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Explaining the Adoption of Diesel Fuel Passenger Cars in Europe

Joshua Linn

1616 P St. NW
Washington, DC 20036
202-328-5000 www.rff.org

RESOURCES
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Abstract

Compared with gasoline engines, diesel fuel engines significantly reduce fuel consumption and greenhouse gas emissions from passenger vehicles, but they emit more nitrogen oxides and other pollutants. Across countries, the market share of diesel fuel engines in passenger vehicles varies from close to zero to more than 80 percent. Using a structural model of vehicle markets in seven European countries, I show that vehicle taxes and willingness to pay for fuel costs, rather than fuel prices or supply, explain adoption. The model is used to compare the environmental implications of fuel taxes and carbon dioxide emissions rate standards.

Key Words: vehicle demand estimation, demand for fuel economy and performance, fuel taxes, vehicle taxes, carbon dioxide emissions rates

JEL Classification Numbers: L62, Q4, Q5

Contents

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1. Introduction

An extensive literature has analyzed consumer demand for a wide range of energy-consuming durables, such as passenger vehicles and home appliances (e.g., Dubin and McFadden 1984; Hausman 1979). A central objective of this literature has been to estimate consumers' willingness to pay for expected energy cost savings (or, alternatively, the discount rate consumers apply to such savings). Although evidence exists that in certain contexts consumers are willing to pay approximately $1 for a dollar of expected energy cost savings (e.g., Busse et al. 2013), there is also evidence that many consumers undervalue such savings (e.g., Houde 2012). Undervaluation of future energy cost savings is often referred to as the energy paradox, and many hypotheses have been offered to explain it, including imperfect information and learning costs (Sallee 2013), loss aversion (Greene 2011), and the fact that less intensive users save less money from a given energy efficiency improvement than do more intensive users (Verboven 2002).

Despite the vast literature on consumer demand for energy-intensive durables and the energy paradox, there has been very little analysis of consumer demand for diesel fuel vehicles. Such vehicles achieve about 30 percent higher fuel economy and emit about 20 percent less carbon dioxide (CO_2) than comparable gasoline-powered vehicles.[1] On the other hand, partly because of higher production costs, diesel fuel vehicles typically have higher retail prices: the average diesel fuel vehicle in Europe costs about €1,800 more than the average gasoline vehicle. Facing average European fuel prices, a typical consumer purchasing a diesel fuel vehicle would recover the additional purchase cost after about 4 years.[2] Between 1980 and 2005 the diesel fuel vehicle market share increased from less than 10 percent to about 50 percent (Schipper et al. 2002). The adoption of diesel fuel vehicles has varied widely across Europe, ranging from 25

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[1] Diesel fuel contains more carbon per gallon of fuel than gasoline, which explains why diesel fuel vehicles have a larger fuel economy advantage than a CO_2 emissions rate advantage.

[2] This calculation assumes a discount rate of 10 percent and that the typical vehicle is driven 10,000 miles per year.

percent (the Netherlands) to 75 percent (France and Belgium), but is close to zero in the United States. In fact, although other power train technologies, such as plug-in electric, receive far more public attention, diesel fuel vehicles represent the only technology that significantly reduces fuel consumption compared with gasoline vehicles and has attained more than 10 percent of any major market.

This paper poses a straightforward question: why do consumers in some European countries adopt diesel fuel vehicles more than consumers in other countries? Despite the considerable literature on consumer adoption of energy-intensive durables, the literature does not explain cross-country variation in adoption of diesel fuel vehicles. Although they save fuel and reduce greenhouse gas emissions, diesel fuel vehicles have higher emissions rates of other pollutants, such as nitrogen oxides. Therefore, the adoption of diesel fuel vehicles—and the effects of transportation policies on adoption—has broad environmental implications.

Demand or supply factors could explain cross-country variation in diesel fuel vehicle adoption, and I consider four specific hypotheses. The first is taxes— for either fuels or vehicles. Largely because of fuel taxes, both the levels of fuel prices and the relative prices of gasoline and diesel fuel differ considerably across European countries. Because of diesel fuel vehicles' high fuel economy, high gasoline prices—either in absolute terms or relative to diesel fuel prices—could encourage adoption of diesel fuel vehicles. Supporting this hypothesis, in the U.S. market for new passenger vehicles, the recent literature has demonstrated a strong link between fuel prices and the purchase of vehicles with high fuel economy (e.g., Li et al. 2009; Klier and Linn 2010; Gillingham 2012; Busse et al. 2013). Klier and Linn (2013a) report a connection between fuel prices and fuel economy in Europe, albeit a weaker one than in the United States; their results suggest that fuel prices are not the major explanation for consumer adoption, but the analysis in that paper considers only the short run. Furthermore, Klier and Linn (2012b) document extensive cross-country variation in vehicle taxation, but they do not quantify the effects of vehicle taxes on the adoption of diesel fuel vehicles.

Second, conditional on taxes, demand for fuel economy may vary across countries. For example, for heavily driving consumers, a given fuel economy increase yields higher expected fuel expenditure savings than for other consumers. Such high-mileage consumers would have higher demand for diesel fuel vehicles because of these vehicles' higher fuel economy (Verboven 2002). Thus, differences in demand for fuel economy, perhaps because of differences in driving behavior, could explain cross-country market share variation. Verboven (2002) documents some, though limited, demand variation for three countries in the early 1990s, but the analysis does not formally attempt to explain cross-country variation in adoption.

Third, diesel fuel vehicles differ from gasoline vehicles along other dimensions besides fuel costs, including performance and engine lifetime. Kahn (2007) suggests that some consumers may have higher preferences for hybrid vehicles, such as the Toyota Prius, because of perceived status or concerns about pollution emissions; by analogy, some consumers may have lower willingness to pay for diesel fuel vehicles than other consumers because of the higher emissions of certain pollutants. Likewise, differences in demand for performance or for engine lifetime could explain cross-country variation in adoption rates.

Finally, manufacturers could offer different vehicles in each country because of consumer demand or other factors. Recent studies have considered manufacturers' response to fuel economy or greenhouse gas emissions rate standards (e.g., Klier and Linn 2012a and 2013b; Knittel 2011; Whitefoot and Skerlos 2012; Whitefoot et al. 2013), but the previous literature has not examined manufacturers' response to consumer demand conditions or to fuel prices. These factors could cause differences in the fuel economy, performance, or other characteristics of vehicles supplied to the markets, which could help explain cross-country variation in market shares.

Before testing these hypotheses, I proceed, in Sections 2 and 3, with a reduced-form analysis of the effects of fuel prices on diesel fuel vehicle market shares. Section 2 describes the European markets. Focusing on the seven largest markets in continental Europe, I document large and persistent cross-country differences in diesel fuel vehicle market shares from 2002 to 2010.

Most European countries tax diesel fuel at a lower rate than gasoline, which makes the average retail gasoline price about 11 percent higher than that of diesel fuel. The tax preference for diesel fuel varies across countries, however; the Netherlands gasoline tax is about 67 percent higher than the diesel fuel tax, whereas the Spanish gasoline tax is about 30 percent higher. A natural hypothesis is that fuel prices explain the cross-country variation in diesel fuel market shares, but these market shares are not strongly correlated with fuel prices or taxes, either in the cross section or over time. The lack of a strong correlation is consistent with Verboven (2002) and Klier and Linn (2013a). Verboven (2002) concludes that because of second-degree price discrimination, fuel prices have a smaller effect on diesel fuel vehicle market shares than would be implied by a Bertrand model of vehicle pricing that does not account for heterogeneous driving behavior. Klier and Linn (2013a) report a relatively weak relationship between fuel prices and vehicle market shares, for both gasoline and diesel fuel prices.

I also document statistically significant but economically small cross-country differences in supply conditions. Most vehicle models are sold in all continental European markets, and the mix of specific power trains varies little across countries. The descriptive analysis thus suggests that fuel prices and supply conditions, by themselves, do not explain the cross-country variation in market shares and that other factors are likely important.

Sections 4 and 5 test the four hypotheses using a structural model of the vehicles market. Developing a structural model presents the challenge that diesel fuel vehicles differ from gasoline vehicles not only by fuel economy, but also by performance and other characteristics, some of which are unobserved. An extensive literature has confronted the fact that many characteristics of passenger vehicles, such as reliability, are difficult to measure. To address the resulting price endogeneity, Berry Levinsohn and Pakes (1995; henceforth, BLP) provide an instrumental variables strategy that much of the ensuing literature has employed. However, manufacturers choose vehicle characteristics based on consumer demand and on the choices of other manufactures. Klier and Linn (2012a) argue that because of these choices, observed vehicle characteristics, such as fuel economy and performance, may be correlated with unobserved characteristics, such as reliability. This correlation invalidates the standard instrumental variables approach, which relies on the exogeneity of vehicle characteristics. Several studies have avoided this complication by estimating the demand for fuel economy using plausibly exogenous variation in gasoline prices while controlling for unobserved vehicle characteristics (e.g., Busse et al. 2013). However, in the context of consumer demand for diesel fuel vehicles, performance (or other attributes of diesel engines) may be correlated with unobserved vehicle characteristics; fuel price variation alone cannot be used to identify preferences for performance as well as for fuel economy.

I address that challenge as follows. First, I focus on the consumer choice between two very closely related vehicles, which are identical in all physical dimensions with the exception that one vehicle uses gasoline and the other uses diesel fuel. More specifically, the analysis considers model trims and power trains that are sold in both gasoline and diesel fuel versions (such pairs account for most of the market in each country; see Section 2). I specify a nested logit vehicle choice model in which consumers first choose a vehicle model; then a trim, engine size, and transmission type; and finally the fuel type. This nesting structure enables a straightforward instrumental variables strategy that allows for the endogeneity of vehicle characteristics.

Furthermore, I explicitly model manufacturers' choice of fuel economy and performance. Manufacturers first make a discrete choice from available power trains, taking account of consumer demand for vehicle characteristics. Specifically, manufacturers first determine the fuel economy and performance of the gasoline and diesel fuel versions. Conditional on this choice, manufacturers choose the prices of the two versions. The two-stage approach allows me to control for unobserved characteristics in the second stage and endogenizes the choice of these characteristics in the first stage.

I document considerable cross-country differences in consumer preferences for fuel economy and performance. The cross-country differences are stable both across market segments and over time. The fact that preferences for performance vary across countries underscores the importance of including all characteristics of the product, and not just energy costs, in the demand model. The cross-country heterogeneity is consistent with recent findings of extensive consumer heterogeneity in appliance and vehicle choices (e.g., Houde 2012; Leard 2013).

Having estimated the demand parameters, I recover the cost parameters, including the relationships between fuel economy, performance, and marginal costs. I use the demand and supply parameter estimates to distinguish among the four hypotheses. Consistent with the descriptive analysis, fuel prices and supply conditions have very little explanatory power. With the exception of the Netherlands, demand for fuel economy explains nearly all of the cross-country market share variation; vehicle taxes play an important role for the Netherlands.

The central puzzle of why adoption varies so much across countries, as well as recent policy developments, motivates the analysis in this paper. Amid concerns about global warming and energy security, Europe has been tightening CO_2 emissions rate standards (CO_2 emissions rates vary inversely with fuel economy); European standards tighten by more than 30 percent between 2010 and 2021. Because of diesel fuel vehicles' lower emissions rates, such tightening standards could increase their market shares, but this would have broader environmental implications. Although diesel fuel vehicles have higher fuel economy and lower CO_2 emissions rates than comparable gasoline vehicles, they also have different emissions of other pollutants. Diesel fuel vehicles meeting current European standards emit three times as much nitrogen oxides, but half as much carbon monoxide, as gasoline vehicles; both pollutants impose significant health and environmental costs. Given European concerns about urban air pollution and public health (Wolff forthcoming), policies that affect the adoption of diesel fuel vehicles thus introduce environmental trade-offs.

In Section 6, I use the empirical estimates to characterize the environmental implications of two recently discussed European transportation policies. First, because fuel taxes vary so much across European countries, these countries have considered harmonizing fuel taxes. Using the structural model I simulate the effects of equalizing fuel prices across countries. The results suggest that equalizing fuel prices would have little effect on diesel fuel vehicle market shares or emissions rates in many countries because market shares are relatively insensitive to fuel prices. However, a tighter CO_2 emissions rate standard would have large effects on market shares and emissions rates, and these effects vary dramatically across countries. The policy simulations also show that although either fuel taxes or CO_2 emissions rate standards could reduce average CO_2 emissions rates, the policies have different effects on diesel fuel vehicle market shares and emissions rates of other pollutants. For example, standards have much larger effects on German diesel fuel vehicle market shares than do fuel taxes.

This paper makes several contributions to the literatures on differentiated products, passenger vehicles, and the energy paradox. First, I implement a straightforward empirical strategy that allows for the endogeneity of observed and unobserved vehicle characteristics; unobserved product characteristics are typically taken as exogenous in the differentiated products literature (Sweeting 2010; Draganska et al. 2012). Second, I model manufacturers' choice of characteristics, which allows supply to respond to market demand conditions; the vehicles literature has only allowed for responses to fuel economy regulation (e.g., Whitefoot et al., 2013). Third, I confront the puzzle of why adoption of diesel fuel passenger vehicles varies so much across European countries, and characterize the policy implications of the answer to this question. Although Verboven (2002) similarly analyzes European demand for diesel fuel vehicles, there are several important differences. That paper focuses on price discrimination, whereas this paper focuses on adoption and uses more recent data for a wider set of countries and a much larger set of vehicles. I also allow for endogenous vehicle supply in the estimation and simulations. Finally, the empirical strategy in this paper allows me to relax the assumptions in Verboven (2002) that the total sales of each diesel-gasoline pair are exogenous and that driving preferences are the only source of consumer heterogeneity; relaxing both assumptions significantly affects the results.

2. Data

2.1 Vehicle Registrations and Characteristics

The primary data are from RL Polk and include vehicle characteristics and registrations for the countries with the seven largest markets in continental Europe: Austria, Belgium, France, Germany, Italy, the Netherlands, and Spain. The seven countries account for about 92 percent of annual new vehicle registrations in the continental EU15.[3] The data include monthly new registrations and vehicle characteristics by trim line, number of cylinders, transmission type, and fuel type (gasoline or diesel fuel). *Trim* refers to a unique model name, body type, number of doors, number of wheels, trim line, and axle configuration. Transmission type can be either manual or automatic. I define a *trim–power train* as a unique trim–number of cylinders–transmission type. A trim–power train can have two *versions*—gasoline and diesel fuel. Figure 1 illustrates the nomenclature. Trim–power trains that belong to the same trim have (nearly) identical physical characteristics, but fuel economy and horsepower can vary substantially across power trains within a trim because of differences in the number of cylinders and transmission type. For a given trim–power train, fuel type explains any differences in fuel economy, horsepower, weight, or other power train characteristics.[4]

The vehicle characteristics include retail price, fuel consumption (liters of fuel per 100 kilometers), fuel economy (mpg), weight, length, width, height, horsepower, engine size (cubic centimeters of displacement), number of transmission speeds, and the CO_2 emissions rate. Fuel consumption and fuel economy are available for the years 2005–2010, but all other characteristics are available for 2002–2010. Fuel consumption and fuel economy are imputed for 2002–2004, as in Klier and Linn (2013a).

Most of the passenger vehicles literature uses the ratio of horsepower to vehicle weight as a proxy for performance, arguing that the ratio is proportional to the time needed to accelerate

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[3] The EU15 comprises Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

[4] Manufacturers could offer different options for gasoline and diesel fuel versions of the same trim–power train (e.g., leather versus cloth seats). Because some such options include unobserved characteristics, this practice would cause fuel economy or performance to be correlated with unobserved characteristics. Verboven (2002) addresses this issue by using the characteristics of the base version of each model. In this paper, restricting the analysis to trims that are sold with gasoline and diesel fuel versions has the same effect. For example, the “Standard” and “Sport” trims may have different unobserved features (e.g., the seating material or the quality of the sound system), but the demand estimation controls for this possibility.

from 0 to 100 kilometers per hour (km/h). Rather than use such a proxy, I measure performance as the time, in seconds, required for the vehicle to reach 100 kilometers per hour (km/h), starting from 0 km/h. The Polk data do not include this variable, but I impute it using a second data set.[5] The second data set includes horsepower, weight, transmission type, drive type (all-wheel or front-wheel drive), vehicle height, and the number of cylinders, for 2,383 vehicles in the UK market in 2013. The imputation relies on the coefficient estimates from a linear regression:

$$\ln(0to100_i) = \alpha_0 + \alpha_1 \ln(hp_i / w_i) + \alpha_2 m_i + \alpha_3 a_i + \alpha_4 f_i + \alpha_5 \ln(h_i) + \gamma_i + \varepsilon_i \,, \qquad (1)$$

where the dependent variable is the log 0 to 100 km/h time, hp_i / w_i is the ratio of the vehicle's horsepower to weight, m_i is a dummy variable equal to one if the vehicle has a manual transmission, a_i and f_i are dummy variables equal to one if the vehicle has all-wheel or front-wheel drive, h_i is the vehicle's height, and γ_i includes a set of fixed effects for the number of cylinders. The α s are coefficients to be estimated, and ε_i is an error term.

I estimate equation (1) by ordinary least squares (OLS) separately for diesel fuel and gasoline vehicles. Appendix Table 1 shows the results. The signs of the coefficients are as expected, and the high R-squared value indicates that the independent variables are jointly strong predictors of the log of the 0 to 100 km/h time. The coefficient estimates are used to impute the 0 to 100 km/h time for all vehicles in the Polk data. The 0 to 100 km/h time is the measure of performance used in the rest of the paper; a longer time implies less performance.

Appendix Figure 1 plots the imputed 0 to 100 km/h time against the log of the ratio of horsepower to weight. The two variables are strongly negatively correlated with one another. However, the figure demonstrates substantial scatter, which illustrates the importance of including the other attributes in equation (1) rather than using the ratio of horsepower to weight, as in most of the literature.

I supplement the vehicle data with fuel prices from Eurostat and vehicle and fuel tax rates from the European Automobile Manufacturers Association. Klier and Linn (2012b) describe the data sources in more detail. From these sources I calculate the average gasoline price, gasoline tax, diesel fuel price, and diesel fuel tax by country and year.

[5] In principle, consumers could care about other measures of performance besides 0 to 100 km/h time, such as low-end torque (the amount of torque available at low engine speed) or the time needed to accelerate from 30 to 80 km/h (relevant when accelerating on a highway on-ramp). The primary advantage of the chosen measure is that it can be imputed using the available data.

2.2 Summary Statistics

Table 1 provides some basic summary information about the data. The first row reports average annual registrations by country and shows that Germany has the largest market, followed by France and Italy. The size of the markets varies considerably across countries: the Austrian market, for example, is less than 1/10th the size of the German market.

Figure 2 shows the diesel fuel vehicle market shares (Panel 2a) and the ratio of the gasoline to diesel fuel price (Panel 2b), by country and year. Diesel fuel vehicle market shares vary substantially across countries and years. The Netherlands consistently has the lowest market share, and Belgium and France have the highest shares for most of the time period. The market shares also are quite persistent; with the exception of Austria, the ranking of market shares across countries does not change over time.

Likewise, the fuel price ratios vary considerably across countries, but little over time. The Netherlands has the highest price of gasoline relative to diesel fuel, whereas Spain and Austria typically have the lowest relative gasoline prices. Fuel taxes explain much of the cross-country variation in the relative price of gasoline (not shown). As noted in the Introduction, although all countries tax diesel fuel at a lower rate than gasoline, countries vary in the extent to which they differentially tax the two fuels.

Next, I provide some descriptive information on vehicle supply. Most of the analysis in this paper focuses on trim–power trains sold with a diesel fuel and gasoline version in the same country and year. The second row of Table 1 shows that such vehicles account for a very large share of the market in each country—more than 70 percent in most cases. Although restricting the analysis to such vehicles might raise the concern that the samples are not representative of the corresponding markets, Appendix Figure 2 shows that the diesel fuel vehicle market shares of the restricted samples are quite similar to the market shares computed using the full samples in Figure 2.

The third row of Table 1 shows that nearly all of the trim–power trains sold in each of the smaller markets are also sold in Germany. However, Table 2 shows that there are more subtle cross-country differences in vehicle supply. The table reports coefficient estimates from a regression of log fuel economy (column 1) or log 0 to 100 km/h time (column 2) on trim–power train by year interactions and country fixed effects. Because of the trim–power train by year interactions, all the remaining fuel economy and time variation occurs within a trim–power train and year, and across countries. The table reports coefficients on the country fixed effects, with Germany being the omitted category. The coefficients are interpreted as the percentage difference in fuel economy or time for the corresponding country, relative to Germany. For example, the coefficient for Austria in column 1 implies that vehicles in Austria have about 1 percent higher fuel economy than vehicles with the same trim–power train in Germany. Although the cross-country differences in vehicle characteristics are highly statistically significant, they are quite small in magnitude. The small differences suggest that supply conditions are quite similar across countries.

Figure 3 provides information about the differences between gasoline and diesel fuel versions of the same trim–power train. To construct the figure, for three variables (fuel economy, 0 to 100 km/h time, and price) I compute the log of the ratio of the gasoline version's value to the diesel fuel version's value. The figure plots the estimated density functions of these three log ratio variables. Gasoline versions have about 30 percent lower fuel economy than corresponding diesel fuel versions, but there is a lot of variation around this mean. Average 0 to 100 km/h time is similar for gasoline and diesel fuel vehicles, but the standard deviation of the log ratio is more than 10 percent. Gasoline versions are priced at about a 10 percent discount, on average, with discounts also varying dramatically across trim–power trains.

Not only do fuel prices and taxes vary across countries, but vehicle taxes do as well. The bottom of Table 1 shows the percentage difference of the present discounted value of vehicle taxes for the gasoline and diesel versions of the trim–power train. Belgium, Germany, Italy, and the Netherlands tax diesel fuel vehicles more heavily than diesel fuel vehicles, whereas Austria, France, and Spain tax gasoline vehicles more heavily. Vehicle taxes differ between gasoline and diesel fuel vehicles both because the tax rates in some countries depend on fuel type, and also because the taxes depend on vehicle characteristics, which vary systematically between gasoline and diesel fuel vehicles (see Figure 3).

3. Descriptive Analysis: Market Shares and Fuel Prices

As noted in the Introduction, a recent literature has documented a strong relationship between fuel prices and new vehicle market shares. This finding suggests that fuel prices could explain the diesel fuel vehicle market share variation in Europe. Before turning to a structural model to test this hypothesis, in this section I use aggregate data and show that fuel prices do not by themselves explain cross-country or temporal variation of diesel fuel vehicle market shares.

I begin by plotting each country's diesel fuel vehicle market share against the ratio of the gasoline price to the diesel fuel price. If relative fuel prices explain cross-country variation, the two variables would be positively correlated. Figures 4a and 4b show scatter plots for 2002 and

2010, and the correlation is not positive in either case. Figure 4c shows that within-country changes in relative fuel prices are not positively correlated with changes in diesel fuel vehicle market shares between 2002 and 2010.

An alternative to the graphical analysis is a simple statistical test of the correlations between fuel prices and market shares. Column 1 of Table 3 reports a regression of a country's diesel fuel vehicle market share on the log price of gasoline, the log price of diesel fuel, and year and country fixed effects. This specification allows gasoline and diesel fuel prices to have independent effects on market shares, rather than assuming that the effects are equal and opposite, as in Figure 4. In fact, gasoline prices have a positive correlation with diesel fuel vehicle market shares, and diesel fuel prices have a negative correlation, which suggests that fuel prices may explain at least some of the cross-country market share variation. Column 2 yields a similar conclusion, in which fuel taxes replace the fuel prices in column 1.

Columns 3 and 4, however, show that the results change when taking first differences. The standard errors are similar whether taking first differences or estimating the regression in levels (as in columns 1 and 2), but the first-differenced coefficients are much smaller in magnitude. The fact that the first-differenced and levels results do not agree implies that omitted and time-varying factors may be correlated with fuel prices, which are not controlled for in the levels regressions. The lack of a strong correlation between fuel prices and diesel fuel vehicle market shares is consistent with Klier and Linn (2013a), who find that monthly fuel price variation has a small effect on the market share of diesel fuel vehicles. A structural model is needed, however, to compare quantitatively the importance of fuel prices and other factors that could explain market shares.

4. Structural Model of Vehicle Demand and Supply

The Introduction discussed four hypotheses for explaining market shares: taxes, demand for fuel economy, demand for performance and other attributes, and supply. Testing these hypotheses directly requires an economic model that synthesizes consumer demand and manufacturers' choices of vehicle characteristics. This section describes the demand and supply of the vehicles market, derives the estimating equations, and reports estimates of the key parameters.

4.1 Vehicle Demand

Each country and year represents a separate market, and each country's market consists of consumers deciding whether to purchase a new or used car; let Q_{cy} be the total size of the market in country c and year y. I focus on the demand for new cars and define the purchase of a used car as the "outside option."

Following the standard BLP approach, I assume that consumer i in country c and year y has indirect utility for vehicle j that is linear in the characteristics of the vehicle and in an idiosyncratic error term:

$$U_{ijcy} = \alpha_{1c} \ln(P_{jcy}) + \alpha_{2c} \ln(FC_{jcy}) + \alpha_{3c} \ln(0to100_{jcy}) + \alpha_{4c} D_{jcy} + \xi_{jcy} + \varepsilon_{ijcy}$$

where the price of the vehicle is P_{jcy}, which includes the present discounted value of taxes; FC_{jcy} is the per kilometer fuel cost of the vehicle; $\ln(0to100_{jcy})$ is the log of the time required to go from 0 to 100 km/h; D_{jcy} is the utility from other attributes of the diesel engine technology, such as engine lifetime; ξ_{jcy} is a scalar representing the mean indirect utility of all other vehicle characteristics; ε_{ijcy} is an error term specific to the consumer and vehicle; and the α s are country-specific coefficients. The variable FC_{jcy}, which is the product of the current fuel price and the vehicle's fuel consumption, is proportional to the present discounted value of future fuel costs, assuming a constant discount rate and assuming that fuel prices follow a random walk. Because higher vehicle prices and fuel costs reduce income available to spend on other goods, the price and fuel cost coefficients are negative. Consumers may care about other attributes of the diesel technology besides fuel costs and performance, such as engine lifetime or noise. Because the additional characteristics are not observed in the data, I use the number of transmission speeds as a proxy for the other attributes in D_{jcy}. In the European data, the diesel fuel version almost always has one more transmission speed than the gasoline version belonging to the same trim–power train. Consequently, this variable is a monotonic transformation of the joint utility of other diesel-specific attributes that are not included in equation (4). Because the other attributes are not measured, I do not interpret the transmission speed coefficient as reflecting consumers' willingness to pay for transmission speeds per se. Rather, I interpret the coefficient as being proportional to consumers' willingness to pay for characteristics of the diesel engine other than fuel costs and performance. The parameter ξ_{jcy} includes utility from all other characteristics, such as size, exterior design, and cabin features; the variable does not include characteristics specific to the diesel fuel technology, which are captured in D_{jcy}. Note that because all coefficients and ξ_{jcy} are indexed by c, I allow consumer preferences to vary across countries but not over time or within a country (these restrictions are subsequently relaxed).

Consumer demand follows a nesting structure such that a consumer decides whether to purchase a new car, then chooses a model (indexed by m), then a trim–power train (indexed by p), and finally a gasoline or diesel fuel version (see Figure 1). The standard extreme value assumption on the error term yields an equation in which the vehicle's market share is a linear function of its characteristics and market shares of the trim–power train and model (Berry 1994):

$$\begin{aligned}\ln(Q_{jcy}/Q_{cy}) - \ln(Q_{0cy}/Q_{cy}) &= \alpha_{1c}\ln(P_{jcy}) + \alpha_{2c}\ln(FC_{jcy}) + \alpha_{3c}\ln(0to100_{jcy}) \\ &+ \alpha_{4c}D_{jcy} + \sigma_1\ln(s_{jcy|pcy}) + \sigma_2\ln(s_{pcy|mcy}) + \xi_{jcy}\end{aligned}, \qquad (2)$$

where the dependent variable is the difference between the log market share of the vehicle and the log market share of the outside option ($j = 0$). The variable $s_{jcy|pcy}$ is the share of registrations of the version in total trim–power train registrations, and the variable $s_{pcy|mcy}$ is the share of trim–power train registrations in total model registrations. The coefficients σ_1 and σ_2 are between 0 and 1; the closer is σ_1 to 1, the stronger the correlation of the consumer-specific shocks (i.e., ε_{ijcy}) for two versions of the same trim–power train, and likewise for σ_2. The nesting structure implies that $\sigma_1 > \sigma_2$, such that a consumer's idiosyncratic preference shocks for the two versions of the same trim–power train are more strongly correlated than shocks for two trim–power trains belonging to the same model.

Estimating equation (2) by OLS would likely yield biased estimates because ξ_{jcy} is unobserved and is likely to be correlated with the vehicle price, and because $s_{jcy|tcy}$ and $s_{tcy|mcy}$ are endogenous. For example, whether the vehicle has a sunroof is not reported in the data. ξ_{jcy} includes the indirect utility from a sunroof, and manufacturers are likely to set a higher price for a vehicle with a sunroof than for an otherwise identical vehicle.

The endogeneity of these variables is the same problem that BLP and many other vehicle demand papers address by instrumental variables. The standard set of instruments is computed from the observed characteristics of other vehicles in the same market segment and from other vehicles sold by the same manufacturer.

In the present context, however, these instruments are likely to yield biased estimates. Klier and Linn (2012a) argue that manufacturers are likely to select unobserved characteristics that are correlated with observed characteristics. For example, cars with better (observed) performance may have better (unobserved) sound systems. Furthermore, a manufacturer's choice of sound system quality may be correlated with the sound system and performance of vehicles sold by other manufacturers. This correlation between observed and unobserved characteristics violates the exclusion restrictions assumed in the standard instrumental variables strategy.

I show that a straightforward two-stage estimation approach circumvents this difficulty. To implement the first stage, I add to equation (2) a country-year trim–power train intercept, η_{pcy}, which controls for all omitted vehicle characteristics that are common to the two versions, yielding

$$\ln(Q_{jcy}/Q_{cy}) - \ln(Q_0/Q_{cy}) = \alpha_{1c}\ln(P_{jcy}) + \alpha_{2c}\ln(FC_{jcy}) + \alpha_{3c}\ln(0to100_{jcy}) + \alpha_{4c}D_{jcy} + \sigma_1\ln(s_{jcy|pcy}) + \eta_{pcy} + \upsilon_{jcy} \quad (3)$$

where υ_{jcy} is the error term. Importantly, η_{pcy} absorbs the trim–power train market share variable, $s_{pcy|mcy}$, because the variable is the same for both versions of the same trim–power train.

Rearranging equation (3) and accounting for the fact that the market share of the outside good is the same for two versions, I obtain the first-stage estimating equation:

$$\ln(Q_{jcy}) = \beta_{1c}\ln(P_{jcy}) + \beta_{2c}\ln(FC_{jcy}) + \beta_{3c}\ln(0to10_{jcy}) + \beta_{4c}D_{jcy} + \eta_{pcy} + \upsilon_{jcy} \quad (4)$$

where $\beta_{kc} = \alpha_{kc}/(1-\sigma_1)$ for $k = 1,2,3,4$. Therefore, it is not possible to identify the parameters in the consumer's utility function using equation (4) alone. However, price is no longer correlated with the error term in equation (4), and OLS estimation of the equation yields unbiased estimates.

In the second stage I estimate the parameters σ_1 and σ_2, which allows me to recover the underlying utility function parameters. From equation (2), the estimated country-year trim–power train intercept, η_{pcy}, in equation (4) is

$$\eta_{pcy} = \frac{\ln(Q_0)}{1-\sigma_1} - \frac{\sigma_1}{1-\sigma_1}\ln(Q_{pcy}) + \frac{\sigma_2}{1-\sigma_1}\ln(s_{pcy|mcy}) + \frac{\xi_{pcy}}{1-\sigma_1}, \quad (5)$$

where $\xi_{pcy} = \xi_{jcy} - \upsilon_{jcy}$ is the mean unobserved utility of the trim–power train. Equation (5) shows that σ_1 and σ_2 can be estimated by regressing η_{pcy} on a constant, the log of total registrations of the trim–power train, Q_{pcy}, and the log of the ratio of trim–power train registrations to model registrations. However, estimating equation (5) by OLS would likely yield biased estimates because of the correlation between ξ_{pcy} and the independent variables. As before, the standard BLP instruments are invalid because the characteristics of other vehicles are likely to be correlated with ξ_{pcy}. Therefore I estimate equation (5) by instrumental variables, where the instruments are the interactions of fuel prices with the log fuel consumption and log 0 to 100 km/h time of the trim–power train's gasoline and diesel fuel versions. I include in equation (5) trim–power train fixed effects, because of which the first stage is identified by temporal fuel price variation interacting with vehicle characteristics. The underlying assumption is that fuel price variation is uncorrelated with changes in consumer preferences for these characteristics—the same assumption is made in the recent literature on consumer demand for fuel economy (e.g., Allcott and Wozny forthcoming).

Although the nested logit demand structure imposes different behavioral restrictions from those in a random coefficients logit model, the two-stage approach implemented here has two advantages.[6] The first advantage is that the coefficient estimates in the first stage (equation 4) do not depend on the validity of the instrumental variables. If the instruments were invalid, only the second-stage coefficients would be biased, whereas all coefficients would be biased in a random coefficients logit model. This is an important distinction because certain attributes of the utility function, such as the willingness to pay for fuel economy, depend only on the first-stage estimates.[7] The second advantage is that equation (5) addresses the potential endogeneity of vehicle characteristics in a straightforward manner (and avoiding the need for the extensive engine data used in Klier and Linn 2012a). In short, estimation of equations (4) and (5) is robust to the possibility that observed and unobserved characteristics of trim–power trains are correlated with one another, unlike estimation using the standard BLP approach. Verboven (2002) likewise does not rely on the standard instruments, but equations (4) and (5) relax that paper's assumptions that total trim–power train registrations are exogenous and that driving preferences are the only source of consumer heterogeneity. Furthermore, note that because equation (4) includes trim–power train and year interactions, the first-stage estimates would be identical under any alternative nesting structure in which the final nest is the choice of fuel type. This feature partially addresses concerns, which apply to any nested logit demand system, that the assumed nesting structure is ad hoc.

4.2 Vehicle Supply

The supply side of the model is static, and manufacturers take as exogenous the set of trim–power trains sold in each market. The supply model consists of two stages. In the first

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[6] Grigolon and Verboven (forthcoming) conclude that a random coefficients logit and nested logit model yield reasonably similar substitution elasticities. The authors suggest that the nesting structure may proxy for random coefficients on continuous product characteristics.

[7] Some vehicle demand models in the literature include model fixed effects, in which case the price coefficient is identified by within-model variation over time. In practice, manufacturers regularly change observed and unobserved vehicle characteristics during minor and major vehicle redesigns (Klier and Linn 2012a; Blonigen et al. 2013). Because of these redesigns, within-model price variation may be correlated with unobserved vehicle characteristics. Therefore, including model fixed effects does not circumvent the endogeneity of the vehicle's price and other characteristics.

stage, the manufacturer chooses the fuel economy and 0 to 100 km/h time of the vehicle. In the second stage, the manufacturer chooses each vehicle's price.

For tractability, I assume that the manufacturer maximizes profits of each trim–power train separately; that is, when the manufacturer chooses the prices of the gasoline and diesel fuel versions of a particular trim–power train, the manufacturer accounts for the effect of the prices on new registrations of the two versions, but not the effects of the prices on the new registrations of its other vehicles. The subscripts g and d index the gasoline and diesel fuel versions of the trim–power train.

In the second stage, conditional on the choice of fuel economy and 0 to 100 km/h time, the manufacturer chooses prices to maximize the profits:

$$\max_{P_{gpcy},P_{dpcy}} Q_{gpcy}(P_{gpcy}-mc_{gpcy})+Q_{dpcy}(P_{dpcy}-mc_{dpcy})$$

where mc_{gpcy} and mc_{dpcy} are the marginal costs of the two versions. The first-order conditions for the gasoline and diesel fuel prices are

$$\begin{aligned} Q_{gpcy}+\frac{\partial Q_{gpcy}}{\partial P_{gpcy}}(P_{gpcy}-mc_{gpcy})+\frac{\partial Q_{dpcy}}{\partial P_{gpcy}}(P_{dpcy}-mc_{dpcy})=0 \\ Q_{dpcy}+\frac{\partial Q_{dpcy}}{\partial P_{dpcy}}(P_{dpcy}-mc_{dpcy})+\frac{\partial Q_{gpcy}}{\partial P_{dpcy}}(P_{gpcy}-mc_{gpcy})=0 \end{aligned} \quad . \qquad (6)$$

The first-order conditions show that the manufacturer chooses a vehicle's price accounting for the own-price elasticity of demand and for the cross-price elasticity of demand for the other vehicle with the same trim–power train.

In the first stage the manufacturer chooses the fuel economy and 0 to 100 km/h time of each vehicle. The choices affect second-stage profits in two ways. First, the marginal cost of producing the vehicle depends on the two characteristics chosen in the first stage:

$$\ln(mc_{gpcy})=\gamma_{pcy}+\gamma_1\ln(M_{gpcy})+\gamma_2\ln(0to100_{gpcy}), \qquad (7)$$

where γ_{pcy} is a constant that depends on the (assumed) exogenous attributes of the trim–power train, such as body style and number of doors, and γ_1 and γ_2 are the elasticities of marginal costs to fuel economy (M_{gpcy}) and 0 to 100 km/h time. The elasticity with respect to fuel economy should be positive and the elasticity to 0 to 100 km/h time should be negative, which reflects the increase in production costs needed to raise the vehicle's fuel economy or reduce its acceleration time, while holding fixed the other vehicle attributes. A similar equation applies to the marginal cost of the diesel fuel version.

The second effect of choosing the fuel economy and 0 to 100 km/h time is that these characteristics affect consumer demand according to equation (2). The manufacturer faces a trade-off between increasing demand for the vehicle and increasing its marginal cost.

To characterize the manufacturer's choice of these characteristics, it is necessary to specify the set of feasible values the characteristics can take. One approach would be to use an engineering-based simulation tool to determine the values of fuel economy and 0 to 100 km/h time that could be offered for each vehicle, similarly to Whitefoot et al. (2013). However, lacking such a tool for the European market, I instead define the feasible set based on observed values of these attributes in the data. In particular, I assume that the manufacturer could have chosen values of these variables that exist for the same trim–power train but in other markets. For example, for a trim–power train in Germany, the manufacturer could have chosen the values of fuel economy and time of the same trim–power train in Italy. Table 2 and Figure 2 show the extent of the variation across countries in the values of these characteristics. For most vehicles, manufacturers can vary fuel economy and performance by more than 5 percent.

4.3 Estimation Results

4.3.1 Demand Parameters

Table 4 reports estimates of equation (4). A separate regression is estimated for each country, and the sample is restricted to trim–power trains with gasoline and diesel fuel versions (see Table 1). Standard errors are in parentheses, clustered by trim–power train and year. The dependent variable is the log of the vehicle's new registrations, and besides the reported variables, the equations include the interaction of trim–power train and year. The reported price, fuel cost, and 0 to 100 km/h coefficients are all negative, as expected. The magnitudes differ considerably across countries—by a factor of about 2 for the price coefficient, and a factor of about 3 for the fuel cost and 0 to 100 km/h coefficients.

To interpret the magnitudes of the coefficients in Table 4, it is necessary to estimate σ_1 and σ_2 in equation (2). This is accomplished by estimating equation (5), in which the dependent variable is the trim–power train and year intercept estimated in the regressions reported in Table 4, and the independent variables include the log of the trim–power train's registrations and the log of the share of trim–power train registrations in model registrations; regressions also include trim–power train and year fixed effects. I estimate equation (5) using the instrumental variables described in Section 4.1. Panel A reports the estimated coefficients on the two main independent variables. The coefficients are all statistically significant, and the estimates imply that $0 < \sigma_1 < 1$ and that $\sigma_1 > \sigma_2 > 0$ for all countries.

Turning to the magnitudes of the preference parameters, the coefficients on fuel costs imply that many consumers overvalue fuel economy. Assuming a 10 percent discount rate and 10,000 miles driven per year, consumers in Belgium, France, and Italy are willing to pay almost €2 for a euro of discounted fuel savings (see Panel B). On the other hand, consumers in Germany are willing to pay €0.74 for a euro of discounted fuel savings. This variation could reflect differences in driving behavior—for example, if consumers in France and Belgium drive more miles than consumers in Germany. Discount rates or other factors could also explain the variation.

The coefficients on log 0 to 100 km/h time imply that consumers are willing to pay between €500 (Belgium) and €1,300 (Spain) for a 1-second decrease (compared with a sample mean of about 10 seconds).[8]

Panel C of Table 5 reports the estimated own and cross-price elasticities computed from the estimates in Table 4 and in Panel A of Table 5. The first row reports the own-price elasticity, which is the percentage change in registrations for a 1 percent increase in the vehicle's price. The elasticities range from –4.7 in Spain to –9.8 in Germany and suggest that consumers are highly price responsive overall, with greater responsiveness in some countries than in others. The large magnitudes are consistent with the fact that the data are much more disaggregated than most of the vehicle demand literature, in which a vehicle model and year typically defines a unique observation.

When a vehicle price increases, much of the substitution is to the other version of the same trim–power train. This is shown by the large cross-price elasticities, which are the percentage change in registrations given a 1 percent increase in the price of the other version belonging to the same trim–power train. The large within-pair cross-price elasticities indicate that consumers regard the two versions as close substitutes.

In Table 4, the transmission speed coefficient is positive and statistically significant at conventional levels for most countries. As noted in Section 4.1, however, the number of

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[8] A willingness to pay of €1,000 translates to about $150 per horsepower per ton at the sample means, which is in the range of estimates of willingness to pay for horsepower per ton from the previous literature (summarized in Whitefoot and Skerlos 2013).

transmission speeds is correlated with unobserved attributes of the diesel technology, because of which I do not interpret this coefficient as being proportional to the willingness to pay for transmission speeds. Instead, the coefficient suggests that, after controlling for fuel costs and performance, consumers have higher willingness to pay for diesel fuel than for gasoline versions of the same trim–power train (recall that the diesel fuel version has more transmission speeds than the gasoline version).

A potential concern with the demand model is that certain attributes of the diesel technology, such as engine lifetime, are not observed. If the transmission speed variable does not control for these factors, the fuel cost and performance coefficients would be biased. In that case, adding another variable to the demand estimation, which is also correlated with the diesel fuel technology, would cause the fuel cost and performance coefficients to change. Diesel fuel engines typically have greater displacement than their gasoline counterparts, but adding engine displacement does not affect the main coefficient estimates (see Appendix Table 2).

As noted above, I estimate a nested logit model to account for the endogeneity of vehicle characteristics. An important restriction of the nested logit is that the coefficients are the same across vehicles in the same country. The appendix reports the results of relaxing this assumption in several ways.

In Appendix Table 3, I assign each trim–power train to a fuel consumption quartile based on the distribution of fuel consumption of diesel fuel vehicles in the corresponding country and year. Trim–power trains in quartile 1 have the lowest fuel consumption (highest fuel economy) and trim–power trains in quartile 4 have the highest fuel consumption (lowest fuel economy). I estimate a separate regression by country and quartile. The magnitude of the price coefficient tends to be larger for the lower quartiles than for the higher quartiles. The opposite pattern is apparent for the fuel cost coefficient, which tends to increase across quartiles. The country patterns for each quartile are similar to those observed in Table 4.

Appendix Table 4 is similar to Appendix Table 3 except that vehicles are assigned quartiles based on 0 to 100 km/h time rather than fuel consumption. Because 0 to 100 km/h time is strongly negatively correlated with fuel consumption, the trends across quartiles within a country are the opposite in Appendix Table 4 as compared with Appendix Table 3. The cross-country patterns are similar to those in Table 4 (for readability, the transmission speed coefficient is not reported in these appendix tables).

Finally, Appendix Table 5 shows the results from estimating equation (4) for two separate time periods. Although for several countries demand appears to be more price-elastic in

2007–2010 than in 2002–2006, the cross-country patterns and most of the coefficient estimates themselves are fairly similar in the two time periods. Thus, there is consistent evidence for substantial cross-country differences in preferences for fuel economy and performance. These differences are stable over time and across subsets of the markets. Because of this stability, I use the estimates in Tables 4 and 5 in the analysis in the next two sections.

4.3.2 Supply Parameters

I use the coefficient estimates from equations (4) and (5) to solve for the marginal costs in the first-order conditions in (6). The marginal costs vary by trim–power train, fuel type, country, and year.

Using the marginal costs, I estimate the relationships among fuel economy, 0 to 100 km/h time, and marginal costs in equation (7). Specifically, I pool observations across countries and regress the log marginal costs on trim–power train–year interactions, country–market segment interactions, and interactions of market segment with log fuel economy and log 0 to 100 km/h time. The coefficients on the segment–fuel economy and segment-performance interactions, which are reported in Table 6, have the expected signs. Improving fuel economy and performance raises the log of marginal costs more for small cars than for larger cars. This result is consistent with expectations because the coefficients are identified largely by within–trim–power train and cross-country variation in marginal costs. The difference in engine costs between the gasoline and diesel fuel version scales less than proportionately with the total cost of the vehicle.

Figure 5 provides an informal test of the validity of the demand and supply model. One would expect the marginal costs of a particular trim–power train–fuel type to be similar across countries. There may be differences across countries in shipping costs or other factors, but these are likely to be small compared with the cost of manufacturing the vehicle. To test this hypothesis, I regress the estimated marginal costs on trim–power train–fuel type–year interactions, using observations from all seven countries. The figure plots the estimated density functions of the regression residuals, with a separate density function estimated for each country. I expect that the density functions will be similar to one another and that most of their mass will be close to zero. The average marginal costs are about 4 percent higher in Germany than in the other countries, suggesting that there are some slight differences across countries, but for the most part these differences are quite small in magnitude.

5. Explaining Cross-Country Variation in Market Shares

This section uses the model and parameter estimates from Section 4 to examine whether taxes, consumer preferences, or manufacturer choices of vehicle characteristics explain cross-country variation in diesel fuel vehicle market shares. I first describe the assumptions made in the simulations and then present the results.

5.1 Assumptions Used to Test the Hypotheses

I test the hypotheses by performing five simulations. The first hypothesis is that fuel or vehicle taxes explain consumer adoption of diesel fuel vehicles. In the first simulation, I replace the fuel prices in each country with the German fuel prices for the same year. Given these fuel prices, manufacturers choose vehicle prices to maximize profits. I compute counterfactual diesel fuel vehicle market shares using German fuel prices and the simulated vehicle prices. If fuel prices have a large effect on market shares, the counterfactual market share in each country would be similar to the market share in Germany.[9] The simulation uses the supply conditions in the last year of the sample, 2010. I assume that the counterfactual total market size is the same as the actual market size.[10] A second simulation uses German fuel prices as well as German vehicle tax rates to compute vehicle taxes. Compared with the first simulation, the differences in predicted market shares correspond to the effect of vehicle taxes on consumer adoption.

To test the second hypothesis, that demand for fuel economy explains market shares, for each country I adjust the fuel cost coefficient so that the average willingness to pay for fuel costs is the same as in Germany (the coefficient on vehicle price and the other parameters are unchanged). As with the first and second simulations, I test whether the simulated market shares are close to the German market shares; similarity would suggest that fuel economy preferences explain much of the cross-country market share variation. The fourth simulation is the same as the third except that it equates the average willingness to pay for performance and transmission speeds in each country with the average willingness to pay for these attributes in Germany.

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9 An alternative approach would be to equalize fuel taxes across countries, but then it would be necessary to assume pass-through rates of fuel taxes. Marion and Muehlegger (2011) report approximately full pass-through of fuel taxes in the United States, but direct empirical evidence does not exist for the European countries included in this analysis.

10 I make this assumption because the data are insufficient for reliably estimating the choice between purchasing a new vehicle and the outside option. The assumption does not affect the estimation of the demand model because equation (5) allows for separate intercepts by country and year, which eliminates the need to calculate the market share of the outside option.

Comparing the third and fourth simulations informs the importance of consumer demand for performance and other characteristics of the diesel technology.

The final simulation includes the first stage of the supply model, in which manufacturers choose the profit-maximizing fuel economy and performance of each vehicle. For a particular trim–power train, country, and year, I first determine the values of fuel economy and performance for the same trim–power train–fuel type offered in other countries. This step yields, for each vehicle, up to seven possible values of fuel economy and performance (one possibility for each country). I estimate profits for each of these possibilities and choose the possibility with the highest profits. This first stage determines the values of fuel economy and performance for the two vehicles, and the manufacturer chooses the profit-maximizing prices in the second stage, conditional on the first-stage choice and on preference coefficients, which are the same as in the previous simulation.[11] If endogenous supply is an important factor in explaining cross-country market shares, the simulated market shares would be more similar to the German market shares than in the previous simulation.

5.2 Simulation Results

Table 7 reports the results of the simulations. The top panel reports the observed diesel fuel vehicle market shares in 2010 for each country. The remaining panels report the market shares in each simulation. When the fuel price, tax, and demand hypotheses are tested (Panels A–E), the simulated German market shares are always identical to the actual German market shares because the demand parameters, fuel prices, and taxes are unchanged in the German simulations.

Comparing Panel A and Panel B shows that fuel prices have very small effects on diesel fuel vehicle market shares. Simulated market shares never differ by more than a few percentage points from the actual market shares and are not close to the German market shares. Panel C shows that vehicle taxes have a significant effect on the diesel fuel vehicle market share in the Netherlands—and, to a lesser extent, in Austria—but not in the other counties; in fact, the market share in the Netherlands is fairly close to the market share in Germany in this simulation. This result arises because the Netherlands taxes vehicles much more heavily than other countries, and reducing the level of the taxes makes diesel fuel vehicles relatively more attractive (this effect

[11] The first stage is initially simulated holding fixed the prices of vehicles sold by other manufacturers at their observed levels. After simulating the second stage, I check that the profit-maximizing choice in the first stage remains the profit-maximizing choice after replacing the observed prices with the simulated prices.

dominates the fact that Germany taxes diesel fuel vehicles more heavily than does the Netherlands).

Panel D reports the results of the third simulation, in which the average willingness to pay for fuel costs in each country is identical to that in Germany. The simulated market shares turn out to be fairly close to Germany's—within about 10 percentage points. Market shares in Panel E are similar to those in Panel D, suggesting that preferences for performance and other diesel fuel engine characteristics have little explanatory power. The final simulation, reported in Panel F, in which the choices of fuel economy and performance are endogenous, yields results that are essentially the same as the results in Panel E.[12] Therefore I conclude that preferences for fuel economy explain most of the cross-country variation in diesel fuel vehicle market shares. The exception is the Netherlands, where vehicle taxes explain most of the difference with Germany.

6. Effects of Fuel Taxes and CO_2 Standards on Diesel Fuel Vehicle Market Shares and Emissions Rates

This section quantifies two policy implications of the conclusion that demand for fuel economy largely explains consumer adoption of diesel fuel vehicles. I first consider the possibility that European countries harmonize fuel taxes, which has been discussed in recent years. Harmonization could take a variety of forms, but in this analysis I consider a scenario in which fuel taxes are set such that retail fuel prices are equalized across countries.[13] The second policy is the CO_2 emissions rate standards, which tighten by more than 30 percent between 2010 and 2021. Each manufacturer is subject to the standard and pays a fine for failing to comply.

Nitrogen oxides and carbon monoxide contribute to health and other environmental problems, particularly in urban areas. Because emissions rates of these pollutants differ between gasoline and diesel fuel vehicles, policy-induced changes in diesel fuel vehicle market shares could have broad environmental implications. The literature has not considered the effects of the

[12] The market share for Germany in Panel F is not identical to the actual market share in Panel A because the simulations result in small changes in fuel economy or performance for a subset of the vehicles; these choices do not have a large effect on the predicted market share, however.

[13] This scenario does not necessarily imply that taxes are equalized across countries because there may be other factors, such as the distance to refineries, which cause the nontax portion of the retail price to vary across countries. As in Section 5, simulations use changes in fuel prices rather than changes in fuel taxes because of a lack of evidence on tax pass-through.

two policies on air pollution emissions. For both policies, I estimate the effects on diesel fuel vehicle market shares as well as on emissions rates of CO_2, nitrogen oxides, and carbon monoxide.

6.1 Fuel Price Harmonization

Table 8 shows the estimated effects of setting fuel prices in each country equal to the European averages. Panel A reports the fuel prices, diesel fuel vehicle market share, and registrations-weighted average emissions rates in the initial (no-policy) equilibrium in 2010. The first column shows the Europe-wide average and the remaining columns show the individual countries.

Starting from the initial equilibrium, I simulate counterfactual vehicle prices and market shares assuming that each country's fuel prices are set equal to the European average prices. The simulations use the demand parameter estimates for each country reported in Tables 4 and 5.

The first column shows that Europe-wide average market shares and emissions rates change very little, which is not surprising because the average fuel prices in the counterfactual are equal to the average fuel prices in the 2010 equilibrium. This result masks considerable cross-country variation in the policy's effects, however. Austria and Spain had the lowest fuel prices in Europe in 2010, and the simulations cause a relatively large increase in diesel fuel vehicle market shares, with corresponding decreases in the CO_2 and carbon monoxide emissions rates; the nitrogen oxides emissions rate increases substantially. As Li et al. (2013) report (based on estimates from McCubbin and Delucchi 1999 and Muller and Mendelsohn 2009), damages from nitrogen oxides emissions are roughly four times higher than damages from an equal amount of carbon monoxide emissions. The results in Table 8 indicate that, overall, the damages from the increased nitrogen oxides emissions are roughly comparable to the benefits of the decreased carbon monoxide emissions. These results are only suggestive, however, because the effects on health and environmental quality depend on driving behavior and the relationship between emissions and ambient pollution levels; a detailed air pollution model would be needed to quantify these effects.

Italy also experiences a fairly large change in the diesel fuel vehicle market share—and associated changes in emissions rates—not because fuel prices change very much in the simulations but because Italian market shares are relatively sensitive to fuel prices. Germany, in contrast, experiences relatively large changes in fuel prices but a small change in market share because the country's market share is less sensitive to fuel prices. Results are also noteworthy for the Netherlands, where gasoline prices would decrease substantially, greatly reducing the diesel fuel vehicle market share. Overall, the results indicate substantial differences across countries, both because fuel prices would change by different amounts across countries and because market shares are more sensitive to fuel prices in some countries than in others.

6.2 CO_2 Emissions Rate Standards

I model manufacturers' responses to tightening CO_2 emissions rate standards. Manufacturers can reduce emissions rates by changing market shares—increasing prices of high-emissions vehicles and reducing prices of low-emissions vehicles. This is therefore a short-run analysis, in which the set of vehicles and the characteristics of those vehicles do not change.[14]

Because manufacturers can reduce emissions rates only by changing market shares, there are two relevant compliance margins in these simulations. First, holding fixed diesel fuel vehicle market shares, there could be substitution within fuel type from vehicles with high emissions rates to vehicles with low emissions rates. Second, market shares of diesel fuel vehicles may increase at the expense of gasoline vehicles. The first response (within-fuel, cross–trim–power train substitution) would be greater than the second (within–trim–power train, cross-fuel substitution) if consumers substitute readily across trim–power trains. In the simulations, the parameters σ_1 and σ_2 affect the relative importance of these possibilities (see equation (2)). The distinction between the two responses is environmentally important because the first response would imply that the tighter standards do not affect carbon monoxide or nitrogen oxides emissions rates, whereas the second response would reduce carbon monoxide emissions rates but increase nitrogen oxides emissions rates. Thus, determining the relative importance of these responses has implications for local air quality.

An emissions rate standard introduces a shadow cost of reducing the emissions rates of vehicles subject to the standard. In particular, the standard imposes on each manufacturer the constraint that its registrations-weighted average emissions rate equal the level of the standard:

[14] It would be preferable to use a vehicle market model that includes other compliance margins, such as the introduction of new power trains. Even allowing for the choice of fuel economy and 0 to 100 km/h time, as in Section 4.2, does not include potentially important compliance margins available to manufacturers, such as adopting technology that improves energy efficiency. Implementing such a model is beyond the scope of the paper; for example, it would be necessary to estimate the fixed costs of vehicle entry and exit.

$\sum_{i \in F} Q_i (e_i - c) = 0$, where the summation is taken over all vehicles i sold by firm F, e_i is the vehicle's emissions rate, and c is the standard.

This constraint is added to the second-stage profit maximization problem in Section 4.2. The manufacturer chooses vehicle prices to maximize profits, subject to the constraint. By the envelope theorem, the shadow cost of the standard equals the value of the Lagrange multiplier on the constraint. The standard introduces an implicit tax for vehicles with emissions rates above the standard (i.e., $e_i > c$), and the standard introduces an implicit subsidy for vehicles with emissions rates below the standard (Roth 2012).

To sharpen the comparison across countries, I model an emissions rate standard that equalizes the shadow cost of reducing emissions rates across countries and manufacturers. Implicitly, the simulations include the assumption that a credit-trading market exists, in which manufacturers that exceed the standard can sell credits to manufacturers that do not meet the standard. The trading equalizes the shadow costs across manufacturers.

The shadow cost is chosen to equal €57.7 per g CO_2/km per vehicle, and the standard is set at 130 g CO_2/km. Vehicles with emissions rates above the standard are implicitly taxed, and vehicles with emissions rates below the standard are implicitly subsidized. For example, a vehicle with an emissions rate of 140 g CO_2/km faces an implicit tax of €57.7 * (140 – 130) = €577. The standard is chosen to equal the actual European emissions rate standard in 2015, which is therefore below the actual emissions rate in 2010 (about 141 g CO_2/km), but is not so different from the average emissions rate in 2010. The similarity to the 2010 level reduces concerns about the out-of-sample validity of the estimated coefficients on which the simulations depend. The rate of €57.7 per g CO_2/km is chosen so that the Europe-wide average emissions rate across manufacturers equals the standard.[15]

Table 9 shows the effects of the standard in Panel B (Panel A shows summary statistics of the 2010 equilibrium). Vehicles in each country face the same shadow cost, but the policy has much larger effects on diesel fuel vehicle market shares in some countries than in others. The market share in Germany increases substantially because German price elasticities are estimated to be relatively high and because the initial emissions rate in Germany is relatively high (which

[15] The shadow cost is smaller than the fine that manufacturers pay for noncompliance: €95 per vehicle per g CO_2/km by which they exceed the limit set by the standard. The standard is equivalent to a feebate with a pivot of 130 g CO_2/km and a tax (subsidy) rate of €57.7 per g CO_2/km per vehicle (Roth 2012).

causes the average implicit tax under the standard to be larger than in other countries; see Panel A). The large increase for Germany contrasts with the results in Section 6.1, which showed that fuel price harmonization causes a small decrease in German diesel fuel vehicle market shares. The difference arises because German market shares are much more sensitive to (implicit) vehicle taxes and subsidies than to fuel prices. Thus, fuel taxes and CO_2 emissions rate standards have different effects on non-CO_2 pollutants in Germany.

The diesel fuel vehicle market share increases the most in the Netherlands, partly because of the high initial emissions rate but also because the market share in the Netherlands starts at a very low level (hence a small percentage point change corresponds to a large percentage change). By comparison, France and Italy show relatively small changes in diesel fuel vehicle market shares because the implicit taxes and subsidies are relatively small in magnitude in these countries. Thus, the effects of the standard vary considerably across countries, and the main underlying factors are differences in price elasticities of demand as well as differences in the initial emissions rate—and hence the average implicit tax and subsidy.

7. Conclusions

Diesel fuel vehicle market shares vary widely across European countries. One possible explanation for this variation is that fuel and vehicle taxes differ across European countries. A second is that consumers may have different demand for fuel economy. Third, consumers may have different demand for performance or for the other attributes of the diesel technology. Finally, the characteristics of vehicles supplied in each market may differ.

I use a structural model to test those hypotheses, focusing on consumers' choices between gasoline and diesel fuel versions of the same trim–power train. Manufacturers choose fuel economy and performance of the two versions of each trim–power train, taking as exogenous consumer preferences for these characteristics as well as manufacturers' choices for other trim–power trains in the market. Unlike nearly all of the previous vehicle demand literature, the estimation allows for the endogenous choice of vehicle characteristics.

The results of the simulations show that fuel prices and vehicle supply explain very little of the observed cross-country variation in market shares, but preferences for fuel economy appear to explain a very large share; the exception is the Netherlands, where vehicle taxes are the dominant factor.

I have used the vehicle market model to characterize the effects of two policies on diesel fuel vehicle market shares and on vehicle emissions rates. Harmonizing fuel prices across countries would not affect the Europe-wide average diesel fuel vehicle market share, but it would affect market shares in certain countries—especially in Austria, Belgium, Italy, and the Netherlands. Differences in these price changes, as well as the effects of prices on market shares, explains the cross-country variation. These changes affect average emissions rates of nitrogen oxides and carbon monoxide in different directions, and quantifying the environmental effects of these changes is left for future research.

I have also considered the effects of tightening the CO_2 emissions rate standards. Such tightening increases diesel fuel vehicle market shares in all countries, but again the magnitudes differ dramatically across countries. Germany and the Netherlands experience the largest percentage changes in CO_2 emissions rates. Comparing the effects of the two policies reveals that although fuel prices or standards could reduce average CO_2 emissions rates, the two policies would have much different effects on diesel fuel vehicle market shares and on emissions of nitrogen oxides and carbon monoxide.

Another direction for future research is to explain the underlying sources of heterogeneity in consumer preferences for fuel cost savings and for performance. Verboven (2002) shows that driving preferences account for at least some of the variation in demand for fuel economy, and other research documents substantial preference heterogeneity for fuel cost savings (e.g., Leard 2013). Additional research is needed to distinguish among the possible explanations for this heterogeneity, including driving or environmental preferences, income, and other factors.

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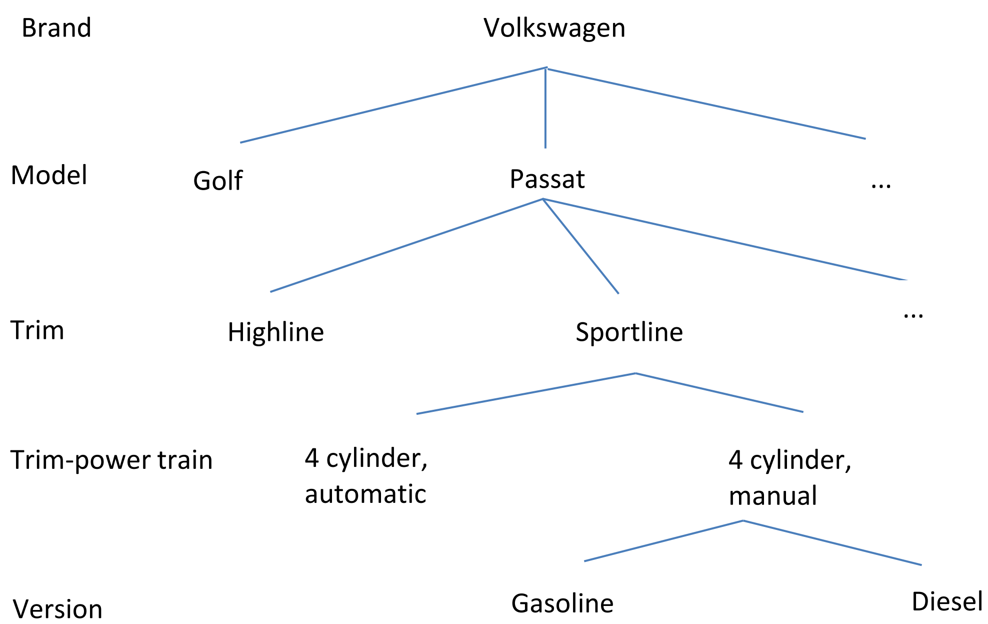
Figures and Tables

See following pages.

Figure 1. Vehicle Nomenclature



Notes: The figure provides a schematic representation of the vehicle nomenclature used in the paper. For each model sold under a particular brand, the trim indicates a unique trim name, body type, number of doors, number of wheels, and axle configuration. Trim-power trains differentiate by number of cylinders and transmission type for vehicles belonging to the same trim. Fuel type can be gasoline or diesel fuel.

Figure 2a. Market Share of Diesel Fuel Vehicles by Country, 2002-2010

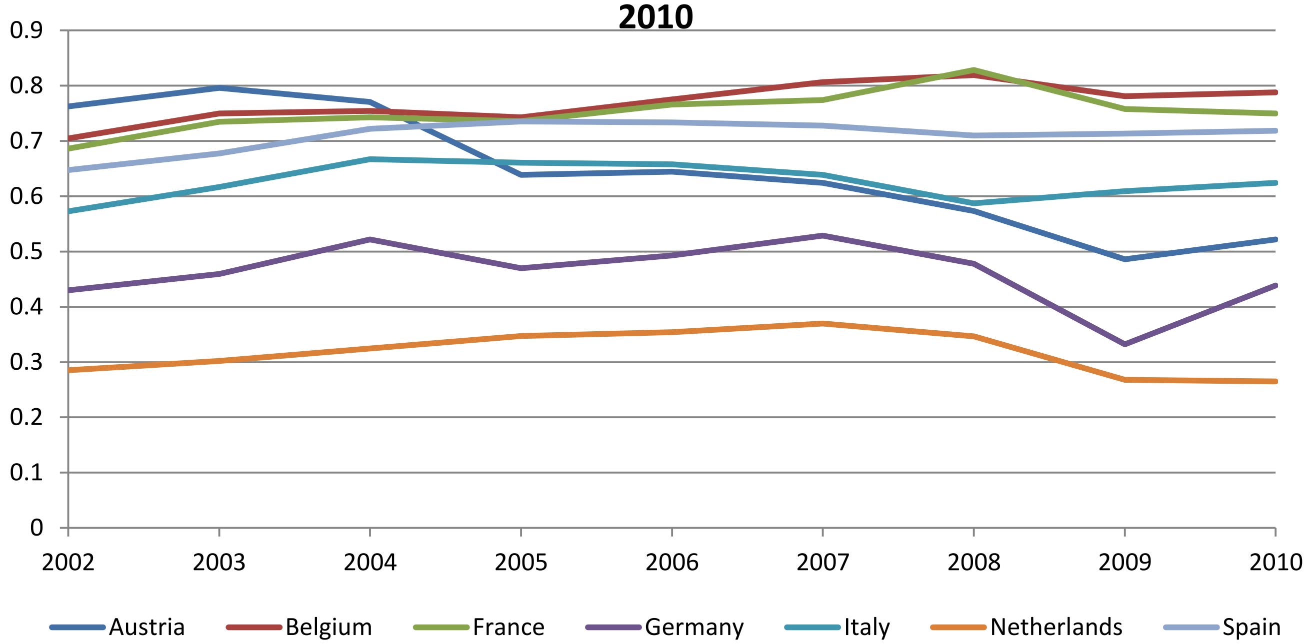
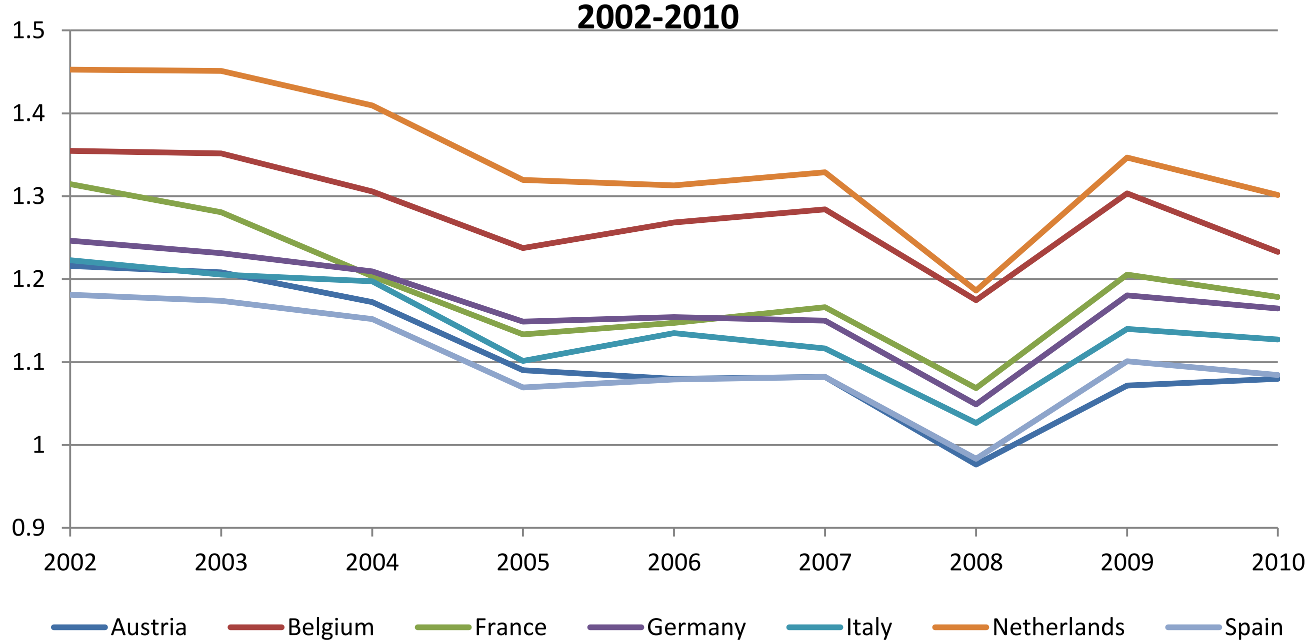
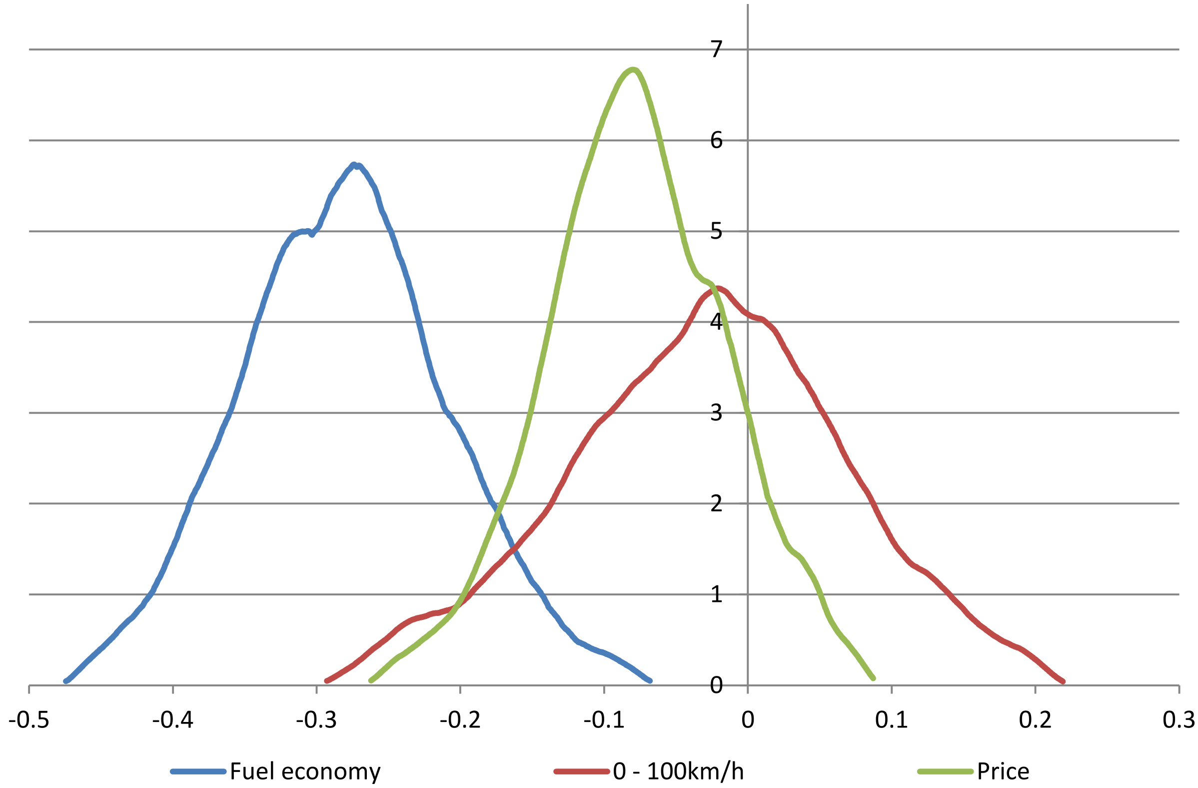


Figure 2b. Ratio of Retail Gasoline to Diesel Fuel Price by Country, 2002-2010



Notes : Figure 2a plots the share of diesel fuel vehicle registrations in annual registrations by country for 2002-2010. Figure 2b plots the ratio of the retail gasoline price to the retail diesel fuel price by country and year.

Figure 3. Estimated Density Functions of Differences Between Gasoline and Diesel Fuel Versions



Notes : The sample includes trim-power trains with a gasoline and diesel fuel version sold in the same country and year. The difference between the gasoline and diesel fuel version is the log of the ratio of the characteristic (fuel economy, 0 to 100 kilometers per hour, or price) for the gasoline version to the diesel fuel version. The figure plots the estimated density function of the difference for the three characteristics.

Figure 4a. Fuel Price Ratio vs. Diesel Fuel Vehicle Market Share (2002)

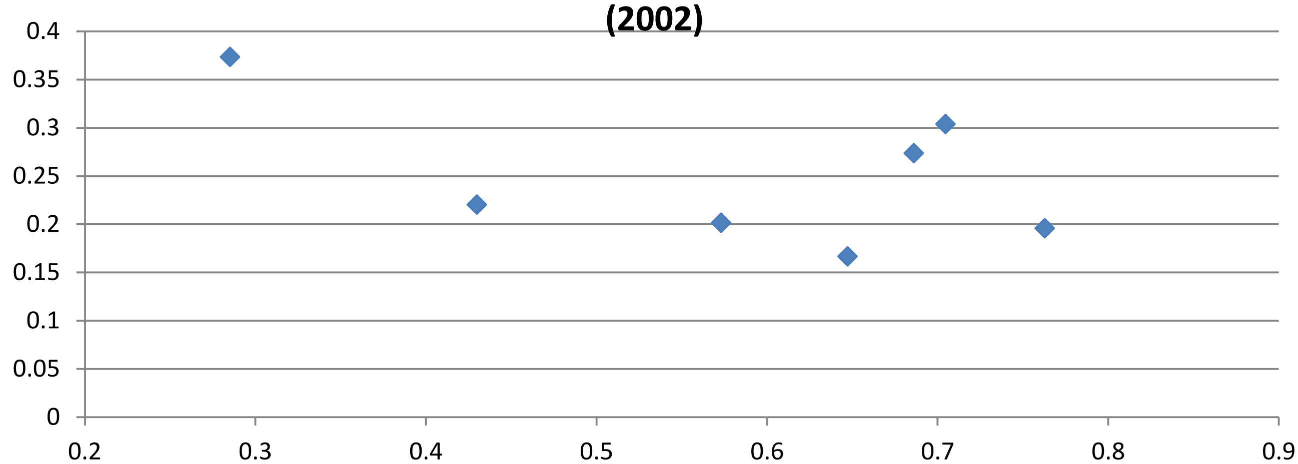


Figure 4b. Fuel Price Ratio vs. Diesel Fuel Vehicle Market Share (2010)

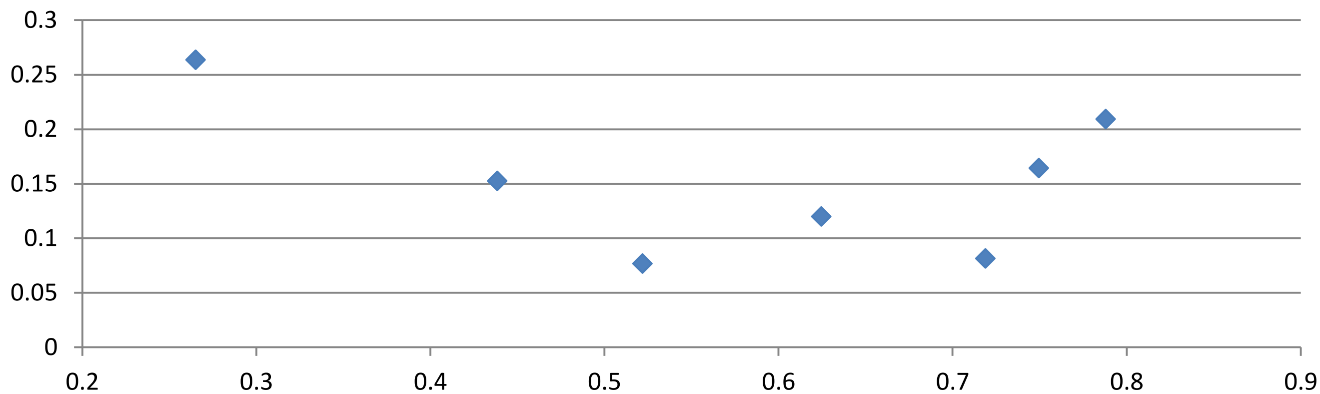
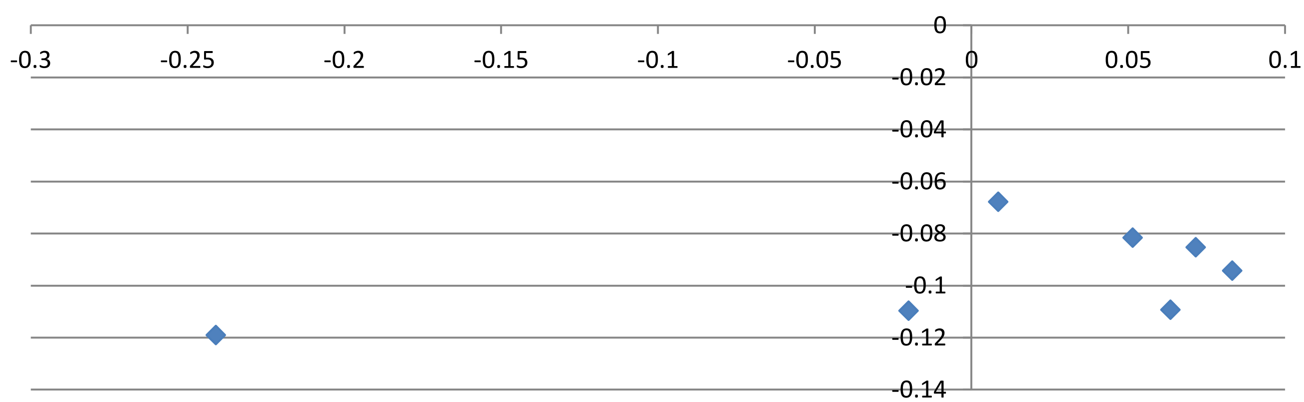
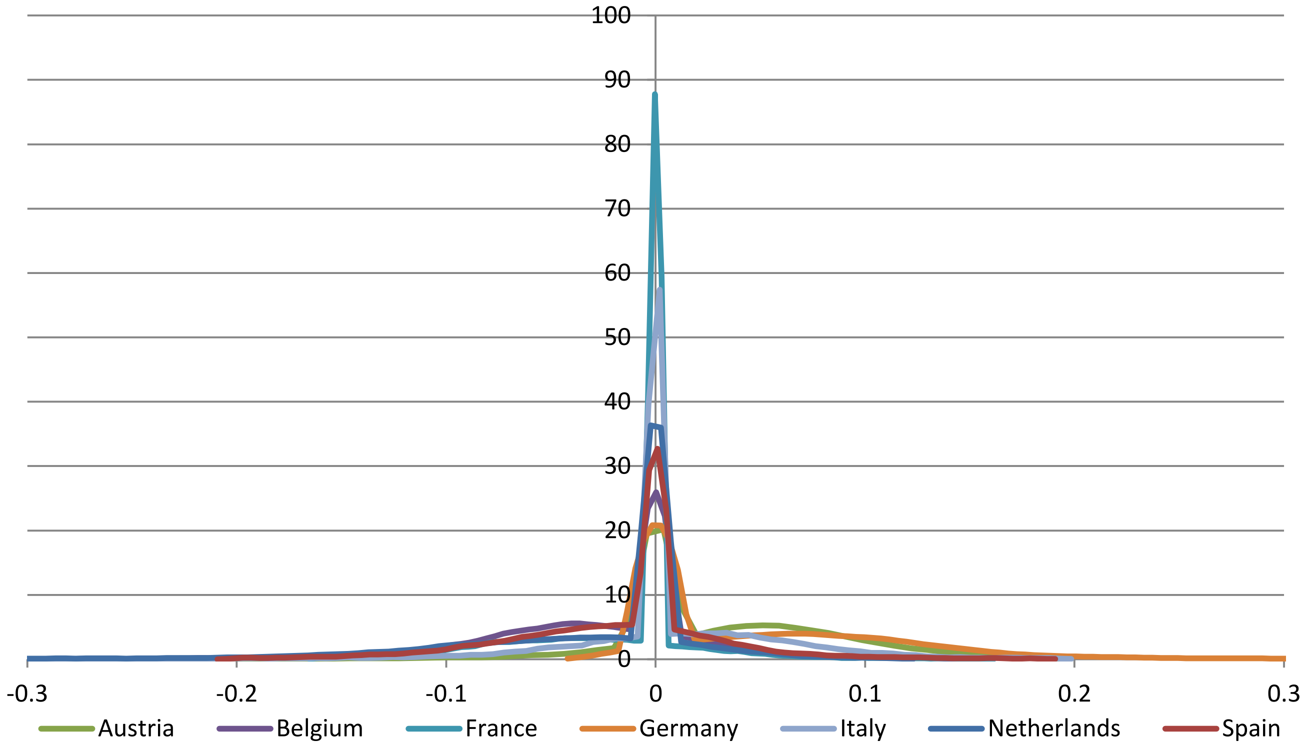


Figure 4c. Change in Fuel Price Ratio vs. Change in Diesel Fuel Vehicle Market Share (2002-2010)



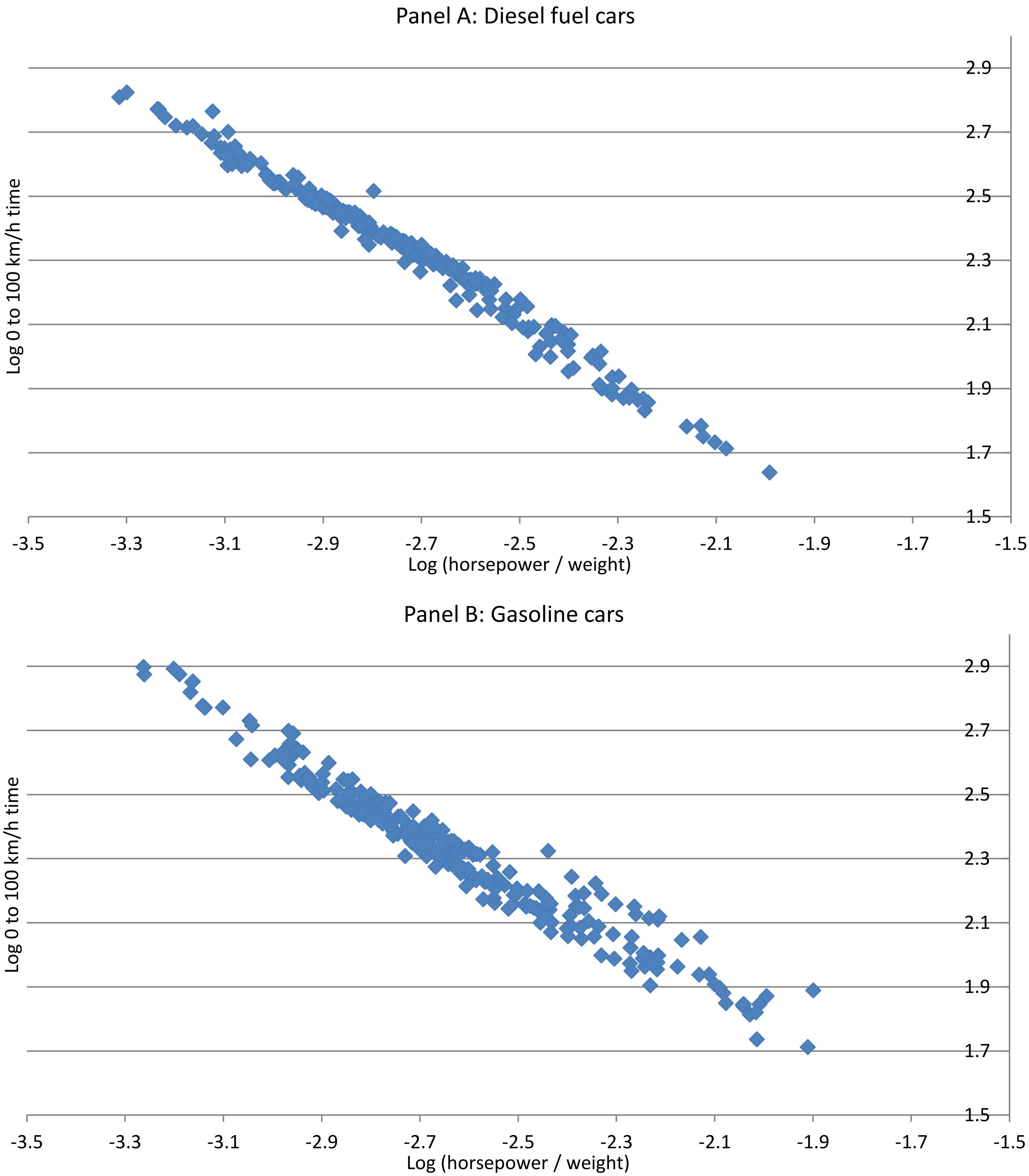
Notes : Figures 3a and 3b plot the log of the ratio of the retail gasoline price to the diesel fuel price against the diesel fuel vehicle market share for each country in 2002 and 2010. Figure 3c plots the change in the log price ratio against the change in the market share by country for 2002-2010.

Figure 5. Density Functions of Marginal Cost Residuals



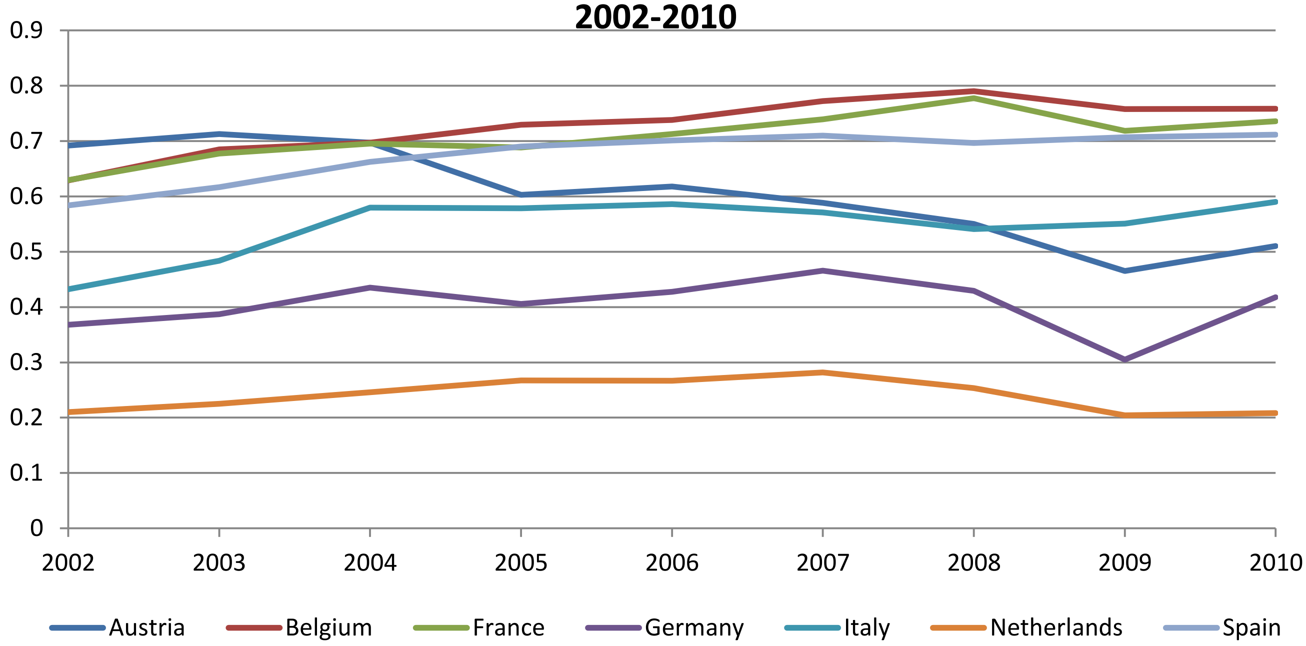
Notes : To construct the figure, the log marginal costs is regressed on trim-power train-fuel type-year interactions. The sample includes all observations in all countries. The figure plots the estimated density function of the residuals, with a separate density function estimated for each country.

Appendix Figure 1: Log 0 to 100 km/h Time Vs. Log (Horsepower / Weight)



Notes : The figure plots the imputed log 0 to 100 kilometers per hour time against the log of the ratio of horsepower to weight. Imputations are made using the coefficients in Appendix Table 1. Panel A includes diesel fuel cars and panel B includes gasoline cars.

Appendix Figure 2. Market Share of Diesel Fuel Vehicles by Country, 2002-2010



Notes : The figure is the same as Figure 2 except that the sample includes all cars, rather than limiting the sample to include gasoline-diesel pairs as in Figure 3.

Table 1: Total Registrations, Share of Combinations in Total Registrations, and Share of German Combinations in Registrations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Austria	Belgium	France	Germany	Italy	Netherlands	Spain
Average annual registrations (millions)	0.286	0.483	2.019	3.161	1.959	0.458	1.358
Share of trim-power trains	0.685	0.721	0.777	0.706	0.689	0.615	0.773
Share of trim-power trains also sold in Germany	0.979	0.968	0.974	1.000	0.981	0.981	0.979
Average percent difference in tax on gasoline cars	8.22	-33.18	102.48	-156.68	-65.84	-61.03	16.38

Notes: The first row reports the average annual registrations in millions for 2002-2010. A model-trim-power train refers to a unique model, trim, body type, number of doors, number of wheels, transmission type, axle configuration, and number of cylinders. The second row reports the share in total registrations of trim-power trains with a gasoline and diesel fuel version sold in the same country and year. The third row reports the share in total registrations of trim-power trains that are sold in Germany and the corresponding country. The percent difference in tax on gasoline cars is the percent difference between the present discounted value of vehicle taxes on the gasoline version compared to the diesel fuel version of a trim-power train. The fourth row reports the mean of the variable.

Table 2: Cross-Country Variation of Fuel Economy and 0-100 Time

	(1)	(2)
	Dep var: log fuel economy	Dep var: log 0 to 100 km/h
Austria	0.0102	0.0122
	(0.0004)	(0.0005)
Belgium	0.0091	0.0139
	(0.0006)	(0.0005)
France	0.0058	0.0045
	(0.0009)	(0.0007)
Italy	0.0073	0.0027
	(0.0006)	(0.0006)
Netherlands	0.0016	-0.0016
	(0.0005)	(0.0003)
Spain	0.0008	-0.0049
	(0.0005)	(0.0007)
Number of observations	135,134	135,134
R^2	0.604	0.918
Mean in Germany	36.02	10.44

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by country. The sample includes trim-power trains with a gasoline and diesel version in the same country and year. The dependent variable in column 1 is log fuel economy and the dependent variable in column 2 is the log of the estimated 0 to 100 kilometers per hour time. The table reports coefficients on fixed effects for the indicated country, with Germany being the excluded country. Regressions also include trim-power train-year interactions. The bottom of the table reports the mean fuel economy (in miles per gallon) in column 1 and the mean 0 to 100 kilometers per hour time (in seconds) in column 2.

Table 3: Correlation Between Diesel Fuel Vehicle Market Shares and Fuel Prices or Taxes

	(1)	(2)	(3)	(4)
	Dependent variable: log market share of diesel fuel vehicles			
Log gas price	2.982 (0.897)		0.279 (0.719)	
Log diesel fuel price	-2.703 (1.003)		-0.648 (0.655)	
Log gas tax		1.313 (0.482)		0.455 (0.487)
Log diesel fuel tax		-0.999 (0.425)		-0.110 (0.283)
Number of observations	63	63	56	56
R^2	0.946	0.945	0.412	0.414
Regression estimated in	Levels	Levels	First differences	First differences

Notes: The table reports coefficient estimates with standard errors in parentheses, robust to heteroskedasticity. Observations are by country and year. The dependent variable is the log share of diesel fuel vehicle registrations in total registrations. Columns 1 and 3 include the log of the ratio of the gasoline to diesel fuel price as an independent variable. Columns 2 and 4 use taxes instead of prices. All columns include year fixed effects and columns 1 and 2 include country fixed effects. Columns 3 and 4 are estimated in first differences by country.

Table 4: Nested Logit Coefficient Estimates by Country

	(1) Austria	(2) Belgium	(3) France	(4) Germany	(5) Italy	(6) Netherlands	(7) Spain
Log price	-10.853 (0.885)	-9.189 (0.738)	-8.392 (0.883)	-14.093 (0.739)	-8.959 (0.762)	-7.431 (0.349)	-5.932 (0.656)
Log fuel costs	-3.199 (0.175)	-4.513 (0.174)	-5.148 (0.197)	-3.457 (0.234)	-5.763 (0.283)	-2.016 (0.161)	-3.529 (0.163)
Log 0 to 100 km/h	-3.388 (0.664)	-1.967 (0.564)	-4.070 (0.571)	-5.760 (0.515)	-4.024 (0.667)	-1.924 (0.359)	-3.341 (0.510)
Transmission speeds	0.365 (0.114)	0.407 (0.128)	0.522 (0.117)	0.628 (0.100)	0.635 (0.124)	0.161 (0.079)	0.499 (0.113)
N	15,734	16,510	23,496	24,970	16,478	22,374	15,360
R^2	0.775	0.819	0.858	0.846	0.840	0.847	0.850

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by model-year. Each column reports the results of a separate regression. The sample includes trim-power trains that have a gasoline and diesel fuel version in a particular country and year. The dependent variable is the log of registrations. Log price is the log of the sum of the retail price, purchase taxes, and discounted registration taxes. Log fuel costs is the log of the product of the vehicle's fuel consumption and the corresponding fuel price. Log 0 to 100 km/h is the log of the 0 to 100 km/h time in seconds, which is imputed using the coefficients in Appendix Table 1. All regressions include trim-power train-year interactions.

Table 5: Second-Stage Estimates, Willingness to Pay for Fuel Savings and Acceleration, and Price Elasticities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Austria	Belgium	France	Germany	Italy	Netherlands	Spain
				Panel A: Second stage estimates			
Log pair registrations	-5.563 (0.799)	-3.188 (0.351)	-2.556 (0.347)	-3.122 (0.358)	-4.019 (0.745)	-2.294 (0.256)	-1.630 (0.213)
Log model share	4.553 (0.769)	2.243 (0.366)	1.337 (0.348)	1.878 (0.324)	3.382 (0.612)	1.606 (0.228)	1.262 (0.217)
N	7,867	8,255	11,748	12,485	8,239	11,187	7,680
				Panel B: Willingness to pay (WTP) for fuel cost savings and acceleration (euros)			
WTP for 1 euro fuel savings	1.24	1.83	1.97	0.74	1.93	1.42	2.25
WTP for 1 second 0 to 100 km/h decrease	843.32	479.79	946.89	1,093.76	941.77	1,171.44	1,264.73
				Panel C: Own and cross-price elasticities			
Own-price elasticity	-7.447	-6.502	-5.909	-9.800	-6.559	-5.622	-4.735
Within-pair cross-price elasticity	2.728	2.234	2.306	3.909	1.743	1.516	0.799

Notes: Panel A reports coefficient estimates with standard errors in parentheses, clustered by model-year. Observations are by country, trim-power train, and year. The dependent variable is the trim-power train fixed effect estimated in Table 5 and the independent variables include the log of trim-power train registrations, the log of the ratio of trim-power train registrations to model registrations, trim-power train fixed effects, and year fixed effects. The equation is estimated by instrumental variables, instrumenting for the two registrations variables using the interactions of the gasoline and diesel fuel price with the fuel consumption and 0 to 100 km/h times of both versions. Panel B reports the willingness to pay for 1 euro of present discounted value of fuel savings and the willingness to pay for a 1 second decrease in 0 to 100 km/h time. The fuel savings calculation assumes a 12 year vehicle life, a 10 percent discount rate and that the vehicle is driven 15,000 km per year. Panel C reports the mean own-price and cross-price elasticities for each country. Calculations in Panels B and C use the coefficient estimates in Table 4 and in Panel A.

Table 6: Marginal Cost Function Estimates

	Dependent variable: log marginal costs	
	Log fuel economy	Log 0 to 100 km/h time
Mini / small	0.463 (0.003)	-0.420 (0.011)
Lower medium	0.387 (0.003)	-0.492 (0.009)
Medium	0.246 (0.003)	-0.367 (0.010)
Upper medium /	0.029 (0.005)	-0.201 (0.013)

Notes: The table reports coefficient estimates from a single regression. Observations are pooled across the country samples used in Table 4. The number of observations is 134,920 and the R-squared is 0.97. The dependent variable is the marginal costs estimation from equation (7). The first column of the table reports coefficient estimates from interactions of segment fixed effects with log fuel economy. The second column reports coefficient estimates from interactions of segment fixed effects with log 0 to 100 km/h time. The regression also includes trim-power train-year interactions and country-segment interactions. Standard errors are clustered by trim-power train-year.

Table 7: Do Fuel Prices, Taxes, Preferences, or Supply Explain Diesel Fuel Vehicle Market Shares?

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Austria	Belgium	France	Germany	Italy	Netherlands	Spain
			Panel A: Actual market shares			
0.527	0.789	0.747	0.438	0.625	0.260	0.719
			Panel B: German fuel prices			
0.585	0.744	0.735	0.438	0.667	0.218	0.766
			Panel C: German fuel prices and tax rates			
0.445	0.665	0.652	0.438	0.573	0.544	0.710
			Panel D: German fuel prices, tax rates, and fuel cost preferences			
0.373	0.468	0.417	0.438	0.349	0.448	0.548
			Panel E: German fuel prices, tax rates, and preferences			
0.386	0.527	0.434	0.438	0.357	0.448	0.528
			Panel F: Endogenous supply			
0.384	0.532	0.439	0.448	0.353	0.453	0.533

Notes: Panel A reports the actual diesel fuel vehicle market share in 2010 using the estimation sample from Table 4. Each cell in Panels B-F reports simulated diesel fuel vehicle market share under hypothetical conditions indicated in the panel headings. Panel B uses the fuel prices in Germany and Panel C also uses the German tax rates to compute diesel taxes. Panel D is the same as Panel C except that it assumes that the mean willingness to pay for fuel costs is the same in each country as in Germany. Panel E also assumes the mean willingness to pay for fuel costs, performance, and transmission speeds is the same in each country as in Germany. Panel F is the same as Panel E except that manufacturers choose the profit-maximizing fuel consumption and performance for each vehicle. The simulations use fuel prices and vehicles in the market in the year 2010. The simulations use the assumed fuel prices, nested logit coefficients, and first order conditions from the text to compute the profit-maximizing prices for the gasoline and diesel fuel version of each combination. The prices are used to calculate annual registrations for each combination, from which diesel fuel vehicle market shares are computed.

Table 8: Effects of Fuel Price Harmonization on Diesel Fuel Vehicle Market Shares and Emissions Rates

	(1) Europe	(2) Austria	(3) Belgium	(4) France	(5) Germany	(6) Italy	(7) Netherlands	(8) Spain
				Panel A: 2010 market equilibrium				
Gasoline price (euro/L)	1.34	1.18	1.40	1.34	1.39	1.36	1.49	1.15
Diesel fuel price (euro/L)	1.16	1.09	1.13	1.13	1.19	1.20	1.14	1.06
Diesel market share	0.59	0.53	0.79	0.75	0.44	0.62	0.26	0.72
CO_2 emissions rate (g/km)	140.86	143.86	137.05	128.27	152.33	135.58	149.07	138.32
CO emissions rate (g/km)	0.70	0.74	0.61	0.63	0.78	0.69	0.87	0.64
NO_x emissions rate (g/km)	0.13	0.12	0.15	0.15	0.11	0.13	0.09	0.15
				Panel B: Percent changes caused by harmonization				
Gasoline price		13.41	-4.09	0.26	-3.26	-1.31	-9.91	16.12
Diesel fuel price		5.61	1.99	1.91	-2.82	-4.04	1.15	8.64
Diesel market share	0.51	10.44	-6.24	-2.17	-0.89	5.88	-16.60	6.15
CO_2 emissions rate	0.01	-0.17	0.46	0.11	0.00	-0.10	0.70	-0.41
CO emissions rate	-0.22	-3.74	4.07	1.29	0.25	-2.67	2.48	-3.45
NO_x emissions rate	0.28	5.36	-3.82	-1.30	-0.41	3.26	-5.68	3.63

Notes: Panel A reports the average levels of the indicated variables in 2010 for Europe (column 1) and each country (columns 2-8). The carbon monoxide (CO) emissions rate is calculated assuming each gasoline car emits 1.0 g/km and each diesel fuel car emits 0.5 g/km. The nitrogen oxides (NO_x) emissions rate is calculated assuming each gasoline car emits 0.06 g/km and each diesel fuel car emits 0.18 g/km. All emissions rates are registrations-weighted averages. Panel B reports the percent change in each variable assuming that each country's fuel prices are equal to the European average fuel prices reported in Panel A.

Table 9: Effects of an Emissions Rate Standard on Diesel Fuel Vehicle Market Shares and Emissions Rates

	(1) Europe	(2) Austria	(3) Belgium	(4) France	(5) Germany	(6) Italy	(7) Netherlands	(8) Spain
				Panel A: 2010 market equilibrium				
Implicit tax or subsidy (euros/vehicle)	626.59	799.48	406.70	-99.57	1288.63	321.81	1100.28	480.14
Diesel market share	0.59	0.53	0.79	0.75	0.44	0.62	0.26	0.72
CO_2 emissions rate (g/km)	140.86	143.86	137.05	128.27	152.33	135.58	149.07	138.32
CO emissions rate (g/km)	0.70	0.74	0.61	0.63	0.78	0.69	0.87	0.64
NO_x emissions rate (g/km)	0.13	0.12	0.15	0.15	0.11	0.13	0.09	0.15
				Panel B: Percent changes caused by emissions rate standard				
Diesel market share	8.64	10.95	8.58	4.91	12.38	7.32	24.21	9.29
CO_2 emissions rate	-7.71	-6.63	-8.50	-6.38	-9.71	-7.31	-4.47	-5.07
CO emissions rate	-3.64	-3.92	-5.60	-2.93	-3.48	-3.33	-3.61	-5.21
NO_x emissions rate	4.69	5.62	5.25	2.94	5.78	4.07	8.28	5.48

Notes: Panel A reports the average levels of the indicated variables in 2010 for Europe (column 1) and each country (columns 2-8). The standard is equal to 130 g CO_2/km. The implicit tax or subsidy reported in the first row is the registrations-weighted average of the implicit tax under the emissions rate standard; the variable is negative for a subsidy. Emissions rates are calculated as in Table 8. Panel B reports the percent change in each variable assuming that the purchase of each vehicle is assigned an implicit tax or subsidy of 57.7 euros multiplied by the difference between the vehicle's CO_2 emissions rate and 130 g CO_2/km.

Appendix Table 1: Coefficient Estimates Used to Impute 0-100 km/h Times

	(1)	(2)
	Dep var: log 0 to 100 km/h time	
Log (horsepower / weight)	-0.756	-0.816
	(0.012)	(0.013)
Manual transmission	0.005	-0.017
	(0.004)	(0.006)
All wheel drive	0.033	0.036
	(0.006)	(0.014)
Front wheel drive	0.038	0.036
	(0.005)	(0.008)
Log height	0.189	0.482
	(0.030)	(0.058)
3 cylinders	0.208	0.120
	(0.029)	(0.011)
4 cylinders	0.086	0.039
	(0.011)	(0.006)
5 cylinders	0.098	0.045
	(0.011)	(0.019)
6 cylinders		0.100
		(0.016)
Constant	-1.236	-3.439
	(0.205)	(0.406)
Number of observations	1,371	1,012
R^2	0.894	0.897
Sample includes	Diesel fuel cars	Gasoline cars

Notes: The table reports coefficient estimates with standard errors in parentheses, robust to heteroskedasticity. The sample includes a set of vehicles offered in the European market in 2013. The dependent variable is the log of the vehicle's 0-100 km/h time. Log (horsepower / weight) is the log of the vehicle's horsepower to weight. Manual transmission is a dummy variable equal to one if the vehicle has a manual transmission, and likewise for the variables for the number of cylinders. Log height is the log of the vehicle's height. The sample in column 1 includes diesel fuel cars and the sample in column 2 includes gasoline cars.

Appendix Table 2: Additional Controls for Diesel Technology

	(1) Austria	(2) Belgium	(3) France	(4) Germany	(5) Italy	(6) Netherlands	(7) Spain
Log price	-12.099	-10.131	-8.586	-13.185	-6.650	-7.901	-5.431
	(1.036)	(1.039)	(1.035)	(0.887)	(0.870)	(0.411)	(0.718)
Log fuel costs	-3.063	-4.588	-5.150	-3.332	-5.654	-2.140	-3.570
	(0.174)	(0.187)	(0.197)	(0.247)	(0.285)	(0.176)	(0.163)
Log 0 to 100 km/h	-3.528	-2.035	-4.055	-5.652	-4.105	-1.841	-3.336
	(0.652)	(0.563)	(0.570)	(0.521)	(0.671)	(0.361)	(0.509)
Transmission speeds	0.430	0.423	0.530	0.582	0.573	0.196	0.477
	(0.113)	(0.127)	(0.118)	(0.098)	(0.123)	(0.079)	(0.112)
Displacement (/ 100)	0.066	0.042	0.012	-0.046	-0.166	0.046	-0.032
	(0.025)	(0.032)	(0.028)	(0.023)	(0.029)	(0.019)	(0.024)
N	15,734	16,510	23,496	25,027	16,478	22,374	15,360
R^2	0.776	0.819	0.858	0.849	0.845	0.847	0.850

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by model-year. Regressions are the same as in Table 4 except that the regressions include the number of gears and engine displacement (cubic centimeters divided by 100, for readability).

Appendix Table 3: Nested Logit Coefficient Estimates by Country and Fuel Consumption Quartile

	(1) Austria	(2) Belgium	(3) France	(4) Germany	(5) Italy	(6) Netherlands	(7) Spain
				Panel A: Lowest fuel consumption quartile			
Log price	-13.376	-8.538	-9.911	-10.362	-4.775	-8.472	-6.014
	(1.725)	(1.503)	(2.430)	(1.280)	(1.498)	(0.786)	(1.572)
Log fuel costs	-1.512	-3.017	-3.575	-0.491	-1.782	-2.291	-1.871
	(1.185)	(0.364)	(0.606)	(0.484)	(0.618)	(0.455)	(0.395)
Log 0 to 100 km/h	-5.747	-2.786	-5.042	-3.429	-2.254	-4.262	-2.809
	(1.182)	(0.829)	(1.243)	(0.888)	(1.316)	(0.769)	(0.980)
				Panel B: Second fuel consumption quartile			
Log price	-8.336	-10.141	-8.864	-10.962	-7.894	-6.800	-2.977
	(1.988)	(1.700)	(1.775)	(1.333)	(1.286)	(0.758)	(1.047)
Log fuel costs	-3.607	-4.958	-6.050	-2.866	-5.405	-1.894	-3.377
	(0.362)	(0.393)	(0.453)	(0.455)	(0.528)	(0.373)	(0.272)
Log 0 to 100 km/h	-2.576	-3.300	-5.114	-5.346	-2.637	-1.823	-2.111
	(1.438)	(1.132)	(0.941)	(1.009)	(1.086)	(0.721)	(0.861)
				Panel C: Third fuel consumption quartile			
Log price	-3.204	-8.517	-4.992	-10.989	-3.234	-5.427	-4.450
	(2.131)	(1.500)	(2.116)	(1.377)	(1.459)	(0.707)	(1.491)
Log fuel costs	-4.037	-5.031	-5.530	-3.852	-5.804	-1.349	-4.883
	(0.394)	(0.383)	(0.404)	(0.394)	(0.479)	(0.325)	(0.307)
Log 0 to 100 km/h	0.507	-1.255	-2.016	-5.889	-2.112	0.163	-3.823
	(1.531)	(1.106)	(1.256)	(0.944)	(1.177)	(0.628)	(1.145)
				Panel D: Highest fuel consumption quartile			
Log price	-3.507	-3.585	0.087	-3.298	-4.042	-5.595	1.325
	(1.435)	(0.958)	(1.121)	(1.426)	(1.176)	(0.548)	(1.168)
Log fuel costs	-4.711	-4.871	-5.420	-3.423	-7.307	-1.659	-4.494
	(0.275)	(0.214)	(0.207)	(0.296)	(0.349)	(0.195)	(0.256)
Log 0 to 100 km/h	-1.222	0.792	-2.215	-4.820	-2.889	-1.525	-2.139
	(0.858)	(0.776)	(0.712)	(0.756)	(0.923)	(0.578)	(0.826)

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by model-year. Each pair is assigned a fuel consumption quartile based on the fuel consumption of the diesel fuel version of the trim-power train and the fuel consumption distribution of diesel fuel versions in the corresponding country and year. Regressions are the same as in Table 4 except that a separate regression is estimated for each fuel consumption quartile and country.

Appendix Table 4: Nested Logit Coefficient Estimates by Country and 0-100 km/h Quartile

	(1) Austria	(2) Belgium	(3) France	(4) Germany	(5) Italy	(6) Netherlands	(7) Spain
				Panel A: Lowest 0-100 km/h quartile			
Log price	-5.409	-7.133	-4.613	-10.143	-6.619	-7.051	-3.557
	(1.407)	(1.051)	(1.401)	(1.446)	(1.268)	(0.557)	(1.117)
Log fuel costs	-3.186	-4.394	-5.180	-3.628	-6.796	-1.665	-3.220
	(0.254)	(0.200)	(0.219)	(0.308)	(0.385)	(0.194)	(0.213)
Log 0 to 100 km/h	-2.339	-1.245	-4.493	-6.867	-5.840	-2.370	-2.293
	(1.026)	(0.896)	(0.698)	(0.946)	(1.114)	(0.514)	(0.834)
				Panel B: Second quartile			
Log price	-7.283	-10.079	-8.150	-10.565	-5.837	-6.791	-5.907
	(2.085)	(1.478)	(1.766)	(1.572)	(1.244)	(0.779)	(1.596)
Log fuel costs	-4.164	-5.209	-5.846	-2.588	-5.860	-1.679	-4.098
	(0.415)	(0.375)	(0.413)	(0.515)	(0.435)	(0.405)	(0.321)
Log 0 to 100 km/h	-1.823	-0.832	-3.400	-3.274	-1.735	0.711	-2.840
	(1.656)	(1.165)	(1.107)	(0.961)	(0.995)	(0.821)	(1.276)
				Panel C: Third quartile			
Log price	-12.057	-7.908	-8.845	-10.534	-5.195	-6.619	-4.971
	(1.871)	(1.966)	(2.162)	(1.898)	(1.330)	(0.861)	(1.439)
Log fuel costs	-3.633	-4.437	-5.468	-2.193	-4.531	-1.688	-3.898
	(0.355)	(0.479)	(0.537)	(0.631)	(0.494)	(0.439)	(0.359)
Log 0 to 100 km/h	-1.952	-0.131	-2.963	-2.967	0.895	-0.976	-3.703
	(1.313)	(1.391)	(1.173)	(1.179)	(1.153)	(0.818)	(0.984)
				Panel D: Highest quartile			
Log price	-18.720	-8.978	-7.387	-15.179	-5.386	-8.634	-9.421
	(1.620)	(1.460)	(2.651)	(1.340)	(1.543)	(0.700)	(1.691)
Log fuel costs	-3.488	-3.859	-3.858	-3.207	-2.690	-2.852	-3.694
	(0.369)	(0.352)	(0.647)	(0.513)	(0.629)	(0.407)	(0.448)
Log 0 to 100 km/h	-8.832	-3.794	-4.550	-5.771	-2.985	-5.025	-4.933
	(1.067)	(0.845)	(1.241)	(0.949)	(1.228)	(0.711)	(1.052)

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by model-year. Each pair is assigned a 0-100 km/h quartile based on the 0-100 km/h time of the diesel fuel version of the trim-power train and the 0-100 km/h time distribution of diesel fuel versions in the corresponding country and year. Regressions are the same as in Table 4 except that a separate regression is estimated for each quartile and country.

Appendix Table 5: Nested Logit Coefficient Estimates by Time Period

	(1) Austria	(2) Belgium	(3) France	(4) Germany	(5) Italy	(6) Netherlands	(7) Spain
				Panel A:2002-2006			
Log price	-7.752	-9.030	-7.500	-13.228	-7.496	-7.058	-6.267
	(1.308)	(1.080)	(1.100)	(0.923)	(1.187)	(0.471)	(0.885)
Log fuel costs	-3.419	-4.438	-4.420	-2.975	-5.451	-1.810	-3.239
	(0.233)	(0.282)	(0.269)	(0.280)	(0.533)	(0.211)	(0.217)
Log 0 to 100 km/h	-2.054	-2.679	-3.808	-4.698	-2.474	-2.139	-3.721
	(0.991)	(0.766)	(0.728)	(0.634)	(1.019)	(0.458)	(0.698)
Transmission speeds	0.540	0.588	0.527	0.944	0.765	0.330	0.672
	(0.195)	(0.179)	(0.173)	(0.119)	(0.219)	(0.114)	(0.151)
N	7,212	8,888	12,552	11,948	8,128	12,028	8,252
R^2	0.783	0.825	0.859	0.851	0.827	0.848	0.855
				Panel B: 2007-2010			
Log price	-12.682	-9.097	-7.637	-14.596	-13.905	-7.795	-4.950
	(1.138)	(1.061)	(1.345)	(1.085)	(1.330)	(0.504)	(0.968)
Log fuel costs	-2.632	-4.576	-5.827	-3.803	-6.263	-2.258	-3.981
	(0.259)	(0.217)	(0.255)	(0.360)	(0.311)	(0.243)	(0.244)
Log 0 to 100 km/h	-4.034	-0.971	-3.290	-6.460	-7.018	-1.653	-2.528
	(0.846)	(0.872)	(0.930)	(0.752)	(0.946)	(0.542)	(0.755)
Transmission speeds	0.373	0.265	0.492	0.490	0.624	0.035	0.332
	(0.147)	(0.173)	(0.156)	(0.133)	(0.146)	(0.107)	(0.153)
N	8,522	7,622	11,262	13,368	8,350	10,346	7,108
R^2	0.777	0.814	0.860	0.836	0.856	0.843	0.841

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by model-year. The regressions are the same as in Table 4 except that Panel A includes observations from 2002-2006 and Panel B includes observations from 2007-2010.