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Interactions between Climate and Local Air Pollution Policies

The Case of European Passenger Cars

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Abstract

Several studies have found that taxing vehicle purchase or ownership on the basis of carbon dioxide (CO_2) emissions reduces CO_2 emissions. In this paper I show that CO_2-based vehicle taxation can raise emissions of other pollutants that harm air quality and that the magnitude of this unintended effect depends on consumer substitution across and within gasoline and diesel fuel vehicles. Using data on European vehicle registrations, fuel prices, fuel taxes, and vehicle taxes from 2002 through 2010, I estimate the relevant substitution patterns and compare the performance of several empirical strategies based on the recent vehicle tax literature. According to the preferred specification, vehicle tax reforms have increased nitrogen oxide emissions, which harm local air quality. Moreover, fuel-based CO_2 taxes introduce milder trade-offs between CO_2 and nitrogen oxides emissions than do vehicle taxes.

Key Words: fuel taxes, vehicle taxes, carbon dioxide, nitrogen oxides, passenger cars, Europe

JEL Classification Numbers: L62, Q4, Q5

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Joshua Linn*

1. Introduction

Passenger vehicles account for a large share of emissions of greenhouse gases and pollutants that harm local air quality. For example, passenger vehicles cause about 15 percent of greenhouse gas emissions in the United States and Europe and about 25 percent of US nitrogen oxides emissions, which contribute to fine particulates and ground-level ozone. These emissions cause global warming and air quality problems that affect many major urban areas in the United States, Europe, and elsewhere around the world.

Although standard economic theory favors pricing emissions from all vehicles, policymakers seldom take this approach. Most countries target the rate of emissions per distance traveled or fuel economy for new vehicles, and the literature has identified two inefficiencies of this approach. First, regulating newer but not older vehicles increases the relative cost of new vehicles and delays retirement of older and typically higher-emitting vehicles (Gruenspecht 1982; Stavins 2006; Jacobsen and van Benthem 2015). Second, because a vehicle's fuel economy is tightly linked to its carbon dioxide (CO_2) emissions rate, regulating CO_2 emissions rates reduces per-mile driving costs and induces a rebound effect that raises miles traveled (Borenstein 2015; Chan and Gillingham 2015). Despite these inefficiencies, Europe has been at the forefront of an emerging trend of linking a vehicle's tax to its CO_2 emissions rate. The taxes incentivize consumers to purchase vehicles with lower CO_2 emissions.

Several recent studies demonstrate that these tax reforms reduce CO_2 emissions from passenger vehicles (e.g., Ryan et al. 2009; D'Haultfoeuille et al. 2014; Klier and Linn 2015; Yan and Eskeland 2016). However, the literature on multipollutant regulation (e.g., Ambec and Coria 2013) analyzes cases in which regulating one pollutant can affect emissions of another pollutant.

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For example, policies aiming to reduce greenhouse gas emissions may have a cobenefit of reducing local air pollution (e.g., Parry et al. 2014).

This paper, in contrast to the recent literature, concentrates on the effect of CO_2-based vehicle taxes on emissions of pollutants that harm air quality, focusing on nitrogen oxides. The potential interaction between vehicle taxation and local air quality is particularly important for regions with high market shares of diesel fuel vehicles, such as Europe. Many major European cities experience poor air quality and the associated health and environmental costs. Vehicles contribute to these problems by emitting nitrogen oxides, and diesel fuel vehicles have higher nitrogen oxides emissions than do gasoline vehicles for two reasons. First, regulations such as those in the United States and Europe typically allow higher emissions rates for diesel fuel than for gasoline vehicles. For example, the European nitrogen oxides standards for diesel fuel vehicles are three times higher than those for gasoline vehicles. Second, on-road performance of gasoline vehicles is often similar to the tested emissions, whereas on-road performance of diesel fuel vehicles is substantially worse than tested emissions (Chen and Borken-Kleefeld 2014), even putting aside cases of emissions cheating such as Volkswagen.

Although diesel fuel vehicles have higher nitrogen oxides emissions rates than gasoline vehicles, they have lower CO_2 emissions rates—about 20 percent lower for vehicles that are otherwise identical (Klier and Linn 2016). Therefore, taxing vehicle CO_2 emissions rates can cause consumers to shift to diesel fuel vehicles and away from gasoline vehicles. Such a shift would reduce CO_2 emissions but increase nitrogen oxides emissions. Past research on CO_2-based vehicle taxation has not considered this effect.

The two aims of this paper are to demonstrate that CO_2-based taxes, combined with regulations of non-CO_2 emissions, create a trade-off between CO_2 emissions and local air quality; and to estimate the extent of this trade-off for CO_2-based vehicle taxation compared with taxation based on the carbon content of fuels. The comparison between vehicle and fuel taxation is motivated by the fact that some European countries have considered introducing carbon-based fuel taxes. Moreover, the literature has concluded that fuel taxes are more economically efficient than vehicle taxes or emissions standards (e.g., Jacobsen 2013), but this literature has not considered the welfare costs of emissions that affect air quality.

The paper consists of three main parts. First, after presenting background information on the European vehicle market and taxation, I show that the effect of CO_2-based taxation on nitrogen oxides emissions depends on consumer responses to the taxes. Specifically, a CO_2-based tax—on either vehicles or fuels—induces consumer substitution within a fuel type, from high- to low-CO_2-emitting vehicles, and across fuel types, from gasoline to diesel fuel vehicles. The greater the substitution across fuel types, the larger the increase in nitrogen oxides emissions.

This conclusion motivates the second part of the paper, which consists of an empirical analysis of the effects of fuel prices and vehicle taxes on consumer substitution within and across fuel types. The empirical analysis uses highly detailed vehicle registration and characteristics data from 2002 to 2010 that cover most of Europe. The tax reforms have coincided with other policy changes, oil price shocks, and economic recession. Recent vehicle tax studies, particularly those using structural demand models, have not controlled for the potential correlation between such supply or demand shocks and observed vehicle attributes (e.g., D'Haultfoeuille et al. 2014; Grigolon et al. 2015). Moreover, the literature has diverged in terms of whether to use aggregated data and the degree to which taxes and fuel costs can have different effects across vehicle types and markets. A major focus of the empirical section is to compare alternative specifications that are based on those used in the literature. Specifically, the specifications vary in the extent to which they control for vehicle attributes and consumer preferences and allow the effects of fuel prices and vehicle taxes to vary across vehicle types and markets. The specifications that use aggregated data or do not control for demand and supply shocks perform poorly. The specification that allows the effects of taxes and fuel costs on registrations to vary by fuel type and CO_2 emissions rate performs best in predicting in sample and out of sample. In the preferred specification, fuel costs and taxes have strong effects on vehicle registrations, with a larger elasticity of registrations to fuel costs than to taxes. These effects vary with a vehicle's fuel type and CO_2 emissions rate.

Finally, I compare a hypothetical CO_2-based vehicle tax, which is modeled after recent tax reforms, with a carbon-based fuel tax. Because of the substitution patterns estimated from the data, fuel taxes induce less cross-fuel substitution than do CO_2-based vehicle taxes. Therefore, a fuel tax increase raises nitrogen oxides emissions substantially less than does a CO_2-based vehicle tax. The results demonstrate an unintended environmental cost of CO_2-based vehicle taxation and suggest that fuel taxes may induce less of a trade-off between CO_2 emissions and local pollution.

Aside from assessing the implications of CO_2-based taxes for local air pollution, this paper makes several contributions to the literature. First, I compare the effects of fuel and vehicle taxes, whereas most other studies focus on either one policy or the other (e.g., Klier and Linn 2015). Second, I demonstrate the importance of cross- and within-fuel type consumer substitution for determining the effects of CO_2-based taxation on local air pollution. Similar conclusions would apply to other policies aiming to reduce CO_2 emissions, such as a CO_2 emissions rate or fuel economy standard. Grigolon et al. (2015) reach a similar conclusion about the superiority of fuel to vehicle taxes, but their conclusion arises from the inefficiencies of vehicle taxation noted above, rather than the effects on local air pollution. Third, methodologically, recent vehicle tax studies have differed in the extent to which they control for unobserved demand or supply shocks and in the aggregation of the data. I compare the merits of these approaches. In this application, the specification that uses disaggregated data, controls explicitly for unobserved shocks, and allows parameters to vary across vehicles performs best. I show that using aggregated data would misleadingly have precisely the opposite policy implications. More generally, the results indicate the importance of comparing model fit across a range of specifications, which is seldom done in the literature. Fourth, the tax analysis spans nearly the entire European market, whereas many studies focus on one or a few countries.

2. Data, Summary Statistics, and Policy Context

2.1. Data: Vehicles, Taxes, and Fuel Prices

The primary data are from RL Polk and include vehicle characteristics and registrations for nine countries: Austria, Belgium, France, Germany, Italy, the Netherlands, Spain, Sweden, and the United Kingdom. The data cover the years 2002 through 2010, and the nine countries account for about 93 percent of annual new vehicle registrations in the entire EU-15.[1] The data include annual new registrations and vehicle characteristics by trim, number of cylinders, transmission type, and fuel type (gasoline or diesel fuel).

Figure 1 illustrates the vehicle nomenclature used in this paper, using the Ford Focus as an example. *Trim* refers to a unique model and trim 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 *variants*: gasoline and diesel fuel. Power trains that belong to the same trim have (nearly) identical physical characteristics, but fuel economy and horsepower can vary across power trains within a trim because of differences in the number of cylinders and

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[1] The EU-15 refers to the 15 member states of the European Union from January 1995 through April 2004: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

transmission type. For a given trim–power train, fuel type explains any differences in fuel economy, horsepower, weight, or other power train characteristics.[2]

The vehicle characteristics include price, fuel type, fuel consumption rate (liters of fuel per 100 kilometers), weight, length, width, height, horsepower, engine size (cubic centimeters of displacement), number of transmission speeds, and CO_2 emissions rate. Price represents the retail price by trim–power train, fuel type, country, and year. Fuel consumption rate and fuel economy are determined using a consistent methodology across countries, and they are available for the years 2005–2010; all other characteristics are available for 2002–2010. Fuel consumption rate and fuel economy are imputed for 2002–2004, as in Klier and Linn (2013). As shown there, the imputation likely introduces little measurement error because it is based on extensive vehicle information that predicts fuel economy accurately.

Much of the passenger vehicles literature uses the ratio of horsepower to vehicle weight as a proxy for performance, arguing that the ratio is a function of the time needed to accelerate from 0 to 100 kilometers per hour (km/h). Rather than use the ratio alone as a proxy for performance, I combine the ratio with other vehicle information to construct a more refined proxy for performance. I define performance as the time, in seconds, required for the vehicle to reach 100 km/h, starting from rest. The Polk data do not include this variable, but I impute it using a second data set, which includes acceleration time, 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 regression:

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

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-

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[2] Manufacturers could offer different options for gasoline and diesel fuel versions of the same model (e.g., leather versus cloth seats). Because some such options include unobserved characteristics, such as a sunroof, this practice would cause fuel economy or performance to be correlated with unobserved characteristics in the empirical analysis in Section 4. Verboven (2002) addresses this issue by including only the base version of each model in the sample. In this paper controlling for trim and power train, as I do in the preferred specification, controls for such characteristics. For example, the "standard" and "sport" trims may have different unobserved features (e.g., the seating material or the presence of a sunroof), but these features do not vary within a trim and power train.

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 values indicate that the independent variables are jointly strong predictors of the log of the acceleration time. The coefficient estimates are used to impute the acceleration time for all vehicles in the Polk data. The acceleration time is the measure of performance used in the rest of the paper; a longer time implies less performance. The statistical significance and magnitude of the coefficients on the vehicle attributes other than the horsepower-to-weight ratio support the use of the chosen performance proxy, rather than the ratio alone. I have also estimated equation (1) by class or manufacturer, which does not affect the paper's main conclusions.[3]

Fuel prices are from Eurostat, and vehicle and fuel tax rates are from the European Automobile Manufacturers Association. From these data I calculate the average gasoline price, gasoline tax, diesel fuel price, and diesel fuel tax by country and year. Klier and Linn (2015) describe the fuel price and tax data in more detail.

2.2. Summary Statistics

Table 1 provides summary information about the data. Each row shows the average annual registration (in millions), diesel fuel vehicle market share, and average CO_2 emissions rate for the indicated country. Germany has the largest market, followed by the United Kingdom, France, and Italy. The size of the markets varies considerably across countries, partly due to population: the Austrian market, for example, is less than one-tenth the size of the German market. The table also compares the average fuel costs (in 2005 euros per 100 km) across fuel types. Gasoline vehicles have higher fuel costs than diesel fuel vehicles, and this differential varies across countries because of variation in fuel prices and fuel consumption rates.

Table 1 also shows that the diesel fuel vehicle market share varies across countries, and Figure 2 provides temporal detail, plotting the diesel fuel vehicle market share by country and

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[3] 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. The measure is likely to be highly correlated with other performance measures.

year (panel A). For most of the time period the Netherlands has the lowest market share, and Belgium and France have the highest shares. Each country's market share is persistent, with the exceptions of Austria, Sweden, and the United Kingdom.

Panel B shows that the ratios of gasoline to diesel fuel prices vary across countries, but little over time. Fuel taxes explain much of the cross-country variation in the relative price of gasoline. Although most countries tax diesel fuel at a lower rate than gasoline, countries vary in the extent to which they differentially tax the two fuels. The price ratio is the highest in the Netherlands and lowest in the United Kingdom. The fact that these countries both have lower market shares of diesel fuel vehicles than most other countries suggests that fuel prices are not the dominant factor explaining market shares; Klier and Linn (2013) document this empirically.

Table 2 shows the subtle cross-country differences in vehicle supply. The table reports coefficient estimates from a regression of log fuel economy (column 1) or log acceleration time (column 2) on trim–power train by year interactions and country fixed effects; observations are by variant, country, and year. Because of the trim–power train by year interactions, the country fixed effects are identified by variation 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 acceleration time for the corresponding country, relative to Germany. For example, the coefficient for Austria in column 1 implies that vehicles in Austria have about 2 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 small in magnitude. The small differences reflect variation in the purchased variants of a particular trim–power train, rather than manufacturers designing vehicles specifically for each market. Most vehicles sold in Germany are sold in other countries, and these patterns suggest that supply conditions are quite similar across countries.

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

2.3. Policy Context and Tax Variation

Vehicle manufacturers in the EU face emissions rate standards for nitrogen oxides. Each manufacturer must achieve an average emissions rate for its vehicles, with higher emissions rates allowed for diesel fuel than for gasoline vehicles. During most of the period analyzed, the emissions rate for diesel fuel vehicles was three times that of gasoline vehicles.

In 2007 EU vehicle manufacturers agreed to meet a specific CO_2 emissions rate target by the year 2015 for all vehicles sold in the EU. Prior to this agreement, manufacturers had agreed to meet specific targets by 2007 and 2008 (depending on the manufacturer). The earlier agreement did not include penalties for noncompliance, and in fact, manufacturers did not achieve the targets; the 2007 agreement includes fines for noncompliance. Because of the second agreement, during the later years of the sample period manufacturers adopted fuel-saving technology to reduce CO_2 emissions rates (Klier and Linn 2016). Concurrently, many countries reformed their vehicle taxation programs, partly by linking taxes more closely to CO_2 emissions rates than previously. The tax changes were intended to complement the CO_2 emissions rate standards by incentivizing consumers to purchase low-CO_2-emitting vehicles.

The empirical analysis in this paper estimates the effects of vehicle taxes on diesel fuel vehicle market shares using both cross-sectional and time series tax variation. To illustrate the sources of variation, Figure 4 plots vehicle taxes against CO_2 emissions rates for each country. For each observation in the data, I compute the present discounted value of purchase and annual ownership taxes, using a 10 percent discount rate and 12-year vehicle lifetime. The figure plots each vehicle's tax (in 2005 euros) against its CO_2 emissions rate, using observations from 2002 and 2010.

Figure 4 indicates three sources of tax variation in the data. First, taxes vary across vehicles within a year and country. Each country has its own tax system, but all countries tax vehicles according to their characteristics, such as horsepower or weight. Consequently, the tax variation indicated by the range of taxes along the vertical axis reflects underlying variation in vehicle attributes and the country's tax structure. Second, taxes vary across countries within a year, which is indicated by comparing across countries the distributions of taxes along the vertical axis. Third, the tax systems changed in most countries over time. For most countries taxes generally increased between 2002 and 2010, and taxes depended more strongly on CO_2

emissions rates in 2010 than in 2002. The latter change is indicated by the fitted curves, which represent the fitted values from a linear regression of a vehicle's tax on its emissions rate (each regression includes a constant term). In each country the fitted line is steeper in 2010 than in 2002, demonstrating a larger effect of a vehicle's emissions rate on its tax.

3. Estimation Strategy

3.1. Empirical Framework

To motivate the empirical analysis, I show that because of consumer substitution across fuel types, vehicle and fuel taxation induce trade-offs between CO2 and nitrogen oxides emissions. For simplicity, I analyze the European-wide average emissions rates rather than focus on manufacturer-level emissions. I begin by characterizing the average CO2 emissions rate of vehicles sold in Europe in a particular time period, E_c, in terms of the diesel fuel vehicle market share, s; the average CO_2 emissions rate of diesel fuel vehicles, e_c^d; and the average CO_2 emissions rate of gasoline vehicles, e_c^g:

$$E_c = se_c^d + (1-s)e_c^g \tag{2}$$

The average emissions rate is a weighted average of emissions from diesel fuel and gasoline vehicles, with the market shares as weights.

Suppose the government introduces a small tax, τ, which depends on the vehicle's CO_2 emissions. In the policy analysis later in the paper, the tax can be imposed either on fuel or on the vehicle, in which case it is proportional to the CO_2 emissions rate of the vehicle. This distinction does not matter for the present discussion. Either type of tax raises the cost of obtaining or driving all vehicles, but the tax raises costs more for vehicles with high CO_2 emissions rates than for vehicles with low CO_2 emissions rates. Because diesel fuel vehicles have lower CO_2 emissions rates than gasoline vehicles, the tax raises the diesel fuel vehicle market share, and $\frac{ds}{d\tau} > 0$.

Taking the derivative of equation (2) with respect to τ yields the change in the market-wide average emissions rate per change in τ:

$$\frac{dE_c}{d\tau} = \frac{ds}{d\tau}(e_c^d - e_c^g) + s\frac{de_c^d}{d\tau} + (1-s)\frac{de_c^g}{d\tau} \tag{3}$$

Equation (3) shows that the change in emissions rate depends on two effects. The first effect, $\frac{ds}{d\tau}(e_c^d - e_c^g)$, is proportional to the change in diesel fuel vehicle market share. In Europe, diesel fuel vehicles have lower CO_2 emissions rates than gasoline vehicles, and $(e_c^d - e_c^g)$ is negative, implying that $\frac{ds}{d\tau}(e_c^d - e_c^g) < 0$. The greater the consumer substitution from gasoline to diesel fuel vehicles, the larger the magnitude of the first term.

The second effect, $s\frac{de_c^d}{d\tau} + (1-s)\frac{de_c^g}{d\tau}$, represents the effect of within-fuel-type consumer substitution on the average emissions rate. The average emissions rate of diesel fuel or gasoline vehicles (e_c^d or e_c^g) is the weighted sum of vehicle-level emissions rates, where weights equal the share of a vehicle's sales in the total sales of the fuel type. Because τ raises the relative costs of vehicles with high CO_2 emissions rates, the tax raises the sales weights for vehicles with low CO_2 emissions rates and decreases the sales weights for vehicles with high CO_2 emissions rates. Therefore, the derivatives $de_c^d/d\tau$ and $de_c^g/d\tau$ are negative. In equation (3) both effects are negative, and the change in the average CO_2 emissions rate depends on the magnitudes of the within- and cross-fuel substitution.

The market-wide emissions rate of nitrogen oxides is $E_n = s\overline{e}_n^d + (1-s)\overline{e}_n^g$, where variables are defined similarly to those in equation (2) and the bars over the emissions rates indicate that they are fixed by regulation in Europe (recall that during the time period being analyzed, CO_2 emissions rates were not fixed by regulation). That is, manufacturers can adjust their vehicles' nitrogen oxides emissions rates to precisely meet the standards. Because regulation fixes the average nitrogen oxides emissions rates by fuel type, the derivative of the average nitrogen oxides rate includes only one term:

$$\frac{dE_n}{d\tau} = \frac{ds}{d\tau}(\overline{e}_n^d - \overline{e}_n^g) \tag{4}$$

The right-hand side is positive because regulations set higher average nitrogen oxides emissions for diesel fuel than for gasoline vehicles (i.e., $\overline{e}_n^d > \overline{e}_n^g$). A comparison of equations (3) and (4) shows that the trade-off between CO_2 emissions rates and nitrogen oxides emissions rates depends on consumer substitution within fuel type versus across fuel types. The greater the substitution across fuel types, the larger the reduction in CO_2 emissions but also the larger the increase in nitrogen oxide emissions rates. Substitution within a fuel type does not induce this trade-off, however, because regulation fixes the nitrogen oxides emissions rates of both fuel types. Therefore, the extent of the trade-off can be assessed by estimating the effects of CO_2-based taxes on consumer substitution within and across fuel types. Estimating these substitution patterns from the data is the empirical focus of this paper.

3.2. Country-Level Aggregation

To estimate the effects of vehicle taxes on CO_2 emissions rates, researchers have used both aggregated and disaggregated data. Some studies (e.g., Ryan et al. 2009) use aggregated data on the diesel fuel vehicle market share and emissions rates, say with observations by country and year. Using aggregated data, one can estimate the derivatives in equations (3) and (4). For example, suppose observations are by country, fuel type, and year, and one knows the average tax rate and fuel costs at this level of aggregation. One could specify a reduced form equation:

$$s_{ct} = \beta_1 \tilde{F}_{ct} + \beta_2 \ln \tilde{T}_{ct} + \beta_3 \ln \tilde{A}_{ct} + \tau_t + \varepsilon_{ct} \qquad (5)$$

where the dependent variable is the share of diesel fuel vehicles by country and year; $\tilde{F}_{ct}$ is the average fuel cost of diesel fuel vehicles normalized by the average fuel cost of gasoline vehicle (the tilde indicates that the variable is a ratio); $\tilde{T}_{ct}$ is the average tax on diesel fuel vehicles normalized by the average tax on gasoline vehicles; $\tilde{A}_{ct}$ is the acceleration time for diesel fuel vehicles, normalized by the time for gasoline vehicles; τ_t is a set of year fixed effects; ε_{cft} is an error term; and the βs are coefficients to be estimated. As is customary in the literature, I define fuel costs as the cost of driving the vehicle 100 km, which equals the price of fuel (in euros per liter of fuel) multiplied by the fuel consumption rate (liters of fuel consumption per 100 km traveled). The fuel cost variable is proportional to expected discounted fuel costs over the vehicle's lifetime under the assumption that the current price equals the expected future price (Allcott and Wozny 2014). The tax variable includes taxes that are directly linked to the vehicle's CO_2 emissions rate or other attributes that may be correlated with the emissions rate, such as weight or engine size. The taxes include those paid at the time of purchase and those paid in the future (for example, annual registration taxes); future taxes are discounted to the present as in Section 2. Equation (5) includes acceleration time to account for the differential performance between gasoline and diesel fuel vehicles indicated in Figure 3.

Each β coefficient is interpreted as the equilibrium effect on the market share of an increase of the corresponding variable. For example, suppose a country increases its tax on diesel fuel vehicles between one year and the next. The tax increase raises the relative cost of owning diesel fuel vehicles, reducing demand for those vehicles. Therefore, one expects the market share to decrease and the coefficient on the tax variable to be negative. The coefficients on fuel costs and acceleration time are also expected to be negative, as an increase in fuel costs or acceleration time (i.e., lower acceleration) of diesel fuel relative to gasoline vehicles reduces demand for diesel fuel vehicles and their equilibrium market share. Because of the time fixed effects, the coefficients are identified by cross-country variation as well as deviations from the average annual change in the variables. For example, if one country reduces its diesel fuel vehicle taxes at a faster rate than a second country, the relative reduction in taxes would help identify the coefficient on the tax variable.

There are several positive aspects to estimating equation (5), or a variation thereof, using aggregated data. First, by using the diesel fuel vehicle market share or alternative forms of equation (5) that use emissions rates as dependent variables, it is straightforward to estimate each derivative in equations (3) and (4) and characterize the effects of taxes on emissions rates. Second, the data requirements are more modest than for regression models that use disaggregated data, which are discussed next.

3.3. Disaggregated Estimation

Using aggregated data, the limited degrees of freedom necessitate a sparse set of controls in equation (5). Consequently, a negative aspect of the aggregated analysis is that one must assume that fuel costs, acceleration time, and taxes are exogenous to other supply and demand factors that affect the diesel fuel vehicle market share.

There are at least three potential sources of omitted variable bias in equation (5). First, in equation (5) the coefficients would be biased if the independent variables are correlated with supply-side factors that affect equilibrium registrations. For example, manufacturers regularly introduce new vehicles to the market, which tend to have higher (unobserved) quality than previously marketed vehicles. The market entrants may also differ in fuel costs, taxes, or acceleration, and unobserved quality would therefore bias estimates of the coefficients in equation (5). As part of the process of introducing vehicles to the market, manufacturers adopted fuel-saving technology in the late 2000s in anticipation of the 2015 CO_2 standards. If, at the same time that they adopt fuel-saving technology, manufacturers changed other vehicle attributes, such as updating the interior design, then these other changes would be correlated with fuel costs, biasing estimates in equation (5).

Second, diesel fuel vehicles may have other characteristics that are omitted from equation (5) and that affect consumer demand for these vehicles. The equation includes taxes, fuel costs, and acceleration, because those attributes differ between gasoline and diesel fuel vehicles, as Figure 3 indicates. However, in some cases a luxury trim includes only a diesel fuel engine, whereas the base trim includes a gasoline engine. For example, suppose the luxury trim uses diesel fuel and includes an advanced sound system, whereas the standard trim uses gasoline and includes an inferior sound system. Because it uses diesel fuel, the diesel fuel trim has lower fuel costs than the standard gasoline trim. In this example, the coefficient on fuel costs would reflect consumer valuation of the sound system, as well as the valuation of fuel costs, yielding a biased estimate of the effect of fuel costs on the market share. For similar reasons the tax coefficient would also be biased.

Third, omitted demand-side factors may be correlated with the independent variables. For example, if equation (5) is estimated using data from the late 2000s, the sample would include the period of the economic recession. The recession in the late 2000s may have affected vehicle markets differentially across European countries—for instance, between 2007 and 2009 new car registrations decreased 41 percent in Spain and 13 percent in Italy, whereas registrations increased 12 percent in France. Diesel fuel vehicles have higher purchase prices than otherwise comparable gasoline vehicles, and the decrease in typical household income and wealth during the recession may have differentially affected demand for diesel fuel vehicles across European countries. Equation (5) includes time fixed effects, which controls for the average effect of the recession on the diesel fuel vehicle market share across countries. Adding country-specific time trends would partially address the issue, although it would not account for the nonlinear effect of the recession over time (i.e., the recession was more severe in 2008 or 2009 than in 2010). In addition, it becomes difficult to identify the fuel cost and tax coefficients in equation (5) when including country-specific trends.

These three sources of bias reflect omitted shocks that differentially affect vehicles in the market and that cannot be controlled for using aggregated data. However, the potential sources of bias can be addressed by estimating a disaggregated version of equation (5).

The approach using disaggregated data has two steps. The first is to estimate the effects of fuel costs and taxes on equilibrium registrations of individual vehicles. The second is to simulate fuel cost or tax changes and calculate the derivatives in equations (3) and (4). I discuss the first step here and the second step in Section 5.

For example, suppose observations are by variant i, country c, and year t. The log registrations of the variant is the dependent variable:

$$\ln q_{ict} = \beta_1 F_{ict} + \beta_2 \ln T_{ict} + \beta_3 \ln A_{ict} + \eta_p + \mu_{ct} + \varepsilon_{ict} \tag{6}$$

where the tax, fuel cost, and acceleration variables are defined as in equation (5) except that they are the levels of the variables, rather than the ratios; η_p is a set of trim–power train fixed effects; and μ_{ct} is a set of country-year fixed effects.

Importantly, the trim–power train coefficients absorb all variation that is common to the diesel fuel and gasoline variants of the trim–power train. Although different versions of a model often have differing levels of seating comfort, electronics features, or other attributes, variants that share the same trim–power train have identical attributes. For example, as Figure 1 indicates, the trim–power train fixed effects control for differences between the "sport" and other trims of the model. The trim–power train interactions control for the possibility that consumers who choose diesel fuel vehicles have stronger preferences for certain attributes (such as leather seats) than do consumers who choose gasoline vehicles. The interactions thus address an important identification issue in the vehicle demand literature: the potential correlations among observed and unobserved vehicle attributes. Note that several recent papers that have used disaggregated data, such as D'Haultfoeuille et al. (2014) and Grigolon et al. (2015), have not addressed the potential correlation between observed vehicle attributes and unobserved demand or supply shocks. The trim–power train fixed effects used here control for unobserved attributes and represent an alternative approach to strategies used elsewhere in the literature, such as instrumenting for vehicle price in a demand system (e.g., Berry et al. 1995; Klier and Linn 2012), or restricting the sample to the base version of each model (Verboven 2002). In this context, the fixed effects control for all attributes except fuel costs, taxes, and acceleration time.

Identification and interpretation of the coefficients in equation (6) are different from those in equation (5). The trim–power train fixed effects control for all attributes of the trim–power train that are common to the gasoline and diesel fuel variants of the trim–power train and are fixed over time. Therefore, the β s are identified by variation in taxes, fuel costs, or acceleration time across the diesel fuel and gasoline versions of the trim power train; and deviations from country-specific means of changes over time in taxes, fuel costs, or acceleration time.

For example, consider an increase in the gasoline price between one year and the next. For two variants of a particular trim–power train, the price increase raises fuel costs for the gasoline variant but not the diesel fuel variant. The trim–power train fixed effects in equation (6) control for the mean fuel costs of the two variants. The fuel cost coefficient is identified by the increase in fuel costs of the gasoline variant and the decrease in fuel costs of the diesel variant, relative to the mean fuel costs across the two variants.

In terms of residual demand curves for the two variants, the fuel price change causes the demand curve for the diesel fuel variant to shift away from the origin and the demand curve for the gasoline variant to shift toward the origin. The manufacturer may respond to the demand curve shifts by raising the price of the diesel fuel variant and reducing the price of the gasoline variant. On balance, the equilibrium registrations of the diesel fuel variant increase and the gasoline variant decrease, implying a negative coefficient on fuel costs. In other words, the coefficient reflects the effect of fuel prices on equilibrium registrations, after accounting for vehicle price changes caused by the fuel price change.

The identification and interpretation of the tax and acceleration coefficients are straightforward. An increase in the tax on a diesel fuel variant raises the cost of purchasing or owning the variant and reduces the variant's equilibrium registrations, all else equal. The equilibrium change is net of any vehicle price changes the manufacturer makes in response to the tax change. Likewise, one expects a negative coefficient on acceleration time.

To summarize, equation (6) addresses three potential sources of omitted variables bias in equation (5). Specifically, the trim–power train fixed effects address supply or demand side shocks, such as the introduction of new vehicles and the adoption of fuel-saving technology. They also control for consumer demand for unobserved attributes of the trim–power train. Finally, the country-year fixed effects address external shocks to consumer demand that affect consumer demand proportionately across variants. (I discuss the possibility of disproportionate demand shocks in the next section.)

Besides enabling controls for supply and demand shocks, the disaggregated data also make it possible to allow consumer substitution patterns to vary across vehicles and countries. Equations (3) and (4) illustrate the importance of specifying a model that captures both cross- and within-fuel-type consumer substitution. Equations (5) and (6) include the functional form assumption that substitution is determined by absolute tax differences across vehicles. For example, consider a hypothetical market that includes three vehicles, two that use gasoline and one that uses diesel fuel. Starting from an equilibrium with no taxes, if the government sets a high tax on one gasoline vehicle and a lower but equal tax on the other two vehicles, equation (6) predicts that consumers substitute equally from the high-tax vehicle to the two lower-tax vehicles. In practice, consumers may be more likely to substitute from one gasoline vehicle to another than from a gasoline to a diesel fuel vehicle.

I allow for these possibilities by letting the tax coefficient vary across vehicles or markets. Specifically, I interact the tax coefficient with fuel type, which allows substitution patterns to vary by fuel type. For three alternative specifications, the tax coefficient varies by the vehicle's fuel type and CO_2 emissions quartile; fuel type and market segment; and fuel type and country. The country specifications are motivated partly by the fact that the tax variable includes taxes paid at the time of purchase and taxes paid annually based on ownership. The underlying assumption in equation (6) is that registrations respond by the same proportion to purchase and discounted future ownership taxes. Some countries use CO_2-based purchase taxes, and others use CO_2-based ownership taxes, but no country uses both. Therefore, estimating the tax coefficients by country effectively allows registrations to respond differently to the two types of taxes (in contrast, Grigolon et al. 2015 assume that purchase and ownership taxes have the same effects on consumer choices). In addition, estimating coefficients by country allows for the possibility that culture, income, or other factors create cross-country variation in the responsiveness of registrations to fuel costs and taxes. Thus, the third alternative allows for differences in substitution patterns across countries or tax regimes.

In a reduced-form setting such as this, the objective of considering alternative specifications is to identify a specification that suitably models the observed consumer choices. For that reason I compare the specifications according to their within- and out-of-sample predictions. This approach contrasts somewhat to the approach taken in specifying a structural demand model, such as by D'Haultfoeuille et al. (2014). In that case, the researcher must choose whether preference variation across consumers depends on observed consumer characteristics (such as income) or varies randomly (Berry et al. 1995). Because the objective in this paper is to estimate within- and cross-fuel substitution, it is not necessary to specify underlying preferences.

4. Estimation Results

The objective of this section is to identify the specification that best fits the observed data and predicts out-of-sample. The preferred specification is used for the policy analysis in the next section.

4.1. Coefficient Estimates

In this subsection I compare the coefficient estimates across specifications. Tables 3 through 5 report coefficient estimates from seven specifications. In presenting the results, I focus on the fuel cost and tax coefficients because of their importance in the policy simulations in the next section. I compare the coefficient estimates with other estimates in the literature and interpret their economic significance.

Column 1 in Table 3 shows the estimates of equation (5), in which the dependent variable is the share of diesel fuel vehicles in total registrations by country and year. The fuel cost, acceleration time, and tax variables all have the expected negative signs, and each is statistically significant at the 1 percent level (standard errors are robust to heteroskedasticity). The average diesel fuel vehicle market share in the sample is about 0.5, and the tax coefficient estimate implies an elasticity of the diesel fuel vehicle market share to taxes of –0.5. This estimate is larger than that of Ryan et al. (2009), but it is consistent with the cross-country variation observed in the data. For example, the tax variable is 0.34 log point higher in Germany than in Italy, and the point estimate suggests that the diesel fuel vehicle market share should be about 9 percentage points higher in Italy than in Germany; the actual difference is about 14 percentage points.

The previous section discussed three reasons why the estimates of equation (5) may be biased. To assess whether these potential sources of bias are important in practice, I compare the estimates from equation (5) with the estimates from equation (6). Before I proceed to the estimates using the fully disaggregated variant-level data, it is instructive to consider a specification in which observations are not fully disaggregated. In this specification, observations are by model, fuel type, country, and year, which corresponds to situations in which a researcher has access to model-level data but not the fully disaggregated data (perhaps because of data acquisition costs).

The dependent variable is the log of a vehicle’s registrations, and the regression includes model by year fixed effects, which control for model-level demand or supply shocks, such as the introduction of a new model. The fuel cost, acceleration time, and tax variables are interacted with an indicator variable for whether the vehicle uses diesel fuel. Column 2 of Table 3 reports the coefficients on the three main effects as well as the interaction terms. The fuel cost coefficient is interpreted as the effect of fuel costs on registrations for gasoline vehicles, and the sum of the main effect and corresponding interaction term is the effect for diesel fuel vehicles.

As expected, fuel costs, acceleration time, and taxes have negative effects on registrations. Fuel costs have a statistically significant effect on registrations for gasoline but not for diesel fuel vehicles. Registrations of gasoline vehicles are more sensitive to fuel costs than are registrations of diesel fuel vehicles, whereas registrations of gasoline vehicles are less sensitive to taxes than are registrations of diesel fuel vehicles.

In column 2, the coefficients imply that a 1 percent increase in a vehicle’s tax reduces its registrations by 0.65 to 1 percent, depending on fuel type. These estimates are larger than those in Klier and Linn (2015) and other studies, and the magnitudes imply a large effect of taxes on registrations. For example, in the sample, diesel fuel vehicles in Germany have a 60 percent higher tax than gasoline vehicles. The implausibility of the estimates suggests that they may be biased.

The regression in column 2 represents one approach to addressing potentially omitted demand or supply shocks that were discussed in the previous section. However, even this level of disaggregation may not fully address the problems. For example, manufacturers regularly introduce or discontinue variants of a particular model. They may also add fuel-saving technology to some variants of a model and not others. Another possibility is that there may be shifts in consumer preferences that affect registrations of some variants of a model more than registrations of others. For any of these possibilities, omitted variables would be correlated with fuel costs, acceleration time, and taxes. Because the omitted variables vary over time, the model fixed effects would not control for them, and the estimates would be biased.

It is possible to control for these possibilities by further disaggregating the data. In column 3 of Table 3, observations are by country, variant, and year. For comparison with column 2, I include model fixed effects and also add controls for the vehicle attributes noted at the bottom of the table. The magnitudes of the tax coefficients are smaller in column 3 than in column 2. The magnitudes of the fuel cost coefficients are also smaller in column 3 than in column 2.

Even column 3 may yield biased estimates if omitted demand and supply shocks are correlated with the attributes included in the regression. To assess whether this is the case, I include trim–power train fixed effects in column 4 of Table 3. These fixed effects control for all unobserved and time-invariant attributes of the vehicle. The fuel cost, acceleration time, and tax coefficients are identified by differences in these variables across fuel types and within a trim–power train; as discussed above, unobserved attributes do not differ across fuel types and within a trim–power train. Column 4 shows that including these fixed effects does not affect the fuel cost or tax coefficients.

Next, I allow for the possibility that the effects of fuel costs, acceleration time, and taxes vary across vehicles. I consider three types of heterogeneous effects of these variables: (1) I assign vehicles to quartiles based on their CO_2 emissions rates and estimate separate coefficients for each quartile and fuel type; (2) I separate vehicles by market segment and estimate separate coefficients for each segment and fuel type; and (3) I estimate separate coefficients for each country and fuel type. The first two types of heterogeneity allow consumers to respond differently depending on the emissions rate or market segment, which allows for variation across consumers in their concern about CO_2 emissions or demand for other vehicle attributes.

Tables 4 and 5 report these results. Overall, coefficient estimates vary across categories, although in some cases the differences are not statistically significant. Fuel costs have larger effects for diesel fuel vehicles with lower CO_2 emissions than for diesel fuel vehicles with higher emissions (panel A of Table 4). When separating vehicles by market segment (panel B of Table 4), the gasoline vehicle tax coefficients differ between the small/mini and other segments. The country-specific estimates in Table 5 indicate substantial variation in the coefficients across countries. Some of the estimated elasticities for diesel fuel vehicles, particularly the tax elasticities, are positive; this appears to be due to a high correlation between the fuel cost interaction terms and other independent variables. This is illustrated in Appendix Table 2, which shows the country-level results from estimating specifications that do not include the fuel-type interactions. The tax and fuel cost coefficients are uniformly negative in this case, and the point estimates are consistent with those of Klier and Linn (2015). The appendix table also indicates that there is insufficient tax variation to identify the tax coefficient for Austria. The anomalous coefficient estimates in Table 5 raise concerns about using the specification in Table 5 for the policy analysis.

Across the variant-level specifications (i.e., columns 3 and 4 of Table 3, as well as the three heterogeneity specifications), the estimated tax elasticities are smaller in magnitude than the elasticities from the model by year specification in column 2 of Table 3. The fuel cost elasticities also differ across specifications, illustrating the importance of considering alternative specifications when estimating these effects.

I briefly discuss the implications of the coefficient estimates for cross-fuel substitution induced by fuel price or vehicle tax changes. The aggregated specification implies that the elasticity of the diesel fuel vehicle market share to fuel costs is similar to the elasticity of the market share to taxes (see Table 1 for mean fuel costs). In contrast, as the policy simulations in Section 5 illustrate, the disaggregated specifications imply that the market share is less sensitive to fuel costs than to taxes.

4.2. Comparing Fit Across Specifications

Aside from the tax elasticities for the country-specific estimates, the specifications reported in Section 4.1 yield coefficient estimates with the expected signs. In most cases the magnitudes are plausible, particularly for the variant-level analysis. To select a specification for the policy analysis, I assess the ability of the specifications to fit the observed data.

I consider first whether the specifications predict observed diesel fuel vehicle market shares. Comparing observed and predicted diesel fuel market shares is relevant because of the focus in the next section on the effect of tax policies on counterfactual market shares; it would be preferable to use a specification that can reproduce observed outcomes.

By construction, the aggregated specification exactly predicts the average diesel fuel market share over the sample. Therefore, I compare the predicted and observed diesel fuel market share by country. Figure 5 shows that the aggregated model does not accurately predict the diesel fuel vehicle market share for countries with relatively high market shares (e.g., France) and for countries with low market shares (e.g., the Netherlands).[4]

I compare the country-level predicted diesel fuel vehicle market share across the aggregated and disaggregated specifications. For the disaggregated specifications, I use the predicted registrations of each observation to compute the registration-weighted diesel fuel vehicle market share. Because the dependent variable is log registrations rather than market share, even for the specification that allows the coefficients to vary by country, the disaggregated specifications do not perfectly predict the country-level market share by construction, and comparing predicted and observed shares can help select a specification for the policy analysis. Considering each specification shown in Figure 5, for certain countries, such as Sweden, all of the specifications predict the market share accurately. For other countries, such as the Netherlands and the UK, performance varies across the specifications. For these countries, two specifications perform best: estimates by CO_2 emissions quartile and by country. Table 6 shows that these two specifications have the lowest in-sample prediction error (panel A).

One limitation of comparing the predicted market share across specifications is that the specifications differ in the extent of the fixed effects they include. The specifications with more fixed effects, such as those including trim–power train fixed effects, as in column 4 of Table 3, could overfit the data. That is, the specification that provides the best fit of the predicted diesel

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[4] Adding country fixed effects to equation (3) would cause the aggregated model to perfectly predict the country-level market share over the entire sample. However, this specification does a poor job fitting within-country temporal variation in the market share, which underscores the importance of considering not only the ability of the models to predict the mean diesel fuel market share but also their ability to fit the observed variation from the mean. Table 6 focuses on the latter.

market share could outperform the other specifications because it includes more fixed effects than some of the other specifications.

A related concern about within-sample fit is that the specifications that include trim–power train fixed effects identify the coefficients from consumer substitution within trims and power trains. In principle, consumer substitution patterns within trims and power trains could differ from substitution patterns across trims and power trains. That situation would create misleading results from the policy simulations, which include both types of substitution.

I can address both issues—overfitting and substitution patterns—by comparing the out-of-sample prediction error across specifications. If a specification overfits the data or if substitution within trims and power trains differs from substitution across trims and power trains, the specification would perform poorly out-of-sample. For each full sample in panel A of Table 6, I randomly select a 90 percent subsample. In panel B, column 3 reports the square root of the mean square of the difference between the predicted values from the full sample and the subsample. The smaller this statistic, the less sensitive are the predictions to the estimation sample. In column 3, the CO_2 quartile specification outperforms the other specifications that allow for heterogeneity. Column 4 reports the out-of-sample prediction error for each specification, using the 10 percent of observations that were not included in the estimation subsample. The out-of-sample prediction error for the CO_2 quartile specification is about the same as the prediction error for the variant-level specifications that do not allow for heterogeneity and is lower than the other two specifications that allow for heterogeneity.

Considering the predicted market shares and prediction error, the specifications that include observations at the variant level perform better than the specifications that include observations at the model or country level. Among the variant-level specifications, the CO_2 specification performs the best. Allowing for heterogeneity by CO_2 quartile substantially improves the fit of the diesel market share and within-sample prediction and does not affect out-of-sample predictions. In the following analysis I use the CO_2 quartile specification as the preferred specification.

5. Effects of Fuel Taxes and CO_2 Emissions Rate Taxes on Nitrogen Oxides Emissions Rates

5.1. Policy Scenarios

The first of the two policies is a tax that is directly proportional to a vehicle's CO_2 emissions rate. Because diesel fuel vehicles have lower emissions rates than otherwise comparable gasoline vehicles, the emissions rate tax raises the tax on gasoline vehicles relative to the tax on diesel fuel vehicles. The coefficient estimates in the preferred specification suggest that the tax would increase the market share of diesel fuel vehicles and decrease the market share of gasoline vehicles.

Setting the tax proportionately to the emissions rate is consistent with the tax changes that many countries implemented during the sample period, as Figure 4 indicates. This is an important consideration because of the reduced form approach that is taken to estimate consumer substitution within and across fuel types. For consistency with the estimation, the tax is implemented as a purchase tax for countries that tax vehicle purchase and as an ownership tax for countries that tax vehicle ownership (the ownership taxes use the same discount rates and vehicle lifetimes as in Section 2; both the empirical results and policy simulations are similar using alternative assumptions). For purchase taxes, the tax is equal to 20 euros per gram of CO_2/km. Taxes are imposed such that two vehicles in different countries have the same present discounted value of taxes if they have the same CO_2 emissions rate, regardless of whether purchase or ownership is being taxed.

The second policy is a fuel tax based on the carbon content of fuel equal to 14.40 euros per metric ton of CO_2. As Figure 3 indicates, diesel fuel vehicles typically consume about 30 percent less fuel per distance traveled. The carbon content of diesel fuel is about 10 percent higher than that of gasoline, however. Therefore, the combined effect of the fuel tax is to increase fuel costs for gasoline vehicles about 20 percent more than for diesel fuel vehicles. The differential fuel cost change causes the diesel fuel vehicle market share to increase at the expense of gasoline vehicles. The magnitudes of the tax and fuel price changes are consistent with the sample variation used to identify the tax and fuel cost coefficients.[5]

For both policies, I compare a predicted and counterfactual scenario. The predicted scenario uses the observed fuel costs, acceleration, and fuel taxes to predict log registrations of each variant in the full sample, using estimates from panel A of Table 4. In the counterfactual vehicle tax, each variant's tax is equal to its actual tax plus the emissions rate tax. The

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[5] I assume that the fuel taxes are passed through fully to retail fuel prices. I am not aware of empirical evidence of fuel tax pass-through in Europe, but Marion and Muehlegger (2011) document full pass-through in the United States. I assume that consumers respond similarly to fuel price changes induced by tax changes as those induced by other factors such as oil prices. Li et al. (2014) find that consumers respond more strongly to fuel taxes in the United States. Allowing for this possibility would strengthen the qualitative conclusions of these policy scenarios.

counterfactual tax is used to predict counterfactual log registrations of each vehicle. For the fuel tax scenario, the tax is added to the observed fuel price, and the counterfactual fuel price is used to predict counterfactual registrations of each vehicle. For both policy scenarios, I compute the difference between counterfactual and predicted diesel fuel market shares, as well as emissions rates.[6]

The vehicle and fuel taxes are calibrated to achieve the same reduction in average CO_2 emissions rates across the fleet of vehicles sold. In both cases, tax revenue is returned in lump-sum rebates to households in each country. Given the magnitude of the tax increases, the resulting refund represents less than 1 percent of income for most new car-buying households. Consequently, I do not consider income effects.

5.2. Results

Table 7 reports the results for the vehicle tax and Table 8 for the fuel tax. In both tables the three panels compare the observed and counterfactual diesel fuel market shares, CO_2 emissions rates, and nitrogen oxides emissions rates. Table 7 shows that the vehicle tax raises the market share of diesel fuel vehicles across the entire sample and by varying amounts across countries. The variation stems from two factors. First, some countries have higher-CO_2-emitting vehicles than others, and observed diesel fuel vehicle market shares differ. For example, the UK typically has higher-CO_2-emitting vehicles and lower market share than does Belgium, and taxes rise more for vehicles in the UK than for vehicles in Belgium. Second, the estimated coefficients vary across quartiles. The results in Table 7 reflect the combined effects of these two forces.

The changes in CO_2 and nitrogen oxides emissions rates imply a trade-off for emissions of the two pollutants. The vehicle tax reduces sample-wide CO_2 emissions rates by 1.3 percent and increases nitrogen oxides emissions rates by 3.6 percent, which is more than a one-for-one trade-off.

The fuel tax implies a milder trade-off between CO_2 and nitrogen oxides emissions rates. The fuel tax achieves the same reduction in CO_2 emissions rates (by construction), but the

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[6] Throughout, I assume that on-road emissions of vehicles equal the corresponding emissions rate standards. Chen and Borken-Kleefeld (2014) show that in Switzerland, on-road emissions of diesel fuel vehicles exceeded the standards by a wide margin, whereas on-road emissions of gasoline vehicles were similar to the standards. Accounting for this discrepancy would exacerbate the estimated environmental effects of an increase in the diesel fuel vehicle market share. This would strengthen the conclusions about the relative effects of the two taxes on nitrogen oxides emissions rates.

increase in nitrogen oxides emissions rates is one-tenth the increase caused by the vehicle tax. This difference arises because the estimation results imply that fuel price changes induce less cross-fuel substitution than do vehicle tax changes. It is noteworthy that the estimates of the aggregated regression have precisely the opposite policy implication. Furthermore, note that the policy simulations are qualitatively similar using the estimates from the other variant-level specifications from Section 4.

This analysis does not include the effect of the taxes on miles traveled. The CO_2-based fuel tax raises per-km fuel costs and reduces miles traveled, whereas the CO_2-based vehicle tax reduces per-km fuel costs and raises miles traveled (i.e., the vehicle tax induces a rebound effect). Accounting for these changes would imply recalibrating the policies to achieve the same reductions in CO_2 emissions rather than CO_2 emissions rates. The resulting fuel tax would be smaller than that described above, and thus accounting for driving changes would strengthen the conclusion that the fuel tax creates a milder trade-off than the vehicle tax.

6. Conclusions

In this paper I have asked whether CO_2-based taxes on fuels or vehicles affect nitrogen oxides emissions, which harm air quality. Diesel fuel vehicles have lower CO_2 emissions rates than otherwise comparable gasoline vehicles, and CO_2-based fuel or vehicle taxes increase the market share of diesel fuel vehicles. Because regulation fixes nitrogen oxides emissions rates at higher levels for diesel fuel vehicles than gasoline vehicles, the shift toward diesel fuel vehicles would increase the market-wide average nitrogen oxides emissions rates. The larger the substitution across vehicle fuel types that the taxes induce, the greater the increase in nitrogen oxides emissions.

I estimated the extent of this substitution using highly detailed data on new passenger car registrations across most of Europe for the years 2002 through 2010. I compared within- and out-of-sample fit across a variety of specifications. The comparison demonstrates the importance of controlling for supply and demand shocks that are correlated with vehicle fuel costs and taxes and of allowing the effects of fuel costs and taxes to vary across vehicles. In the preferred specification, fuel costs induce less cross-fuel substitution than do vehicle taxes. These results suggest that existing CO_2-based vehicle taxes have increased nitrogen oxides emissions rates by more than would have a hypothetical carbon-based fuel tax increase that achieved the same CO_2 savings.

This paper has focused on the effects of CO_2-based taxation, for either vehicles or fuels, on emissions that harm air quality, between 2002 and 2010. During these years, manufacturers were preparing to meet future CO_2 emissions standards, and the analysis in this paper, as well as other recent research, suggests that CO_2-based vehicle taxes reduced CO_2 emissions rates. Assuming that the CO_2 emissions standards continue to bind, CO_2-based vehicle taxation should not affect CO_2 emissions rates in the future. However, with the binding standards, future CO_2-based vehicle taxes may increase the market share of diesel fuel vehicles, in which case they would harm local air quality for reasons similar to those identified in this paper.

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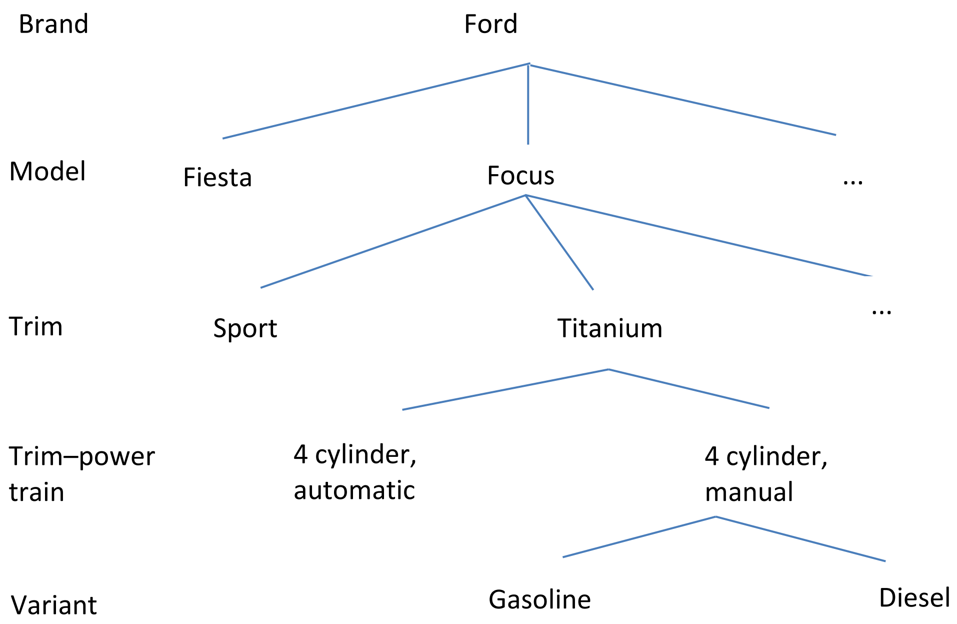
Figures and Tables

See following pages.

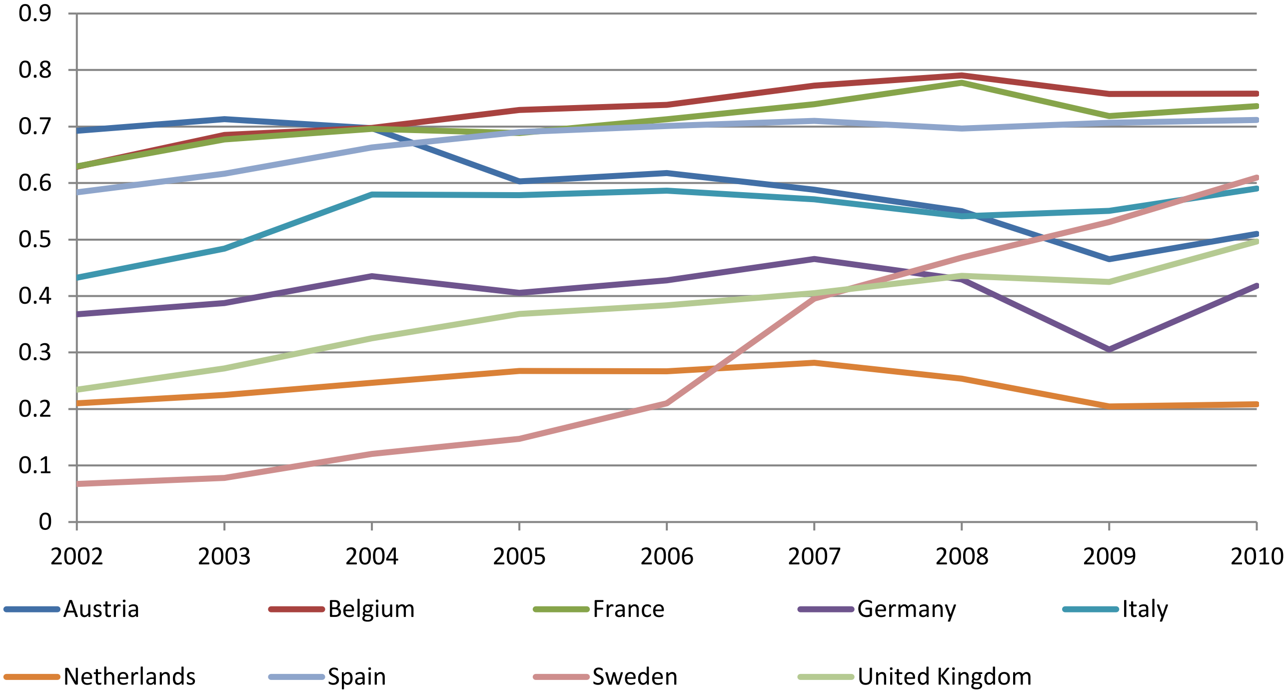
Figure 1. Vehicle Nomenclature



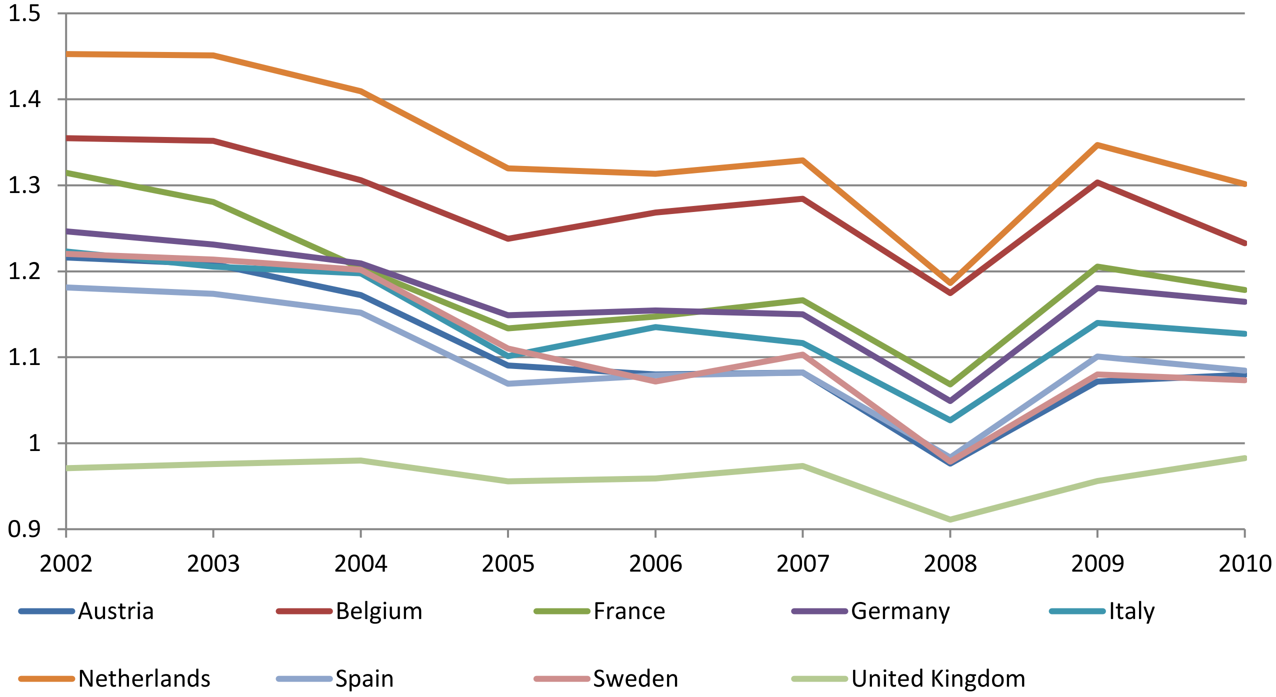
Notes: The figure provides a schematic representation of the vehicle nomenclature used in the paper. For each model sold under a particular brand, the trim indicates a unique model and trim name, body type, number of doors, number of wheels, and axle configuration. Trim–power trains are differentiated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

Figure 2. Market Share of Diesel Fuel Vehicles and Relative Fuel Prices by Country, 2002 - 2010.

Panel A: Diesel fuel vehicle market share

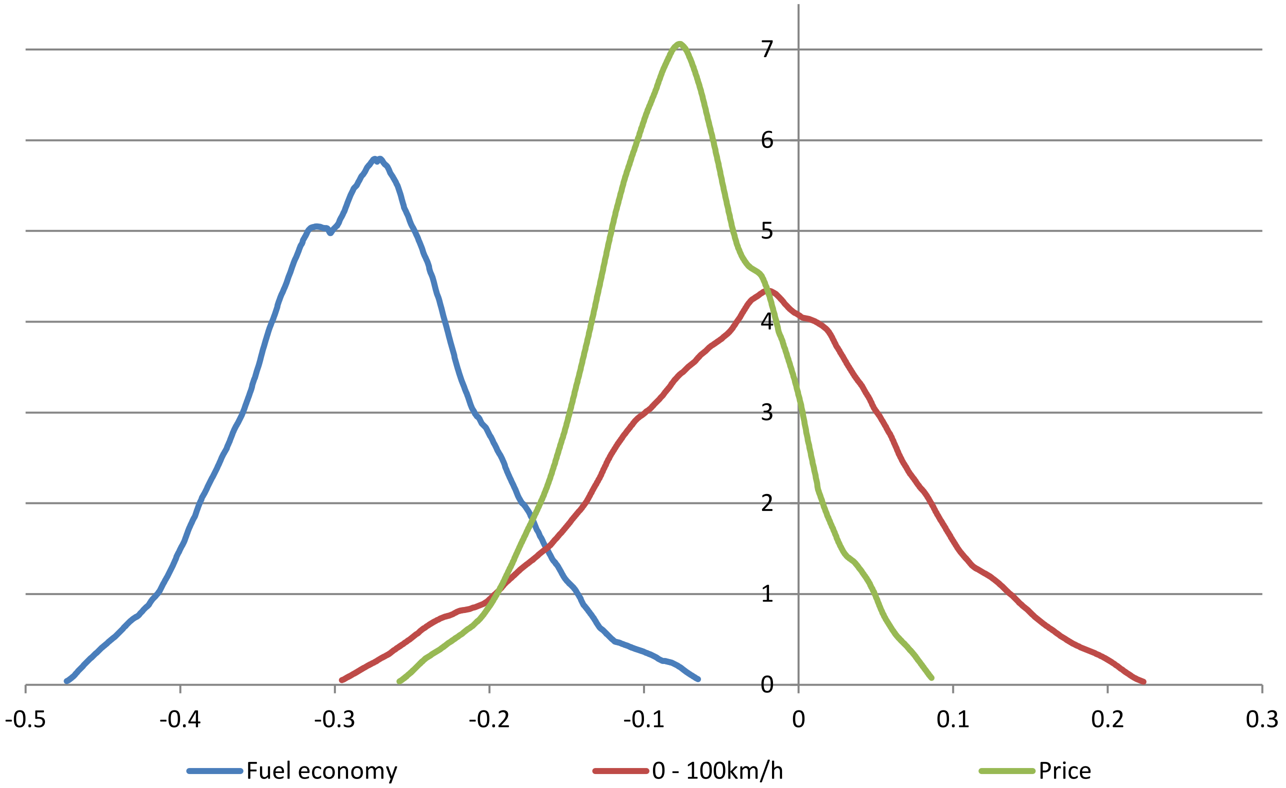


Panel B: Ratio of retail gasoline to diesel fuel price



Notes: Panel A plots the share of diesel fuel vehicle registrations in annual registrations by country for 2002-2010. Panel B plots the ratio of the retail gasoline price to the retail diesel fuel price by country and year.

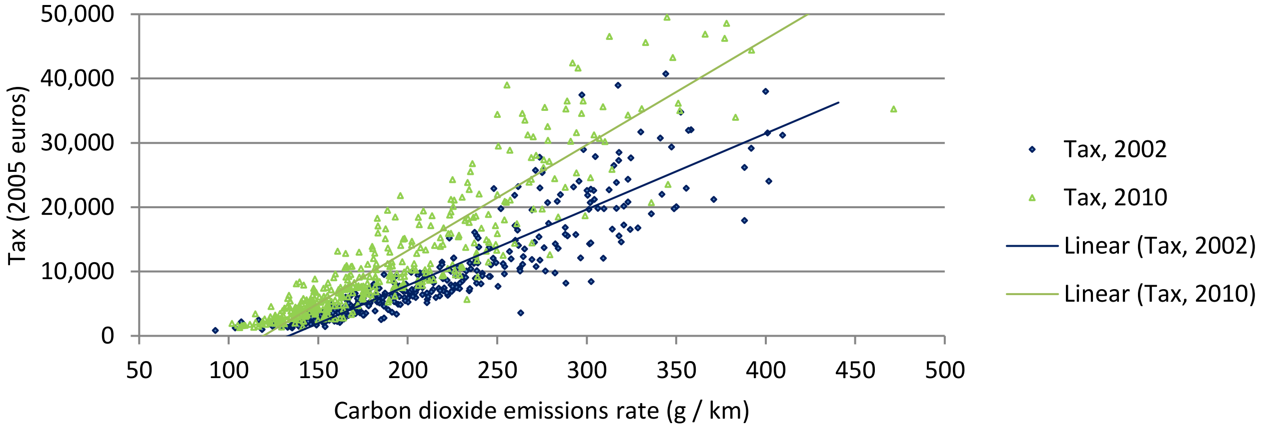
Figure 3. Estimated Density Functions of Differences between Gasoline and Diesel Fuel Variants



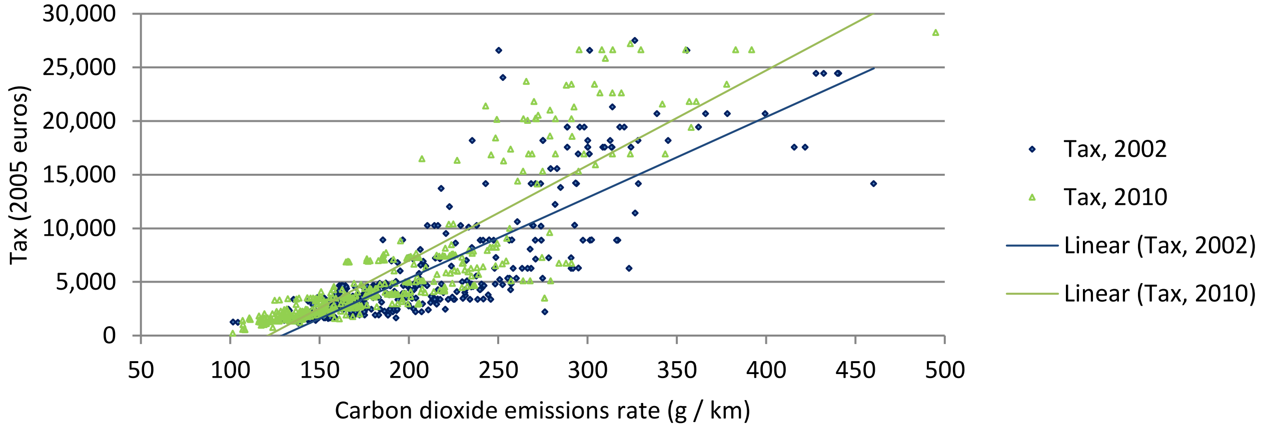
Notes: The sample includes trim–power trains with a gasoline and diesel fuel variant sold in the same country and year. The difference between the gasoline and diesel fuel variant is the log of the ratio of the characteristic (fuel economy, 0 to 100 kilometers per hour, or price) for the gasoline variant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

Figure 4. Vehicle Taxes and Carbon Dioxide Emissions Rates, 2002 and 2010

Panel A: Austria



Panel B: Belgium



Panel C: France

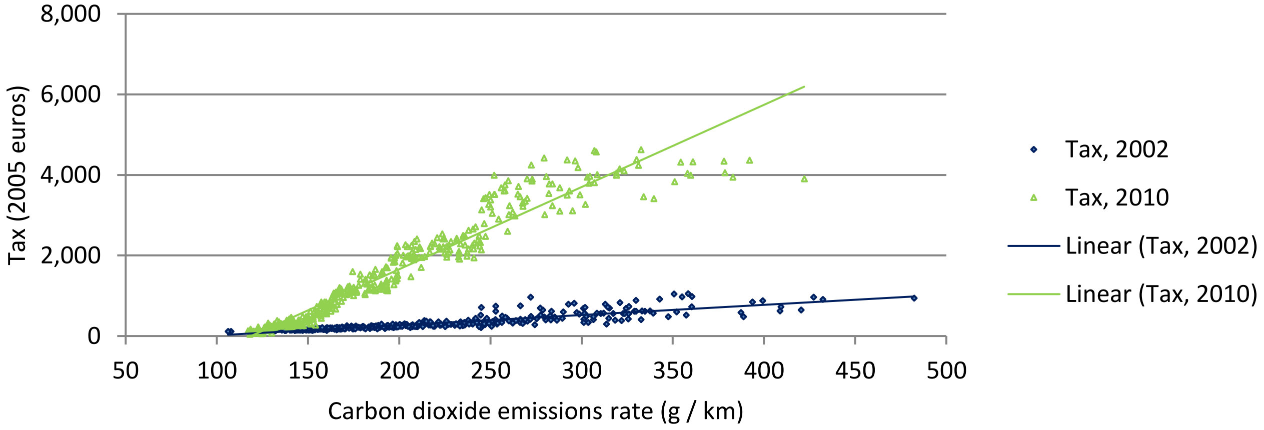
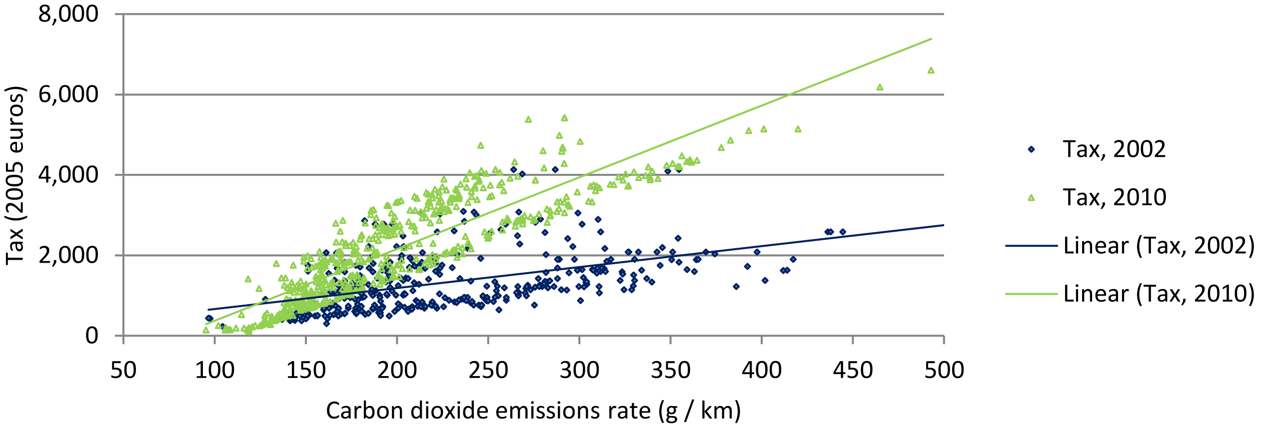
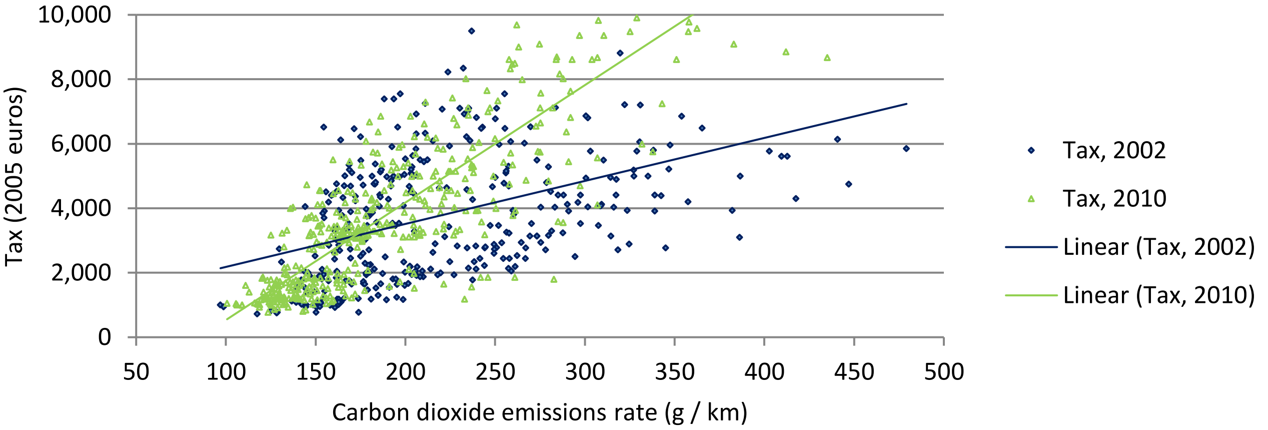


Figure 4 (continued)

Panel D: Germany



Panel E: Italy



Panel F: Netherlands

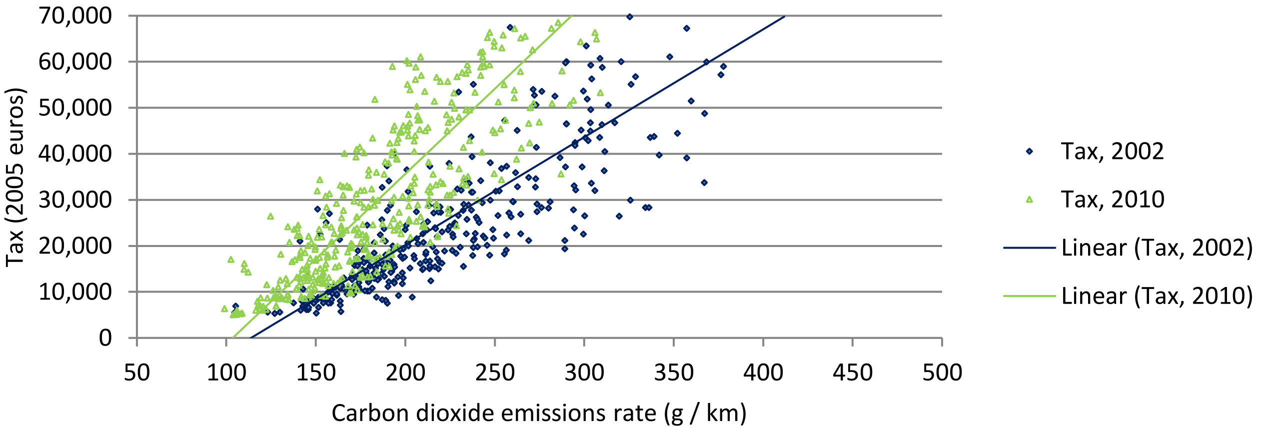
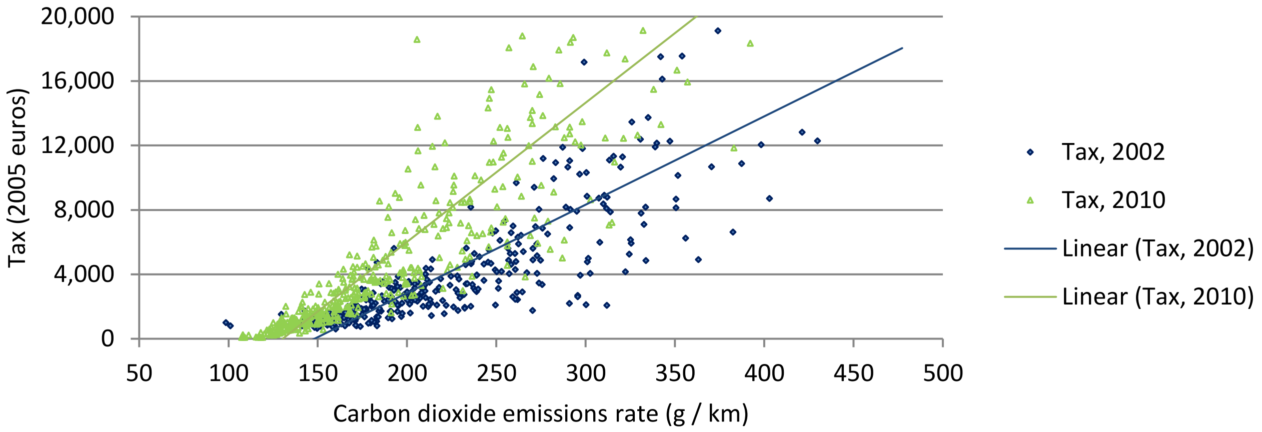
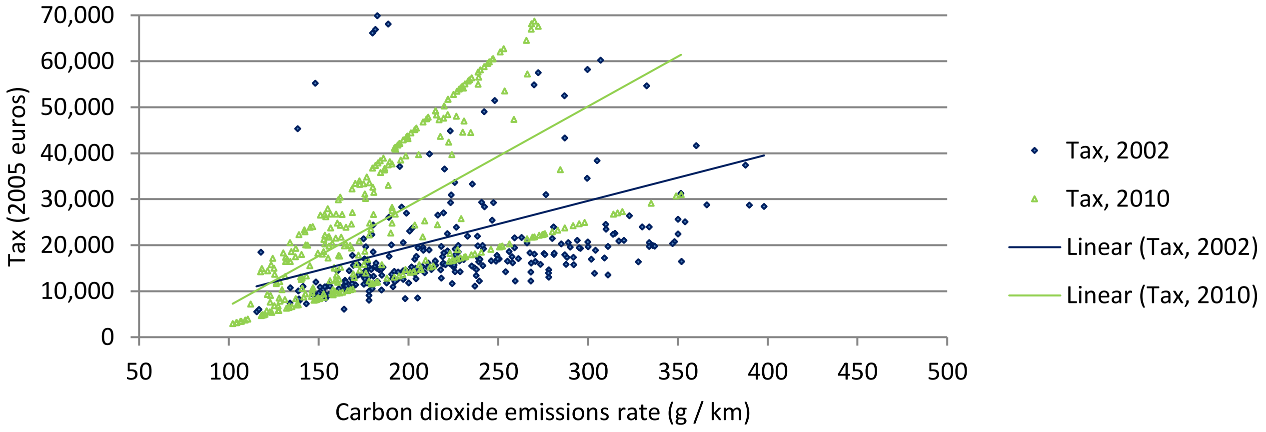


Figure 4 (continued)

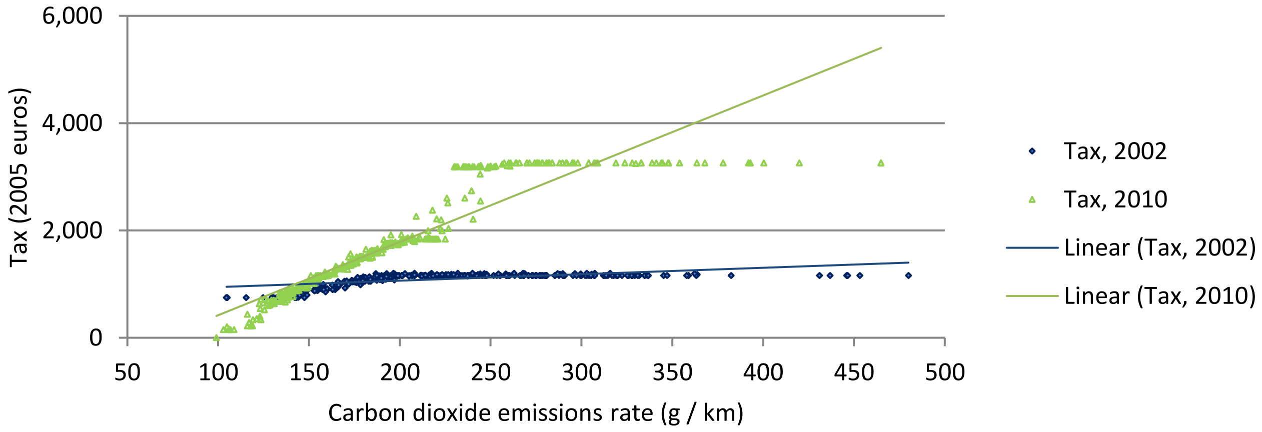
Panel G: Spain



Panel H: Sweden



Panel I: United Kingdom



Notes: Each panel plots the variant's tax in 2005 euros against its carbon dioxide emissions rate in g / km, for 2002 and 2010. The fitted values represent a linear regression of the tax on emissions rate.

Figure 5. Predicted Diesel Fuel Vehicle Market Share by Regression Model

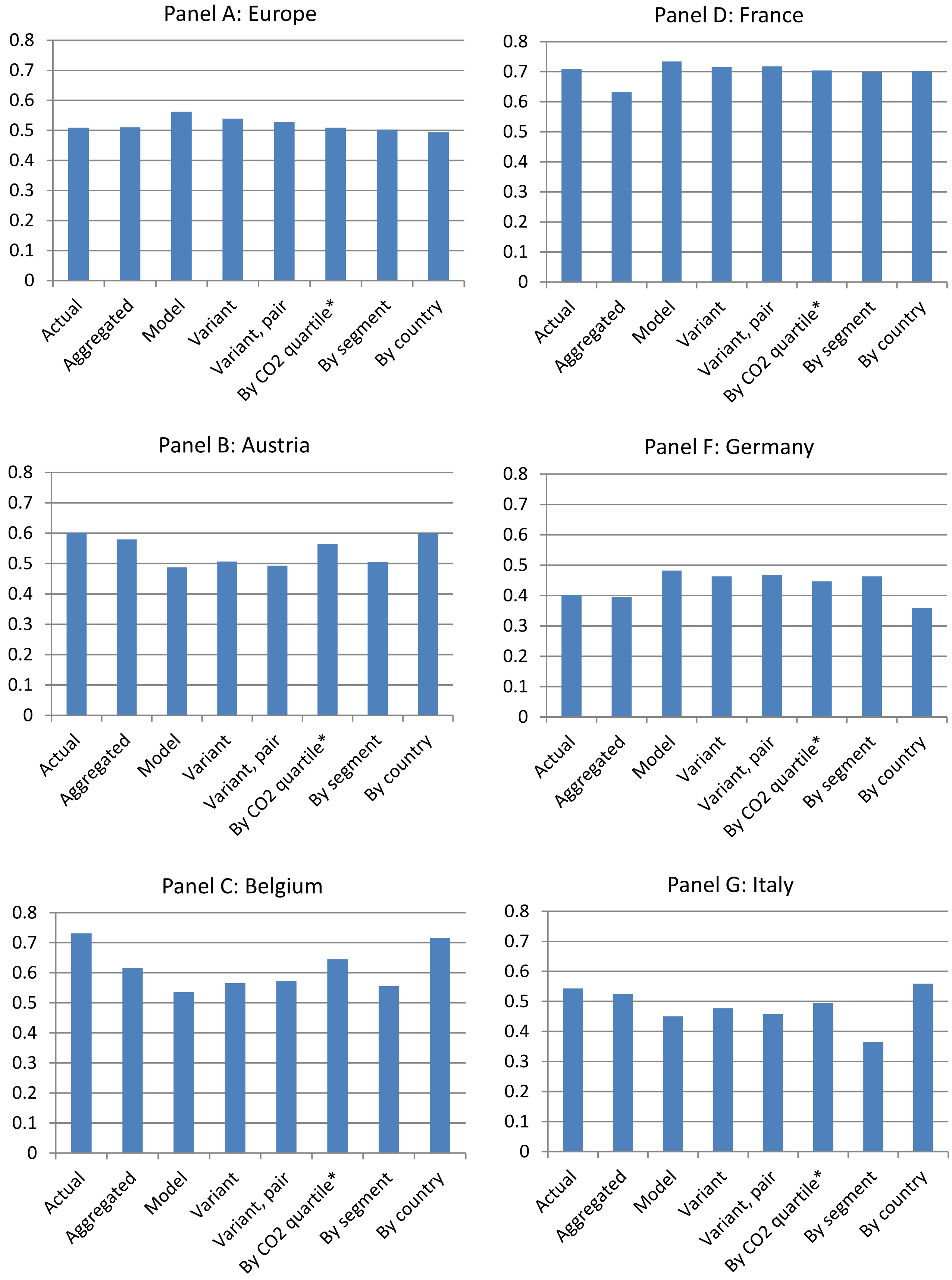
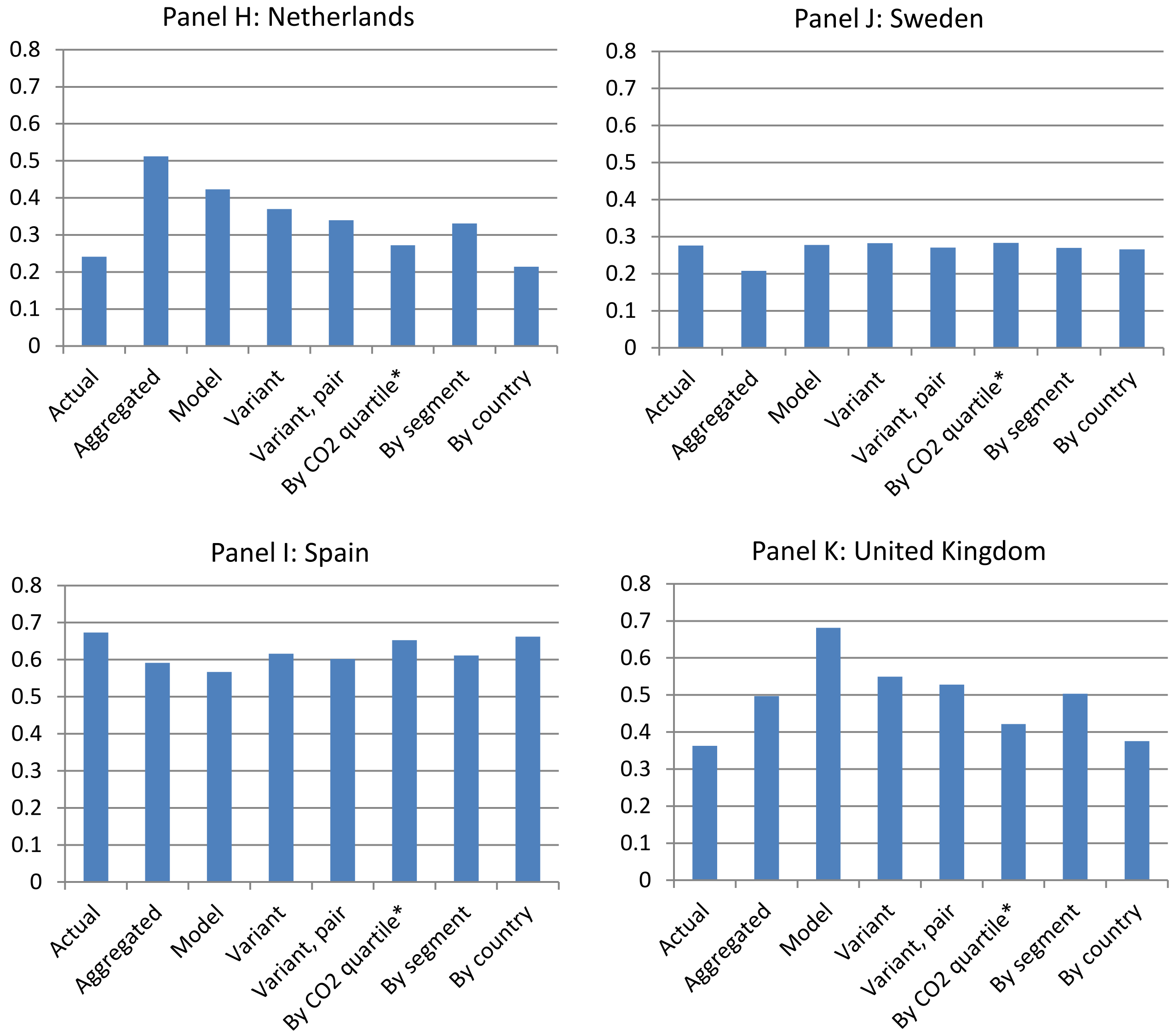


Figure 5 (continued)



Notes: The figure compares the actual and predicted market shares of diesel fuel vehicles across Europe (panel A) and by country (panels B through K). Each bar indicates the predicted market shares using the regression model indicated at the bottom of the panel. Aggregated refers to the regression reported in column 1 of Table 3; model to column 2 of Table 3; variant to column 3 of Table 3; variant, pair to column 4 of Table 3; by CO_2 quartile to panel A of Table 4; and by segment to panel B of Table 4. By country refers to estimating the regression in column 4 of Table 3 by country. The asterisk indicates that "by CO_2 quartile" is the preferred specification.

Table 1. Summary Statistics by Country

	(1) Average annual registration (millions)	(2) Diesel fuel vehicle market share	(3) CO_2 emissions rate (g / km)	(4) Average fuel costs of gasoline vehicles (euros / km)	(5) Average fuel costs of diesel fuel vehicles (euros / km)
Austria	0.28	0.60	161	7.14	5.69
Belgium	0.48	0.73	154	8.00	5.51
France	2.00	0.71	149	7.56	5.51
Germany	3.10	0.40	171	8.86	6.71
Italy	1.94	0.54	151	7.63	6.14
Netherlands	0.45	0.24	166	9.39	6.11
Spain	1.35	0.67	157	6.67	5.10
Sweden	0.22	0.28	185	9.11	7.19
United Kingdom	2.17	0.36	168	8.86	8.03

Notes: The table reports the summary statistics indicated in the column headings, for each country over the years 2002 through 2010. Emissions rates are reported in grams per kilometer (g / km) of carbon dioxide. Fuel costs are reported in 2005 euros per 100 km.

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

	(1) Dep var: log fuel economy	(2) Dep var: log 0 to 100 km/h
Austria	0.021 (0.001)	0.009 (0.000)
Belgium	0.025 (0.001)	0.011 (0.001)
France	0.021 (0.001)	0.004 (0.001)
Italy	0.018 (0.001)	0.003 (0.001)
Netherlands	-0.003 (0.001)	-0.003 (0.000)
Spain	0.015 (0.001)	-0.003 (0.001)
Sweden	-0.009 (0.001)	-0.016 (0.001)
United Kingdom	0.001 (0.001)	-0.002 (0.001)
Number of observations	326,720	326,720
R^2	0.83	0.96
Mean in Germany	33.06	10.24

Notes: The table reports coefficient estimates with standard errors in parentheses, clustered by country. 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, by variant and year. 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. Comparing Specifications: Effects of Fuel Costs, Acceleration Time, and Taxes on Registrations

	(1)	(2)	(3)	(4)
Dependent	Diesel share	Log registrations	Log registrations	Log registrations
Fuel costs	-0.789 (0.276)	-0.318 (0.026)	-0.262 (0.017)	-0.316 (0.025)
Diesel X fuel costs		0.314 (0.028)	0.119 (0.017)	0.146 (0.024)
Log 0 to 100 km/h time	-1.797 (0.418)	-1.364 (0.408)	0.400 (0.177)	-0.705 (0.341)
Diesel X log 0 to 100 km/h time		-0.605 (0.349)	-1.113 (0.188)	-1.584 (0.275)
Log vehicle tax	-0.263 (0.028)	-0.654 (0.052)	-0.474 (0.031)	-0.483 (0.042)
Diesel X log vehicle tax		-0.317 (0.018)	-0.260 (0.012)	-0.304 (0.016)
N	81	45,869	325,152	325,152
R^2	0.53	0.74	0.47	0.70
Aggregation level	Country X year	Country X model X fuel type X year	Country X variant X year	Country X variant X year
Fixed effects included in regression	Year	Model, country X year, fuel type	Model, body type, number of doors, driven wheels, transmission type, country X year, fuel type	Trim–power train, country X year, fuel type

Notes: The table reports regression coefficients with standard errors in parentheses, robust to heteroskedasticity in column 1 and clustered by model in columns 2 through 4. The dependent variable in column 1 is the share of diesel fuel vehicles in total registrations by country and year, and the dependent variable in columns 2 through 4 is the log of registrations. In column 1 the independent variables indicated in the row headings are the log ratio of the mean value for diesel fuel vehicles to the mean value of gasoline vehicles; in columns 2 through 4 the variables are computed using only the vehicle's own characteristics. The bottom two rows of the table indicate the level of aggregation and the fixed effects included in the regressions. In addition, column 3 includes a control for the vehicle's area, which is defined as the product of length and width.

Table 4. Effects of Fuel Costs, Acceleration Time, and Taxes on Registrations by Carbon Dioxide Emissions Quartile or Market Segment

	(1)	(2)	(3)	(4)
	Dependent variable is log registrations			
	Panel A: Estimation by CO_2 emissions quartile			
	First quartile (lowest)	Second quartile	Third quartile	Fourth quartile (highest)
Fuel costs	-0.235	-0.155	-0.227	-0.175
	(0.076)	(0.068)	(0.062)	(0.035)
Diesel X fuel costs	-0.130	0.102	0.019	0.083
	(0.067)	(0.060)	(0.040)	(0.031)
Log 0 to 100 km/h time	-0.329	-1.496	-1.922	-3.673
	(0.760)	(0.578)	(0.655)	(0.580)
Diesel X log 0 to 100 km/h time	-3.222	-0.953	-1.515	-0.035
	(0.812)	(0.591)	(0.485)	(0.471)
Log vehicle tax	-0.251	-0.547	-0.357	-0.268
	(0.062)	(0.106)	(0.111)	(0.091)
Diesel X log vehicle tax	-0.281	-0.298	-0.343	-0.354
	(0.040)	(0.046)	(0.049)	(0.042)
N	80,100	81,114	82,258	81,680
R^2	0.70	0.74	0.77	0.78
	Panel B: Estimation by market segment			
	Small and mini	Lower medium	Medium	Upper medium/large
Fuel costs	-0.391	-0.190	-0.188	-0.121
	(0.052)	(0.054)	(0.039)	(0.029)
Diesel X fuel costs	-0.184	-0.045	-0.019	0.032
	(0.071)	(0.049)	(0.030)	(0.031)
Log 0 to 100 km/h time	-0.990	-1.192	-2.892	-3.888
	(0.645)	(0.435)	(0.549)	(0.900)
Diesel X log 0 to 100 km/h time	-1.180	-0.390	0.851	-0.031
	(0.576)	(0.430)	(0.366)	(0.516)
Log vehicle tax	-0.351	-0.623	-0.677	-0.504
	(0.049)	(0.058)	(0.064)	(0.090)
Diesel X log vehicle tax	-0.329	-0.303	-0.373	-0.366
	(0.028)	(0.030)	(0.026)	(0.028)
N	62,233	93,289	113,086	56,544
R^2	0.67	0.65	0.72	0.74

Notes: The table reports regression coefficients with standard errors in parentheses, clustered by model. The specifications are the same as in column 4 of Table 3, except that the samples are restricted to variants in the groups indicated by the row headings. Panel A defines groups based on CO_2 emissions quartile, with the first quartile corresponding to the lowest emissions rate. Panel B defines groups based on market segment.

Table 5. Estimates by Country

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
					Dependent variable is log registrations				
	Austria	Belgium	France	Germany	Italy	Netherlands	Spain	Sweden	UK
Fuel costs	-0.200 (0.062)	-0.372 (0.052)	-0.407 (0.058)	-0.549 (0.057)	-0.411 (0.060)	-0.200 (0.054)	-0.392 (0.062)	-0.405 (0.052)	-0.307 (0.044)
Diesel X fuel costs	-0.298 (0.046)	0.119 (0.042)	0.141 (0.043)	0.249 (0.036)	0.220 (0.061)	-0.004 (0.033)	0.149 (0.037)	0.449 (0.044)	0.122 (0.036)
Log 0 to 100 km/h time	-1.601 (0.690)	0.511 (0.522)	-1.077 (0.479)	-2.097 (0.498)	-1.513 (0.677)	-0.540 (0.414)	-2.084 (0.515)	-0.808 (0.592)	-0.315 (0.475)
Diesel X log 0 to 100 km/h	4.645 (0.508)	0.277 (0.401)	-0.401 (0.384)	-0.368 (0.376)	0.236 (0.571)	0.403 (0.342)	1.131 (0.358)	-0.559 (0.406)	-1.080 (0.383)
Log vehicle tax	-1.278 (0.445)	-0.797 (0.200)	-0.452 (0.061)	-0.528 (0.151)	-0.524 (0.287)	-1.076 (0.304)	-0.667 (0.106)	-0.166 (0.299)	-1.712 (0.161)
Diesel X log vehicle tax	3.103 (0.253)	0.399 (0.170)	0.272 (0.068)	0.922 (0.263)	1.132 (0.282)	1.799 (0.241)	0.610 (0.107)	-1.184 (0.258)	1.656 (0.197)
N	33,305	32,959	44,438	47,013	32,916	46,056	30,014	20,166	38,285
R^2	0.69	0.69	0.73	0.67	0.74	0.68	0.71	0.65	0.67

Notes: The table reports regression coefficients with standard errors in parentheses, clustered by model. The specifications are the same as in column 4 of Table 3, except that the samples are restricted to the countries indicated in the column headings.

Table 6. Comparing Prediction Error across Specifications

	(1)	(2)	(3)	(4)
	Panel A: Full sample		Panel B: 90 percent subsample	
	Standard deviation of dependent variable	RMS prediction error	RMS difference between predicted values from full sample and subsample	RMS out-of-sample prediction error
Aggregated	0.20	0.13	0.01	0.15
Model	2.57	1.31	0.16	0.80
Variant	2.15	1.56	0.06	0.64
Variant, pair	2.15	1.17	0.19	0.64
By CO_2 quartile	2.15	1.02	0.16	0.65
By segment	2.15	1.14	0.16	0.70
By country	2.15	1.12	0.20	0.91

Notes: Each row reports summary statistics for the regression model indicated in the row heading. Panel A reports statistics from specifications that include the full samples from Tables 3 through 5, and Panel B reports statistics from specifications that include a randomly selected 90 percent of the observations from the full sample. Column 1 reports the standard deviation of the dependent variable. Column 2 reports the square root of the mean (RMS) square prediction error from the corresponding regression. Column 3 reports the root mean square difference between the predicted values from the full sample and 90 percent subsample. Column 4 reports the out-of-sample prediction error using estimates from the 90 percent subsample.

Table 7. Effects of a Vehicle Carbon Dioxide Emissions Rate Tax on Diesel Market Shares and Emissions Rates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Diesel fuel vehicle market share			CO_2 emissions rate (g / km)			Nitrogen oxides emissions rate (g / km)		
	Observed	Counter-factual	Percent change	Observed	Counter-factual	Percent change	Observed	Counter-factual	Percent change
Austria	0.60	0.62	2.21	162	161	-0.13	0.132	0.134	1.21
Belgium	0.65	0.68	5.01	156	155	-0.58	0.138	0.142	2.83
France	0.67	0.70	5.11	153	151	-1.69	0.140	0.144	2.93
Germany	0.43	0.53	23.99	172	169	-1.80	0.111	0.123	11.04
Italy	0.48	0.53	10.02	151	149	-1.08	0.118	0.123	4.91
Netherlands	0.30	0.30	2.85	168	168	-0.15	0.096	0.097	1.06
Spain	0.66	0.69	4.27	157	157	-0.16	0.140	0.143	2.43
Sweden	0.30	0.31	4.03	186	186	-0.14	0.096	0.097	1.50
United Kingdom	0.42	0.44	4.49	169	167	-1.52	0.110	0.113	2.05
Europe	0.50	0.54	7.11	162	161	-1.02	0.121	0.125	3.57

Notes: The table reports the results of a hypothetical feebate that sets country-specific pivots equal to the registrations-weighted average CO_2 emissions rate, and an emissions rate price of 20 euros per g CO_2 / km. Columns 1, 4, and 7 report the predicted diesel fuel market shares, CO_2 emissions rates, and nitrogen oxides emissions rates using the observed taxes, the full 2002-2010 sample, and the regression model from Panel A of Table 4. Columns 2, 5, and 8 report the predicted shares and emissions rates if the feebate were added to observed taxes, and using the same regression model.

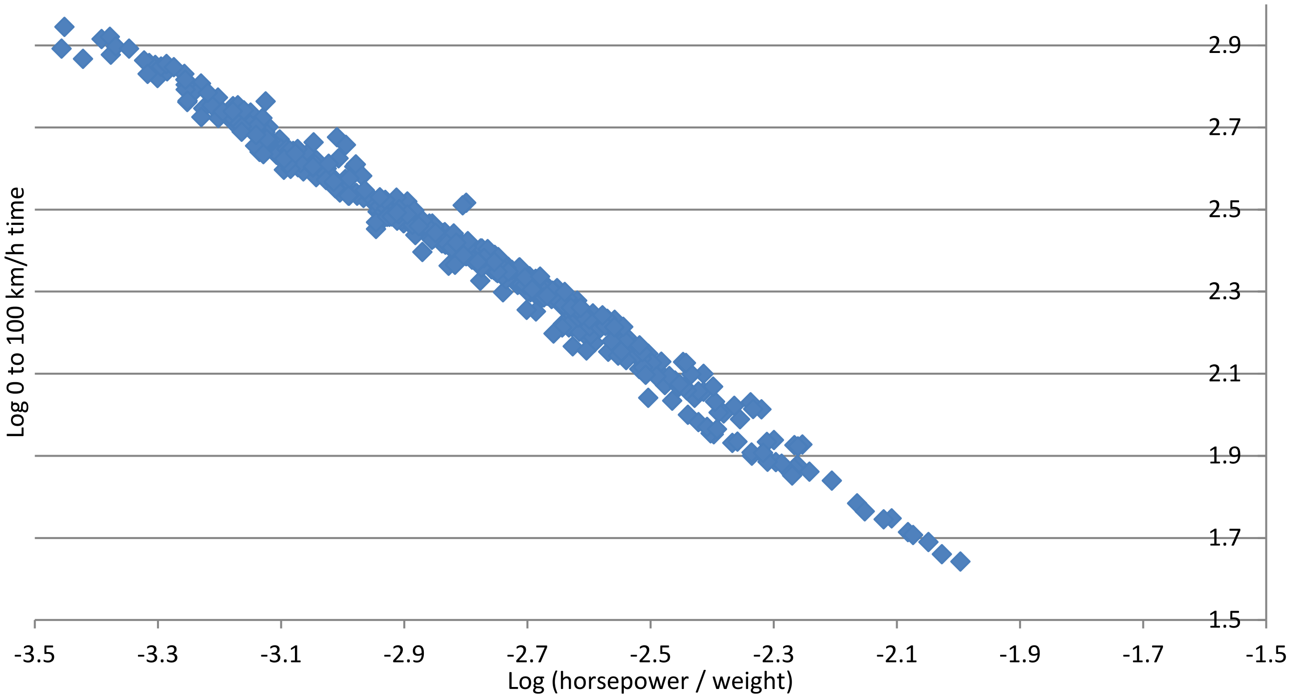
Table 8. Effects of a Carbon-Based Fuel Tax on Diesel Market Shares and Emissions Rates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Diesel fuel vehicle market share			CO_2 emissions rate (g / km)			Nitrogen oxides emissions rate (g / km)		
	Observed	Counter-factual	Percent change	Observed	Counter-factual	Percent change	Observed	Counter-factual	Percent change
Austria	0.60	0.60	0.09	162	160	-0.94	0.132	0.132	0.05
Belgium	0.65	0.65	0.12	156	154	-0.86	0.138	0.138	0.07
France	0.67	0.67	0.38	153	152	-0.79	0.140	0.141	0.22
Germany	0.43	0.43	0.87	172	170	-0.99	0.111	0.112	0.40
Italy	0.48	0.48	-0.54	151	150	-0.81	0.118	0.117	-0.27
Netherlands	0.30	0.30	0.72	168	167	-1.03	0.096	0.096	0.27
Spain	0.66	0.67	0.86	157	156	-0.91	0.140	0.140	0.49
Sweden	0.30	0.30	1.63	186	184	-0.97	0.096	0.096	0.61
United Kingdom	0.42	0.43	1.48	169	168	-1.06	0.110	0.111	0.68
Europe	0.505	0.509	0.83	162.4	160.7	-1.02	0.1206	0.1211	0.42

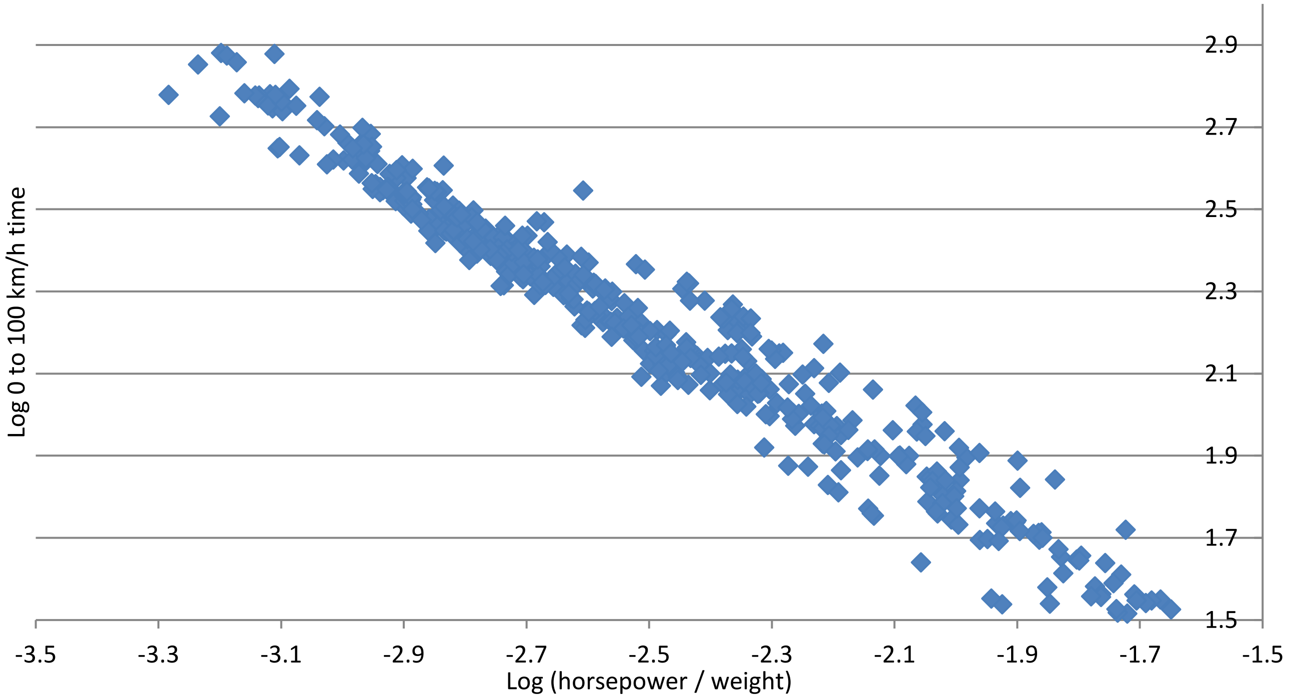
Notes: The table reports the results of a hypothetical carbon tax imposed on fuels of 14.40 euros per metric ton of CO_2. Columns 1, 4, and 7 report the predicted diesel fuel market shares, CO_2 emissions rates, and nitrogen oxides emissions rates using the observed fuel prices, the full 2002-2010 sample, and the regression model from Panel A of Table 4. Columns 2, 5, and 8 report the predicted shares and emissions rates if fuel prices were 10 percent higher than observed, and using the same regression model.

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

Panel A: Diesel fuel cars



Panel B: Gasoline cars



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 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 (0.012)	-0.816 (0.013)
Manual transmission	0.005 (0.004)	-0.017 (0.006)
All-wheel drive	0.033 (0.006)	0.036 (0.014)
Front-wheel drive	0.038 (0.005)	0.036 (0.008)
Log height	0.189 (0.030)	0.482 (0.058)
3 cylinders	0.208 (0.029)	0.120 (0.011)
4 cylinders	0.086 (0.011)	0.039 (0.006)
5 cylinders	0.098 (0.011)	0.045 (0.019)
6 cylinders		0.100 (0.016)
Constant	-1.236 (0.205)	-3.439 (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. Estimates by Country, without Fuel Type Interactions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
					Dependent variable is log registrations				
	Austria	Belgium	France	Germany	Italy	Netherlands	Spain	Sweden	UK
Log fuel costs	-0.398 (0.049)	-0.437 (0.020)	-0.499 (0.024)	-0.425 (0.028)	-0.502 (0.030)	-0.167 (0.023)	-0.485 (0.029)	-0.265 (0.048)	-0.244 (0.041)
Log 0 to 100 km/h time	0.334 (0.762)	0.420 (0.482)	-1.764 (0.536)	-3.140 (0.573)	-2.029 (0.659)	-1.260 (0.400)	-1.848 (0.541)	-1.215 (0.656)	-0.960 (0.584)
Log vehicle tax	0.146 (0.561)	-0.694 (0.145)	-0.283 (0.059)	-1.479 (0.134)	-0.107 (0.099)	-3.269 (0.254)	-0.121 (0.052)	-1.243 (0.143)	-0.190 (0.151)
N	33,305	32,959	44,438	47,013	32,916	46,056	30,014	20,166	38,285
R^2	0.66	0.69	0.73	0.65	0.73	0.67	0.70	0.63	0.65

Notes: The table reports regression coefficients with standard errors in parentheses, clustered by model. The specifications are the same as in Table 5, except that the fuel type interactions and diesel indicator variable are omitted.