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DESIGNING CARBON TAXATION SCHEMES FOR AUTOMOBILES: A SIMULATION EXERCISE FOR GERMANY

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Designing Carbon Taxation Schemes for Automobiles: A Simulation Exercise for Germany[*]

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Abstract

Vehicle taxation based on CO_2 emissions is increasingly being adopted worldwide in order to shift consumer purchases to low-carbon cars, yet little is known about the effectiveness and overall economic impact of these schemes. We focus on feebate schemes, which impose a fee on high-carbon vehicles and give a rebate to purchasers of low-carbon automobiles. We estimate a discrete choice model of demand for automobiles in Germany and simulate the impact of alternative feebate schemes on emissions, consumer welfare, public revenues and firm profits. The analysis shows that a well-designed scheme can lead to emission reductions without reducing overall welfare.

Keywords: CO_2 emissions, German automobile market, feebates, carbon taxation.

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1 Introduction

Transportation is globally the largest final energy consuming sector. It is responsible for about 19% of worldwide energy consumption and 23% of energy-related CO_2 emissions, and these shares are projected to increase in the future. In the absence of serious technological progress and policies to enable the adoption of low-carbon technologies, the sector's carbon emissions are expected to rise by 50% in 2030 and over 80% in 2050, with almost all of this growth coming from non-OECD countries (International Energy Agency, 2009). This comes in sharp contrast to greenhouse gas mitigation achievements in other energy end-use sectors in which energy efficiency improvements and substitution with low-carbon fuels is less costly. However, even with substantial greenhouse gas emission reductions in all other economic sectors, without deep reductions in the emissions of the transport sector it is not possible to meet the emission reduction objectives that are considered necessary in order to avoid serious climate change in the 21st century.

The most widely discussed policy instruments for limiting automobile fuel consumption and CO_2 emissions are fuel economy standards, which aim to induce technological progress in vehicle manufacturers, and fuel taxes, which intend to encourage consumers to purchase fuel efficient cars (and to limit their use). A third policy option, which is receiving increased attention in Europe and the United States, is the design of a motor vehicle taxation system that will change relative prices, inducing consumers to purchase vehicles with low CO_2 emissions. This may be a promising policy option since it involves a market-based instrument that can affect consumer behavior, in contrast to command-and-control regulations that may be economically inefficient. Consumers may adjust their behavior more easily than auto producers, as the latter have to find a difficult (and costly) compromise between regulatory mandates for high fuel economy and consumer willingness to purchase bigger and more powerful (and hence less fuel efficient) cars. If the tax levied per unit of carbon emitted is fixed (i.e. if the tax is a linear function of a car's carbon emissions) this equates marginal compliance costs across car models and automakers, thus leading to an efficient outcome (Anderson, Parry, Sallee, and Fischer, forthcoming). In countries that already have automobile taxes in place, the shift to CO_2-based taxation can be designed to be revenue-neutral by adjusting existing taxes and is therefore politically more palatable than unpopular gasoline taxes.

Most European Union countries currently have in place a CO_2-based component in their calculation of vehicle taxes - either as a part of registration taxes (paid upon purchase) or of circulation taxes (paid annually).[1] Some countries have recently introduced feebate schemes,

[1]See European Automobile Manufacturers Association (2009) and OECD (2009) for overviews of the CO_2-

which pay a rebate to consumers purchasing a fuel-efficient vehicle and impose a penalty on those purchasing gas-guzzlers. Despite the increased use of such schemes, there is little research regarding their appropriate design and impact at the European level.

The aim of this paper is to contribute to this debate by analyzing the environmental and economic effects from the hypothetical adoption of a feebate system in Germany. Germany is an important country to study because it is the largest European economy and its regulatory initiatives can have a wider impact across the continent. We specify a discrete-choice demand and supply model for automobiles, estimate demand using a detailed dataset of car sales, and use the results to simulate feebate policies of varying stringency. We compute the impact of the various policies on consumer welfare, profits, public revenues, and CO_2 emissions.

We specify demand with a two-level nested logit model that can produce quite rich substitution patterns between automobile models belonging to different market segments. With the aid of this model we experiment with different parameters of a potential feebate program. We introduce a linear tax for new car purchases that is positive for cars with CO_2 emissions over a given emission level (the so called pivot point) and negative for cars with emissions lower than this threshold. Then we explore trade-offs between environmental effectiveness and economic impact. Our analysis shows that it is possible to design a feebate system for new automobiles that brings about carbon emission reductions without reducing total welfare; in fact it can also increase welfare through the combined effect of improved public finances and lower environmental damage through reduced CO_2 emissions, despite a decline in consumer surplus and firms' profits. This is possible if one sets the pivot point at a level that is considerably lower than the current average CO_2 emission level of newly sold cars in a country, and ensures that the marginal tax rate is not too high, i.e. corresponds to a price of less than 100 euros per tonne of CO_2.

Our work adds to only a handful of studies of the impact of carbon-based vehicle taxation. Most work in the area has analyzed the US case (Fischer, 2008; Greene, Patterson, Singh, and Li, 2005). A small number of studies for Europe that have been carried out on behalf of the European Commission, the EU's executive body, have dealt with this issue in an aggregate manner and with simple statistical/econometric methods (European Commission, 2002a,b). Other studies have made descriptive ex-post assessments of taxation schemes impemented in specific countries, such as Rogan, Dennehy, Daly, Howley, and Ó Gallachóir (2011) for Ireland or Bastard (2010) for France. To our knowledge, ours is the first study attempting an ex-ante econometric analysis of the possible impact of CO_2-based taxation schemes in a European country.

based taxation schemes implemented before the end of year 2009 by individual countries.

2 Existing literature

The feebate option currently implemented nationwide in Canada and France and to some extent in other European countries[2] has been a subject of debate in North America for several years (Fischer, 2008; Greene, Patterson, Singh, and Li, 2005). Recently, Peters, Mueller, de Haan, and Scholz (2008) have discussed issues regarding the design of a feebate system in Europe on the basis of stated preference data from consumer surveys in Switzerland. Moreover, de Haan, Mueller, and Scholz (2009) have applied an agent-based microsimulation model of car purchasing consumer behavior that attempts to account for both direct monetary effects of such a system on consumer behavior and indirect effects because of gradual changes in consumer preferences. In a very recent development, Bunch, Greene, Lipman, Martin, and Shaheen (2011) have explored the effectiveness of alternative feebate programs in California with the aid of a dynamic multi-period optimization model that simulates automobile manufacturers' behavior and consumer response. Liu, Cooke, Greene, and Bunch (2011) have extended this assessment by evaluating the effectiveness of these programs if implemented across the whole United States.

Enviromental reforms of vehicle taxation schemes are often required to be revenue-neutral in order to make them politically viable. Depending on vehicle tax systems currently in place in each country, revenue neutrality can be achieved in two ways:

- In countries with registration taxes on all new car purchases (such as numerous European countries), registration taxes can be calculated on the basis of CO_2 emissions in a way that equates total revenues of the new tax scheme to that of the previous scheme. This calculation would have to take into account the estimated shifts in market shares of car models because of the response of consumers to tax incentives.
- Countries without a registration tax (such as the United States, Japan, Canada as well as the automobile producing countries in Europe) implement a feebate system in which consumers receive a rebate when purchasing low-CO_2 cars or incur an additional fee when purchasing a high-CO_2 car.[3] If the system is properly designed, then total revenues from fees may be approximately equal to governmental payments for rebates. In general, a feebate system is almost equivalent to a fuel economy regulation with flexibility mecha-

[2]See the review of Bunch, Greene, Lipman, Martin, and Shaheen (2011); countries such as Denmark, the Netherlands and Norway have implemented some type of feebate program but have combined it with wider reforms in their car registration tax systems.

[3]It is also possible to apply the feebate on the supply side, i.e. on automobile manufacturers or dealers. In theory the effect would be the same regardless of where the tax is levied, in practice however it seems that price incentives are more effective if levied at the consumer rather than the producer level (Sallee, 2010).

nisms, i.e. allowing trading of fuel economy credits across vehicle types and manufacturers (Fischer, 2008).

In our econometric analysis we specify and estimate a discrete choice model of demand for differentiated products. We chose to use the nested multinomial logit model (NML) as in Berry (1994) and Verboven (1996) over the random coefficients model developed by Berry, Levinsohn, and Pakes (1995) (widely referred to as BLP). The random coefficients model is more flexible but also more computationally demanding. Both models have been used widely to estimate demand and market equilibrium in markets for differentiated products, and particularly automobile markets. We opted for the nested logit model because it is easier to estimate and it has been successfully used in many applications. In order to allow for a more flexible specification with more consumer heterogeneity we specified two levels of nests, as in Verboven (1996).

The random coefficients model was first used to estimate the impact of policy and environmental changes on market shares by the BLP authors in Pakes, Berry, and Levinsohn (1993). Fershtman, Gandal, and Markovich (1999) estimated a nested logit model with a single nest and simulated the impact of tax reform in the Israel automobile market. In a related application, Vance and Mehlin (2009) examine whether tax incentives promote the purchase of more efficient vehicles in Germany. They estimate a variant of the nested logit equation that departs somewhat from the underlying utility framework. They find that vehicle operating costs (such as circulation fees and fuel taxes) enter significantly in the purchase decision.

3 The model

3.1 The choice problem

There are J products to choose from. The utility of consumer i from consuming product j can be written as

$$u_{ij} = \delta_j + \mu_{ij}, \tag{1}$$

where δ_j is the utility component common to all consumers (the mean utility) and μ_{ij} is the individual-specific component. The mean utility is specified as a function of price p_j, a k-dimensional vector of observed attributes of product j (such as horsepower, engine size, emission levels, etc.) and an unobserved product attribute ξ_j. Mean utility is typically parameterized as

$$\delta_j = x_j\beta - \alpha p_j + \xi_j. \tag{2}$$

The individual-specific component μ_{ij} is assumed to follow a Type I extreme value distribution, which yields convenient logit-style purchase probabilities. In the simple multinomial logit the μ_{ij}'s are assumed to be independent and the market share equation reduces to the familiar $s_j = e^{\delta_j}/[1+\sum_{k=1}^{J} e^{\delta_k}]$. This functional form is known to be very restrictive. It implies, for example, that all products with the same price and market share have the same own price elasticities.

The NML model relaxes the independence assumption on the μ_{ij}'s by allowing for correlation in individuals' preferences for products that are similar, in a sense to be specified by the econometrician. This might seem arbitrary, but in practice one can often adopt already existing conventions or industry classifications. In the case of automobiles for example, different models can be classified as compact, economy, midsize, luxury, SUV, MPV, estate, and so on. It is reasonable to assume that products within each class have common characteristics that provide a certain level of utility. One could use class-specific dummy variables to capture the mean utility from each vehicle class. The NML specification provides an alternative approach that allows the level of utility derived from each group to vary across individuals.[4]

Extending the idea to multiple levels of nests is straightforward (though the algebra can get tedious). Groups of products can de divided into subgroups and preferences are allowed to be correlated for products within each subgroup. Consider the two-level case. Let the J products by divided into $G+1$ exhaustive and mutually exclusive groups indexed by g. Let each $g = 0, 1, \ldots, G$ be further divided into H_g subgroups indexed by h_g. The variance component structure of the μ_{ij} is defined as follows:

$$\mu_{ij} = \nu_{ig}^1 + (1-\sigma_2)\nu_{igh}^2 + (1-\sigma_1)\varepsilon_{ij}. \tag{3}$$

The term ν_{ig}^1 represents the utility consumer i derives from consuming a product in group g and ν_{igh}^2 represents the utility from consuming a product in subgroup h of group g. The term $(1-\sigma_1)\varepsilon_{ij}$ represents an idiosyncratic preference of consumer i for product j.[5]

From the utility framework described above one can derive the following equation to be taken

[4]Essentially, the NML model is equivalent to a specification with random coefficients on group-specific dummy variables (Berry, 1994).

[5]Cardell (1997) has shown that there is a unique distribution such that if ν_{ig}^1 and ν_{igh}^2 follow that distribution and ε_{ij} is distributed Type I extreme value, then $\nu_{ig}^1 + (1-\sigma_2)\nu_{igh}^2 + (1-\sigma_1)\varepsilon_{ij}$ is also distributed Type I extreme value.

to the data (see the appendix for details):

$$\ln(s_j) - \ln(s_0) = x_j\beta - \alpha p_j + \sigma_1 \ln(s_{j/h}) + \sigma_2 \ln(s_{h/g}) + \xi_j. \tag{4}$$

In the equation above, s_j is the market share of product j (sales divided by M consumers); s_0 is the outside good share; $\ln(s_{j/h})$ is the share of product j in subgroup h and $\ln(s_{h/g})$ is the share of all subgroup-h products in group g. McFadden (1978) has shown that the nested logit model with two nests is consistent with random utility maximization if $0 \leq \sigma_2 \leq \sigma_1 \leq 1$. If both σ_1 and σ_2 are zero, an individual's preferences are uncorrelated across all available models, and the model reduces to the simple multinomial logit model. If σ_1 is positive and σ_2 is zero, preferences are correlated across cars from the same subgroup, resulting in localized competition between cars from the same subgroup. If in addition σ_2 is positive, individual preferences are also correlated across cars from different subgroups within the same group. If σ_2 approaches σ_1, preferences are equally correlated across all cars belonging to the same group, meaning that the second grouping is not needed. If σ_1 approaches one, cars in the same subgroup become perfect substitutes. If in addition σ_2 approaches one, all cars in the same group become perfect substitutes.

Most papers employing the NML model to estimate demand for automobiles use vehicle class (compact, midsize, etc.) as the main criterion for dividing products into groups. In addition, one can specify additional groupings based on product characteristics that are critical in consumer decisionmaking. One such characteristic is engine (and, by extension, fuel) type. Diesel engines are widely used in Europe (unlike the United States) and the choice between a gasoline and a diesel engine is one of the most important criteria in vehicle choice (Verboven, 2002). We therefore allow for correlation across models using the same engine type.

3.2 The supply side

Multi-product firms are assumed to choose prices in order to maximize total profits from all of their products. As in Verboven (1996), the first order condition under the assumption of Bertrand-Nash equilibrium in prices is given by the following relationship (see appendix for details):

$$\frac{P_j}{1+v} = mc_j + \frac{1}{\alpha(1+v)\left[\frac{1}{1-\sigma_1} - \left(\frac{1}{1-\sigma_1} - \frac{1}{1-\sigma_2}\right)s_{f/h} - \frac{\sigma_2}{1-\sigma_2}s_{f/g} - s_f\right]}. \tag{5}$$

The first order condition implies that price net of VAT (v denotes the VAT rate) is equal to marginal cost (mc_j) plus a markup term. Parameters α, σ_1 and σ_2 come from the demand equation (4). The term $s_{f/h} = \sum_f s_{j|h}$ denotes the share of firm f's products within subgroup h; $s_{f/g} = \sum_f s_{j/g}$ denotes the share of firm f's products within group g; and $s_f = \sum_f s_j$ represents the share of firm f's products in the potential market.

One can proceed by estimating the demand equation (4) in isolation, or by estimating (4) and (5) jointly.[6] Joint estimation increases efficiency at the cost of imposing the assumption of Bertrand-Nash pricing. Since we have enough data, we opted for simplicity and fewer assumptions and estimated only the demand equation. Once we have the estimates of α, σ_1 and σ_2, we plug them into equation (5) in order to recover estimates of marginal cost for each product.

In order to obtain consistent estimates of the demand equation it is necessary to address the endogeneity of prices and 'within' shares. If firms observe unobserved quality ξ_j they will take it into account when they set prices. This will induce a positive correlation between price and the error term, leading to an upward bias (lower α in absolute terms) in the estimated coefficient in an OLS regression. The other endogenous variables are also positively correlated with unobserved quality and the coefficients σ_1 and σ_2 will also be biased upwards in the OLS case. For this reason, general method of moments (GMM) or instrumental variable (IV) methods should be used. Further details are provided in section 5.

4 Data

Data covering the period 2002-2008 were obtained from *JATO Dynamics*, a company specializing in the collection of automotive data worldwide. For every type of car on the market in each year we observe 17 attributes such as vehicle weight, engine size, sales volume and sales price. The data are highly disaggregated; two model variants that differ in only one of the 17 attributes (e.g. whether they have climate control or not) are recorded as different observations. As a result there is a very large number of observations (157,047 in total), some of which correspond to a very small number of units sold. Estimation of the model at this level of disaggregation is not advisable as observations with very low sales are susceptible to measurement or recording errors. Typically in studies of automobile markets the observation is at the level of the model (nameplate), e.g. Ford Focus or Renault Scenic. We opted for a slightly smaller degre of aggregation by splitting

[6]The latter would require an assumption on the marginal cost function. Typically it is assumed that marginal cost is constant in output and linear in product characteristics: $mc_j = w_j\gamma + \omega_j$, where w_j is a vector of product characteristics that affect production costs and ω_j is an unobserved characteristics of product j.

models into separate observations when there was substantial variation in engine size. The rule was to split models based on 200cc increments (1100-1300cc, 1300-1500cc, etc.) In addition we split models according to engine type (gasoline or diesel).[7] Hence, an observation is defined by model name, engine type and engine size (the latter in 200cc increments); for example "Ford Focus, diesel, 1.9-2.1 liters".

The sales assigned to each observation are the total sales of all model variants corresponding to the observation. Price and vehicle characteristics are from the best-selling variant. Observations with a sales volume of under 50 units in a year, or with a sales price of over €100,000 or with engine capacity over 5 liters were removed from the dataset as they can be considered to be market niches. Non-passenger cars such as pickups and large vans were also excluded. This process led to a dataset of 5,982 observations in total. Some basic variables are described in Table 1.

Table 1: Means of key variables (obs: 5,982)

Stats	Eng. size liters	CO_2 emis. g/km	Power HP	Frame m^2	Sales units	Prices 2005€
Min	0.6	81	41	3.79	51	6,745
5%	1.2	126	68	6.08	83	12,101
25%	1.6	157	102	7.13	320	17,850
50%	2.0	187	136	7.89	1,029	24,822
75%	2.4	227	177	8.55	3,377	35,100
95%	4.0	294	292	9.43	16,748	64,485
Max	5.0	440	530	10.18	115,451	101,312
Mean	2.14	196	149	7.80	3,667	29,025
Std dev.	0.81	53	69	1.02	7,616	16,009

Source: *JATO Dynamics*. Prices are deflated (that is why the upper bound of €100,000 is exceeded). Frame is length × width.

Each automobile model in our data is assigned to one of 24 market segments. This classification was too detailed for our purposes, so we aggregated up to seven broader segments (small, medium, large, luxury, sport, MPV, SUV). Table 2 shows the average prices, sales, engine capacity and CO_2 emissions by vehicle class and engine type. As expected, larger cars have higher CO_2 emissions on average. In general, diesel cars have lower CO_2 emissions compared to their gasoline counterparts due to the higher fuel economy of diesel engines. This automobile classification (two fuel types and seven segment classes for each fuel type) is the one we use in

[7]There are other engine/fuel types (electric, CNG, LPG, E85, hydrogen, methanol) but they only make up 0.8% of observations, so we removed them from the dataset.

the demand estimation below. Note also that we have taken into account that the value added tax rate in Germany (variable v in equation 5) was 16% until 31 December 2006 and increased to 19% thereafter.

Table 2: Means of key variables by vehicle class

Class	Obs.	Eng. size	CO_2 emis.	Sales	Price
Gasoline engine					
Small	659	1.33	149.07	6917	13.318
Medium	643	1.76	182.28	4741	19.948
Large	742	2.25	211.88	2520	29.456
Luxury	411	3.24	257.64	1183	53.416
SUV	425	2.86	267.02	977	37.004
Sport	401	2.64	230.03	1464	43.003
MPV	662	1.86	198.57	2657	22.693
Diesel engine					
Small	273	1.46	121.90	2227	15.037
Medium	280	1.82	142.92	7140	21.373
Large	377	2.13	166.95	7223	29.373
Luxury	228	2.82	212.77	4799	50.032
SUV	321	2.66	243.83	2885	40.367
Sport	49	2.16	163.69	1211	35.245
MPV	511	1.94	171.64	3521	25.373

Source: *JATO Dynamics.*

The averages reported in Table 2 mask substantial variability in CO_2 emissions of relatively similar cars. Even within the same market segment, CO_2 emissions vary by up to a factor of two. This suggests that appropriate incentives such as vehicle taxation can induce consumers to switch to a low-CO_2 vehicle in their preferred segment without much utility loss. In the United Kingdom it has been assessed that choosing the lowest CO_2 emitters in any car market segment can make a difference of about 25% to fuel efficiency and CO_2 emissions (King, 2007).

5 Estimation

Extensive experimentation with different nesting structures led us to the choice of engine type and market segment as the most appropriate classifications for our data. We estimated the model using each variable as the group variable and the other as the subgroup variable. Estimation using market segment as the group and engine type as the subgroup produced the relationship

$\sigma_1 < \sigma_2$, meaning that the particular nesting structure is not consistent with random-utility maximization (McFadden, 1978). The reverse nesting structure (with engine type as the group and market segment as the subgroup) produced $\sigma_1 > \sigma_2$, as required for consistency with random-utility maximization. The results presented below use this structure.

Table 3: Estimates of demand equation

Variables	1-level NML		2-level NML	
	OLS	IV	OLS	IV
Price	-0.0052**	-0.061**	-0.0052**	-0.059**
	(0.00029)	(0.0047)	(0.00029)	(0.0047)
$\ln(s_{j\|g})$	0.990**	0.764**		
	(0.0012)	(0.032)		
$\ln(s_{j\|h})$			0.990**	0.756**
			(0.0012)	(0.032)
$\ln(s_{h\|g})$			0.989**	0.651**
			(0.0025)	(0.028)
Engine capacity	-0.153**	0.284**	-0.153**	0.273**
	(0.0063)	(0.038)	(0.0063)	(0.038)
CO_2 emissions	0.0022**	-0.0012**	0.0022**	-0.0017**
	(0.000061)	(0.00043)	(0.000061)	(0.00041)
Horsepower	0.0019**	0.0060**	0.0019**	0.0056**
	(0.000070)	(0.00060)	(0.000070)	(0.00058)
Frame	-0.040**	0.082**	-0.040**	0.087**
	(0.0022)	(0.010)	(0.0022)	(0.011)
Manual gearbox	-0.019**	-0.270**	-0.019**	-0.244**
	(0.0055)	(0.029)	(0.0055)	(0.028)
Climate control	-0.0013	0.055**	-0.0013	0.056**
	(0.0043)	(0.020)	(0.0043)	(0.021)
Constant	-3.018**	-4.708**	-3.019**	-4.897**
	(0.018)	(0.188)	(0.018)	(0.180)
F-test	35,675.25**	763.35**	34,395.89**	706.98**
Wald test, null: $\sigma_1 = \sigma_2$			0.09	32.91**
Underidentification test		103.25**		112.99**
Overidentification test		3.48		3.51

Significance levels: $\dagger$: 10%, $*$: 5%, $**$: 1%. $N = 5,982$. Standard errors are reported in parentheses. Time dummies are included but not reported for brevity. Country dummies are reported in Table 5 in the appendix.

OLS and IV estimates for this nesting structure are presented in Table 3. In the same table we also present estimation results for the one-level NML with engine type as the nest. A Wald test rejects the null hypothesis $\sigma_1 = \sigma_2$, meaning that the two-level NML is the better model.

The choice of instruments in this model specification was guided by the existing literature and by the appropriate tests for instrument relevance and overidentification.[8] From the set of potential instruments, we choose to use the sum of CO_2 emissions of other products sold by the same firm, the sum of frame of other products sold by the same firm, the sum of frame of other products sold by the same firm square, the number of other products in the subgroup and the number of other products outside the subgroup but within the group. The Anderson canonical correlation LM statistic - a test of the null hypothesis that the model is under-identified - was rejected. The Sargan statistic - a test of the null hypothesis that the instruments are valid - cannot be rejected.

In comparing OLS and IV estimates for both one-level and two-level NML models, recall that the OLS estimate of the price coefficient will be biased towards zero if the endogeneity problem exists. This is because price is positively correlated with the error term, which represents unobserved quality. This is clearly the case here: the coefficient on price drops substantially when we instrument for price. Similarly, the coefficient on the other endogenous variables, the within-shares, are positively correlated with unobserved quality and they also drop once we instrument for them.

Estimates of the demand parameters α, σ_1 and σ_2 are all consistent with the restrictions of the nested logit model: $\alpha > 0$ and $0 \leq \sigma_2 \leq \sigma_1 \leq 1$. Engine capacity, horsepower, frame, automatic transmission and climate control are important car attributes and have the expected signs. CO_2 emissions turned out to be negative and statistically significant, implying that consumers take emissions explicitly into consideration when deciding to purchase a car. On the other hand, the small coefficient (in absolute terms) indicates that emissions are less important to consumers than other car attributes. We found the same result when we replaced the CO_2 variable with a variable expressing fuel costs per kilometer. The signs on country dummies are also what might be expected (e.g. German cars are highly regarded while Chinese cars are not). The median own price elasticity corresponding to the α, σ_1 and σ_2 coefficients from the 2-level NML IV regression is 6.001, similar to estimates from other automobile markets.

Public revenue (due to VAT receipts) from sales of the models included in our estimation in the year 2008 was 11.1 billion euros (at 2005 prices) or 3,847 euros per car. Average CO_2 emissions are 164 grams per kilometer per car. Manufacturer profits are estimated at 12.3 billion euros and consumer welfare (without the constant C - see Appendix A.2) is 3.9 billion euros.

[8] See discussions in Berry, Levinsohn, and Pakes (1995) and Bresnahan, Stern, and Trajtenberg (1997), among others.

6 Policy simulations

Using the estimated model parameters, we can simulate the implementation of a feebate in the German car market and assess the effects on automobile sales, prices, public revenues, firm profits, consumer welfare and sales-weighted CO_2 emissions. All results presented in this section show the effect of taxation in the year 2008, the last year covered by our data. This provides a reasonably good indication about eventual changes in car sales in the near future (e.g. in year 2011 or 2012)[9]. A simple way to proceed is to assume that the amount of the feebate will be completely passed through to the final price. That is, the final price will change by the amount of the feebate and the producer's price will remain the same. With this assumption, all one has to do is to plug the new final prices (old price plus feebate) into the demand system to compute counterfactual shares and all other desired magnitudes.

This may provide a good first approximation but a proper analysis should take into account manufacturers' pricing responses. This requires solving for equilibrium prices in the hypothetical scenario where a feebate scheme is introduced. The supply model outlined in section 3 produces a set of pricing equations (one equation like (5) for each car model). Our counterfactual exercise involves simulating the equilibrium in year 2008, in which there were 902 car models. We therefore have a system of 902 nonlinear equations that need to be solved to produce the 902 prices. The technical details of how this was implemented are described in appendix A.3. One point worth mentioning is that the results using optimal prices are very similar to those obtained under the assumption of 100% feebate pass-through.

We assume that a feebate A_j is introduced. The VAT applied in Germany remains the same as before. The feebate takes the form of a linear tax that is positive for cars with CO_2 emissions over a given emission level (the so called pivot point) and negative for cars with emissions lower than this threshold:

$$A_j = t(CO_2 - PP),$$

where CO_2 is the CO_2 emissions level of model j and PP is the pivot point. Both CO_2 and PP are expressed in grams of CO_2 per kilometer (g/km), t is the tax rate in euros per g/km and A_j in euros per car of model j. It is possible to simulate programs with a nonlinear feebate function, or with different functions for the 'fee' and the 'rebate' part, as implemented in some countries so far (see e.g. Bunch, Greene, Lipman, Martin, and Shaheen (2011)); however we

[9]In fact, using data of more recent years 2009 and 2010 might have been misleading: automobile demand and supply patterns may have been temporarily altered during those two years due to the implementation of accelerated car scrappage schemes as part of fiscal stimulus measures.

simulated a linear tax only because such a system imposes equal marginal abatement costs for all manufacturers, thus leading to an economically efficient solution.

We carried out multiple simulations using different values of t and PP corresponding to feebates of varying stringency, keeping in mind that public revenues should not decrease to an unrealistically low level due to very generous rebates offered to low-carbon cars. More specifically, we conducted simulations with three different pivot points (160, 140 and 120 g/km) and four different feebate levels (t taking values of 15, 30, 45 and 60). It is important to keep in mind the correspondence between such a feebate system and an equivalent carbon tax. Assuming that a car travels 200,000 kilometers throughout its lifetime, $t = 15$ corresponds to a tax of 75 euros per tonne of CO_2, while a feebate with $t = 60$ corresponds to a tax of 300 euros per tonne of CO_2. Although such values are higher than the usual value used to assess marginal CO_2 damage costs (approximately 15-30 euros per tonne CO_2), it is still quite lower than the implied marginal carbon tax rates of some CO_2-based vehicle tax systems currently implemented in European countries (Braathen, forthcoming).

We next present some results that show in detail the effects of different feebates by fuel, car segment and CO_2 emissions class, focusing on the case in which the pivot point is 140 g/km. As will be shown in Figures 5 and 6 below, choosing such a pivot point can lead to significant environmental gains without strongly compromising other economic variables.

Figure 1 shows the change in automobile prices in different fuel/vehicle segment combinations from the implementation of a lenient feebate ($t = 15$) and a stringent feebate ($t = 60$) respectively. For simplicity we only report here segments small, medium and large, but effects are similar in the other four segments (SUV, sports, luxury and MPV) as well. In the lenient feebate case (upper part of Figure 1), price changes are relatively small, from -2.5% for small diesel low-carbon cars up to 4% for medium gasoline high-carbon cars. Note that these values are sales-weighted averages across specific emissions classes, which means that individual models may experience higher or lower price changes depending on each model's CO_2 emission levels. In the stringent feebate case (lower part of Figure 1), average price changes range from -12% (for small gasoline cars with low carbon emissions) to 17% (for the highest emissions class of medium gasoline cars). Overall, the feebate is more favorable to most small cars and to medium-sized diesel cars as will also be shown in Figure 4 below.

Changes in total automobile sales – compared to actual sales in Germany in year 2008 – are displayed in Figure 2 for the two extreme feebate cases mentioned above. In each subgroup belonging to a specific class, cars which belong to the lowest CO_2 emission class (less than 130 g/km) gain significantly in sales. There is also a sales increase for cars belonging to the second

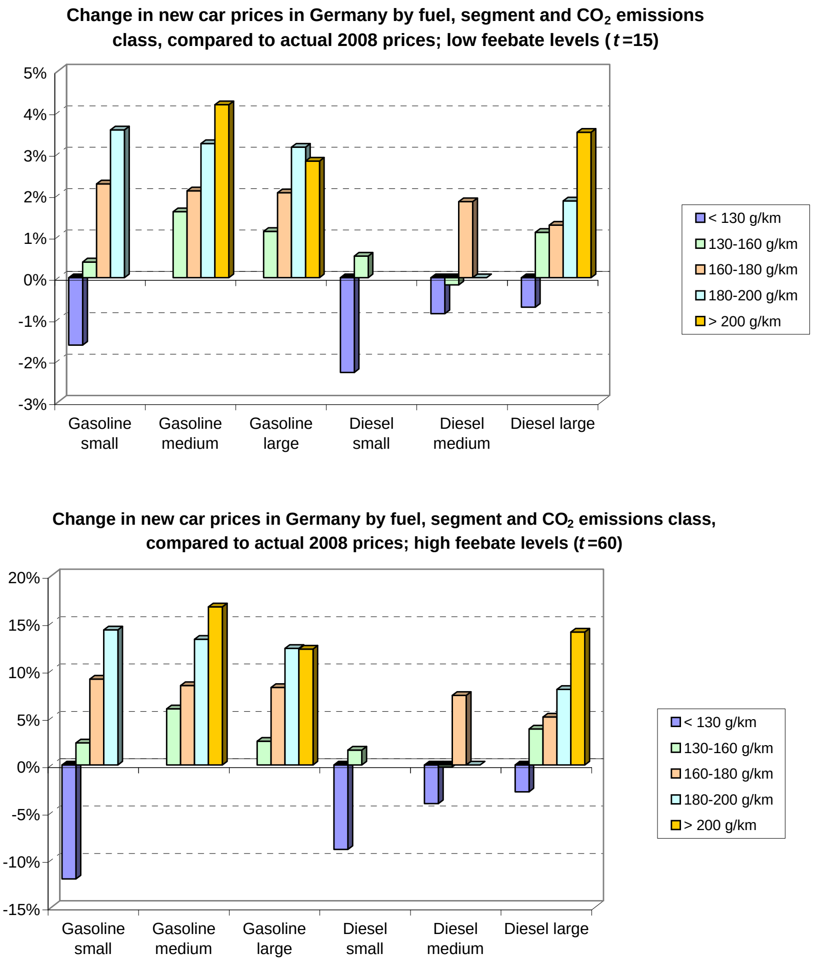

Figure 1: Simulated changes in prices in the German automobile market.

lowest CO_2 emission class (130-160 g/km). Total sales of new cars (not shown on the graph), which amounted to about 2.9 million cars in year 2008, decrease by 0.6% in the lenient feebate case and by 4.2% in the stringent feebate case. This is the primary reason for reduced markups and consumer welfare as will be demonstrated in Figures 5 and 6.

In order to provide more insight into shifts in the automobile market induced by the feebate system, Figure 3 illustrates the simulated sales shares by emissions class, according to the four different feebate levels described above, and compares them with the actual sales shares observed in the German market in year 2008. Obviously, the more stringent the feebate the higher the fraction of low- and medium-CO_2 cars sold in the market. From 57% of actual total sales, automobiles with emission levels up to 160 g/km dominate the market in the strong feebate

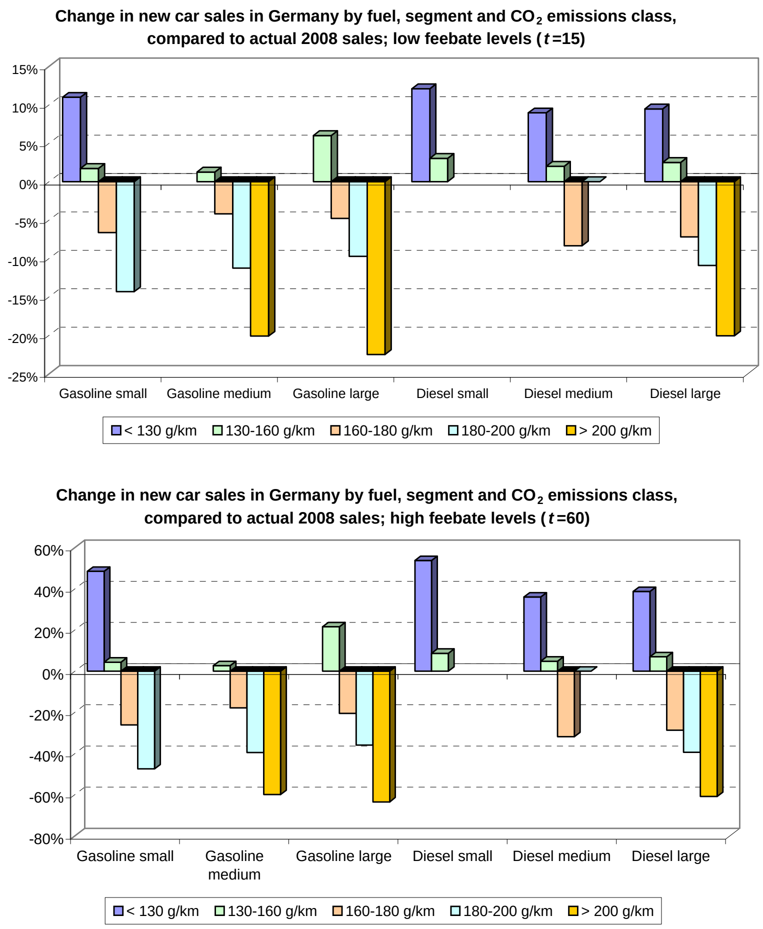

Figure 2: Simulated changes in sales volumes in the German automobile market.

case, approaching 70% of total sales. Higher emitting vehicles are faced with a drop in their sales; in the strong feebate case, the share of cars emitting over 200 g/km drops to less than half, from 9.0% to 3.6%; and the share of cars emitting between 160 and 180 g/km falls from 10.6% to 7.1%.

The feebate leads to a shift towards sales of lower-carbon cars, and smaller sized cars. As Figure 4 demonstrates, the sales fraction of the 'small' segment rises from almost 25% (actual sales in 2008) to over 31% (simulated sales with a strong feebate). As was shown in Figure 2, small gasoline cars are the main winners because they exhibit the lowest average CO_2 emission levels. Although the share of medium-sized gasoline cars falls with increasing feebate stringency, the corresponding fraction of medium-sized diesel cars rises considerably as there is a shift to this segment primarily from larger diesel cars. The share of all larger cars (segments 'large',

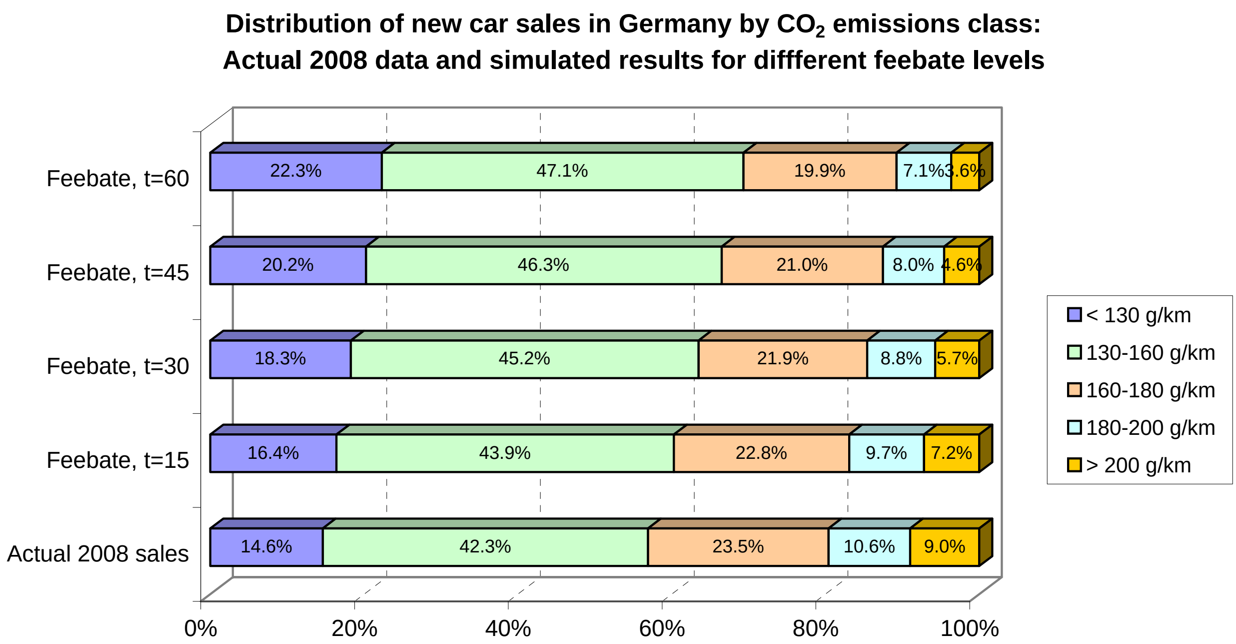

Figure 3: Actual and simulated sales shares in Germany by emissions category.

'SUV', 'sports' and 'luxury'), both gasoline and diesel powered, diminishes substantially because of their higher than average CO_2 emissions. Obviously this graph describes only average changes in sales between segments, and does not display the shifts taking place within each segment, from high-carbon to low-carbon cars, which also contribute to the simulated reductions in carbon emissions.

When consumers purchase a more fuel efficient (and low-carbon) car it is possible that they drive more with it because fuel costs are cheaper (the so called rebound effect) or that they drive more with it and drive less with a second, less fuel efficient car that they own. Such an effect might partly offset the environmental benefit of a low-carbon car. However, in these calculations we have implicitly assumed that each consumer chooses the mileage to drive with a car before purchasing a specific car model, regardless of its size and the fuel it uses. Moreover, the rebound effect has been found to diminish in recent years, at least in the US (Small and Van Dender, 2007).

Coming to the aggregate simulation results, Figure 5 illustrates the trade-off between environmental effectiveness and three economic variables - public revenues, markups and consumer welfare respectively. They display the results of simulations carried out with all three different

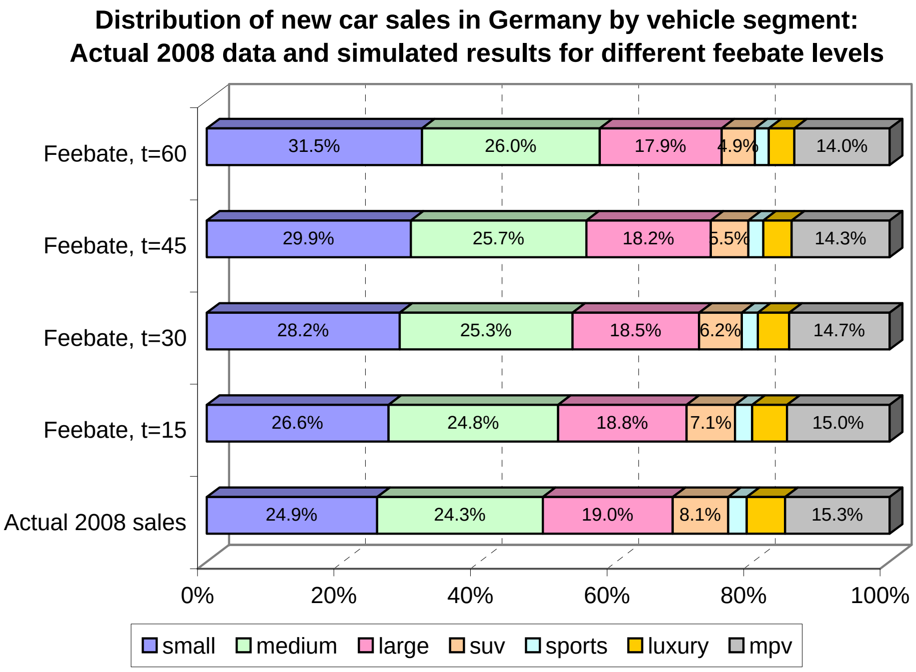

Figure 4: Actual and simulated sales shares in Germany by fuel and engine size.

pivot points and four different feebate levels mentioned above.

The higher the tax rate t, the more stringent the system for high-carbon cars and the more generous to low-carbon ones. Therefore, with higher values of t it is possible to attain higher reductions of new car CO_2 emissions through strong shifts in sales from high-carbon to low-carbon cars. On the other hand, such a system substantially increases the price of most large and medium-sized cars, thereby reducing automobile sales in general and leading to a drop in both markups (due to lower demand) and consumer welfare (since some consumers avoid purchasing a new car at these prices). Depending on the level of the pivot point, public revenues sometimes decrease with increasing stringency of the feebate (as more rebates have to be paid to buyers of low-carbon cars whose sales increase greatly) and sometimes increase (as the tax revenues collected by high-carbon cars outweigh the rebates paid to low-carbon ones).

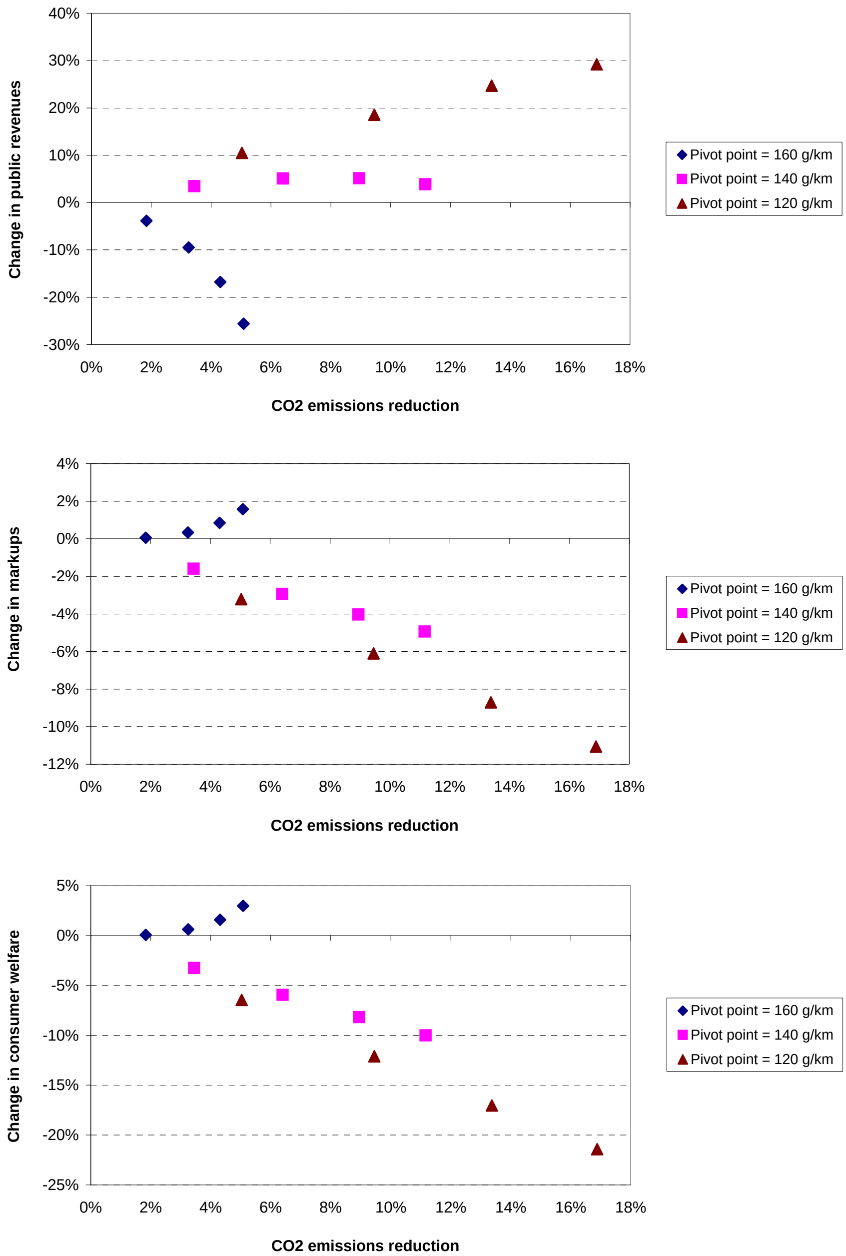

Figure 5: Effect of a feebate on public revenues, firm markups and consumer welfare for different stringency levels and different pivot points. Changes are expressed in percentage terms compared to the values of the corresponding variables according to actual sales in the German car market in year 2008. The value of t increases as we move to the right of each graph, corresponding to increasing stringency.

If the pivot point is set at relatively high levels (e.g. 160 g/km) then the system is more lenient towards high-carbon cars (their prices do not rise very much), and at the same time it is more generous in rebates to low-carbon vehicles (as their emissions are much lower than the pivot point). This combination keeps firm markups and consumer welfare unchanged or even slightly higher than the no feebate case, but leads to a significant decline in public revenues: high-carbon cars do not pay a high fee while low-carbon cars receive substantial amounts in rebates and therefore increase their sales. The environmental effectiveness of such a system is limited due to the effects mentioned above. Using lower pivot points may keep public revenues under control - and may even substantially increase them in the case of a low pivot point such as 120 g/km, but this comes at the detriment of firm and consumer surplus, which decline because car sales drop. These simulations illustrate that it is possible to design a feebate system (for example with a pivot point close to 140 g/km) that can be reasonably effective in terms of reducing CO_2 emissions of new cars without being particularly detrimental to other economic variables.

To construct Figure 5, we have assumed that the environmental effect comes from both a decrease in emissions per car and a decline in the total number of new cars sold. However, in a country like Germany, with a nearly saturated car market, lower car sales do not lead to a proportional reduction in emissions because most of the new cars sold are intended to replace existing older vehicles. This means that if new sales are reduced this will largely cause a higher use of existing cars, whereby the environmental benefit is unclear (it mainly depends on the emission levels of older cars that are not replaced by new ones due to the change in the tax regime). Therefore, we show in Figure 6 an alternative indicator of environmental benefit, where the horizontal axis expresses the reduction in emissions per car, i.e. how much sales-weighted average new-car emissions per kilometer have decreased compared to the actual values of year 2008. In most cases the CO_2 effect is smaller when using the latter indicator because most scenarios examined here lead to a decline in new car sales and hence not counting this decrease as an environmental benefit reduces the total effectiveness. In practice, the environmental effect – for each tax rate and pivot point – lies probably between the two different values shown in Figures 5 and 6 respectively: some of the cars sold are not intended for replacing older ones, hence a part of the drop in automobile sales will indeed decrease total CO_2 emissions due to lower automobile ownership in the country. For example, for a pivot point of 140 g/km (the points indicated with squares in Figures 5 and 6), the environmental effect according to Figure 5 is 3.4% for the low tax rate and 11.2% for the high tax rate respectively, whereas it is 1.9% and 6.4% for the corresponding tax rates according to Figure 6.

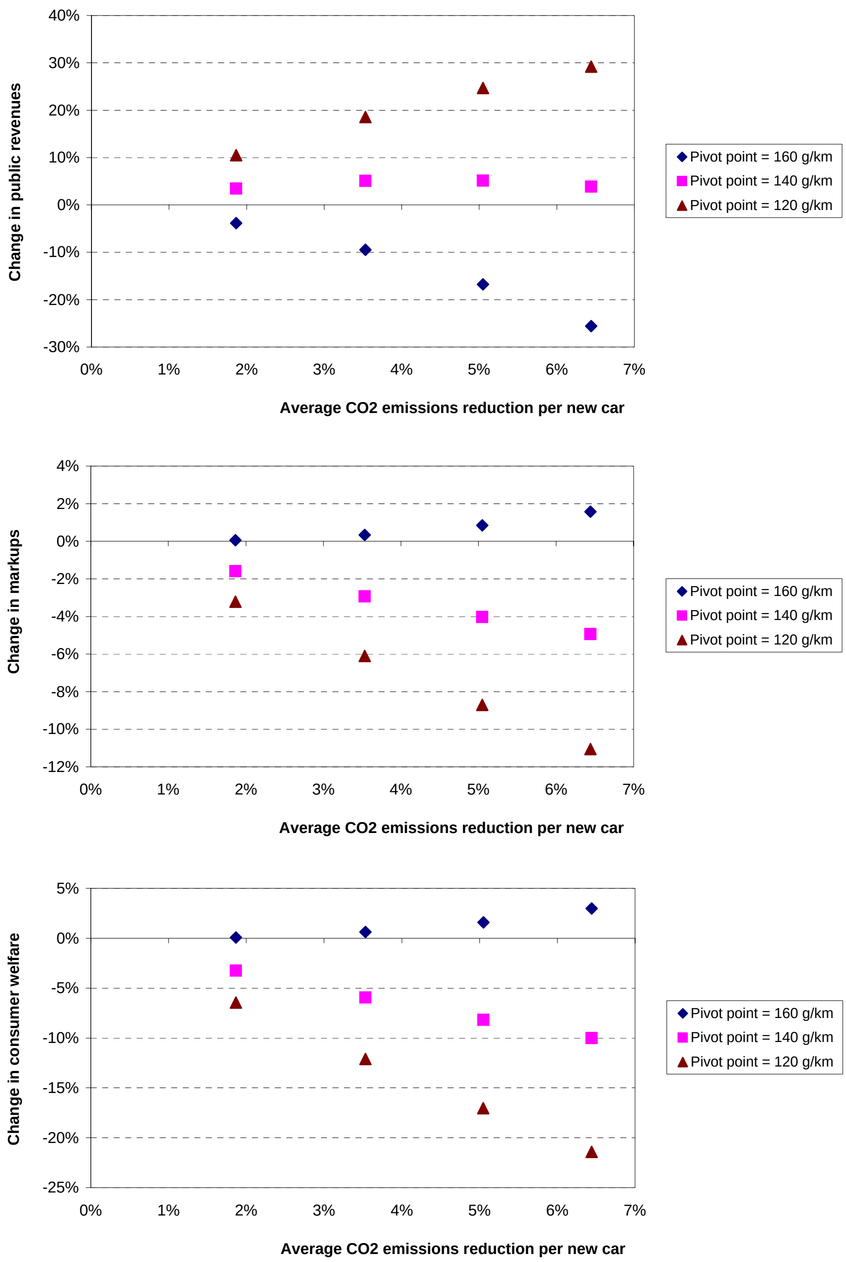

Figure 6: Effect a feebate on public revenues, firm markups and consumer welfare for different stringency levels and different pivot points. The horizontal axis expresses the reduction in sales-weighted average new-car emissions per kilometer.

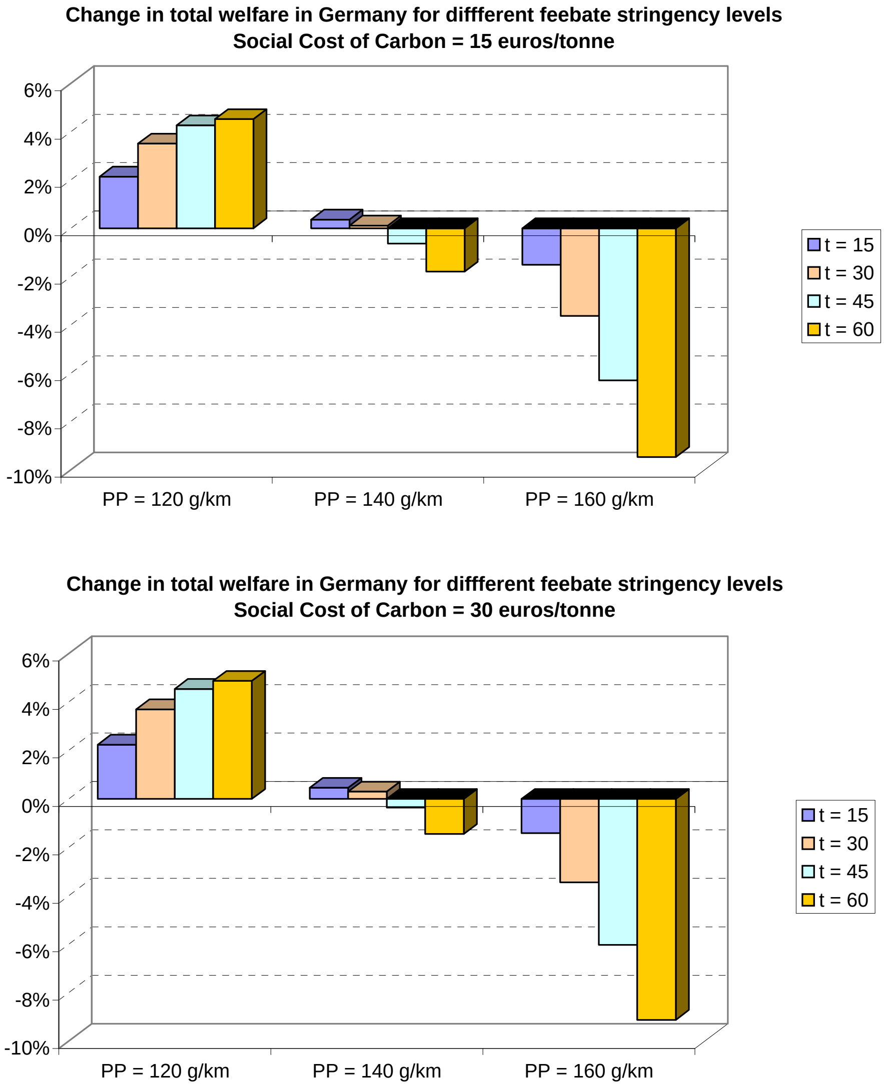

Figure 7: Total economic impact of each simulated feebate program, for two different values for the social cost of carbon.

Figure 7 and Table 4 illustrate the overall economic impact of these policies by adding up all four effects (on emissions, public finances, firm markups and consumer surplus) mentioned above. Thus they display the change in total social welfare as a result of each feebate alternative. For this purpose it is necessary to express emission reductions in monetary terms, in order to reflect the increase in social welfare due to reduced environmental damage because of reduced carbon emissions in each feebate scenario. Here we assumed that a car has a lifetime of 200,000 kilometers and that its CO_2 emission level remains constant (at the initial registered level) throughout its lifetime. Reduced environmental damage comes from lower average carbon emissions per car and in some cases also from reduced new car sales. However, as explained earlier in this section, the fact that fewer cars may be sold under a feebate program than without the program does not lead to a proportional environmental benefit since many of those cars would replace older ones. Hence in order to estimate the net environmental benefit realistically it is necessary to account only for those cars which would enter the market without replacing other ones. Comparing the German statistics of total car stock with those of new automobile registrations in the 2000s we found that the annual increase in the stock represents only 4-7% of new registrations (European Commission, 2010). We therefore assumed that if a feebate scenario leads to reduced car sales, only 6% of these sales will indeed cause an environmental benefit and thus increase social welfare. Finally, in line with the central estimates provided by expert groups for policy makers (Aldy, Krupnick, Newell, Parry, and Pizer, 2010; Interagency Working Group on Social Cost of Carbon, 2010), we assumed a social cost of carbon (SCC) equal to 15 euros (at 2005 prices) per tonne of CO_2 [10]. According to a standard definition, the SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year, to account for adverse economic impacts of climate change to agricultural productivity, human health, natural disasters etc. (Interagency Working Group on Social Cost of Carbon, 2010). For sensitivity analysis we also calculated total welfare changes assuming a higher SCC value equal to 30 euros/tonne.

As Figure 7 shows, a feebate can increase social welfare if the program's threshold (pivot point) is set at relatively low levels, e.g. at 120 g/km, regardless of program stringency. At moderate pivot point such as 140 g/km the effect may be marginally positive or negative for welfare. For reasons explained earlier in this section, setting the pivot point at higher levels will generate more costs than benefits; and high stringency levels (i.e. high values of t) do not make much economic sense since they imply a very high carbon tax. Assumptions regarding the social cost of carbon have a negligible effect on the whole result. This is because the overall environmental benefit is quite low because of the modest amount of carbon emissions saved per car and because the feebate applies to new cars only, thus leaving the rest of the car stock unaffected.

These welfare changes are expressed in absolute terms in Table 4. Overall, economic impacts - depending on feebate settings and carbon values - range from -2.5 to +1.3 billion euros at 2005 prices; with a total national GDP of about 2.5 trillion 2005€ (European Commission, 2010),

[10] This value corresponds to the value of 21 US dollars at 2007 prices per tonne of CO_2 suggested by Interagency Working Group on Social Cost of Carbon (2010), deflated to prices of year 2005 that we use throughout the paper, and assuming an exchange rate of 1.4 US dollars per Euro.

Table 4: Total economic impact of each simulated feebate program, for two different values for the social cost of carbon (SCC), in million euros at 2005 prices

SCC=15 euros/tonne CO_2		Pivot Point	
t	160 g/km	140 g/km	120 g/km
15	-397.4	94.1	562.4
30	-954.3	29.3	921.7
45	-1654.2	-165.7	1120.6
60	-2489.2	-471.9	1188.4
SCC=30 euros/tonne CO_2		Pivot Point	
t	160 g/km	140 g/km	120 g/km
15	-371.1	120.4	588.8
30	-904.3	79.2	971.7
45	-1582.9	-94.3	1192.0
60	-2398.2	-380.8	1279.4

these welfare effects range from -0.10% to +0.05% of the German GDP.

It has to be noted that, since our model is static, these calculations may not be able to capture the full long-run effects of a feebate policy because they do not take into account future changes on the supply side, i.e. the response of auto manufacturers who may proceed with investments in new technologies in order to produce more low-carbon cars in the longer term. Notwithstanding this caveat, it is reasonable to state that a feebate program, although having a small immediate impact because it addresses only new cars sold in the market, can provide a long-term signal to both auto manufacturers and consumers and hence can induce technological progress in the auto industry. This signal will be even stronger if the system's pivot point decreases over the years, which is equivalent to an increasingly more stringent CO_2 standard and provides incentives for continuous technological improvements.

7 Concluding remarks

This paper has described a model of oligopolistic competition in markets with differentiated products, simulating demand and supply under alternative tax regimes in the car market. The model can be applied using detailed sets of car data that are typically available (though not freely) for OECD countries. We have shown through empirical estimations that the model is an improvement over the standard nested logit model that is widely used in the literature, thereby enabling the estimation of richer demand patterns without imposing a high computational burden. The objective is to perform simulations in order to evaluate policies that could shift consumer purchases towards low-CO_2 cars and thus lead to the reduction of fuel use and CO_2 emissions. Using a detailed dataset for the period 2002-2008, we have presented results from the econometric analysis and policy simulations for the car market of Germany. We found automobile fuel cost and CO_2 emissions to be almost insignificant for consumers when they determine to purchase a new car; this lends support to the statement of Greene (2010) that consumers substantially undervalue fuel economy relative to its expected present value.

We simulated the effect from the implementation of feebates on newly purchased cars, which impose an additional fee to be paid by high-carbon vehicles and a rebate to be given to purchases of low-carbon automobiles. A linear tax was introduced in such a way that it is positive for cars with CO_2 emissions over a given emission level (the so called pivot point) and negative for cars with emissions lower than this threshold.

It turns out that, if the pivot point is set at high levels (approaching the current sales-weighted new-car average CO_2 emissions in the country), then it is much more difficult to reduce CO_2 emissions even if the tax rate is very high. A high pivot point may increase car sales (and hence firm profits and consumer welfare) but leads to a significant loss of public revenues. On the other hand, a pivot point set at low levels may increase public revenues and reduce CO_2 emissions effectively at the cost of a large decline in total car sales, leading to a substantial drop of markups and welfare. It is essential for policy makers to choose wisely the pivot point and the linear tax rate in a way that they weigh precisely both costs and benefits. Our analysis for Germany has shown that it is possible to design a feebate program for new automobiles that brings about carbon emission reductions without reducing total welfare; in fact it can also increase welfare through the combined effect of improved public finances and lower environmental damage through reduced CO_2 emissions.

This analysis has important policy implications. At a time when national governments increasingly adopt a CO_2-based element in the calculation of their vehicle taxes, the model described in this paper constitutes a tool for the evaluation of real-world policy options. This is particularly important as current car taxation policies seem to have been designed in many cases without a sound analysis of consumer response to these policies. As a result, the effect on public revenues is often assessed by governments in a very rough manner, which may lead to significant errors. If consumer response is overestimated then a specific policy does not have the effect it was initially assumed to have; on the other hand, if consumer response is underestimated then the policy may prove to be more successful than initially thought, which in turn may lead to a significant loss of public revenues - this was indeed so in at least three cases we are aware of: the CO_2 rebate system in the Netherlands in year 2002, the French feebate system ('bonus-malus') that was launched in 2008 (Bastard, 2010) and a CO_2-based car taxation scheme introduced in Ireland in 2008 (Rogan, Dennehy, Daly, Howley, and Ó Gallachóir, 2011).

Results of this study can also have important implications for EU-wide policies towards vehicle taxation. Although taxation generally remains under the competence of national authorities, attempts to harmonize vehicle taxes at EU level are under way. Some years ago, the European Commission issued a proposal for a law (Directive) that would, inter alia, oblige EU Member States to change their taxation schemes so that at least half of the total revenues from vehicle taxation came from CO_2-based taxes (European Commission, 2005). Virtually no progress has been made on this proposal, primarily because of issues of national sovereignty in taxation matters. However, in an ever more carbon-constrained world, these topics are always open for discussion and economic research has an important role to play.

The analysis can be enriched in several ways, such as estimating a richer demand model or experimenting with additional taxation schemes. Perhaps the greatest challenge in this literature is in the modeling of the dynamic adjustment of auto manufacturers to gradual changes in consumer preferences due to increasingly stringent environmental taxation. Nonetheless, even this static framework can be a quite useful tool for analyzing carbon-based tax policy options and contributing towards a more effective and efficient low-carbon transportation policy.

References

Aldy, J., A. J. Krupnick, R. Newell, I. W. H. Parry, and W. A. Pizer, 2010, "Designing Climate Mitigation Policy," *Journal of Economic Literature*, 48(4), 903–934.

Anderson, S. T., I. W. H. Parry, J. Sallee, and C. Fischer, forthcoming, "Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives," *Review of Environmental Economics and Policy*, doi:10.1093/reep/req021.

Bastard, L., 2010, "The Impact of Economic Instruments on the Auto Industry and the Consequences of Fragmenting Markets - Focus on the EU Case.," Discussion Paper No 2010-08, International Transport Forum. `http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DP201008.pdf`.

Berry, S. T., 1994, "Estimating Discrete Choice Models of Product Differentiation," *RAND Journal of Economics*, 25(2), 242–262.

Berry, S. T., J. Levinsohn, and A. Pakes, 1995, "Automobile Prices in Market Equilibrium," *Econometrica*, 63(4), 841–890.

Braathen, N.-A., forthcoming, "CO_2-Based Taxation of Motor Vehicles," in *Cars and Carbon: Automobiles and European Climate Policy in A Global Context*, ed. by T. Zachariadis. Springer.

Bresnahan, T. F., S. Stern, and M. Trajtenberg, 1997, "Market segmentation and the sources of rents from innovation: personal computers in the late 1980s," *RAND Journal of Economics*, 28, S17S44.

Bunch, D. S., D. L. Greene, T. Lipman, E. Martin, and S. Shaheen, 2011, "Potential Design, Implementation, and Benefits of a Feebate Program for New Passenger Vehicles in California.," Final Report to California Air Resources Board and California Environmental Protection Agency, February.

Cardell, N. S., 1997, "Variance Components Structures for the Extreme-Value and Logistic Distributions with Application to Models of Heterogeneity," *Econometric Theory*, 13(2), 185–213.

de Haan, P., M. G. Mueller, and R. W. Scholz, 2009, "How Much Do Incentives Affect Car Purchase? Agent-based Microsimulation of Consumer Choice of New Cars Part II: Forecasting Effects of Feebates Based on Energy-Efficiency," *Energy Policy*, 37, 1083–1094.

European Automobile Manufacturers Association, 2009, "Overview of CO_2 Based Motor Vehicle Taxes in the EU," `http://www.acea.be/images/uploads/files/20090428_CO2_taxation_overview.pdf`.

European Commission, 2002a, "Fiscal Measures to Reduce CO_2 Emissions from New Passenger Cars," European Commission DG Taxation and Customs Union.

——— , 2002b, "Fiscal Measures to Reduce CO_2 Emissions from New Passenger Cars," Final report, European Commission DG Environment.

——— , 2005, "Proposal for a Council Directive on passenger car related taxes," European Commission, Document COM(2005) 261 final, Brussels.

——— , 2010, "EU Energy and Transport in Figures Statistical Pocketbook 2010," Publications Office of the European Union, Luxembourg.

Fershtman, C., N. Gandal, and S. Markovich, 1999, "Estimating the Effect of Tax Reform in Differentiated Product Oligopolistic Markets," *Journal of Public Economics*, 74, 151–170.

Fischer, C., 2008, "Comparing Flexibility Mechanisms for Fuel Economy Standards," *Energy Policy*, 36, 3116–3124.

Greene, D., 2010, "Why the Market for New Passenger Cars Generally Undervalues Fuel Economy," *Discussion Paper No. 2010-6, International Transport Forum, Paris, France.*

Greene, D. L., P. D. Patterson, M. Singh, and J. Li, 2005, "Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy," *Energy Policy*, 33, 757–775.

Interagency Working Group on Social Cost of Carbon, 2010, "Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866," Interagency Working Group on Social Cost of Carbon of the United States Government, Washington, DC, February.

International Energy Agency, 2009, "Transport, Energy and CO_2 - Moving Toward Sustainability," International Energy Agency, Paris, France.

King, J., 2007, "The King Review of Low-Carbon Cars - Part I: The Potential for CO_2 Reduction," Independent review, HM Treasury, London, http://hm-treasury.gov.uk/king.

Liu, C., E. C. Cooke, D. L. Greene, and D. Bunch, 2011, "Impacts of feebates and fuel economy standards on U.S. light-duty vehicle fuel use and greenhouse gas emissions," Paper No. TRB-11-2027 presented at Transportation Research Board Annual Meeting, Washington, DC, January.

McFadden, D., 1978, "Modelling the Choice of Residential Location," in *Spatial Interaction Theory and Planning Models*, ed. by A. Karlvist, L. Lundqvist, F. Snickars, and J. Weibull. North Holland, Amsterdam, Studies in Regional Science and Urban Economics, pp. 75–96.

OECD, 2009, "Incentives for CO_2 Emission Reductions in Current Motor Vehicle Taxes," Document ENV/EPOC/WPNEP/T(2009)2/FINAL, Organisation for Economic Co-operation and Development, Paris, France.

Pakes, A., S. T. Berry, and J. A. Levinsohn, 1993, "Applications and Limitations of Some Recent Advances in Empirical Industrial Organization: Price Indexes and the Analysis of Environmental Change," *American Economic Review Papers and Proceedings*, 83(2), 240–246.

Peters, A., M. Mueller, P. de Haan, and R. Scholz, 2008, "Feebates promoting energy-efficient cars: Design options to address more consumers and possible counteracting effects," *Energy Policy*, 36, 1355–1365.

Rogan, F., E. Dennehy, H. Daly, M. Howley, and B. P. Ó Gallachóir, 2011, "Impacts of an emission based private car taxation policy - First year ex-post analysis," *Transportation Research Part A*, 45, 583–597.

Sallee, J., 2010, "The Taxation of Fuel Economy," Working Paper 16466, National Bureau of Economic Research.

Small, K. A., and K. Van Dender, 2007, "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect," *The Energy Journal*, 28, 25–51.

Trajtenberg, M., 1989, "The welfare analysis of product innovations, with an application to computed tomography scanners," *Journal of Political Economy*, 50, 647–658.

Vance, C., and M. Mehlin, 2009, "Fuel Costs, Circulation Taxes, and Car Market Shares: Implications for Climate Policy," *Transportation Research Record: Journal of the Transportation Research Board*, (2134), 31–36.

Verboven, F., 1996, "International Price Discrimination in the European Car Market," *RAND Journal of Economics*, 27(2), 240–268.

———, 2002, "Quality-Based Price Discrimination and Tax Incidence: Evidence From Gasoline and Diesel Cars," *RAND Journal of Economics*, 33(2), 275–297.

A Appendix

A.1 Derivation of the demand equation for the two-level nested logit

Here we derive the demand equation for the nested logit with two nests. Following Verboven (1996), the specific functional form of the share for a car j, belonging to a subgroup h of group g, is given by:

$$s_j = \left[\frac{\exp\left(\frac{\delta_j}{1-\sigma_1}\right)}{\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)}\right]\left[\frac{\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}}{\sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}}\right]\left[\frac{\left[\sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}\right]^{1-\sigma_2}}{\sum_{g\in G}\left[\sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}\right]^{1-\sigma_2}}\right]. \tag{6}$$

The outside good is the only member of group zero and $s_{0/h_0} = s_{h_0/g_0} = 1$. Hence,

$$s_0 = \frac{1}{\sum_{g\in G}\left[\sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}\right]^{1-\sigma_2}}.$$

The ratio of the two previous equations is:

$$s_j/s_0 = \left[\frac{\exp\left(\frac{\delta_j}{1-\sigma_1}\right)}{\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)}\right]\left[\frac{\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}}{\sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}}\right]\left[\sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}\right]^{1-\sigma_2}.$$

Define $D_h = \sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)$ and $D_g = \sum_{h\in g}\left[\sum_{j\in h}\exp\left(\frac{\delta_j}{1-\sigma_1}\right)\right]^{\frac{1-\sigma_1}{1-\sigma_2}}$.

We can now derive a simple analytic expression for mean utility levels that depend on the unknown values of D_h and D_g. Taking logs of market shares,

$$\ln(s_j) - \ln(s_0) = \frac{\delta_j}{1-\sigma_1} + \frac{\sigma_2-\sigma_1}{1-\sigma_2}\ln(D_h) - \sigma_2\ln(D_g). \tag{7}$$

Next we need to find analytic expressions for D_h and D_g as functions of $s_j, s_0, s_{j|h}$ and $s_{h|g}$. It is known that $s_g = \frac{D_g^{1-\sigma_2}}{\sum_{g\in G} D_g^{1-\sigma_2}}$. So $s_g = D_g^{1-\sigma_2}s_0$ and $\ln(D_g) = \frac{1}{1-\sigma_2}\left[\ln(s_g) - \ln(s_0)\right]$. As $s_g = \frac{s_j}{s_{j|h}s_{h|g}}$, then

$$\ln(D_g) = \frac{\ln(s_j) - \ln(s_0) - \ln(s_{j|h}) - \ln(s_{h|g})}{1-\sigma_2}. \tag{8}$$

The share of j in subgroup h, $s_{j|h}$, is equal to $\frac{\exp\left(\frac{\delta_j}{1-\sigma_1}\right)}{D_h}$. By taking logs, the following analytic expression for $\ln(D_h)$ is obtained:

$$\ln(D_h) = \frac{\delta_j}{1-\sigma_1} - \ln(s_{j|h}). \tag{9}$$

Substituting equations (9) and (8) into equation (7) concludes to the demand equation for nested logit with two nests as follows:

$$\ln(s_j) - \ln(s_0) = \delta_j + \sigma_1 \ln(s_{j|h}) + \sigma_2 \ln(s_{h|g}),$$

where $\delta_j = x_j\beta - \alpha P_j + \xi_j$.

A.2 Public revenues, environmental effects, firm profits and welfare

Using the estimates $\hat{\gamma}$, $\hat{\beta}$,$\hat{\alpha}$, $\hat{\sigma_1}$ and $\hat{\sigma_2}$, we can compute the share of the outside good, firm profits (from the markup term), and public revenues. Public revenues from product j are $\frac{vP_j}{1+v}$, and firm profits from product j are given by the markup term in equation (5). We multiply both with sales volume (shares*M) to obtain the sum per market and year. The environmental effect is the sum of CO_2 emissions; we multiply CO_2 emissions with sales volume and then sum them up for each market and year.

Our measure of consumer welfare is obtained by integrating over the demand system, which leads to the following expression (Trajtenberg, 1989; Verboven, 1996):

$$W = \frac{1}{\alpha} \ln \left(\sum_{g \in G} \left[\sum_{h \in g} \left[\sum_{j \in h} \exp(\frac{\delta_j}{1 - \sigma_1}) \right]^{\frac{1-\sigma_1}{1-\sigma_2}} \right]^{1-\sigma_2} \right) + C,$$

where C is the constant of integration and can be ignored because only the change in welfare $(W_{simul} - W_{actual})$ is of interest.

A.3 Simulation details

We need to solve a system of 902 nonlinear equations of the form (5). Matlab's built-in nonlinear equation solver failed to produce a solution. To circumvent this problem we resorted to contraction mapping techniques. Consider a slightly simplified form of equation (5) in vector form:

$$P = MC + MU(P). \tag{10}$$

The vector of prices P is equal to marginal cost MC plus a markup term MU, which is itself a function of P. We know MC and the functional form $MU(P)$ and we are interested in the unique vector P^* that solves (10). Define T as the mapping:

$$T[P] = MC + MU(P). \tag{11}$$

Suppose we start from an initial vector of prices P^0 and repeatedly apply T:

$$P^n = MC + MU(P^{n-1}) \tag{12}$$

Then, if T is a contraction mapping with modulus less than one (more on that below), $lim_{n\to\infty}P^n = P^*$. In other words, starting from P^0 and repeatedly applying T will converge to the unique solution P^*.

We conjectured that T is indeed a contraction and applied this procedure to our problem. The method converged to a solution in both the 1-level and the 2-level nested logit. Verifying that the convergence point is a solution to (10) is straightforward; one just has to plug it into (10) and verify that the equation holds. Showing that the solution is unique is more difficult. Ideally one would like to establish uniqueness by showing that T is a contraction mapping with modulus less than one. A contraction mapping, or contraction, on a metric space (M, d) is a function T, with the property that there is some nonnegative real number $k \in (0, 1)$ such that for all P in M, $d(T(P), T^2(P)) \leq kd(P, T(P))$.

Unfortunately we were not able to show that T is a contraction. In order to ensure that our solution was unique we experimented with different starting points P^0. The procedure converged to the same solution no matter where we started from, even from out-of-the-way points such as identical prices. This does not constitute formal proof that the solution is unique, yet it is hard to see what another possible solution could lie. We therefore use the solution obtained from this method to conduct the analysis in section 6.

A.4 Additional estimates

Table 5: Estimates of country dummies in demand equation

Variables	1-level NML		2-levels NML	
	OLS	IV	OLS	IV
China	0.029	-0.686*	0.028	-0.876**
	(0.089)	(0.334)	(0.089)	(0.341)
Czech Rep.	0.014	0.030	0.014	0.058
	(0.012)	(0.045)	(0.012)	(0.046)
England	0.011	0.042	0.011	0.056*
	(0.0067)	(0.026)	(0.0068)	(0.027)
France	-0.0082	-0.066**	-0.0081	-0.050†
	(0.0058)	(0.024)	(0.0058)	(0.026)
Germany	0.013*	0.379**	0.013*	0.387**
	(0.0054)	(0.031)	(0.0054)	(0.031)
Italy	-0.047**	-0.178**	-0.047**	-0.178**
	(0.0075)	(0.039)	(0.0075)	(0.040)
Korea	-0.023**	-0.352**	-0.023**	-0.343**
	(0.0077)	(0.033)	(0.0077)	(0.034)
Romania	0.034	-0.161	0.034	-0.109
	(0.035)	(0.134)	(0.035)	(0.136)
Russia	-0.054†	-0.654**	-0.054†	-0.665**
	(0.029)	(0.112)	(0.029)	(0.114)
Spain	-0.024*	-0.215**	-0.024*	-0.194**
	(0.010)	(0.041)	(0.010)	(0.042)
Sweden	-0.0087	-0.037	-0.0088	-0.054
	(0.0087)	(0.041)	(0.0087)	(0.041)
Switzerland	0.017	-0.356**	0.017	-0.320**
	(0.015)	(0.057)	(0.015)	(0.059)
USA	-0.077**	-0.461**	-0.077**	-0.490**
	(0.015)	(0.057)	(0.015)	(0.060)

Significance levels: $\dagger$: 10%, $*$: 5%, $**$: 1%. Standard errors are reported in parentheses. Variables shown here denote the country of origin of each car model. See further explanations in table 3.