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Abstract

Spurred by Volkswagen's introduction of the TDI diesel engine in 1989, market penetration of diesel cars in Europe increased from 10% in 1990 to over 50% in 2000. Using Spanish automobile registration data, we estimate an equilibrium discrete choice, oligopoly model of horizontally differentiated products. We find that changing product characteristics and the increasing popularity of diesels leads to correlation between observed and unobserved (to the researcher) product characteristics, an aspect we allow for in the estimation. Despite widespread imitation by its rivals, Volkswagen was able to capture 32% of the potential innovation rents and diesels accounted for approximately 60% of the firm's profits. Moreover, diesels amounted to an important competitive advantage for European auto makers over foreign imports. We provide evidence that the greenhouse emissions policy enacted by European regulators, and not preferential fuel taxes, enabled the adoption of diesels. In so doing, this non-tariff policy was equivalent to a 20% import tariff; effectively cutting imports in half.

JEL Classification: F13, L62 and O33

Keywords: diesel cars, emission standards, import tariff equivalence and innovation rents

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1 Introduction

The European automobile market is inconspicuously unique in a way that might escape tourists traveling to the Old Continent. Most American tourists will recognize that European vehicles are smaller (something not unique to Europe) but those renting a vehicle will likely be surprised to learn that they have to refuel with diesel rather than gasoline. The introduction of a new technology – the turbocharged direct injection (TDI) diesel engine – by VOLKSWAGEN in 1989 took diesel penetration from around 10% market share in most European countries to in excess of 60% market share by the beginning of the financial crisis in 2008.[1] Surprisingly, this dramatic transformation of the European automobile industry has failed to attract the interest of innovation economists.[2]

We evaluate the effects of this technological innovation using automobile registration data from Spain – a country which exhibited diesel adoption rates representative of Europe as a whole. We employ the equilibrium discrete choice oligopoly model of 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 plausible substitution patterns between similar products while accounting for product characteristics known to consumers and firms but not to the researcher. For us, the framework also provides an opportunity to evaluate many counterfactuals of interest since changes in regulation, taxes, or demand and supply conditions result in new equilibrium prices and market configurations.

An important identification assumption used in the standard *BLP* estimation is that observable and unobservable product characteristics are uncorrelated. This is problematic in our context as we observe both a substantial increase in diesel purchases and changing product characteristics. Further, both observable and unobservable product attributes determine sales of vehicles but the latter likely drive the sales of diesels as consumers discover the greater performance of this new technology during the diffusion period of our sample. Instead, our estimation approach accounts for the potential correlation between observable and unobservable automobile characteristics by allowing firms to choose product attributes, observed or otherwise. Firm product choices then influence optimal equilibrium prices of automobile manufacturers through own and cross-price effects of manufacturers' vehicle offerings.

[1] See *Automobile Registration and Market Share of Diesel Vehicles* in "ACEA European Union Economic Report," December 2009. This quick adoption process compares favorably to many others innovations such as steam and diesel locomotives (Greenwood, 1997); the basic oxygen furnaces for steel mills (Oster, 1982); and the coal-fired, steam-electric high-pressure power generation (Rose and Joskow, 1990).

[2] Perhaps a plausible explanation for this state of affairs is that well over two decades after the TDI breakthrough the European automobile market remains an oddity in the global automobile industry as diesel passenger vehicles failed to succeed anywhere else except, recently, in India. See Chug, Cropper and Narain (2011).

We are not the first to allow for correlation between observed and unobserved product characteristics. Indeed, Petrin and Seo (2015) first made use of optimal instruments to account for the possibility of endogenous product characteristics. We borrow their methodology and confirm most of their conclusions obtained using the original *BLP* database. We find significant correlation between observed and the estimated unobserved product characteristics. We also find that our estimation approach yields demand estimates which are more elastic than employing a standard *BLP* estimation and more significant point estimates, particularly for the random coefficients – a noted difficulty with the standard *BLP* model. The cost of obtaining more efficient estimates of random coefficients is the substantially increased computational burden but our results add to the claim of Petrin and Seo (2015) that *BLP* overestimates equilibrium markups.

In order to measure the importance of the TDI innovation we follow an approach similar to Berry, Levinsohn and Pakes (1999) in addressing the effects of Voluntary Export Restraints, or Petrin (2002) to account for the redistribution of profits among auto makers after the introduction of the minivan. We find that eliminating diesels altogether generates significant losses for European auto makers – the firms who adopted the technology – but would have resulted in nearly a doubling in market share for non-European auto makers, particularly Asian manufacturers such as Honda and Toyota. This indicates that diesel vehicles represented a significant competitive advantage for domestic (*i.e.*, European) auto makers. We also show that despite large-scale imitation by its European rivals, VOLKSWAGEN was able to secure significant profits from the TDI and captured 32% of the potential rents from its innovation.

Subsidization of diesel fuel is commonly credited with providing drivers with strong incentives to purchase diesel vehicles. We evaluate this hypothesis and conclude that diesel fuel subsidization is only responsible for a small 1.5% additional market share of diesel vehicles in 2000. This is clearly not enough to explain the large shift of demand in favor of diesel vehicles.[3]

Instead we provide evidence that the success of diesel vehicles in Europe was, in large part, the consequence of the European greenhouse standards implemented in the early 1990s. If European authorities had followed an emissions policy similar to the United States, focused on the effects of acid rain, the overwhelming adoption of diesels automobiles would have not taken place in Europe, leaving diesels as a market niche well below the levels of the 1980s. Under such alternative policy, mileage conscious drivers would have shifted their purchases towards the fuel efficient gasoline Asian imports, leading to a near doubling of their market share from 11% to 19 percent.

[3] Linn (2014) relates fuel taxes and environmental considerations to explain the within-Europe, cross-country differences in diesel automobiles market penetration while Grigolon, Reynaert and Verboven (2014) evaluate whether a fuel tax or a tax linked to vehicle fuel efficiency helps achieve larger fuel savings by steering consumers to purchase different cars and/or driving less. Both studies use a more mature market sample period than ours, 2002-2010 and 1998-2011, respectively, once the growth of diesel penetration rates have stabilized.

Therefore, the European emissions policy induces important distortion effects in the European automobile market. We find that the induced protection was substantial, nearly the equivalent of a 20% import tariff when the actual import duty amounted only to 10.3%. These results are important as they provide evidence that in a world with ever more free trade agreements, national policies such as environmental regulations might be used as a tool to favor local manufacturers over competitive imports, *e.g.*, Ederington and Minier (2003) – an important finding and perhaps the most original contribution of the paper.

To be clear, we are not claiming that European regulators designed their emission standards strategically to explicitly promote domestic auto makers. Rather, we argue that regardless of whether it was the intent of the policymaker or not, environmental policy became a powerful tool to protect the domestic European auto makers.[4] Linking environmental and trade policies, our work builds on the literature related to the interaction of domestic policy and international trade.[5] Our work contributes to this literature by being, to the best of our knowledge, the first application of equilibrium models commonly used in empirical industrial organization to provide evidence of rent-seeking by countries using domestic regulation policy.

The paper is organized as follows. In section 2, we describe the TDI innovation, its imitation by European auto makers, and summarize the main features of the Spanish market for diesel automobiles. Section 3 describes the equilibrium model of discrete choice demand for horizontally differentiated products with endogenous prices and characteristics. Section 4 reports the estimation results, summarizes the main findings, and documents the need to obtain optimal instrumental variables to address the potential correlation between observed and unobserved product characteristics. Section 5 addresses the dissipation of VOLKSWAGEN's innovation rents due to the generality of the TDI technology and the increase of competition in the diesel segment. In Section 6 we discuss the trade effects of emissions policies enforced by European regulators and investigate the equilibrium implications different emission standards: survival of diesel engines under the U.S. NO_x emission standards and the magnitude of the implicit trade protection level induced by the European environmental regulation. In Section 7 we discuss the robustness of our results by evaluating the role of favorable diesel fuel taxation; comparing our results to those implied by a standard *BLP* model and estimation strategy; and addressing alternative modeling assumptions. Finally, Section 8 concludes. Details of the estimation, additional results, data sources, and institutional details of the Spanish automobile market are documented in the Appendices.

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[4] As far as we know the trade consequences of the environmental policy did not occur by design, *i.e.*, it was not an explicit attempt to protect the European automobile industry, but rather the result of legislative inertia.

[5] The seminal contribution on this topic is Bhagwati and Ramaswami (1963) who address the substitutability between domestic policy and import tariffs. More recent works (*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.

2 The European Market for Diesel Automobiles in the 1990s

This section intends to get the reader familiarized with the basic characteristics of the diesel technology and TDI innovation; 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.

2.1 What Is a TDI Engine?

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 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 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. 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, Europeans enthusiastically embraced diesel automobiles. The incredible pace of adoption of diesel automobiles suggests that the TDI proved to be a significant technological and consumers gained little from waiting for additional incremental improvements, which have been few and of minor importance.[7]

2.2 Initial Market Conditions

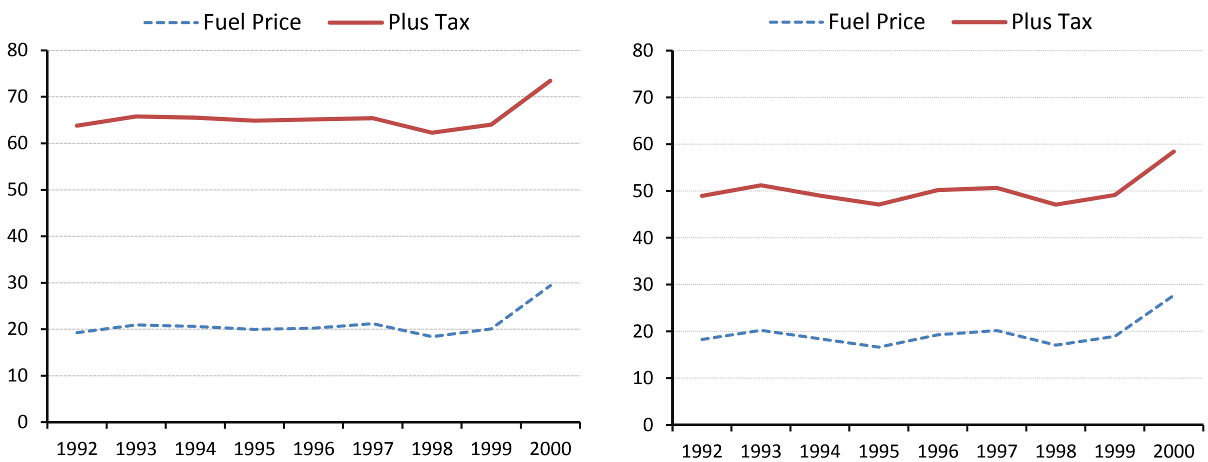
There are important institutional circumstances that helped build the initial conditions that were particularly favorable for the adoption of this new technology in Europe. The key element triggering all these favorable development is the *European Fuel Tax Directive* of the 1973.

[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 recently 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.

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. 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. This favorable treatment of diesel fuel 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]

[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.

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 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 the way they did it. 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.

2.3 Imitation

Figure 2 demonstrates that imitation of the TDI occurred quickly and was largely driven by rival European auto makers. This indicates the ineffectiveness of VOLKSWAGEN to defend its innovation via the patent system since it was not difficult for rival firms to offer their own equivalent diesel models in a relatively short period of time. This suggests a low cost of imitation – a trait which characterizes all "general technologies" (*e.g.*, Bresnahan 2010) – due to the fact the technology can be easily modified or reverse engineered.

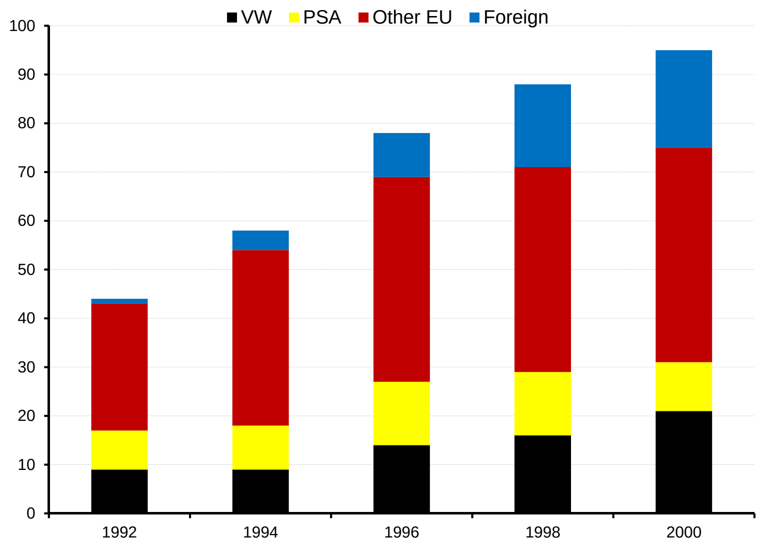
For the consumers, imitation led to the introduction of more variety and better quality of vehicles to choose from while competition intensified in this market segment, keeping diesel vehicles affordable, and therefore reinforcing the fast diffusion of this new technology.[11] When imitation is

[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 retrofitted 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.

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

[11] VOLKSWAGEN was an important firm but not the leader in the Spanish market: RENAULT was by far the leader in the gasoline segment and PSA, which includes the French brands CITROËN and PEUGEOT, in diesel. See Figure D.1 in the Web Appendix.

Figure 2: Number of Diesel Models Offered

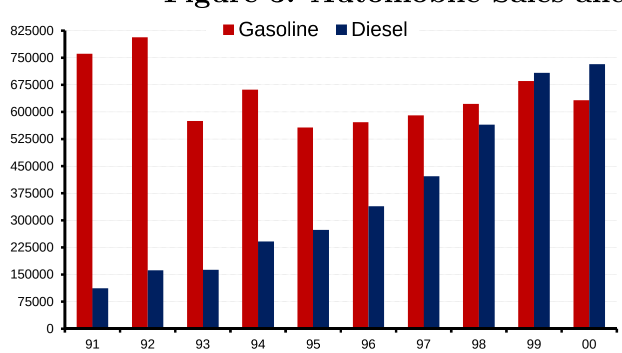


easy and potentially massive, uncertainty about recouping sunk investment costs may hinder the development of new technologies in the first place. Consequently, the financial repercussions for firms of working with this general technology, are uncertain. We will address this issue in Section 5 for the case of VOLKSWAGEN.

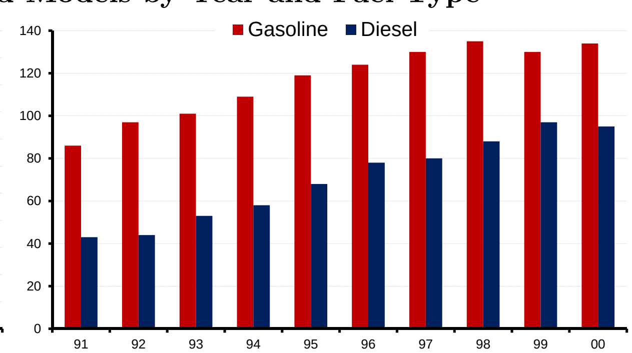
2.4 Evolution of Automobile Characteristics in Spain

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. 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 3: Automobile Sales and Models by Year and Fuel Type



(a) Sales (thousands of vehicles)



(b) Models Available

Figure 3 documents the evolution and composition of sales in Spain during the 1990s. Figure 3(a) shows that sales of gasoline models were essentially identical in 1993 and 1995, about 573,000, despite a scrappage program in 1994, when they temporarily increased by 15%. Since then, sales of gasoline models increased at a steady pace until 1999 but they never reached the 1992 peak level again. The evolution of sales of diesel automobiles is starkly different. Initially in 1992, they only represented 16% of total sales. After the scrappage programs were implemented, they grew at faster rates between 1994 and 1999. Thus, by the end of the decade diesels represented 54% of the market, as they grew from 161,667 to 732,334 units sold in years 1992 and 2000, respectively.

There was an equally impressive transformation of supply to meet this quick shift in demand. Figure 3(b) shows that by 1992, manufacturers already offered 44 diesels out of 141 models sold (although not all of them comparable to TDI). Such a large number of diesel models hints at automobile manufacturers fearing business stealing much more than the consequences of cannibalizing the sales of their own gasoline models. It also suggests that VOLKSWAGEN expected competitors to enter this segment when it decided to introduce the TDI technology. 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.[12] Since the entry of new models should reduce markups, consumers benefited from both an increase in variety and lower prices.

Table 1 summarizes the evolution of the features of vehicles sold in the Spanish automobile market during the 1990s.[13] Prices of gasoline and diesel models increased roughly the same, 35% and 32%, respectively. However, notice 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. Overall, a quarter of a million fewer gasoline vehicles were sold by the end of decade while the production of diesel models increased by over half a million units, almost quadrupling production. Sales of diesel became so important that non-European auto makers began introducing their own diesel models.[14]

[12] 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.

[13] Table D.1 in Appendix D complements this description of the evolution of product features reporting statistics by market segment.

[14] See Busser and Sadoi (2004, Footnote 2). Demand for diesel vehicles in their countries of origin was so small that Asian manufacturers acquired engines from other European firms as a less costly way to satisfy local European demand rather than investing in the development of diesel engines from scratch.

Table 1: Car Model Characteristics by Origin and Engine Types

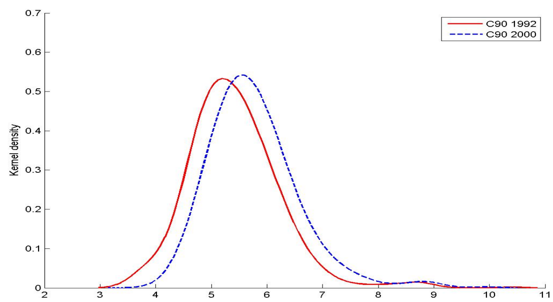
YEAR/GROUP	MODELS	SHARE	PRICE	C90	KPE	SIZE	HPW
1992							
EU: DIESEL	43	16.60	12.26	4.45	46.42	73.84	31.43
EU: GASOLINE	73	79.45	11.05	5.39	29.62	71.50	41.22
NON-EU: DIESEL	1	0.09	13.76	5.30	38.58	80.51	28.61
NON-EU: GASOLINE	24	3.86	14.88	5.82	27.31	77.99	45.27
ALL	141	100.0	11.40	5.25	32.33	72.15	39.74
2000							
EU: DIESEL	75	50.95	16.19	4.55	38.18	76.32	31.43
EU: GASOLINE	84	37.28	14.93	5.68	24.23	73.40	38.98
NON-EU: DIESEL	20	2.71	17.20	5.41	32.63	82.48	32.15
NON-EU: GASOLINE	50	9.06	13.66	6.11	22.80	75.32	40.85
ALL	229	100.0	15.52	5.13	31.43	75.31	35.12

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 thousand pounds of weight.

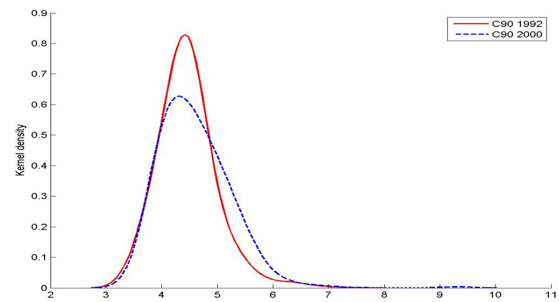
When deciding what type of engine to purchase, consumers compare product characteristics, observable to us, and expected performance of each engine, unobservable to us but likely related to the characteristics of each engine type. Diesel and gasoline versions of a particular model have the exact same size although the latter are lighter. Overall, 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 gasoline models, allowing for about 58% longer distances per euro of fuel.

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 4 and formal tests of first and second order stochastic dominance are presented in Table D.2 in Appendix D. 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. Diesel vehicles on the other hand, show sign of substantial change during the decade: diesel vehicles 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 these hints at diesel vehicles becoming better products capable of increasingly attracting the interest of many drivers.

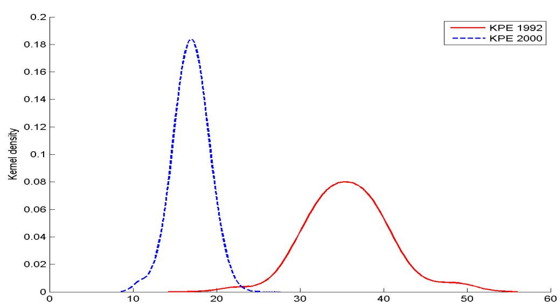
Figure 4: Change in the Distribution of Automobile Attributes



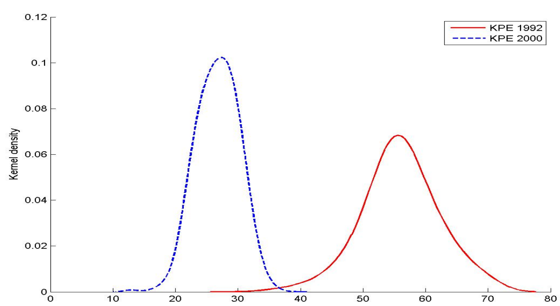
(a) Gasoline: Mileage (C90)



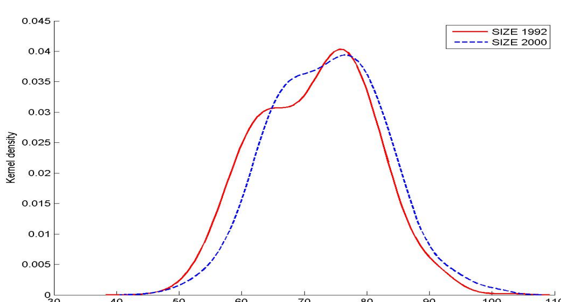
(b) Diesel: Mileage(C90)



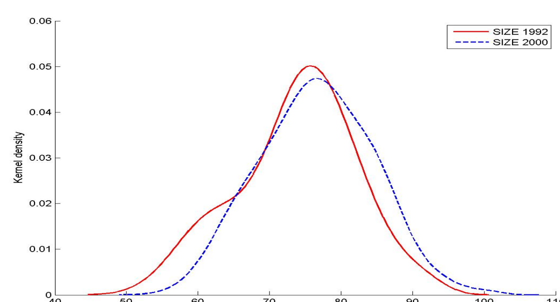
(c) Gasoline: Cost of Driving (KPE)



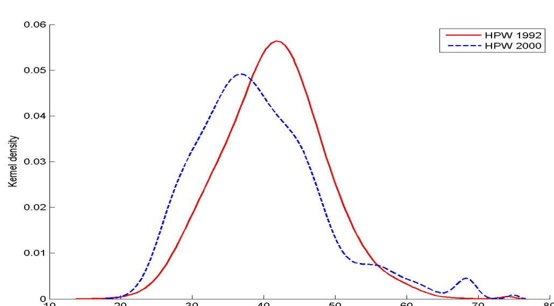
(d) Diesel: Cost of Driving (KPE)



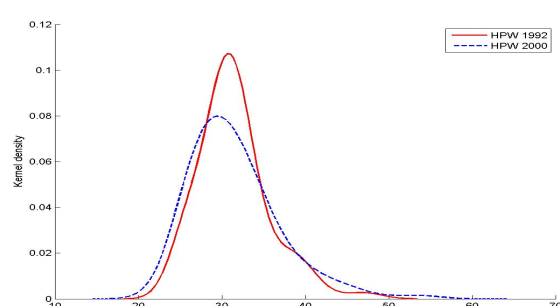
(e) Gasoline: SIZE



(f) Diesel: SIZE



(g) Gasoline: Performance (HPW)



(h) Diesel: Performance (HPW)

3 An Equilibrium Oligopoly Model of the Automobile Industry with Correlated Product Characteristics

We follow Petrin and Seo (2015) in extending the well-known *BLP* equilibrium model of discrete choice oligopoly with horizontally differentiated products to allow for correlation between observed and unobserved product characteristics. In this section we first present a standard model of discrete-choice demand with heterogenous consumers. Then we describe an oligopoly model of supply in which multi-product firms comprising several brands detailed in Table A.1 choose product characteristics first (*e.g.*, car size) and then compete in retail price given observed and unobserved product attributes.

3.1 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:

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

This Lancasterian approach makes the payoff of a consumer depend on the set of characteristics of the vehicle purchased, which includes a vector of n 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:[15]

$$\begin{pmatrix} \alpha_i^* \\ \beta_i^* \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta_t \end{pmatrix} + \Pi_t D_{it} + \Sigma_t \nu_{it}\,, \quad \nu_{it} \sim N(0, I_{n+1})\,. \tag{2}$$

Consumer i in period t is characterized by one unobserved and a d vector of observed demographic attributes, D_{it} and ν_{it}. In our case, we allow the estimate of the slope of demand to vary with per capita income. 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

[15] 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.

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}. These mean utilities of choosing product j and the idiosyncratic deviations around them are given by:

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

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

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:

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

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 ν_{it}, denoted by $P_D(D_t)$ and $P_\nu(\nu_t)$, respectively, leads to the model prediction of the market share for product j at time t:

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

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

3.2 Supply

The industry is characterized by multi-product automobile manufacturers behaving as oligopolistic, non-cooperative profit maximizers which take product entry, including engine type, as given and choose observed and unobserved (to the econometrician) product characteristics and price. While a firm's choice of observable product characteristics may be intuitive, it is worthwhile to provide some intuition as to what it means for a firm to choose an unobservable product characteristic. For example, increasing popularity of diesel vehicles over the decade may encourage AUDI to not only introduce more varieties of diesel vehicles but also improve these vehicles torque, reliability, *et cetera*. Ignoring this relationship could potentially lead to a violation of product characteristic exogeneity, leading to biased results.[16]

As Petrin and Seo (2015) did with the *BLP* data, we also consider the problem of a multi-product firm f which chooses product characteristics x_j^k in period t to solve:

$$\max_{x_j^k} E\left[\sum_{r\in\mathcal{F}_f}(p_r - c_r)\times s_r(\cdot)\,\Big|\,\Psi_f\right], \tag{7}$$

where $\mathcal{F}_f$ is the set of vehicles of all brands sold by firm f and Ψ_f is its information set. The t subscript has been dropped to simplify notation. The subsequent optimal pricing strategy will be a function of product positioning of all competing firms. Thus, in choosing product attributes, profit maximization yields the following first order condition:

$$E\left[s_j\times\frac{\partial(p_j-c_j)}{\partial x_j^k}+\sum_{r\in\mathcal{F}_f}(p_r-c_r)\times\frac{\partial s_r}{\partial x_j^k}\,\Big|\,\Psi_f\right]=0\,, \tag{8}$$

where:

$$\frac{\partial s_r}{\partial x_j^k}=\begin{cases}\displaystyle\int_{\nu^k}\int_D(\beta^k+\sigma^k\nu^k+\pi^kD)\times s_{ij}(1-s_{ir})dP_D(D)dP_\nu(\nu)+\sum_{m\in\mathcal{F}_f}\frac{\partial s_r}{\partial p_m}\frac{\partial p_m}{\partial x_j^k}, & r=j,\\[2ex] \displaystyle-\int_{\nu^k}\int_D(\beta^k+\sigma^k\nu^k+\pi^kD)\times s_{ij}s_{ir}dP_D(D)dP_\nu(\nu)+\sum_{m\in\mathcal{F}_f}\frac{\partial s_r}{\partial p_m}\frac{\partial p_m}{\partial x_j^k}, & \text{otherwise}\,.\end{cases} \tag{9}$$

In the *BLP* framework product attributes are taken as given although they determine pricing strategies and the ability to charge a higher or lower markups depending on the product positioning of all firms. Profit maximization conditions (8)-(9) 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 and firms do not respond 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 and unobserved attributes are unlikely to be uncorrelated with observable product characteristics.

[16] Of course, a cleverly chosen set of control variables would also remove any exogeneity concerns (*e.g.*, Nevo 2000), but this is often difficult in practice. An advantage of our approach is that we can be agnostic about the controls in the estimation and identify patterns in unobserved demand via OLS afterwards. The downside of our approach is obviously the substantially increased computational burden. We discuss the potential implications of assuming exogeneity of product entry decisions, particularly related to engine type, in Section 7.

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

$$p_j^\tau = \frac{p_j}{1+\tau_j} = mc_j + \underbrace{\Delta^{-1}(p, x, \xi; \theta) s_j(p, x, \xi; \theta)}_{b_j(p, x, \xi; \theta)}, \tag{10}$$

where τ_j is the import duty applicable model j, if any; $b_j(\cdot)$ is the vector of equilibrium markups; $s_j(\cdot)$ is the vector of market share estimates for each vehicle-year pair; and $\Delta(\cdot)$ is the ownership matrix with elements:

$$\Delta_{rj}(x, p, \xi; \theta) = \begin{cases} \dfrac{\partial s_r(x, p, \xi_t; \theta)}{\partial p_j^\tau}, & \text{if products } \{r, j\} \in \mathcal{F}_f\,, \\ \\ 0 & \text{otherwise}\,. \end{cases} \tag{11}$$

Finally, as it is common in the literature, we assume that firms have Cobb-Douglas cost functions of the following (log-linear) form:

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

Marginal costs are therefore a function of both observed and unobserved product characteristics, via X and ξ, and an unknown (to the econometrician) cost component η. 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.*, $\partial c/\partial \xi$. This is particularly relevant in our case as many features likely driving the cost of diesel vehicles such as torque, reliability, and durability remain unobservable to us.

4 Estimation

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. 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 to control for the differentiated import taxation faced by manufacturers depending on their national origin. Finally, 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.[17]

As we have argued, supply and demand of diesel vehicles is likely to be driven by product characteristics such as torque ratio or reliability that might be observable to manufacturers, learned by consumers, but remain unobserved for econometricians. The common practice in the *BLP* literature is to assume that all product characteristics are exogenous while price is not and then construct price instruments using functions of the product characteristics. However, these unobservable product characteristics are likely correlated with other observable vehicle attributes. This is true even in a static frameworks but in our case product characteristics change rapidly and diesels are fast improving during the decade, which suggest that this correlation among attributes will be even more likely to happen.

In our data, we observe that the product characteristics embodied in the car models offered by firms do not appear to be random. Rather, we documented an increasing number of diesel vehicles in the choice set, *e.g.*, Figures 2 and 3, as well as cars becoming larger, heavier, and more fuel efficient, etc during the 1990s, *e.g.*, Figure 4. Consequently, assuming product characteristic exogeneity is not appropriate in our context. Instead, we propose an alternative estimation strategy which allows for endogenous product characteristics and uses the firms' first-order conditions for profit maximization to identify the structural demand and supply parameters. Specifically, we consider the case where firms choose vehicle size, horsepower/weight ratio, and fuel efficiency as well as the unobserved component, ξ. This allows us to account for changes in the demand valuation and cost of diesel vehicles over time as captured via ξ.

4.1 The GMM Estimator

We estimate the structural parameters of the model by generalized method of moments (GMM) as in Hansen (1982). Define the parameter vector $\Theta = [\beta, \Sigma, \Pi]$. First, we solve for the mean utilities $\delta(\theta)$ using the standard contraction mapping outlined in Appendix I of *BLP*. Next we solve for the implied markups b_{jt} and use price data to construct marginal costs, assuming a pure strategy Bertrand-Nash equilibrium. Next, we recover γ by regressing log marginal costs on the observable (*e.g.*, SIZE) and unobservable (ξ) product characteristics as well as a set of controls such as fuel type, a time trend, and brand (*e.g.*, Audi) and segment (*e.g.*, LUXURY) fixed effects. Our identifying assumption is that the remaining error constitutes i.i.d. cost shocks which are uncorrelated with

[17] See Table A.1 in Appendix A for further details on import tariffs and mergers in the European automobile industry during the 1990s.

the product characteristics and controls. This is a reasonable assumption since firms in the model take the product set, including fuel type, as given.[18] With the supply estimates at hand we then construct the structural error $\varepsilon_j^k(\Theta)$ defined by equations (8) as follows:

$$\varepsilon_j^k(\theta) = s_j(\theta) \times \frac{\partial[p_j^\tau - c_j(\theta)]}{\partial x_j^k} + \sum_{r \in J_f} [p_r \tau - c_r(\theta)] \times \frac{\partial s_r(\theta)}{\partial x_j^k}\,. \tag{13}$$

The evaluation of the response of demand for all products of each firm to each change in product characteristics makes this task particularly computationally-intensive as it requires solving repeatedly for the equilibrium price responses due to changes in product characteristics in addition to evaluating numerically the multiple integrals of equation (9).

Profit-maximization requires that in each period t the expectation of the structural error ε conditional on product characteristics equals zero for all products $j \in \mathcal{F}_f$ and characteristics k, *i.e.*, $E[\varepsilon_{j,t}^k(\theta)|X, W, \omega] = 0)$. Since any function of the demand and supply characteristics X, W are valid instruments, the set of potential instruments is large. Chamberlain (1987) shows the "optimal" (*i.e.*, most efficient) instruments are:

$$H_j^k(\theta) = E\left[\frac{\partial \varepsilon_j^k(\theta)}{\partial \theta}\Big| X, W, \omega\right]\,. \tag{14}$$

The logic behind these instruments is straightforward: they place relatively more weight on observations that are responsive to changes in the estimates of θ. We solve for the value of the GMM objective function conditional on θ by interacting the structural errors (13) with the identifying moment conditions (14) as follows:

$$\theta^\star = \underset{\theta}{\operatorname{argmin}}\, G(\theta)' A^{-1} G(\theta)\,, \tag{15}$$

where $G(\theta) \equiv E[H(\theta) \otimes \varepsilon]$ and A^{-1} is a positive-semidefinite weighting matrix that exists because there are $(K+1)$ instruments for each element of θ. In constructing the weighting matrix, we allow for the structural errors ε within a car model to be correlated across characteristics and time. Consistent estimation of θ^* requires updating both the instruments H and the weight matrix A^{-1}. To improve efficiency of the estimation we implement the iterative GMM estimator of Hansen, Heaton and Yaron (1996). Thus, we obtained our parameter estimates by GMM where the estimator exploits the fact that at the true value of parameters $\theta^\star$, the instruments H are orthogonal to the errors $\varepsilon(\theta^\star)$, *e.g.*, $E\left[H \otimes \varepsilon(\theta^\star)\right] = 0$. We repeatedly update the weighting matrix A^{-1} until the

[18] Alternatively, we could have relaxed our OLS assumption and allowed for correlation between η and the product characteristics, including γ in θ and recovered these point estimates via GMM. Since it is difficult to identify a reason for such a correlation once accounting for ξ, we chose our current approach which simplifies the estimation by decreasing the size of the parameter space. See Appendix B for details.

estimates of θ converge. To ensure the robustness of our 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).

This model represents a complex, nonlinear mapping from parameters to data. 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 prices conditional on similar product characteristics identifies the product price elasticities while cross-price elasticities are identified by differential changes in prices and quantities across products with similar characteristics. Variation between product characteristics and sales pins down the mean utility parameters (β) so diesel market share conditional on other product characteristics identifies consumer preferences for diesel engines (β_{DIESEL}). The interaction between product characteristics (*e.g.*, price) and distribution of demographics identifies the interaction coefficient (Π). Variation in the product set, product characteristics (*e.g.*, SIZE), prices, and quantities identifies the random coefficients (σ). Lastly, the Bertrand-Nash equilibrium plus variation in price elasticities conditional on product characteristics identifies marginal costs (γ).

4.2 Estimation Results

We estimate the model using the 1992-2000 sample period. Demand includes a measure of automobile performance, horsepower divided by weight (HPW); exterior dimensions (SIZE); and fuel cost of driving, (KPE), with units defined in the caption to Table 1. All these variables includes a random coefficient as well as DIESEL to generate substitution within the diesels and CONSTANT to capture changes in substitution patterns due to the increasing product set.

On the supply side, the log of marginal cost of production is made a function of the type of fuel, DIESEL; logs of product characteristics (HPW, WEIGHT, SIZE, C90); a time trend aimed at capturing potential efficiency gains, TREND; and the unobservable attribute, ξ. In addition to the reported estimates, the cost equation also included brand-specific and segment fixed effects. We further allow for small differences between the demand and supply characteristics, including C90 in the supply equation to account for the cost of improving a purely technical measure of fuel efficiency while KPE, which includes the effect of fluctuations in the price of oil, independent of production technology is included in the demand specification. Consequently, AUDI's choice of fuel efficiency for a gasoline 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, changes in the price of steel are allowed to impact HPW and SIZE in supply but not demand.

Table 2: Demand and Supply Estimates

Variable	Coefficient	Rob. SE	Variable	Coefficient	Rob. SE
Mean Utility (β)			Cost (γ)		
KPE	0.2679	(0.3290)	C90	0.1311	(0.0260)***
SIZE	−13.2042	(0.6000)***	SIZE	0.8429	(0.0497)***
HPW	1.5288	(0.4961)***	HPW	0.3558	(0.0187)***
CONSTANT[b]	5.7410	(0.2243)***	CONSTANT	0.3964	(0.0761)***
DIESEL[b]	−2.3586	(0.5275)***	DIESEL	0.1948	(0.0087)***
DIESEL_{93}^{b}	0.7559	(0.6620)	TREND	0.0137	(0.0013)***
DIESEL_{94}^{b}	2.2892	(0.6524)***	ξ	0.0428	(0.0014)***
DIESEL_{95}^{b}	2.0952	(0.6377)***			
DIESEL_{96}^{b}	3.0923	(0.6308)***			
DIESEL_{97}^{b}	3.7642	(0.6389)***			
DIESEL_{98}^{b}	2.3827	(0.6428)***			
DIESEL_{99}^{b}	3.5044	(0.6495)***			
DIESEL_{00}^{b}	2.2448	(0.6684)***			
NON-EU[b]	−1.5035	(0.1882)***			
Standard Dev. (σ)			Interactions (Π)		
KPE	3.1142	(0.2649)***	Price/Income	−16.8963	(0.8800)***
SIZE	1.4304	(0.9971)			
HPW	1.4671	(0.5383)***			
CONSTANT	2.8582	(0.0274)***			
DIESEL	2.1196	(0.0493)***			
Elasticity Statistics			Margin Statistics (%)		
- Average	8.7		- Average	12.9	
- Maximum	20.8		- Maximum	20.0	
- Minimum	5.4		- Minimum	6.3	
Estimation Statistics					
Number of observations	1,740				
Simulated agents per year	5,000				
J-statistic (df)	116.8 (27)				

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 Table A.1 in Appendix 2.

The GMM estimation generates a $1,740 \times 1$ vector of unobserved product characteristics. We projected this vector onto a set of dummies to identify systemic patterns in demand. As this time period covers the diffusion of diesel vehicles, we include a DIESEL dummy as well as a nonlinear time interaction with DIESEL in order to capture the evolution of preferences in favor of the new technology (in addition to non-reported segment fixed effects and a time trend). Finally, we added the NON-EU dummy to account for differences in valuation of the recently introduced Asian imports in the European market.[19]

Table 2 reports the estimation results. Estimates are reasonable and congruent with the descriptive evidence of the industry of Section 2. Starting with supply, diesels are more expensive to manufacture than gasoline models. Marginal cost of production are also higher for fuel efficient vehicles, larger, and more powerful cars. It 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, observe that costs are also increasing in the unobserved 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.

Figure 5: Production Costs Differences Across Brands (Reference: Renault)

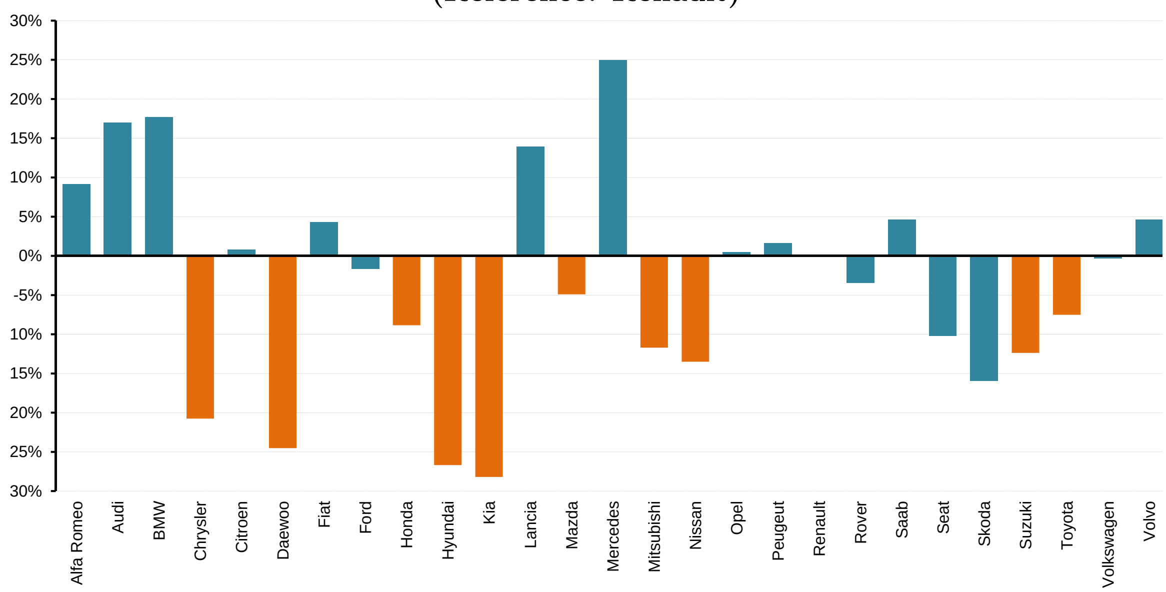


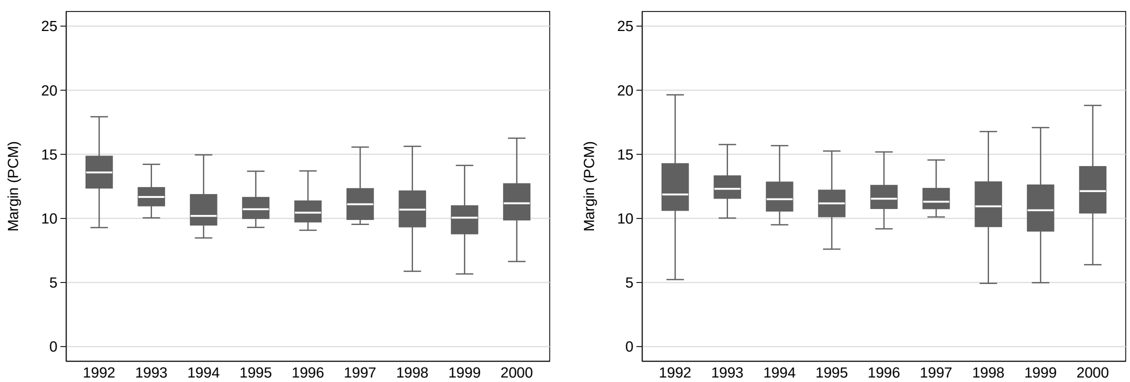
Figure 5 depicts the non-reported, cost related, brand fixed effects relative to the Spanish market leader, RENAULT. Results are very reasonable, capturing the common perception of the automobile market in Spain. German upscale brands AUDI, BMW, and MERCEDES, are among the most expensive to produce. Chrysler (U.S. based) and Asian imports are quite competitive, with Korean imports DAEWOO, HYUNDAI, and KIA, averaging a 25% relative cost advantage. European

[19] Not reported is a small, positive but insignificant SEAT indicator intended to capture any potential home bias effect in Spanish drivers' automobile purchasing decisions. In addition we also considered the aggregate output of each model in the European market aggregating sales by model (not distinguishing by fuel type) from Belgium, France, Germany, Italy and United Kingdom to Spanish sales using Frank Verboven's data available at `http://www.econ.kuleuven.be/public/ndbad83/frank/cars.htm`. This measure of scale was never significant though, implying that automobile manufacturers enjoy Europe-wide constant returns to scale.

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 low quality 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.

As for demand, Table 2 shows that it is downward slopping and always elastic, with an average 8.7 price elasticity that in combination with the cost estimates leads to an average 13% margin for the Spanish automobile industry during the 1990s. There is however substantial heterogeneity, with margins as low as 6% and as high as 20%. 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.[20] Figure 6 shows that average margins, both of gasoline and diesel vehicles, remain quite stable, only decreasing very slightly during the 1990s. In the case of diesel vehicles this margin reduction is more pronounced at the beginning of the decade when the number of diesel models available increases significantly. For both engine types, the dispersion of margins is substantially larger during the last three years of the sample.

Figure 6: Evolution of Price-Cost Margins



(a) Diesel Vehicles (b) Gasoline Vehicles

Estimates of Table 2 show that Spanish drivers mostly value smaller European cars delivering high performance (negative SIZE, negative NON-EU, and positive HPW). The negative sign of NON-EU is an empirical regularity in the international trade literature and is commonly referred to as the "home bias" effect. 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

[20] 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.

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.

On average, fuel cost does not rank high among Spanish drivers' concerns (insignificant KPE) as fuel prices remain quite stable until the end of the decade, precisely when jobs and personal income is growing at record rates. Yet, there exists very significant heterogeneity of preferences regarding fuel cost of driving (large positive σ_{KPE}). As for performance, tastes vary but the vast majority of drivers favor high HP to WEIGHT ratios (significant but relatively small σ_{SIZE}). There is however little heterogeneity regarding the preference for small vehicles (insignificant σ_{SIZE}).

Notice that diesel vehicles are not particularly valued at the beginning of the 1990s. However, during the economic growth phase of the second half of the decade, drivers clearly favored them. The interaction of the nonlinear time trend and the DIESEL dummy captures this change in preferences in favor of diesel vehicles. It is therefore likely that consumers become increasingly aware of the features of diesel vehicles as they encounter them more frequently on the road.[21] These results show that consumers' perception of diesels evolves favorably over the decade as diesel vehicles become more widespread.

Table 3: Are Product Characteristics Correlated?

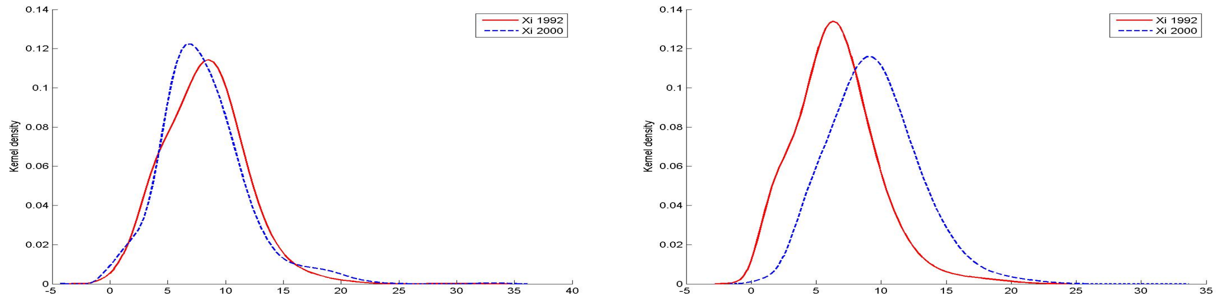
	KPE	SIZE	HPW	$\hat{\xi}$
KPE	1.0000 -			
SIZE	-0.3215 (0.0276)	1.0000 -		
HPW	-0.5955 (0.0303)	0.3921 (0.0187)	1.0000 -	
$\hat{\xi}$	-0.2997 (0.0273)	0.8337 (0.0098)	0.5222 (0.0166)	1.0000 -

Standard errors reported in parentheses.

We have appealed repeatedly 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 presents the correlations between the observable product characteristics and the estimated unobserved product characteristic $\hat{\xi}$ implied by the model. The reported results provide clear evidence that the observed and unobserved product characteristics are indeed very much correlated – consistent with the results of **?**. Assuming they are orthogonal as in the *BLP* model could produce important estimation biases – a topic we address in Section 7.2.

[21] No matter how likely this explanation might appear, this Bayesian model of diffusion cannot be estimated using few years of aggregate data only.

Figure 7: Change in the Distribution of Unobserved Attributes



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

One could have argued for the plausibility of exogenous product characteristics using the fact that auto makers typically introduce new vehicle models in several markets simultaneously. Since Spain is relatively small market in Europe (8% of total sales), any nuances in the Spanish market would not be accounted for by the auto makers. The fact that we find significant correlations not only indicates that this argument is not valid but it also suggests that Spanish consumers are indeed representative European consumers.

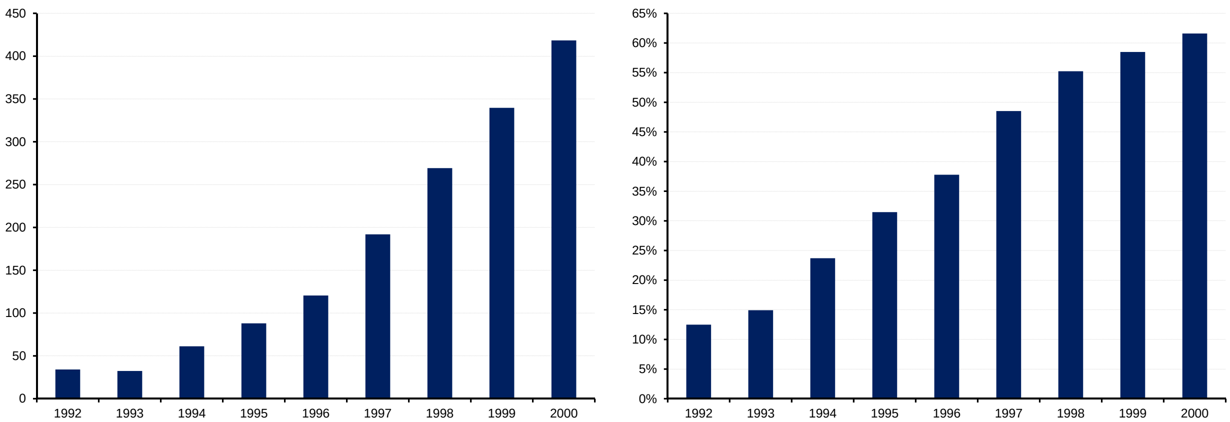
Finally, to conclude our analysis of results, Figure 7 shows the different distribution of the estimated unobservable quality $\hat{\xi}$ by year and fuel type. Table D.2 in Appendix D also reports test of stochastic dominance for these distribution. It is remarkable that while the unobservable attributes of gasoline vehicles are undistinguishable 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. Our analysis shows that not only they (or their perception) improved during the 1990s but that they are also linked to power, size, brand, and other observable automobile attributes.

5 The Value of the TDI

Diffusion of a new technology might be hampered for many reasons: consumer skepticism about its added value (durability, cost of repairs), compatibility issues, lack of complementary services (trained mechanics, access to refuel stations), high cost of production and a slow learning curve, and last but no least the inability to secure innovation rents. This is a serious concern when patents cannot be effectively enforced or when technologies are general in nature, *i.e.*, when competitors can easily imitate or modify existing technologies to offer competing alternatives.

VOLKSWAGEN surely contemplated the scenario where its competitors will shortly come up with their own improved alternatives to TDI. Evidently, TDI was patented, but its generality, could help others, such as PSA in the mid-nineties, to come up with successful, high performance, diesel-based, engine alternatives. A not so difficult process of reverse engineering might have allowed competitors to limit VOLKSWAGEN's ability to appropriate the rents necessary to develop the TDI engine, therefore questioning the wisdom of such innovation strategy in the first place.[22]

Figure 8: Importance of Diesels to Volkswagen Group's Profits (Spain)



(a) Profit (Millions) (b) Diesel Share of Profits

A revealed preference argument suffice to conclude that despite this imitation, TDI must have been a very profitable initiative as it was still sold many years after its invention and others entered this apparently very profitable segment. Figure 8(a) demonstrates that VOLKSWAGEN was indeed able to generate a lot of profit from the TDI and that TDI profits grew rapidly over the decade, while Figure 8(b) indicates that sales of TDI became an increasingly important contributor to the auto maker's profits. These figures are obviously limited to Spain but they include sales and profits for AUDI, SEAT, SKODA, and VOLKSWAGEN vehicles. Profits will be much larger when considering the whole European market.

That said, imitation by European auto makers undoubtedly had an impact on the value of the TDI to VOLKSWAGEN. In Table 4 we use the estimates of the model to conduct a couple of counterfactuals that help us assess the importance of potential innovation rents captured by VOLKSWAGEN – or equivalently estimate how much business were other European auto makers able to steal by imitating this general technology.

To evaluate the profitability of TDI for VOLKSWAGEN, we make use of two counterfactuals. The "Benchmark" column summarizes the sales-averaged price, market share, sales-averaged margins and profits originating from the diesel and gasoline segments in year 2000. The "No TDI" counterfactual of Table 4 considers the possibility that diesels are either not allowed by regulators, or were simply never developed by any automobile manufacturer. This would characterize any market other than the European automobile market as diesels failed to succeed anywhere else than

[22] It is the generality of this technology what allows it to be imitated and reused easily by other manufacturers, a good example of limited appropriability of profits of innovations of general purpose technologies that can be recombined and reused in other applications. See Bresnahan (2010).

Table 4: Value of TDI Technology to Volkswagen (2000)

	No TDI	Benchmark	Monopoly
Price (€Thousand)	15.84	16.14	17.42
- Diesel	-	16.72	18.42
- Gas	15.84	15.24	15.66
Market Share (%)	20.30	23.43	37.00
- Diesel	-	26.53	100.00
- Gas	20.30	19.84	17.60
Margin (%)	14.51	13.73	17.95
- Diesel	-	13.29	19.04
- Gas	14.51	14.40	16.05
Profit (€Million)	432.25	679.13	1,211.84
- Diesel	0.00	418.36	863.54
- Gas	432.25	260.78	348.29

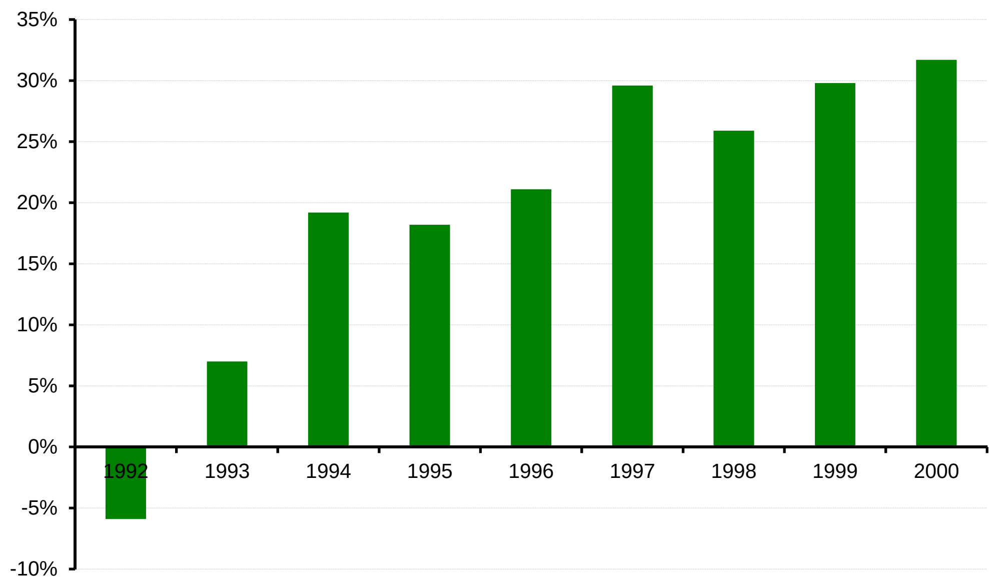
All numbers refer to year 2000. "Price" is in thousands of 1994 Euros. 'Market Share" is the percent share of cars sold in the respective category. "Margin" is defined as $\left(\frac{p-c}{c}\right)$ where price includes tariffs. "Profit" is measured in millions of 1994 Euros.

in Europe. Under this scenario VOLKSWAGEN's overall profits are m€247 lower despite the fact that profits from the gasoline division grow by m€171. This latter effect is due to the fact that we consider the number of gasoline model constant. Thus, removing the whole set of fuel efficient diesel vehicles allows manufacturers of gasoline models, including VOLKSWAGEN, to increase their sales and profits.

In order to determine how much of the innovation rents VOLKSWAGEN was able to secure, we need to evaluate another counterfactual where the TDI technology is assumed to be exclusive for VOLKSWAGEN and where competitors cannot come up with close substitutes in the diesel segment. In the "Monopoly" counterfactual, VOLKSWAGEN (including its affiliate brands) is the sole seller of diesel vehicles. We thus recompute the equilibrium by removing all 2000 diesel models other than those produced by the VOLKSWAGEN group, which now enjoys monopoly power over that market segment. Profits then become substantially larger for VOLKSWAGEN under such scenario, up to bn€1.2, or about m€533 higher. Profits from the diesel segment alone more than doubled, from m€418 to m€864. It would be wrong to conclude that VOLKSWAGEN was able to secure almost half of the rents of innovation because comparing these two number ignores the effect that not having diesel models available at all, or only sold by VOLKSWAGEN has on profits through increased sales of efficient gasoline models. Since firms produce a variety of products, the maximum innovation rents is not only determined by the possibility of selling diesel vehicles or not, but also by the indirect effect that demand may have on substitute gasoline models.

Thus, the maximum value of the innovation rents amount to m€780, the difference between VOLKSWAGEN's total profits of being a diesel monopolist and the scenario when diesels do not exists. Therefore, starting from the "No TDI" scenario, we can compare the maximum total incremental profits of being a monopolist m€1212 – m€432 = m€780, with the incremental profits of the benchmark scenario m€679 - m€432 = m€247, to conclude that VOLKSWAGEN is able to keep 31.7% of the potential rents of the TDI innovation under a much more strict patent protection or less easily reusable technology. Competition is thus responsible for the dissipation of two thirds of the innovation rents, which will benefit consumers in the form of lower prices and more products to choose from. Table 4 also show that relative to a scenario where VOLKSWAGEN was the solely producer of diesel vehicles, prices of VOLKSWAGEN's gasoline models were about 2.5% lower while VOLKSWAGEN's diesel models were almost 10% less expensive.

Figure 9: Volkswagen's Rent Capture Across the Decade



At the beginning of the 1990s VOLKSWAGEN was not the leader of the Spanish market in neither gasoline or diesel. RENAULT, FORD, and GM (better known as OPEL in continental Europe) led the gasoline segment and CITROËN, PEUGEOT, and RENAULT the diesel segment. The diffusion of diesels during the decade shook these rankings with RENAULT still leading the gasoline segment (although with half the sales) and the PSA group dominating the diesel segment, *e.g.*, see Figure D.1 in Appendix D. VOLKSWAGEN was a close second top diesel seller thanks to the early acquisition of the local producer SEAT. Because of this, Figure 9 shows that the share of potential rents captured by VOLKSWAGEN kept growing, during the decade. Only at the very beginning, in 1992, it appears that the introduction of the TDI cannibalized profits from the gasoline segment.

A clear conclusion from Figure 8 and Table 4 is that the TDI was a valuable innovation for VOLKSWAGEN. In Appendix D we repeat the analysis of Table 4 for years 1992 and 2000 and all automobile groups. Table D.4 shows that in 2000, PSA, the local leader in the diesel segment, benefit the most from the widespread acceptance of diesels among drivers, followed by VOLKSWAGEN, RENAULT, GM, and FORD. Only MERCEDES and NON-EU auto makers saw their profits reduced because of the existence of diesels. In Table 5 we summarize these results distinguishing the type of engine and geographical origin of automobiles. Specifically, we compare the current market equilibrium ("Base") for the Spanish market to one in which diesels do not exist ("CF") in 1992 (top panel) and 2000 (bottom panel).

Table 5: Value of Diesels to Domestic and Foreign Manufacturers

	Products		Price		Share		Markup		Profit	
	Base	CF	Base	CF	Base	CF	Base	CF	Base	CF
1992										
EU: DIESEL	43	0	12.3	-	16.6	-	15.0	-	281.2	-
EU: GASOLINE	73	73	11.1	11.3	79.4	95.2	14.3	14.4	1,134.7	1,306.4
NON-EU: DIESEL	1	0	13.8	-	0.1	-	12.4	-	1.4	-
NON-EU: GASOLINE	24	24	14.9	15.2	3.9	4.8	11.5	11.7	54.2	65.2
2000										
EU: DIESEL	75	0	16.2	-	51.0	-	13.0	-	1,404.0	-
EU: GASOLINE	84	84	14.9	15.5	37.3	81.0	14.0	14.1	987.1	1,613.9
NON-EU: DIESEL	20	0	17.2	-	2.7	-	11.1	-	63.1	-
NON-EU: GASOLINE	50	50	13.7	14.2	9.1	19.0	13.4	13.7	191.8	307.8

"Base" refers to benchmark equilibrium in the data while "CF" refers to the equilibrium without diesels cars. "Price" is the average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Share" is the percent of vehicles sold in the category. "Markup" is the price-cost margin defined as $100 \times \left(\frac{p-c}{p}\right)$ where price does not include tariffs, if applicable. "Profits" are measured in millions of 1994 Euros.

Removing diesels has a significant negative effect on the automobile industry but these effects are not evenly distributed. Rather they are concentrated on European auto makers – the firms who adopted the diesel technology in the early 1990s. Further, these effects early in the decade are relatively small compared to later in the decade when diesels had become popular with consumers. Specifically, we find that removing diesels in 1992 has modest effects on the industry as aggregate profits fall 6.8% and most of this decrease is born by European auto makers. By 2000 diesels contribute a much larger proportion of the total industry profits. The removal of diesels after their successful diffusion decreases product options for consumers substantially. European auto makers, however, are unable to entirely replace the profits generated by their diesel fleet and aggregate profit falls 32.5% to bn€1.6. Asian manufacturers, on the other hand, are clearly winners of not having to compete with the diesel technology that they cannot effectively produce, and thus their aggregate profits increase 20.8% to m€307.

Perhaps the most interesting evidence reported in Table 5 is the profound transformation of the European automobile industry during the 1990s. The change in composition of European sales was dramatically different: in 1992 only one in five vehicles was diesel while in 2000 diesels represented more than half of sales. More importantly, despite the elimination of import quotas and the reduction of import tariffs, European manufacturers remained in a dominant position;

accounting for 96% of automobile sales in Spain in 1992 and only losing about 8% share to imports by the end of the decade.[23] But if diesels had not existed, for whatever the reason, Europeans would have lost another 7% market share to imports. Thus, the existence and viability of the diesel technology clearly benefited domestic European manufacturers.

So far we have shown that diesels were an incredibly profitable product for European auto makers. A natural question then is why did foreign firms not offer diesels. 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.[24] This suggests that the reason the TDI was invented and imitated by European firms is that diesel popularity was fundamentally a European phenomenon so only firms which generated a significant percentage of their profits from the European market were willing to spend the money to develop the technology. Consequently, the competitive advantage offered by diesels resulted from the fact that European firms were willing to spend the money to develop a product which catered to the idiosyncratic tastes of European consumers.

6 Emissions Policies as Industry Protection

Using the model to measure the effects of removing all diesel vehicles from the European market might, in most circumstances, be contemplated as a simple theoretical exercise. In this section we present evidence that European regulatory policies on fuel and particularly emissions standards could have realistically choked the diffusion of diesel vehicles in the early stages of its adoption. The trade implication of such policies are significant – a near doubling of the share of imports from 11.8 to 19 percent. By not adopting such damaging policies, whether inadvertently or not, European policymakers implicitly helped European manufacturers enhance their dominance in the domestic market. To our knowledge this is the first time a structural equilibrium model of oligopoly industry competition in differentiated products has been used to evaluate trade frictions, in particular the trade protective impact of environmental regulation.

6.1 Vehicle Emissions Standards in the United States and Europe

We have thus far identified the generality of diesel technology as the main cause behind the success of the diffusion of diesel vehicles in Europe in such a short period of time: the increased competition

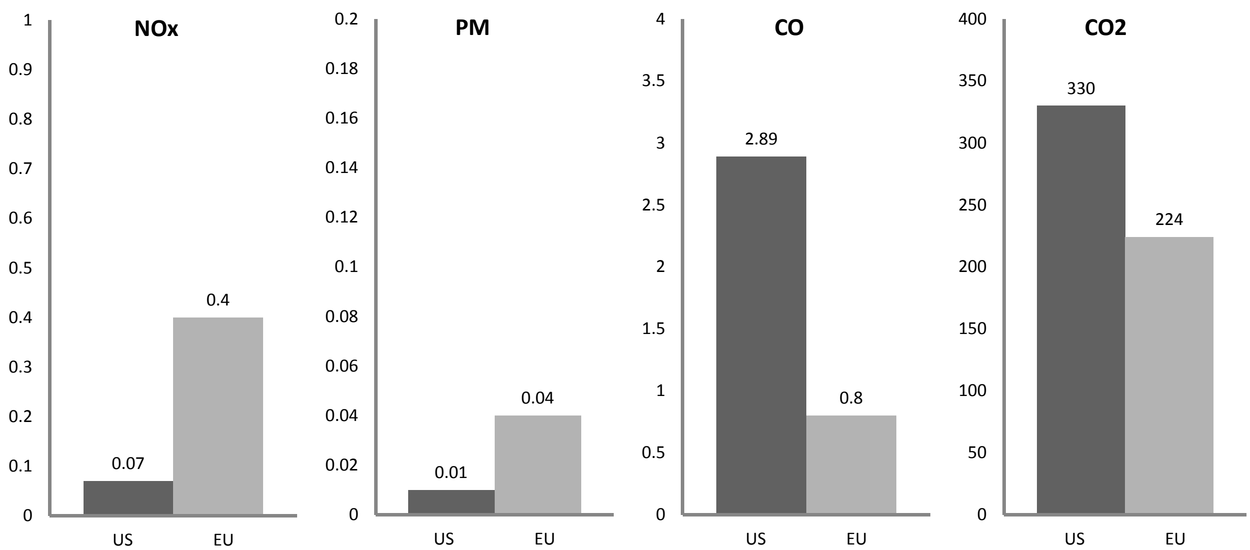
[23] This compares to a 34% penetration of Asian in the United States in year 2000. See Automotive News Market Data Book (1980-2006).

[24] 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).

lowered the price of diesel vehicles, increased the supply of models for sale, and help dissipating the innovation rents among economic agents. And yet, despite how easy imitation appears to be, diesels almost disappeared in the U.S. during the same period of time. 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. 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. While Americans were concerned mostly with reduction in emissions leading to acid rain, Europeans aimed at reducing green house emissions.

Figure 10 illustrates the differences in emissions standards between the United States and Europe in the year 2000.[25] 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 10: Europe and U.S. Emissions Standards



Source: `www.dieselforum.org`. All statistics are for the year 2000 and are in grams per mile. "NOx" refers to nitrogen oxide limits; "PM" to particulate matter; "CO" carbon monoxide; and "CO2" carbon dioxide.

[25] 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 10 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`.

European regulators took a different approach and chose a less stringent NO_x emission standard. While in 1994 U.S. Tier 1 standard allowed NO_x emissions of 1 gram per mile (g/mi), the Euro I standard was 1.55g/mi. By year 2000, the U.S. policy allowed only 0.07g/mi while the Euro III standard set the NO_x emission level at a far less demanding 0.4g/mi level.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 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 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.[26] 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, auto makers 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 the 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?

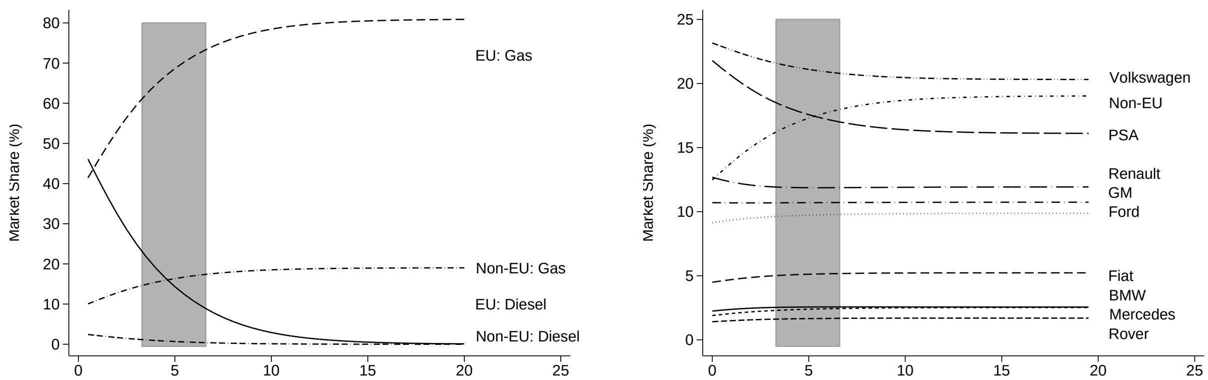
6.2 Retrofitting Costs

We now focus on the likely cost of retrofitting diesel engines in order to make them comply with the NO_x emission standards set by the EPA. In so doing we test whether an alternative an emissions policy like the one employed by the United States would have materially affected the European industry. We show that meeting these regulatory standards is expensive and we can conclude that such a shift in policy would have had effects commensurate with the results presented in Table 5.

[26] 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.

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 retrofitted 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 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 reductant (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.[27]

Figure 11: Market Shares and Retrofitting Costs



(a) By Region, 1000€ (b) By Firm, 1000€

Had this technology been available in the 1990s, retrofitting costs would have been even higher. Figures 11(a) and 11(b) plots the results of using our estimates to recompute the market equilibrium repeatedly after adding a wide range of retrofitting costs to the marginal cost of production of diesels. The shaded area highlights the limits of the retrofitting cost region of the lean and selective catalysts corrected for exchange rate and inflation. Figure 11(a) describes the effect on market shares distinguishing by type of engine and geographical origin of manufacturers while Figure 11(b) reports the combined market shares (gasoline & diesel) of each automobile group.

Figure 11(a) shows that a retrofitting cost of €3,300 for the lean catalyst in year 2000, the NO_x emission regulation has effectively reduced the diesel segment to a market niche comparable to the diesel market penetration in Europe prior to the TDI innovation. The increase in production

[27] On retrofitting costs see *Diesel Retrofit Devices.* EPA's National Clean Diesel Campaign, 2013. `http://www.epa.gov/cleandiesel/technologies/retrofits.htm`

costs required to comply with environmental regulations puts diesel at a huge price disadvantage and consumers will opt for other, less expensive, fuel efficient vehicles. At about the €6,600 of the selective catalyst, the market share of European diesel vehicles falls well below the share of gasoline imports, who grow monotonically with the retrofitting costs although the production of European gasoline models grows much faster.

Figure 11(b) shows that, in terms of market shares, the only clear beneficiary of an alternative stringent European NO_x emission policy would be foreign automobile manufacturers. Although the composition of sales changes with retrofitting costs, most European manufacturers manage to hold to their current market presence. 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 retrofitting costs erode their competitiveness and their market shares.

Therefore, given the exorbitant cost of retrofitting diesel engines to capture NO_x emissions, we conclude that it is reasonable to expect that a stringent, EPA-like, NO_x emission standard would have effectively hindered the diffusion of diesel vehicles in Europe, particularly if such policy was enforced soon after the introduction of the TDI, at the early stages of the diffusion of the new technology.

6.3 Import Tariff Equivalence of Environmental Regulation

We have so far shown that diesel vehicles were a popular choice among Spanish consumers; generating substantial profits for European auto makers. Removing these vehicles, presumably from a EPA-like emissions policy, would have resulted in substantial 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 green house emissions. Whether this emission policy was designed explicitly to promote sales of domestically produced diesel vehicles is inconsequential. In practice, targeting CO_2 rather than NO_x generated precisely that result.

Table 6 reports the tariff-equivalence of the European NO_x emission policy during the 1990s. After the "Benchmark" scenario of 2000, the middle section of the table reports the outcome of the counterfactual where TDI, and therefore modern diesel engines, never existed. Relative to the benchmark, market share of Asian manufacturers jumps from 11.77% to 19.04% as their profits increase by almost 21% as they increase the price, margin, and sales of their gasoline models following the disappearance of fuel efficient diesel vehicles from the market. Starting from this scenario, without diesel vehicles in the choice set, we solve for an import tariffs such that the pricing equilibrium generates a market share for gasoline imports equal to 11.77%, the combined share of imported diesel and gasoline automobiles sold in year 2000. Figure 12 summarizes the

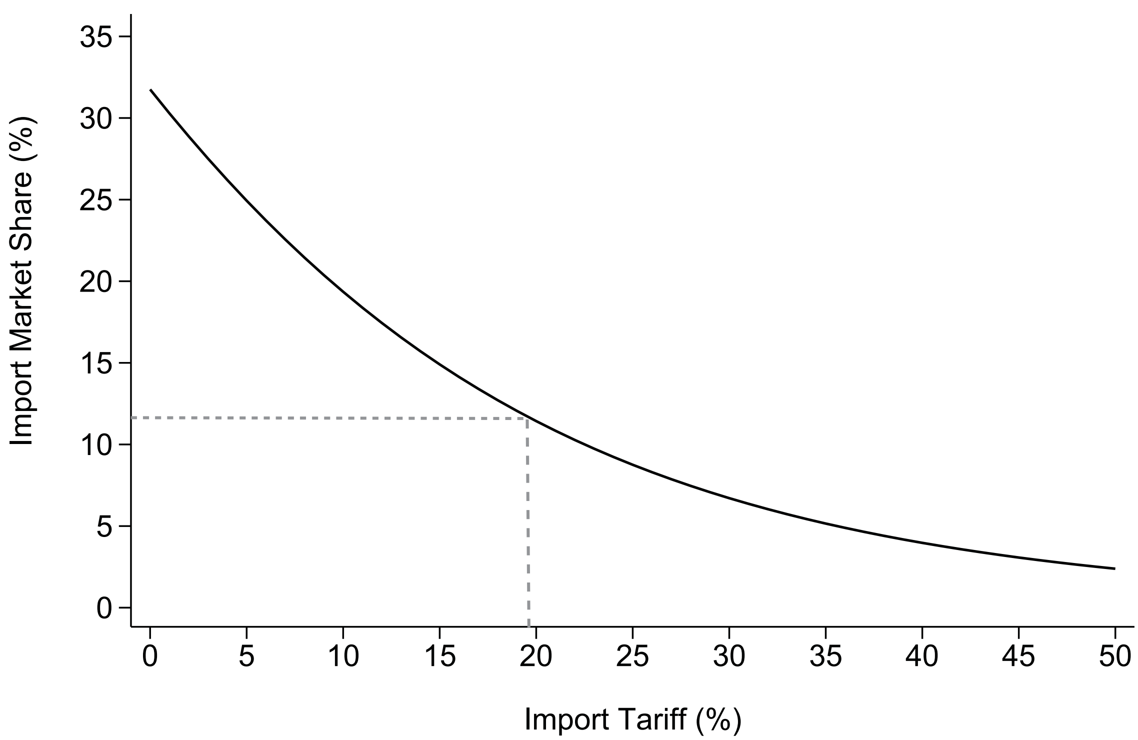
Table 6: Effects of Imposing Equivalent Import Tariffs

Scenario	Models	Price	Quantity	Margin	Share	Profit
Benchmark						
EU: DIESEL	75	16.19	695.37	12.98	50.95	1,404.01
EU: GASOLINE	84	14.93	508.70	13.96	37.28	987.12
NON-EU: DIESEL	20	17.20	36.97	11.12	2.71	63.12
NON-EU: GASOLINE	50	13.66	123.65	13.41	9.06	191.77
Equilibrium without Diesels						
EU: GASOLINE	84	15.51	796.78	14.13	80.96	1,613.93
NON-EU: GASOLINE	50	14.24	187.40	13.69	19.04	307.82
Import Tariff of 19.6%						
EU: GASOLINE	84	15.56	837.80	14.24	88.23	1,715.18
NON-EU: GASOLINE	50	14.62	111.76	13.39	11.77	171.24

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.

result of repeatedly computing the equilibrium at increasing rates of import duties. Because of the convexity of this relationship, import tariffs are quite effective in quickly reducing imports from the maximum of about 32% under free trade. Tariffs need to increase far more when the presence of imports in the domestic market is very low (under 10%).

Figure 12: Non-European Imports in the Absence of Diesels (2000)



We thus find that, in a world without diesels, a 19.6% import tariff would limit Asian imports and lead to a similar market outcome as the European green house emission policy that implicity favored the development of diesel vehicles. While large in its own right, this implied tariff is roughly double the nominal tariff (10.3%) which existed at the time. Moreover, the market penetration of Asian imports in Spain is similar to that of Europe overall and thus our analysis could be vied as representative of the average protective power of this environmental regulation across Europe. France is the most important outlier among large European automobile markets, with Asian imports barely exceeding 5% market share in year 2000. For the French case, the tariff equivalence of the European environmental policy reaches 35.3%. In summary, the emissions policy employed by European regulators seems to have favored domestic auto makers as a *de facto* non-tariff trade policy and further fostered the adoption of diesel vehicles in Europe during the 1990s.

7 Robustness

In this section we evaluate the robustness of our results. First, we evaluate the extent to which favorable tax treatment of diesel fuels in Europe can explain the massive adoption of diesel vehicles in Europe. Second, we discuss the appropriateness of our model and estimation approach; assessing the qualitative and quantitative implications of assuming exogeneity of product characteristics.

7.1 Fuel Taxes and Diffusion of Diesel Vehicles

Our novel argument is that targeting CO_2 emissions (or not targeting NO_x) had far reaching consequences for the successful diffusion. But relative to what? Wasn't the diffusion of diesels the result of favorable diesel fuel taxation? In this section we evaluate this commonly-held hypothesis, including the effects of the new European fuel taxation principles implemented in 2013. We show that favorable fuel taxation had an almost negligible effect on the market penetration of diesel vehicles despite the popular belief. The change in fuel taxation principles is also inconsequential. By comparison, the implications of the emission policy are dramatically more important.

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 2.2 that the reduced diesel fuel tax rate was instrumental for the development of a diesel market niche that eased the adoption of TDI and other improved diesel vehicles in the 1990s, two decades after the European Fuel Tax Directive was adopted. We dispute, however, that by itself, the favorable taxation of diesel fuels could explain the widespread adoption of diesel vehicles in Europe. In order

Table 7: Modifying Diesel Fuel Taxes (2000)

Scenario	Fuel Tax	Models	Price	Quantity	Margin	Share	Profit
Benchmark Diesel and Gas Excise Taxes							
EU: DIESEL	0.23	75	16.19	695.37	12.98	50.95	1,404.01
EU: GASOLINE	0.35	84	14.93	508.70	13.96	37.28	987.12
NON-EU: DIESEL	0.23	20	17.20	36.97	11.12	2.71	63.12
NON-EU: GASOLINE	0.35	50	13.66	123.65	13.41	9.06	191.77
Diesel and Gas Excise Taxes are the Same							
EU: DIESEL	0.35	75	16.27	667.39	12.98	49.44	1,353.59
EU: GASOLINE	0.35	84	14.92	520.08	13.97	38.53	1,009.32
NON-EU: DIESEL	0.35	20	17.24	36.31	11.14	2.69	62.24
NON-EU: GASOLINE	0.35	50	13.65	126.13	13.42	9.34	195.71
Diesel Excise Tax is Increased							
EU: DIESEL	0.38	75	16.29	662.47	12.98	49.16	1,344.69
EU: GASOLINE	0.35	84	14.91	522.20	13.97	38.75	1,013.51
NON-EU: DIESEL	0.38	20	17.25	36.19	11.14	2.69	62.08
NON-EU: GASOLINE	0.35	50	13.65	126.59	13.42	9.39	196.45

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.

to support our position we conduct a couple of counterfactuals in Table 7 modifying the excise fuel tax of gasoline and diesel fuels. It should be noted that any change in fuel taxation enters our model through the effect that the cost of driving has on drivers choices among vehicles.

In our first experiment (middle panel of Table 7) we eliminate the favorable tax treatment of diesel fuel by setting a common fuel tax equal to the higher gasoline excise tax of 35%. Comparing results to the benchmark case, we notice that sales of diesels would be just 28,640 units lower in year 2000. These lower diesel sales will reduce auto makers profits in the order of m€25, or about 1% of profits. Therefore, the favorable diesel fuel taxation is responsible from an additional market penetration of just 1.5%, *i.e.*, 52.13% of the counterfactual compared to 53.66% of the benchmark.

Finally, after almost two decades of deliberation and negotiation among European policy makers, 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.[28] The bottom panel of Table 7 shows that under the current system diesel

[28] Excise fuel taxes at the bottom panel of Table 7 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`

fuels are more heavily taxed than gasoline. Notice however that the much debated fuel taxation reform has negligible effects when compared with the outcome of equal taxation of fuels by volume. Relative to the benchmark case of 2000, the market penetration of diesels would be just 1.81% lower. Relative to the scenario of equal excise taxation across fuels based on volume, the difference is an almost nil 0.28% lower market share penetration of diesels.

7.2 Alternative Modeling Choices

In this section we address the implications and limitations of our modelling and estimation approach. Broadly, we view our paper as a step towards developing a more realistic model of the automobile industry by providing useful insights into the quantitative price and profit implications of attribute choices made by firms.[29] Further, we believe our modeling choices are sufficient to address the objectives in this paper, balancing a feasible extension of the *BLP* framework while meeting the institutional limitations of our application.

First, an important attribute of the estimation approach is that we allow for but do not impose correlation between observed and unobserved product characteristics – and we find that, indeed, the estimated model does generate significant correlations among product characteristics. Whether imposing zero correlation has significant qualitative and/ or qualitative implications to our analysis is unclear ex ante. Table D.3 in Appendix D compares the estimation and counterfactual results under both our current model ("MMT") and a comparable, standard *BLP* estimation. The results indicate that imposing product exogeneity leads to less precise estimates, particularly for the random coefficients, and exaggerates the market power of automobile firms by triplicating the estimated average price-cost margin of the industry. While using the standard *BLP* estimation approach has little qualitative implications regarding our results (*e.g.*, value of the TDI to VOLKSWAGEN, emissions policy as a non-tariff policy, *et cetera*), the quantitative implications are significant.

Second, in the model, based on Petrin and Seo (2015), we assume that automobile manufacturers first choose product characteristics based on their induced profits via future prices, which happen to be determined non-cooperatively depending on the product positioning of all automobile sold. An alternative would be to allow auto makers to choose prices and product attributes simultaneously as prices might affect product design. Estimating such a model would be difficult in our context as major releases of new model versions occur infrequently. Thus, we do not consider the direct effect of product attributes on profits as in Fan (2013). Further, the data does not contain "one clear event" leading to a total reorganization of the industry, including prices and

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

product attributes. In our case we observe multiple introduction of new products with changing attributes over time. Thus, while this alternative approach would be interesting in many contexts, it may not be appropriate for the automobile industry as auto makers design new vehicles several years ahead of selling them. When choosing automobile attributes, observable or otherwise, they account for the expected profits that those attribute choices may generate through future increased markups. When cars are sold though, the primary strategic variable is price rather than product attributes.

Lastly, it is worthwhile to discuss the rationale and potential implications of holding the product set, including engine type, fixed in the model and estimation. It is perhaps more appropriate to think of the automobile industry as dynamic where manufacturers decide the timing of introduction of new products and attributes, particularly diesel engines. Ignoring this relationship has the potential to introduce bias into the estimates, though it is unclear what the size and direction of those biases and the implications on our overall results would be.

Estimating such a dynamic model of product entry in the automobile industry would increase the model's complexity substantially and introduce new sources of uncertainty of which there are no clear answers in the literature (*e.g.*, modelling firm beliefs, multiple equilibria, *et cetera*).[30] And unlike Sweeting (2013), our data covers one geographical market with limited demographic variability and automobile attributes are not limited to few standardized categories but are mostly continuous. Consequently, we have opted for a simpler model but one which is sufficiently flexible to address the research goals of this paper. Further, the fact that diesel adoption in Spain occurred earlier, though at a similar rate, than most European countries likely mitigates estimation bias since it is unlikely that auto makers would have responded to increased Spanish demand for diesels.

8 Concluding Remarks

The goal in this paper was to measure the impact of a new diesel technology on the European auto 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 that the two sets of characteristics are indeed correlated. We also documented not only that there is significant heterogeneity of preferences but that on average Spanish drivers do not only favor smaller and high performance cars but also that their perception of diesel improved substantially

[30] The overwhelming majority of diesel vehicles are also offered as a gasoline version and the only difference between the two versions is the engine type and all the characteristics associated with the engine. For example, a 1998 AUDI A4 TDI is quicker (*i.e.*, more torque), heavier, and more fuel efficient than a gasoline-powered A4 but it does not differ in size, interior space, creature comforts, *et cetera*. Consequently, a model with endogenous engine choice would be similar to a dynamic model of product entry requiring firm beliefs about future profitability and information to identify the fixed costs of establishing the product.

during the 1990s. Widespread imitation of the TDI by European auto makers due to the generality of the technology, enabled domestic firms to generate substantial profits from the technology while limiting prices via increased competition, again favoring the adoption of diesel vehicles. Despite the increased competition in the diesel segment, the TDI technology remained profitable for VOLKSWAGEN as the firm overcame the business stealing of it rivals to generate significant profits from the technology and captured 32% of the potential innovation rents. We also find that, contrary to popular belief, reduced fuel taxation was only responsible for just 1.5% fraction of diesel sales. Instead, the greenhouse oriented emissions policy employed by European regulators had a much more significant effect on the diesel technology's widespread success.

Perhaps the most novel result of our paper is to show that seemingly non-trade policies such as environmental standards can have important and quantitatively significant trade effects. Regardless of whether the European pro-greenhouse emission policy was intended to favor the sales of domestically produced diesel vehicles or not, we show that alternative NO_x reduction policies would have effectively halted the commercial success of diesel vehicles in the early 1990s, and, given the large market share of diesels by year 2000, this policy amounted to an import tariff of 19.6% or approximately double the tariff employed by the European Union at the time. This is, to the best of our knowledge, the first use of a structural equilibrium model of demand and industry oligopoly competition to evaluate the trade effects of a non-tariff policy. Moreover, 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.

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Appendix

A Spanish 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.[31] 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 and those perceived by manufacturers.

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.

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[31] 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 given their smaller size will be grouped under the NON-EU label later in the analysis.

B Estimation: Solving the Model

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

1. Compute δ_j using the contraction mapping described in (Berry et al., 1995, Appendix I).

2. Use $\mu(\Sigma, \Pi)$ and $s_{ijt}(\theta)$ to solve for the implied markups b_j and use price data to construct marginal costs.

3. Estimate γ by projecting $\ln(c_j)$ onto the vector of cost shifters Z using OLS. Since cost likely varies by car segment (*e.g.*, SEDAN) and brand (*e.g.*, AUDI vs RENAULT) we include segment and brand fixed effects.

4. Construct the structural error ε_j^k defined as:

$$\varepsilon_j^k(\theta) = s_j(\theta) \times \frac{\partial(p_j^\tau - c_j)}{\partial x_j^k} + \sum_{r \in \mathcal{F}_f} (p_r^\tau - c_r) \times \frac{\partial s_r}{\partial x_j^k}\,. \tag{B.1}$$

   (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:

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

   (c) Solve for $\frac{p_m^\tau}{\partial x_j^k}$. Recall the first-order condition for the price of product j is:

$$s_j + \sum_{r \in \mathcal{F}_j} (p_r^\tau - c_r) \times \frac{\partial s_r}{\partial p_j^\tau} = 0\,. \tag{B.3}$$

   Total differentiation of (B.3) with respect to the vector of prices (dp^τ) and characteristic k of product n (dx_n^k) yields:

$$\sum_{m=1}^{J} \underbrace{\left[\frac{\partial s_j}{\partial p_m^\tau} + \sum_{r=1}^{J} T(r,j)\frac{\partial^2 s_r}{\partial p_j^\tau \partial p_m^\tau} \times (p_r^\tau - c_r) + T(m,j)\frac{\partial s_m}{\partial p_j^\tau}\right]}_{g(j,m)} dp_m^\tau + \underbrace{\left[\frac{\partial s_j}{\partial x_n^k} + \mathbb{1}\{f = j\}\frac{\partial c_j}{\partial x_n^k}\right]}_{h(j,n)} dx_n^k = 0\,, \tag{B.4}$$

   where $T(r,j)$ is equal to one when products r and j are produced by the same firm and zero otherwise. Stack j conditions and define the matrix G with element $g(j,m)$ and the matrix H with element $h(j,n)$. This implies that $Gdp^\tau - H_f dx_n^k = 0$ where H_n is the nth column of H. Finally, we have $\frac{dp^\tau}{dx_n^k} = G^{-1}H_n$, or more generally in matrix notation: $\Delta^p = G^{-1}H$ where $\Delta^p(i,j) = \frac{\partial p_i^\tau}{\partial x_j^k}$. In practice, we found that the $\frac{\partial^2 s_r}{\partial p_j^\tau \partial p_m^\tau}$ terms played an insignificant role in constructing Δ^p and that one could decrease computing time significantly by setting these terms to zero.

   (d) Define Δ^s as the matrix of partial derivatives with element $(i,j) = \frac{\partial s_i}{\partial x_j^k}$. The matrix Δ^s is an equilibrium object which is a function of Δ^p which is, in turn, a function of Δ^s. Consequently, solving (B.4) requires solving for a fixed point. While we have no proof that our operator is a contraction or that it results in a unique solution, we found that updating guesses using a convex combination of the previous and new guess yielded fast, monotonic convergence and that starting from different initial guesses yielded the same results.

C 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:

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

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

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

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

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

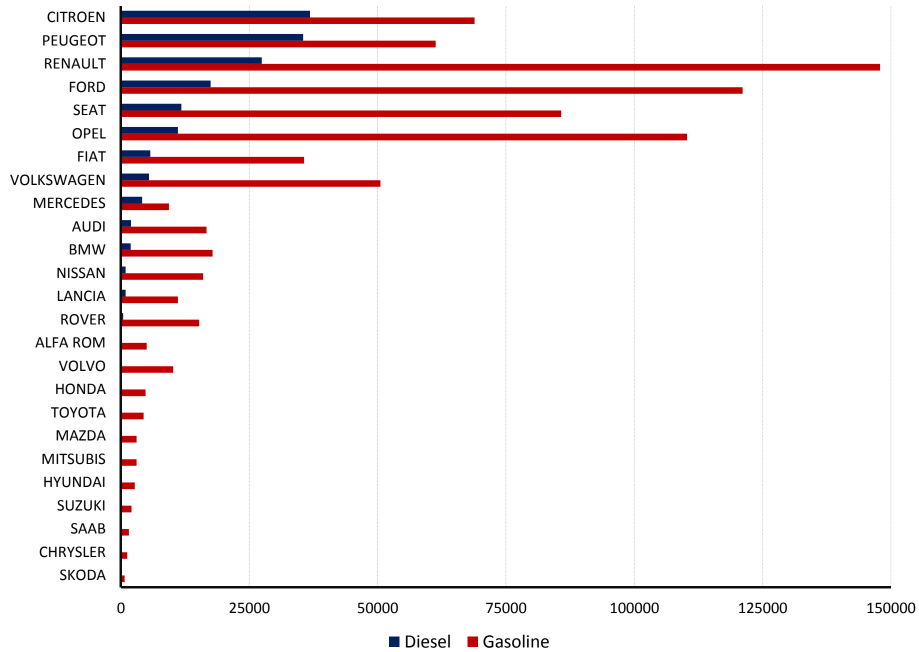
where an element of the matrix Ω is defined as:

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

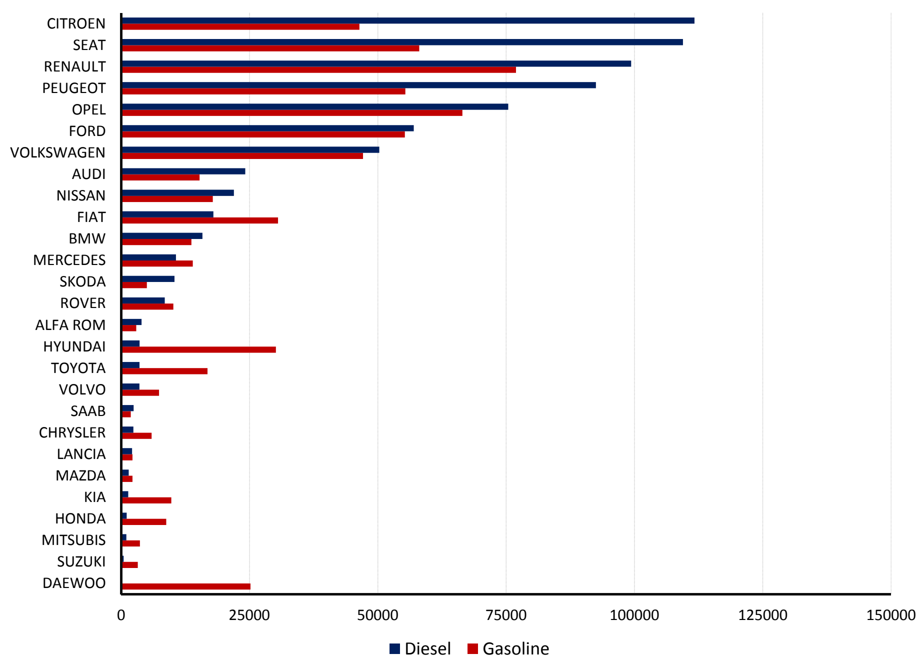
For a given vector of marginal costs c, we use (C.3) to find the fixed point to the system of equations – a common practice in the literature dealing with this class of models. To our knowledge there exists no proof of convergence or uniqueness for this contraction operator and fixed point. Our experience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

D Additional Results

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



(a) Year 1992



(b) Year 2000

Table D.1: Car Model Characteristics Across Engine Types

SEGMENT	MODELS	SHARE	PRICE	C90	KPE	SIZE	HPW
1992							
SMALL	28	35.82	7.98	4.68	35.00	62.51	36.50
COMPACT	31	35.79	10.96	5.33	32.07	74.34	39.83
SEDAN	39	22.31	14.26	5.69	30.27	80.10	42.55
LUXURY	39	5.77	24.01	6.49	25.75	87.07	48.41
MINIVAN	4	0.32	17.28	6.93	24.21	81.66	37.88
ALL	141	100.00	11.40	5.25	32.33	72.15	39.74
2000							
SMALL	49	32.75	10.42	4.86	31.61	66.36	31.79
COMPACT	56	34.43	14.86	5.00	32.53	76.54	35.90
SEDAN	52	25.97	19.45	5.26	31.60	81.92	36.33
LUXURY	40	3.72	34.53	6.72	23.31	89.72	51.65
MINIVAN	32	3.13	20.80	6.39	25.91	83.47	31.61
ALL	229	100.00	15.52	5.13	31.43	75.31	35.12

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. 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 thousand pounds of weight.

Table D.2: 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.

Table D.3: Summary of Results Under Different Estimation Strategies

	MMT Estimation		*BLP* Estimation	
	Coefficient	Rob. SE	Coefficient	Rob. SE
Mean Utility (β)				
KPE	0.2679	(0.3290)	2.5246	(2.8746)
SIZE	−13.2042	(0.6000)***	15.4544	(3.2785)***
HPW	1.5288	(0.4961)***	5.2816	(2.2653)**
CONSTANT	5.7410	(0.2243)***	−12.7685	(1.3451)***
DIESEL	−2.3586	(0.5275)***	−12.0386	(7.9469)
DIESEL_{93}	0.7559	(0.6620)	0.2174	(0.1827)
DIESEL_{94}	2.2892	(0.6524)***	1.5916	(0.3679)***
DIESEL_{95}	2.0952	(0.6377)***	1.5923	(0.6693)**
DIESEL_{96}	3.0923	(0.6308)***	2.4296	(0.7362)***
DIESEL_{97}	3.7642	(0.6389)***	3.3822	(1.1014)***
DIESEL_{98}	2.3827	(0.6428)***	3.0462	(1.4294)**
DIESEL_{99}	3.5044	(0.6495)***	3.7110	(1.6814)**
DIESEL_{00}	2.2448	(0.6684)***	3.8723	(1.7594)**
NON-EU	−1.5035	(0.1882)***	−1.0459	(0.1628)***
Standard Dev. (σ)				
KPE	3.1142	(0.2649)***	2.0041	(4.8462)
SIZE	1.4304	(0.9971)	0.1983	(3.1098)
HPW	1.4671	(0.5383)***	1.8594	(1.8937)
CONSTANT	2.8582	(0.0274)***	0.2138	(1.3674)
DIESEL	2.1196	(0.0493)***	7.7169	(4.0209)*
Interactions (Π)				
Price/Income	−16.8963	(0.8800)***	−4.8779	(0.6368)***
Cost (γ)				
γ_{lnc90}	0.1311	(0.0260)***	0.2594	(0.0898)***
γ_{LnSize}	0.8429	(0.0497)***	2.1385	(0.1720)***
γ_{LnHPW}	0.3558	(0.0187)***	0.6705	(0.0790)***
γ_{Xi}	0.0428	(0.0014)***	-	-
γ_{Diesel}	0.1948	(0.0087)***	0.3593	(0.0469)***
γ_{const}	0.3964	(0.0761)***	2.9119	(0.4758)***
γ_{Trend}	0.0137	(0.0013)***	0.0025	(0.0042)
Demand Statistics				
- Average Elasticity	8.7		2.9	
- Average Margin	12.9%		37.7%	
Volkswagen				
- Profits from Diesel	61.6%		58.2%	
- Innovation Rents	31.7%		26.7%	
Value of Diesels				
- Profits from Diesel (European Firms)	55.4%		54.4%	
- Implied Import Tariff	19.6%		48.3%	

Robust standard errors in parentheses. Significant estimates with p-values less than 0.1, 0.05, and 0.01 are identified with *, **, and ***, respectively. The *BLP* estimation results based on employing a standard two-step GMM estimator using the instruments discussed in Berry et al. (1995). "Margin" defined as $100 \times \frac{p-c}{p}$ where price excludes import tariffs, if applicable.

Table D.4: Value of Diesels to Different Firms

	Number of Models Offered		Prices without Diesel		Quantity Sold		Profit	
Year	Base	CF	Δ €	%Δ	Base	CF	Base	CF
1992								
BMW	5	3	56.7	0.2	19.8	21.8	43.1	48.0
FIAT	20	14	30.7	0.3	58.5	57.5	76.9	74.9
FORD	10	6	45.7	0.3	148.8	146.0	208.7	207.6
GM	14	9	53.7	0.3	122.9	124.6	181.2	188.2
MERCEDES	7	4	22.7	0.1	13.5	12.5	39.0	35.4
NON-EU	25	24	44.4	0.3	38.3	43.4	55.6	65.2
PSA	17	9	-15.3	-0.1	202.6	148.5	311.3	205.9
RENAULT	12	8	34.9	0.3	175.4	164.8	261.0	246.4
ROVER	7	5	31.9	0.2	15.7	17.1	21.7	24.0
VOLKSWAGEN	24	15	45.2	0.3	173.0	171.8	273.1	276.0
2000								
BMW	7	4	0.1	0.0	29.5	25.2	88.2	79.6
FIAT	27	14	60.5	0.5	59.8	51.5	97.9	83.7
FORD	17	10	60.9	0.4	123.2	97.2	230.6	189.4
GM	15	9	53.0	0.4	146.2	105.7	269.1	203.5
MERCEDES	12	6	9.8	0.1	24.6	24.9	71.0	73.4
NON-EU	70	50	56.4	0.4	160.6	187.4	254.9	307.8
PSA	19	9	-5.7	0.0	306.0	158.5	608.5	299.2
RENAULT	11	6	53.6	0.4	176.3	117.4	309.4	219.2
ROVER	9	5	60.7	0.4	18.7	16.7	37.4	33.9
VOLKSWAGEN	42	21	27.0	0.3	319.8	199.8	679.1	432.3

"Base" refers to benchmark equilibrium in the data while "CF" refers to the equilibrium without diesels cars. Under "Prices without Diesel", Δ€ refers to the average price change (in 1994 Euros) while %Δ refers to the average percentage price change. "Quantity Sold" is the number of new car sales (in thousands). "Profit" measured in millions of 1994 Euros.