Innovation, Emissions Policy, and Competitive Advantage in the Diffusion of European Diesel Automobiles *

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Abstract

Import tariffs have decreased significantly over the past 30 years due to a large number of economic integration agreements. We investigate whether national policies, such as environmental regulations, can be an effective replacement to protect domestic industry. Our focus is the European automobile market where diesel vehicles are dominant and emissions policy favors these vehicles. We estimate a discrete choice, oligopoly model of horizontally differentiated products using changes in observed product characteristics to identify the underlying demand and cost parameters while allowing for correlation between observed and unobserved (to the researcher) product characteristics. We find diesels were an important competitive advantage for European automakers over foreign imports during our sample. Further, EU emissions policy favored diesels and amounted to a significant non-tariff trade policy equivalent to a 13-16% import tariff. Imposing product characteristic exogeneity in the estimation leads the researcher to over-state these effects.

Keywords: Trade Policy, Import Tariff Equivalence, Diesel Cars, Emission Standards.

JEL Codes: O33, L62, F13.

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1 Introduction

The proliferation of economic integration agreements (EICs) – particularly free trade agreements – is a significant feature of the global economy over the past 30 years (Bergstrand, Larch and Yotov, 2015). Such agreements are valuable as they enable countries to credibly commit to lowering trade barriers both today and in the future, effectively tying the hands of future governments. There is increasing interest, therefore, in understanding the degree to which seemingly innocuous national policies can be an effective tool for protecting domestic industry given that traditional trade barriers have been negotiated into non-existence (Bagwell and Staiger, 2001; Ederington and Minier, 2003). In this paper we estimate an equilibrium oligopoly model for automobiles to evaluate the tariff protection equivalence of domestic environmental regulation which had the effect of favoring domestic firms.

Our setting is the European marketplace where diesel vehicles are dominant and emissions policy targets the greenhouse gases carbon monoxide (CO) and carbon dioxide (CO_2) but not nitrogen oxide (NO_x).[1] This distinction is important as the policy appears to favor diesel cars which produce a large amount of NO_x emissions and little CO and CO_2 while gasoline engines do just the opposite. Hence, the gasoline vehicles exported to Europe by foreign firms faced stricter standards (likely increasing their production costs) than the diesel vehicles produced predominantly by domestic automakers. The natural question then is whether the vehicle emissions policy employed by the European Union protected the domestic auto industry from foreign competition?

Using detailed automobile registration data from Spain – a country with diesel adoption rates representative of Europe – we estimate a structural discrete choice oligopoly model similar to Berry, Levinsohn and Pakes (1995), henceforth *BLP*, to study an industry which is far from competitive and where products are horizontally differentiated. The *BLP* framework has become a workhorse model in the empirical Industrial Organization literature as it is flexible enough to generate reasonable substitution patterns between similar products while accounting for product characteristics known to consumers and firms but not to the researcher. For our purposes, the estimated model provides a laboratory to explore the equilibrium effects of more rigorous NO_x emissions policies which we model as an increase in the marginal costs of production required to reduce diesel NO_x emissions. We call these additional costs "abatement costs."

In estimating the model we allow for correlation between observable and unobservable automobile characteristics using the firms' first-order conditions for profit-maximization as moment conditions (Petrin and Seo, 2016) and add exogenous macroeconomic shocks to demand and

[1] While the contribution of CO_2 to global warming is well-documented, the role of CO as a greenhouse gas is weaker though still relevant (see `http://tes.jpl.nasa.gov/mission/climateroles`).

supply to aid in the identification of key parameters. The idea is straightforward. Each period firms choose product attributes, observed or otherwise, to maximize profits. Though firms may have different beliefs or information regarding competitors' attribute choices, they all understand that their attribute choices influence equilibrium prices of automobile manufacturers through own and cross-price effects. The first-order conditions implied by the Bayes-Nash equilibrium provide moment conditions to estimate the structural demand and cost parameters. Intuitively, a firm's choice to make both larger (observable to the researcher) and more reliable cars (*unobservable* to the researcher) provides information about consumer preferences and production costs for both attributes even though vehicle reliability, for example, can only be inferred by consumer purchases conditional on observable characteristics.

Our results indicate the pro-diesel emissions policy did indeed amount to a significant trade policy. For even moderate levels of abatement costs firms maximize profits by increasing diesel prices and consumers respond by shifting consumption towards fuel-efficient gasoline engines produced by foreign automakers. In other words, had the EU chosen a more rigorous NO_x standard, the popularity of diesels and the inherent competitive advantage they provided domestic automakers would have decreased significantly, leading to an increase in imports from primarily Asian car manufacturers.

Only by imposing an import tariff of between $13 - 16\%$ could EU regulators have pushed import penetration back to the level observed under the current EU emissions policy. This indicates the pro-diesel EU emissions policy amounted to a significant non-tariff trade policy as it had a disproportionately positive impact on those firms which had invested to offer diesels, namely domestic automakers. We further show that ignoring the correlation between observable and unobservable product characteristics in the estimation would have led us to significantly over-state estimated markups and the profitability of diesels to European firms. The effect on the implicit import tariff is less stark, however, particularly for small abatement costs.

A unique feature of our data set is that it captures the rapid consumer adoption of next generation diesel engines. Diesels were now significantly quieter, cleaner (*i.e.*, no black smoke), and more reliable than their predecessors while maintaining superior fuel efficiency and torque relative to comparable gasoline models. Our structural model then enables us attribute the diffusion of diesel vehicles to observable characteristics such as price and unobservable factors such as customers learning about these next generation diesel vehicles. Our estimates indicate that customer learning did play a role in the diffusion of diesels, therefore imposing more rigorous NO_x standards early in the diffusion of this innovation not only would have limited contemporaneous diesel sales but also would have decreased future demand for diesels. Further, we find this channel has large quantitative

implications as it nearly doubles the equivalent import tariff implied by EU emissions policy (from 13% to 24%).

We address the robustness of our results in two ways. First, we acknowledge that any national policy which favors diesel vehicles has the potential to promote domestic automakers over foreign competitors. One such policy we evaluate is the role of fuel excise taxes in promoting diesels – a policy often cited to explain diesel popularity in the region.[2] Contrary to popular conception, however, we find this effect is small.

Second, we appeal to recent emissions scandals as perhaps our most telling support as Volkswagen's admission to cheating on EPA NO_x emissions standards in its American diesel fleet will likely result in the effective disappearance of diesel vehicles from the US market for a second time in two decades due to failure to meet American emission standards.[3] In contrast the firm's admission to also cheating on *European* emissions policy since 2004 resulted in EU regulators choosing to change the rules; increasing the NO_x ceiling facing cars sold in Europe and committing itself to not revisiting the policy until 2019. We view this as stark evidence that the NO_x emissions policy employed in Europe was intimately related to the health of at least Volkswagen, if not all European automakers.

While it is tempting to view our results as an indictment of European emissions regulation, our intention is not to make a normative statement about Pareto optimality nor are we claiming that European regulators explicitly designed their emission standards to promote domestic automakers. Our point is that regardless of whether it was the intent of the policymaker or not, *the effect* of the environmental policy was to protect domestic European automakers by encouraging a "home bias" by domestic consumers. More generally, this episode provides confirmation that national policies can indeed be an effective substitute for traditional trade barriers such as import tariffs.

The remaining paper is organized as follows. In Section 2, we provide a brief review of related literature. In Section 3, we describe the growth of diesel vehicles in Europe, while in Section 4 we document differences in emissions policy between the US and EU. Section 5 describes the equilibrium model of discrete choice demand for horizontally differentiated products. Section 6 describes the estimation approach, discusses identification, and reports the estimation results in comparison to those implied by the standard *BLP* estimation strategy. In Section 7, we use the estimated model to quantify the equilibrium implications of alternative emissions policy on

[2] Our model is also sufficiently flexible to evaluate the role of preferential vehicle registration taxes based on engine type though such taxes did not exist in Spain during our sample.

[3] On September 18th, 2015 the United States Environmental Protection Agency (EPA) accused Volkswagen of devising a sophisticated scheme to deceive environmental authorities when testing for nitrogen oxide (NO_x) emissions. The notice of violation, and Volkswagen's subsequent admission, translated into an immediate 20% drop in the stock market value of VW shares due to concerns about the company's credibility as well as an estimated $18 billion in fines.

the European automobile industry. In Section 8, we evaluate the implications to our results of assuming product exogeneity. Finally, Section 9 summarizes our results and contribution as well as discusses avenues for future research. Details of the estimation, additional results, data sources, and institutional details of the Spanish automobile market are documented in the Appendix.

2 Related Literature

As our objective is to evaluate the tariff protection equivalence of domestic environmental regulation, the paper lies at the intersection of international trade and industrial organization – a rich history dating back to Krugman (1980) and more recently Eaton and Kortum (2002) and Melitz (2003). The focus of many researchers in this area has historically been on the role of explicit trade policies in shaping industries. An important example in the automobile industry is the voluntary export restraints placed on Japanese cars during the 1980s and early 1990s. Feenstra (1988) documents significant quality-upgrading by Japanese firms leading to the growth of luxury brands Acura, Infiniti, and Lexus in the US market. Berry, Levinsohn and Pakes (1999) show this policy increased profits for domestic firms and decreased welfare for domestic consumers while leaving significant tariff revenue on the table.

While the most popular tool to distort trade flows has been historically import tariffs, multilateral negotiations have largely driven these to zero. The result has been a growing empirical literature documenting the effects of trade liberalization on firm behavior. For example, Edmond, Midrigan and Xu (2015) evaluate the competitive effects of international trade on the Taiwanese electronics industry finding that foreign competition decreases misallocation and markups. Aw, Roberts and Xu (2011) find empirical evidence that international markets also provide incentive for firms to innovate.

Interest in the trade literature about the degree to which domestic policy may be an effective replacement for tariffs dates back to the seminal theoretical contribution by Bhagwati and Ramaswami (1963) and more recently by Ederington and Minier (2003). Other researchers (*e.g.*, Staiger 1995, Bagwell and Staiger 2001, Deardorff 1996, Thurk 2014) take a more game theoretic approach and show that countries can use their domestic policies to extract rents from the rest-of-the-world leading to a suboptimal aggregate outcome. Our contribution then is to provide quantitative evidence of the substitutability between import tariffs and domestic policy.

We also show that a non-tariff domestic policy which promotes the adoption of domestic innovations (or of innovations uniquely preferred by domestic consumers) can have a significant effect on trade by influencing demand while tariffs just target price. This is a novel insight since such a policy may be welfare improving whereas tariffs are generally thought to be welfare decreasing.

We, of course, are not the first to note that government policy, particularly environmental, can have differential impacts on domestic and foreign firms; *e.g.*, Jacobsen (2013), Goldberg (1998) and Ito and Sallee (2015) show the introduction of corporate average fuel economy (CAFE) standards in the United States favored foreign over domestic firms. Our contribution is to demonstrate that national policies such as environmental regulation can be an effective substitute for traditional trade barriers made unavailable through international agreements.

Finally, the paper contributes to the current discussion on identification and estimation of *BLP* models by showing the practical repercussions of ignoring potential correlation between observable and unobservable product attributes. An important identification assumption used in a standard *BLP* estimation is that observable and unobservable product characteristics are uncorrelated. Given the paucity of observable characteristics – a common trait of *BLP* models – it seems plausible that unobservable characteristics are quantitatively important factors in determining consumer purchases as well as correlated with the observable characteristics either in the cross-section or across time.[4] Assuming exogeneity, therefore, may introduce quantitatively significant biases into the estimation and subsequent policy experiments – a hypothesis which we test. Perhaps not surprisingly, we do find significant correlation between the product characteristics we observe and the unobserved product characteristics needed to reconcile consumer purchases. We also find that our estimation approach yields demand estimates which are more elastic than employing a standard *BLP* estimation as well as more reasonable and significant point estimates – a similar finding to Petrin and Seo (2016).

3 The European Market for Diesel Automobiles in the 1990s

This section familiarizes the reader with the basic characteristics of the diesel technology; the institutional features of the European market that allowed for a swift take off of diesel sales in the early 1990s; and the evolution of the Spanish market.

3.1 A Significant Innovation - Next Generation Diesel Engines

In the late 19th century, Rudolf Diesel designed an internal combustion engine in which heavy fuel self-ignites after being injected into a cylinder where air has been compressed to a much higher degree than in gasoline engines. However, it was only in 1927, many years after Diesel's death, that the German company Bosch built the injection pump that made the development of the engine for trucks and automobiles possible. The first diesel vehicles sold commercially followed soon after: the

[4] Crawford (2012) presents a recent overview of the challenges of fully addressing the endogeneity of product attributes in discrete choice models of demand.

1933 Citroën Rosalie and the 1936 Mercedes-Benz 260D. Large passenger and commercial diesel vehicles were common in Europe from the late 1950s through the 1990s.

In 1989, Volkswagen introduced the turbocharged direct injection (TDI) diesel engine in its Audi 100 model, a substantial improvement over the existing Perkins technology. A TDI engine uses a fuel injector that sprays fuel directly into the combustion chamber of each cylinder.[5] The turbocharger increases the amount of air going into the cylinders and an intercooler lowers the temperature of the air in the turbo, thereby increasing the amount of fuel that can be injected and burned. Overall, TDI allows for greater engine performance while providing more torque at low r.p.m. than alternative gasoline engines. They are also credited with being more durable and reliable than gasoline engines although this was something yet to be learned by consumers at the time this technology was first introduced.[6] Following this major technological breakthrough, European manufacturers other than VOLKSWAGEN improved their diesel engines and European drivers enthusiastically embraced diesel automobiles. The incredible pace of adoption of diesel automobiles suggests that the TDI proved to be a significant technological advance and consumers gained little from waiting for additional incremental improvements, which have been few and of minor importance.[7]

3.2 Initial Market Conditions

There are important institutional circumstances that helped build the initial conditions that were particularly favorable for the adoption of this new technology in Europe. The key element triggering all these favorable development is the *European Fuel Tax Directive* of 1973. Following the first oil crisis of 1973, the then nine members of the European Economic Community gathered in Copenhagen in December of that year and agreed to develop a common energy policy. A main idea was to harmonize fuel taxation across countries so that drivers, and fossil fuel users in general, faced a single and consistent set of incentives to save energy. Coordination also limited the possibility of arbitrage across state lines as well as some countries free riding on the conservation efforts of other members. Fuel prices or their taxation were not harmonized overnight but the new Tax Directive offered principles of taxation that were eventually followed in every country. For the purposes of this study, the two most prominent features of this Directive are that fuels are taxed by volume rather than by their energetic content and that diesel fuel is taxed at a lower rate than gasoline.

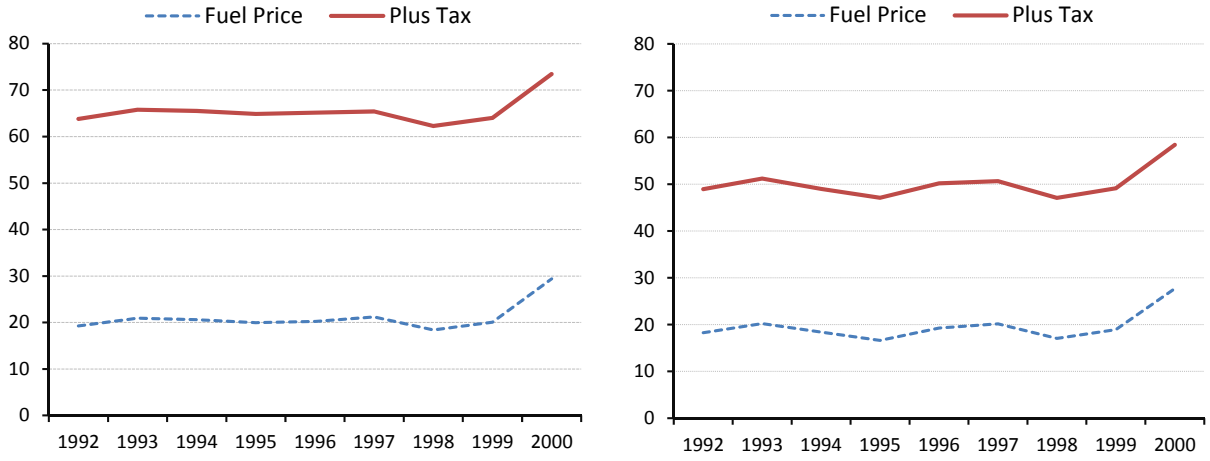
[5] The 1987 Fiat Croma was actually the first diesel passenger car to be equipped with turbo direct-injection. Whereas the Audi 100 controlled the direct injection electronically, the Fiat Croma was mechanical. The difference proved crucial for commercial success as electronic controls improved both emissions and power.

[6] See the 2004 report "Why Diesel?" from the European Association of Automobile Manufacturers (ACEA).

[7] This argument was first put forward by Schumpeter (1950, p.98) and later formalized by Balcer and Lippman (1984). More recently, it has been used by Manuelli and Seshadri (2014) to explain the half a century time span needed for the diffusion of the much studied case of tractors.

Figure 1 shows that in our sample diesel tax amounted to about 69% of gasoline tax (32 *vs.* 46 Euro cents per liter) resulting in systematically lower prices for diesel fuel.

Figure 1: Fuel Prices Gross and Net of Taxes (1994 Eurocents/liter)



(a) Gasoline (b) Diesel

Taxing fuels by volume offers a transparent criteria to monitor national policies. However, it also creates an incentive to use diesel fuel as diesel engines consume less per mile due to its higher energy content (129,500 BTU per gallon *vs.* gasoline's 114,000). The favorable tax treatment of diesel fuels exacerbated this effect. Historically, this approach was intended partly to help two economic industries particularly hit by the increase in oil prices: road transport and agriculture. With minor modifications, these principles have guided European fuel taxation until very recently. In 1997 the European Commission first suggested modifying these principles of taxation to reduce the differential treatment of diesel and gasoline fuels and incorporating elements of environmental impact of each type of fuel when setting taxes. It should be noted that this change in principles were only adopted in 2013. Thus, consumers faced stable and consistent incentives favoring diesel fuel consumption for a very long period of time.[8]

This favorable tax treatment of diesel fuel fostered the sale of diesel vehicles from the mid-1970s on. By the end of the 1980s, some large passenger cars and many commercial vehicles comprising almost 10% of the market ran on diesel fuel. Thus, when the TDI was first sold in 1989, Europeans, unlike Americans, were familiar with diesels and did not have a particularly negative perception of the quality of diesel vehicles.[9] More importantly, Europeans did not have to cope with the additional network costs commonly delaying the adoption of alternative fuels: by 1990 diesel

[8] See `http://ec.europa.eu/taxation_customs/taxation/excise_duties/energy_products/legislation/index_en.htm` for a complete description of the European Fuel Tax Directive and its evolution over time.

[9] See `http://www.autosavant.com/2009/08/11/the-cars-that-killed-gm-the-oldsmobile-diesel/` for an account of how badly GM's modified gasoline engines delivered poor performance when running on diesel fuel in the late 1970s and early 1980s and how such experience conformed the negative views of Americans on diesel vehicles for many years.

pumps were ubiquitous, indeed available in every gas station, and it was easy to find mechanics trained to service these vehicles in case repairs were needed.

Initial conditions were thus more conducive to the success of the TDI technology than in any other automobile market in the world. And yet, it was not obvious that consumers were going to end up embracing this new technology when VOLKSWAGEN introduced the TDI engine. Diesels are known to achieve better mileage than otherwise identical gasoline vehicles, leading to future fuel cost savings, but they are also more expensive to purchase, presumably due to higher production costs or because manufacturers' attempt to capture consumer rents of drivers favoring diesel vehicles.[10] But since the diffusion of TDI coincided with a long period of historically low and stable fuel prices documented in Figure 1, the value of potential fuel savings were limited and so was the manufacturers' ability to overprice diesel automobiles.

3.3 Evolution of Automobile Characteristics

Our data include yearly car registrations by manufacturer, model, and fuel engine type in Spain between 1992 and 2000. After removing a few observations, mostly of luxury vehicles with extremely small market shares, our sample is an unbalanced panel comprising 99.2% of all car registrations in Spain during the 1990s.[11] Spain was the fifth largest automobile manufacturer in the world during the 1990s and also the fifth largest European automobile market by sales after Germany, France, the United Kingdom, and Italy. In our sample automobile sales range from 968,334 to 1,364,687 units sold annually.

Figure 2 documents the evolution and composition of European automobile sales during the 1990s. Figure 2(a) shows that European diesel penetration, defined as the share of new vehicles sold with diesel engines, steadily increased over the 1990s and that Spain, our country of interest, exhibited growth representative of the continent as a whole or even served as a leading indicator.[12]

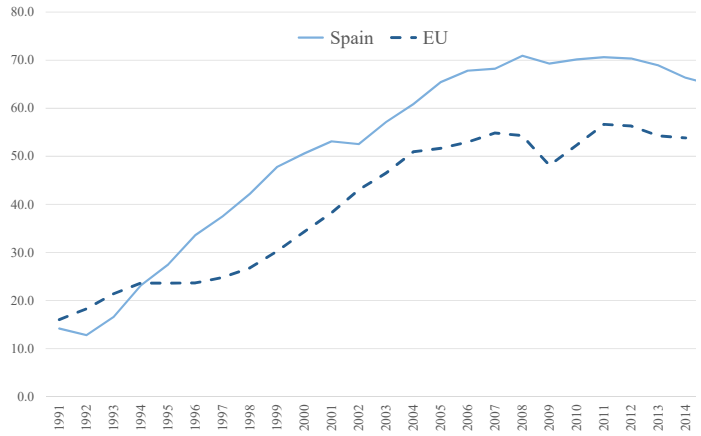
Figure 2(b) provides more detail in the growth and changing composition of the Spanish automobile market. Sales of gasoline models were flat in 1993 and 1995, about 573,000, despite a scrappage program in 1994, when they temporarily increased by 15%. While the sales of gasoline models has grown steadily since, it pales in comparison to the growth of diesels. Initially in 1992, they only represented 16% of total sales but by the end of the decade diesels represented 54% of the market, growing from 161,667 to 732,334 units sold in years 1992 and 2000, respectively.

[10] Verboven (2002) the price premium of diesel vehicles relative to otherwise identical gasoline model, as a business strategy aimed to capture some of the rents of consumers with heterogeneous driving habits.

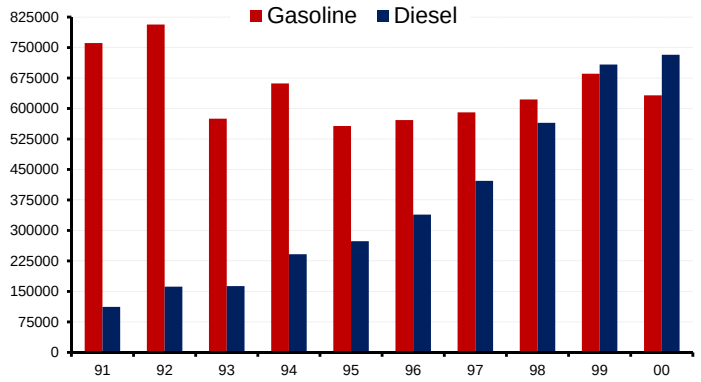
[11] See Appendix A for further details.

[12] There is variance in the adoption of diesels across countries, however, as smaller countries such as Denmark were slow adopters while France, led by Peugeot, adopted diesels earlier than Spain.

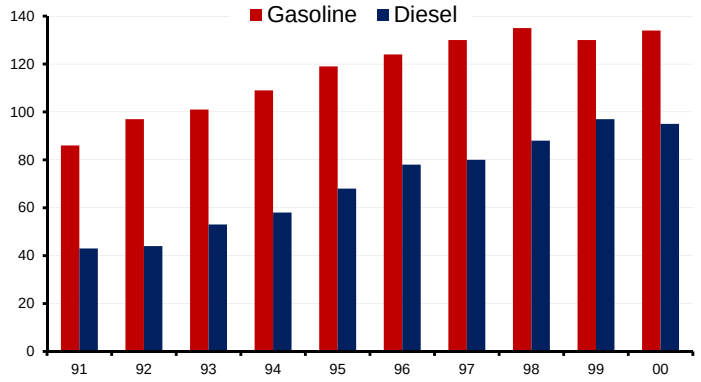
Figure 2: Trends in the European Automobile Market



(a) Diesel Share of New Vehicle Sales



(b) Sales (thousands of vehicles)



(c) Models Available

Notes: Authors' calculations. New passenger car registration data from *Association Auxiliaire de l'Automobile (AAA)*. In panel (a), European diesel penetration (dashed line) constructed gross domestic product as weights (source: World Bank Development Indicators). Countries included: Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Portugal, and the United Kingdom.

There was an equally impressive transformation of supply to meet this quick shift in demand. Figure 2(c) shows that by 1992, manufacturers already offered 44 diesels out of 141 models sold (although not all of them comparable to TDI). Furthermore, the number of models available grew significantly, both in the gasoline and the diesel segments, reflecting the effective entry of Asian manufacturers in the European market and a substantial increase in competition among fuel-efficient vehicles.[13] Since the entry of new models should reduce markups, consumers benefited from both an increase in variety and lower prices.

Table 1: Car Model Characteristics by Origin and Engine Types

YEAR/GROUP	MODELS	SHARE	PRICE	C90	KPE	SIZE	HPW
1992							
EU: DIESEL	43	16.60	12.26	4.45	46.42	73.84	3.14
EU: GASOLINE	73	79.45	11.05	5.39	29.62	71.50	4.12
NON-EU: DIESEL	1	0.09	13.76	5.30	38.58	80.51	2.86
NON-EU: GASOLINE	24	3.86	14.88	5.82	27.31	77.99	4.53
ALL	141	100.00	11.40	5.25	32.33	72.15	3.97
2000							
EU: DIESEL	75	50.95	16.19	4.55	38.18	76.32	3.14
EU: GASOLINE	84	37.28	14.93	5.68	24.23	73.40	3.90
NON-EU: DIESEL	20	2.71	17.20	5.41	32.63	82.48	3.22
NON-EU: GASOLINE	50	9.06	13.66	6.11	22.80	75.32	4.08
ALL	229	100.00	15.52	5.13	31.43	75.31	3.51

Statistics weighted by relevant quantity sold. SHARE is the market share as defined by automobiles sold. PRICE is denominated in the equivalent of thousands of 1994 Euros and includes value added taxes and import tariffs. C90 is consumption (in liters) of fuel required to cover 100km at a constant speed of 90 km/hr. KPE is the distance, measured in kilometers, traveled per euro of fuel. SIZE is length×width measured in square feet. HPW is the performance ratio of horsepower per hundred pounds of weight.

Table 1 summarizes the evolution of the features of vehicles sold in the Spanish automobile market during the 1990s.[14] By the end of the decade automakers produced cars which were 36.1% more expensive, are 4.4% larger, and 11.6% less powerful (*i.e.*, HPW). The combined effect are cars that are 2.3% less fuel-efficient in terms of mileage and 2.8% less expensive to drive when we account for increasing fuel prices.

We document even more dramatic changes across gasoline and diesel models. While the prices of gasoline and diesel models both increased over the decade, the increase for gasoline

[13] Asian imports include DAEWOO, HONDA, HYUNDAI, KIA, MAZDA, MITSUBISHI, NISSAN, SUZUKI, and TOYOTA. CHRYSLER is the only non-Asian imported brand. Thus, we use the terms "Asians" or "non-Europeans" when referring to imports. CHRYSLER sold its production facilities to PEUGEOT in 1978 and since then the few models sold in Europe are imported from the United States. On the contrary FORD and GM are considered European manufacturers. FORD has 12 manufacturing plants and has been continuously present in Europe since 1931. GM entered the European market in 1911, acquired the British brand Vauxhall and the German Opel in the 1920s and today operate 14 manufacturing facilities in Europe.

[14] Table A.2 in Appendix G.2 complements this description of product features reporting statistics by market segment.

models was much larger (46.5% vs 27.7%). Interestingly, this coincided with the transformation of European production in just a few years: European vehicles represented 96% of sales at the beginning and 88% at the end of the 1990s. But while only less than one out of five European cars was a diesel in 1992, by year 2000 they sold four diesels for every three gasoline models. Importantly, diesel models were largely offered by only European automakers.[15]

When deciding what type of engine to purchase, drivers compare observable product characteristics as well as likely related expected performance attributes of each engine, unobservable to econometricians. Since the difference between a diesel and gasoline version of a particular car model depends on only what's under the hood (*i.e.*, they share the same chassis), a consumer deciding between aa Audi A4 gas or diesel car bases her decision on differences in performance not car size. Specifically, diesel vehicles are about 10% heavier than similar gasoline versions; have 15% to 20% less horsepower than gasoline vehicles; and are between one and two thousand euros more expensive. Finally, diesel vehicles consume $20\% - 40\%$ less fuel than a comparable gasoline model, enabling a diesel to travel about 63% farther on a euro of fuel.

4 Vehicle Emissions Standards in the United States and Europe

Thus far we have documented the popularity of diesels among consumers (Figure 2). Yet, at the same time diesels almost disappeared in the U.S. market. The common explanation for the different evolution of these two large markets attributes the success of diesels in Europe to the favorable tax treatment of the diesel fuels in Europe. This is a popular explanation that lacks empirical support, however. While it is true that reduced taxation of diesel fuel favors larger penetration of diesel vehicles in a cross-section of mature markets, *e.g.*, Grigolon, Reynaert and Verboven (2015), fifteen years of such policy only led to a 10% market share penetration by the early 1990s. This suggests that preferential diesel fuel taxes played a minor role in promoting diesel adoption prior to the TDI.[16]

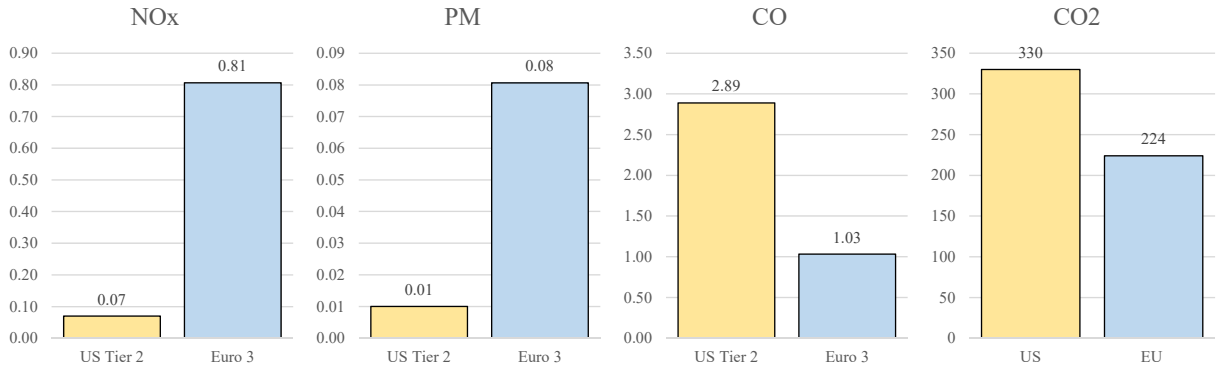
In this section we put forward the novel hypothesis that the different fate of diesels in Europe and the U.S. was instead due to the different goals pursued by the environmental policies in the U.S. and in Europe (Figure 3). While Americans were concerned mostly with reduction in emissions leading to acid rain, Europeans aimed at reducing greenhouse emissions.

[15] A natural question then is if diesels had become so important to European consumers, why did foreign firms not offer diesels? Thurk (2016) points out that the difference lies in the fact that for European auto makers a significant portion of their profits came from European consumers whereas Europe was a small market for foreign auto makers. The percent of revenue from the European market for BMW, PSA, RENAULT, and VOLKSWAGEN was 65%, 93%, 84%, and 74%, respectively, while for HONDA, MAZDA, and TOYOTA the shares are substantially smaller – 11%, 10%, and 8%, respectively (source: company 10-K SEC filings).

[16] In Appendix F we use the estimated model to show the effect after the TDI's introduction was also small.

In the United States, the approval of the 1990 Clean Air Act Amendments (CAAA) directed the U.S. Environmental Protection Agency (EPA) to, among many other things, reduce acid rain produced by nitrogen oxide (NO_x) and sulfur dioxide (SO_2). The EPA therefore chose a policy largely aimed at power generating plants which set emission reduction goals (Title IV-A) and established a cap-and-trade system (Title V), but it also translated into an ever more stringent NO_x emission standards for light-duty vehicles (Title II-A).

Figure 3: Europe and U.S. Emissions Standards



Source: `www.dieselforum.org`. "NOx" refers to nitrogen oxide limits; "PM" to particulate matter; "CO" carbon monoxide; and "CO2" carbon dioxide. US statistics for NO_x, PM, and CO are based on fleet averages under Tier 2 of the 1990 Clean Air Act Amendments (CAAA) while the statistic for CO_2 is based on a CAFE standard of 27.5 mpg. EU statistics for NO_x, PM, and CO are based on the Euro III standards implemented in 2000 while the CO_2 statistic is the 2008 fleetwide commitment. Prior to 2008 the EU did not regulate CO_2 emissions. All statistics are in grams of emissions per mile driven.

European regulators took a different approach and chose a less stringent emission standard on NO_x and PM (Figure 3).[17] While in 1994 U.S. Tier 1 standard allowed NO_x emissions of 1 gram per mile (g/mi) while the Euro I standard was 1.55 g/mi. By year 2000, the U.S. policy allowed only 0.07 g/mi while the Euro III standard set the NO_x emission level at a far less demanding 0.81 g/mi level. Similar results hold for PM.[18] The fast diffusion of diesel vehicles in the 1990s likely also enabled European authorities to choose more stringent CO_2 emission standards than the United States; the goals of local automobile manufacturers and European environmental regulators were thus perfectly aligned. Were these differences in environmental goals enough to explain the

[17] European authorities set NO_x and particulate matter (PM) standards for each vehicle while U.S. authorities set a fleet-wide limit. As for CO and CO_2 emissions, these depend on fleet average fuel consumption standards and are reported in Figure 3 as realized fleet-wide levels. See Section IV of the 2001 report: "Demand for Diesels: The European Experience. Harnessing Diesel Innovation for Passenger Vehicle Fuel Efficiency and Emissions Objectives" available at `www.dieselforum.org`.

[18] The negative health effects of PM are well documented. Capturing PM is however easier and far less expensive than capturing NO_x and we will not address it in our counterfactual analysis. See The World Bank's report: *Reducing Black Carbon Emissions from Diesel Vehicles: Impacts, Control Strategies, and Cost-Benefit Analysis* available at `https://openknowledge.worldbank.org/bitstream/handle/10986/17785/864850WP00PUBL010report002April2014.pdf`. In page 27 it indicates that the cost of complying with the most stringent PM emissions for a 4-cylinder 1.5 L diesel engine was $\$1,400$ in 2014.

different evolution of diesels in the U.S. and Europe? Absent any data on sales of automobiles by type of engine in the American market, we argue that this is the case based on anecdotal evidence for the U.S. and our counterfactual analysis for Europe.

The differences between the U.S. and European standards are significant for automobiles since reducing NO_x emissions is much harder for diesel engines as the three-way catalytic converters used to reduce emissions in gasoline engines cannot cope with the high concentrations of NO_x generated by diesel engines (*e.g.*, Canis 2012). Thus, rather than investing to redesign their diesel engines to meet these stringent emission standards, VOLKSWAGEN and MERCEDES chose to stop selling their diesel models in the U.S. market in 1993 and 1994, respectively, precisely at the time of the implementation of the U.S. emission standards mandated by the CAAA.[19] Only in 2010 did the EPA finally address the issue of NO_x emissions from diesel vehicles by requiring the installation of an urea-based selective catalytic reduction that injects an aqueous solution into the vehicles' exhaust stream to "scrub" NO_x emissions. Since then, automakers have introduced more diesel models into U.S. market, including those states that adhere to the even more demanding California emission standards. All these circumstances suggest that the imposition of these emission standards amounted to a *de facto* ban of diesel vehicles in the U.S. market. Could then a similar European emission policy have eliminated any chance of success for diesels in Europe?

5 An Equilibrium Oligopoly Model of the Automobile Industry

In this section we represent a structural equilibrium model of demand and supply which we use to discipline the analysis. We do so by working backwards present first a standard *BLP* model of discrete choice demand with heterogenous customers and Bertrand-Nash price competition among multi-product firms. This provides a set of generating the structural equations commonly used to recover the underlying demand and cost parameters provided one is willing to assume that characteristics observable to the econometrician are uncorrelated with characteristics which are not. The remainder of the section extends the standard *BLP* model to allow for this correlation by letting firms choose product characteristics conditional on their beliefs about the actions of their rivals as well as macroeconomic variables such as income.

[19] According to Stewart (2010), the NO_x emissions level of the least polluting diesel model available in Canada, the VOLKSWAGEN *Jetta* (known as *Bora* in Europe), was 0.915 and 0.927g/mi for the 1991 and 1997 year models, respectively. This indicates that the NO_x emissions standards imposed by the EPA were indeed binding constraints for diesel vehicles since even the cleanest diesel models barely met the 1994 U.S. emission standards and would have generated NO_x emissions thirteen times greater than the 2000 limit.

5.1 Demand

Demand can be summarized as follows: consumer i derives an indirect utility from buying vehicle j at time t that depends on price and characteristics of the car:

$$\begin{aligned} u_{ijt} &= x_{jt}\beta_i^* - \alpha_i^* p_{jt} + \xi_{jt} + \epsilon_{ijt}\,, \\ \text{where } \; & i = 1, \ldots, I_t; \quad j = 1, \ldots, J_t; \quad t = \{1992, ..., 2000\}\,. \end{aligned} \tag{1}$$

where we define a product j as model-engine type pair. This Lancasterian approach makes the payoff of a consumer depend on the set of characteristics of the vehicle purchased, which includes a vector of K observable vehicle characteristics x_{jt} as well as others that remain unobservable for the econometrician, ξ_{jt}, plus the effect of unobserved tastes of consumer i for vehicle j, ϵ_{ijt}, which is assumed i.i.d. multivariate type I extreme value distributed. We allow for individual heterogeneity in response to vehicle prices and characteristics by modeling the distribution of consumer preferences over characteristics and prices as multivariate normal with a mean that shifts with consumer attributes:[20]

$$\begin{pmatrix} \alpha_i^* \\ \beta_i^* \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta_t \end{pmatrix} + \Pi_t D_{it} + \Sigma_t \rho_{it}\,, \quad \rho_{it} \sim F\,. \tag{2}$$

Consumer i in period t is characterized by a d vector of observed demographic attributes, D_{it}, as well as a vector of random tastes, ρ_{it} distributed i.i.d. with cumulative distribution function F which is commonly assumed to be standard normal. Π_t is a $(n+1) \times d$ matrix of coefficients that measures the effect of income on the consumer valuation of automobile characteristics, *e.g.*, average valuation and price responsiveness. Similarly, Σ_t measures the covariance in unobserved preferences across characteristics. We decompose the deterministic portion of the consumer's indirect utility into a common part shared across consumers, δ_{jt}, and an idiosyncratic component, μ_{ijt}. The mean utilities of choosing product j and the idiosyncratic deviations around them are given by:

$$\delta_{jt} = x_{jt}\beta + \alpha p_{jt} + \xi_{jt}\,, \tag{3a}$$

$$\mu_{ijt} = \begin{pmatrix} x_{jt} & p_{jt} \end{pmatrix} \times \left(\Pi_t D_{it} + \Sigma_t \rho_{it} \right)\,. \tag{3b}$$

Consumers choose to purchase either one of the J_t vehicles available or $j = 0$, the outside option of not buying a new car with zero mean utility, $\mu_{i0t} = 0$. We therefore define the set of individual-specific characteristics leading to the optimal choice of car j as:

[20] Random coefficients generates correlations in utilities for the various automobile alternatives that relax the restrictive substitution patterns generated by the Independence of Irrelevant Alternatives property of the logit model.

$$A_{jt}\left(x_{\cdot t}, p_{\cdot t}, \xi_{\cdot t}; \theta\right) = \left\{\left(D_{it}, \rho_{it}, \epsilon_{ijt}\right) | u_{ijt} \geq u_{ikt} \quad \forall k = 0, 1, \ldots, J_t\right\} , \tag{4}$$

with θ summarizing all model parameters. The extreme value distribution of random shocks allows us to integrate over the distribution of ϵ_{it} to obtain the probability of observing A_{jt} analytically.

The probability that consumer i purchases automobile model j in period t is:

$$s_{ijt} = \frac{\exp\left(\delta_{jt} + \mu_{ijt}\right)}{1 + \sum\limits_{k \in J_t} \exp(\delta_{kt} + \mu_{it})} . \tag{5}$$

Integrating over the distributions of observable and unobservable consumer attributes D_{it} and ρ_{it}, denoted by $P_D(D_t)$ and $P_\rho(\rho_t)$, respectively, leads to the model prediction of the market share for product j at time t:

$$s_{jt}(x_t, p_t, \xi_t; \theta) = \int_{\rho_t} \int_{D_t} s_{ijt} dP_{D_t}(D_t) dP_{\rho_t}(\rho_t) , \tag{6}$$

with s_{0t} denoting the market share of the outside option.

5.2 Pricing

Equilibrium prices are found as the solution to a non-cooperative Bertrand-Nash game among the competing automakers. Specifically, equilibrium prices (p_j^w) can be written a nonlinear function of the product characteristics (x), market shares $s_j(x, p, \xi; \theta)$, retail prices (p), and markups:

$$p_j^w = mc_j + \underbrace{\Delta^{-1}(p, x, \xi; \theta) s_j(p, x, \xi; \theta)}_{b_j(p, x, \xi; \theta)} ; \tag{7}$$

where $p_j = p_j^w \times (1 + \tau_j)$ and τ_j is the import duty applicable to model j, if any. The vector of equilibrium markups $b_j(\cdot)$ depends on market shares $s_j(\cdot)$ and the matrix $\Delta(\cdot)$ with elements:

$$\Delta_{rj}(x, p, \xi; \theta) = \begin{cases} \dfrac{\partial s_r(x, p, \xi_t; \theta)}{\partial p_j} \times \dfrac{\partial p_j}{\partial p_j^w} , & \text{if products } \{r, j\} \in J^f , \\ \\ 0 & \text{otherwise} . \end{cases} \tag{8}$$

In estimating costs we make a common assumption that firms have Cobb-Douglas cost functions, therefore:

$$\log c = Z\gamma + \omega , \tag{9}$$

where Z are logged observable characteristics and ω are cost components unknown to the researcher.

If one makes the common assumption that the product set (and the corresponding characteristics) is exogenous so that $E[\xi|X] = 0$ and $E[\omega|Z] = 0$, demand and supply parameter estimates $(\Sigma, \Pi, \beta, \gamma)$ are recovered using the structural equations for demand (3a) and supply (9) using observable product characteristics as basis functions to construct identifying moment conditions. Of course, violation of this assumption leads to biased parameter estimates.

5.3 Product Characteristics

5.3.1 Overview. In this section we describe a more general model of supply which allows for the estimation of key demand and supply parameters with limited restrictions on the relationship between the observable (X, Z) and unobservable (ξ) product characteristics. We do so by extending Petrin and Seo (2016), hereafter *PS*, to allow for uncertainty about macroeconomic factors such as input prices and consumer income, thereby providing additional exogenous variation to pin-down the structural parameters. Broadly, the model amounts to a two-stage game where firms simultaneously choose the observed and unobserved characteristics of the products in their portfolios during stage one. In the second stage firms observe the products offered by their rivals and engage in Bertrand-Nash price competition to maximize profits.

While allowing a firm to choose observable product characteristics may be natural, it is worthwhile to provide some intuition as to what it means for a firm to choose an unobservable product characteristic. Consider and automaker such as AUDI which chooses to both increase the fuel efficiency (observable to us) and reliability (not observable to us) of a car in its portfolio. The latter choice is captured in the model via an increase in ξ, thereby violating the *BLP* identifying assumption of product characteristic exogeneity.[21]

5.3.2 Detail. There are n decision-making, multi-product firms indexed $f = 1, ..., n$. Let $\Psi^f \in \Psi$ denote the information set available to firm f when it chooses its actions. We define $\mathcal{X}$ be the set of actions firm f could take and the strategy played by firm f is then a mapping $S^f : \Psi^f \to \mathcal{X}$ which makes clear that observed decisions $x^f = S^f(\Psi^f)$ are a function the strategy and information set for each player.

We model product entry and exit as a firm-specific, time-varying random variable $(J_t^f, \eta_t^f) \sim \Phi_t^f$ which firms observe at the beginning of stage one. The draw informs each firm of how many products are in its period t product portfolio (J_t^f) and a product-level marginal cost shock (η_t^f). Both are private information until the set of products available to consumers is made available in

[21] A cleverly chosen set of control variables could also remove any exogeneity concerns (*e.g.*, Nevo 2000), but this is often difficult in practice. An advantage of this approach is that it allows the researcher to be agnostic about controls in the estimation and test for exogeneity afterwards.

stage two. We assume Φ_t^f is an autoregressive process so automakers like VOLKSWAGEN which offer a large number of products in period t are likely to continue doing so in period $t+1$. The fact (J_t^f, η_t^f) is private information introduces uncertainty so firms make their product characteristic choices in the first stage with limited information about the state of their rivals (J_t^{-f}, η_t^{-f}). Finally, firms also face uncertainty about aggregate macroeconomic factors ($y^f \in Y^f$) such as shocks to input prices (*i.e.*, cost shocks), fuel prices (*i.e.*, demand shock), and consumer income (*i.e.*, demand shock). All of these factors impact product profitability but are unknown to each period t firm when it makes product characteristic choices in stage one.

As in Pakes, Porter, Ho and Ishii (2015), the inclusion of private information and macroeconomic uncertainty generates ex post errors in firm first-order conditions which will be fundamental for identification. In a Bayes-Nash equilibrium the chosen product characteristics (and the ensuing retail prices) therefore maximize profits conditional on each firm's belief about the product characteristics of its rivals.

To be more concrete, the profit function for firm f map its product characteristic decisions ($x^f \in \mathcal{X}$), the decisions of its rivals ($x^{-f} \in \mathcal{X}$), and macroeconomic shocks ($y^f \in Y^f$) to pay-offs ($\pi : \mathcal{X}^f \times \mathcal{X}^{-f} \times Y^f \to \mathbb{R}$). Primitives of the game are then functions (π, S_f) and the joint probability distribution (Ψ^f, Y^f) where each multi-product firm f chooses period t product characteristics $x_{jt}^k \in \mathcal{X}^f$ to solve:

$$\max_{x_{jt}^k} E\left[\pi(x_t^f, x_t^{-f}, y_t^f) \,\middle|\, \Psi_{\tau\leq t}^f\right] \equiv \max_{x_{jt}^k} E\left[\sum_{r\in J_t^f} [p_r^w(x_t, y_t) - c_r(x_t, y_t)] \times s_r(x_t, p_t, \xi_t, y_t) \,\middle|\, \Psi_{\tau\leq t}^f\right], \quad (10)$$

provided $x_t{=}(x_t^f, x_t^{-f})$, J_t^f is the set of vehicles of all brands sold by firm f in period t, and $\Psi_{\tau\leq t}^f$ is the payoff-relevant information available to the firm in period $\tau \leq t$, *i.e.*, in stage one. The expectation operator $E[\cdot]$ is with respect to the joint distribution (Ψ^f, Y). Importantly, Equation (10) does not constrain the relationship between firms' perceptions and the expectation operator emanating from the data generating process; therefore perceptions need not be "correct" (Pakes et al., 2015).

While in principle the model allows firms to make product characteristic choices years in advance, for simplicity we restrict attention to the case when $\tau = t$ so firms choose product characteristics at the beginning of the year. In this case firm f may use period $t-1$ product sets, product characteristics (observable and unobservable), and realized macroeconomic shocks to forecast period t profits.

To simplify notation going forward, we drop t subscripts and will note when timing considerations are important. The subsequent optimal pricing strategy will be a function of product

positioning of all competing firms. Thus, in choosing product attribute x_j^k profit maximization yields the following first order condition:

$$E\left[\sum_{r\in J^f}\frac{\partial(p_r^w-c_r)}{\partial x_j^k}\times s_r+(p_r^w-c_r)\times\frac{\partial s_r}{\partial x_j^k}\,\Big|\,\Psi^f\right]=0\,, \tag{11}$$

where

$$\frac{\partial s_r}{\partial x_j^k}=\begin{cases}\displaystyle\int_{\rho^k}\int_D(\beta^k+\sigma^k\rho^k+\pi^kD)\times s_{ij}(1-s_{ir})dP_D(D)dP_\rho(\rho)+\sum_{m\in J^f}\frac{\partial s_r}{\partial p_m}\frac{\partial p_m}{\partial x_j^k}, & r=j,\\[2ex] \displaystyle-\int_{\rho^k}\int_D(\beta^k+\sigma^k\rho^k+\pi^kD)\times s_{ij}s_{ir}dP_D(D)dP_\rho(\rho)+\sum_{m\in J^f}\frac{\partial s_r}{\partial p_m}\frac{\partial p_m}{\partial x_j^k}, & \text{otherwise}\,.\end{cases}$$

Note that profit-maximization in the two-stage game requires firms choose product characteristics conditional on how these choices impact the pricing equilibrium via $\frac{\partial p}{\partial x^k}$. We maintain the assumption of Cobb-Douglas marginal costs while explicitly incorporating both observed and unobserved product characteristics, via X and ξ, and the product-level marginal cost shock η,

$$\log c_j=\sum_k\gamma^k\log(X_j^k)+\underbrace{\gamma^\xi\xi_j+\eta_j}_{\omega_j}\,. \tag{12}$$

Explicitly modeling ξ in the cost function does two things. First, it illustrates the potential endogeneity and subsequent estimation bias in the supply-side estimation since movements in ξ will be captured in ω in any standard *BLP* model. Second, it provides the structure to account for changes in unobserved product attributes ξ on marginal cost, *i.e.*, $\partial c/\partial\xi$.

In summary, product attributes in the standard *BLP* estimation are taken as given even though they determine pricing strategies and the ability to charge a higher or lower markups depending on the product positioning of all firms. The profit maximization conditions (11) describe an alternative framework where firms first choose product characteristics while taking into account the expected impact of these choices on profits through retail prices facing consumers and the induced cross-price effects on the demand of other products offered by the firm. Product attributes and prices are chosen sequentially so firms do not respond by changing attributes to respond to prices as in a model where prices and attributes were chosen simultaneously. Thus, product characteristics, observed or unobserved, condition the optimal pricing strategies that are set in equilibrium.

6 Estimation

We estimate the structural parameters of the model by GMM as in Hansen and Singleton (1982). Define the parameter vector $\theta = [\beta, \Sigma, \Pi, \gamma]$. First, we solve for the mean utilities $\delta(\theta)$ using the contraction mapping outlined in Appendix I of *BLP*. Next we solve for the implied markups b_{jt} using the observed product ownership structure and use prices to solve for marginal costs, assuming a pure strategy Bertrand-Nash equilibrium. In principle, the first-order conditions (11) are necessary for any Bayes-Nash equilibrium with multiple interacting players, although meeting these conditions does not rule out the possibility of multiple equilibria nor does it imply a restriction regarding the equilibrium selection mechanism should multiple equilibria exist. An advantage of imposing firm beliefs, however, is that solving the model amounts to solving a series of single agent problems, thereby removing issues of multiple equilibria.[22]

We combine observed firm decisions and stage one first-order conditions to construct the structural errors $\nu(\theta)$, defined as:

$$\nu_{jt}^{k}(\theta) = \sum_{r \in J_t^f} \frac{\partial [p_{rt}^{w} - c_{rt}(\theta)]}{\partial x_{jt}^{k}} \times s_{rt}(\theta) + [p_{rt}^{w} - c_{rt}(\theta)] \times \frac{\partial s_{rt}(\theta)}{\partial x_{jt}^{k}} \,. \tag{13}$$

These errors exist due to the *ex ante* uncertainty in the model as firms use their information sets Ψ^f to forecast not only the products sold by their rivals but also macroeconomic shocks.[23]

Identification of the parameter vector θ takes advantage of the fact that firms use elements in their information sets to make their decisions so the structural errors must be uncorrelated with the information sets. Further, any function of variables in the information set are valid instruments so the set of potential instruments is large. Following Newey (1990) we assume that

$$\Omega(\hat{\theta}) = E[\nu(\hat{\theta})' \nu(\hat{\theta})] \tag{14}$$

is a constant square matrix which defines the covariance structure of optimization errors where $\nu(\hat{\theta}) = [\nu_{\cdot,t}^{k=1}(\hat{\theta}), ..., \nu_{\cdot,t}^{k=K+1}(\hat{\theta})]$ is a matrix of structural errors and $K+1$ is the number of endogenous characteristics chosen by firms. Chamberlain (1987) shows that we can use the model to generate instruments H, defined as:

$$H_{jt}(\hat{\theta}) = E\left[\frac{\partial \nu_{jt}(\hat{\theta})}{\partial \hat{\theta}} \Big| \Psi_t^f \right]' \Omega^{-1} \,, \tag{15}$$

[22] Alternatively, one can follow Bajari, Benkard and Levin (2007) and use the data – the observed product, price, and consumption choices – as the equilibrium selection mechanism which is sufficient provided the data is generated by a single equilibrium.

[23] Measurement error may also play a role. Appendix B presents specific details of the solution algorithm.

where H_{jt} is N-by-$(K+1)$ matrix with N corresponding to the number of elements in $\hat{\theta}$. The logic behind these instruments is straightforward: they place relatively more weight on observations that are responsive to deviations of the parameter vector in a neighborhood of the estimated value.[24] Since the value of the structural error ν is dependent upon the assumed information structure, so are the instruments.

We estimate θ using a commonly employed two-step GMM estimation. Specifically, in each step we solve for the value of the GMM objective function conditional on θ by interacting the structural errors (13) with the identifying moment conditions (15) as follows:

$$\theta^{\star} = \underset{\theta}{\operatorname{argmin}}\, G(\theta) A^{-1} G(\theta)', \tag{16}$$

where $G(\theta) \equiv E[\tilde{\nu}(\theta)' \times \tilde{H}(\hat{\theta})]$, $\tilde{\nu}(\theta) = [\nu^{k=1}(\theta); ...; \nu^{k=K+1}(\theta)]$ is a stacked vector of structural errors, $\tilde{H}(\hat{\theta})$ is a block-diagonal instrument matrix , *i.e.*,

$$\tilde{H}(\hat{\theta}) = \begin{bmatrix} H^1(\hat{\theta}) & \dots & 0 \\ \vdots & H^k(\hat{\theta}) & \vdots \\ 0 & \dots & H^{K+1}(\hat{\theta}) \end{bmatrix}, \tag{17}$$

with elements $H^k(\hat{\theta})$ each amounting to a $N \times 4$ matrix. The inclusion of a positive-semidefinite weighting matrix A^{-1} is to increase estimation efficiency as the number of instruments exceeds the number of parameters in θ.

The estimator exploits the fact that at the true value of parameters $\theta^{\star}$, the instruments $\tilde{H}$ are orthogonal to the errors $\tilde{\nu}(\theta^{\star})$, *e.g.*, $E\left[\tilde{H}' \times \tilde{\nu}(\theta^{\star})\right] = 0$. In the initial step we solve for $\tilde{H}$ and A^{-1} using the parameter estimates under product characteristic exogeneity*i.e.*, *BLP* estimation. We then update $\hat{\theta}$ by solving (16) and using this value to update the instrument and weight matrices.[25] Additional updates changed the estimates little. To ensure robustness of the GMM results we employed a state-of-the-art estimation algorithm (KNITRO) shown to be effective with this class of models; considered a large variety of initial conditions; and used the strict inner-loop convergence criterion for calculating the mean utility δ suggested by Dubé, Fox and Su (2012).

As a final step we identify systematic trends in estimated unobserved demand, $\hat{\xi}$, and cost, $\hat{\eta}$, by projecting these vectors onto a set of dummy variables (*e.g.*, diesel, segment, firm) and time trends. We view these results as descriptive as many factors could be driving why consumers prefer European to foreign cars or why BMW is, *ceteris paribus*, more expensive to produce than RENAULT.

[24] See Appendix C for computational details regarding H.

[25] In constructing the weighting matrix (A^{-1}), we allow for the structural errors ν within a car model to be correlated across characteristics and time. See Newey (1993).

6.0.1 Firm Information Sets. A remaining non-trivial task is to map the firm information sets, Ψ_t^f, into pay-off relevant beliefs about rivals actions. Unfortunately, there is no clear way to construct the mapping *ex-ante* as it is unclear the degree to which firms in this industry are knowledgeable of the likely innovation decisions of their rivals or of the tastes of consumers today conditional on their previous purchase decisions. We instead take a simpler approach and impose these beliefs directly using the assumed autocorrelation in the product entry and exit process to generate simple but realistic beliefs. Specifically, period t firms maximize profits based on the the period $t-1$ product set and characteristics of their rivals, including marginal costs (and therefore η_{t-1}), though each firm of course knows its own period t product set and the corresponding cost shocks (η) via Φ_t^f. We also assume that firms forecast period t macroeconomic shocks to steel prices, fuel prices, and consumer income using period $t-1$ realized shocks to these factors. Alternatively, mergers among firms and changes in tariff rates are perfectly forecasted since these are the result of lengthy and generally observed negotiations.[26]

6.0.2 Specification. Our estimation must account for several important changes taking place during the 1990s such as increasing personal income, reduction of import duties, and multiple mergers of automobile manufacturers as well as differences in the information available to firms when they choose product characteristics. When estimating the model we simulate individuals from yearly census data to account for growth in income and the expansion of the Spanish economy (time-varying outside option). Similarly, the marginal cost equation (Equation 7) controls for relevant import taxes faced by manufacturers depending on their national origin and varies over the period considered. To account for changes in firms' product portfolios, we update matrix Δ_{rj} every year to match the ever changing ownership structure of this industry during the 1990s and correctly define the multi-product first-order profit maximization conditions of the equilibrium model to be estimated.

Consumer demand (both mean and idiosyncratic) includes measures of automobile performance – horsepower divided by weight (HPW) and exterior dimensions (SIZE) – as well as engine type (DIESEL). We also include the fuel cost of driving, kilometers per euro (KPE), as a "random coefficient" but we assume the distributions for KPE is distributed i.i.d. exponential, therefore σ_{KPE} plays a dual role, controlling not only the mean valuation but also the substitution pattern within fuel (in)efficient vehicles. The advantage of this approach is that *ex-ante* all agents value fuel-efficient cars (*i.e.*, will value paying less to get from point A to point B) though we allow agents to be heterogenous in how much they value fuel-efficient cars (*e.g.*, some agents may value producing less emissions of some kind, *e.g.*, CO_2 or NO_x).

[26] See Appendix A for details on acquisitions and mergers in the European automobile industry during the 1990s.

We also include a constant random coefficient (CONSTANT) to capture changes in substitution patterns due to the increasing product set. The inclusion of a DIESEL random coefficient allows for different substitution patterns within the diesel segment. As the sample period covers the diffusion of diesel vehicles, we include a DIESEL linear time interaction which captures the evolution of preferences in favor of the new technology. Demographic interactions (Π) are limited to be just an interaction between price and income as described in Section 5.1 where we simulate individuals from yearly census data to account for growth in income and the expansion of the Spanish economy (time-varying outside option).

On the supply side, we include the logged values of the observed product characteristics (HPW, SIZE, KPE) with the following modifications. Since KPE includes the effect of fluctuations in fuel price, we replace it with a measure solely based on fuel-efficiency, C90.[27,28] Consequently, AUDI's choice of fuel-efficiency for a gasoline model A4 impacts its cost directly as measured by C90, but demand for A4's will also be influenced by changes in the price of gasoline due to economic factors outside of AUDI's control. Hence, we include KPE in the demand rather than in the supply equation. Similarly, we allow for increasing steel prices to impact the cost of producing larger, heavier cars by multiplying car weight and size by an index for the price of steel. This leads to shifts of HPW and SIZE in supply but not demand.

Finally, we define a product as a model-engine pair thus the number of models equipped with a diesel engine for each firm is a random variable via Φ_t^f and not a choice. While the model allows for engine choice as an endogenous object, there are few examples of an automaker adding a diesel engine to an existing car model making it difficult to identify this fixed cost.[29] Our identification of diesel-oriented parameters then is based on systematic variation in the structural errors across engine type which we discuss below.

6.0.3 Parameter Identification This model represents a complex, nonlinear mapping from parameters to data, though the intuition behind our estimation approach is straightforward. In the model consumers maximize utility by evaluating a car based not only price but also product characteristics, some of which are unobserved to the researcher but known to consumers and firms. In Section 3.3 we documented that there is variation in product characteristics over the decade. Our estimation then uses the firms' choices in product characteristic space to reveal the underlying demand and

[27] KPE is equal to the inverse of C90 times fuel price.

[28] A further environmental scandal pertains to the self-reported fuel mileage statistics in Europe where several firms admitted to inflating this statistics. To our knowledge, these misdeeds do not extend into the period in question with the lone exception being MITSUBISHI who admitted to inflating fuel mileage statistics for the past 25 years.

[29] Note that a firm's choice to offer a model with a diesel engine is a discrete choice while the structural errors implied by the first-order conditions, equation (13), are based on continuous characteristics. An alternative approach would be to redefine ν to include moment inequalities for diesel engines as in Pakes et al. (2015).

cost parameters via the correlation between the unobserved shocks (in both demand and cost) and observable product characteristics. For example, if car size is positively correlated with reliability and the latter increases consumer utility, AUDI's choice to produce large, reliable cars provides information regarding the utility associated with car size in our estimation whereas the two are assumed exogenous in the standard *BLP* approach leading to a biased estimator.

While there is no clear one-to-one mapping between a parameter and a specific moment in the data, the intuition into how data variation identifies different components of θ is as follows. Variation in the product set, product characteristics (*e.g.*, SIZE), prices, and quantities identifies the random coefficients, Σ. The DIESEL mean utility and random coefficient parameters are identified by variation in the moment conditions by fuel type. A similar argument holds for the constant random coefficient which is identified by variation across moment conditions as the number of products increase. Finally, the Bertrand-Nash pricing equilibrium plus variation in price elasticities conditional on product characteristics identifies marginal costs, γ.

The intuition behind the identification of α (*i.e.*, Π) is embedded in the structural error $\nu(\theta)$ – Equation (13) – where the key tension is between the objects $(p-c)$ and $\frac{\partial[p_j^\tau - c_j(\theta)]}{\partial x_j^k} \times s_j(\theta)$. As $\alpha \uparrow 0$ consumers become less price-sensitive and the markups implied by our Bertrand-Nash pricing equilibrium increase, driving down estimated marginal costs and increasing $(p-c)$. This effect is also true in *BLP*. The innovation here then is the second term, $\frac{\partial[p_j^\tau - c_j(\theta)]}{\partial x_j^k} \times s_j(\theta)$, which becomes large as consumer demand becomes more inelastic. As this term reflects the sensitivity of price to changes in product characteristics, allowing for product characteristic endogeneity enables the researcher to use changes in product characteristics to also infer market-power via α. As we will see below, adding this additional level of identification leads to demand estimates which are much more elastic.

6.1 Estimation Results

Estimation results are presented in Table 2. Overall, the estimates are reasonable, statistically significant, and congruent with the descriptive evidence of the industry of Section 3. We find that diesels are more expensive to manufacture than gasoline models. Marginal cost of production are also higher for larger and more powerful cars. Marginal cost is decreasing in fuel efficiency (increasing in C90), though the effect is small and not statistically different than zero when we condition firm decisions on the previous year's product characteristics. It also appears that there are no important efficiency gains occurring during the decade but rather a small long term increase in cost of production perhaps driven by factors associated to the long term increase in sales of larger and more powerful vehicles during the 1990s. Finally, costs are also increasing in the unobserved

Table 2: Demand and Supply Estimates for Different Specifications

	"MMT"		"BLP"	
	Coefficient	Rob. SE	Coefficient	Rob. SE
Standard Dev. (σ)				
HP/Weight	1.6258	(0.2060)***	3.9037	(0.3717)***
KM/Euro	1.8003	(0.0908)***	2.1083	(0.2665)***
Diesel	6.8429	(1.2848)***	7.0359	(0.3987)***
Constant	3.8922	(0.8962)***	2.1011	(0.3579)***
Interactions (Π)				
Price/Income	−4.3618	(0.3875)***	−2.1563	(0.1764)***
Mean Utility (β)				
HP/Weight	−0.0770	(0.3687)	3.9996	(1.3082)***
Size	5.0385	(0.3084)***	5.7068	(1.0388)***
Diesel	−9.6992	(0.2064)***	−10.6753	(0.8381)***
Diesel × Trend	0.5579	(0.0416)***	0.5016	(0.0386)***
Non-Euro[b]	−1.4706	(0.1187)***	−1.1276	(0.1713)***
Seat[b]	0.0491	(0.1756)	0.8839	(0.2791)***
Cost (γ)				
Horsepower	0.2138	(0.0308)***	0.8121	(0.0657)***
Size	1.0090	(0.0956)***	2.5370	(0.1678)***
Fuel Efficiency	0.0211	(0.0130)	0.2727	(0.0711)***
Diesel	0.8333	(0.0132)***	0.3662	(0.0354)***
Unobserved Demand (ξ)	0.0711	(0.0097)***		
Constant[b]	0.7123	(0.0158)***	−0.0857	(0.1528)
Trend[b]	0.0159	(0.0018)***	−0.0011	(0.0038)
Elasticity Statistics:				
- Average	5.7		3.1	
- Maximum	18.4		10.6	
- Minimum	2.9		1.4	
Margin Statistics (%)				
- Average	20.3		37.7	
- Maximum	38.1		74.7	
- Minimum	6.1		10.0	
Estimation Statistics				
Number of observations	1,740		1,740	
Simulated agents per year	5,000		5,000	
J-Statistic	52.9		151.9	

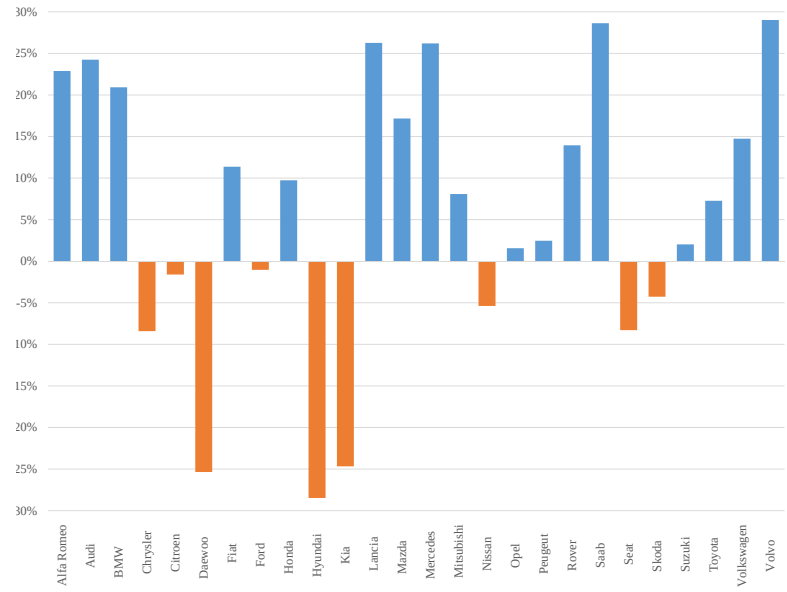
Notes: Estimation results for segment dummies (demand, cost) and firm-level cost fixed effects not reported. Robust standard errors in parentheses. Significant estimates with p-values less than 0.1, 0.05, and 0.01 are identified with *, **, and ***, respectively. Cost fixed effects for brand and segment not reported. [b] Estimates based on projecting the estimated values of the demand unobservable ξ on other demand characteristics, including segment fixed effects and a time trend. "Margin" defined as $100 \times \frac{p-c}{p}$ where price excludes import tariffs, if applicable. Equilibrium prices account for year-specific ownership structure as reported in Appendix A (Table A.1).

quality attribute, ξ. This may include better performance measured as reliability (or torque for diesel vehicles) as well as cost associated to setting up dealership networks for Asian newcomers.

In Figure 4 we report differences in marginal costs across brands relative to the Spanish market leader, RENAULT. Results are very reasonable, capturing the common perception of the

automobile market in Spain. German upscale brands AUDI, BMW, and MERCEDES, are among the most expensive to produce. Chrysler (U.S. based) and Asian imports are quite competitive, with Korean imports DAEWOO, HYUNDAI, and KIA, averaging a 26% relative cost advantage. European manufacturers with lower unit costs of production than RENAULT, include the Czech brand SKODA and the old Spanish brand SEAT, both of them acquired by VOLKSWAGEN to sell streamlined versions of their vehicles targeting lower income customers. Another interesting case of relatively low cost of production is FORD, which produces most of its smaller European models in a large plant located in Spain. These results reassure us that our specification is reasonable and that our estimates will be helpful in evaluating meaningful counterfactuals.

Figure 4: Production Cost Differences Across Brands



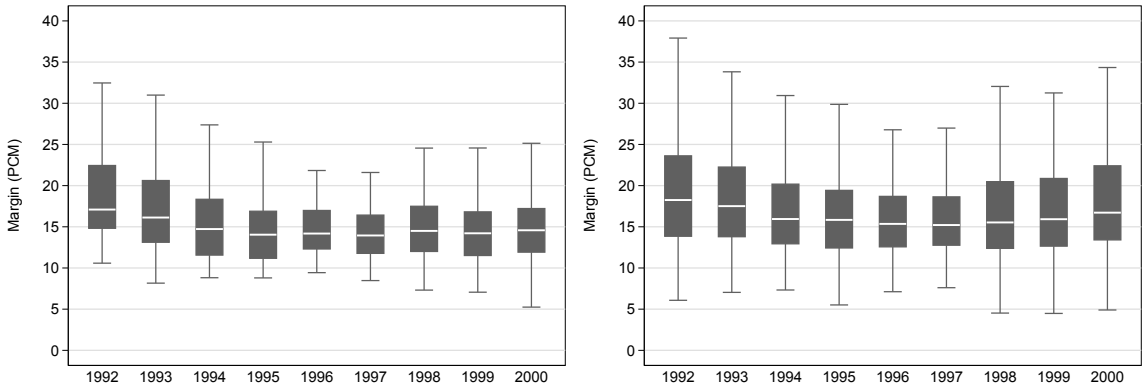
Notes: Figure presents estimated brand fixed effects. Reference category is RENAULT.

As for demand, Table 2 shows that it is downward slopping and always elastic. We estimate an average estimated price elasticity around 5.7 implying an average of 20% margin for the Spanish automobile industry during the 1990s. There is however substantial heterogeneity, with margins as low as 4.9% and as high as 38.1 percent. This wide range of margins are due to heterogeneous valuation of cars' characteristics at a moment in time, the evolution of preferences over time, and the changing product offering over the decade.[30] Figure 5 shows that average estimated margins, both of gasoline and diesel vehicles, remain quite stable, only decreasing very slightly during the middle 1990s for gasoline models. In the case of diesel vehicles margins are relatively large at the beginning of the decade but they fall as the decade proceeds due to increased imitation and

[30] Although ignoring the distinction between diesel and gasoline models, Moral and Jaumandreu (2007) show that demand elasticities are smaller but also very heterogeneous across market segments and product life cycle.

competition in the segment. At the same time, consumer preferences towards diesels are improving ($\beta_{Diesel \times Trend} > 0$) so the net effect is to stabilize diesel margins over the latter half of the decade. For both engine types, the dispersion of margins grows during the last three years of the sample as a growing economy increases dispersion of consumer incomes.

Figure 5: Evolution of Estimated Price-Cost Margins



(a) Diesel Vehicles (b) Gasoline Vehicles

Estimates of Table 2 show that after we control for price and fuel efficiency, drivers prefer larger cars (positive coefficient for SIZE) even after controlling for segment. The average consumer is indifferent about performance (insignificant coefficient for HPW in mean utility) but, not surprisingly there is a great deal of heterogeneity as captured through the significant random coefficient for HPW. The negative and significant sign of NON-EU is an empirical regularity in the international trade literature and is commonly referred to as the "home bias" effect.[31] Since our focus is on a specific industry rather than a set of bilateral trade flows across many sectors, we can provide a more detailed interpretation. At this time, Asian imports were first sold in the European market and were considered low quality, fuel-efficient alternatives to European vehicles but they lacked both brand recognition as well as a widespread network of dealerships for maintenance. Thus, the negative sign of NON-EU is not surprising.

The large and significant value for KPE as a random coefficient indicates that Spanish drivers are both concerned with fuel efficiency on average while their heterogenous tastes towards fuel efficiency leads to different substitution patterns between fuel-efficient and fuel inefficient vehicles. The results also indicate that some drivers strictly prefer diesel vehicles while on average diesels are relatively unpopular after controlling for their primary competitive advantage, fuel efficiency.

We have thus far appealed to intuitive arguments to justify why we expect that observed and unobserved product characteristics are likely to be correlated. Now that we have estimated the model and recovered the unobserved quality index ξ, we can corroborate our intuition. Table 3

[31] See Coşar, Grieco, Li and Tintelnot (2015) for estimates of cross-country home bias in the automobile industry.

Table 3: Are Product Characteristics Correlated?

	SIZE	HPW	$\hat{\xi}$
HPW	1.0000		
	-		
SIZE	0.3921	1.0000	
	(0.0187)	-	
$\hat{\xi}$	0.7171	0.3109	1.0000
	(0.0128)	(0.0199)	-

Notes: Estimated unobserved product characteristics ($\hat{\xi}$) based on previous year characteristics (*i.e.*, Model 1).Standard errors reported in parentheses.

presents the correlations between the observable product characteristics included in the *BLP* estimation and the estimated unobserved product characteristic $\hat{\xi}$ implied by our alternative estimation approach. The reported results provide clear evidence that the observed and unobserved product characteristics are indeed very much correlated – consistent with the results of Petrin and Seo (2016).

The natural question then is whether these correlations are quantitatively important. In Table 2 we juxtapose estimates from our model with estimation results when we assume that product characteristics are exogenous ("BLP"). In an attempt to keep the specifications as close as possible to each other, we maintained the same set of random coefficients and demographic interactions as well as the same simulated agents. We also included the post-GMM regressors from our model into the GMM *BLP* estimation. Our only departure from Berry et al. (1995) pertains to the instruments which we found uninformative for our data. Instead we employed "differentiation IVs" introduced by Gandhi and Houde (2015).[32]

The comparison reveals that assuming orthogonality produces significant differences in the estimation, particularly for the estimated price coefficient where we find a much smaller value under product exogeneity, leading to lower estimated price elasticities and higher estimated markups. We also find larger random coefficients for HPW and KPE but a smaller random coefficient for the constant.

[32] The idea is similar to the concentration instruments proposed in Berry et al. (1995) but instead of simple sums or averages (*e.g.*, sum of HPW for products not owned by the producer of product j in period t), we include summary statistics for the distribution of distances in product space (*e.g.*, average distance in HPW of products not owned by the producer of product j *and* far away from product j in HPW space). Specifically, the period t instrument for product j and characteristics k is

$$H_{jt}^{k,\lambda}(\hat{\theta}|\Psi_t^f) = \sum_{r \neq j}^{\mathcal{J}_t} 1(d_{rj,t}^k < c_\lambda) \times d_{rj,t}^k \tag{18}$$

where c_λ designates a cut-off in the cdf in which to construct the instrument and $d_{rj,t}^k$ is the distance in product characteristic space k defined as $x_{r,t-1}^k - x_{j,t}^k$. In practice, we chose c_λ for each characteristic such that the bins are evenly-distributed and set $\lambda = 4$.

Which estimation is most appropriate for our setting? We cite two pieces of information which leads us to reject the assumption of product characteristic exogeneity in favor of the "MMT" estimation results from Table 2. First, Spain is both a significant market in Europe and its adoption of diesels mirrored that of other countries (Section 3), therefore it is reasonable to assume our demand system is representative of the European continent. Since auto makers likely design cars with the entire European marketplace in mind, our demand system likely reflects any correlations between observed and unobserved product characteristics. Second, assuming product endogeneity generates a superior model fit, though the J-statistic still leads us to reject the model – a common trait of *BLP* discrete choice models and an area of active research.[33]

7 Environmental Policy as Strategic Trade Policy

In this section we present evidence that emissions standards did indeed drive the rise of diesels in Europe. Said differently, we show that had the EU imposed more rigorous NO_x emissions standards the diffusion of diesels would have been much smaller. By not adopting such damaging policies, whether inadvertently or not, European policymakers implicitly helped European manufacturers enhance their dominance in the domestic market. While we cannot definitively prove the intent of the emissions regulation was to protect domestic industry, we show the effect of the policy was equivalent to a significant import tariff, thereby documenting that seemingly innocuous domestic policies can effectively replace import tariffs as strategic trade policy – an important and novel result.

We model a change in emissions policy as an in increase in marginal cost applicable only to diesel vehicles.[34] We think of this "abatement" cost as the additional equipment required to make the diesel fleet compliant with the new standard. We assume that all diesel models require the same cost. The task then is to identify a "realistic" cost to modify an automaker's diesel fleet to the new standard. For years, a technology to successfully capture NO_x emissions at the tailpipe simply did not exist. When it finally became available, in the late 2000s, it was still very expensive. By the EPA's own estimates in 2010, diesel engines could be modified to comply with both EPA and California NO_x emission standards by means of a *Lean* NO_x *Catalyst* at an estimated cost of between \$6,500 to \$10,000 per vehicle. Lean NO_x catalysts use diesel fuel injected into the exhaust stream to create a catalytic reaction and reduce pollution. However, these catalysts still require specific exhaust temperatures for appropriate NO_x emission control performance, and on average

[33] See Reynaert and Verboven (2014) and Gandhi and Houde (2015) for a further discussion on instruments and identification of discrete choice demand systems.

[34] Today, abatement also results in a moderate (*e.g.*, 8%) decrease in fuel efficiency thereby further decreasing the attractiveness of diesels. As the effect is small given our demand estimates for fuel efficiency and our analysis focuses on a range of abatement costs rather than a specific value, we chose to exclude this factor from the analysis.

they reduce emissions up to a maximum of 40%. German manufacturers BMW and MERCEDES were certified to be sold in all 50 states of the U.S. in 2009 only after equipping their new vehicles with a *Selective Catalytic Reduction System* that injects a reluctant (a urea-based solution) into the exhaust stream where it reacts with a catalyst to convert NO_x emissions to nitrogen gas and oxygen. This system is more effective, reducing NO_x emissions up to 75% but the EPA estimated that its cost ranged between $10,000 and $20,000 per vehicle in 2010.[35]

Computing the equilibrium of a counterfactual environmental policy reintroduces issues about multiple equilibria as firms could potentially adjust both product characteristics and prices in response to an alternate regulation. Rather than computing all potential equilibria and evaluating the consequences of each, we take a simpler approach and keep the product characteristics fixed while allowing firms to re-optimize their prices.[36] While there is no guarantee of uniqueness in the pricing game either, we've found little evidence of multiple equilibria as solving the pricing game from different initial conditions leads to the same equilibrium.

We believe this simpler approach is indeed a good first-order approximation to the short-term impacts of alternative emissions and fuel taxation policies in the late 1990s. Evidence suggests that product innovations in this industry are slow as redesigning a car's size, engine, drive-chain, *etc.* is costly and time-consuming – an issue consistent with our estimation. This is particularly true for changes in the characteristic which diesels hold a competitive advantage, fuel efficiency, since designing and redesigning engines are both extremely expensive and time consuming.[37] This would suggest that our results are best thought of as a realistic approximation for the short-term (though still denominated in years) effects of emissions policy, while the longer term (*i.e.*, 10-20 years) are unclear.

7.1 Consumer Response to a More Rigorous NO_x Policy

Figure 6 presents the consumer response as we vary the additional abatement costs (x-axis) required to make diesels compliant with a more rigorous NO_x emissions policy. The shaded area highlights the limits of the estimated EPA abatement costs corrected for the exchange rate and inflation.

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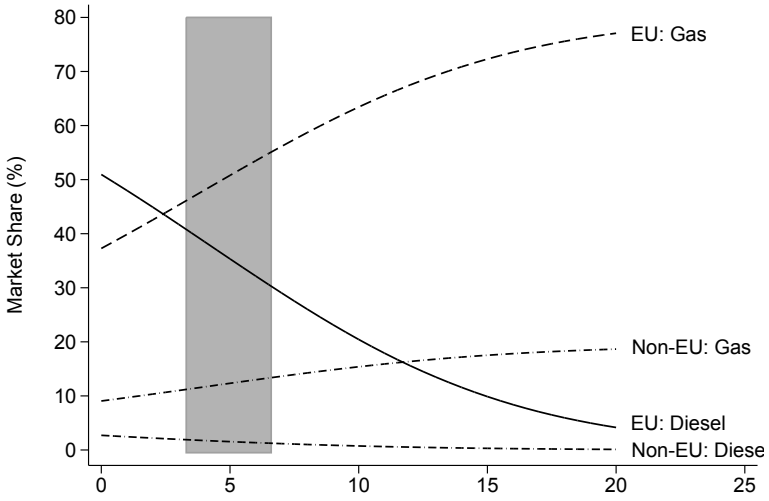
[35] On abatement costs see *Diesel Retrofit Devices.* EPA's National Clean Diesel Campaign, 2013. `http://www.epa.gov/cleandiesel/technologies/retrofits.htm` as well as our summary in Appendix D.

[36] Specifically, one could identify all potential equilibria using a homotopy algorithm as in Besanko, Doraszelski, Kryukov and Satterthwaite (2010). Although difficult, one could presumably evaluate the likely impact of a policy change by assessing commonalities between the equilibria (*e.g.*, change in diesel market share and profits). A complicating factor is that an alternative NO_x emissions policy would have likely impacted the evolution of consumer preferences for the diesel over the decade; a fact currently captured in the positive and significant estimate for the diesel trend variable $\beta_{Diesel \times Trend}$.

[37] Busser and Sadoi (2004, Footnote 2) document that since demand was small in their countries of origin, Asian manufacturers such as Toyota acquired engines from other European firms as a less costly way to satisfy European demand rather than investing in the development of diesel engines from scratch.

Figure 6: Market Shares and Abatement Costs



Notes: Results for $t = 2000$. Abatement costs (in 1994 Euros) on the x-axis. Shaded region reflects 2010 EPA estimates of diesel abatement (in 1994 Euros).

Notice that the increase in production costs required to comply with the more rigorous NO_x environmental regulation leads consumers to substitute away from diesel vehicles for even small abatement costs. At the lower bound for the EPA estimate, an abatement cost of €3,300, we already see a significantly negative impact on the popularity of diesel vehicles as diesel market share falls by 12 percent. At the upper bound, an abatement cost of €6,600, the market share of European diesel vehicles is nearly cut in half. For an abatement cost of €12,000 the market share of European diesels returns to the level observed at the beginning of the sample and below the share of gasoline imports, who grow monotonically with the abatement costs although the sales of European gasoline models grows much faster.

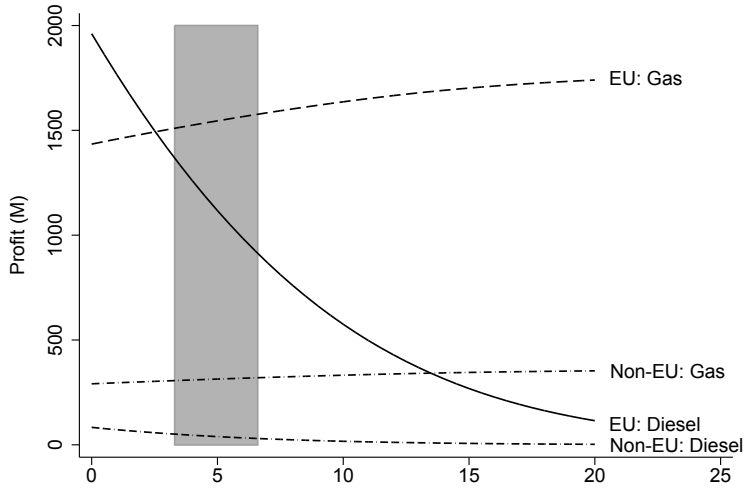
A detailed analysis of market shares of the different manufacturers reveals that the only clear beneficiaries of an alternative stringent European NO_x emission policy would be foreign automakers. As producers of inexpensive, fuel-efficient gasoline vehicles, the foreign automakers benefit as consumers substitute away from the expensive diesel engines and towards gasoline. Although the composition of sales changes with abatement costs, most European manufacturers maintain a significant share of the market. That is not the case for the two European diesel leaders PSA and VOLKSWAGEN. Both of them are also the largest producers of diesel vehicles in Europe and thus, having to face these large abatement costs erode their competitiveness and their market shares. Lastly, it is important to note that the consumer's general preference for domestic automakers ($\beta_{NonEU} < 0$) limits their willingness to choose foreign imports. Had this home bias not existed, the shift from domestic to foreign cars would have been much larger.

7.2 Impact to Firms

The emphasis on market shares hides aggregate industry effects as more stringent emissions policy leads to higher retail prices and lower profits (Figure 7). The mechanism driving this decline is straightforward. While the model does allow for rich substitution patterns for consumers to switch to an alternative new car if the price of their first choice increases, the fact the alternative emissions policy increases the costs for a large number of cars simultaneously causes firms to increase price for both diesel and gasoline vehicles. Consumers then decide to delay in their new car purchases.[38]

The results for most firms, particularly European firms, are equally negative. VOLKSWAGEN and the PSA group, the heaviest adopters of diesels, are the biggest losers though most European firms experience a material reduction in profits. In comparison, Asian firms which had invested little in developing diesel products see their profits increase as consumers switch to their fuel-efficient gasoline models.

Figure 7: Financial Impact of Alternative Emissions Policies on Firms



Notes: Results for $t = 2000$. Abatement costs (in 1994 Euros) on the x-axis. Shaded region reflects 2010 EPA estimates of diesel abatement (in 1994 Euros).

To quantify the aggregate impact of diesels, Table 4 reports the extreme case where an alternative emissions policy results in the elimination of diesels from the marketplace. For simplicity we just report results for year 2000 but other years yield similar results. While we admit this is a limiting case, it is worthwhile to remind the reader that this is indeed what happened in the United States market after CAAA implementation in the mid 1990s. Relative to the benchmark, the market shrinks considerably as consumers move to the outside good (*e.g.*, used car market).

[38] By holding the value of the outside option (*i.e.*, not buying a new car) fixed, we are assuming the average price and quality of a used car does not change with the regulation.

Table 4: Value of the Diesel

Scenario	Models	Price	Quantity	Margin	Share	Profit
Benchmark						
EU: DIESEL	75	16.19	695.37	18.68	50.95	1,961.00
EU: GASOLINE	84	14.93	508.70	21.09	37.28	1,434.37
NON-EU: DIESEL	20	17.20	36.97	14.84	2.71	83.26
NON-EU: GASOLINE	50	13.66	123.65	21.18	9.06	291.05
Equilibrium without Diesels						
EU: GASOLINE	84	21.11	412.58	16.95	80.40	1,236.29
NON-EU: GASOLINE	50	18.03	100.58	25.83	19.60	394.89

Results based on year 2000 equilibrium. "Price" is the sales-weighted average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Quantity" is measured in millions of cars. "Profit" is measured in the equivalent of millions of 1994 Euro. "Margin" and "Share" are reported as percentages. "Margins" include import duties paid by consumers.

European automakers absorb the most of this impact as profits fall €2.2 billion, or 64 percent. Non-European, primarily Asian, automakers, however, are better off as their market share jumps from 11.8% to 19.6% resulting in more market power and an increase retail prices, margins, and sales of their gasoline models following the disappearance of fuel-efficient diesel vehicles from the market. On net, profits for these firms increase €21 million, or 5.5 percent.

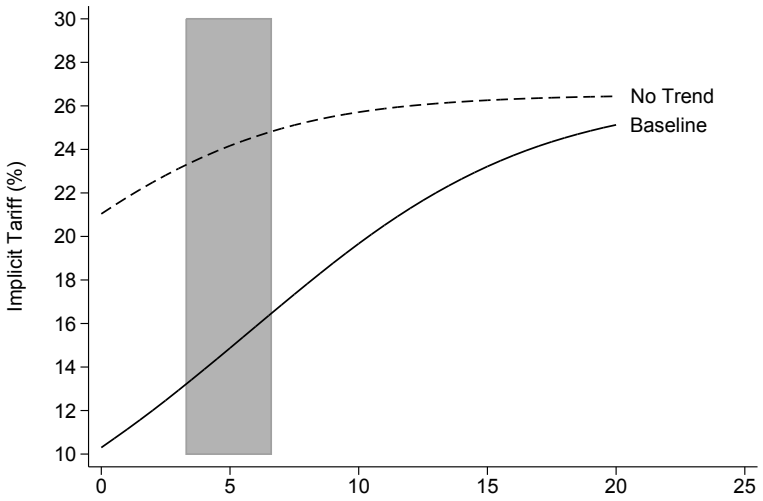
7.3 Import Tariff Equivalence

We have so far shown that diesel vehicles were a popular choice among consumers; generating substantial profits for European automakers. Reducing the popularity of these vehicles, presumably from an EPA-like emissions policy, would have resulted in a substantial reduction in profits for these firms while nearly doubling the market share of imports. In this section we use the structural model to measure the tariff-equivalence of European authorities' targeting of greenhouse emissions.

In Figure 8 we plot the import tariff required to generate the import share we observe (*e.g.*, 11.8% in 2000) for each level of abatement cost. We interpret each point as the import tariff-equivalence of the diesel-friendly emissions policy employed by EU regulators. For simplicity, we again restrict the current discussion to the year 2000 and show in Appendix G.2 (Table G.2) the results are similar for other years as well.

We find that the implicit tariff from by our "Baseline" estimation is significant, ranging from 13.4% when abatement costs are on the lower bound of the EPA estimates to 16.4% at the upper bound. For reference, the official import tariff facing Asian imports was 10.3% in 2000 so the diesel-friendly EU emissions policy amounted to 30-60 percent increase on the official rate, a significant effect. In the extreme case, an abatement cost which effectively eliminates the diesel

Figure 8: Tariff Equivalence of EU Emissions Policy



Notes: Results for $t = 2000$. Abatement costs (in 1994 Euros) on the x-axis. Shaded region reflects 2010 EPA estimates of diesel abatement (in 1994 Euros).

corresponds to a 26.5% import tariff. In other words, if the costs of modifying the diesel engine to meet stronger NO_x emissions standards are very large, the protective effect of adopting an emissions policy with a weak NO_x emissions standard is equivalent to imposing a tariff two-and-a-half times the official rate.

An advantage of our data set is that it covers a period of massive adoption of the diesel technology. In the estimation we allowed for consumer preferences towards diesels to change over the decade due to potentially learning or unobserved improvements in these vehicles. In the analysis thus far, we've held consumer preferences as fixed and only allowed substitution through changes in vehicle price due to abatement costs. We argue that the implementation of an alternative emissions policy early in the decade would not only affect immediate diesel sales through the changes in price but also future sales, particularly if one believes the increasing favorability of consumers is due to learning about the new technology. One would expect the EU's pro-diesel policy to increase the competitive advantage of diesels by buying time for consumers to learn about them. Conversely, an alternative emissions policy would limit consumer adoption due to increases in price, leave preferences towards diesels unchanged, and require a larger tariff to defend domestic automakers.

In Figure 8 we confirm this hypothesis by presenting results where we allow for the change in emissions policy to impact diesel demand through this second channel – *i.e.*, through consumer learning. We do this in the model by setting the diesel trend equal to zero ($\beta_{Diesel \times Trend} = 0$). The underlying assumption is that a positive estimate for the diesel trend in demand is due solely to increased consumer awareness of this next generation diesel technology. We then solve for the

implicit tariff as in the "Baseline" experiment; finding implicit tariff increases from 13 to 24% at the lower bound of the EPA estimate and from 16 to 25% at the upper bound. Further, the "No Trend" curve is flatter suggesting that small abatement costs effectively eliminate the diesel segment. While we view this experiment as aggressive, it does reveal the quantitative importance of consumer learning in the evaluation of any policy that promotes diffusion of a new technology. For us, it also reveals that our "Baseline" estimates likely understate the trade implications.

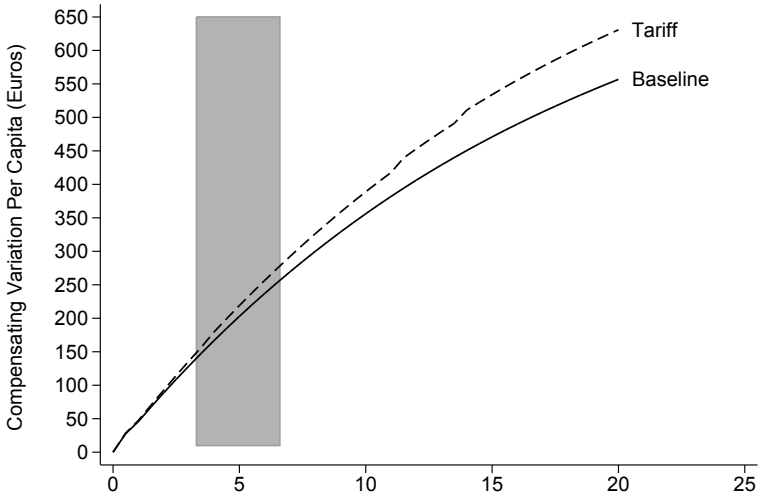
Further refinement of the estimated implicit tariff depends crucially on pinning down a "realistic" abatement cost which is complicated since the reference EPA estimates are based on technology developed much later (2010) and one can imagine that European automakers may have been able to develop a less expensive technology to protect their investment in diesels. The recent Volkswagen scandal suggests, however, that the costs of modifying these engines are indeed large since the company chose to incur severe financial penalties rather than meet the stricter EPA's NO_x thresholds. We take this as further evidence that a conservative estimate for the tariff-equivalent of observed EU emissions policy is between 13.4 and 16.4 percent, though we note that these values likely understate the actual effect provided one believes that the growth in diesels was due at least in part to consumer learning. Regardless, it is clear the emissions policy employed by European regulators favored domestic automakers as a quantitatively significant *de facto* non-tariff trade policy during the 1990s.

7.4 Impact to Consumers

Thus far our analysis has focused on the impact of emissions regulation on firms in the automobile industry, particularly domestic and foreign firms. In this section we pivot to focus on consumers. In Figure 9 we show the amount of money required to compensate the average consumer in year 2000 under more rigorous emissions policies. The solid line indicates the average consumer requires between €150 and €250 in compensation for the abatement costs within the range estimated by the EPA. The dashed line shows that consumers are further hurt (*i.e.*, require more compensation) when government imposes the "Baseline" import tariffs from Figure 8.

While our welfare analysis does not account for the reduction in negative health externalities due to more rigorous NO_x standards, it does provide an interesting insight into non-tariff trade policies more broadly. Recall that so far we have shown that the emissions policy employed by EU regulators had the effect of promoting a domestic innovation. Further, we show in Figure 9 that this policy is unambiguously welfare improving if we assume health externalities are negligible. Putting these points together indicates that non-tariff trade policies which promote domestic innovations (or the adoption of products by domestic consumers) can not only be an effective tool to influence consumption towards domestic products but they may also improve consumer

Figure 9: Impact of Alternative Emissions Policies on Consumers



Notes: Results for $t = 2000$. Abatement costs (in 1994 Euros) on the x-axis. Shaded region reflects 2010 EPA estimates of diesel abatement (in 1994 Euros).

welfare. This stands in stark contrast with tariffs which influence consumption by distorting price, leading to less consumer surplus – a fact also illustrated in Figure 9.[39]

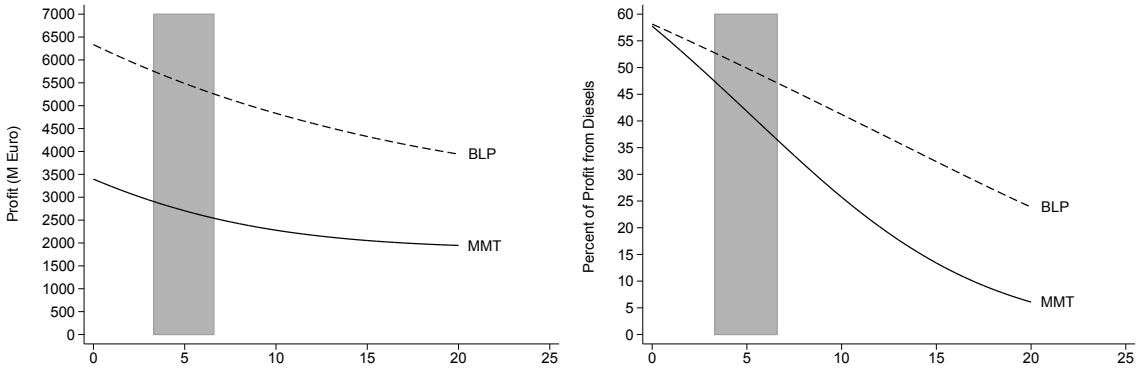
8 Robustness

In Section 6 we demonstrated that assuming product characteristic exogeneity led to steeper estimated demand curves and greater margins. In this section we assess whether these differences materially affect our headline result that domestic environmental policy was an effective trade policy. In Figure 10 we compare the total profits of European firms (left panel) and the share of total profits contributed by diesels (right panel) as we vary the abatement costs across our baseline estimation ("MMT") and the alternative *BLP* estimates ("BLP") from Table 2.

The steeper demand estimates from the *BLP* estimation leads to larger margins and greater profits for all products, not just diesels. We see this aggregate effect in a shifting up of the profit curves when moving from our baseline specification to the *BLP* estimates. The right panel illustrates that the shift is not uniform as diesels in our baseline model decrease in importance at a faster rate than in the *BLP* specification as the larger estimate for the diesel random coefficient in the latter specification makes consumers more willing to stay with the engine type despite increases in price. The lower estimated price elasticities in the *BLP* estimation also enables automakers

[39] There is a large and growing empirical literature documenting the negative effects of tariffs on consumer welfare. See Ruhl (2008) for a review.

Figure 10: Value of Diesels by Estimation Approach

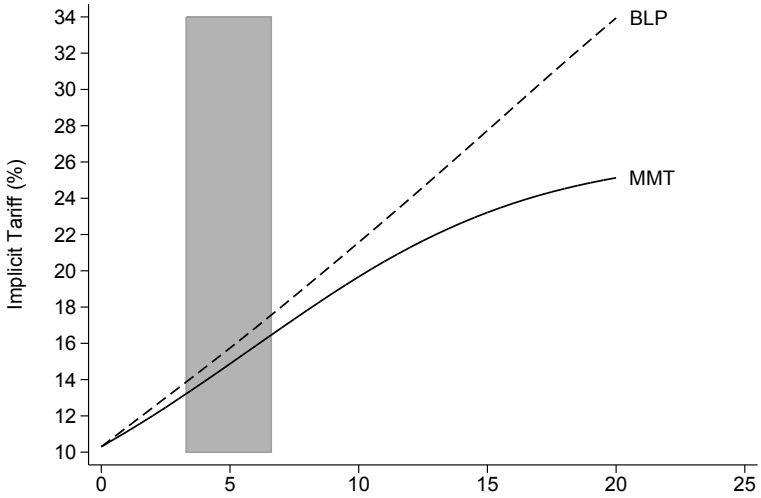


(a) Total Profits (b) Share of Profits from Diesels

Notes: Results for $t = 2000$. Abatement costs (in 1994 Euros) on the x-axis. Shaded region reflects 2010 EPA estimates of diesel abatement (in 1994 Euros).

to pass-through increases in marginal cost to consumers leading to a more linear relationship between abatement costs and the importance of diesels, measured in total profits or in market share. We interpret these results as evidence that assuming product characteristic exogeneity biases the estimated value of diesel vehicles upwards, thereby overstating the effects of pro-diesel emissions policy on automakers and consumers alike.

Figure 11: Implicit Tariff by Estimation Approach



Notes: Results for $t = 2000$. Abatement costs (in 1994 Euros) on the x-axis. Implicit import tariff for alternate years presents in Appendix G.4, Table G.2. Shaded region reflects 2010 EPA estimates of diesel abatement (in 1994 Euros).

Interestingly, this bias largely disappears, particularly for low estimates of the abatement costs, when we compare the implicit import tariffs from each demand estimation (Figure 11). Why does the estimation matter when analyzing the importance of diesels but not when we compare the

implicit import tariff implied by these vehicles? The answer lies in the firms' first-order conditions for price:

$$p = [1+\tau] \times [\hat{\mathbf{mc}} + \underbrace{\Delta^{-1}(p, x, \hat{\xi}; \hat{\theta}) s_j(p, x, \hat{\xi}; \hat{\theta})}_{\textbf{markups}}]. \tag{19}$$

The different estimation approaches impact our conclusions to the overall value of diesels through the markups via the estimated product elasticities, *e.g.*, see Panel (a) of Figure 10. Given that we observe price and use (19) to back-out marginal costs consistent with profit-maximization, the estimated price elasticities help the researcher split observed prices into marginal costs and markups. Therefore, under the *BLP* approach we find that consumers are less price-sensitive than under our baseline model which, in turn, leads us to allocate more of the observed prices to markups and greater profits for all cars, including diesels.

Recall that in Figure 11 we vary the import tariff τ to move the import share for each abatement cost back to the value observed in the data. Importantly, the import tariff τ increases marginal costs and markups proportionately so the relative size of the two matters less. Consequently, the net impact of using the simpler *BLP* approach depends on the complex substitution patterns embedded in the markup function, $\Delta^{-1}(p, x, \hat{\xi}; \hat{\theta}) s_j(p, x, \hat{\xi}; \hat{\theta})$, which in this case appears to be small particularly in a neighborhood of the equilibrium observed in the data.

We use the above evidence to form two conclusions. The first is cautionary as Figure 10 clearly shows that a researcher who uses a discrete choice model to estimate markups (*e.g.*, quantifying the value of a good) should be wary of estimates based on product exogeneity as such an assumption will significantly bias her results upwards. The second is more optimistic as researchers interested in economic mechanisms in which the estimated markups are not of themselves important may be able to use the much simpler *BLP* approach to generate reasonable results. Proving this distinction more formally is an interesting and, given the prevalence of *BLP*-type models, potentially important area of future research.

9 Concluding Remarks

The goal in this paper was to estimate the tariff equivalence of a domestic policy which favored the domestic automobile industry. To do so we estimated a structural oligopoly model of differentiated products where we allowed for correlation between observed and unobserved product characteristics, finding the two are indeed correlated. Our estimation allowed for significant heterogeneity of preferences, finding that consumers not only favor fuel efficiency and car size but also that their perception of diesels improved dramatically in the decade following the introduction of these next generation engines.

We find that the pro-diesel emissions policy employed by the EU amounted to a significant trade policy which we estimate to be equivalent to a 13% to 16% import tariff. Moreover, we show this result is robust across a variety of assumptions, including the estimation approach. This is, to the best of our knowledge, the first use of a structural equilibrium model of demand and industry oligopoly competition to show that seemingly innocuous domestic policies can be an effective replacement for traditional trade policies. Our results illustrate that in an increasingly global economy, governments can effectively construct non-trade oriented national policies, including environmental regulations, to protect domestic industries when traditional trade policies are no longer available. We further show that, in contrast to tariffs, such a policy may be welfare improving.

While our modeling choices are sufficient to address the objectives in this paper – balancing a feasible extension of the *BLP* framework while meeting the institutional details of our application – we view this paper as a step towards developing a more realistic empirical model of the automobile industry by providing useful insights into the quantitative implications of attribute choices made by firms. That said, it is perhaps more appropriate to think of the automobile industry as dynamic where manufacturers develop new cars (*i.e.*, products) and redesign old ones (*e.g.*, Blonigen, Knittel and Soderberry, 2013) taking into account expectations about industry evolution. Although estimating a dynamic model of product entry in the automobile industry increases the technical challenges substantially and introduces new sources of uncertainty of which there are no clear answers in the literature (*e.g.*, modeling the evolution of firm beliefs, multiple equilibria, *et cetera*), we view this avenue as the logical next step.

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Appendix

A Data Sources

To control for household income distribution a thousand individuals are sampled each year from the *Encuesta Continua de Presupuestos Familiares* (Base 1987 for years 1992-1997 and Base 1997 for years 1998-2000) conducted by INE, the Spanish Statistical Agency.[40] The outside option varies significantly during the 1990s due to the important recession between 1992 and 1994 and the very fast growth of the economy and population (immigration) in the second half of the decade. We also use these consumer surveys to set the size of the outside option for each year in our sample. Starting with 1992, they are: 0.92, 0.94, 0.93, 0.93, 0.93, 0.92, 0.91, 0.89, and 0.89, respectively.

Fuel prices were also obtained from INE. In real 1994 euro-equivalent denominations per liter, these are 0.445, 0.488, 0.490, 0.493, 0.543, 0.560. 0.530, 0.565, and 0.695 for diesel and 0.580, 0.628, 0.655, 0.678, 0.706, 0.724, 0.702, 0.737, and 0.875 for gasoline, for years 1992 to 2000, respectively. As for the Spanish steel prices used as instruments for the cost equations, they are obtained from the 2001 edition of *Iron and Steel Statistics – Data 1991-2000* published by the European Commission (Table 8.1).

For the analysis of demand we build a data set using prices and vehicle characteristics as reported by *La guía del comprador de coches*, ed. Moredi, Madrid. We select the price and characteristics of the mid-range version of each model, *i.e.*, the most popular and commonly sold. Demand estimation also makes use of segment dummies. Other than the LUXURY segment, which also includes sporty cars, our car segments follow the "Euro Car Segment" definition described in Section IV of "Case No. COMP/M.1406 - Hyundai/Kia." *Regulation (EEC) No. 4064/89: Merger Procedure Article 6(1)(b) Decision.* Brussels, 17 March 1999. CELEX Database Document No. 399M1406.

Until Spain ended its accession to the European Union transition period in 1992, it was allowed to charge import duties on European products. Similarly, import duties for non-European products converged to European levels. European imports paid tax duty of 4.4% in 1992, and nothing thereafter. Non-European manufacturers had to pay 14.4% and 10.3%, respectively. Thus, for the estimation of the equilibrium random coefficient discrete choice model of Table 2 we distinguish between prices paid by consumers (p) and those chosen by manufacturers (p^τ) .

The other relevant factor that changes during the 1990s is the ownership structure of automobile firms. During this decade FIAT acquired ALFA ROMEO and LANCIA; FORD acquired VOLVO; and GM acquired SAAB. BMW acquired ROVER in 1994 but sold it in May 2000 (with the exception of the "Mini" brand) so these are treated as separate firms. Table A.1 describes the ownership structure at the beginning and end of the decade.

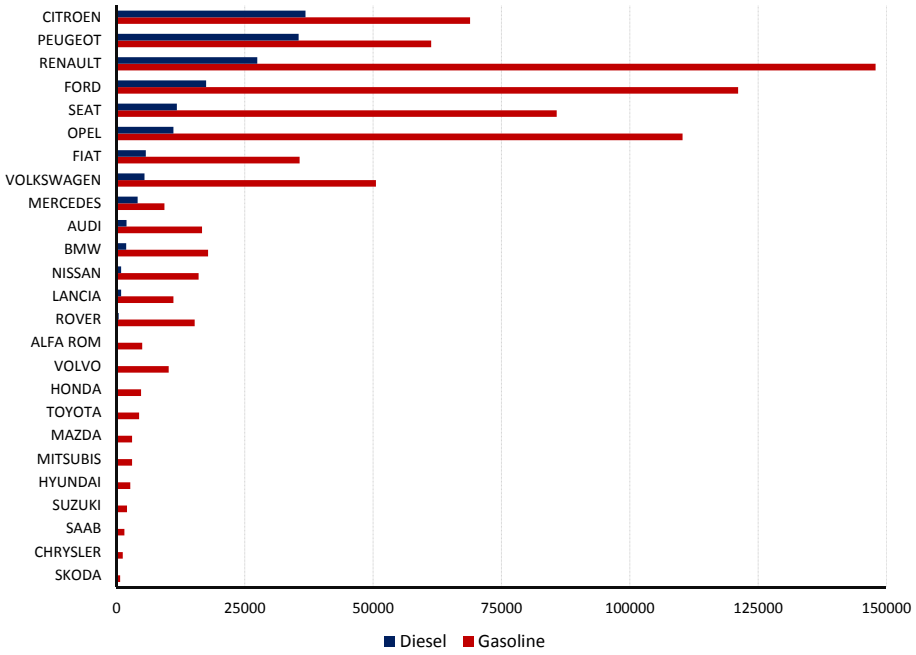
[40] See `http://www.ine.es/jaxi/menu.do?L=1&type=pcaxis&path=/t25/p458&file=inebase` for a description of these databases in English.

Table A.1: Automobile Groups: 1992 vs. 2000

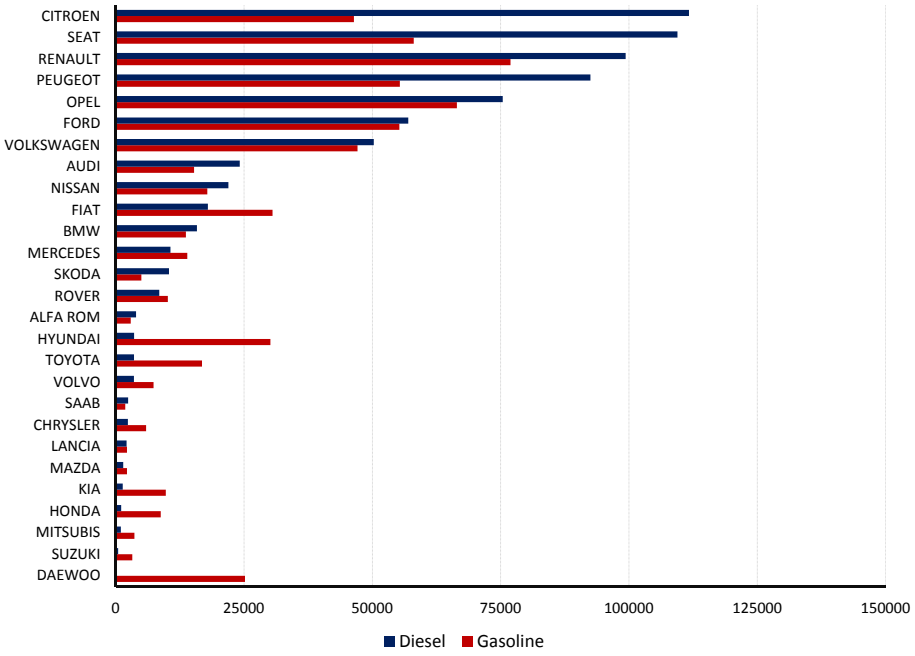
	Year 1992			Year 2000		
Firm	Gasoline	Diesel	Owner	Gasoline	Diesel	Owner
ALFA ROMEO	5,038	64	ALFA ROMEO	2,941	3,983	FIAT
AUDI	16,689	1,982	VOLKSWAGEN	15,273	24,184	VOLKSWAGEN
BMW	17,855	1,906	BMW	13,683	15,838	BMW
CHRYSLER	1,243	–		5,941	2,389	
CITROËN	68,890	36,851	PSA	46,420	111,694	PSA
DAEWOO	–	–		25,201	–	
FIAT	35,677	5,733	FIAT	30,557	17,967	FIAT
FORD	121,140	17,468	FORD	55,268	57,013	FORD
HONDA	4,805	–		8,782	1,072	
HYUNDAI	2,704	–		30,150	3,590	
KIA	–	–		9,778	1,387	
LANCIA	11,117	905	LANCIA	2,206	2,126	FIAT
MAZDA	3,064	–		2,205	1,480	
MERCEDES	9,352	4,129	MERCEDES	13,953	10,684	MERCEDES
MITSUBISHI	3,041	–		3,660	1,013	
NISSAN	16,010	905		17,855	21,971	
OPEL	110,286	11,099	GM	66,488	75,418	GM
PEUGEOT	61,323	35,494	PSA	55,371	92,496	PSA
RENAULT	147,907	27,448	RENAULT	76,925	99,360	RENAULT
ROVER	15,255	425	ROVER	10,173	8,491	ROVER
SAAB	1,551	–	SAAB	1,867	2,424	GM
SEAT	85,773	11,787	VOLKSWAGEN	58,072	109,447	VOLKSWAGEN
SKODA	724	–	SKODA	5,003	10,385	VOLKSWAGEN
SUZUKI	2,058	–		3,250	486	
TOYOTA	4,425	–		16,827	3,584	
VOLKSWAGEN	50,561	5,471	VOLKSWAGEN	47,125	50,296	VOLKSWAGEN
VOLVO	10,179	–	VOLVO	7,379	3,566	FORD

Sales of vehicle by manufacturer and fuel type. "Owner" indicates the name of the automobile group with direct control on production and pricing. Those without a group are all non-European manufacturers and defined as NON-EU in the analysis.

Figure A.1: Sales by Firm and Type of Engine



(a) Year 1992



(b) Year 2000

Table A.2: Car Model Characteristics Across Engine Types

SEGMENT	MODELS	SHARE	PRICE	C90	KPE	SIZE	HPW
1992							
Compact	31	35.79	10.96	5.33	32.07	74.34	3.98
Sedan	39	22.31	14.26	5.69	30.27	80.10	4.26
Luxury	39	5.77	24.01	6.49	25.75	87.07	4.84
Minivan	4	0.32	17.28	6.93	24.21	81.66	3.79
Small	28	35.82	7.98	4.68	35.00	62.51	3.65
All	141	100.00	11.40	5.25	32.33	72.15	3.97
2000							
Compact	56	34.43	14.86	5.00	32.53	76.54	3.59
Sedan	52	25.97	19.45	5.26	31.60	81.92	3.63
Luxury	40	3.72	34.53	6.72	23.31	89.72	5.17
Minivan	32	3.13	20.80	6.39	25.91	83.47	3.16
Small	49	32.75	10.42	4.86	31.61	66.36	3.18
All	229	100.00	15.52	5.13	31.43	75.31	3.51

Notes: SHARE is the market share as defined by automobiles sold. PRICE is denominated in the equivalent of thousands of 1994 Euros and includes value added taxes and import tariffs. KPE is the distance, measured in kilometers, traveled per euro of fuel. SIZE is length×width measured in square feet. HPW is the performance ratio of horsepower per hundred pounds of weight.

B Solving for the Structural Errors

In this section we describe the algorithm to solve the model conditional on parameter guess $\theta = [\beta, \Sigma, \Pi, \gamma]$. Since solving the model is independent across years, we drop the t subscripts for brevity. The algorithm is as follows:

1. Compute δ using the contraction mapping described in (Berry et al., 1995, Appendix I). In so doing we approximate market shares (6) via simulation using a large number of Halton draws.

2. Use $\mu(\Sigma, \Pi)$ and $s_{ijt}(\theta)$ to solve for the implied markups b_j. Use the firms' first-order conditions for the pricing game (Equation 7) and the observed prices to construct marginal costs (c).

3. Use δ from (1) and the β parameter vector guess to solve for ξ.

4. Use the marginal costs (c) from (2) and the γ parameter vector guess to solve for ω.

5. Construct the structural error ν_j^k:

$$\nu_j^k(\theta; \Psi) = \sum_{r \in J^f} s_r(\theta; \Psi) \times \frac{\partial (p_r^w - c_r(\theta; \Psi))}{\partial x_j^k} + (p_r^w - c_r(\theta; \Psi)) \times \frac{\partial s_r(\theta; \Psi)}{\partial x_j^k}\,. \tag{B.1}$$

   using the following algorithm:

   (a) Use $\hat{\gamma}$ and the Cobb-Douglas specification of the marginal cost equation to generate $\frac{\partial c_j}{\partial X_j^k}$.

   (b) Evaluate the indirect (price-induced) market share response to attributes from:

$$\frac{\partial s_r}{\partial x_j^k} = \begin{cases} \displaystyle\int_{\nu^k} \int_D (\beta^k + \sigma^k \nu^k + \pi^k D) \times s_{ij}(1 - s_{ir}) dP_D(D) dP_\nu(\nu) + \sum_{m \in J^f} \frac{\partial s_r}{\partial p_m} \frac{\partial p_m}{\partial x_j^k}, & r = j, \\ \displaystyle -\int_{\nu^k} \int_D (\beta^k + \sigma^k \nu^k + \pi^k D) \times s_{ij} s_{ir} dP_D(D) dP_\nu(\nu) + \sum_{m \in J^f} \frac{\partial s_r}{\partial p_m} \frac{\partial p_m}{\partial x_j^k}, & \text{otherwise}\,. \end{cases} \tag{B.2}$$

   where we solve for $\frac{p_m^w}{\partial x_j^k}$ using Equation (7) and the implicit function theorem.

   (c) Since we allow for $\Psi = \Psi_t^f$ to vary by firm (*i.e.*, firms may have different beliefs about the future), we solve for the structural errors (ν) firm-by-firm.

C Approximating the Optimal Instruments

This section provides an outline for how we approximate the Chamberlain's "optimal" instruments (Equation 15) where the derivative of η_j^k with respect the $\theta_l \in \theta^\star$ is

$$\frac{\partial s_r}{\partial x_j^k} = \sum_{r \in J^f} \left[\begin{array}{c} \dfrac{\partial s_r}{\partial \theta_l} \times \dfrac{\partial (p_r^w - c_r)}{\partial x_j^k} + s_r \times \dfrac{\partial^2 (p_r^w - c_r)}{\partial x_j^k \partial \theta_l} \\ \\ + \dfrac{\partial^2 (p_r^w - c_r)}{\partial x_j^k \partial \theta_l} \times \dfrac{\partial s_r}{\partial x_j^k} + \dfrac{\partial (p_r^w - c_r)}{\partial x_j^k} \times \dfrac{\partial^2 s_r}{\partial x_j^k \partial \theta_l} \end{array} \right] \tag{C.1}$$

and J^f is the product portfolio of firm f – the firm which owns products r and j. Dependence upon the information set Ψ^f is implied in the market shares s and prices (p, p^w). Solving for the "optimal" instruments is difficult as it requires integrating (C.1) over the set of potential firm beliefs and economic shocks (Ψ, Y) at the "true" θ vector. To make the problem tractable, we choose to follow a common strategy[41] and approximate these instruments along the following dimensions:

1. Use $\hat{\theta}$ as an estimate of $\theta^\star$, employing the two-stage GMM estimation outlined in Section 6.
2. Restrict the set of firm beliefs Ψ^f to contain period $t-1$ realized values for macroeconomic shocks and rival product portfolios, including product characteristics (both observed and unobserved). Similarly, economic shocks to fuel prices and steel prices are the period $t-1$ observed values.
3. In calculating (C.1) we assume $\frac{\partial x^j}{\partial \hat{\theta}_l} = \frac{\partial p}{\partial \hat{\theta}_l} = 0$ to ease the computational burden.

While the resulting instruments H_{jl}^k are valid, one cannot say with precision whether how close these instruments are to Chamberlain's "optimal" instruments.

[41] See Berry et al. (1999), Reynaert and Verboven (2014), and Petrin and Seo (2016).

D EPA Cost Estimates for Abatement Diesel Vehicles

The following information was taken from *'Diesel Retrofit Devices."* Environmental Protection Agency (`http://www.epa.gov/cleandiesel/technologies/retrofits.htm`), last updated January 23, 2013. As described in the text, the abatement technology we consider is the "Lean NOx Catalyst (LNC)" as this technology is most relevant for limiting NOx emissions in passenger cars. Our inclusion of the remaining technologies recommended by the EPA shows both the breadth of technologies available to reduce a variety of emissions as well as the variety of costs (of which the LNC is near the bottom) required to modify a vehicle.

> Diesel retrofit devices for after-treatment pollution control can be installed on new or existing vehicles and equipment to reduce particulate matter (PM), nitrogen oxides (NOx), hydrocarbons (HC), or carbon monoxide (CO) as well as other air pollutants. The information below provides estimated emission reductions.

Table D.1: Estimated Costs to Modify Diesel Vehicles

Technology	Typical NO_x Emission Reduction	Typical Cost ($)
Lean NOx Catalyst (LNC)	5-40%	$6,500-$10,000
Selective Catalytic Reduction (SCR)	<75%	$10,000-$20,000; Urea $0.80/ gallon

Source: United States Environmental Protection Agency.

> Lean NOx Catalyst (LNC) Lean NOx Catalysts (LNC) use diesel fuel injected into the exhaust stream to create a catalytic reaction and reduce pollution. Verified LNCs are paired with either a DPF or a DOC. An LNC can also be paired with an active DPF to reduce NOx emissions and enable filter regeneration over a range of duty cycles. However, an LNC still requires specific exhaust temperatures for appropriate NOx emission control performance. *LNCs can increase fuel usage by 5-7 percent* (emphasis added).

> Selective Catalytic Reduction (SCR) Selective Catalytic Reduction (SCR) Systems inject a reductant, also known as diesel exhaust fluid (DEF), into the exhaust stream where it reacts with a catalyst to convert NOx emissions to N2 (nitrogen gas) and oxygen. The catalytic reaction requires certain temperature criteria for NOx reduction to occur. As with DPFs, knowing the age and type of each engine in the fleet as well as the drive cycles of the vehicles is important. Data logging must be performed to determine if the exhaust gas temperatures meet the specific SCR system requirements.
>
> SCR systems require periodic refilling of the DEF, and the system should ensure that the DEF never freezes. SCR systems are commonly used in conjunction with a DOC and/or DPF to reduce PM emissions. Because of new NOx standards, most 2010 and

newer on-highway diesel engines come equipped with an SCR system. A DEF refueling infrastructure is in place, facilitating the use of SCRs.

E Solving for Counterfactual Automobile Prices

In this section we provide computational details to find the profit-maximizing prices under each policy experiment. For the sake of brevity, we suppress the period subscripts. Each firm f produces some subset $\mathcal{F}_f$ of the $j = 1, \ldots, J$ automobile brands and chooses a vector of pre-tariff prices $\{p_j^\tau\}$ to solve:

$$\max_{\{p_j^\tau\}} \sum_{j \in \mathcal{F}_f} \left(p_j^\tau - c_j \right) \times M s_j \,, \tag{E.1}$$

The firm's first-order condition for price conditional on product characteristics is given by:

$$s_j + \sum_{r \in \mathcal{F}_f} (p_r^\tau - c_r) \times \frac{\partial s_r}{\partial p_j^\tau} = 0 \,. \tag{E.2}$$

Optimality requires that Equation (E.2) hold for all products sold in period t. We express the set of firm f first-order conditions in matrix notation as:

$$s + \Delta \times (p^\tau - c) = 0 \,, \tag{E.3}$$

where an element of the matrix Ω is defined as:

$$\Omega_{jr} = \begin{cases} \dfrac{\partial s_j}{\partial p_r^\tau} \,, & \text{if } \{j, r\} \subset \mathcal{F}_f \,, \\ \\ 0 \qquad \text{otherwise} \,. \end{cases} \tag{E.4}$$

For a given vector of marginal costs c, we use (E.3) to find the fixed point to the system of equations – a common practice in the literature dealing with this class of models. To our knowledge there exists no proof of convergence or uniqueness for this contraction operator and fixed point. Our experience (as is common) is that convergence is monotonic and proceeds quickly. Further, starting from different starting values yields an identical result.

F Fuel Taxation as a Policy Tool to Promote Diesels

Following the European Fuel Taxation Directive of the 1970s, diesel fuel received a favorable treatment that has convinced many to conclude that the success of diesel vehicles in Europe was due primarily to this favorable treatment of diesel fuel taxation. We argued in Section 3.2 that the reduced diesel fuel tax rate was instrumental for the development of a diesel market niche that eased the adoption of TDI (and likely influenced its development) and other improved diesel vehicles

in the 1990s, two decades after the European Fuel Tax Directive was adopted. Given this initial condition, it is unclear to what degree preferential fuel taxes influenced the domestic market versus the diesel-friendly environmental emissions policy. Moreover, both policies have the potential to protect domestic industry by promoting its competitive advantage among consumers. The goal of this appendix is to quantify the impacts of each to assess the relative impact on the industry.

In our first experiment (third panel of Table F.1) we replace the European fuel taxes with average values employed in the United States where taxes are not only lower but also favor gasoline.[42] The reduction in fuel price increases their fuel efficiency, KPE, and consequently the attractiveness of new cars (since $\sigma_{\text{KPE}} > 0$), increasing total consumption 10.6 percent, though the increase is across both gasoline and diesel. The increase in diesel is more muted (3.7%) than gasoline (18.7%) and both European firms and Non-European firms experience significant increases in profits (9.7% and 11.6%, respectively). Conversely, quantity sold for diesels in our estimated equilibrium (first panel) are 3.5% lower than under U.S. fuel taxes and both European firms and Non-European firms experience are worse off under the current tax policy (8.8% and 10.4%, respectively).

In the fourth and fifth panels we evaluate the consequences of equalizing fuel taxes and increasing fuel taxes by 8.1% in line with current policy.[43] When we increase fuel taxes to the level applied to gasoline, the higher fuel prices and lower fuel economy lead consumers to substitute towards gasoline. Consequently, diesel sales and profits in the estimated equilibrium are 5.4% and 5.4% greater in the estimated equilibrium. We see similar results in the current EU fuel taxation policy where higher diesel fuel taxes lead consumers to substitute away from diesel varieties indicating that the policy employed in the 1990s did the opposite – it encouraged consumers to purchase the diesel cars largely produced by domestic automakers.

We compare these results to the market equilibrium when automakers are required to meet stricter emissions requirements on NO_x emissions (panel 2). Here, we use the lower-bound on the EPA abatement cost as a conservative estimate. While pro-diesel fuel taxes increased consumption of diesels around six percent, the pro-diesel emissions policy employed by the EU increased total sales of diesels by 61.1% and most of these gains were captured by European automakers – profits for EU automakers in our estimated equilibrium increased €610 million (21.9%). Total profits for non-European automakers also increases since some of these firms had adopted diesels though the results are meager compared to their European rivals. These results indicate that while preferential fuel taxes did play a role in promoting diesels and protecting domestic automakers, fuel taxes play a minor role compared to the diesel-friendly emissions policy employed by EU regulators.

[42] In constructing these average tax rates we computed the average fuel taxes across states, weighting by aggregate state fuel usage.

[43] Finally, after almost two decades of deliberation and negotiation among European policymakers, the European Fuel Tax Directive of the 1970s was updated to account for the energy content of each type of fuel (instead of just its volume) as well as for their disparate environmental impact. These new taxation principles were supposed to eliminate the favorable taxation of diesel fuels among others. Excise fuel taxes at the bottom panel of Table F.1 are those in place during 2015 according to E.U. Technical Press Briefing available at `http://ec.europa.eu/taxation_customs/resources/documents/taxation/review_of_regulation_en.pdf`

Table F.1: Modifying Diesel Fuel Taxes

Benchmark Diesel and Gas Excise Taxes

	Fuel Tax	Price	Quantity	Margin	Share	Profit
EU: DIESEL	0.23	16.19	695.37	18.68	50.95	1,961.00
EU: GASOLINE	0.35	14.93	508.70	21.09	37.28	1,434.37
NON-EU: DIESEL	0.23	17.20	36.97	14.84	2.71	83.26
NON-EU: GASOLINE	0.35	13.66	123.65	21.18	9.06	291.05
TOTAL	0.29	15.52	1,364.70	19.70	100.00	3,769.68

Abatement Expense of $3,600 Euros

	Fuel Tax	Price	Quantity	Margin	Share	Profit
EU: DIESEL	0.23	20.02	462.89	15.12	40.15	1,336.27
EU: GASOLINE	0.35	14.90	537.88	21.08	46.66	1,514.13
NON-EU: DIESEL	0.23	21.24	21.40	12.23	1.86	49.52
NON-EU: GASOLINE	0.35	13.65	130.64	21.18	11.33	307.27
TOTAL	0.30	16.93	1,152.81	18.53	100.00	3,207.18

US Fuel Taxes

	Fuel Tax	Price	Quantity	Margin	Share	Profit
EU: DIESEL	0.15	16.11	721.96	18.73	47.82	2,033.11
EU: GASOLINE	0.14	14.52	606.24	21.31	40.16	1,691.01
NON-EU: DIESEL	0.15	17.14	37.16	14.84	2.46	83.47
NON-EU: GASOLINE	0.14	13.29	144.35	21.35	9.56	334.35
TOTAL	0.14	15.23	1,509.71	19.92	100.00	4,141.95

Diesel and Gas Excise Taxes are the Same

	Fuel Tax	Price	Quantity	Margin	Share	Profit
EU: DIESEL	0.35	16.24	658.35	18.62	49.34	1,855.48
EU: GASOLINE	0.35	14.92	514.78	21.10	38.58	1,451.84
NON-EU: DIESEL	0.35	17.25	36.20	14.82	2.71	81.63
NON-EU: GASOLINE	0.35	13.66	125.02	21.19	9.37	294.38
TOTAL	0.35	15.52	1,334.34	19.71	100.00	3,683.32

Diesel Excise Tax is Increased

	Fuel Tax	Price	Quantity	Margin	Share	Profit
EU: DIESEL	0.38	16.25	651.51	18.61	49.03	1,835.82
EU: GASOLINE	0.35	14.92	515.92	21.10	38.83	1,455.11
NON-EU: DIESEL	0.38	17.26	36.04	14.82	2.71	81.30
NON-EU: GASOLINE	0.35	13.66	125.27	21.19	9.43	295.00
TOTAL	0.37	15.52	1,328.74	19.72	100.00	3,667.22

Notes: Results based on year 2000 equilibrium. "Fuel Tax" is measured in 1994 Euros per liter and TOTAL is the sales-weighted average fuel excise tax. "Price" is the sales-weighted average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Quantity" is measured in thousands of cars. "Profit" is measured in millions of 1994 Euro. "Margin" and "Share" are reported as percentages.

G Additional Results

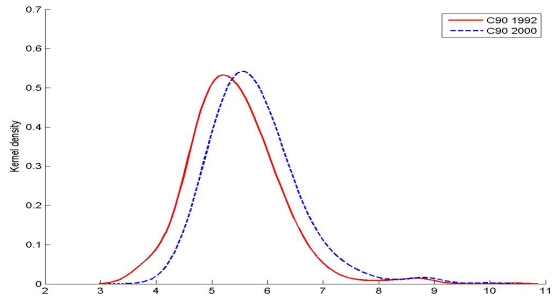
G.1 Descriptive Statistics For diesels to succeed as they did, it is likely that this new technology was seen as desirable in many ways, and not only regarding fuel economy. The shift in the distributions of some observable automobile characteristics is shown in Figure G.1 and formal tests of first and second order stochastic dominance are presented in Table G.1 in Appendix G.2. Despite the fact that all vehicles became larger, heavier and slightly more powerful during the decade, there is little evidence that gasoline vehicles differ much during the 1990s. Kolmogorov-Smirnov tests indicate that neither the early or late distribution of attributes of gasoline models dominate each other with the exception of KPE; the cost of driving gasoline vehicles is definitely higher by year 2000 (as a consequence of increasing fuel prices). Diesel vehicles on the other hand, show sign of substantial change during the decade; they are also more expensive to drive (KPE) by year 2000 despite the fact that they became more fuel-efficient (C90), as they are also larger (SIZE) and show weakly better performance (second order stochastic dominance in HPW). All this descriptive evidence hints at diesel vehicles becoming better products capable of increasingly attracting the interest of many drivers.

G.2 Unobserved Characteristics In Figure G.2 we present the evolution of estimated unobservable quality $\hat{\xi}$ by year and fuel type. Table G.1 reports tests of stochastic dominance for these distributions. It is remarkable that while the unobservable attributes of gasoline vehicles are indistinguishable at the beginning and end of the 1990s, the perceived quality of diesels clearly improved during that same time period. Consumers were uncertain about unobservable features such as durability, torque, or reliability at the introduction of TDI. We also find that not only diesels (or consumers' perception of diesels) improve during the 1990s but that they are also linked to power, size, brand, and other observable automobile attributes.

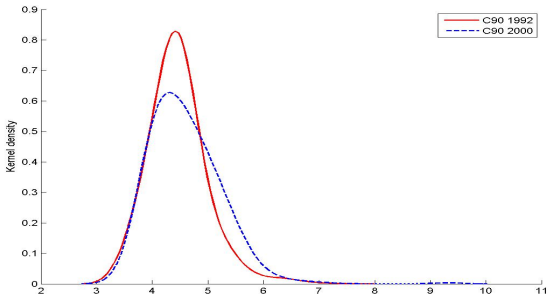
G.3 Substitution Patterns In Figure G.3 we present evidence that our model generates reasonable substitution patterns. We show this by first solving for the distance between each pair of products in a particular characteristic (*e.g.*, HPW). We then divide the product-pairs into deciles where the first decile correspond to pairs which are most alike. Finally, we compute the average cross-price elasticity for each bin. The results are plotted in panels (a-c) where we see clearly that for all of the characteristics considered in our estimation, substitution between similar products is much more likely than for products far apart in characteristic space. Since diesel is a discrete variable, we show the average cross-price elasticity within and across fuel types (panel d). Again, we see that consumers are much more likely to substitute within fuel type.

G.4 Implicit Tariff Across the 1990s In Table G.2 we show that although the analysis focused on the year 2000, our conclusions extend across the 1990s.

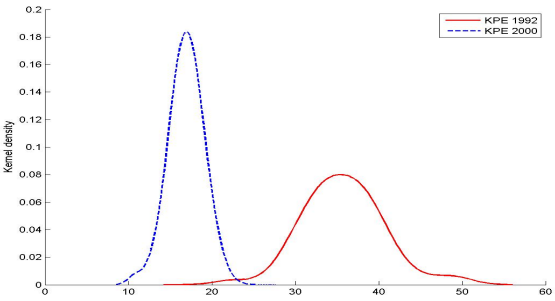
Figure G.1: Change in the Distribution of Automobile Attributes



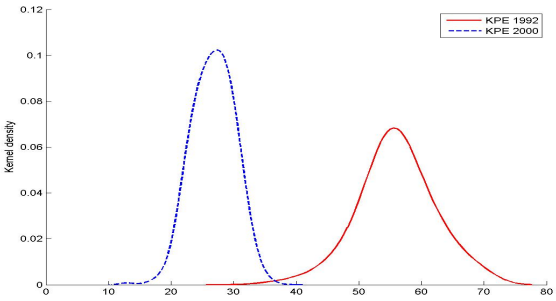
(a) Gasoline: Mileage (C90)



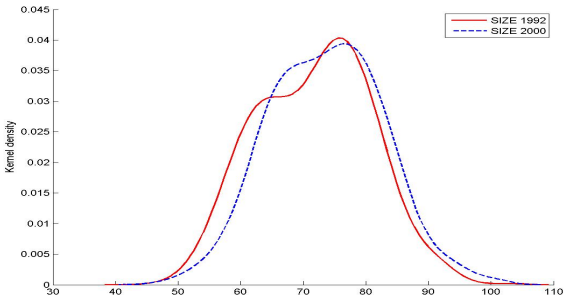
(b) Diesel: Mileage(C90)



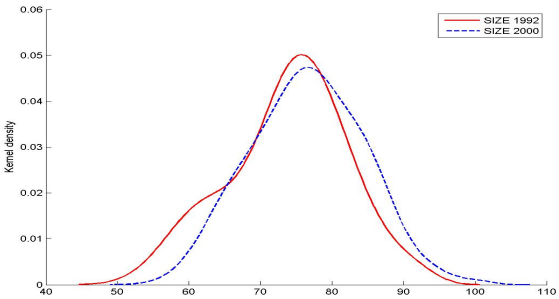
(c) Gasoline: Cost of Driving (KPE)



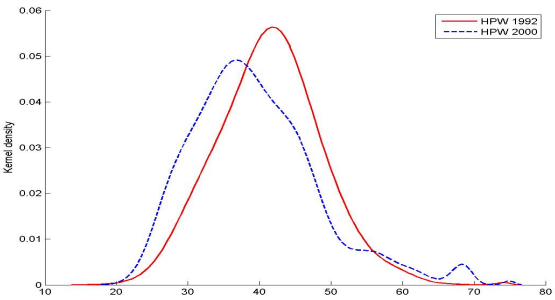
(d) Diesel: Cost of Driving (KPE)



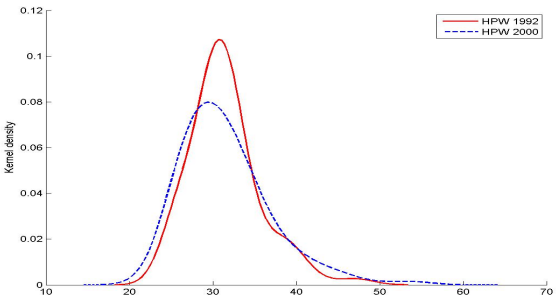
(e) Gasoline: SIZE



(f) Diesel: SIZE

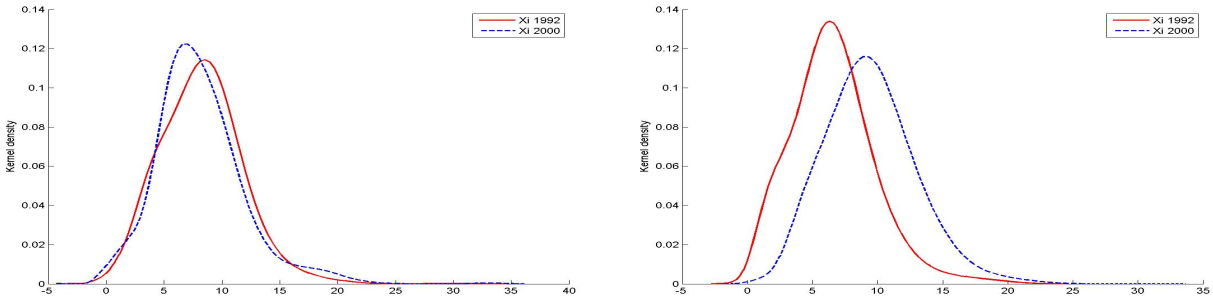


(g) Gasoline: Performance (HPW)



(h) Diesel: Performance (HPW)

Figure G.2: Change in the Distribution of Unobserved Attributes



(a) Gasoline: $\hat{\xi}$

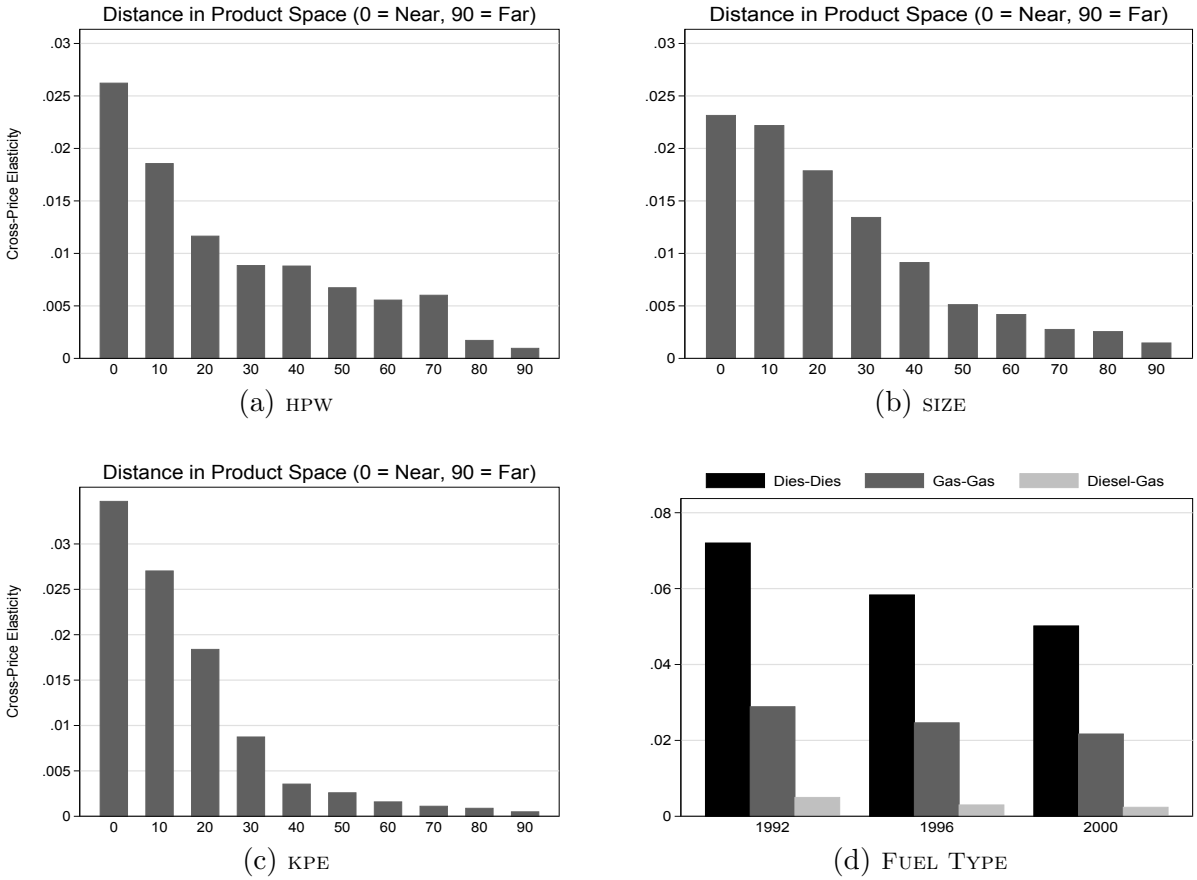
(b) Diesel: $\hat{\xi}$

Table G.1: Distribution of Attributes

	2000 *vs* 1992		1992 *vs* 2000	
	SD1	SD2	SD1	SD2
GASOLINE				
C90	0.202	0.207	0.723	0.509
KPE	0.000	0.000	1.000	0.789
SIZE	0.697	0.825	0.454	0.273
HPW	1.000	0.830	0.024	0.003
$\hat{\xi}$	0.798	0.532	0.202	0.174
DIESEL				
C90	0.845	0.670	0.000	0.000
KPE	0.000	0.000	1.000	0.780
SIZE	1.000	0.865	0.000	0.000
HPW	0.002	0.123	0.000	0.000
$\hat{\xi}$	1.000	0.736	0.000	0.000

Kolmogorov-Smirnov tests of first (SD1) and second (SD2) order stochastic dominance where reported p-values are based on the consistent inference of Barrett and Donald (2003) using 1000 replications and 100 grid points on two random samples, for 1992 and 2000, of a thousand draws from the kernel distribution densities of each attribute. A p-value smaller than 0.05 *rejects* the null stochastic dominance hypothesis.

Figure G.3: Cross-Price Elasticities



(a) HPW (b) SIZE

(c) KPE (d) FUEL TYPE

Table G.2: Implicit Tariff by Year and Estimation Approach

	Import	Baseline		No Trend		BLP	
Year	Tariff	LB	UB	LB	UB	LB	UB
1992	14.40	16.29	17.23	16.29	17.23	16.84	18.48
1993	10.30	12.67	13.81	13.22	14.15	13.35	15.46
1994	10.30	12.55	13.83	13.69	14.60	12.95	14.93
1995	10.30	12.92	14.64	15.05	16.04	13.73	16.37
1996	10.30	12.78	14.54	15.76	16.83	13.67	16.08
1997	10.30	12.74	14.63	16.56	17.53	13.12	15.50
1998	10.30	12.97	15.27	18.73	19.87	13.43	16.04
1999	10.30	13.58	16.52	21.82	23.40	14.22	17.62
2000	10.30	13.41	16.36	23.41	24.78	14.09	17.44

Notes: "Import Tariff" is the official import tariff placed on foreign imports. Lower bound ("LB") and upper bound ("UB") abatement estimates based on installing a Lean NOx Catalyst (LNC). Technical and cost details located in Appendix D.