Diesel Cars and Environmental Policy

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Preliminary

Abstract

In this paper, I assess the costs of environmental taxation of car ownership and usage in Denmark. Using high quality Danish register data covering 1997–2006, I estimate a discrete-continuous model of car choice and usage allowing for endogenous selection of cars based on expected usage. I validate the model out of sample using a major Danish reform in 2007 which prompted a substantial shift in the characteristics of purchased cars — in particular the diesel market share — unique to the Danish setting compared to the rest of Europe. Through counterfactual simulations, I find that both Danish reforms in 1997 and 2007 were cost-ineffective at reducing CO_2 emissions. Moreover, the diesel market share is highly affected by taxation but environmental goals can be reached both with and without a large diesel share in the fleet.

Keywords: Car taxation, fuel taxation, environmental policy, discrete/continuous choice estimation.
JEL codes: D12, H23, Q53, Q58, L98.

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1 Introduction

980, greenhouse gas emissions from the Danish transport sector have increased from 10 to 15 mio tons CO_2 annually while all remaining sectors together have reduced emissions from 55 to 30 mio tons. In Denmark as well as the rest of the developed world, a consensus is emerging that emissions from the transport sector must be decreased if environmental goals are to be reached. The goal of this paper is to measure the cost-effectiveness of various tax policy instruments targeting car choice and use in reaching these goals.

Towards this end, I estimate a structural 2-period discrete-continuous model of new car purchase and subsequent usage by Danish households. The data cover all new car purchases for the period 1997–2006 which I match with subsequent driving over a 4-year period and with the Danish demographic registers. In 2007, a major Danish *feebate* reform was implemented — giving a *rebate* to greener cars and a higher *fee* to dirty cars, hence the name — followed by substantial changes in new car purchases not seen in other European countries. I observe new purchases after the reform but not driving so I use this to validate the model.

The paper contributes to the understanding of the costs of environmental car taxation by estimating household behavioral responses. The model gives predictions on car choices and subsequent driving, allowing me to analyze the impact of counterfactual policy scenarios on tax revenue, substitutions in the new car market, total driving, fuel demand and CO_2 emissions. I that the welfare costs CO_2 reductions implied by the Danish 2007 reform far exceeded the social valuation of CO_2. Moreover, I show through a counterfactual policy setup that the huge shift towards diesel cars could have been avoided without losing increasing CO_2 emissions.

Moreover, I show that the concrete feebate in question was a less efficient tool for reducing CO_2 emissions than a fuel tax. The main reason for this is that the 2007 reform caused a stronger shift on the car choice margin towards the high-efficiency cars, which were both cheaper pre-reform and on top of that received a sizable tax reduction due to the asymmetric nature of the reform. This result is in line with Adamou, Clerides, and Zachariadis (2013) who report that for a feebate to be optimal, a feebate must look more like a fee than a rebate while the reverse was the case with the Danish 2007 feebate.

I also consider the question of whether diesel cars are attractive from a social point of view. To the individual household, diesel cars are typically more expensive but yield lower operating cost. From an environmental point of view, they typically have lower CO_2 emissions but emit local air pollutants such as NO_x and SO_2. According to Miravete, Moral, and Thurk (2014), differing tax treatments of the local vs. global pollutants is the primary reason for the wide adoption of diesels in Europe and the reverse in the US. Fuel taxes typically favor diesel fuel but Danish car taxes discourage diesel car purchase. I construct a counterfactual setting where the fuel taxes are aligned with the external costs of the pollutants and where the car purchase and ownership taxes are equalized and find a socially optimal level of diesel cars between the 2006 and 2007 level for Denmark at 23.3%. However, most of the CO_2 reductions brought about by the 2007 reform could have been achieved without any change in the diesel market share, indicating that diesel cars and the accompanying local air pollutants are not a necessary evil to achieve environmental goals.

The setting studied in this paper is unique in the literature. Recently, Reynaert (2014) has provided evidence that firm responses to policy initiatives is substantial, primarily in terms of technological progress. Most papers in the literature study major economies or policies affecting many markets, implying that the equilibrium outcome may be a combination of household and firm responses. I show that the Danish 2007 reform prompted clear responses in Denmark that were not seen in other European countries. Given that the model is able to fit these responses counterfactually, I conclude that the household behavior is well captured by the model.

The data employed are also of a higher quality than previously studied. Using the Danish register data, I can observe all new car purchases by private households in the period 1997Q2–2006Q2 and the subsequent driving. Households are matched to individual level demographics, including tax register based income, household composition and a unique work distance variable based on a income tax deduction based on the per-day commuting.

In terms of the modeling approach, I follow the discrete-continuous approach by Gillingham (2011), which incorporates selection on unobserved driving needs into a Dubin and McFadden (1984) type econometric framework. I add more flexibility to the model and show how to extend the model to incorporate fixed effects in a manner similar to Berry, Levinsohn, and Pakes (1995, henceforth BLP) in this non-linear model. Work is not complete estimating this model but preliminary results indicate that this is necessary to avoid large error variances by allowing for unobserved car attributes.

The rest of the paper is organized as follows; Section 1.1 discusses the contributions from this paper in the context of related literature. Section 2 presents the institutional setting and the data and presents some preliminary descriptive evidence. Section 3 lays out the theoretical model. Section 4 gives the empirical strategy and section 5 presents the estimates and structural elasticities. Section 6 contains the counterfactual simulations and section 7 concludes. Appendix A contains a list of the notation used throughout the paper as well as the core equations of the structural model for easy reference.

1.1 Related Literature

I mainly contribute to the literature on the cost of environmental policies in the car market. Recently, a number of papers have emphasized various European settings. D'Haultfæuille, Givord, and Boutin (2013) study the French *Bonus/Malus* reform of 2008 which is a feebate similar to the Danish one. They find that the reform had a negative environmental impact, mainly because it led to more cars being sold at the extensive margin. My model conditions on entry into the new car market so I make no claims on the extensive margin results. Adamou, Clerides, and Zachariadis (2013) counterfactually study the impact of a feebate, finding that the reform needs to look more like a fee than a rebate in order to be optimal. Mabit (2014) analyzes the 2007 reform that is also under study in this paper but does not model driving and car choice jointly, focusing exclusively on the purchase decision. He finds that the reform had virtually no effect on car demand in Denmark which is in sharp contrast with my results.

A number of other studies consider more small-scale reforms, typically affecting smaller segments. These are generally found to be cost-ineffective. Huse and Lucinda (2013) consider a Swedish reform affecting only highly efficient green cars using a BLP model. They find that the implicit price of CO2-emissions from that reform was far above the social cost of carbon in Sweden. Beresteanu and Li (2011) and Chandra, Gulati, and Kandlikar (2010) study incentive schemes aimed at hybrid cars in the US and Canada and both find them to be cost-ineffective.

The papers cited above all target new car demand but a large American literature focuses on supply side instruments, primarily the Corporate Average Fuel Economy (CAFE) standards. These require car makers to reach a certain weighted average fuel economy across their sold cars, subject to a number of technical details. Building on the framework by Bento et al. (2009), Jacobsen (2013) compares the cost-effectiveness of CAFE standards and fuel taxes, finding the latter to be the more effective. Reynaert (2014) and Clerides and Zachariadis (2008) are among the few papers studying the effects of the European fuel economy standards, announced in 2007 and to be fully binding by 2015. Reynaert (2014) focuses on the responses of the European automakers, finding that they primarily respond by technology adoption. European standards were also studied by .

This paper puts some focus on the matter of the fuel type choice of diesel vs. gasoline. This is a much more prevalent option in the European than the American context and the diesel market share increased substantially up through the early 1990's, following the introduction of the direct injection or common rail technology. Miravete, Moral, and Thurk (2014) study this in the Spanish setting, finding that the policy treatment of diesel vs. gasoline in Europe functioned in effect as a subsidy to European car makers. On the methodological side, Verboven (2002) uses within-model variation between car models that only differ in using gasoline or diesel fuel for identification in a BLP framework.

Endogenous selection of consumers into car types based on individual driving demand has been emphasized in recent work. This paper builds on Gillingham (2011) who introduces endogenous selection both based on observables, unobservables and explicitly on expectations about future fuel prices. The model builds on Dubin and McFadden (1984). Some work has used 2-step approaches to integrating type choice and usage (e.g. Goldberg 1998; West 2004; D'Haultfæuille, Givord, and Boutin 2013), while more recent work has promoted simultaneous estimation (e.g. Bento et al. 2009; Feng, Fullerton, and Gan 2013; Jacobsen 2013 and in particular Gillingham, 2011). The model explicitly accounts for the selection effect required to identify the so-called *rebound effect*, namely the effect on driving of increasing fuel efficiency (see e.g. Small and Van Dender, 2007).

In terms of the data used, this paper is novel in applying micro data on car choice and usage matched with household-level demographics for the full Danish population over a long period of 9 years. Many papers in the car demand literature have only used market-level data (e.g. Berry, Levinsohn, and Pakes 1995; Miravete, Moral, and Thurk 2014; Reynaert 2014; Verboven 2002). The papers using micro-level data either use survey data (West 2004; Bento et al. 2009; Jacobsen 2013), often with only a limited number of years, or do not observe household demographics at the micro level (e.g. Gillingham, 2011).

Two major aspects of car demand that I do not tackle in this paper are multi-car households, dynamics and myopia. Even though the data would allow it, I choose not to include 2-car households in this study.[1] This is to make sure the choice set in the model remains tractable. I could assume that the two car choices were independent but given that there are very few 2-car households in Denmark (less than 10%) in this period, this simplification does not seem too bad.

A recent literature has looked at the question of whether consumers correctly take into account future savings in fuel cost when making a car purchase.[2] I make no claims to

[1]Spiller (2012); Borger, Mulalic, and Rouwendal (2013); Wakamori (2011) consider households making car portfolio choices but apart from these, the literature on multi-car households is somewhat limited.

[2]The findings have been mixed with some support for myopia (Allcott and Wozny, 2012) and some against (Busse, Knittel, and Zettelmeyer (2013); Sallee, West, and Fan (2010)). The interested reader is referred to the literature review by Greene (2010) which documents that there has been extremely mixed evidence in the empirical literature. Another strand of literature emphasizes certain behavioral aspects that I will not consider in this paper; Gallagher and Muehlegger (2011) find that tax incentives working through

answering this question but will follow the latter, assuming that consumers are rational and time-consistent when they make their vehicle and driving decisions. However, I will allow some flexibility in consumer expectations about future fuel prices.

Finally, some authors have emphasized the dynamics of vehicle ownership decisions, opting for a fully dynamic structural model.[3] While this facilitates the study of important aspects such as the used-car market, scrappage and ownership durations one must trade off complexity elsewhere in the model and it is central to maintain a high-dimensional choice set to accurately fit in the effects of the policies considered. As most other non-dynamic papers, the model presented in this paper conditions on entry into the new car market. If the reforms change substitutions between the used and new car market, such effects will be ignored. In that sense, the focus of this paper is purely on the substitution patterns in the car market.

2 Data

2.1 Institutional Setting

Car taxation in Denmark consists of three elements; registration tax, bi-annual ownership tax and fuel taxes. The rates of each of these taxes were updated during the sample period which aids identification by providing policy-induced variation in the cost of acquisition, ownership and usage of cars. For a more detailed review of the reforms and the rates and timing of changes herein, the reader is referred to an earlier version of this paper.[4]

The registration tax is paid at the time of purchase and is a linear function of the purchase price with a kink,

$$\tau_t^{\text{reg}}(p^{\text{car,raw}}) = 1.05 \cdot \min(K_t, p^{\text{car,raw}}) + 1.80 \cdot \max(0, p^{\text{car,raw}} - K_t),$$

where K_t is a politically set kink, updated at irregular intervals, and $p^{\text{car,raw}}$ is the raw car price including VAT (25%) but net of deductions.[5] Effectively, the mean Danish car

the purchase price are more effective than ones working through income tax deductions, and Li, Linn, and Muehlegger (2014) find that driving responds more strongly to fuel taxes than to changes in the fuel product price.

[3]Many recent dynamic models build on the optimal replacement model by Rust (1987). These models are much better suited to looking at issues like vehicle scrappage (Adda and Cooper, 2000; Schiraldi, 2011), and the used car market (Chen, Esteban, and Shum, 2010; Gavazza, Lizzeri, and Rokestkiy, 2012; Stolyarov, 2002; Gillingham et al., 2013). Such issues are beyond the scope of this paper.

[4]A copy can be emailed upon request.

[5]Deductions are given for example for installed safety equipment which are not observed in the data and therefore ignored in this paper.

gets an additional 160% tax in addition to VAT, yielding an effective tax rate of 200%. The ownership tax is paid twice a year and depends on the fuel efficiency of the car. The rate is higher for diesel cars of a given fuel efficiency than comparable gasoline cars. The fuel taxes consist of the 25% proportional VAT plus a selection of fixed taxes that are updated more or less frequently. The product prices of gasoline and diesel are almost identical but gasoline is taxed much higher, making diesel cheaper throughout the sample period.

There were two major reforms of interest; A change in the bi-annual tax in 1997 and a change in the registration tax in 2007. All cars first registered before July 1st 1997 have their bi-annual tax rate set according to the weight (and still follow that scheme) while those first registered after that date follow the fuel efficiency. The 2007 reform was a so-called *feebate*, working through the registration tax and giving a rebate to green cars and added a fee to dirty cars. The rebate was DKK 4,000 per unit of km/l over the pivot (16 km/l for gasoline cars and 18 km/l for diesel cars) and the fee was DKK 1,000.

2.2 Data

The analyzed sample contains all new cars purchased between July 1st 1997 and December 31st 2006 and is based on matched Danish administrative data. The car ownership information comes from The Central Motor Register, which holds license plate ownership information. Driving information comes from the mandatory safety inspection which all cars must attend four years after purchase. At this test, it is evaluated whether the car is in safe condition and the odometer is measured and recorded. Demographic informations on the car owners and their household is obtained by matching the personal identifier (CPR number) with the Danish registers. The most important variable is the computed work distance measure (described in appendix B.3). Car characteristics are extracted by using the Vehicle Type Approval number which is the identifier assigned by the Ministry of Transportation when the car is approved for import and sale in Denmark. New car prices and depreciation rates are available from a dataset maintained by the Danish Automobile Dealer Association (DAF). The depreciation rates are used by used car dealers in Denmark when they make an offer on a used car of a given age in normal condition. Fuel prices are available at the daily level from the Danish Oil Industry Association (EOF; www.eof.dk). These prices are recommended retail prices so local variations and price wars do not show up in the data. All tax rates are taken directly from the law texts using www.retsinformation.dk.

This paper abstracts from the used car market due to missing data. While car ownership is observed for used cars, prices and characteristics are only available beginning in

1997.

In order to evaluate the welfare consequences of the counterfactual policies, one needs a measure of the marginal external costs of driving. These are taken from DTU Transport (2010) and I recalculate from a per kilometer to per liter externality in terms of air pollution from CO_2 and other particle emissions. Since driving an extra km in a car yields the same externality in terms of accidents, congestion, etc. I will abstract from those.[6] The details are in appendix B.2.

2.3 Summary Statistics

After cleaning the data, there are $N = 128,910$ new car purchases by Danish couples in 1997–2006.[7] The sample selection is described in appendix B.1. Cars differ at the finest level of aggregation (the type approval number), yielding a total of $J = 1,177$ different cars to choose from.[8] Working with a discrete choice model of such high dimensionality is essential because for a given car type of the typical type definition (make, model and variant), there may be a diesel and a gasoline version. Therefore, further aggregation would remove the very choice of interest. Furthermore, reducing to a simple binary choice of diesel gave results in the out-of-sample simulation of the 2007 reform that were far too unresponsive. However, the choice set faced by each household will be smaller than 1,177 because no car type was available in all years as new models enter and exit the car sellers' portfolios.

The most notable change in the period 1997–2006 is the large increase in the diesel share of newly purchased cars, as shown in figure 2.1. The share went from a long-term stable level around 5% to almost 30% in 2003–2006 and further up to around 40% in 2008 (figure 2.2). A central goal of this paper is to understand which factors drove that development.

More detailed descriptives are presented in appendix B.3 but to paraphrase, the only household demographic that appears to predict diesel purchase is the home-work distances of each of the spouses. This variable is also an important predictor of the household's vehicle kilometers travelled (VKT) and elasticity of driving with respect to the price per kilometer (PPK). The variable is rarely available in empirical studies and often considered to be the main component of household fixed effects in driving equations.

[6] A policy maker might also be interested in the fact pushing consumers towards diesel cars results in cheaper driving and therefore also more driving which therefore increases congestion, accidents and so forth.

[7] The current dataset only contains information on couples but in the future it will hopefully become possible to obtain data for the singles as well.

[8] I deselect any car having fewer than 30 units sold.

Figure 2.1: Diesel Share in Denmark by Vintage

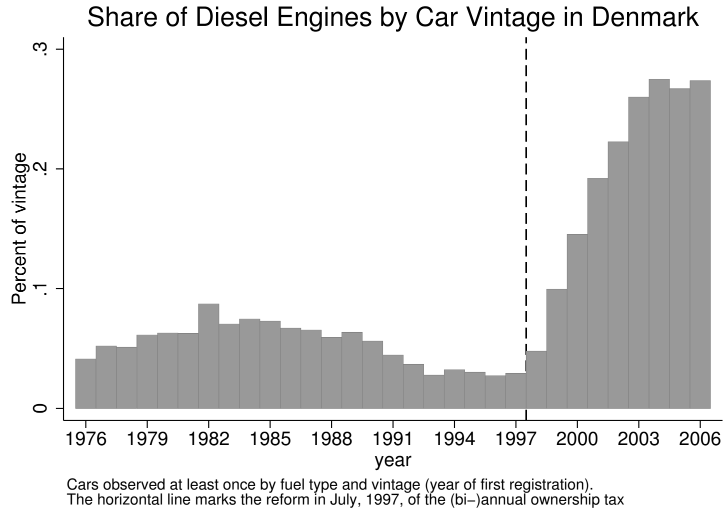
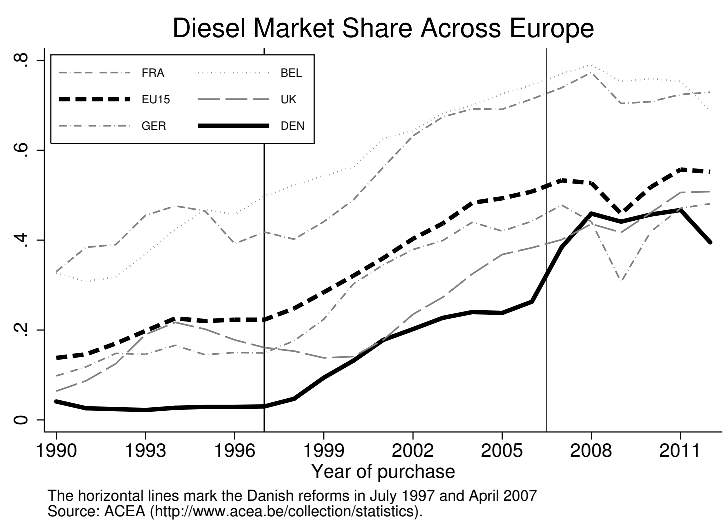


Figure 2.2: Diesel Cars — Fraction of Total New Car Sales in Europe



3 Model

The model studied in this paper is closest to the one proposed by Gillingham (2011). This model in turn builds on the discrete-continuous selection model literature going back to Dubin and McFadden (1984). This type of framework has seen many applications to modeling car choice and usage recently. Here, the discrete choice is the car type (the extensive margin) and the continuous choice is the mileage (the intensive margin which conditions on the type choice). At the core it is a selection model, specifically addressing that households select into particular car types based on their driving needs.

The model is a two-period model where in the first period, t_{1i}, the household i purchases a car of type j from the set of available cars $\mathcal{J}_{t_{1i}}$ at the price $p^{\text{car}}_{jt_{1i}}$ under uncertainty about the conditions under which household i will drive the car during the second period, t_{2i}. For all consumers, there are four years from purchase to the test inspection, so $t_{2i} - t_{1i} = 4$.[9] Note that fuel prices vary across consumers because prices are matched to the driving period at the daily level and vary across car types because there is a separate price time series for diesel and gasoline. At the end of the second period, the car is sold at the value $\delta_j^4 p^{\text{car}}_{jt_{1i}}$, where δ_j is a car-specific annual depreciation rate obtained from the data. There is no outside option to not own a car and there are no used cars in the choice set.[10] In that sense, the model conditions on entry into the new car market but remains agnostic about why and when this entry occurs.[11]

The utility function takes the form

$$u_{ij} = u_{ij1} + \beta^4 \mathbb{E}(u_{ij2}),$$

where β is the discount factor (fixed at 0.95) and there are 4 years between purchase and

[9] In reality, the test falls within a 2-month window of the 4-year date but I abstract from that by looking at average daily driving and then multiplying by $365 \cdot 4$ to get at the corresponding driving over a four-year period.

[10] There are two reasons for not having an oustide option; Firstly, it would mean bringing in an observation for every single household not owning a car in all years at great computational cost. Secondly, this particular structural model is not suited to capturing the decision to become a car owner which would require great care since the model would have to fit the very large fluctuations in new car purchases over the business cycle. As argued by Train and Winston (2007), one should not claim to be modelling the outside option unless one has a clear identification strategy for this.

Similarly, there are two reasons for not modeling the used-car market; Firstly, the choice set would be doubled many times over, making estimation of the model computationally infeasible. Secondly, many of the key car characteristics for this study, including the fuel efficiency, are not available for cars registered before 1997 so all used cars would be dropped in the earlier years, creating a highly skewed sample selection over time.

[11] One could imagine a fully dynamic optimal stopping problem where the consumer in each period considers replacing his current car, e.g. Schiraldi (2011). However, then it would be computationally impossible to have a choice set of $J = 1,177$ cars.

driving period. Both of the period-utilities are quasi-linear in the consumption of the composite outside good. First-period utility takes the form

$$u_{ij1} = \gamma_i \left(y_{it_{1i}} - p^{\text{car}}_{jt_{1i}} - 4\tau_j \right) + u^{\text{own}}(j),$$

where $u^{\text{own}}(j)$ is utility from owning a car but not related to the driving, τ_j is the annual tax and y_{it} denotes household income in period t. The parameter γ_i scales the utility of money relative to that of driving and it varies across households according to $\gamma_i \equiv \gamma_z' z_i$, where z_i is a vector of household demographics. For the primary results, I let $u^{\text{own}}(j) = \alpha_0' q_j$, where q_j is a vector of observable characteristics for the car such as weight, engine power but not including fuel efficiency, e_j, which is restricted to enter the model through the cost structure.[12] This term shifts mean utilities of buying a given car in a way that is unrelated to the driving utility so as to better fit market shares. I also estimate a version of the model with car fixed effects, $u^{\text{own}}(j) = \xi_j$, to address concerns about unobserved quality characteristics correlated with observables.[13]

The second-period utility is given by

$$u_{ij2} = \gamma_i \left(y_{it_{2i}} + \delta_j^4 p^{\text{car}}_{jt_i} - \frac{p^{\text{fuel}}_{jt_{2i}}}{e_j} x \right) + \alpha_{1ij} x + \alpha_2 x^2,$$

where x is the vehicle kilometers travelled (VKT) — the decision variable in the second period — and α_{1ij} is a parameter that affects the utility of driving an extra kilometer and varies across households and cars, defined as

$$\alpha_{1ij} \equiv \alpha_{10} + \alpha_{1z}' z_i + \alpha_{1q}' q_j + c_i.$$

The variable c_i captures heterogeneity in the utility of driving that is unobserved by the econometrician but observed by the household. The assumption that utility from driving is quadratic yields a computationally attractive form for optimal driving as we shall see. Unfortunately, it implies theoretically a bliss point in driving but in practice, all households were far below this point. The coefficient α_2 has also been allowed to vary over i and j but the additional parameterization did not improve model fit so I chose the more parsimonious specification.

[12] In future work, it would also be interesting to include information on parents' automobile choice where available in the registers as persistence in brand preference within a family has been documented in the literature(Anderson et al., 2013).

[13] The literature following Berry, Levinsohn, and Pakes (1995) has emphasized possible price endogeneity given that firms set prices taking ξ_j into account. I have formulated a GMM-based IV approach to assess the importance of this and I am working on estimating that model.

3.1 Optimal Driving

In period t_{2i} when the household makes its VKT choice, x, it conditions on the purchased car. Thus, optimal driving maximizes u_{ij2} conditional on j. Interior solutions must therefore satisfy the first-order condition;[14]

$$x = -\frac{1}{2\alpha_2}\left(\alpha_{1ij} - \gamma_i \frac{p^{\text{fuel}}_{jt_{2i}}}{e_j}\right) \equiv x^*_{ij}(p^{\text{fuel}}_{jt_{2i}}). \tag{3.1}$$

Thus, optimal driving is characterized by a simple linear equation which for appropriate coefficients can be written as

$$x_i = \zeta_0 + \zeta'_{1z} z_i + \zeta'_{1q} q_j + \zeta_{2p}\text{PPK}_i + \zeta'_{2p,z} z \cdot \text{PPK}_i + c_i, \tag{3.2}$$

where $\text{PPK}_i \equiv p^{\text{fuel}}_{d_i t_{2i}}/e_{d_i}$ is the price per kilometer for household i's chosen car, d_i. From (3.2) one can obtain more intuitive interpretations of the primitives of the model; Coefficients entering into α_{1ij} shift the mean driving while those in γ_i shift the price-sensitivity of VKT. In particular, the unobserved effect, c_i, shifts the mean driving. Gillingham (2011) only allows demographics and car characteristics to enter through γ_i which may lead to somewhat drastic responses in driving to counterfactual changes in the price of driving.

3.2 Full Conditional Utility

Inserting the optimal driving rule from (3.1) back into the full utility function, an expression emerges which can be computed based on data. Due to the quasi-linearity, the income term, $\gamma_i(y_{it_{1i}} + \beta^4 y_{it_{2i}})$, does not vary over j so we simply drop it from the specification.[15]

$$\begin{aligned} u_{ij} \quad = \quad & -\gamma_i 4\tau_j + \gamma_i\left[1-(\beta\delta_j)^4\right] p^{\text{car}}_{jt_{1i}} + u^{\text{own}}(j) \\ & + \beta^4 \mathbb{E}\left\{-\gamma_i \frac{p^{\text{fuel}}_{jt_{2i}}}{e_j} x^*_{ij}(p^{\text{fuel}}_{jt_{2i}}) + \alpha_{1ij} x^*_{ij}(p^{\text{fuel}}_{jt_{2i}}) + \alpha_2\left[x^*_{ij}(p^{\text{fuel}}_{jt_{2i}})\right]^2\right\}. \end{aligned} \tag{3.3}$$

All that remains is to specify the expectations about fuel prices at time t_{2i} conditional on fuel prices at time t_{1i}. In the literature, many implementations have used static expectations, whereby the expectation in (3.3) collapses to a single number. Gillingham (2011) uses a unit root and also allows consumers to use prices of futures on fuel in their forecast,

[14] As soon as reasonable starting parameter values were found, the model only predicts strictly positive VKT for all households.

[15] Note that income will be included in z_i, thus allowing it to shift the utility of driving and price sensitivity of driving. The intuition is that income proxies for the households' possibility of various leisure activities.

finding that it makes little difference to his results. I have implemented both static expectations, perfect foresight and a unit root with a drift and found that the conclusions were not seriously affected by the specification of expectations.[16] Note that the model is re-estimated when the specification for expectations is changed. The intuition for the fairly small sensitivity to the type of expectations is that the variation in fuel efficiency in the choice set is much larger than the variation in fuel prices. For the preferred specification, I have used perfect foresight since these estimates are more conservative in the sense of implying less price responsiveness.

4 Empirical Strategy

4.1 Econometric Methodology

The econometric methodology follows Gillingham (2011). An error term is added to both choice margins; An IID Gaussian measurement error to the optimal driving equation and an IID Extreme Value term to the conditional utility, u_{ij}.

The observed VKT for household i, x_i, is therefore written as

$$x_i = x^*_{id_i}(p^{\text{fuel}}_{d_i t_{2i}}) + \eta_i, \quad \eta_i \sim \mathcal{N}(0, \sigma_x^2),$$

where d_i is the car that the household purchased and $p^{\text{fuel}}_{d_i t_{2i}}$ is the average daily fuel price in 2005 DKK (gasoline or diesel depending on d_i) over the driving period $[t_{1i}; t_{2i}]$. This means that the partial likelihood contribution for the observed driving is given by

$$\ell_i^{\text{VKT}}(\theta) = -\log \sigma_x - \frac{\left[x_i - x^*_{id_i}(p^{\text{fuel}}_{d_i t_{2i}})\right]^2}{2\sigma_x^2}.$$

For the type choice, the full utility for household i from choosing car $j \in \mathcal{J}_{t_{1i}}$ becomes

$$\tilde{u}_{ij} = u_{ij} + \varepsilon_{ij}, \quad \varepsilon_{ij} \equiv \frac{1}{\lambda}\tilde{\varepsilon}_{ij} \quad \tilde{\varepsilon}_{ij} \sim \text{IID Extreme Value}.$$

In the literature, the parameter $\lambda > 0$ is sometimes estimated and sometimes treated as tuning parameter akin to setting the bandwidth in a Nadaraya-Watson estimator, balanc-

[16] More specifically, the annual drift of the unit root was set to 0.1. Estimating the drift based on fuel time series is infeasible as it depends entirely on what subset of 1972–2013 one uses to estimate it. The choice of 0.1 corresponds to the average annual growth in the full period although the realized growth in 1997–2006 was closer to 0.25.

ing bias and variance. In this application it was set to 10,000.[17] The probability that car j maximizes household i's utility is therefore given by

$$\Pr_i(j|\theta) = \frac{\exp(u_{ij}/\lambda)}{\sum_{j' \in \mathcal{J}_{t_{1i}}} \exp(u_{ij'}/\lambda)},$$

where $\mathcal{J}_{t_{1i}}$ is the set of cars available in year t_{1i}. Note that there is no outside choice with utility normalized to zero.

In the preferred specification, $c_i = 0$ for all i, the full likelihood contribution for household i becomes

$$\ell_i^{\text{full}}(\theta) = \ell_i^{\text{VKT}}(\theta) + \log \Pr_i(d_i|\theta).$$

In the general case, I will assume that $c_i \sim \mathcal{N}(0, \sigma_c^2)$ and the likelihood gets the typical integrated loglikelihood form,

$$\ell_i^{\text{sim}}(\theta) = \log \int f_x(x_i|\theta, \sigma_c c) \Pr_i(d_i|\theta, \sigma_c c)\, \mathrm{d}\Phi(c),$$

where $f_x(x|\theta, \sigma_c c) = \exp\left[\ell_i^{\text{VKT}}(\theta, \sigma_c c)\right]$, and Φ is the Gaussian cdf. The conditioning on the individual effect $c = \sigma_c c_i$ is made explicit in the equation to underline that it enters into α_{1ij} and thus in both optimal driving and conditional utilities. The integral will be computed using Gauss-Hermite quadrature.[18]

4.2 Car Type Fixed Effects

To address the potential concern that car prices might be endogenous to unobserved car characteristics, I also formulate a version of the model with car type fixed effects, $u^{\text{own}}(j) = \xi_j$. This model may be estimated in two ways; A direct approach would be to simply estimate all the $J - 1 = 1,176$ dummies with maximum likelihood. Estimating such a large number of parameters would not be feasible using numerical derivatives, but with analytic derivatives and the BHHH approximation of the Hessian, complexity only

[17] Extensive experimentation showed that this gave the most sensible results. A higher value of λ would tend to generate a much more precise fit to the observed data but a highly inelastic demand curve. A lower value produced too poor of a fit to the observed shares. The parameter has also been estimated , which yielded an estimate of $\hat{\lambda} \cong 100,000$ but this was found to produce unrealistic elasticities, i.e. overfitting the sample, so the lower value of 10,000 was chosen.

[18] For the results presented here, only 8 nodes were used. Future work is under way using more nodes. Comparing quadrature with simulation using simple, smooth functions and univariate integrals, it was found that quadrature attains the same level of precision as simulation using five to ten times more evaluations of the integrand. This point was also highlighted by Dubé, Fox, and Su (2012) and Judd and Skrainka (2011).

increases linearly in the number of parameters.

An alternative approach is to apply a fixed point like that proposed by Berry (1994). Let $\Gamma : \mathbb{R}^{J-1} \to \mathbb{R}^{J-1}$ be the operator defined by $\Gamma(\xi^{[i]}) = (\Gamma_1(\xi^{[i]}), ..., \Gamma_{J-1}(\xi^{[i]}))$, where

$$\Gamma_j(\xi^{[i]}) = \xi_j^{[i]} + \sum_{t \in \mathcal{T}_j} \varpi_{jt} \left[\log s_{jt}^{\text{data}} - \log s_{jt}^{\text{pred}}(\xi^{[i-1]}) \right],$$

where s_{jt} is the market share for car j in year t, $\mathcal{T}_j$ is the set of years where car j was available and

$$\varpi_{jt} = \frac{N_t}{\sum_{t \in \mathcal{T}_j} N_t},$$

where N_t is the number of households going on the market in year t. Letting $\tilde{u}_{ij} \equiv u_{ij} - u^{\text{own}}(j)$, the predicted market share is given by

$$s_{jt}^{\text{pred}}(\xi^{[i-1]}) = \frac{1}{N_t} \sum_{i=1}^{N_t} \frac{\exp\left[(\tilde{u}_{ij} + \xi_j^{[i-1]})/\lambda \right]}{\sum_{k \in \mathcal{J}_t} \exp\left[(\tilde{u}_{ik} + \xi_k^{[i-1]})/\lambda \right]}.$$

This gives rise to the following algorithm;

Algorithm: A Berry (1994) fixed point.

> **Initialization:** Set $\xi_j^{[0]} := \sum_{t \in \mathcal{T}_j} \varpi_{jt} \log s_{jt}^{\text{data}}$ and pick a reference car, j_0, for which $\xi_{j_0} := 0$.
>
> **Iteration:** Given $\xi^{[i-1]}$, let $\xi^{[i]} = \Gamma(\xi^{[i-1]})$. Continue until $\|\xi^{[i]} - \xi^{[i-1]}\| < \epsilon$.

Recently, Dubé, Fox, and Su (2012) have emphasized the importance of using a tight tolerance of ϵ to numerical problems leading to biased estimates. They find that a tolerance of $\epsilon = 10^{-16}$ is suitable but that this is extremely time consuming compared using a fixed point like the one outlined above and they suggest using the MPEC approach (Judd and Su, 2012). Instead, I propose using a root-finding algorithm but implementing the analytic Jacobian of the operator Γ, which has a computationally simple form. With this algorithm, convergence occurs in 13 iterations.

4.3 Simulating From the Model

As with most structural models, it is essential to be able to simulate counterfactual behavior from the model. Essentially, we want to compute simple statistics characterizing the final market outcome of making changes to taxes, prices or the characteristics of cars.

These outcomes might be the CO_2 emitted, tax revenue, the average fuel efficiency, etc. Formally, suppose we are interested in some outcome ω_{ij}. Then define the average expected outcome as

$$\tilde{\mathbb{E}}(\omega|\theta) \equiv \frac{1}{N}\sum_{i=1}^{N}\sum_{j\in\mathcal{J}_i} \mathrm{Pr}_i(j|\theta)\omega_{ij}. \tag{4.1}$$

This is the average (over households) weighted average (over available choices weighted with conditional choice probabilities) outcome.

Note that in the computation of (4.1), I need to take a stand on the stochastic variables in the model; η_i, ε_{ij} and c_i. The measurement error is set to zero, $\eta_i := 0$. Since I am weighting by conditional choice probabilities, the expression is implicitly an expectation over ε_{ij}. Lastly, c_i is set to zero for all households.[19] Standard errors have not been computed for the expected outcomes.

Two examples of outcomes of particular interest require an extra comment. Firstly, the CO_2 emissions; These are calculated using the kg of CO_2 that is emitted by the combustion of a liter of each fuel,[20] yielding the following CO_2 emissions (in kg) conditional on choosing car j and realized fuel price $p^{\text{fuel}}_{jt_{2i}}$,

$$\mathrm{CO}_{2,ij} \equiv \left(\mathbf{1}_{\{j \text{ is gas}\}} 2.392^{\text{kg/l}} + \mathbf{1}_{\{j \text{ is diesel}\}} 2.64^{\text{kg/l}}\right) \frac{x^*_{ij}(p^{\text{fuel}}_{jt_{2i}})}{e_j}.$$

Setting $\omega_{ij} := \mathrm{CO}_{2,ij}$ in (4.1) gives the average expected CO_2 emissions.

Secondly, the tax revenue can be calculated conditional on car purchase and subsequent usage. The conditional total tax revenue, τ^{total}_{ij}, is given by

$$\tau^{\text{total}}_{ij} \equiv \tau^{\text{fuel}}_j \frac{p^{\text{fuel}}_{jt_{2i}}}{e_j} x^*_{ij}(p^{\text{fuel}}_{jt_{2i}}) + \tau^{\text{reg}}(p^{\text{car}}_{tj}) + 4\tau^{\text{annual}},$$

where $\tau^{\text{reg}}(\cdot)$ gives the registration tax and τ^{fuel}_j is the fuel taxes in pct. of the total fuel price. Setting $\omega_{ij} := \tau^{\text{total}}$ in (4.1) gives the average expected tax revenue for the government.

Lastly, following Small and Rosen (1981) and Gillingham (2011), the model yields the

[19]Work is under way to instead integrate c_i out, thus instead using

$$\tilde{\mathbb{E}}(\omega|\theta) \equiv \frac{1}{N}\sum_{i=1}^{N}\int \sum_{j\in\mathcal{J}_i} \mathrm{Pr}_i(j|\theta,\sigma_c c)\omega_{ij}(\sigma_c c)\, \mathrm{d}\Phi(c).$$

[20]These numbers come from www.ecoscore.be (and are confirmed by www.environment.gov and www.epa.gov).

usual “logsum” welfare measure defined as

$$\text{CS} \equiv \frac{1}{N}\sum_{i=1}^{N}\log\left[\sum_{j\in\mathcal{J}_i}\exp(u_{ij})\right], \tag{4.2}$$

which can be used to evaluate the welfare impacts on consumers from changing parameters of the choice set such as car characteristics or tax rates. It should be noted though that since there is no outside option, this welfare measure does not take into account that households may choose not to own a car.

5 Results

Table C.1 shows the structural estimates from the preferred specification allowing random effects ($c_i \neq 0$) and with perfect foresight expectations. The signs of the coefficients are all as expected; The parameters shifting the mean driving (through α_{1ij}) and the price-sensitivity of driving (through γ_i) have the same sign as what comes out of reduced-form regressions of VKT on PPK and PPK interacted with demographics.[21]

However, the structural coefficients are not easily interpreted directly so I instead turn to considering a range of elasticities. Table 5.1 shows the elasticities of VKT with respect to the fuel efficiency, the weight of the car, and the fuel price. This is the intensive-margin elasticity which conditions on the actual vehicle choice by the household, disallowing substitutions to other vehicles. Note that the fuel price elasticity and the fuel efficiency elasticity (what Small and Van Dender, 2007, refer to as the *rebound effect*) are identical by assumption.[22] The rebound estimate of –72.5% is fairly close to the estimate of approximately –80% that Frondel, Peters, and Vance (2008); Frondel, Ritter, and Vance (2012) find using German data. However, the elasticities based on the full simulated likelihood that account for endogenous selection into car types is –28.2%, which indicates a strong selection bias in in upwards direction. Gillingham (2011) finds a bias in the same direction but smaller in magnitude with a rebound effect of –21% dropping to –15% when selection is accounted for. Bento et al. (2009) find a mean elasticity of –35% which also controls for selection. Finally, note that the weight elasticity of 85.8% shown in table 5.1 (with weight proxying for comfort or carrying capacity for children or goods) is very high.

Table 5.2 shows elasticities of a range of expected outcomes, computed based on (4.1). Column (1) shows the relative change in each expected outcome when the fuel efficiency

[21] For example, work distances (WDm and WDf) are positive in both terms; Higher WD increases mean driving and it also decreases the fuel price elasticity (bringing it up towards zero).

[22] For example, Gillingham (2011) allows e_j to shift the mean u_{ij} by putting it in the term $\alpha_0' q_j$ in (3.3).

Table 5.1: Elasticities of VKT From the Structural Model — Partial Estimates and Preferred Specification

	Partial Likelihood (using ℓ^{VKT})		
	Fuel efficiency	Weight	Fuel Prices
Mean	0.718	1.323	–0.725
Std.	0.426	0.339	0.431
	Preferred Specification (using ℓ^{sim})		
	Fuel efficiency	Weight	Fuel Prices
Mean	0.279	0.858	–0.282
Std.	0.085	0.171	0.086

of each car in the choice set is increased by 1%. Fuel efficiency has an elasticity of 0.90 so that the average expected fuel efficiency is not a full 1% higher, implying that households would substitute some of the technological gain away for higher weight, better engine and smaller probability of buying a diesel. Even more interesting, the CO_2 elasticity is –57%, so that a 1% improvement in fuel efficiency does not give a full 1% improvement in CO_2 emissions. This is partly due to consumers switching away from efficient cars and partly due to consumers driving longer since the cost of driving an extra km is now lower. This result has huge implications for climate policy since it means that in order to reduce CO_2 emissions by 1%, the required improvement in fuel efficiency is approximately $\frac{1\%}{0.57\%} = 1.75\%$.

Column (2) shows the effects of increasing the weight of all cars by 1%. This increases VKT by 1.01% and CO_2 by 1.06%. This is quite interesting since a key feature of the data is that cars have been steadily increasing in weight since 1985. This indicates that even though VKT has fallen over the sample period, it would have fallen much more drastically if cars had not been getting heavier, i.e. more comfortable and useable.

Column (3) shows the effects of increasing the real fuel price at the pump by 1%.[23] The most notable result here is that tax revenue *falls*, indicating that the Danish taxes are at the wrong side of the Laffer curve's top; While revenue from fuel taxes increase, revenue from the registration tax and the ownership tax fall by much more because households buy different types of cars. The fall in CO_2 emissions of 0.41% is highly policy relevant for the scope of fuel taxes in climate policy.

[23] Note that to obtain this using taxes, one would have to take into account supplier responses. For the US, Marion and Muehlegger (2011) find a pass-through to consumers of almost 100% but given the substantially higher taxes in Denmark, that conclusion might not be valid here. Nonetheless, I abstract from the question of passthrough.

Table 5.2: Structural Elasticities — Quasi, Perfect Foresight, Random effect

	Levels	Elasticities			
	(1) Baseline	(2) Fuel efficiency	(3) Weight	(4) Fuel prices	(5) O95 prices
Consumer welfare					
CS	114970.09	0.25	1.29	-0.25	-0.20
Total taxes					
E(total taxes)	146623.83	0.08	0.40	-0.08	-0.06
Ownership tax					
E(Regtax revenue)	106556.44	0.23	0.27	-0.23	-0.14
E(Owntax revenue)	11093.62	0.29	0.31	-0.28	-0.16
Fuel tax					
E(O95 revenue)	25115.85	-0.49	0.63	0.50	-0.02
E(Diesel revenue)	3857.92	-0.89	2.98	0.88	2.33
Driving/fuel use					
E(VKT)	79663.89	0.30	1.01	-0.30	-0.19
E(litre O95)	4340.92	-0.49	0.63	-0.50	-1.01
E(litre D)	891.32	-0.89	2.98	-0.12	2.33
E(litre D | urban)	188.02	-0.86	3.04	-0.14	2.24
E(kg CO2)	12736.56	-0.57	1.06	-0.43	-0.39
Characteristics					
E(fe)	15.92	0.90	-0.00	0.10	0.20
E(we)	1.70	0.09	1.15	-0.09	-0.04
E(kw)	77.08	0.24	0.13	-0.23	-0.25
E(displace)	1.65	0.18	0.12	-0.18	-0.16
E(% diesel)	18.49	-0.16	1.86	0.15	2.33
E(% diesel | urban)	3.89	-0.14	1.88	0.13	2.24

The model is quasi-linear with perfect foresight and
and random effects (σ_α is estimated).
The baseline column is expected outcomes, all other are elasticities.
(1): baseline 2006 scenario, (2) fuel efficiency up by 1%, (3): weight up by 1%,
(4): all fuel prices up by 1%, (5): only O95 up by 1%.
Counterfactuals are run on 2006 data.

Finally, column (4) increases gasoline prices by 1% but keeps diesel prices constant. The result is a 2.33% change in the probability of purchasing a diesel car (and thus of the diesel market share). This gives a first indication that the diesel market share is highly sensitive to cost differences.

Based on the elasticities of CO_2, tax revenues and welfare with respect to fuel prices, it is possible to compute the marginal cost of CO_2 reductions from a fuel tax. Back of the envelope calculations indicate, that a reduction of 1 ton of CO_2 would cost society 7061.22 DKK.[24] This number will be useful for comparison later.

To examine robustness, the model has also been estimated assuming static expectations and a unit root as described in section 3.2. These different specifications gave quite similar results in terms of elasticities and implications for the counterfactual simulations so the perfect foresight assumption was chosen. The results with static expectations are shown in appendix C.1; The structural elasticities and main conclusions are unchanged but the price sensitivity is generally higher.

An alternative model has also been formulated in which the utility from outside consumption is logarithmic instead of linear. This complicates solving for optimal VKT substantially but in the end, it produced unrealistically low elasticities so it was discarded. Work is underway in estimating on subsamples and adding fixed effects for vehicle class and make to address the potential endogeneity of prices to unobserved characteristics, as advocated in the literature based on Berry, Levinsohn, and Pakes (1995).[25]

6 Counterfactual Simulations

In this section, a number of counterfactual simulations are presented. Three important restrictions of this analysis should be stressed; Everywhere, supply side responses to the proposed reforms are ignored, i.e. assuming a 100% passthrough. In reality, profit maximizing car sellers in oligopolistic competition will likely change the relative prices of cars

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[24]The required change in fuel prices to reduce CO_2 by 1 ton is approximately $\Delta p = \left(\mathcal{E}_{CO_2,p}\frac{CO_2}{p}\right)^{-1} = \left(0.43\frac{12.7\,\text{ton}}{8.5\,\text{DKK/l}}\right)^{-1} \cong 1.48\text{DKK/l}$. This implies an approximate change in consumer surplus and taxes of

$$\begin{aligned}\Delta\text{CS} &= \text{CS} \times \mathcal{E}_{\text{CS},p} \times \frac{\Delta p}{p} = 114,970.09 \times -0.25 \times \frac{1.48}{8.5} \cong -5014,71\,\text{DKK} \\ \Delta\text{Taxes} &= 146,623.83 \times -0.08 \times \frac{1.48}{8.5} = -2046.52\,\text{DKK}.\end{aligned}$$

[25]Given that micro data is available, I could potentially try to estimate a full set of 1,177 choice fixed effects. And if estimation proves computationally infeasible, a strategy like the one proposed in Ackerberg et al. (2007, section 1.4.2.2)

in their portfolio in response to tax changes to counteract the effects of the taxes. This implies that some of the results presented here may be biased towards stronger behavioral responses. In defense of this assumption, Adamou, Clerides, and Zachariadis (2013) find little difference between their simulation results when they use their estimated supply side pricing function or simply assuming 100% passthrough in a European context. Similarly, Gallagher and Muehlegger (2011) find that passthrough of fuel taxes in the US on to consumers is approximately 100%. Moreover, given that Denmark is a small market relative to the rest of Europe, it is unlikely that manufacturers are producing cars catering only to the Danish market as opposed to just importing models. Finally, while car prices may be endogenous to unobserved attributes, they are unlikely to be severely endogenous to the Danish political environment since anyone can import cars from foreign countries and pay the registration fee.[26]

Secondly, the restriction that consumers can only buy new cars takes away alternative substitution possibilities. Ignoring the existence of other substitutes will tend to bias the consumer welfare losses computed from (4.2) in an upwards direction. Thirdly, one would have to consider in each case, the effect on the outside option of not owning any car or on owning more than one.[27]

6.1 The 2007 Reform — Model Validation

As described in 2.1, the 2007 reform was a feebate, essentially giving a rebate to green cars and putting a fee on dirty cars. The "pivot point" of the reform, differentiating green cars from dirty ones, was set to 16 km/l for gasoline cars and 18 km/l for diesel cars. Recall that 2007 is not in the estimation sample because driving information is only available for a small number of cars purchased in this year.

Table 6.1 shows the implications of implementing the 2007 feebate in 2006. Most importantly, the diesel market share goes up from 18.5% to 24.5%, an increase of 32.3%. The true response to the 2007 reform was an increase in the diesel share of 46.0%. I view this as a quite good out-of-sample fit, in particular when one considers that the reform may have caused changes on the extensive margin of car ownership, inducing some households to advance car purchases so that the selection into the new car market changes. An alternative interpretation is that of the 46.0% increase in the diesel share following the 2007 reform, 32.3% can be attributed directly to the reform.

[26] Technically, the car must have a *Type Approval Number* which is issued by the Danish Transport Authority when the vehicle is tested for safety and the official fuel efficiency in km/l is registered.

[27] Indeed, more Danish households have two cars later in the sample. However, the simultaneous modeling of the driving of two cars means that the choice set of households becomes $|\mathcal{J}_i|^2$ and computational

Table 6.1: Counterfactual Simulations — The 1997 and 2007 Reforms

	(1) Baseline	(2) 1997	(3) 2007	(4) Internalization
Consumer welfare				
CS	114,970.09	99,607.67	115,989.89	115,569.79
Total taxes				
E(total taxes)	146,623.83	176,422.24	134,398.55	146,854.69
Ownership tax				
E(Regtax revenue)	106,556.44	117,238.77	98,175.80	107,363.31
E(Owntax revenue)	11,093.62	26,613.14	9,813.59	9,131.02
Fuel tax				
E(O95 revenue)	25,115.85	31,519.34	21,695.96	23,698.46
E(Diesel revenue)	3,857.92	1,050.99	47,13.20	6,661.89
Driving/fuel use				
E(VKT)	79,663.89	78,391.96	78,740.62	79,518.56
E(litre O95)	4,340.92	5,447.67	3,749.84	4,095.94
E(litre D)	891.32	242.82	1,088.92	1069.70
E(litre D | urban)	188.02	50.40	230.59	230.87
E(kg CO2)	12,736.56	13,671.87	11,844.36	12,621.51
Characteristics				
E(fe)	15.92	14.69	17.04	16.12
E(we)	1.70	1.73	1.64	1.71
E(kw)	77.08	89.93	70.07	76.64
E(displace)	1.65	1.86	1.54	1.65
E(% diesel)	18.49	4.97	24.48	23.28
E(% diesel | urban)	3.89	1.03	5.18	5.03

The counterfactuals are run on data for 2006.
1997: The green ownership tax is replaced with the weight based annual tax.
2007: The 2007 feebate reform is implemented on 2006 data.
Internalization: Annual and registration taxes for diesels are set in the same way as gasoline cars but the diesel price is increased by 1.923 DKK/l.

One important note to make in this regard is that the diesel share in the sample in 2006 is 18.5% whereas in the full population it is 21.8%. As discussed in appendix B.1, this is due to diesel cars being over represented in the car types that are only purchased by very few households and therefore dropped from the sample. However, given that this group is so small in terms of the number of purchases, results are unlikely to be badly affected by this.

Regarding the predicted environmental impact of this reform, the average expected CO_2 emissions fall by 7.0%. Some of this comes through the intended channel of improved fuel efficiency which increases by 7.0%, but recall from table 5.2 that this only translates into approximately $0.57 \cdot 7.0\% = 4.0\%$ reductions in CO_2. In particular, the reform as a by-product reduces weight by 3.5% which gives approximately $1.01 \cdot 3.5\% = 3.5\%$ reductions. In other words, the reform's impact on the weight of the chosen vehicles is almost as important as the intended impact via fuel efficiency.

We also see that the 2007 reform increased consumer surplus by 1,019.8 DKK per household but decreased taxes by 12,225.28 DKK. With CO_2 savings of 892.2 kg and reduced driving externalities of about 923.27 km valued at about 600 DKK, the price of CO_2 that would match the tax revenues lost would be $10,605.48/0.8922 = 11,886.89$ DKK/ton. The Danish Ministry of the Environment's suggested rate was 180 DKK per ton in 2007, so society's value of CO_2 emissions should have been $\frac{11,886.89}{180} \cong 66.03$ times higher to make the reductions worth the lost revenues. This cost is much larger than what Beresteanu and Li (2011) and Huse and Lucinda (2013) find. However, the rebate of 4,000 DKK per km/l is much larger than the fee so given the results in Adamou, Clerides, and Zachariadis (2013) we might not expect the feebate to have been very effective.

Recall that the results in section 5 indicated an approximate marginal cost of 7,061.22 DKK/ton. Thus, the feebate was 68.3% more expensive per ton of CO_2 saved. However, one might expect that a more optimally designed feebate, perhaps symmetric or with a higher fee than the rebate, would be able to come much closer to the cost implied from the fuel tax.

As an addendum, the 2007 reform was implemented using pivots of 16 km/l for gasoline and 20 km/l since the difference between the median fuel efficiency between gasoline and diesel cars is approximately 4.5, not 2. The results of this counterfactual are shown in table C.2; The diesel share only increases marginally by 6.2%. This adds to the general picture that policy has played a very large role in the increase of the diesel share studied in this paper. Most interestingly, this alternative version of the reform yields 91% of the CO_2 reductions of the actual reform with almost identical consumer surplus and tax revenue.

complexity is linear in the size of the choice set.

This provides evidence that the CO_2 reductions achieved by the feebate were not simply due to a shift to diesel cars.

6.2 The 1997 Reform: The Role of Taxation in the Dieselization

The 1997 reform changed the annual tax from being based on the weight of the car to being based on the fuel efficiency (see section 2.1). However, cars first registered before July 1st 1997 still follow a weight-based scheme. In this counterfactual, I compute the annual tax for all cars based on that scheme instead of the actual, fuel efficiency based scheme. The average expected outcomes in 2006 under this counterfactual are shown in column (2) of table 6.1. Figure 6.1 shows this development year-by-year. The results show that while the diesel share would still have increased, the increase would have been substantially lower. In other words, policy played the largest role in the Danish dieselization.

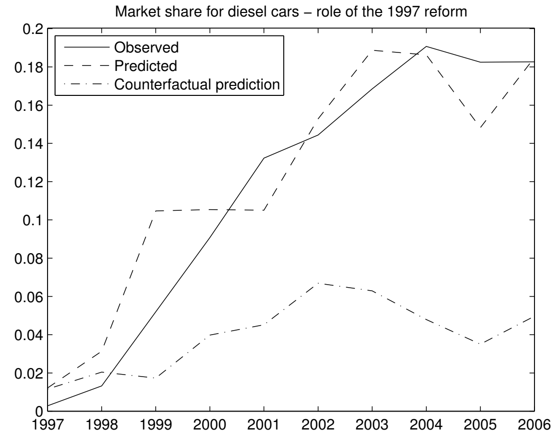
Using similar calculations as for the 2007 reform, it can be computed that the actual valuation of CO_2 should have been about 80 times higher to make the reductions worth the foregone tax revenue, accounting for the change in the change in consumer surplus.

Figure 6.1 shows for each year the diesel share in the sample, the predicted share by the model and the predicted share under the 1997 counterfactual described in section 6.2. While there is still an increasing trend in the diesel share, it is substantially lower than the observed share, ending up at 4.97% compared to the baseline of 18.49% in 2006. The conclusion is that the 1997 played a large role in the increase in the diesel share from 1997 to 2006. There are a few caveats worth mentioning; Firstly, the counterfactual that is implemented might not accurately reflect the policy that would have been chosen if a weight-scheme had been abided to. For instance, policy makers might have set the weight-based ownership tax higher to incentivize the scrapping of older cars. Secondly, there might have been general trends in diesel car technology that are not captured by the observed variables. For example, the fuel injection technology is not observed and the advent of the Common Rail technology in diesel cars played a large role in making diesel cars a viable option for typical households. However, from private conversations with a car salesman, I have learned that by 1999, almost all diesel cars used Common Rail direct injection so this is not a huge concern.

One final comment about figure 6.1 that seems odd is that the model does not predict a rise in the diesel share immediately following the reform.[28] There may be several explanations for this; One is that there were much fewer diesel car types in the choice set early on and the logit smoothing (λ) tends to bias the results towards the share of diesels

[28] I am grateful to Bo Honoré for pointing this out to me.

Figure 6.1: Predicted Dieselization From the Baseline Model vs. the Weight Tax Counterfactual.



in the choice set. This might be particularly important in 97 and 98 where the number of diesels in the choiceset is very small so that the response to counterfactual reforms is coming from the choice probabilities for a very small number of choices which can only change so much given the logit smoothing. This is underpinned by the fact that predicted and counterfactual shares only really start differing greatly in 99 where there are many more diesels in the choice set.

6.3 Diesel Internalization Counterfactual

In this section, a counterfactual simulation is constructed to estimate the socially optimal diesel share accounting for CO2, local air pollution, consumer welfare, and tax revenue. Assuming a 100% passthrough to consumers, the tax system is changed so that diesel cars follow the same tax scheme in the ownership tax as gasoline cars. Then the diesel fuel taxes are changed to first be identical to the tax on gasoline fuel and then an additional tax is added to the diesel fuel, corresponding to the extra marginal external cost of burning a liter of diesel compared to a liter of gasoline. The estimates of marginal external costs are taken from DTU Transport (2010) (see appendix B.2).

In other words, the counterfactual is constructed so that the higher marginal external cost of diesel fuel is internalized via a Pigovian tax but where there is otherwise no discrimination in taxation between the car types. When consumers trade in this market, standard economic theory tells us that the market will arrive at a socially optimal outcome. It should be stressed again that supply side reactions are ignored in this.[29]

[29] There are two reasons for disregarding producers. Firstly, modeling producers would require a significant expansion of the model, presumably in the direction of a nonlinear version of e.g. Berry, Levinsohn,

The results are shown in column (4) of table 6.1. The central conclusion is the predicted diesel share of 23.3%, corresponding to an increase of 25.9% based on the 2006 diesel share. If this increase translates to the full sample, that would correspond to a diesel market share of $21.8\% \cdot 1.259 = 27.4\%$;[30] That is, somewhere between the 2006 and 2007 level. Note that the assumption of complete passthrough matters here since it determines how firms respond with car prices to taxation.

An interesting conclusion that can be drawn from this counterfactual is that the proposed policy appears to represent an unambiguous improvement; Consumer surplus and tax revenue go up, CO_2 emissions go down and VKT also goes down (so externalities from congestion and accidents also decrease). However, these improvements are very small economically.

7 Conclusion

In this paper, I estimate a structural discrete-continuous model of car choice and usage, allowing endogenous selection into car types based on expected future driving. The model is estimated using high quality full population register data for Denmark covering 1997–2006. To validate the estimates, I exploit the Danish car taxation reform of 2007 which prompted clear changes in new car type decisions immediately, unique to Denmark, in particular in the diesel market share. Implementing the 2007 reform counterfactually in 2006, I obtain a predicted increase of 32%, which is reasonably close to the 46% that actually occurred in 2007. I have not been able to find any other papers using out of sample validation except Reynaert (2014). By using the 2006 sample, I avoid the potential issue that much of the developments over time is simply due to changes in the choice set, implying that a naive model assigning uniform probability to all cars would also capture many of the long-term trends.

A consistent finding is that Danish households have responded very strongly to the tax incentives given by the 1997 and the 2007 reform. The implication is that both reforms were highly cost-ineffective ways of obtaining CO_2 reductions by any sensible valuation of emissions, mainly due to foregone tax revenue. A central mechanism behind this is that according to simulations from the model, a 1% technological increase in the fuel efficiency of all cars only translates into a 0.57% reduction in CO_2 emissions; Partially due

and Pakes (1995). But secondly, Denmark has no local producers of cars and so they are not a primary concern to Danish policy makers, and since oil is traded on the international market they would not necessarily be hit too hard by differences in local taxation.

[30]This is to bring up the diesel share from the estimation sample's 18.5% to the full sample's 21.8%. See appendix B.1.

to households substituting away some of the gain in fuel efficiency for other attributes (engine power and car size) but mainly due to increased driving at the cheaper price per km of more fuel efficient cars (an elasticity of 30%). This greatly limits the effectiveness of environmental policies.

Comparing the tax reforms working through the purchase and ownership taxes with a fuel tax, the results indicate the latter to be the more efficient. However, the difference is not as stark as has been found elsewhere in the literature, perhaps due to the generally quite high level of taxes in Denmark.

Another finding is that the reforms were responsible for most of the increase in the diesel share. In particular, there would have been almost no increase in the diesel share if the distinction between gasoline and diesel cars in the 2007 reform had been in accordance with the actual differences between fuel efficiencies. Moreover, approximately the same emissions reductions and welfare implications are obtainable within the gasoline segment alone. This implies that the diesel market share should not be seen as a necessary evil in achieving environmental goals but rather should be a deliberate choice by policy makers.

To guide a notion of what the optimal diesel market share would look like, I construct a counterfactual policy scenario where the de facto subsidy of diesel fuel is removed and replaced with a Pigovian tax based on the differential marginal external costs of diesel and gasoline fuel respectively. In turn, the purchase and ownership taxes are made symmetric so that the simulated outcomes may be interpreted as the socially optimal. I find a socially optimal share of 26%, between the 2006 and 2007 levels. In other words, the cost to society in terms of higher local air pollution is outweighed by the benefits in terms of cheaper transportation and lower CO_2 emissions.

In conclusion, it appears that car taxation in Denmark is a very expensive way of achieving environmental goals.

Appendix

A Notation and Core Equations

This section is meant as a quick reference to give an overview of the model and the notation used in this paper.

The notation is as follows,

$$
\begin{aligned}
j &\; - \; \text{car type (e.g. 2003 Volvo V70 Turbo Diesel),}\\
d_i &\; - \; \text{the chosen car type by household } i,\\
x &\; - \; \text{vehicle kilometers travelled (VKT, a generic decision variable),}\\
x_i &\; - \; \text{the observed driving for household } i \text{ (conditioning on } d_i),\\
x^*_{ij}(p^{\text{fuel}}) &\; - \; \text{the optimal driving rule,}\\
e_j &\; - \; \text{fuel efficiency of a car of type } j \text{in } {}^{\text{km}}/_{\text{l}},\\
p^{\text{car}}_{tj} &\; - \; \text{price of a new car of type } j \text{ in year } t,\\
p^{\text{fuel}}_{tj} &\; - \; \text{fuel price (the subscript } j \text{ is there to distinguish diesel or octane),}\\
\gamma_i &\; - \; \text{utility of driving relative to outside consumption (household-specific),}\\
z_i &\; - \; \text{household attributes correlated with driving utility,}\\
y_{it} &\; - \; \text{household income in period } t,\\
\beta &\; - \; \text{discount factor (fixed at 0.95),}\\
\delta_j &\; - \; \text{vehicle-specific depreciation rate (e.g. 0.8),}\\
\alpha_{1ij}, \alpha_2 &\; - \; \text{utility from driving is quadratic in VKT with these coefficients,}\\
\alpha_0 &\; - \; \text{coefficients on } q_j\text{; Utility from car } j \text{ that is not related to driving,}\\
\varepsilon_{ij} &\; - \; \text{IID extreme value type II shock (to the car type choice utility),}\\
\eta_i &\; - \; \text{measurement error in the VKT equation,}\\
\zeta &\; - \; \text{coefficients used in the linear interpretation of optimal driving.}
\end{aligned}
$$

The full utility can be written as

$$
\begin{aligned}
u_{ij} \;=\;& \gamma_i \left[1 - (\beta\delta_j)^4\right] p^{\text{car}}_{jt_{1i}} - 4\gamma_i\tau_j + u^{\text{own}}(j) \\
&+ \beta^4 \mathbb{E}\left\{ -\gamma_i \frac{p^{\text{fuel}}_{jt_{2i}}}{e_j} x^*_{ij}(p^{\text{fuel}}_{jt_{2i}}) + \alpha_{1ij} x^*_{ij}(p^{\text{fuel}}_{jt_{2i}}) + \alpha_2 \left[x^*_{ij}(p^{\text{fuel}}_{jt_{2i}})\right]^2 \right\}.
\end{aligned}
$$

where

$$\begin{aligned}
\gamma_i &= \gamma_z' z_i, \\
u_{ij}^{\text{drive}}(x) &= \alpha_{1ij} x + \alpha_2 x^2, \\
\alpha_{1ij} &= \alpha_{10} + \alpha_{1z}' z_i + \alpha_{1q}' q_j + c_i, \quad c_i \sim \mathcal{N}(0, \sigma_c^2).
\end{aligned}$$

The driving rule, $x_{ij}^*(p_{jt}^{\text{fuel}})$, is given by

$$x_{ij}^*(p_{jt}^{\text{fuel}}) = -\frac{1}{2\alpha_2}\left(\alpha_{1ij} - \gamma_i \frac{p_{jt}^{\text{fuel}}}{e_j}\right).$$

In the estimation, z_i contains mean spouse age, age squared, work distance for both spouses, real gross income, the number of kids and a dummy for living in a major urban area (Copenhagen, Odense, Aarhus or Aalborg). The characteristics, q_j, are vehicle total weight, engine displacement in cc, engine horsepower in kW and squares of all these variables and a dummy for diesel. To keep the number of parameters down, only the total weight and its square was used in α_{1ij} — the remaining were close to insignificant and greatly increased estimation running time.

B Data

B.1 Sample Selection

Table B.1 shows how the sample size (new car purchases) gradually drops from the initial 311,057 cars to 128,910 as different sample selection criteria are imposed. The first criterion states that the household purchasing the car must own it for at least 90% of the 4-year driving period. This causes the most dramatic reduction in sample size because many households sell the car within this period. Figure B.1 shows a histogram of the fraction of the 4-year period that the purchasing household owns the car for the full sample of 311,057 purchases (disregarding the mass point at 100%). This shows that the share declines steadily down from 90% to 0%. The choice of 90% is to emphasize the need for accurate data on the driving to ensure that the selection on anticipated driving is pinned down by the data. Future work should look checking the sensitivity of the results to reducing the 90%.

The second criterion deselects 2-car households but allows a second car to be present for up to 50% of the period.

Table B.1: Sample Selection

	(1) New cars	(2) Owns>90%	(3) Ncars<1.5	(4) #sold > 30	(5) Final sample
1997	14,500	8,866	8,252	6,453	6,019
1998	45,075	27,986	24,895	22,248	21,374
1999	42,260	25,846	22,540	20,165	19,525
2000	30,070	17,699	15,350	12,764	12,461
2001	23,774	12,182	10,389	8,057	7,893
2002	28,648	16,305	14,035	11,611	11,016
2003	22,733	12,516	10,774	8,961	8,600
2004	29,535	16,552	14,095	11,901	11,548
2005	36,722	22,794	18,999	15,863	15,490
2006	37,740	24,670	19,793	15,458	14,984
N	311,057	185,416	159,122	133,481	128,910

(2): The family owns the car at least 90% of driving period,
(3): The family may own another car but no more than 50% of the driving period of this car,
(4): At least 30 of this car sold in full sample, (5): final sample.

Figure B.1: Fraction of the Driving Period Where the Original Owner Still Owns the Car

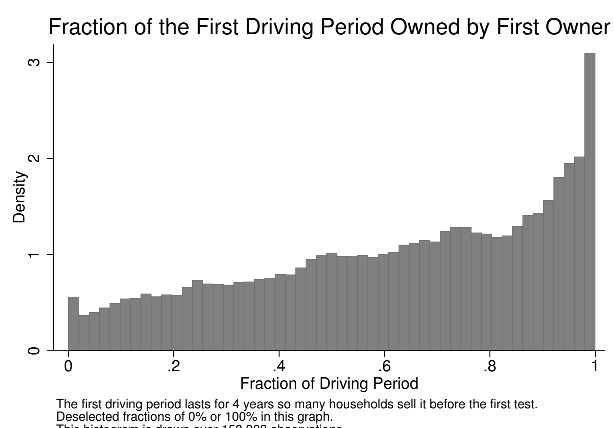


Table B.2: Deselecting Cars That are Rarely Sold and the Resulting Diesel Share

Threshold	Diesel % in 06	$\|\mathcal{J}\|$	N
30	18.5%	1,177	128,007
20	19.6%	1,518	136,977
10	20.6%	2,105	144,820
5	21.0%	2,783	149,112
0	21.8%	7,572	154,089

Table B.3: Marginal External Costs per Km Travelled by Fuel Type[a]

2010 DKK/km	Total	Air pollution	Climate	Noise	Accident	Congestion	Infrastructure
Gasoline car	0.63	0.011083	0.0162	0.0478	0.2095	0.3368	0.0097
Diesel car	0.66	0.044565	0.0140	0.0478	0.2095	0.3368	0.0097

[a] Source: DTU Transport (2010).

The third criterion deselects certain car types from the choice set by deleting purchases of cars that were purchased fewer than 30 times in the period 1997–2006. This has a very unfortunate implication in that diesel cars are heavily over represented in this group. Table B.2 shows the implications on the sample size (N), the number of cars ($|\mathcal{J}|$) and the diesel market share in 2006 of setting this limit to 20, 10, 5 and 0 respectively. The true market share in 2006 was 21.8% but the restriction on the choice set results in a share of just 18.5%. However, bringing this up towards the truth increases the size of the choice set immensely, making estimation computationally very burdensome.

The final criterion makes routine checks such as dropping extreme observations (outside of the 0.1th or 99.9th percentiles) or rows with missing or senseless values.

B.2 Marginal External Costs of Driving

In this subsection, the marginal external cost estimates used for welfare calculations and for the construction of the diesel internalization counterfactual in section 6.3 are described. The cost estimates are taken from DTU Transport (2010) and they are provided by a major Danish research institution and used by Danish policy makers. The external costs of driving a km in a gasoline and diesel car respectively are reproduced in table B.3.

Two things are worth noting; Firstly, pollution and climate change costs are dwarfed by the congestion and accident externalities. While this particular externality is not well addressed with the model applied in this paper because it depends critically on when and where the driving takes place, it does mean that an increased traffic flow should be highly discouraged.

Secondly, the only place where diesel car externalities are different from those of gasoline cars is in terms of air pollution and climate change. The difference in climate change externalities stem from the fact that diesel cars typically drive farther per litre of fuel (a sales-weighted average of 18.1 versus 13.5 km/l for in 2006) while diesel only contains 10.4% more CO_2 per litre than gasoline does (2.640 kg/l 2.392 kg/l). The difference in air pollution comes primarily from particulate matter. For the Belgian context, Mayeres and Proost (2013) report that particulate matter makes up 85.0% of all emissions-related externalities per ton of diesel, far more than the externalities from SO_2 and NO_x. In fact, the marginal externality of diesel air pollution depends crucially on the population density. Since a dummy for living in one of the four largest Danish cities is already in the model, the expected diesel use and diesel market share has been calculated conditional on urban residence. It turned out that urban diesel use and purchases followed the overall numbers quite closely for the reforms considered here.

B.3 Descriptives

Table B.4 shows summary statistics for the main variables used in this paper as well as the symbol or variable name used to refer to them.

All the demographics are taken directly from the registers except for the work distance variable. This one is calculated based on the travel tax deduction which comes from the personal tax registers. In Denmark, anyone living further than 12 km from their work place is eligible for a deduction depending on the distance times the number of days worked. The deduction is regardless of the number of hours worked and regardless of the type of transportation actually used by the worker. The deduction is a linear function of the km travelled above 24 (to and from work) but the rate drops to half after 100 km. In 2005, for example, it was DKK 1.68 for each km above 24 but below 100 and 0.84 for each km above 100. The rate was changed each year and twice in 2000. Moreover, as a part of a larger Danish reform in 1998 dubbed the Whitsun package, there was an adjustment to give a lift for the low-paid. The interested reader is referred to a previous version of this paper available upon request for all the details.

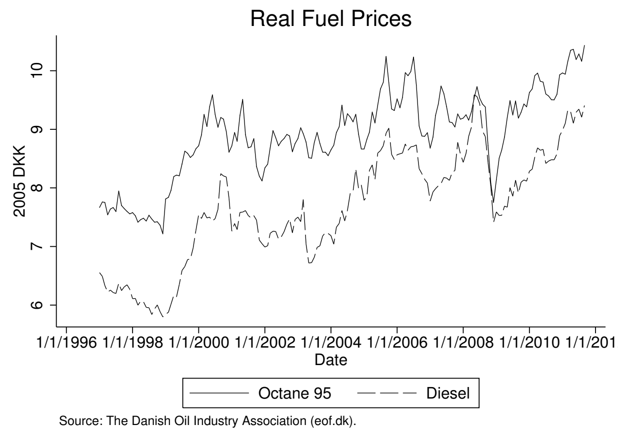
Note that in order to construct a work distance measure, one needs to know the number of days worked which is not observed. Therefore, it is assumed that everyone work 225 days a year.[31] Note, however, that this only means that the work distance variable may be imprecise for the actual distance to the work but still precise about the variable of

[31] The official numbers for public sector employees in 2007–2010 were 224, 226, 225 and 228.

Table B.4: Summary Statistics — Shortened Names in Parentheses

Car Variables					
	N	Mean	Std.	Min	Max
Fuel efficiency (km/l, e)	128,910	14.68	2.56	9.3	23.3
Weight (tons, q^{weight})	128,910	1,660.80	201.63	1,150	2,400
Horsepower (kW, q^{kw})	128,910	70.71	16.94	37	173
Displacement (cc, q^{displace})	128,910	1,580.08	265.40	796	3,342
Diesel (%)	128,910	0.1108	0.31	0	1
Price (2005 DKK, p^{car})	128,910	219,284.20	66,522.11	87,340.52	576,257.40
Depreciation factor (δ)	128,910	0.8741	0.0118	0.8249	0.9046
Units Sold	128,910	228.20	213.48	1	1,069
Demographic Variables					
	N	Mean	Std.	Min	Max
Work distance, male (WDm)	128,910	11.80	19.63	0	317.71
Work distance, female (WDf)	128,910	8.12	14.84	0	264.12
Gross income (2005 DKK, inc)	128,910	701,058.5	456,223.5	3	85,182,968
Number of kids (nkids)	128,910	0.9866	1.07	0	10
Unemployment, male (unempm)	128,910	0.0859	0.28	0	1
Unemployment, female (unempf)	128,910	0.1616	0.37	0	1
Age, male (agem)	128,910	43.99	10.12	18	60
Age, female (agef)	128,910	42.00	10.27	16	85
Male income %	128,910	0.5894	0.13	0	1
Urban area (bigcity)	128,910	0.2084	0.41	0	1

Figure B.2: Real Price of Octane 95, 1980–2011



interest that is the annual km commuted to work.

B.3.1 Fuel Prices

Figure B.2 shows the development in gasoline and diesel prices in Denmark in 2005 DKK. Prices have generally been increasing and moreover, it appears that diesel prices were converging on gasoline prices up towards 2008.

B.3.2 Car Characteristics

Figures B.3–B.5 show the development in median characteristics of sold cars. The most notable development is the increasing trend in weight for both types of fuel that has occured all the way back to the 80's. In this paper, weight proxies for the quality of the car by measuring comfort and the carrying capacity of the car. Similarly, fuel efficiency has gone up dramatically but here we see that while it has been somewhat monotone for gasoline cars, almost all the growth for diesel cars occured in 1997–99. Two things are worth noting there; Firstly, only 17 diesel cars are in the sample in 1997 so we are talking about very small numbers. Secondly, the advent of the Common Rail injection technology which quickly became standard in all diesel engines was the main reason for this. Apart from improving performance in terms of fuel efficiency, it also greatly improved the torque of the cars (which is not in my data) and changed the sound signature, making it more appealing to many consumers (according to an car salesman I have talked to).

The development in engine displacement, horse power and purchase price are much more erratic. This underlines the advantage of the chosen empirical model where all these characteristics are used in the household's comparison across cars, rather than focusing

Figure B.3: Median Characteristics Over Time — Weight and Fuel Efficiency

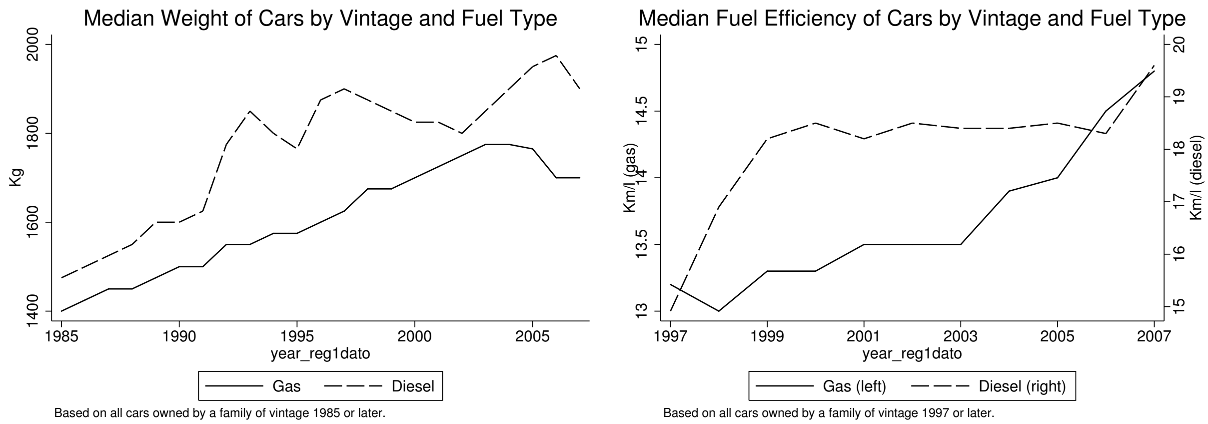
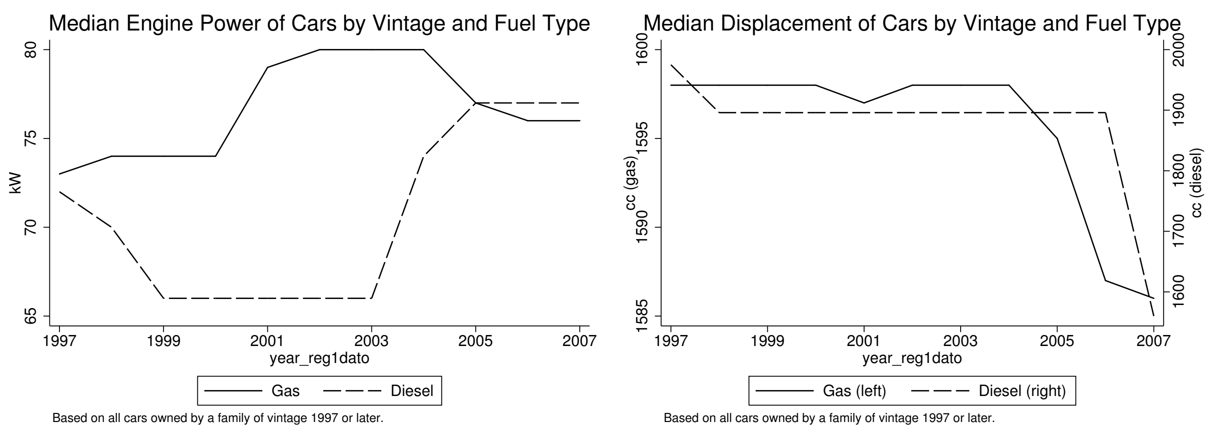


Figure B.4: Median Characteristics Over Time— Engine Power and Displacement



on each characteristic separately.

To better grasp the overall patterns in what car characteristics certain households end up with, table B.5 shows the estimates from regressing each car characterstic on household demographics. The results are much as one would expect with for example richer households purchasing more powerful and luxurious cars. It also shows some ambiguity in the effect of work distance — if males have a long work distance, they tend to prefer having a more comfortable ride whereas females tend to go for a more fuel efficient, smaller car.

B.3.3 Descriptive Evidence on Driving

Figure B.6 shows median vehicle kilometers travelled (VKT) against median fuel price over time for gasoline cars (left panel) and diesel cars (right panel). Both figures show

Table B.5: Car characteristics of new cars

	(1) Km/l	(2) Weight	(3) Diesel	(4) kW	(5) Displace	(6) Real price
$p^{\text{fuel (O95)}}$	0.415***	-0.0193***	0.0410***	-1.923***	-4.645	-8612.1***
	(19.33)	(-10.84)	(14.93)	(-12.53)	(-1.92)	(-14.37)
GDP (2005=1)	-11.39***	-0.165**	-1.771***	-3.053	-978.8***	-244123.3***
	(-17.05)	(-2.98)	(-20.71)	(-0.64)	(-13.01)	(-13.11)
agem	-0.0136	0.00373***	0.000654	0.473***	4.907***	1520.1***
	(-1.48)	(4.88)	(0.55)	(7.18)	(4.72)	(5.90)
agemsq	0.0000800	-0.0000430***	-0.0000207	-0.00549***	-0.0593***	-17.83***
	(0.78)	(-5.03)	(-1.57)	(-7.45)	(-5.10)	(-6.20)
agef	-0.0400***	0.00491***	-0.00118	0.335***	4.149***	1516.1***
	(-4.89)	(7.23)	(-1.13)	(5.73)	(4.50)	(6.64)
agefsq	0.000306***	-0.0000445***	-2.68e-08	-0.00325***	-0.0430***	-14.48***
	(3.30)	(-5.80)	(-0.00)	(-4.92)	(-4.13)	(-5.62)
WDm	0.0150***	0.000136***	0.00262***	-0.00892***	0.555***	84.66***
	(44.34)	(4.86)	(60.59)	(-3.70)	(14.59)	(9.00)
WDf	0.0178***	-0.000444***	0.00238***	-0.0512***	-0.160**	-59.57***
	(39.57)	(-11.91)	(41.42)	(-15.95)	(-3.16)	(-4.76)
real_inc	-0.000000245***	2.45e-08***	-6.92e-09***	0.00000296***	0.0000434***	0.0166***
	(-16.83)	(20.33)	(-3.71)	(28.43)	(26.49)	(40.84)
male inc %	0.00797	-0.000305	0.000721	0.00768	0.287	121.5
	(1.42)	(-0.66)	(1.00)	(0.19)	(0.45)	(0.78)
nkids	-0.303***	0.0417***	0.0000115	1.244***	24.10***	7462.6***
	(-37.23)	(61.88)	(0.01)	(21.43)	(26.33)	(32.94)
bigcity1	0.0198	-0.00707***	-0.00564**	-0.754***	-8.729***	-2115.9***
	(1.22)	(-5.26)	(-2.72)	(-6.51)	(-4.78)	(-4.68)
unempm	0.260***	-0.0407***	-0.00916**	-3.412***	-53.62***	-15345.8***
	(11.16)	(-21.06)	(-3.07)	(-20.47)	(-20.41)	(-23.59)
unempf	0.170***	-0.0146***	0.00574*	-1.426***	-21.18***	-5694.4***
	(9.50)	(-9.86)	(2.51)	(-11.14)	(-10.49)	(-11.40)
t	0.434***	0.0181***	0.0449***	1.082***	14.93***	7397.0***
	(43.37)	(21.76)	(35.06)	(15.11)	(13.23)	(26.49)
Constant	21.45***	1.653***	1.231***	65.59***	2230.9***	404939.1***
	(42.70)	(39.69)	(19.16)	(18.28)	(39.43)	(28.91)
N	128910	128910	128910	128910	128910	128910

Same sample as the one used for the two-period model.
(1) Fuel efficiency in km/l, (2) weight in tons, (3) LPM for diesel,
(4) engine power in kW and (5) displacement in cc.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure B.5: Median Characteristics Over Time— Real Price (2005 DKK)

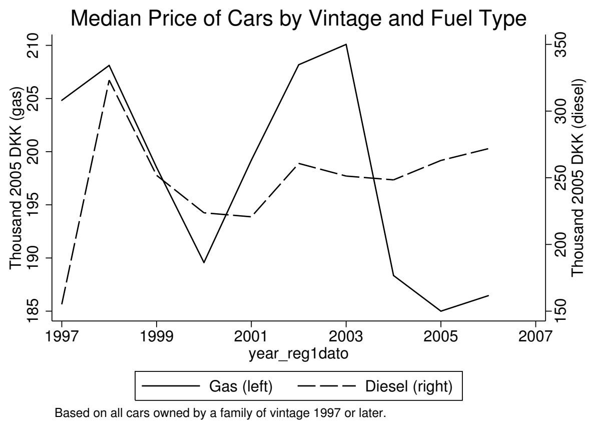
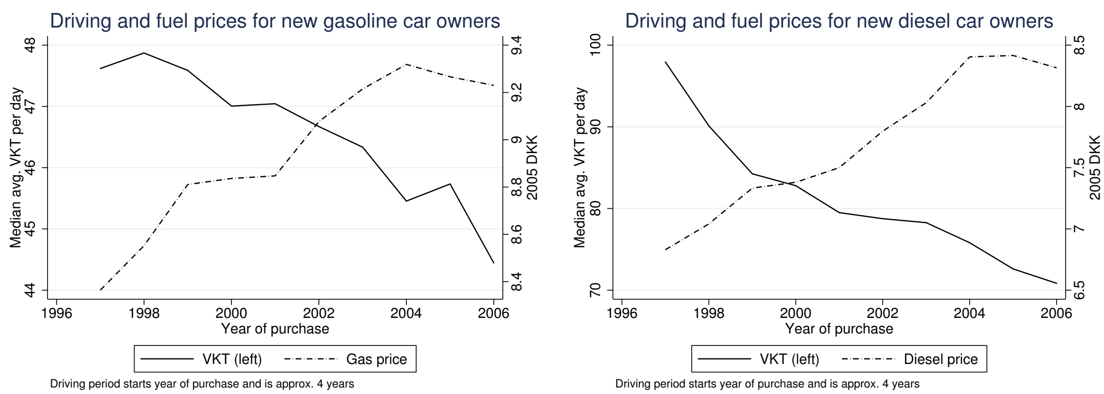


Figure B.6: Median VKT vs Fuel Price Over Time for Gas and Diesel



that the typical car purchased in later years ends up driving less than in earlier years and that fuel prices have been increasing. This is consistent with a negative fuel price elasticity.

The corresponding figures where the price per kilometer (PPK, p_{jt}^{fuel}/e_j) is used are shown in figure B.7 and here the picture is much less clear picture because fuel efficiency also increases over time. This is precisely the selection effect at play where consumers are moving to more fuel efficient cars to counteract the increasing fuel prices.

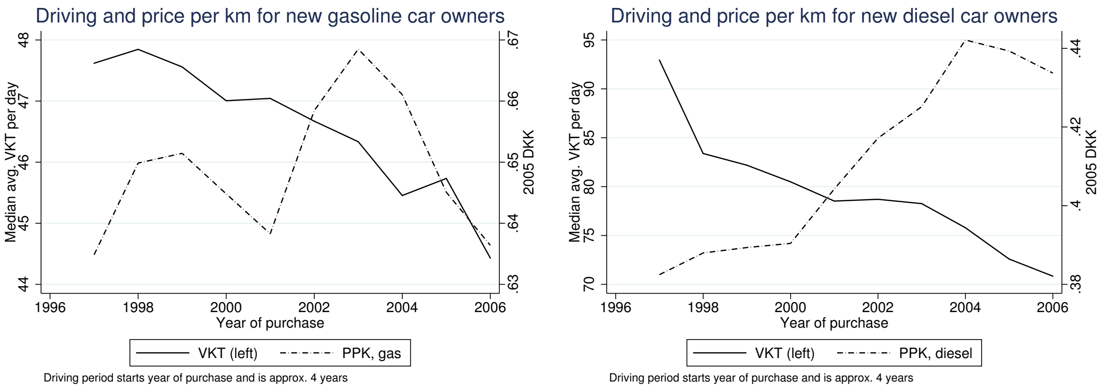
Table B.6 shows the results from regressing VKT on PPK, car characteristics and household demographics. The most central result is that the mean estimated PPK-elasticity depends very strongly on whether a different mean driving is allowed for diesel car households (which decreases the mean elasticity from –.74 to –.30). This is further emphasized by the fact that the elasticity is –0.16 when estimated on the gasoline sample only and –.39 on the diesel subsample. Gillingham and Munk-Nielsen (2013) explore the heterogeneity in the fuel price elasticity on household demographics and the interested reader is referred to that paper.

Table B.6: VKT Regressions — Price per Kilometer (PPK) Elasticity

	(1) Simple	(2) Diesel dummy	(3) Year FE	(4) Only gas	(5) Only diesel
PPK	-50.50***	-20.32***	-16.82***	-10.01**	-65.73
	(-21.52)	(-8.29)	(-6.17)	(-2.83)	(-1.94)
GDP	-41.98***	-35.10***	-57.10***	-50.23***	-82.38***
	(-29.57)	(-24.69)	(-12.38)	(-10.68)	(-3.88)
agem	0.518***	0.538***	0.536***	0.415***	1.256***
	(10.62)	(11.12)	(11.09)	(8.51)	(6.15)
agemsq	-0.00777***	-0.00792***	-0.00789***	-0.00677***	-0.0138***
	(-13.57)	(-13.91)	(-13.87)	(-11.85)	(-5.59)
WDm	0.353***	0.348***	0.348***	0.333***	0.381***
	(119.98)	(118.89)	(118.99)	(104.54)	(47.49)
WDf	0.340***	0.334***	0.334***	0.356***	0.260***
	(87.05)	(85.83)	(85.92)	(84.04)	(24.27)
income	-0.00000250***	-0.00000239***	-0.00000234***	-0.00000231***	-0.00000367***
	(-19.67)	(-18.89)	(-18.54)	(-18.68)	(-4.55)
nkids	0.236***	0.223***	0.219***	0.128	0.515*
	(3.61)	(3.43)	(3.37)	(1.93)	(2.05)
bigcity	-1.131***	-1.106***	-1.092***	-1.262***	0.973
	(-8.84)	(-8.70)	(-8.60)	(-9.88)	(1.80)
unempm	0.492**	0.438*	0.459*	0.565**	-0.499
	(2.64)	(2.36)	(2.48)	(3.03)	(-0.64)
unempf	-0.0700	-0.0930	-0.0784	-0.0474	-0.410
	(-0.49)	(-0.65)	(-0.55)	(-0.33)	(-0.74)
Km/l	0.610***	-0.257*	-0.118	0.117	-1.475
	(6.07)	(-2.51)	(-1.02)	(0.77)	(-1.90)
weight	0.0329***	0.0209***	0.0210***	0.0229***	0.0116***
	(67.23)	(36.60)	(36.45)	(38.60)	(5.36)
kW	-0.0368***	0.0426***	0.0428***	0.0483***	0.101***
	(-5.52)	(6.18)	(6.19)	(6.67)	(3.82)
displace	0.0140***	0.00367***	0.00352***	0.00180***	0.00178
	(33.71)	(7.55)	(7.23)	(3.36)	(1.14)
diesel		17.99***	18.09***		
		(40.22)	(40.37)		
_cons	28.02***	43.76***	66.88***	54.31***	157.5***
	(10.49)	(16.30)	(11.82)	(8.78)	(5.85)
Year FE	No	No	Yes	Yes	Yes
N	128007	128007	128007	114623	13384
r2	0.348	0.356	0.357	0.235	0.216
mean_elast	-0.744	-0.300	-0.248	-0.158	-0.392
p10_elast	-1.186	-0.477	-0.395	-0.242	-0.576
p50_elast	-0.656	-0.264	-0.218	-0.138	-0.358
p90_elast	-0.339	-0.136	-0.113	-0.0852	-0.233

Column 4 contains only gasoline cars and 5 only diesels.
Year FE: for each year, a dummy for whether the driving period covers the year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure B.7: Median VKT vs Price Per Kilometer (PPK) Over Time for Gas and Diesel



C Results

Table C.1 shows the structural elasticities from the preferred specification. The results are estimated based on a model with perfect foresight that allows random effects ($c_i \neq 0$). For the presented set of estimates, α_2 was fixed to -1, but very recently, I have successfully estimated that coefficient as well without it significantly changing the results.

Table C.2 shows the results from the baseline on the 2006 data as well as the 2007 counterfactual implemented in 2006 (same as column (3) of table 6.1) and an additional simulation of the 2007 reform where the pivot point of diesel cars is moved from $18^{\text{km}}/_{\text{l}}$ to $20^{\text{km}}/_{\text{l}}$. The motivation is that the pivot point for gasoline cars is $16^{\text{km}}/_{\text{l}}$ but a typical diesel car drives about 4 km further per liter of fuel than a gasoline car. In that sense, the pivot of $20^{\text{km}}/_{\text{l}}$ should provide a better balance in the incentives.

In figure C.1 is shown the observed diesel share, the simulated diesel share from the model and a counterfactual simulation where both fuel price time series are kept at the 1997 level. The figure shows that the diesel share would have been higher in the later years if fuel prices had not changed. Two important points should be noted; Firstly, since the model conditions on entry into the new car market, raising or lowering fuel prices, for all cars will not change results as drastically as if more households were allowed to switch into car ownership. Nonetheless, raising fuel prices will lower expected driving and utility so given the convex utility in driving, some consumers will move towards more fuel efficient vehicles and therefore also diesel cars. This is also why, in the structural elasticities in table 5.2 we saw that when all fuel prices go up by 1%, the diesel share grows by 0.15%.

Secondly, the more important implication of holding fuel prices at the 1997 level is that the *relative* price of gasoline to diesel is kept constant. Figure C.2 plots two time series. On

Table C.1: Estimated parameters

Fixed Parameters	
Parameter	Value
β	0.95
ψ	1
λ	10000
Model: Perfect foresight, quasi-linear, random effects.	

General Parameters		
Parameter	Estimate	t
σ_x	16.093	(69.12)
σ_α	21.951	(31.77)

Demographics				
	γ_z		α_{1z}	
Parameter	Estimate	t	Estimate	t
Constant	47.596	(35.22)	–	(–)
age	-8.447	(-18.97)	8.901	(8.71)
agesq	7.363	(15.88)	-15.168	(-14.39)
WDm	8.170	(18.95)	17.889	(69.45)
WDf	1.079	(19.46)	9.684	(108.20)
inc	-9.457	(-31.44)	-8.768	(-39.94)
nkids	1.453	(11.65)	-0.458	(-2.93)
city	-0.210	(-1.48)	-1.412	(-10.09)

Car Parameters		
Parameter	Estimate	t
α_{10}	74.927	(14.88)
α_{20}	-1.000	†
$\alpha_{0,\text{weight}}$	124074.734	(41.91)
$\alpha_{0,\text{weight}^2}$	-5009.689	(-5.67)
$\alpha_{0,\text{kw}}$	-413.653	(-25.53)
α_{0,kw^2}	5.114	(46.83)
$\alpha_{0,\text{displace}}$	-194.172	(-0.15)
$\alpha_{0,\text{displace}^2}$	4976.559	(13.12)
$\alpha_{0,\text{diesel}}$	-4235.595	(-24.99)
$\alpha_{1,\text{weight}}$	18.876	(3.12)
$\alpha_{1,\text{weight}^2}$	10.189	(5.64)

†: Fixed parameter, see section **??**.

Table C.2: Simulation of the 2007 Feebate Reform — The Role of the Diesel Pivot

	(1) Baseline	(2) 2007	(3) 2007 alt.
Consumer welfare			
E(CS	114970.09	115989.89	115363.51
Total taxes			
E(total taxes)	146623.83	134398.55	134482.53
Ownership tax			
E(Regtax revenue)	106556.44	98175.80	97702.93
E(Owntax revenue)	11093.62	9813.59	9779.74
Fuel tax			
E(O95 revenue)	25115.85	21695.96	23122.16
E(Diesel revenue)	3857.92	4713.20	3877.70
Driving/fuel use			
E(VKT)	79663.89	78740.62	78323.44
E(litre O95)	4340.92	3749.84	3996.34
E(litre D)	891.32	1088.92	895.89
E(litre D | urban)	188.02	230.59	189.60
E(kg CO2)	12736.56	11844.36	11924.39
Characteristics			
E(fe)	15.92	17.04	16.75
E(we)	1.70	1.64	1.64
E(kw)	77.08	70.07	70.72
E(displace)	1.65	1.54	1.54
E(% diesel)	18.49	24.48	19.63
E(% diesel | urban)	3.89	5.18	4.15

2007: The feebate reform of 2007 is implemented in 2006.
2007 alt.: As 2007 but the diesel pivot is 20 km/l instead of 18 km/l.

Figure C.1: Counterfactual Simulation: The Diesel Share Under Constant Fuel Prices

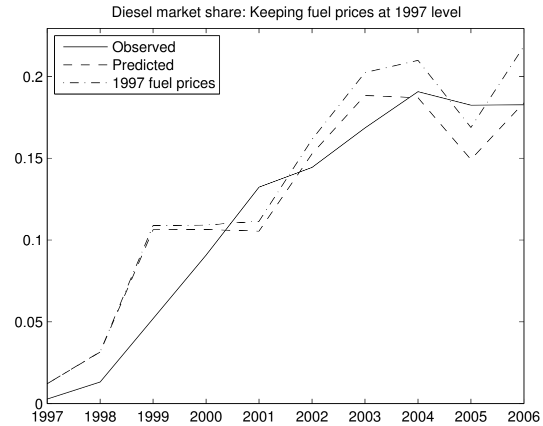
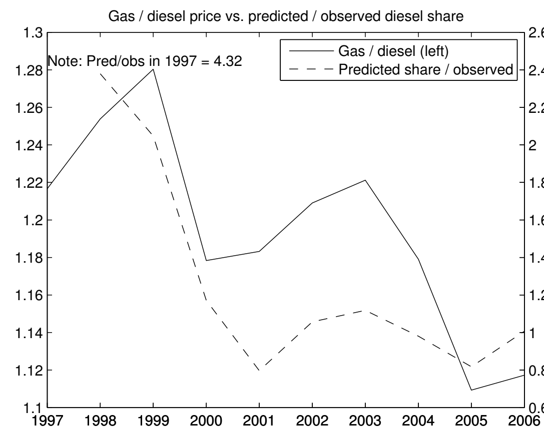
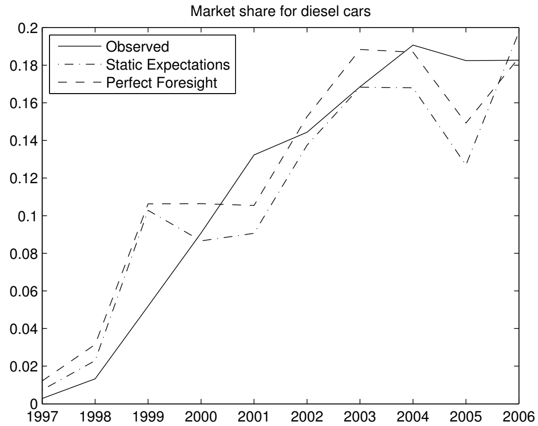


Figure C.2: Relative Fuel Prices and Relative Market Share Error



the left axis is the expected price of gasoline divided by the expected price of diesel (under perfect foresight — i.e. the fuel prices that are driving expectations) for a household going on the market in the given year and on the right axis is the predicted diesel market share for the year divided by the observed share. The figure shows that the tendency of the model to over or under-predict the diesel share is systematically related to the relative fuel prices. For example, the predicted share has two particularly striking periods; In 99–00, the prediction moves from over to under the observed share, coinciding with a sharp jump down in the relative price (diesel caught up with gasoline). In 05, the model has a kink down, under-predicting the diesel share. This coincides with a sharp jump down in the relative price from 117.9% to 110.9%, making diesels less favorable. Note that the predicted to observed share is not shown for 1997 because it is 432%. This extreme number is due to the observed share being quite close to zero in that year.

Figure C.3: Diesel Share Predictions — Comparing the Perfect Foresight and Static Expectations Predictions



C.1 Static Expectations

Table C.3 shows the structural elasticities from the model estimated imposing the assumption of static expectations. The elasticity of driving with respect to PPK is now –39% as opposed to –30% for the perfect foresight estimates, indicating that to fit the data, the estimates must emphasize monetary costs more in this version of the model. Similarly, when the fuel efficiency of all cars in the choice set go up by 1%, the expected fuel efficiency goes up by 0.93% as opposed to 0.90% with perfect foresight. In other words, consumers are still substituting away some technological gains in fuel efficiency for other engine characteristics but not as much as earlier. And in particular, as PPK rises, the expected diesel share now falls. Finally, as the weight of all cars goes up by 1%, the expected weight now goes up by 1.58%, as opposed to just 1.15% earlier and the expected driving response (allowing for changes on the extensive margin) goes up by 1.71% as compared to 1.01% under static expectations.

In short, the estimates from the model imposing static expectations imply that money matters more to consumers and that the weight of the car also matters more for how much it is driven.

Figure C.3 compares the diesel share predictions from the models that impose perfect foresight and static expectations respectively with the observed diesel share. The movements in the two are highly similar but there is a slight tendency in the later years for the static expectations prediction to be slightly below the other.

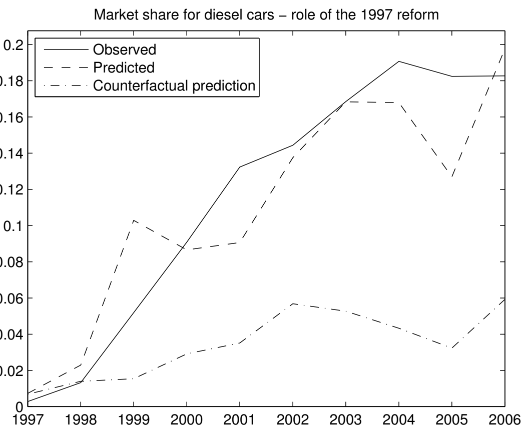
Figure C.4 shows the 1997 counterfactual simulation using the estimates imposing

Table C.3: Structural Elasticities — Static Expectations

	(1) Baseline	(2) Fuel efficiency	(3) Weight	(4) Fuel prices	(5) O95 prices
		Consumer welfare			
CS	64412.21	0.43	2.32	-0.43	-0.33
		Total taxes			
E(total taxes)	139431.76	0.05	1.24	-0.05	0.05
		Ownership and registration tax			
E(Regtax revenue)	101066.75	0.19	1.11	-0.19	-0.02
E(Owntax revenue)	9999.10	0.23	1.37	-0.23	0.03
		Fuel/RUC tax			
E(O95 revenue)	23801.00	-0.55	0.85	0.55	-0.04
E(Diesel revenue)	4564.90	-0.43	6.32	0.41	2.08
		Driving/fuel use			
E(VKT)	81183.20	0.39	1.74	-0.39	-0.21
E(litre O95)	4113.67	-0.55	0.85	-0.44	-1.03
E(litre D)	1054.66	-0.43	6.32	-0.58	2.08
E(litre D | urban)	225.43	-0.40	6.40	-0.61	1.99
E(kg CO2)	12624.18	-0.52	2.04	-0.47	-0.34
		Characteristics			
E(fe)	16.18	0.93	-0.18	0.06	0.15
E(we)	1.70	0.10	1.58	-0.10	-0.01
E(kw)	72.07	0.14	0.71	-0.14	-0.06
E(displace)	1.53	0.10	0.58	-0.10	-0.00
E(% diesel)	19.77	0.25	4.36	-0.26	2.08
E(% diesel | urban)	4.20	0.27	4.39	-0.29	1.98

Elasticities based on estimates imposing static expectations
(2): Relative changes when e_j increases by 1% for all j.
(3): Relative changes when weight_j increases by 1% for all j.
(4): Relative changes when fuel prices increase by 1%.
(4): Relative changes when gasoline prices increase by 1%.
All numbers are averages weighted with CCPs.

Figure C.4: 1997 Counterfactual — Static Expectations



static expectations. It shows that the conclusion from the perfect foresight model still holds; The counterfactual simulation where the 1997 reform was never imposed show a dramatically smaller diesel share in all years (but still an increase over time).

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