk} \tag{4.21}$$

The first component in Equation (4.21) represents the change in the external cost inside the limited zone, and the second component relates to the change in the external cost outside the limited zone.

The marginal external costs are calculated differently for EVs and ICEVs. The costs of three externalities are considered: climate change ${e_1}_k^j$, local air pollution ${e_2}_k^j$, and congestion ${e_3}_k^j$.

$$e_k^j = {e_1}_k^j + {e_2}_k^j + {e_3}_k^j \;\; \forall k \in K_t, t \in \{EV, ICEV\}, j \in \{I, O\} \tag{4.22}$$

- *Climate change*: The $CO_2$ emissions of driving (per liter) an ICEV come from the fuel combustion, while the $CO_2$ emissions of EV (per $kWh$) result from the electricity production depending on the energy source. The impact of $CO_2$ emissions from road vehicles on global warming is independent of the timing and location. Therefore, the marginal damage costs of $CO_2$ from inside and outside the zone are the same: ${e_1}_k^I = {e_1}_k^O, \forall k \in K_t, t \in \{EV, ICEV\}$.

- *Local air pollution*: Local emissions ($NO_x$, $SO_2$, PM, NMVOC, $CO_2$ for gasoline) from driving an ICEV (per liter) come from fuel combustion, while emissions ($NH_3$, $NO_x$, $SO_2$, $PM_{2.5}$, NMVOC, $CO_2$) from driving an EV (per $kWh$) result from electricity production. Local emissions give rise to air pollution and cause cardiovascular and respiratory diseases. Emissions are released from high stacks. Within-country externalities of power plants are less dependent on the local population density, whereas externalities of fuel combustion in cars are strongly site-specific. The emissions from ICEVs have higher damage cost inside the limited zone, which is usually highly populated, than outside the zone: ${e_2}_{ICEV}^I > {e_2}_{ICEV}^O$. Emissions from electricity production only affect the residents around the power plant, which is usually located outside of urban areas. Thus, for urban areas inside and outside the zone, the marginal costs of local pollution resulting from electricity production are the same: ${e_2}_{EV}^I = {e_2}_{EV}^O$.

- *Congestion*(per kilometer): External costs of congestion occur when users plan their mobility individually but the required resource (i.e., the infrastructure) is too scarce to fulfil the demand mobility (Jochem et al., 2016). For both EVs and ICEVs, the congestion cost per kilometer are the same, but the congestion cost inside the limited zone, which usually has heavy traffic, is higher than outside the zone: $e3^I_k > e3^O_k, \forall k \in K_t, t \in \{EV, ICEV\}$. To maintain unit consistency in the equations, the marginal congestion cost (per kilometer) can be converted to the marginal congestion cost (per liter for ICEVs and per $kWh$ for EVs) according to the energy efficiency $\mathcal{E}_k$ (in $L/km$ for ICEVs and $kWh/km$ for EVs).

## 4.4 Numerical Experiments

As an application of the proposed framework, we implemented numerical experiments using data generated for a small transport network and the policy scenarios provided in Section 4.3.1. We also performed a sensitivity analysis to determine the robustness of the results with different types of vehicles and transport networks. The computations for the MILP formulation (i.e., equations (4.1)-(4.10)) were coded in A Mathematical Programming Language (AMPL) by using the solver Gurobi 6.5 on a computer with 24 CPU cores and 35 GB of RAM. All of the instances were solved optimally within a time limit of 12 hours. Because of the complexity of the optimization problem, only small-size instances can be solved optimally by exact solvers. The limitation is explained in the Appendix.

### 4.4.1 Problem instances

In this section, we provide the problem instances. All instances were generated for a transport network consisting of 15 customers that are scattered on a square plane with a single depot. The instances differed regarding the purchase subsidy, vehicle taxes, and zone fee for the different scenarios provided in Section 4.3.1 (i.e., each instance corresponds to each scenario with the same transport network but with different values of parameters $S_k$, $f_k$, $\mathcal{C}_k$, and $\mathcal{F}_k$ in the objective function of the optimization model). Figure 4.1 shows an example of a feasible solution for the transport network. The black circles represent the customers. The triangles represent the depots. The area inside the dashed line circle in Figure 4.1 represents the limited zone. The customers inside the limited zone are distributed uniformly. The dotted lines represent the routes performed by EVs and the solid lines represent the routes performed by ICEVs. The customer demands were generated from a uniform distribution between 15% and 25% of the ICEV capacity: $d_j \sim \mathcal{U}(0.15 * \mathcal{Q}_{ICEV}, 0.25 * \mathcal{Q}_{ICEV})$. In order to replicate the experiments, the distance matrix and demands are available upon request.

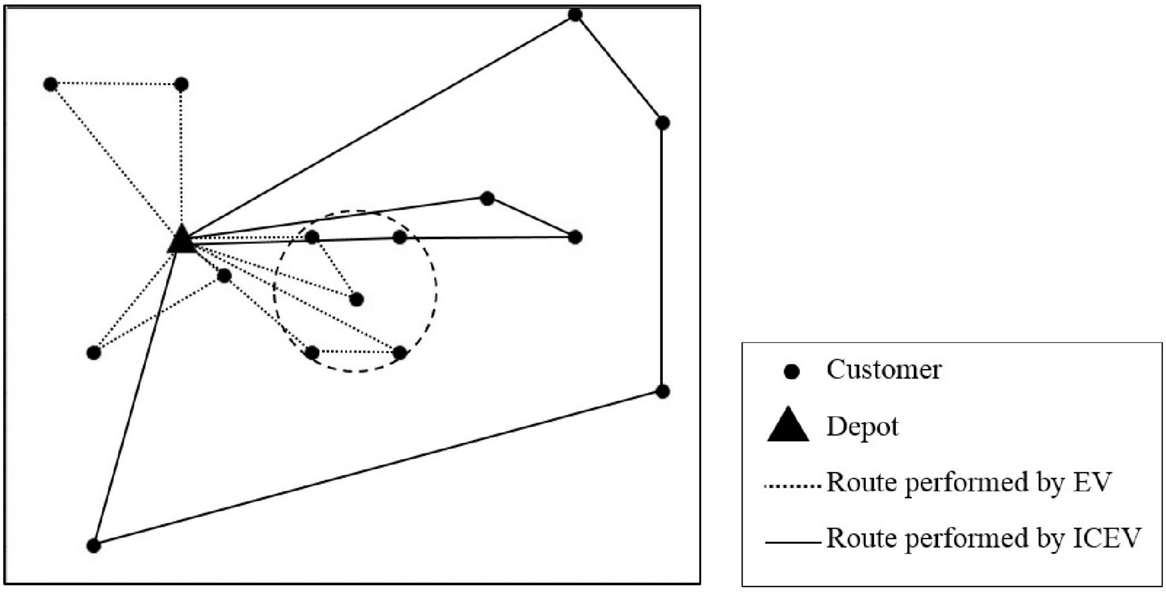

Figure 4.1: Feasible solution for the transport network.

The selected vehicles for urban freight transport were *Renault Kangoo Maxi ZE* for EVs and *Renault Trafic Energy dci 95* for diesel vehicles. Table 4.2 provides the vehicle characteristics that are collected from the official website of the car manufacturer. Header *Price* corresponds to the purchase price of the vehicle. Header *Playload* represents the maximum load weight (in $kg$) that each vehicle can carry. Header *Tailpipe* $CO_2$ corresponds to the amount of $CO_2$ ($g/km$) emitted by each vehicle. Header *Energy efficiency* represents the amount of energy consumed per kilometer by each type of vehicle ($Wh/km$ for EV and $L/km$ for diesel vehicles).[4]

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[4] In sensitivity analysis, we also use a smaller diesel vehicle (*Kangoo Maxi dci 90*) with same car model and a larger diesel vehicle (*Master Energy dci 110*)

Table 4.2: Vehicle characteristics.

| **Type** | **EV** | **ICEV** |
|---|---|---|
| **Model** | Kangoo Maxi ZE | Trafic Energy dci 95 |
| **Price** | 22650 £ | 25750 £ |
| **Playload** | 650 $kg$ | 1040 $kg$ |
| **Tailpipe** $CO_2$ | 0 $g/km$ | 164 $g/km$ |
| **Energy efficiency** | 150 $Wh/km$ | 0.064 $L/km$ |

We converted taxes/costs into a daily basis with an annual discount rate of 5%. Three types of policies were set at three pounds per vehicle per day[5] for the convenience of comparison. For further analysis on the primary scenarios in Section 4.3.1, we generated additional sub-scenarios regarding the related amount of taxation. The amount of taxation (i.e., the vehicle purchase subsidy, vehicle taxes, and zone fee) was changed from one to ten pounds in Scenarios 1, 2, and 3. We compared all scenarios to the baseline for welfare changes.

In this study, we chose the UK as an example to set the parameters in the optimization model and economic analysis. The data from IEA (2017) was used in order to obtain the prices and taxes of electricity and diesel for the UK in 2014. The marginal external costs per unit of electricity are calculated by Yan (2017) based on the energy mix of electricity generation (IEA, 2016), emission factors (Buekers et al., 2014) and social costs of pollutants (Markandya et al., 2010) in UK. The marginal external costs per unit of diesel are calculated based on emission factors and social costs of pollutants by Parry et al. (2014). The congestion cost was taken from Maibach et al. (2008). We regard the terms *inside the limited zone* and *outside the limited zone* as *urban* and *suburban*, respectively, that are defined for calculating different external costs of congestion in Maibach et al. (2008). The marginal cost of emissions or congestion inside the limited zone was set as 50% higher than that outside the zone. The details of the data are presented in the Table 4.3.

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[5] These are reasonable amounts according to the fiscal incentives offered in European countries like the UK and France.

Table 4.3: Data for variables.

| Variable | Data |
|---|---|
| **Electricity price** | 0.1556 $£/kWh$ |
| **Electricity tax** | 0.0074 $£/kWh$ |
| **Diesel price** | 1.3350 $£/L$ |
| **Diesel tax** | 0.8020 $£/L$ |
| **Marginal external cost of $CO_2$ emission (electricity generation)** | 0.0084 $€/kWh$ |
| **Marginal external cost of $CO_2$ emission (diesel combustion)** | 0.2024 $€/L$ |
| **Marginal external cost of local air pollution (electricity generation)** | 0.0045 $€/kWh$ |
| **Marginal external cost of local air pollution (diesel combustion)** | 0.2177 $€/L$ |
| **Marginal external cost of congestion for diesel and electric vehicles** | 0.0100 $€/km$ |

### 4.4.2 Computational results

We tested the proposed framework by using the data provided in Section 4.4.1 under the policy scenarios provided in Section 4.3.1. Table 4.4 provides the results on a daily basis obtained by solving the optimization model under different scenarios. Header *Number* represents the optimal number of vehicles for each type obtained by solving the optimization model. The numbers in parentheses refer to the number of ICEVs entering the limited zone. Columns *Distance (in)* and *Distance (out)* represent the total distance (in kilometers) traveled by each type of vehicle inside the limited zone (i.e., $\sum_{k\in K_t}\sum_{(i,j)\in A}\alpha_{ij}\mathcal{E}_k d_{ij}x_{ijk} \quad \forall t \in \{EV, ICEV\}$) and outside (i.e., $\sum_{k\in K}\sum_{(i,j)\in A}(1-\alpha_{ij})\mathcal{E}_k d_{ij}x_{ijk} \quad \forall t \in \{EV, ICEV\}$), respectively. Header *Total cost* represents the sum of the routing costs, fixed usage cost of vehicles, and entrance fee to the limited zone (i.e., the optimal value for the objective function of the optimization model). Headers $\Delta R$, $\Delta EC$, and $\Delta S$ represent the changes in tax revenues, external costs, and producer surplus, respectively. $\Delta W$ is the change in total welfare for different scenarios.

When the incentive of three pounds *per vehicle* per day (net present value) was provided, the purchase subsidy on EVs and zone fee on ICEVs increased the share of EVs in the vehicle fleet composition. With the purchase subsidy (Scenario 1) and zone fee (Scenario 2), two EVs were purchased in order to replace one diesel car. This means that the operational cost (i.e., routing cost and zone entrance fee) saving of replacing two EVs by one diesel vehicle exceeded the extra purchasing cost of two EVs. However, the vehicle taxes (Scenario 3) on ICEVs made no difference to the company's logistic decisions, compared to the baseline.

With the purchase subsidy and zone fee, the total distance (i.e., either inside or outside the limited zone) covered by all EVs increased almost twofold, while the average distance per EV decreased. For the diesel vehicles, the opposite changes were observed. EVs are limited by their driving range, so ICEVs have to visit customers out of EVs' driving ranges. In particular, without the zone fee, all diesel vehicles crossed the limited zone in order to travel the shortest delivery distance. With the zone fee for ICEVs and fee exemptions for EVs, only one out of two diesel vehicles entered the limited zone. In order to avoid paying the zone fee, the diesel vehicles travel around the zone to reach the customers on the other side of the zone, which increased the total traveling distance. Still, the zone fee did not prevent all diesel vehicles from entering the limited zone. For some diesel vehicles, paying the zone fee to go through the zone led to a lower total cost than traveling around the zone to reach customers on the other side.

The purchase subsidy and zone fee reduced the use of ICEVs both inside and outside the zone. Notably, they reduced the inside-zone distance traveled by ICEVs by more than 50% compared to the baseline. Since every ICEV was at least replaced by one, sometimes even 2 EVs, congestions increased inside the zone while the emissions decreased. But at the end, the total external cost of emissions and congestion were decreased by more than 10%. Because taxes and subsidies are transferred within the society, the change in welfare largely depends on changes in the external cost. As one can see from the results in Table 4.4, the zone fee produced the largest improvement in welfare. The vehicle taxes were not observed to have any impact on the company's decisions and therefore, social welfare.

We also considered the combination of all the three policies and we observed that the combination of all three policies led to the same optimal decisions on vehicle fleet and routing plans as Scenario 2 (zone fee). Therefore, for the sake of brevity, we do not present the results obtained under different combinations of policies.

To directly compare policies, the effects of different amounts of taxation on the resultant welfare were compared.[6] In Figure 4.2, the horizontal axis represents the amount of tax (net present value) for all three policies from one to ten pounds per day. With a daily subsidy/tax rate of two or more than two pounds, the zone fee and purchase subsidy led to increase EV share

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[6] details are provided in Tables 4.5–4.7 in the appendix

and the total social welfare was improved. With a daily subsidy/tax rate of four pounds, these two policies were stable, and no further change was induced, while the vehicle taxes started to impact the company's logistic decisions. Above four pounds, further strengthening of EV policies failed to promote the use of more EVs or improve the welfare. This was due to the limited technical performances of the vehicles rather than the small incentives provided by policies. Especially, we notice that purchase subsidy and vehicle tax work differently before the subsidy/rate of 4 pounds. The difference is reflected on the change in welfare that depends on the change in vehicle routing plan.[7] Planning vehicle routes is, in some cases, affected by policies since the subsidy allows a company to purchase more cars. More cars may also mean a more efficient routing plan and lower cost for the company.

Table 4.4: Impacts of different EV-supporting policy options on the company's decisions and social welfare.

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 2 | 135.43 | 346.05 | 195.23 | | | | |
| | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |
| **Scenario 1 (purchase subsidy)** | EV | 4 | 231.25 | 606.65 | 186.50 | 8.73 | -20.76 | -14.26 | 2.23 |
| | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| **Scenario 2 (zone fee)** | EV | 4 | 231.25 | 606.65 | 201.72 | -6.49 | -5.63 | -17.94 | 5.83 |
| | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| **Scenario 3 (vehicle taxes)** | EV | 2 | 135.43 | 346.05 | 204.23 | -9.00 | 9.00 | 0.00 | 0.00 |
| | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |

Note: The distances and costs are the sums for all EVs or all ICEVs. Individual distance and costs vary among vehicles.

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[7] With equations (4.15)-(4.21), and given the fixed energy price (i.e., $\Delta \sum_{k \in K} \mathcal{P}_k = 0$), the change in welfare (i.e., $\Delta W$ in equation (4.11)) is reduced to $\Delta W = \Delta \sum_{k \in K} 2(e_k^I + e_k^O) \sum_{(i,j) \in A} d_{ij} x_{ijk}$.

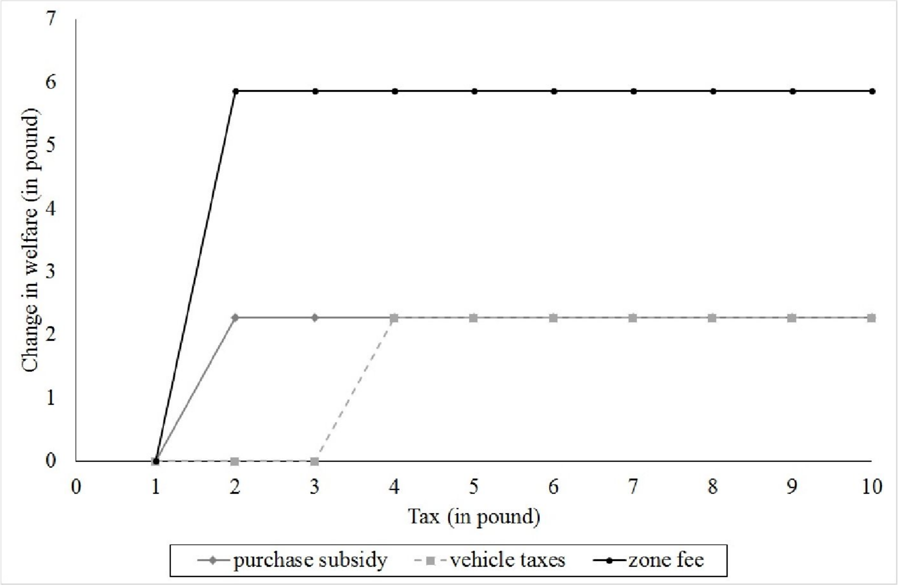
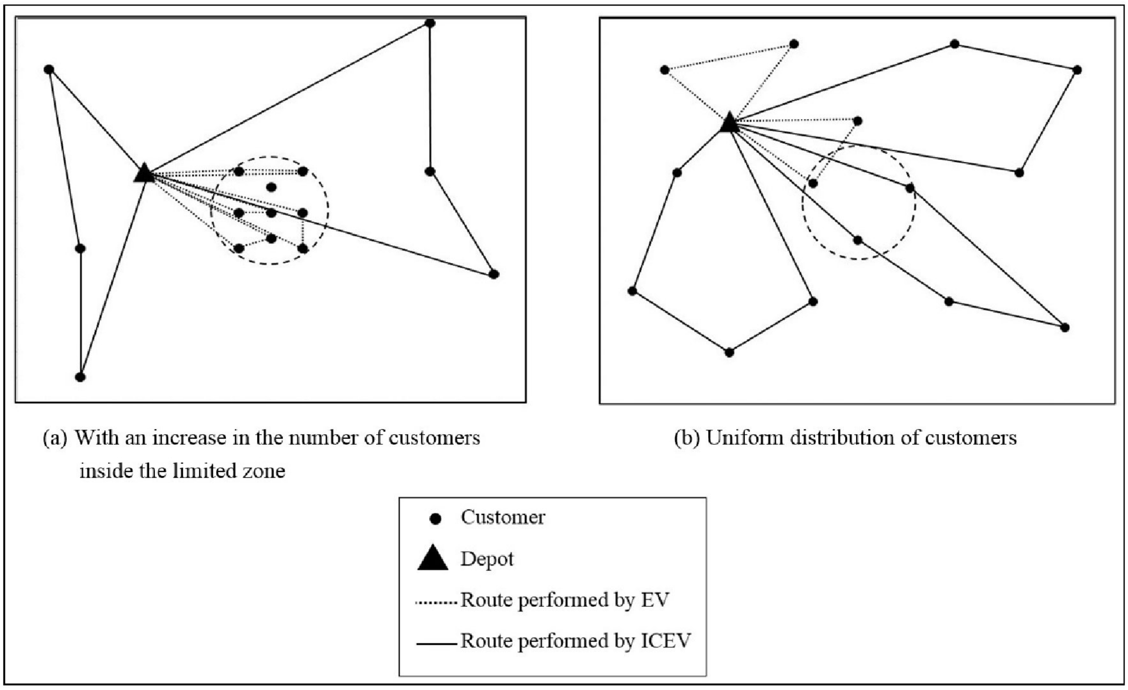


Figure 4.2: Welfare changes corresponding to changes in the daily tax rate.

### 4.4.3 Sensitivity analysis

The results of the sensitivity analysis are presented here. We focus on the fact that a logistics company might have different types of vehicles or operates in different cities. We used the scenarios in Section 4.3.1 to determine the results of changes in EV technology, the transport network, vehicle type (i.e., we considered a smaller diesel vehicle), and customer demand (i.e., we increased the customers' demands by 20%). Regarding the changes in EV technology, we considered two cases; with an increase in driving range of EVs from 258 to 300 km, and with a 25% increase in capacity of EVs. Regarding the changes in transport network, we considered three cases; with the same transport network as provided in Section 4.4.1 but with 50% reduction in distances between customers; and with two other types of transport networks: one with an increase in number of customers inside the limited zone from five to nine and the other with uniform distribution of customers on the plane. Figure 4.3 illustrates feasible solutions for the two other types of transport networks. The results for the sensitivity analysis are provided in Tables 4.8–4.16 in the appendix.


(a) With an increase in the number of customers inside the limited zone

(b) Uniform distribution of customers

Figure 4.3: Feasible solutions for different types of transport networks.

Through comparing each individual scenario in the sensitivity analysis to its own baseline, we observe that the total social welfare hardly improved after the purchase subsidy, zone fee, and vehicle taxes were implemented. For the within-scenario comparison to the main results in Table 4.4, the current policies designed for promoting the use of EVs were less effective according to the sensitivity analysis. As one can see from the results in Tables 4.8–4.10, technological improvements reduced the relative disadvantage of EVs (i.e., limited driving range) in the cases of extended range, enlarged capacity, and smaller diesel vehicles. In these cases, the EV share in the vehicle fleet composition increased compared to the main results. As presented in Tables 4.11–4.12, local factors (e.g., short distances between customers) in favor of EV worked the same way as technological improvements. In a few cases with the zone fee, the social welfare decreased while the vehicle fleet composition did not change. The zone fee increased the total travel distance for diesel vehicles, which led to a higher external cost and lower welfare.

There are two particularly important sensitivity analyses worth further discussion.

The first analysis is to consider that there are differences in vehicle labeled fuel efficiency/$CO_2$ emission rate and real on-road fuel efficiency/$CO_2$ emission rate. We assume that the congestion inside the limited zone (e.g., city center) will increase the fuel consumption and $CO_2$ emission per kilometer by 5% or 25%. Table 4.15 and Table 4.16 present the corresponding results. Comparing the results in these two tables with the main results in Table 4.4, we can see that the additional fuel cost caused by congestion inside the zone can function as zone fee. With a higher additional fuel cost, fewer trips by ICEVs will be planned inside the zone and larger external reductions will be achieved.

The second analysis is related to alternative roads between two or more customers. An interesting case in our study is to discuss the two customers that are outside the limited zone and are visited by an ICEV while the shortest road between them crosses the zone, which means the ICEV has to pay a certain zone fee. Alternative roads could exist that are longer than the shortest one between the two customers. If the alternative road leads to additional routing costs that are lower than the zone fee, the alternative road will be chosen. The same argument applies for alternative roads between more than two customers. However, a more complicated road network and optimization solution approach should be included, which is out of our research scope here.

### 4.4.4 Policy implications

The results in Sections 4.4.2 and 4.4.3 provide some implications for policy making.

First, purchase subsidies for EVs, zone fee with exemptions for EVs and vehicle tax with exemptions for EVs are able to increase the purchase of EVs. The purchase subsidies and vehicle tax affect purchase decisions directly while the zone fee influences the purchase of EVs through its impacts on operational (i.e., routing) plans of EVs. Since logistics companies have more certain operational plans than private passenger car drivers, the influence of zone fee on purchase decisions of logistics companies are more obvious.

Second, in our main results, zone fee leads to the largest reduction in external costs of climate change, local air pollution and congestion. This is because the zone fee significantly reduces the external cost by preventing emissions and congestion inside the limited zone. In some of the sensitivity analyses, the zone fee increased external costs by forcing ICEVs to travel around the zone to reach customers on the other side, which may lead to more emissions from fuel combustion or congestion. It can be seen that, depending on the range of a limited zone, the distribution of consumers inside and outside the zone and road network, the effectiveness of zone fee for promoting EVs is, somehow, geographically based.

Third, although the vehicle taxes and subsidy had almost the same influences on the company and society, they performed differently at low tax/subsidy rates. Unlike previous economic research on EV policy evaluations with assumptions of fixed annual travelling distance, we consider the vehicle upfront purchase costs and routing (driving) costs. Since tax and subsidy have different effects on routing costs, they lead to different decisions on the vehicle fleet composition and routing plans and therefore, social welfare.

Lastly, the sensitivity analysis also showed that the developments in vehicle technology can largely affect a logistics company's decisions on vehicle fleet and routing plans, and therefore are important for designing efficient EV-supporting policies. With better EV technology, EV-supporting policies lead to more purchase and use of electric vehicles. We define the effectiveness of EV policies as EV sales' increase, or reductions in external costs per unit of tax changes. The effectiveness of the EV policies targeted at freight transport can be improved if policy making considers the potential and feasibility of current vehicle technology.

## 4.5 Conclusion

EVs are often considered as a critical solution to climate stabilization. For an individual logistics company, costs and technical disadvantages limit the purchase and use of EVs. EV-supporting policies provide strong incentives for EVs in urban freight transport, which is responsible for a significant amount of $CO_2$ and local pollutant emissions. Only a small body of literature has focused on how EV policies affect logistics companies and therefore society. To throw light on the relevant issues, we examined common vehicle specific EV-supporting policies: the purchase subsidy for EVs, vehicle taxes with exemptions for EVs, and limited access (zone fee) to a low-emission/congestion zone with exemptions for EVs. We developed a framework that combines an optimization model with economic analysis to evaluate the effects of EV-supporting policies on an individual company's optimal decisions regarding vehicle fleet composition and routes, external costs of emissions and congestions, and social welfare.

Our theoretical framework should be seen as a preliminary attempt to evaluate companies response and effectiveness of policies for EVs through the combination of an optimization model and economic analysis, which provide an evaluation of EV policies from a different perspective and also lays an important basis for further explorations. Although the focus was on the vehicle specific policies, mainly, for companies, elaborations on changing demand of consumers might also lead to interesting results from the perspective of market equilibriums. Moreover, different limitations might exist in our method, depending on the research objectives. As opportunities for future research, more comprehensive models and solution approaches can be established to deal with realistic issues such as real-time deliveries, large-scale transport networks, dynamic decision processes, alternative roads, rush-hours/off-hours deliveries, geographic features, idling and battery ageing for electric vehicles.

# Appendix: details of results obtained from tax changes and sensitivity analysis

## Tax changes

Table 4.5: Impacts of different EV-supporting policy options with different purchase subsidy

| Scenario | Subsidy | Type | Number | Distance (in) | Distance (out) | Total cost | $\Delta R$ | $\Delta EC$ | $\Delta S$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario1.10 | 10 | EV | 4 | 231.30 | 606.70 | 158.50 | -48.72 | -14.26 | 36.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.9 | 9 | EV | 4 | 231.30 | 606.70 | 162.50 | -44.72 | -14.26 | 32.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.8 | 8 | EV | 4 | 231.30 | 606.70 | 166.50 | -40.72 | -14.26 | 28.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.7 | 7 | EV | 4 | 231.30 | 606.70 | 170.50 | -36.72 | -14.26 | 24.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.6 | 6 | EV | 4 | 231.30 | 606.70 | 174.50 | -32.72 | -14.26 | 20.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.5 | 5 | EV | 4 | 231.30 | 606.70 | 178.50 | -28.72 | -14.26 | 16.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.4 | 4 | EV | 4 | 231.30 | 606.70 | 182.50 | -24.72 | -14.26 | 12.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.3 | 3 | EV | 4 | 231.30 | 606.70 | 186.50 | -20.72 | -14.26 | 8.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.2 | 2 | EV | 4 | 231.30 | 606.70 | 190.50 | -16.72 | -14.26 | 4.73 | 2.27 |
| | | ICEV | 2(2) | 122.90 | 1106.10 | | | | | |
| Scenario1.1 | 1 | EV | 2 | 135.40 | 346.10 | 193.23 | -2.00 | 0.00 | 2.00 | 0.00 |
| | | ICEV | 3(3) | 275.50 | 1131.80 | | | | | |

Table 4.6: Impacts of different EV-supporting policy options with different zone fees

| **Scenario** | **Fee** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta R$ | $\Delta EC$ | $\Delta S$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario 2.10 | 10 | EV | 4 | 231.25 | 606.65 | 208.72 | 1.41 | -17.94 | -13.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.9 | 9 | EV | 4 | 231.25 | 606.65 | 207.72 | 0.41 | -17.94 | -12.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.8 | 8 | EV | 4 | 231.25 | 606.65 | 206.72 | -0.59 | -17.94 | -11.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.7 | 7 | EV | 4 | 231.25 | 606.65 | 205.72 | -1.59 | -17.94 | -10.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.6 | 6 | EV | 4 | 231.25 | 606.65 | 204.72 | -2.59 | -17.94 | -9.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.5 | 5 | EV | 4 | 231.25 | 606.65 | 203.72 | -3.59 | -17.94 | -8.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.4 | 4 | EV | 4 | 231.25 | 606.65 | 202.72 | -4.59 | -17.94 | -7.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.3 | 3 | EV | 4 | 231.25 | 606.65 | 201.72 | -5.59 | -17.94 | -6.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.2 | 2 | EV | 4 | 231.25 | 606.65 | 200.72 | -6.59 | -17.94 | -5.49 | 5.86 |
| | | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| Scenario 2.1 | 1 | EV | 2 | 135.43 | 346.05 | 198.23 | 3.00 | 0.00 | -3.00 | 0.00 |
| | | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |

Table 4.7: Impacts of different EV-supporting policy options with different vehicle taxes

| **Scenario** | **Tax** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta R$ | $\Delta EC$ | $\Delta S$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario 3.10 | 10 | EV | 4 | 231.25 | 606.65 | 218.50 | 11.28 | -14.26 | -23.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.9 | 9 | EV | 4 | 231.25 | 606.65 | 216.50 | 9.28 | -14.26 | -21.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.8 | 8 | EV | 4 | 231.25 | 606.65 | 214.50 | 7.28 | -14.26 | -19.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.7 | 7 | EV | 4 | 231.25 | 606.65 | 212.50 | 5.28 | -14.26 | -17.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.6 | 6 | EV | 4 | 231.25 | 606.65 | 210.50 | 3.28 | -14.26 | -15.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.5 | 5 | EV | 4 | 231.25 | 606.65 | 208.50 | 1.28 | -14.26 | -13.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.4 | 4 | EV | 4 | 231.25 | 606.65 | 206.50 | -0.72 | -14.26 | -11.27 | 2.27 |
| | | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| Scenario 3.3 | 3 | EV | 2 | 135.43 | 346.05 | 204.23 | 9.00 | 0.00 | -9.00 | 0.00 |
| | | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |
| Scenario 3.2 | 2 | EV | 2 | 135.43 | 346.05 | 201.23 | 6.00 | 0.00 | -6.00 | 0.00 |
| | | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |
| Scenario 3.1 | 1 | EV | 2 | 135.43 | 346.05 | 198.23 | 3.00 | 0.00 | -3.00 | 0.00 |
| | | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |

## Sensitivity analysis

Table 4.8: Impacts of different EV-supporting policy options for EVs with an extended driving range

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 4 | 328.48 | 623.04 | 184.74 | | | | |
| | ICEV | 2(1) | 70.23 | 966.61 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 4 | 328.48 | 623.04 | 172.74 | 12.00 | -12.00 | 0.00 | 0.00 |
| | ICEV | 2(1) | 70.23 | 966.61 | | | | | |
| **Scenario 2 (zone fee)** | EV | 4 | 328.48 | 623.04 | 187.74 | -3.00 | 3.00 | 0.00 | 0.00 |
| | ICEV | 2(1) | 70.23 | 966.61 | | | | | |
| **Scenario 3 (vehicle taxes)** | EV | 4 | 328.48 | 623.04 | 190.74 | -6.00 | 6.00 | 0.00 | 0.00 |
| | ICEV | 2(1) | 70.23 | 966.61 | | | | | |

Table 4.9: Impacts of different EV-supporting policy options for EVs with a larger carrying capacity

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 3 | 142.94 | 515.00 | 182.51 | | | | |
| | ICEV | 2(2) | 143.94 | 1085.06 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 3 | 142.94 | 515.00 | 173.51 | 9.00 | -9.00 | 0.00 | 0.00 |
| | ICEV | 2(2) | 143.94 | 1085.06 | | | | | |
| **Scenario 2 (zone fee)** | EV | 3 | 180.30 | 554.08 | 187.51 | -5.00 | 3.22 | 0.10 | -1.88 |
| | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| **Scenario 3 (vehicle taxes)** | EV | 3 | 142.94 | 515.00 | 188.51 | -6.00 | 6.00 | 0.00 | 0.00 |
| | ICEV | 2(2) | 143.94 | 1085.06 | | | | | |

Table 4.10: Impacts of different EV-supporting policy options with a smaller diesel vehicle

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 3 | 192.91 | 541.25 | 163.26 | | | | |
| | ICEV | 3(3) | 195.01 | 1241.43 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 3 | 192.91 | 541.25 | 154.26 | 9.00 | -9.00 | 0.00 | 0.00 |
| | ICEV | 3(3) | 195.01 | 1241.43 | | | | | |
| **Scenario 2 (zone fee)** | EV | 3 | 276.25 | 429.13 | 170.76 | -7.50 | 7.82 | 9.13 | -8.81 |
| | ICEV | 3(2) | 157.51 | 1315.03 | | | | | |
| **Scenario 3 (vehicle taxes)** | EV | 3 | 192.91 | 541.25 | 167.74 | -4.48 | 4.48 | 0.00 | 0.00 |
| | ICEV | 3(3) | 195.01 | 1241.43 | | | | | |

Table 4.11: Impacts of different EV-supporting policy options for a smaller city

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 6 | 196.19 | 924.57 | 118.32 | | | | |
| | ICEV | 1(1) | 47.78 | 45.82 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 6 | 196.19 | 924.57 | 100.32 | 18.00 | -18.00 | 0.00 | 0.00 |
| | ICEV | 1(1) | 47.78 | 45.82 | | | | | |
| **Scenario 2 (zone fee)** | EV | 6 | 196.19 | 924.57 | 121.32 | -3.00 | 3.00 | 0.00 | 0.00 |
| | ICEV | 1(1) | 47.78 | 45.82 | | | | | |
| **Scenario 3 (vehicle taxes)** | EV | 6 | 196.19 | 924.57 | 121.32 | -3.00 | 3.00 | 0.00 | 0.00 |
| | ICEV | 1(1) | 47.78 | 45.82 | | | | | |

Table 4.12: Impacts of different EV-supporting policy options for a city with larger demands

| Scenario | Type | Number | Distance (in) | Distance (out) | Total cost | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 3 | 231.25 | 434.13 | 208.61 | | | | |
| | ICEV | 3(2) | 174.51 | 1201.07 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 3 | 231.25 | 434.13 | 199.61 | 9.00 | -9.00 | 0.00 | 0.00 |
| | ICEV | 3(2) | 174.51 | 1201.07 | | | | | |
| **Scenario 2 (zone fee)** | EV | 3 | 231.25 | 434.13 | 214.61 | -6.00 | 6.00 | 0.00 | 0.00 |
| | ICEV | 3(2) | 174.51 | 1201.07 | | | | | |
| **Scenario 3 (vehicle taxes)** | EV | 3 | 231.25 | 434.13 | 217.61 | -9.00 | 9.00 | 0.00 | 0.00 |
| | ICEV | 3(2) | 174.51 | 1201.07 | | | | | |

Table 4.13: Impacts of different EV-supporting policy options for a transport network with more customers inside the zone

| Scenario | Type | Number | Distance (in) | Distance (out) | Total cost | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 2 | 253.35 | 217.23 | 191.96 | | | | |
| | ICEV | 3(3) | 181.44 | 1190.50 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 4 | 384.63 | 440.97 | 180.53 | -11.43 | -4.53 | 1.28 | 5.61 |
| | ICEV | 2(1) | 77.81 | 1084.65 | | | | | |
| **Scenario 2 (zone fee)** | EV | 4 | 384.63 | 440.97 | 195.53 | 3.57 | 10.47 | 1.28 | 5.61 |
| | ICEV | 2(1) | 77.81 | 1084.65 | | | | | |
| **Scenario 3 (vehicle tax)** | EV | 4 | 384.63 | 440.97 | 198.53 | 6.57 | 13.47 | 1.28 | 5.61 |
| | ICEV | 2(1) | 77.81 | 1084.65 | | | | | |

Table 4.14: Impacts of different EV-supporting policy options for a transport network with uniform distribution of customers

| Scenario | Type | Number | Distance (in) | Distance (out) | Total cost | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 2 | 6.87 | 410.59 | 200.00 | | | | |
| | ICEV | 3(1) | 134.90 | 1345.66 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 2 | 6.87 | 410.59 | 194.00 | -6.00 | -6.00 | 0.00 | 0.00 |
| | ICEV | 3(1) | 134.90 | 1345.66 | | | | | |
| **Scenario 2 (zone fee)** | EV | 2 | 6.87 | 410.59 | 203.00 | 3.00 | 3.00 | 0.00 | 0.00 |
| | ICEV | 3(1) | 134.90 | 1345.66 | | | | | |
| **Scenario 3 (vehicle tax)** | EV | 2 | 6.87 | 410.59 | 209.00 | 9.00 | 9.00 | 0.00 | 0.00 |
| | ICEV | 3(1) | 134.90 | 1345.66 | | | | | |

Table 4.15: Impacts of different EV-supporting policy options for on-road energy efficiency - 25%

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 2 | 135.43 | 346.05 | 201.90 | | | | |
| | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 4 | 231.25 | 606.65 | 190.29 | -11.61 | -2.73 | -19.29 | 28.18 |
| | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| **Scenario 2 (zone fee)** | EV | 4 | 231.25 | 606.65 | 205.29 | 3.39 | 12.27 | -19.29 | 28.18 |
| | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| **Scenario 3 (vehicle tax)** | EV | 4 | 231.25 | 606.65 | 208.29 | 6.39 | 15.27 | -19.29 | 28.18 |
| | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |

Table 4.16: Impacts of different EV-supporting policy options for on-road energy efficiency - 5%

| **Scenario** | **Type** | **Number** | **Distance (in)** | **Distance (out)** | **Total cost** | $\Delta S$ | $\Delta R$ | $\Delta EC$ | $\Delta W$ |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | EV | 2 | 135.43 | 346.05 | 196.57 | | | | |
| | ICEV | 3(3) | 275.47 | 1131.83 | | | | | |
| **Scenraio 1 (subsidy)** | EV | 4 | 231.25 | 606.65 | 187.29 | -9.27 | -2.86 | -14.52 | 20.94 |
| | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |
| **Scenario 2 (zone fee)** | EV | 4 | 231.25 | 606.65 | 202.16 | 5.60 | 12.27 | -18.21 | 24.89 |
| | ICEV | 2(1) | 104.28 | 1127.26 | | | | | |
| **Scenario 3 (vehicle tax)** | EV | 4 | 231.25 | 606.65 | 205.29 | 8.73 | 15.14 | -14.52 | 20.94 |
| | ICEV | 2(2) | 122.94 | 1106.06 | | | | | |

### Limitations in the optimization models

For large-size instances obtained from real transport networks, a robust heuristic that can provide high-quality solutions would be required in order to fairly compare the results under different policies. Here, we do not provide a solution approach for the problem, but we aim to implement the proposed framework on a small transport network in order to have a fair comparison among the optimal solutions obtained by the optimization model under different scenarios. Table 4.17 provides the results for different sizes of instances consisting 15, 30, 45, 60, and 90 customers. For each size, we considered three instances and provided the results within the time limit of 12 hours. In Table 4.17, columns $|J|$ and $|D|$ represent the number of customers and the number of depots, respectively. Column $CPU$ represents the average time spent (in seconds) on each size of instances. Columns $\overline{GTO}$, $GTO_{min}$ stand for the average and minimum gap to optimality reported by the Gurobi solver on each size of instances, respectively. As one can see from the results, within the given time limit, all instances with 15 customers were solved optimally, while none of the instances with 90 customers were solvable.

Table 4.17: Results of solving the optimization model for different sizes of instances

| Instance size (# of nodes) | $\lvert J\rvert$ | $\lvert D\rvert$ | $CPU$ (s) | $\overline{GTO}$ | $GTO_{min}$ |
|---|---|---|---|---|---|
| 16 | 15 | 1 | 891 | 0.0 | 0.0 |
| 31 | 30 | 1 | 43200 | 20.1 | 15.5 |
| 46 | 45 | 1 | 43200 | 49.8 | 39.4 |
| 61 | 60 | 1 | 43200 | 57.9 | 52.8 |
| 91 | 90 | 1 | 43200 | - | - |

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