Welfare Implications of Automobile Feebates: A Simulation Analysis*

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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 evidence on its effectiveness and economic impact is limited. We focus on feebate schemes, which impose a fee on high-carbon vehicles and give a rebate to low-carbon automobiles. We estimate demand for automobiles in Germany and simulate the impact of alternative feebate schemes on emissions, consumer welfare, public revenues and firm profits. We find that revenue-neutral feebate schemes are welfare-decreasing; welfare can only increase with schemes that increase tax revenues at the expense of consumer and producer surplus.

Keywords: CO_2 emissions, feebates, environmental taxation, carbon taxation.

JEL Classification: Q52, Q58, L92.

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1 Introduction

Transportation is globally the largest final energy consuming sector, accounting for about 19% of worldwide energy consumption and 23% of energy-related CO_2 emissions. These shares are growing; current projections put the sector's carbon emissions at 50% of the total in 2030 and over 80% in 2050 (International Energy Agency, 2009). This increase essentially cancels out any progress toward limiting carbon emissions in other sectors of the global economy. A wide consensus is now emerging that carbon emissions from the transportation sector need to be curbed substantially in order to successfully address the risks associated with global warming.

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 that has been receiving increased attention in Europe and the United States is the design of a motor vehicle taxation system that will induce consumers to purchase vehicles with low CO_2 emissions. The idea is to use the tax system to change the relative prices of vehicles of different carbon emission levels, thus leading to substitution from high-emission to low-emission vehicles. This is the rationale behind recently introduced feebate schemes, which pay a rebate to consumers purchasing a fuel-efficient vehicle and impose a penalty on those purchasing gas-guzzlers.

The feebate system may be a promising policy option because 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, 2011). In countries that already have significant 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. It should be noted, however, that gasoline taxes may be more effective because they apply to all cars and because they penalize usage rather than ownership. Feebates apply to newly sold cars only and – like fuel economy standards and unlike gasoline taxes – may give rise to rebound effects.[1]

[1] The term 'rebound effect' refers to the tendency for vehicle use to increase when fuel efficiency increases (since the cost per unit distance decreases).

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 once upon purchase) or of circulation taxes (paid annually).[2] Despite the increased use of such schemes, there is little research regarding their appropriate design and impact, especially at the European level. The few existing studies focus on the United States, yet the impact of feebate schemes may be different in Europe with its high gasoline taxes and relatively more efficient vehicle fleet. The aim of this paper is to contribute to the debate by analyzing the environmental and economic effects from the hypothetical adoption of a feebate system in Germany. Germany is an important case study because it is the largest European economy and its regulatory initiatives can have a wider impact across the continent. We estimate demand for automobiles during 2002-2008 using three different variants of the widely used nested logit model. We use the estimated demand systems to simulate feebate policies of varying stringency and compute the impact of the various policies on consumer welfare, profits, public revenues, and CO_2 emissions.

With the aid of this model we experiment with different parameters of a potential feebate program. We introduce a 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. The tax can be symmetric – meaning equal rates for the positive and negative parts – or asymmetric. We then explore trade-offs between environmental effectiveness and economic impact. We initially focus on revenue-neutral schemes that are more likely to be implemented for political reasons. We find that revenue-neutrality can be achieved with a low tax rate and a pivot point that is somewhat lower than the current average CO_2 emission level of newly sold cars. However, the environmental benefit – when evaluated using conventional measures of the damage caused by emissions – is not enough to make up for the loss in consumer and producer surplus induced by the scheme. Hence, a key finding that emerges from our analysis is that revenue-neutral schemes cannot be welfare-improving. We then extend our investigation to identify welfare-improving schemes. We find that welfare can increase if the pivot point is set at a level that is considerably lower than the current average emission level and the marginal tax rate is not too high, i.e. corresponds to a price of less than 100 euros per tonne of CO_2. Such a combination increases overall welfare through the combined effect of improved public finances and lower environmental damage through reduced CO_2 emissions, despite a decline in consumer and producer surplus. Essentially, for welfare to increase the feebate must look a lot more like a fee than a rebate; only a small fraction of vehicles should receive rebates. Alternatively, we find that welfare improvements can be achieved with asymmetric schemes where the tax levied on high-emitting vehicles is higher than the rebate offered to low-carbon cars.

[2]See European Automobile Manufacturers Association (2009) and OECD (2009) for overviews of the CO_2-based taxation schemes implemented before the end of year 2009 by individual countries.

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). A few other studies have made ex-post assessments of taxation schemes implemented in specific countries. Some are mostly descriptive (Rogan, Dennehy, Daly, Howley, and Ó Gallachóir (2011) for Ireland or Bastard (2010) for France) while others use econometric frameworks similar to ours (D'Haultfoeuille, Givord, and Boutin (2011) for France and Huse and Lucinda (2013) for Sweden). To our knowledge, ours is the first ex-ante econometric analysis of the possible impact of carbon-based vehicle taxation that conducts a detailed welfare analysis and focuses on the design of schemes that can deliver the desired outcomes.[3]

At a time when national governments increasingly adopt a CO_2-based element in the calculation of their vehicle taxes, it is important to ensure that policies are properly designed in order to achieve their stated objectives. Current vehicle taxation policies seem to have been designed with rough approaches and have typically underestimated consumer response. As a result, these policies have proven more successful than initially thought, which in turn has led to a significant loss of public revenues in the Dutch, Irish and French experiences. Our study highlights the tradeoffs between environmental quality, government revenues, and consumer and producer surplus that factor into the design of effective policies.

2 Existing literature

The feebate option currently implemented nationwide in Canada and France and to some extent in other European countries[4] 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

[3]In parallel work (Adamou, Clerides, and Zachariadis, 2012) we performed an ex-ante analysis of feebate policies for Greece. That study was much more limited in scope than the current paper as it only examined the impact of specific symmetric schemes on market shares; it did not consider welfare implications or explore the design of schemes that are consistent with different objectives.

[4]See the review by 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.

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 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. Other recent work that is close to ours includes D'Haultfoeuille, Givord, and Boutin (2011), on the impact of the 'bonus/malus' feebate system in France; Huse and Lucinda (2013), on the impact of Sweden's green car rebate program; and Beresteanu and Li (2011), which focuses on federal income tax incentives in the US.

Environmental 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.[5] 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 mechanisms, 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

[5] 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).

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. 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. We opted for the nested logit model because it is easier to estimate and it has been successfully used in many applications. We used a flexible specification that allows for more consumer heterogeneity by specifying two levels of nests, as in Verboven (1996). We estimated several variants of the model that lead to the same qualitative conclusions with regard to the questions we are interested in, even though the estimated demand systems have different characteristics. This is important because – unlike most previous work – our analysis does not seek to evaluate a specific program but rather to explore a wider range of options. Experimenting with several model variants allows us to be confident that our conclusions do not depend on a particular specification but have more general applicability.

3 Demand estimation

3.1 Model

We employ the widely-used multinomial nested logit model to estimate demand for automobiles. Since the model is well-known we present just a summary here. In each period, consumers face the problem of purchasing one of many available automobile models or of making no purchase. Each automobile model j is described by a set of characteristics x_j and a price p_j. Consumers have preferences over the characteristics and select the option that delivers the highest level of utility. Products (models) are divided into groups on the basis of some criterion of similarity. This might seem arbitrary, but in practice one can often adopt already existing conventions or industry classifications. In the case of automobiles different models can be classified as compact, economy, medium, luxury, SUV, MPV, estate, and so on. In the two-level nested logit model employed here, products are divided into groups, indexed by g, and each group g is further divided into subgroups, indexed by h. 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 decision making. 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. More details are provided in the estimation subsection below.

From this choice framework one can derive the following regression equation to be taken to the data:[6]

$$\ln(s_{jt}) - \ln(s_{0t}) = x_{jt}\beta - \alpha p_{jt} + \sigma_1 \ln(s_{j/h,t}) + \sigma_2 \ln(s_{h/g,t}) + \xi_{jt}. \quad (1)$$

Variable s_{jt} is the market share (units sold divided by M_t consumers) of product j in period t; s_{0t} is the share of the outside good; $s_{j/h,t}$ is the share of product j in subgroup h and $s_{h/g,t}$ is the share of all subgroup-h products in group g. Parameter α represents the marginal utility of income, while parameters σ_1 and σ_2 capture the degree of substitutability among products in the same group/subgroup. 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 $\sigma_1 = \sigma_2 = 0$, an individual's preferences are uncorrelated across all available models and the model reduces to the simple multinomial logit model. If $\sigma_1 > 0$ and $\sigma_2 = 0$ is zero, preferences are correlated across cars from the same subgroup. If $\sigma_1 > 0$ and $\sigma_2 > 0$, individual preferences are also correlated across cars from different subgroups within the same group. If $\sigma_2 \to \sigma_1$, preferences are equally correlated across all cars belonging to the same group, meaning that the second grouping is not needed. If $\sigma_1 \to 1$, cars in the same subgroup become perfect substitutes. If in addition $\sigma_2 \to 1$, all cars in the same group become perfect substitutes.

On the supply side, multi-product firms are assumed to choose prices in order to maximize total profits from all of their products. The first order condition under the assumption of Bertrand-Nash equilibrium in prices is given by the following relationship:

$$\frac{p_{jt}}{1+v_t} = mc_{jt} + \frac{1}{\alpha(1+v_t)\left[\frac{1}{1-\sigma_1} - \left(\frac{1}{1-\sigma_1} - \frac{1}{1-\sigma_2}\right) s_{f/h,t} - \frac{\sigma_2}{1-\sigma_2} s_{f/g,t} - s_{ft}\right]}. \quad (2)$$

The first order condition implies that price net of value-added tax (denoted by v_t) is equal to marginal cost (mc_{jt}) plus a markup term. Parameters α, σ_1 and σ_2 come from the demand equation (1). The term $s_{f/h,t} = \sum_f s_{j|h,t}$ denotes the share of firm f's products within subgroup h; $s_{f/g,t} = \sum_f s_{j/g,t}$ denotes the share of firm f's products within group g; and $s_{ft} = \sum_f s_{jt}$ represents the share of firm f's products in the potential market.

One can proceed by either estimating the demand equation (1) in isolation or by jointly

[6]The rest of this subsection is based on Verboven (1996).

estimating (1) and (2).[7] 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. The estimates of α, σ_1 and σ_2 from the demand equation are plugged into equation (2) 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_{jt} they will take it into account when they set prices. This will induce a positive correlation between price and the error term in an OLS regression, leading to an upward bias (lower α in absolute terms) in the estimated coefficient. 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 subsection 3.3.

3.2 Data

Data for 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 displacement, 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 separately. 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 product is at the level of the model (nameplate), e.g. Ford Focus or Renault Scenic.

Given that this choice is somewhat arbitrary but potentially important, we constructed two datasets, each at a different level of aggregation. In the 'aggregated' dataset a product is defined by the model and engine type (gasoline or diesel); this results in 729 unique products or 3,139 observations.[8] In the 'disaggregated' dataset models were split into separate products on the basis of engine displacement. The rule was to split models based on 100cc increments (1150-1250cc, 1250-1350cc, etc.). This roughly doubles the dataset to 1,571 products or 6,061

[7] The latter would require an assumption on the marginal cost function.

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

observations. Of the 729 unique products in the aggregated dataset, 289 remain a single product in the disaggregated dataset, 228 are split into two products, and the remaining 212 are split into three products or more. In the aggregated dataset a product is defined by model name and engine type (for example 'Ford Focus, diesel'); in the disaggregated dataset engine displacement is added to the description ('Ford Focus, diesel, 1.6 liters').

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. Summary statistics of key variables for the disaggregated data are provided in Table 1.

Table 1: Means of key variables

Stats	Eng. size liters	CO_2 emis. kg/km	Power HP/1000	Frame m^2	Sales units	Prices 2005€
Min	0.6	0.081	0.041	3.79	51	6,745
5%	1.2	0.126	0.068	6.05	82	11,998
25%	1.6	0.157	0.102	7.13	319	17,727
50%	2.0	0.187	0.136	7.89	1,030	24,700
75%	2.5	0.227	0.177	8.54	3,321	34,981
95%	4.0	0.293	0.286	9.38	16,184	64,108
Max	5.0	0.440	0.530	10.18	115,451	101,312
Mean	2.14	0.196	0.149	7.79	3,619	28,886
Std dev.	0.80	0.053	0.068	1.03	7,539	15,949

Source: *JATO Dynamics*. These are means over the 6,061 observations of the disaggregated data. Prices are deflated (that is why the upper bound of €100,000 is exceeded). Frame (often called 'footprint' by automobile regulators) 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 the demand estimation below. Note also that we have taken into account that the value added tax rate in Germany (variable v_t 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. disp.	CO_2 emis.	Sales	Price
Gasoline engine					
Small	705	1.33	0.149	6466	13.358
Medium	649	1.76	0.182	4660	19.884
Large	749	2.25	0.212	2497	29.496
Luxury	412	3.23	0.258	1179	53.155
SUV	421	2.90	0.268	987	37.229
Sport	408	2.63	0.229	1444	42.667
MPV	669	1.87	0.198	2662	22.654
Diesel engine					
Small	273	1.47	0.122	2227	15.037
Medium	280	1.84	0.143	7139	21.376
Large	378	2.13	0.167	7201	29.315
Luxury	230	2.81	0.213	4757	50.002
SUV	325	2.68	0.244	2849	40.343
Sport	49	2.16	0.164	1211	35.245
MPV	513	1.96	0.172	3508	25.378

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).

The calculation of market shares requires an assumption on potential market size. As is common in the literature, we use the total number of private households in each year, obtained from the UNECE Statistical Database.[9] The measure varies from 38.720 (2002) to 40.076 (2008) million.

[9]UNECE is the United Nations Economic Commission for Europe; its database is available at `http://w3.unece.org/`.

3.3 Estimation

We experimented extensively in order to identify the appropriate nesting structure for each dataset. For the disaggregated data, engine type and market segment emerged as the most appropriate classifications. 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 analysis that follows is based on estimates from this nesting structure. With the aggregated data, the best fitting nesting structure is a single level with engine type as the key variable.

As a further test, we experimented with the way price enters the demand equation. Typically price enters linearly because this is consistent with utility maximization in a discrete choice framework, but some studies have also used a logarithmic specification. A logarithmic specification implies constant expenditure and does not seem appropriate for automobiles, a classic example of discrete choice. On the other hand, if automobiles are purchased with a loan that is paid back over time, then the constant expenditure implication might not be unreasonable. From an empirical standpoint, the two specifications differ in one important dimension. Elasticities in the linear case are typically much more dispersed than in the logarithmic case and, conversely, implied markups are more dispersed in the logarithmic specification. This is simply because price enters directly in the expression for elasticity in the linear case but not in the logarithmic case. The linear model's implication that elasticities are a linear function of price is recognized to be somewhat problematic.[10] Despite the questionable theoretical justification of the logarithmic specification, it provides an opportunity to test whether a tighter range of elasticities has different implications from the other models. We therefore estimated the logarithmic specification using the disaggregated data.

In selecting instruments we followed the standard approach in the literature.[11] Specifically, we used the sum of each continuous product characteristic (engine capacity, CO_2 emissions, horsepower and frame) and of the constant term over all competing products belonging to the

[10]This feature of the model was discussed in Verboven (1996), who tried to circumvent it by using a Box-Cox specification that has the linear and logarithmic specifications as special cases. Note that this implication of linearity extends to the random coefficient case. For a recent lucid exposition of the difference between the linear and logarithmic specifications see Björnerstedt and Verboven (2013).

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

same subgroup. Note that the sum of the constant term is a count of the number of competing products in the subgroup.[12] The Anderson canonical correlation LM statistic - a test of the null hypothesis that the model is under-identified - was rejected for all the three models. The Sargan statistic – a test of the null hypothesis that the instruments are valid – is rejected in all three cases; this is common when all instruments are used. As a robustness test, we experimented extensively with subsets of the potential instruments but were unable to obtain alternative estimates that differ qualitatively from the ones we present below. We are thus confident that the results are robust to the choice of instruments.

In Table 3 we report estimates of three models: a model using the aggregated data and linear price; and two models using the disaggregated data, one with linear and one with logarithmic price. The aggregate dataset did not support a theoretically consistent two-level nesting structure. We therefore estimated a single-level model with engine type as the sole nesting variable. With the disaggregate data the two-level nesting structure worked well. A Wald test rejects the null hypothesis $\sigma_1 = \sigma_2$, and therefore the single-level NML. 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 in all three cases: 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.

Engine capacity, horsepower, frame, automatic transmission and climate control are important car attributes and have the expected signs. The coefficient on CO_2 emissions was only statistically significant in the disaggregate linear case and is negative, implying that consumers like high emissions vehicles. But the coefficient is also small in magnitude and therefore its economic significance limited. We found the same result when we replaced the CO_2 variable with a variable expressing fuel costs per kilometer. This may seem odd but is consistent with our experience with other datasets; the coefficient on emissions (or, equivalently, fuel consumption) is hard to pin down.[13] The signs on country dummies (not shown) are also what might be expected; for example, German cars are more highly regarded than Chinese cars.

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 vehicle. Average CO_2

[12]In the aggregate linear model this instrument was excluded because it had no explanatory power in the first stage regression.

[13]See Adamou, Clerides, and Zachariadis (2012) for an example with Greek data.

Table 3: Estimates of demand equation

Variables	Aggregate		Disaggregate linear		Disaggregate ln	
	OLS	IV	OLS	IV	OLS	IV
α (price)	-0.0094**	-0.054**	-0.0048**	-0.038**	-0.36**	-2.02**
	(0.00041)	(0.0058)	(0.00029)	(0.0022)	(0.011)	(0.091)
σ_1 (group)	0.999**	0.530**	0.99**	0.95**	0.99**	0.84**
	(0.0015)	(0.170)	(0.012)	(0.016)	(0.0011)	(0.020)
σ_2 (subgroup)			0.99**	0.91**	0.98**	0.71**
			(0.0025)	(0.014)	(0.0024)	(0.020)
Engine capacity	0.045**	0.316**	-0.17**	0.062**	-0.17**	0.046*
	(0.0052)	(0.089)	(0.0061)	(0.017)	(0.0056)	(0.019)
CO_2 emissions	1.86**	-3.52	2.53**	1.57**	2.62**	0.37
	(0.082)	(2.26)	(0.066)	(0.24)	(0.062)	(0.33)
Horsepower	1.25**	4.62**	1.88**	4.69**	2.35**	5.79**
	(0.091)	(1.32)	(0.068)	(0.27)	(0.065)	(0.30)
Frame	-0.062**	0.058†	-0.047**	0.025**	-0.0025	0.28**
	(0.0033)	(0.032)	(0.0024)	(0.0057)	(0.0028)	(0.015)
Manual gearbox	0.011	-0.15*	-0.015**	-0.16**	-0.020**	-0.14**
	(0.0076)	(0.062)	(0.0053)	(0.013)	(0.0049)	(0.016)
Climate control	0.0043	0.020	0.0028	0.051**	0.027**	0.15**
	(0.0056)	(0.039)	(0.0041)	(0.0098)	(0.0040)	(0.015)
Constant	-3.04**	-5.82**	-3.00**	-3.59**	-0.0027	12.90**
	(0.025)	(0.98)	(0.019)	(0.083)	(0.091)	(0.77)
F-test	24,727**	262.4**	36,826**	3,134**	41,527**	1,429**
Wald test, H_0: $\sigma_1 = \sigma_2$				29.71**		137.86**
Underidentification test		8.70*		102.07**		164.11**
Overidentification test		7.84*		821.47**		6.16*

Significance levels: † : 10%, $*$: 5%, $**$: 1%. $N = 3,139$ for the aggregate model and $N = 6,061$ for the disaggregate. Standard errors are reported in parentheses. Time and country dummies are included but not reported for brevity.

emissions are 164 grams per kilometer per car. Manufacturer profits are estimated at 12.3 billion euros and consumer welfare (without the constant of integration) is 3.9 billion euros.

3.4 Implications of estimated models

Since the estimated models are going to be used to simulate the impact of price changes, it is important to get a sense of the implied substitution patterns. Table 4 provides the distribution of own price elasticities from each of the three models. We observe that the median elasticity from the aggregate model is 2.7 and 90% of elasticities are in the range 1.5-5.3. These estimates are comparable with existing work. Elasticities from the disaggregate model are substantially higher. This is to be expected because the choice unit is defined at a finer level and therefore some of the choices are very close substitutes to each other. With the linear specification, the median elasticity is 19.5 and a substantial fraction are above 30. The difference with the logarithmic specification is quite striking; here, elasticities are lower overall (though still higher than the aggregate model, as they should be) but they are very tightly packed around the median of 12.5. Both the relative magnitudes and the degree of dispersion of these elasticities are similar to those obtained by Björnerstedt and Verboven (2013), who estimate both a linear and a logarithmic specification and find that elasticities from the linear specification are substantially higher and much more dispersed.[14]

Table 4: Distribution of own price elasticities from the three models

	1%	10%	25%	50%	75%	90%	99%
Aggregate	9.6	5.3	3.8	2.7	1.9	1.5	1.0
Disaggregate linear	67.5	38.3	27.7	19.5	14.1	11.1	7.3
Disaggregate logarithmic	12.6	12.6	12.5	12.5	12.5	12.3	11.6

In order to get a sense of cross price elasticities, we calculated the absolute changes in sales following a hypothetical 10% increase in the price of Nissan Micra, a model in the Diesel-Small subgroup. The disaggregate linear estimates imply that as a result of this increase, Micra sales will drop by 93 units (rounding off to the nearest integer). This loss of 93 sales will be distributed as follows: 41 to vehicles in the same subgroup; 47 to other diesel categories; and 5 to the outside

[14]Björnerstedt and Verboven (2013) use a slightly modified version of the logarithmic specification that they show to be consistent with utility maximization.

good (no purchase). Substitution to models outside the group (petrol models) amounted to a small fraction of a vehicle. With the disaggregate logarithmic model, sales drop by 101, with 44 going to the same subgroup, 40 to other diesel, 1 to gasoline, and 17 to the outside good. With the aggregate model, sales drop by 20, with 11 going to the same group and 9 to the outside good.

To summarize, we estimated three variants of the nested logit model by choosing different levels of data aggregation and different econometric specifications. The models deliver substantially different implications for demand elasticities. This serves as a reminder that every econometric model imposes restrictions that need to be well understood. For our purposes, the variation in outcomes is useful because it allows us to perform our analysis with three different demand systems. If the conclusions from the three cases are similar, then we can state them with greater confidence than if we had a single model. In the next section we present in detail the counterfactual analysis using the estimates from the disaggregate linear model. At the end of the section we discuss the outcome of the same analysis with each of our other two specifications.

4 Policy simulations

4.1 Implementation

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 CO_2 emissions. All results presented in this section show the effect of a hypothetical feebate scheme 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).[15] A simple way to proceed would be 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 markup 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 quantities.

This may provide a good first approximation but a proper analysis should take manufacturers' pricing responses into account. Doing so requires solving for equilibrium prices in the

[15] 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.

hypothetical scenario where a feebate scheme is introduced. The supply model outlined in section 3.1 produces a set of pricing equations: one equation like (2) for each car model. Our counterfactual exercise involves simulating the equilibrium in year 2008, in which there were 912 car models for the disaggregate dataset (and 492 for the aggregate one). We therefore have a system of 912 (492) nonlinear equations that need to be solved to produce the 912 (492) prices. The technical details of how this was implemented are described in appendix A. One point worth mentioning is that the results from the analysis 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 rate remains the same as before. The simplest case is that of a symmetric 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:

$$A_j = t(E_j - PP), \tag{3}$$

where E_j is the CO_2 emissions level of model j and PP is the pivot point. Both E_j 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 is the total tax in euros per car of model j. The rate t is independent of the total amount emitted by the vehicle (linearity) and is the same regardless of whether it is a tax or a subsidy (symmetry). The symmetric linear feebate is theoretically appealing because it imposes equal marginal abatement costs for all manufacturers, thus leading to an economically efficient solution. In practice, asymmetric schemes have been implemented in several countries (see e.g. Bunch, Greene, Lipman, Martin, and Shaheen (2011)). For this reason, we also consider several asymmetric schemes that have different values for the 'fee' and the 'rebate' part. It is also possible to simulate schemes with a nonlinear feebate function but we did not pursue this possibility.

It is important to keep in mind the correspondence between a feebate system and an equivalent carbon tax. Assuming that a car travels 200,000 kilometers throughout its lifetime, a rate $t = 10$ corresponds to a tax of 50 euros per tonne of CO_2, while a rate $t = 40$ corresponds to a tax of 200 euros per tonne of CO_2. Although the latter is higher than the usual value used to assess marginal CO_2 damage costs (approximately 15-30 euros per tonne CO_2 according to Aldy, Krupnick, Newell, Parry, and Pizer (2010) and Interagency Working Group on Social Cost of Carbon (2010, henceforth IWG)), it is comparable to the implied marginal carbon tax rates of some CO_2-based vehicle tax systems currently implemented in European countries.[16]

[16] Braathen (2012, p. 188) estimates implied tax rates as high as €200 per tonne of CO_2 for countries like Ireland, Finland, Netherlands and Norway.

4.2 Impact of feebate schemes on prices and sales

In order to get a better understanding of the demand system, we selected two feebate schemes and calculated their effect on prices, sales and per-car revenues by car segment and CO_2 emissions class (recall that we are using the estimates from the disaggregated linear model). Results are presented in Table 5 for two revenue-neutral schemes: a 'lenient' one with $t = 10$ and a 'stringent' one with $t = 40$ (the pivot points are set at 135.2 and 127.7 g/km respectively). We report only the small, medium and large segments that are the most important in terms of sales, as well as the figures for the overall market (labeled 'All'). We report the median percentage price change among products in each group. In the lenient feebate case price changes are relatively small, from -1.2% for small low-carbon cars up to +3.0% for medium high-carbon cars. In the stringent feebate case, the median price change ranges from -2.7% (for small cars with low carbon emissions) to +13.0% (for the highest emissions class of medium cars).

The middle columns of Table 5 report the percentage change in total category sales compared to actual sales in year 2008. In each segment, cars belonging to the lowest CO_2 emission class ($<$ 130 g/km) gain significantly in sales. There is also a sales increase for cars belonging to the second lowest CO_2 emission class (130-160 g/km) for the 'lenient' case. Total sales of new cars, which amounted to about 2.9 million cars in year 2008, decrease by 0.8% in the lenient feebate case and by 3.3% in the stringent feebate case. This is the primary reason for reduced profits and consumer welfare as will be demonstrated in the next subsection. Substitution across categories is very high, reflecting the high elasticities implied by our estimates.

The last set of columns reports changes in total revenue per vehicle. They are negative for the low carbon cars with the lenient feebate and for small and medium size low carbon cars with the stringent feebate. This happens because in the lenient case the pivot point is set to 135.2 and all the low carbon cars get a rebate. Similarly for the stringent case almost all small cars have lower emissions than 127.7. Although the overall change in revenues per vehicle is positive, the overall reduction in sales leads to revenue neutrality for both scenarios.

4.3 Welfare impact of feebate schemes

In Table 5 we reported results from simulating two revenue-neutral feebate schemes. Revenue neutrality is an objective that is typically associated with the introduction of feebates, therefore we continue focusing on revenue-neutral schemes in this subsection. The top part of Table 6 displays the impact of several schemes of this type on consumers, producers and the level of emissions. We first note that the range of values that the pivot point PP can take is relatively

Table 5: Change in prices, sales and revenues/car by size and CO_2 emission class

	Prices				Sales				Revenues per car			
	S	M	L	All	S	M	L	All	S	M	L	All
Lenient scheme ($t = 10$, $PP = 135.2$)												
<130	-1.2	-0.4	-0.3	-1.0	25.1	19.1	24.1	22.9	-11.5	-4.2	-1.9	-8.4
130-160	0.7	0.7	0.7	0.7	3.5	4.6	8.1	5.8	3.7	4.7	3.0	4.5
160-180	2.1	1.8	1.3	1.6	-14.3	-6.9	-10.1	-6.7	14.4	12.4	8.3	9.7
180-200	2.7	2.5	2.0	2.2	-28.9	-21.0	-17.0	-16.2	19.0	16.3	13.1	14.3
>200		3.0	2.8	2.6		-37.1	-39.3	-36.4		20.3	12.4	12.3
All	0.2	1.3	1.8	1.6	10.6	2.9	-3.0	-0.8	-2.3	4.8	4.9	0.8
Stringent scheme ($t = 40$, $PP = 127.7$)												
<130	-2.7	0.04	0.2	-2.0	118.8	72.6	98.0	101.9	-35.1	-7.1	1.6	-24.3
130-160	5.3	4.3	4.0	4.3	1.0	6.1	18.6	9.4	28.8	27.5	17.2	26.6
160-180	10.2	8.6	6.5	7.8	-53.0	-33.4	-44.4	-34.8	70.5	60.1	39.3	45.7
180-200	12.2	11.2	9.3	10.0	-77.7	-65.7	-60.3	-59.1	85.8	73.8	59.3	63.4
>200		13.0	11.8	11.3		-85.6	-87.0	-84.2		85.9	56.0	50.5
All	3.0	6.6	8.6	7.7	41.0	5.4	-15.9	-3.3	-6.3	21.6	21.1	3.4

Both schemes are revenue-neutral. Reported numbers are percentage changes. S=Small, M=Medium, L=Large.

limited. This is due to the requirements that the scheme be symmetric and revenue neutral. To understand why, consider a hypothetical world with a continuum of emissions levels and a distribution of sales that is symmetric with respect to emissions levels. Suppose further that market shares are fixed; they cannot change after prices change. For a symmetric linear feebate scheme to be revenue-neutral in this world, the pivot point must be exactly equal to the mean level of emissions. This is true for any value of t.

In reality, the sales distribution is not symmetric; depending on its shape, the pivot point might be higher or lower than the mean. But more importantly, market shares are not fixed. Once a feebate is introduced, sales will shift from high-emission to low-emission vehicles. The pivot point would thus have to shift down in order for revenue neutrality to be restored. The higher the tax rate, the lower the pivot point would have to be because there will be greater substitution from high-emission to low-emission vehicles. Generally then, the pivot point of a revenue-neutral linear symmetric scheme would have to be smaller than the mean emissions level and decline slowly with increasing tax rate t. This is indeed what we observe in Table 6. How much lower than the mean emissions level must the pivot point be? This will depend on the elasticities. The more elastic the demand, the greater the substitution due to the feebate, and the lower the pivot has to be in order to achieve neutrality.

Table 6: Simulated impact of selected feebate schemes

Scheme		Change in:				
t	PP	Total sales	Consumer surplus	Producer surplus	Emissions cost	Total welfare
Revenue-neutral symmetric schemes						
10	135.2	-23.8 (-0.8)	-96 (-1.7)	-30 (-0.8)	-60 (-4.2)	-66 (-0.3)
20	132.7	-47.6 (-1.6)	-191 (-3.3)	-58 (-1.5)	-110 (-7.7)	-139 (-0.7)
30	130.2	-71.9 (-2.5)	-288 (-4.9)	-84 (-2.1)	-155 (-10.7)	-217 (-1.0)
40	127.7	-97.3 (-3.3)	-388 (-6.7)	-109 (-2.8)	-196 (-13.4)	-300 (-1.4)
30.7	130	-73.7 (-2.5)	-295 (-5.1)	-86 (-2.2)	-158 (-10.9)	-223 (-1.1)
71.6	120	-186.7 (-6.4)	-732 (-12.6)	-175 (-4.4)	-315 (-20.8)	-593 (-2.8)
Revenue-neutral asymmetric schemes						
-10/+20	130.6	-26.3 (-0.9)	-106 (-1.8)	-34 (-0.8)	-66 (-4.6)	-74 (-0.3)
-20/+10	136.7	-43.5 (-1.5)	-175 (-3.0)	-52 (-1.3)	-101 (-7.0)	-127 (-0.6)
-5/+20	127.2	-14.4 (-0.5)	-58 (-1.0)	-19 (-0.5)	-38 (-2.7)	-39 (-0.2)
-20/+5	139.4	-41.0 (-1.4)	-165 (-2.8)	-49 (-1.2)	-95 (-6.6)	-119 (-0.6)
-10/+30	127.3	-28.2 (-1.0)	-114 (-2.0)	-36 (-0.9)	-70 (-4.9)	-80 (-0.4)
-30/+10	136.6	-61.8 (-2.1)	-248 (-4.3)	-72 (-1.8)	-134 (-9.3)	-185 (-0.9)
-5/+30	123.8	-15.4 (-0.5)	-62 (-1.1)	-21 (-0.5)	-41 (-2.9)	-43 (-0.2)
-30/+5	138.8	-58.8 (-2.0)	-236 (-4.1)	-67 (-1.7)	-127 (-8.8)	-176 (-0.8)
Welfare-improving schemes						
10	130	-29.1 (-1.0)	-118 (-2.0)	-37 (-0.9)	-62 (-4.4)	61 (0.3)
20	120	-73.2 (-2.5)	-293 (-5.0)	-92 (-2.3)	-122 (-8.4)	473 (2.2)
-2/+3	130.6	-6.0 (-0.2)	-24 (-0.4)	-8 (-0.2)	-14 (-1.0)	13 (0.06)
-10/+20	123.8	-34.2 (-1.2)	-138 (-2.4)	-44 (-1.1)	-68 (-4.7)	141 (0.7)
Sales-increasing schemes						
0/+10	120	0.6 (0.02)	3 (0.04)	0.3 (0.01)	-1.5 (-0.1)	-31 (-0.15)
0/+10	140	3.8 (0.1)	15 (0.3)	4 (0.1)	-6 (-0.4)	-167 (-0.8)
0/+10	160	12.7 (0.4)	52 (0.9)	15 (0.4)	-13 (-0.9)	-508 (-2.4)

Notes: reported changes are in levels; percentage changes are in parentheses. Total sales are expressed in thousands. Consumer and producer surplus and emissions costs are expressed in million euros. Government revenues for the welfare-improving schemes are 154 (+1.4%), 736 (+6.5%), 31(+0.3%) and 255(+2.3%) million euros respectively. Government revenues for the total sales-improving schemes are -36 (-0.3%), -193 (-1.7%) and -587 (-5.2%) million euros respectively. For the asymmetric schemes, the first number is the fee part and the second number the rebate part.

Changing relative prices through taxation is distortionary and would be expected to lead to lower consumer and producer surplus relative to the efficient outcome. This is clearly apparent in Table 6. As the tax rate increases and the scheme becomes more distortionary, losses in consumer and producer surplus increase. This is because – as already shown in Table 5 – such a scheme substantially increases the price of most large and medium-sized cars, thereby reducing automobile sales in general (displayed in the column headed 'Total sales') and leading to a drop in both producer prices (due to lower demand) and consumer welfare (since some consumers avoid purchasing a new car at these prices).

Feebate policies can nonetheless be welfare improving if their environmental benefit exceeds the loss in consumer and producer surplus. In order to quantify this benefit we first need to calculate the reduction in emissions caused by each scheme. We assume that each vehicle will travel 200,000 kilometres during its lifetime and its CO_2 emission level will remain constant (at the initial registered level) throughout.[17] With these assumptions we can calculate total emissions pre- and post-feebate and compare the two. This, however, will likely overestimate the reduction in emissions. To see why, note that total emissions from new vehicles are reduced for two reasons: substitution from high-emission to low-emission vehicles and, to a lesser extent, reduced sales. The benefit from substitution is obvious. As an example, suppose that the feebate induces a consumer who would have bought a vehicle emitting 180 g/km to purchase instead a vehicle emitting 160 g/km. This switch reduces emissions by four tonnes during the vehicle's lifetime $(200,000 \times (180 - 160) \div 1,000)$.

The impact of reduced sales on emissions is not as clear-cut. Lower sales will certainly lead to lower emissions from *new* vehicles. But a consumer who switches out of the market because of the feebate might already own an older, possibly more polluting vehicle that she will continue to use. The calculation above essentially assumes that all consumers who opt out of the market will ride bicycles instead. To avoid this assumption, we adjusted pre-feebate emissions downwards by a percentage equal to the ratio of post-feebate to pre-feebate sales. In other words, if post-feebate sales were 98% of pre-feebate sales, then we multiply total pre-feebate emissions by 98%. This is a more reasonable assumption than the switch-to-bicycles assumption described above.[18]

In order to compare this benefit to the loss in consumer and producer surplus, we have to express emission reductions in monetary terms. We use the central estimate of a social

[17]We arrived at the 200,000 figure after consulting with several European transportation policy analysts; it is considered a good approximation of the lifetime mileage of an average car in Europe. In the United States, official data indicate a higher mileage of about 240,000 km (152,000 miles); see Davis, Diegel, and Boundy (2012).

[18]This calculation is mathematically equivalent to measuring the change in emissions as the difference between pre- and post-feebate weighted mean emissions multiplied by post-feebate sales. The details are somewhat tedious available from the authors upon request.

cost of carbon (SCC) equal to 15 euros (at 2005 prices) per tonne of CO_2 provided by expert groups for policy makers.[19] 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, and so on (see IWG). Multiplying the reduction in emissions by €15 gives the value of the environmental benefit in million euros. The resulting figure, reported in the columns headed 'Emissions cost' in Table 6, is clearly less than the sum of consumer and producer surplus lost. For the environmental benefit to make up for lost consumer surplus we would require the SSC to be roughly 1.5-2 times bigger than €15/tonne; to make up for the loss in both consumer and producer surplus we would need it to be 2-2.5 times bigger.[20]

In the second panel of Table 6 we explore several revenue-neutral asymmetric schemes, all of which also turned out to be welfare decreasing. We were unable to come up with linear schemes that are welfare improving. This is not definitive proof, but our results are highly suggestive that the distortionary cost of revenue-neutral schemes far exceeds conventional estimates of the environmental benefits achieved. Revenue-neutral schemes might seem attractive to consumers worried about the government extracting tax revenue from them, but they may be oblivious to a much greater distortionary cost imposed by the schemes.

This raises an important question: is it possible to design welfare-improving feebate schemes? The answer is affirmative. The outcomes of several such schemes are reported in the lower part of Table 6. They differ from the revenue-neutral schemes examined above in featuring a lower pivot point and a low tax rate. The combination of a low pivot and a low tax rate means that more taxes are paid than rebates are collected, resulting in a net revenue gain for the government that – together with the environmental benefit due to reduced emissions costs – is substantial enough to outweigh the consumer and producer surplus loss. A high tax rate would be counter-productive because it would lead to large shifts from high-emission to low-emission vehicles that would generate revenue losses for the government. Lowering further the pivot point (e.g. to 120 g/km) seems to be welfare-improving as well but leads to very strong reductions in consumer and producer surplus that may give rise to undesirable general equilibrium effects on the whole economy. Finally, we note that the reduction in emissions attained by the welfare-

[19] Aldy, Krupnick, Newell, Parry, and Pizer (2010) and Interagency Working Group on Social Cost of Carbon (2010). The €15 figure corresponds to the value of 21 US dollars at 2007 prices per tonne of CO_2 suggested by IWG, deflated to prices of year 2005 that we use throughout the paper, and assuming an exchange rate of 1.4 US dollars per euro.

[20] Some of the loss in producer surplus will likely be absorbed by foreign manufacturers and should not be included in a national calculation. Calculating the German portion of producer surplus is complicated for several reasons such as cross-ownership and the distribution of profits between manufacturers and retailers. For this reason we chose to report the entire producer surplus.

improving schemes is relatively modest. The above hold for symmetric schemes; Table 6 shows that asymmetric schemes can also turn out to be welfare-improving if the the tax levied on high-emitting vehicles is higher than the rebate offered to low-carbon cars, thus ensuring a net gain in public tax revenues.

Table 6 highlights the key tradeoff involved in carbon taxation: higher taxes reduce emissions but also lower consumer and producer welfare. Environmental effectiveness comes at the detriment of consumer and producer surplus. Nonetheless, it is possible to design a feebate system that can be reasonably effective in terms of reducing CO_2 emissions of new cars without being detrimental to overall economic welfare.

4.4 Alternative demand specifications

We repeated the simulation analysis for the our other demand specifications. The main qualitative conclusions from the disaggregate linear model carry through to the other two cases as well. That is, revenue-neutral schemes decrease overall welfare; and welfare can only increase by feebates that reduce consumer and producer surplus and substantially raise government revenue. To avoid repetition we will not discuss the other two cases in detail; for the interested reader, full results (equivalent to Table 6) are provided in Tables 7 and 8 in appendix B. Here we will discuss differences between the three cases that are of interest.

Different outcomes in the simulations arise because of differences in elasticities, which are high and dispersed in the main model, somewhat lower and very tight in the logarithmic model, and significantly lower in the aggregate model. As discussed in the beginning of section 4.3, this should lead to higher pivot points for the logarithmic model than the main model and even higher for the aggregate model. This is indeed what we observe. In terms of consumer surplus, low elasticities in the aggregate model translate to a smaller impact on total sales and thus also to consumer surplus. Producer surplus is relatively small in the main model (high elasticities mean small markups) and therefore absolute changes are also small. The impact on producer surplus is much greater in the aggregate model (because lower elasticities imply higher markups and greater producer surplus) and even more so in the logarithmic model. Interestingly, producer surplus changes are greater in the logarithmic model than in the aggregate model even though elasticities are larger; this is because markups are much more dispersed in the logarithmic model.

5 Summary and conclusions

The effectiveness of different policy instruments in reducing the transport sector's carbon emissions is a subject of much interest in academic and policy circles. This paper aims to contribute to this debate by providing a rigorous analysis of the impact of feebates, a combination of a tax for high-carbon vehicles and a rebate for low-carbon vehicles. Using data from Germany for the period 2002-2008, we estimated demand for automobiles using three variants of the widely used nested logit model. The three demand systems have quite different implications for the level and dispersion of price elasticities; this is a useful reminder of the restrictions imposed by our modeling and data construction choices. Nonetheless, all three demand systems have the same implications with regard to the main questions we are interested in. We can thus be confident that are findings have general applicability.

We used our estimates to simulate the impact of various feebate schemes. We first focused on revenue-neutral schemes that are less likely to face resistance from voters. The analysis showed that the environmental benefit from such schemes is not substantial enough to counterbalance the distortionary effects of taxation, meaning that the schemes are welfare-decreasing overall. We then found that it is possible to design welfare-improving schemes by setting a low pivot point and a low tax rate – essentially the 'fee' part dominating the 'rebate' part. These schemes generate enough government revenue to outweigh the loss in consumer and producer surplus, while the environmental benefit remains modest.

There are several caveats to the analysis. Perhaps the most important one is that it can only address the short term. It analyzes the impact of a policy change in the first year that it is implemented, focusing on consumer response and keeping the supply side fixed. In the longer term manufacturers might respond to this policy by producing more fuel efficient vehicles. If this is the case, then our estimates will understate the policy's true impact. Dynamics might also be important on the demand side. If the feebate is temporary – or is perceived to be so by consumers – then the consumer response might be substantially greater that what the model predicts. Consumers who were perhaps considering buying a new fuel-efficient car in the next couple of years might bring their purchase forward in order to take advantage of the feebate. Similarly, consumers who were planning on buying a gas-guzzler in the year of the rebate might put off their purchase to avoid paying the fee. This will result in a large but temporary shift from high-emission to low-emission vehicles. This may be at least part of the explanation behind the strikingly large consumer response in some countries, such as France.

Our findings are based on linear schemes. There is clearly vast room for experimentation with nonlinear schemes, but it is hard to see intuitively why nonlinearity could produce different outcomes. An additional consideration is that the impact of feebate-like schemes takes many years to materialize because they exclusively target new cars. It will take several years (the average life of a vehicle) for the entire car stock to be replaced with vehicles with lower emissions. This is an important disadvantage of feebate schemes relative to gasoline taxation, which is levied on the entire car stock. Another caveat is that used vehicles were not included in the demand system because of lack of data. Hence, our model does not capture any substitution from new vehicles to used vehicles due to the introduction of a new tax scheme. Finally, it is always possible to estimate more general models that generate richer substitution patterns.

Caveats aside, the analysis is a useful exercise because it highlights and quantifies the trade-offs involved in the design of an appropriate emissions-based taxation scheme for new automobiles. It shows that – if revenue neutrality is a requirement – an automobile feebate system will probably reduce total economic welfare in the short term. This should not be interpreted, however, as a recommendation against such schemes. A feebate program, which is a flexible market-based alternative to fuel economy or CO_2 standards, may have a small immediate impact because it addresses only new cars sold in the market. Nonetheless it can provide a long-term price signal to both auto manufacturers and consumers and hence can induce low-carbon investments 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 stringent CO_2 standard and provides incentives for continuous technological improvements.

References

Adamou, A., S. Clerides, and T. Zachariadis, 2012, "Trade-offs in CO_2-Oriented Vehicle Tax Reforms: A Case Study of Greece," *Transportation Research Part D: Transport and Environment*, 17(6), 451–456.

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, 2011, "Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives," *Review of Environmental Economics and Policy*, 5(1), 89–108.

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.

Beresteanu, A., and S. Li, 2011, "Gasoline Prices, Government Support and the Demand for Hybrid Vehicles in the US," *International Economic Review*, 52(1), 161–182.

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.

Björnerstedt, J., and F. Verboven, 2013, "Does Merger Simulation Work? Evidence from the Swedish Analgesics Market," unpublished manuscript.

Braathen, N.-A., 2012, "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, S17–S44.

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.

Davis, S. C., S. W. Diegel, and R. Boundy, 2012, "Transportation Energy Data Book Edition 31, Oak Ridge National Laboratory Report ORNL-6987," also at http://cta.ornl.gov/data/.

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.

D'Haultfoeuille, X., P. Givord, and X. Boutin, 2011, "The Environmental Effect of Green Taxation: The Case of The French 'Bonus/Malus'," Direction des Études et Synthèses Économiques Working Paper G2011/14, http://www.insee.fr/en/themes/document.asp?reg_id=0&ref_id=G201114.

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.

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. 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.

Huse, C., and C. Lucinda, 2013, "The Market Impact and the Cost of Environmental Policy: Evidence from the Swedish "Green Car" Rebate," *Economic Journal*, this volume.

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.

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

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.

APPENDICES

A Simulation details

We need to solve a system of 912 nonlinear equations of the form (2). Matlab's built-in non-linear equation solver failed to produce a solution. To circumvent this problem we resorted to contraction mapping techniques. Consider a slightly simplified form of equation (2) in vector form:

$$P = MC + MU(P). \tag{4}$$

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 (4). Define T as the mapping:

$$T[P] = MC + MU(P). \tag{5}$$

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

$$P^n = MC + MU(P^{n-1}) \tag{6}$$

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 (4) is straightforward; one just has to plug it into (4) 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 4.

B Simulation results with different demand estimates

Table 7: Simulated impact of feebate schemes with linear price and aggregated data

Scheme		Change in:				
t	PP	Total sales	Consumer surplus	Producer surplus	Emissions cost	Total welfare
Revenue-neutral symmetric schemes						
10	153.5	-6.4 (-0.2)	-18 (-0.5)	-60 (-0.2)	-12 (-0.9)	-66 (-0.2)
20	152.6	-14.2 (-0.5)	-39 (-1.0)	-132(-0.5)	-24 (-1.8)	-148 (-0.4)
30	151.6	-23.2 (-0.8)	-64 (-1.7)	-216 (-0.8)	-36 (-2.7)	-244 (-0.6)
40	150.7	-33.3 (-1.2)	-92 (-2.4)	-311 (-1.2)	-49 (-3.6)	-354 (-0.9)
47.8	150	-41.9 (-1.5)	-116 (-3.0)	-391 (-1.5)	-59 (-4.3)	-449 (-1.1)
110	145	-129.8 (-4.6)	-353 (-9.1)	-1213 (-4.6)	-140 (-9.9)	-1426 (-3.5)
Revenue-neutral asymmetric schemes						
-10/+20	146.6	-7.9 (-0.3)	-22 (-0.6)	-76 (-0.3)	-15 (-1.1)	-84 (-0.2)
-20/+10	159.7	-11.5 (-0.4)	-32 (-0.8)	-103 (-0.4)	-19 (-1.4)	-116 (-0.3)
-5/+20	140.6	-4.4 (-0.2)	-12 (-0.3)	-45 (-0.2)	-9 (-0.6)	-48 (-0.1)
-20/+5	167.6	-9.2 (-0.3)	-26 (-0.7)	-81 (-0.3)	-15 (-1.1)	-92 (-0.2)
-10/+30	142.6	-9.0 (-0.3)	-25 (-0.6)	-89 (-0.3)	-16 (-1.2)	-97 (-0.2)
-30/+10	163.3	-16.2 (-0.6)	-45 (-1.2)	-144 (-0.6)	-26 (-1.9)	-163 (-0.4)
-5/+30	136.7	-5.0 (-0.2)	-14 (-0.4)	-52 (-0.2)	-10 (-0.7)	-56 (-0.1)
-30/+5	171.6	-12.8 (-0.5)	-36 (-0.9)	-113 (-0.4)	-20 (-1.5)	-128 (-0.3)
Welfare-improving schemes						
5	148	-7.3 (-0.3)	-20 (-0.5)	-68 (-0.3)	-8 (-0.6)	3 (0.008)
20	145	-35.5 (-1.2)	-98 (-2.5)	-329 (-1.3)	-34 (-2.5)	19 (0.05)
-2/+3	145	-3.1 (-0.1)	-9 (-0.2)	-29 (-0.1)	-3 (-0.3)	2 (0.004)
-10/+20	136.7	-26.1 (-0.9)	-72 (-1.9)	-243 (-0.9)	-22 (-1.6)	72 (0.2)
Sales-increasing schemes						
0/+10	145	7.2 (0.3)	20 (0.5)	64 (0.2)	-2 (-0.1)	-77 (-0.2)
0/+10	155	13.1 (0.5)	37 (0.9)	117 (0.4)	-3 (-0.3)	-137 (-0.3)
0/+10	165	21.8 (0.8)	61 (1.6)	197 (0.8)	-6 (-0.5)	-220 (-0.5)

Government revenues for the welfare-improving schemes are 83 (+0.8%), 412 (+3.9%), 36 (+0.3%) and 364(+3.4%) million euros respectively. Government revenues for the total sales-improving schemes are -160 (-1.5%), -287 (-2.7%) and -472 (-4.5%) million euros respectively.

Table 8: Simulated impact of feebate schemes with logarithmic price and disaggregated data

Scheme		Change in:				
t	PP	Total sales	Consumer surplus	Producer surplus	Emissions cost	Total welfare
Revenue-neutral symmetric schemes						
10	148.0	-7.1 (-0.2)	-72 (-2.7)	-174 (-2.8)	-34 (-2.4)	-213 (-1.1)
20	144.4	-24.0 (-0.8)	-156 (-5.9)	-355 (-5.8)	-71 (-5.0)	-440 (-2.2)
30	140.8	-50.7 (-1.7)	-250 (-9.4)	-540 (-8.8)	-112 (-7.8)	-678 (-3.4)
40	137.3	-86.9 (-3.0)	-352 (-13.3)	-727 (-11.9)	-156 (-10.7)	-923 (-4.6)
62.6	130	-197.4 (-6.7)	-598 (-22.6)	-1133 (-18.5)	-259 (-17.1)	-1472 (-7.3)
103.8	120	-450.2 (-15.4)	-1023 (-38.6)	-1750 (-28.6)	-434 (-26.0)	-2338 (-11.7)
Revenue-neutral asymmetric schemes						
-10/+20	139.6	-11.9 (-0.4)	-93 (-3.5)	-218 (-3.6)	-45 (-3.2)	-266 (-1.3)
-20/+10	153.3	-15.3 (-0.5)	-119 (-4.5)	-279 (-4.6)	-52 (-3.7)	-346 (-1.7)
-5/+20	134.1	-6.3 (-0.2)	-55 (-2.1)	-132 (-2.2)	-28 (-2.0)	-159 (-0.8)
-20/+5	161.5	-11.0 (-0.4)	-94 (-3.5)	-220 (-3.6)	-39 (-2.8)	-274 (-1.4)
-10/+30	134.1	-16.7 (-0.6)	-109 (-4.1)	-248 (-4.1)	-54 (-3.8)	-304 (-1.5)
-30/+10	155.6	-25.0 (-0.9)	-161 (-6.1)	-365 (-6.0)	-68 (-4.8)	-459 (-2.3)
-5/+30	129.1	-8.8 (-0.3)	-64 (-2.4)	-149 (-2.4)	-33 (-2.3)	-180 (-0.9)
-30/+5	163.8	-18.3 (-0.6)	-127 (-4.8)	-289 (-4.7)	-52 (-3.6)	-365 (-1.8)
Welfare-improving schemes						
10	130	-57.5 (-2.0)	-114 (-4.3)	-207 (-3.4)	-52 (-3.6)	279 (1.4)
20	120	-159.3 (-5.4)	-264 (-10.0)	-440 (-7.2)	-117 (-7.8)	901 (4.5)
-2/+3	139.6	-5.6 (-0.2)	-19 (-0.7)	-41 (-0.7)	-9 (-0.6)	2 (0.01)
-10/+20	129.1	-51.3 (-1.8)	-118 (-4.5)	-226 (-3.7)	-55 (-3.8)	164 (0.8)
Sales-increasing schemes						
0/+10	120	2.9 (0.1)	-0.72 (-0.027)	-7 (-0.1)	-1 (-0.1)	-41 (-0.2)
0/+10	140	14.9 (0.5)	0.16 (0.006)	-23 (-0.4)	-2 (-0.2)	-199 (-1.0)
0/+10	160	46.3 (1.6)	10.6 (0.4)	-46 (-0.7)	0.6 (0.04)	-569 (-2.8)

Government revenues for the welfare-improving schemes are 549 (+4.9%), 1488 (+13.2%), 53 (+0.5%) and 453 (+4.0%) million euros respectively. Government revenues for the total sales-improving schemes are -34 (-0.3%), -178 (-1.6%) and -533 (-4.7%) million euros respectively.