Emission Policy, Competitive Imitation, and the Diffusion of European Diesel Automobiles*

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Abstract

Volkswagen introduced the TDI engine in 1989. Profitable imitation kept the diesel segment competitive and ensured that market penetration of diesels in Europe increased from 10% to over 50% in just a decade. Favorable taxation of diesel fuel also favored this diffusion but was more effective in addressing environmental concerns that prioritized the reduction greenhouse emissions over acid rain. Since European automakers dominate the diesel automobile segment worldwide, the unintended consequence of this environmental policy is that by fostering adoption of domestic diesel vehicles, it worked as a non-tariff trade barrier equivalent to a 37% import tariff that effectively cut Asian imports in half.

Keywords: Technology Generality, Non-Tariff Trade Barriers, Emission Standards,, Diesel Engines.

JEL Codes: O33, L62, F13.

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1 Introduction

The European automobile market is inconspicuously unique in a way that might escape most tourists traveling to the Old Continent. Americans may still notice that European vehicles are smaller, something that is not unique to Europe. Automobiles are also smaller in Asia, Australia, and Latin America. However, those renting a vehicle will likely be surprised to learn that they have to refuel with diesel rather than gasoline. Today, diesels exceed 60% of sales of European passenger vehicles.[1] This is the result of a dramatic transformation of the European automobile industry that began in the early 1990s and that, also surprisingly, has failed to attract the interest of innovation economists.[2]

During the 1990s, following VOLKSWAGEN's development of the turbo charged, direct injection, diesel engine (TDI), Europeans massively embraced diesel automobiles in a short period of time, with diesel market penetration rising in just a decade from as little as 10% to over 50% of annual sales. This quick adoption process compares favorably to many others innovations such as, for instance, the half a century time span needed for the diffusion of the much studied case of tractors.[3] There are numerous questions surrounding this fast adoption of diesel automobiles in Europe. 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 an additional 7% market penetration of diesel vehicles. This is clearly not enough to explain the large shift of demand in favor of diesel vehicles.[4] After evaluating the evidence we instead attribute the fast diffusion of diesel automobiles to a combination of technology generality, lack of subsequent major improvements, and the European fuel taxation framework enacted in the 1970s that shaped the ideal market conditions for the adoption of diesels to take off rapidly in the 1990s. The most novel result of the present paper is our claim that the success of diesel vehicles in Europe was, in part, an unintended consequence of an environmental policy that emphasized green house emission reduction over the negative effects of acid rain.

[1] See *ACEA European Union Economic Report*, December 2009.

[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 mostly an oddity in the global automobile industry as diesel vehicles have failed to succeed anywhere else with the recent exception of India. See Chug, Cropper and Narain (2011).

[3] Manuelli and Seshadri (2014) is the latest account of this interesting case. Other examples of slow diffusions include 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).

[4] 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.

Although automobile manufacturers other than VOLKSWAGEN could not sell TDI engines, it was not difficult for them to offer their own improved diesel models in a relatively short period of time. This low cost of imitation characterizes general technologies (*e.g.*, Bresnahan 2010) that can be easily modified or reverse engineered. When imitation is easy and potentially massive, uncertainty about recouping sunk investment costs may hinder the development of new technologies in the first place. This did not happened with the TDI. Potential profits of diesel engines might have been large enough for VOLKSWAGEN to introduce the TDI engine at a profit even expecting competitors to follow its lead. Our counterfactual analysis shows that this is the case: VOLKSWAGEN was able to capture between 48% and 79% of innovation rents.[5] Thus, within a few years, many other manufacturers offered diesel automobiles and intensified the competition in this market segment. This limited the market power of VOLKSWAGEN in the diesel segment and made diesel vehicles even more attractive to consumers, therefore resulting in a fast diffusion of this new technology.[6]

The other main reason contributing to the fast adoption of diesels has to do with the the initial conditions of the European automobile market in 1989 when the first TDI was sold. Many of the relevant features of the market at that time were a direct consequence of the 1970 Energy Directive. All the common *chicken-and-egg* type of arguments justifying the slow diffusion of a new technology were simply not an issue by the turn of the 1990s, which helps explaining the fast diffusion of diesel vehicles in Europe during a period of historically low, fuel prices.

Even today, European automobile manufacturers remain the leaders in the production of diesel vehicles. During the 1990s, they were the *only* makers of diesel vehicles and Europe the only market where this product was sold. Thus, any policy evaluation that we might consider will include some trade considerations. For instance, if we want to raise the diesel fuel tax to match gasoline taxation we need to to account not only for the expected increase in sales of gasoline models but also for the fact that many of them might be imported from Asia. This is not a minor effect because fuel efficient Asian manufacturers compete fiercely for mileage conscious drivers that constitute the bulk of diesel buyers. In addition to diesel fuel taxation, we analyze in this paper the trade impact of other policies such a more strict enforcement of patents or emission policies aiming at mitigating the effects of acid rain.

Documenting the intricate connection of emissions and trade policies is perhaps the most original contribution of the paper. We show that if European authorities had followed the emissions policy of the U.S. during the 1990s, the overwhelming adoption of diesels automobiles will have not taken place and diesels would have remained a market niche of about 10%, at levels of the 1980s.

[5] The importance of learning spillovers determines where within this range the actual rents captured by VOLKSWAGEN fall. Some classic economic models of innovations, *e.g.*, Mansfield (1961), already emphasized the effect of learning spillovers among adopters as the main driver of the speed of diffusion.

[6] 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 in diesel. See Figure W.3 in the Web Appendix.

Mileage conscious drivers would then favor gasoline efficient Asian imports. We estimate that under that scenario, market share of imports would double. The fact that European emissions policy focused on the reduction of greenhouse gases favored diesel vehicles and thus, domestic European production at the expense of Asian imports. Environmental policy thus became a powerful non-tariff trade barrier.[7] Our equilibrium analysis shows that the induced protection was substantial, nearly the equivalent of an additional 30% import tax 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).

In evaluating the effects of removing diesels from the choice set facing European drivers during the 1990s, our work is related to two streams of research. On the one hand, we use a counterfactual analysis similar to Chaudhuri, Goldberg and Jia (2006) to evaluate different levels of patent protection, *i.e.*, degrees of generality of technology. On the other hand, linking environmental and trade policies, our work also builds on the literature related to the interaction of domestic policy and international trade.[8] 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 policy. Moreover, our calculation of the tariff equivalence of the environmental regulation considered here provides evidence that domestic policy can be an effective replacement for traditional trade barriers such as import tariffs.

In order to measure the the importance of the TDI innovation we follow an approach similar to Berry, Levinsohn and Pakes (1999) in addressing the welfare effects of Voluntary Export Restraints, or Petrin (2002) to account for the redistribution of profits among automakers after the introduction of the minivan. We thus compare the profits of the actual market equilibrium with those estimated in the absence of diesel vehicles. Since diesel technology is only embraced by European manufacturers, this counterfactual also has important trade implications and thus, we also evaluate the induced profit changes by geographical origin of manufacturers. The estimation of the profits associated to the introduction of the TDI engines allows us to address two main research objectives: the measurement of the dissipation of innovation rents due to competition and easy imitation, and the quantification of the equivalent tariff protection effect of the European emissions policy.

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[7] 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.

[8] The seminal contribution here 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.

The adoption of diesel automobiles in Spain was slightly faster in the early years of the 1990s but otherwise, for the rest of the decade, the speed of diffusion is comparable to that of many other European nations.[9] Since the automobile industry is far from competitive, prices respond to firms' relative market power and the introduction of the new diesel models. We thus estimate the well-known discrete choice model of demand with differentiated products of Berry, Levinsohn and Pakes (1995). We assume that, conditional on the set of vehicles offered for sale, the actual observed prices used in the estimation are the Bertrand-Nash equilibrium outcome of an oligopolistic industry with horizontally differentiated products. This empirical strategy enables us to evaluate how consumer preferences evolved over time. This is also the ideal framework to evaluate many of the counterfactuals of interest for the present study.

The reason why we use Spanish automobile registration data rather than France, Germany, or Italy is that we are not aware of other data sources for this sample period that distinguish automobile registrations by make, model, and type of fuel. However, limiting our attention to the Spanish case has one important advantage: we can ignore potential endogeneity problems related to firms' product positioning decisions. The fact that Spain is a relatively small market within Europe —fifth largest by sales— allows us to ignore how changes in Spanish demand may induce automobile manufacturers to introduce new diesel models. Europe rather than Spain is the relevant market for firms to decide which models to sell. Automobile models are introduced in several national markets simultaneously. It is thus reasonable to assume that the introduction of any particular model was not driven by the particularities of the Spanish market so that the deep change in the composition of models sold helps us identify the evolution of perceived substitution among different vehicles and engine types.[10]

The paper is organized as follows. In section 2, we describe the TDI innovation 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 to be estimated. Section 4 reports the estimation results, summarizes the main findings, and documents how unobservable product characteristics are particularly important in explaining the behavior of sales of European diesels and imported gasoline vehicles. Section 5 questions the commonly held view that the success of diesel vehicles in Europe was the direct consequence of high fuel taxation. Section 6 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 7 we document the

[9] See *Automobile Registration and Market Share of Diesel Vehicles* in "ACEA European Union Economic Report," December 2009.

[10] Complicating the analysis is the fact that the 1990s was a period of significant transformation for the Spanish economy. However, non-reported results show that import tariff reductions following the end of the transition period to the accession of Spain to the European Union and the multiple mergers that took place in this industry (see Table A.1 in Appendix A) add little or nothing to explaining the change in sales and profits during the decade.

very different emission standards of U.S. and European authorities and conducts counterfactuals to evaluate how they could impact the market penetration of diesel vehicles. We simulate market configurations at increasingly higher retrofitting costs to show that complying with U.S. NO_x emission standards will reduce the diesel segment to a negligible market niche. Using these market configurations with a much reduced diesel presence we are able to compute the tariff-equivalence estimate of the non-tariff barrier component of the lenient European NO_x emission standards. Finally, Section 8 concludes.

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

In 1989, Volkswagen introduced the TDI engine in its Audi 100 model. 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 although this was something for consumers to learn from experience at the time this technology was first introduced.[11] Following this major technological breakthrough, Europeans massively embraced diesel automobiles, with their market share growing from as little as 10% to over 70% of annual sales in some popular market segment such as mid-sized sedans.

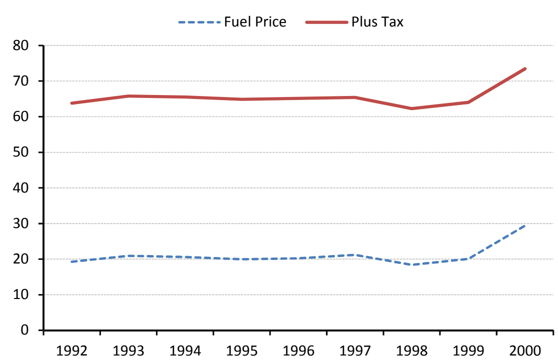
[11] See the 2004 report "Why Diesel?" from the European Association of Automobile Manufacturers (ACEA).

An important feature of this technological innovation is that TDI was a vastly more important technological improvement than anything that followed in the last quarter century. Thus, TDI made diesel technology much more attractive to consumers. In retrospect they gained little from waiting for additional incremental improvements. This may explain in part the fast pace of adoption of diesel automobiles.[12]

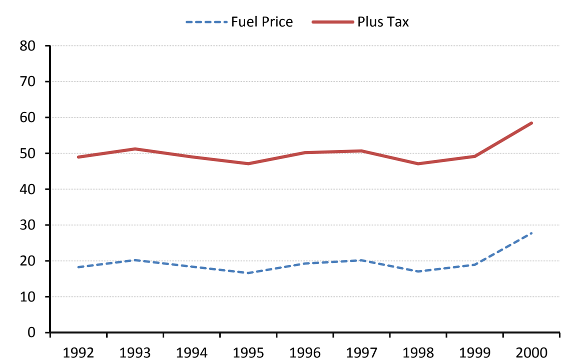
2.2 Initial Market Conditions

There are important institutional circumstances that helped build the initial conditions that were particularly favorable for the adoption of this new technology. The key element triggering all these favorable development is the *European Fuel Tax Directive* of the 1970s.

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



(a) Gasoline



(b) Diesel

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 more in general, faced a single and consistent set of incentives to save energy. This will avoid 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 its energetic content and that diesel fuel is taxed at a lower rate than gasoline. Figure 1 shows the effects of this Fuel Tax Directive on the market price of gasoline and diesel during the sample period used in our study.

Taxing fuels by volume offers a very transparent guideline so that national policies can then be easily monitored. However, it creates an incentive to use diesel fuels as diesel engines

[12] The argument that the expectation of future technology improvements may delay the rate of adoption was first put forward by Schumpeter (1950, p.98) and later formalized by Balcer and Lippman (1984).

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. On average in our sample diesel tax amounted to about 69% of gasoline tax (32 *vs.* 46 Euro cents per liter). This favorable treatment of diesel fuel was intended to help two economic industries particularly hit by the increase in fuel prices: road transport and agriculture. Both of them rely heavily on diesel fuels. 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.[13]

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 run 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.[14] 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 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 massively embracing this new technology when VOLKSWAGEN introduced the TDI engine the way they did it. While diesels are known to achieve better mileage than otherwise identical gasoline vehicles —leading to future fuel cost savings— they are also more expensive to purchase, regardless of whether this is because the technology is more expensive to produce or because manufacturers attempt to capture some of consumer rents of drivers favoring diesel vehicles.[15] But since the diffusion of TDI coincided with a long period of historically low fuel prices, the value of potential fuel savings were limited and so was the manufacturers' ability to overprice diesel automobiles.

[13] 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.

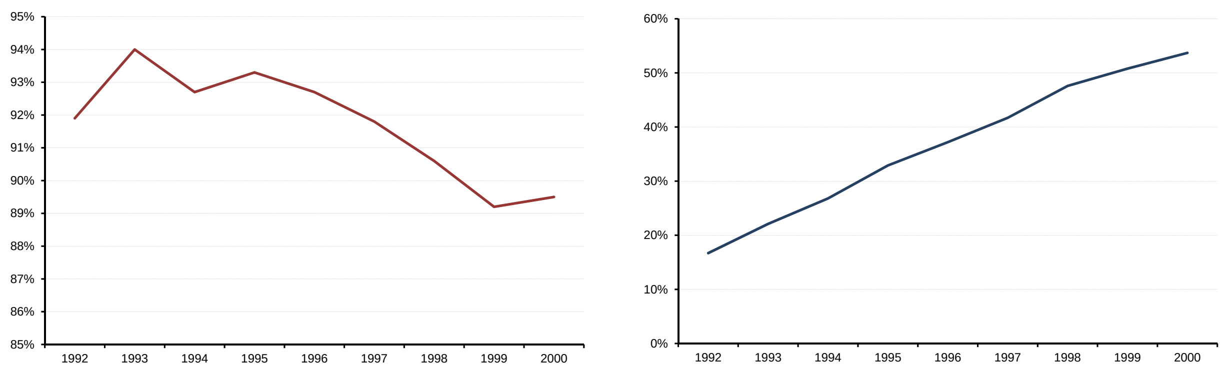
[14] See `http://www.autosavant.com/2009/08/11/the-cars-that-killed-gm-the-oldsmobile-diesel/` for an overview of how badly GM's retrofitted gasoline engines delivered poor performance when running on diesel fuel in the late 1970s and early 1980s and how such experience conformed the negative views of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

[15] 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.

2.3 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 excluding 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 after Germany, France, the United Kingdom, and Italy.

Figure 2: Evolution of Outside Option and Diesel Penetration

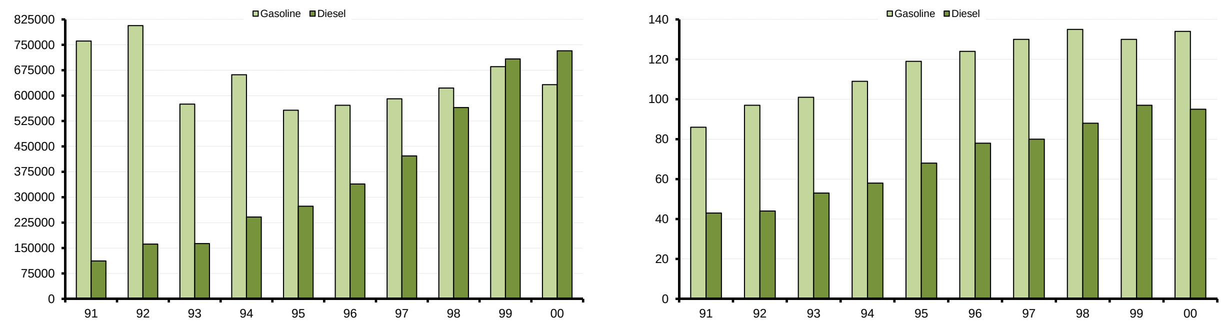


(a) Share of Outside Option (b) Share of Diesel Penetration

Figure 2(a) shows that the share of households who bought a car grew significantly over the decade, from 8% to 11%. The outside option is far from constant during the 1990s. The fast growth of the Spanish economy during the second half of the 1990 triggered important immigration that amounted to about 10% of the local population in little over five years. Sales of automobiles varied widely with the economic cycle with marked differences between the recession of the first half of the decade and accelerated growth of the second half, something that we need to control for at the estimation stage. This reduction in the share of the outside option helps explaining the 46% increase in sales during the decade, from 968,334 to 1,364,687 units sold annually. Figure 2(b) shows that the share of diesel vehicles sold grew steadily during the 1990s. Thus, the growth in sales goes hand in hand with a dramatic change in its composition.

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 the 1994 scrappage program, when they temporarily increased by 15%. Since then, sales of gasoline models increased at a steady pace, between 3% and 10% a year 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 rates between 13% and 25% a year between 1994 and 1999

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



(a) Sales (thousands of vehicles) (b) Models Available

depending on particular automobile segments. 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. Such a rapid introduction 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 the inability of VOLKSWAGEN to prevent imitation of the TDI by the competition. Furthermore, the number of models available grew significantly, both in the gasoline and the diesel segments. The effective entry of Asian manufacturers during the early 1990s increased the number of gasoline models by about 30%, thereby increasing competition among fuel efficient vehicles.[16] Since the entry of new models should reduce markups, consumers benefited from both an increase in variety and lower prices.

Table 1 summarizes the features of vehicles sold in the Spanish automobile market at the beginning and end of the 1990s. 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. Since European vehicles are smaller than those sold in the U.S., they use smaller engines that have less horsepower but are also more fuel efficient. Diesel models 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. All vehicles became larger during the decade but diesels made some inroads in the smaller segments as technology allowed building smaller diesel

[16] Asian imports include DAEWOO, HONDA, HYUNDAI, KIA, MAZDA, MITSUBISHI, NISSAN, SUZUKI, and TOYOTA.

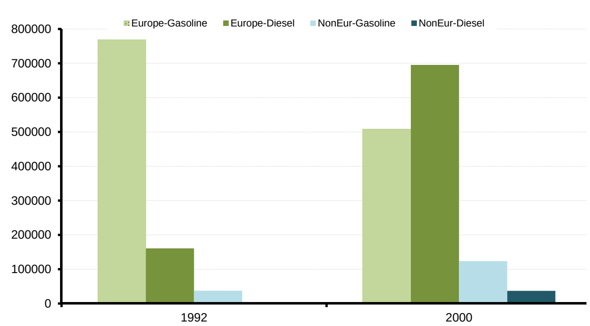
Table 1: Car Model Characteristics Across Engine Types

SEGMENT	MODELS	SHARE	PRICE	KPE	SIZE	HPW
1992						
EU: DIESEL	43	16.6	12.3	46.4	73.8	31.4
EU: GASOLINE	73	79.5	11.1	29.6	71.5	41.2
NON-EU: DIESEL	1	0.1	13.8	38.6	80.5	28.6
NON-EU: GASOLINE	24	3.9	14.9	27.3	78.0	45.3
ALL	141	100.0	11.4	32.3	72.2	39.7
2000						
EU: DIESEL	75	51.0	16.2	38.2	76.3	31.4
EU: GASOLINE	84	37.3	14.9	24.2	73.4	39.0
NON-EU: DIESEL	20	2.7	17.2	32.6	82.5	32.2
NON-EU: GASOLINE	50	9.1	13.7	22.8	75.3	40.9
ALL	229	100.0	15.5	31.4	75.3	35.1

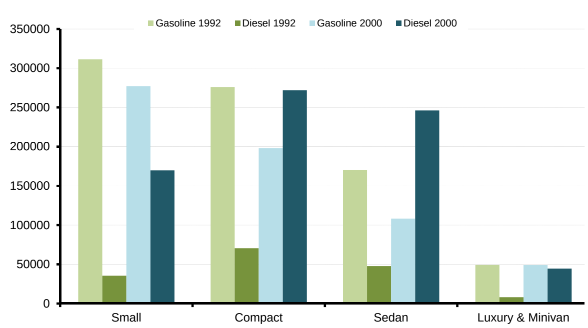
Statistics weighted by relevant quantity sold. SHARE is the market share as defined by automobiles sold. PRICE is denominated in the equivalent of thousands of 1994 Euros and includes value added taxes and import tariffs. KPE is the distance, measured in kilometers, traveled per euro of fuel. SIZE is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

engines. Diesel vehicles also became more powerful to compensate the increase in weight associated to diesel engines and the increase in size. On the contrary, performance —HPW, or the HP to WEIGHT ratio— of gasoline models almost universally worsened over the decade as vehicles became larger and heavier.[17] All these hints at diesel vehicles becoming better products capable of attracting the interest of many drivers. Diesel engines are also reputed for high torque, excellent reliability, and longer durability than gasoline engines. These were unobservable features, surrounded by uncertainty for consumers at the introduction of TDI, which could also be favorably compared against the increased weight and lower power of diesel vehicles.

Figure 4: Automobile Sales by Segment, Fuel Type, and Geographic Origin



(a) Sales by Year (thousands of vehicles)



(b) Sales by Segment (thousands of vehicles)

Figure 4 completes our description of the drastic changes in the Spanish automobile market. Figure 4(a) shows how the production pattern of European manufacturers is turned upside down

[17] The change in the distributions of these automobile characteristics is shown in Figure W.2 in the Web Appendix.

in just a few years. 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 earlier in the decade.

Sales of diesel became so important that non-European automakers began introducing their own diesel models.[18] Since they had not invested in this technology earlier, their diesel models included engines purchased from European automakers.[19] Figure 4(b) further explores the transformation of sales at the car segment level.[20] Notice that only in the SMALL segment are sales of gasoline models larger than their diesel counterparts by 2000. Even in the LUXURY and MINIVAN segment niches, diesels are on par with gasoline vehicles. The largest transformation happens in the COMPACT and SEDAN segments where sales of gasoline vehicles plummet while sales of diesels quintuplicate within few years.

3 An Equilibrium Oligopoly Model of the Automobile Industry

We estimate an equilibrium, discrete choice oligopoly model of horizontally differentiated products put forward by Berry et al. (1995) and now used widely. This model 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. extreme value distributed. We allow for individual heterogeneity in response to vehicle prices and characteristics by modeling the

[18] 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.

[19] 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.

[20] 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.

distribution of consumer preferences over characteristics and prices as multivariate normal with a mean that shifts with consumer attributes:[21]

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

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 and intercept 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 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:

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

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:

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

[21] 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.

with s_{0t} denoting the market share of the outside option.[22]

Since firms manufacture multiple models, the industry is characterized by multi product automobile manufacturers behaving as oligopolistic, non-cooperative, profit maximizers. We assume that marginal costs depend linearly on observable model characteristics z_{jt} and some unobservable characteristics summarized by ω_{jt}:

$$\ln(mc_{jt}) = z_{jt}\gamma_t + \omega_{jt}\,. \tag{7}$$

For each time period, first-order conditions of profit maximization are a nonlinear function of market shares $s_{jt}(x_t, p_t, \xi_t; \theta)$ of each model, their retail prices, and markups:[23]

$$\frac{p_{jt}}{1+\tau_{jt}} = mc_{jt} + \underbrace{\Delta_t^{-1}(p, x, \xi; \theta) s_{jt}(p, x, \xi; \theta)}_{b_{jt}(p,x,\xi;\theta)}\,. \tag{8}$$

where τ_{jt} is the year-specific import duty applicable to each model, if any; $b_{jt}(\cdot)$ is the vector of equilibrium markups; $s_{jt}(\cdot)$ is the vector of market share estimates for each vehicle-year pair; and $\Delta_t(\cdot)$ is the ownership matrix with elements:

$$\Delta_{rjt}(x_t, p_t, \xi_t; \theta) = \begin{cases} \partial s_{jt}(x_t, p_t, \xi_t; \theta)/\partial p_{jt}^{\tau}\,, & \text{if products } \{r, j\} \text{ produced by the same manufacturer}\,, \\ 0 & \text{otherwise}\,. \end{cases} \tag{9}$$

where p_{jt}^{τ} is the price chosen by the firm not including any applicable import tariffs paid by the consumer.[24] The cost equation then becomes:

$$\ln(mc_{jt}) = \ln\left[\frac{p_{jt}}{1+\tau_{jt}} - b_{jt}(p, x, \xi; \theta)\right] = z_{jt}\gamma_t + \omega_{jt}\,. \tag{10}$$

Although the estimation is standard, we need to account other important changes taking place during the 1990s such as increasing personal income, import duties, and the ownership structure of the European automobile industry. When estimating the model we modify both the incomes of consumers to account for growth in the Spanish economy and the marginal cost equation to control for the differentiated import taxation faced by manufacturers depending on their national origin. Similarly, we also control for the corresponding ownership structures at the beginning and

[22] Figure 2(a) shows that the outside option varies significantly during the decade. Starting with 1992, the values of s_{0t} that we employ in our estimation are: 0.92, 0.94, 0.93, 0.93, 0.93, 0.92, 0.91, 0.89, and 0.89, respectively.

[23] The complete derivation of these general first-order conditions is available in Berry et al. (1995, §3).

[24] This treatment of the import tariffs is consistent with how duties are applied in practice. Since the consumer pays the import tariff, foreign firms choose p_{jt}^{τ} but consumers face retail price $p_{jt} = (1 + \tau_{jt})p_{jt}^{\tau}$.

end of the decade when defining the multi-product first-order profit maximization conditions of the equilibrium model to be estimated.[25]

4 Estimation

Estimation of this type of model is now standard and described in detail in Berry et al. (1995, §6). For each year t we first compute δ_{jt}. (Berry et al., 1995, Appendix I) shows that the vector of mean product valuations $[\delta_{jt}]$ is a contraction mapping which can be computed recursively given consumer preferences $[\beta_t, \Pi_t, \Sigma_t]$ over characteristics $[x_{jt}]$ and prices $[p_{jt}]$ as well as the empirical distribution of vehicle market shares $[s_{jt}]$. Instrumental variable regression estimation of equation (3a) then produces a vector of consistent unobservable product characteristics estimates $[\xi_{jt}]$. Next we solve for the implied markups $[b_{jt}]$ and combine these with our guess of $[\gamma_t]$ in (10) to recover the cost side unobservable $[\omega_{jt}]$. Finally we interact the optimal instruments with the vector of $[\xi_{jt}\ \omega_{jt}]$ to obtain θ_t for each sample period by generalized method of moments estimation. As we described below, we considered several combinations of instruments, a large variety of initial conditions, and several convergence criteria to ensure that our estimates are robust.

4.1 Parameter Identification

Variation in prices conditional on similar product characteristics identifies the product price elasticities while cross-price elasticities are identified by differential changes in prices & 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 coefficients (Π). The Bertrand-Nash equilibrium plus variation in price elasticities conditional on product characteristics identifies marginal costs (γ). Finally, variation across time identifies changes in the point estimates.

4.2 Instruments and Robustness

The need for instrumenting arises from the fact that observed prices reflect the effect of unobservable product characteristics. Thus, p_{jt} and ξ_{jt} are not orthogonal and simple ordinary least squares regression of (3a) will produce biased estimates. Automobile prices are then commonly instrumented

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

with their product characteristics, sums of these characteristics for other models produced by the same firm, as well as those of competitors. The idea is that these product characteristics are exogenous, at least in the short run, and help determine the nature of competition and the ability of firms to charge a higher or lower markup depending on the product positioning of competitors. Adding cost characteristics account for cost shifters that also influence pricing.

Using all product characteristics is known to easily lead to serious multicollinearity problems, *e.g.*, Berry et al. (1995, §5). Thus we only use HPW and FUEL as demand instruments while ln HP and ln WEIGHT are used to instrument for cost shifts. We also include their averages for other models produced by the firm and competitors, respectively.[26] Demand instruments are averaged separately for vehicles with different fuel engine types as suggested by Bresnahan, Stern and Trajtenberg (1997). As for supply, we average them across market segments.

We estimated the model using this benchmark instrumentation with those obtained using other alternatives. We added DIESEL and/or SEAT as additional demand shifters and the number of products sold as another cost shifter that can account for potential economies of scope or costs differential perhaps related to the size of the distribution network of the automobile manufacturer. A second source of concern is how sensitive our results to convergence criteria and search algorithms are. Again, results appear to be quite robust.[27] Finally, our evidence appears to indicate that our estimates belong to a global rather than a local optimum.[28]

4.3 Estimation Results

We estimate our model using the 1992-2000 sample period. Demand includes a measure of automobile performance, HPW; class of vehicle, SIZE; and fuel economy, KPE. In addition, we include the SEAT indicator to capture any potential home bias effect in Spanish drivers' automobile purchasing decisions. Since the sample covers a period with important growth of demand we also include a

[26] We use averages rather than sums to ease scaling problems that might appear in the estimation.

[27] We first use a non-derivative, simplex Nelder-Mead search algorithm in our estimation. A gradient-based quasi-Newton method produces very similar estimates although the final value of the objective function is slightly lower. We follow Dubé, Fox and Su (2012) and set the norm for the mean value contraction equal to 1E-14 in order to ensure convergence to consistent stable estimates. We increased it up to 1E-10 without any effect on the estimates. For a more strict 1E-16 tolerance level the computation of the inner fixed point failed to converge. As for the tolerance of the objective function we set a 1E-05 criteria, more demanding than the 1E-03 of Knittel and Metaxoglou (2013). We also estimated the model setting this tolerance level at 1E-08. Results were identical although the computation time increased substantially.

[28] We follow Knittel and Metaxoglou (2013) and generate one hundred initial guess for the (π, σ) parameters using draws from normal distributions with different dispersions. Figure W.1 in the Web Appendix shows the empirical distribution of the value of the estimated objective functions, which is highly concentrated around the value obtained in our estimation. The minimum value found in this exercise is slightly lower but significant parameter estimates are statistically identical to our benchmark case. Table W.1 in the Web Appendix summarizes these robustness checks.

time trend to capture time-varying effects on preferences other than those captured by income. As this time period covers the diffusion of diesel vehicles, we also 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. We explored several random coefficients. The reported results we include those that best capture the heterogeneity of preferences: a random coefficient on the average valuation of vehicles, σ_{CONSTANT}; size, σ_{SIZE}; and fuel efficiency, σ_{KPE}. On the supply side, marginal cost of production is made a function of the type of fuel, DIESEL; product characteristics (HP, WEIGHT, SIZE); a time trend aimed at capturing potential efficiency gains, TREND; and an indicator of imported brands, NON-EU, to control for possible location cost advantages of automobile manufacturers.[29]

Table 2: Demand and Supply Estimates

Variable	Coefficient	Rob. SE	Variable	Coefficient	Rob. SE
Mean Utility (β)			Cost (γ)		
β_{CONSTANT}	−16.1210	(1.8681)***	γ_{CONSTANT}	−0.5130	(0.1121)***
β_{TREND}	−0.0075	(0.0226)	γ_{TREND}	−0.0244	(0.0047)***
β_{HPW}	6.0309	(1.3316)***	$\gamma_{\ln \text{HP}}$	1.1616	(0.0681)***
β_{SIZE}	2.9064	(1.0738)***	$\gamma_{\ln \text{WEIGHT}}$	0.6246	(0.1222)***
β_{KPE}	1.7841	(2.3968)	$\gamma_{\ln \text{SIZE}}$	0.7223	(0.1917)***
β_{SEAT}	1.0307	(0.2935)***	γ_{DIESEL}	0.3007	(0.0310)***
β_{DIESEL}	−0.1109	(0.3308)	$\gamma_{\text{NON-EU}}$	−0.2202	(0.0256)***
$\beta^{94-95}_{\text{DIESEL}}$	−0.9390	(0.3140)***			
$\beta^{96-98}_{\text{DIESEL}}$	0.7385	(0.2339)***			
$\beta^{99-00}_{\text{DIESEL}}$	0.5707	(0.2359)**			
Standard Dev. (σ)			Interactions (Π)		
σ_{CONSTANT}	4.3868	(0.6603)***	$\pi_{p/y}$	−3.6577	(0.4334)***
σ_{SIZE}	2.1590	(0.5695)***			
σ_{KPE}	5.3269	(2.1731)**			
Elasticity Statistics:			Markup Statistics (%)		
- Average	3.1		- Average	37.2	
- Maximum	7.8		- Maximum	65.2	
- Minimum	1.8		- Minimum	14.0	

Significant estimates with p-values less than 0.1, 0.05, and 0.001 are identified with ***, **, and *, respectively. "Markup" defined as $100 \times \frac{p-c}{p}$ where price excludes import tariffs, if applicable. Equilibrium prices account for year-specific make ownership structure as reported in Table A.1 in Appendix 2.

[29] In addition to the characteristics used in the estimation reported in Table 2, 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.

Table 2 reports the estimation results. Estimates are reasonable and congruent with the descriptive evidence of the industry of Section 2. Diesels are more expensive to manufacture than gasoline models. Marginal cost of production are also higher for larger, heavier, and more powerful cars. It appears that there is no substantial efficiency gains occurring during the decade although Asian manufacturers are more cost efficient than domestic European automakers. Therefore, European firms appear to specialize in relatively expensive products while Asians enjoy a non-negligible cost advantage in the production of fuel efficient gasoline vehicles.

As for demand, it is downward slopping and always elastic, with an average 3.1 price elasticity that in combination with the cost estimates leads to an average 37% markup for the Spanish automobile industry during the 1990s. There is however substantial heterogeneity, with markups as low as 14% and as high as 65%. This wide range of markups 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.

Spanish drivers value larger cars (SIZE) and high performance (HPW). Conditional on these and other observable characteristics, they mildly favor the home brand SEAT over other manufacturers, perhaps not so much because of the inherent quality of these vehicles but because of the widespread network of dealers available. As time goes by, SEAT vehicles are increasingly powered with VOLKSWAGEN engines (remember that VOLKSWAGEN purchased the SEAT group in 1989). Therefore, rather than just showing a bias for domestically produced cars, Spanish drivers might simply value high quality mechanics at a discount price.

Estimates also show evidence of heterogeneous preferences. On average, most drivers prefer large cars although some much more than others. This is consistent with the sustained growth in the size of vehicles documented in Table 1 across engine types and in Table C.1 in Appendix C across segments. Similarly, on average, Spanish drivers appear not to care much for fuel efficiency. As the real cost of fuels remain quite stable during the 1990s, see Figure 1, the preference for larger and heavier cars increases the cost of driving by about one kilometer per euro during the decade (see Table 1). However, the size of the estimate of σ_{KPE} is large enough relative to β_{KPE} to ensure that a substantial share of consumers strictly prefer small vehicles.[30]

Diesel vehicles are not particularly valued at the beginning of the 1990s. During 1994 and 1995, when the automobile scrapping programs were implemented, consumers favored gasoline vehicles over diesels, *e.g.*, see Figure 3(a). However, during the fast economic growth phase of the second half of the decade, divers massively favored diesel vehicles. The interaction of a nonlinear time trend and the DIESEL dummy captures this change in preferences in favor of diesel vehicles.

[30] The distribution of the random coefficients is available in Figure W.4 in the Web Appendix.

It is likely that consumers become increasingly aware of the features of diesel vehicles as they are more frequently found on the road.[31]

We will now address two issues that are informative of how the market for automobiles in Spain was transformed during the 1990s. In particular, we will look at the effect on sales of unobservable product characteristics and the evolution of substitution patterns over time.

Table 3: Measuring the Effects of Unobserved Product Characteristics

Scenario	Models	CAFE	Price	Quantity	Markup	Share	Profits
Benchmark (2000)							
EU: DIESEL	75	51.75	16.19	695.37	38.76	50.95	4,112.85
EU: GASOLINE	84	41.43	14.93	508.70	42.09	37.28	2,927.54
NON-EU: DIESEL	20	43.45	17.20	36.97	42.15	2.71	203.64
NON-EU: GASOLINE	50	38.52	13.66	123.65	48.54	9.06	614.14
Equilibrium with $\xi = 0$							
EU: DIESEL	75	54.17	15.53	460.75	38.70	40.16	2,593.06
EU: GASOLINE	84	40.39	15.42	317.12	39.55	27.64	1,793.07
NON-EU: DIESEL	20	44.92	17.35	101.80	42.29	8.87	565.90
NON-EU: GASOLINE	50	37.61	14.56	267.70	47.95	23.33	1,398.24

"CAFE" is the sales-weighted harmonic mean fuel economy, expressed in miles per gallon, as commonly used in the U.S. to evaluate the fuel efficiency of a manufacturer's fleet. "Price" is the sales-weighted average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Quantity" is measured in thousands of cars. "Profits" is measured in the equivalent of millions of 1994 Euro. "Markups" and "Share" are reported as percentages.

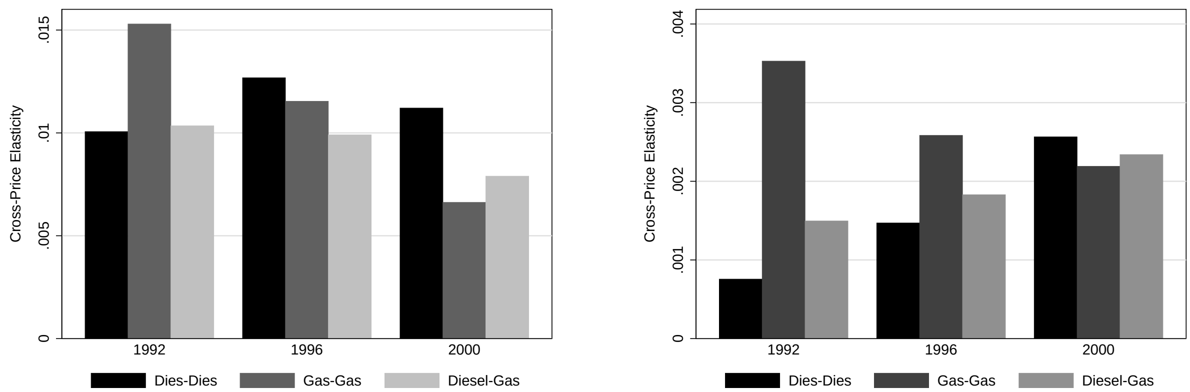
Table 3 compares the Spanish automobile market in 2000 with the predictions of our estimated model if we ignore the effect on demand of unobserved product characteristics, *i.e.*, $\xi = 0$. Overall, there is a reduction of sales across all segments of about 271,000 vehicles. Thus, some of the unobservable product characteristics are responsible for the decision of drivers to purchase a new vehicle. More interesting is to notice the effect that ξ has on the distribution of sales between domestic and foreign manufacturers. If unobservable product characteristics were irrelevant Asian manufacturers would double their sales of fuel efficient gasoline models and raise their combined market share from 9% to 23% even though, on average, these imports would be more expensive. Thus, the lack of brand recognition perhaps due to their recent entry in the Spanish market or a limited network of dealerships costs Asian manufacturers the important amount of €1,000 per vehicle.

In the alternative scenario without unobserved product characteristics, diesels would aslo be less popular, their overall market share dropping by 4.63%, or 170,000 vehicles. It follows that there are important unobservable characteristics of diesel vehicles that drive their demands substantially.

[31] No matter how likely this explanation might appear, this Bayesian learning model is not something we can test using yearly aggregate data only.

The dummy DIESEL already accounts for features such as smell, clattering, and high torque at low r.p.m. that are specific of this technology. The interaction of DIESEL with time may capture the effect of reliability and durability of diesel engines that need time for consumers to learn. What remains, and what Table 3 documents, is again the effect of brand reputation. In addition to be new entrants in the Spanish market, Asian manufacturers are new to this technology and they indeed purchase the diesel engines from European manufacturers. This lack of reputation captured by ξ explains that the market share of Asian diesels is 6% lower than what a model without unobserved product characteristics would predict. Interestingly, Asian diesels are identically priced under the two scenarios.

Figure 5: Substitution Patterns Across Fuel Types



(a) All Cars (b) Just Sedans

Results reported in Table 2 show that consumers' perception of diesels evolves favorably over the decade as diesel vehicles become more widespread. Those estimates allow us to compute cross-price elasticities between any two models sold in the market over time. Figure 5 depicts the evolution of sales-weighted average elasticities by type of engine both for the segments of compact vehicles and sedans, arguably the most important segments for diesels (see Figure 4). In both market segments, diesel and gasoline vehicles appear to become increasingly closer substitutes. Similarly, as time goes by, buyers of diesel vehicles appear to respond faster to changes in prices of other diesels, perhaps reacting to important increase in diesels offerings, *e.g.*, see Figure 3(b).

. These two combined effects limit the market power of diesel manufacturers, thus further easing the adoption of diesel vehicles. Demand for gasoline follows a different pattern. As diesels become more popular, remaining buyers of gasoline vehicles have a stronger preference for gasoline engines, and thus, they are also more loyal customers. The lower elasticity for gasoline vehicles translate into higher markups despite the much larger product offering in the gasoline segment.

5 Fuel Taxes and Diffusion of Diesel Vehicles

Following the European Fuel Taxation Directive of the 1970s, diesel fuel received a favorable treatment that has convinced many to conclude that the 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 to support our position we conduct a couple of counterfactuals in Table 4 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.

Table 4: Modifying Diesel Fuel Taxes (2000)

Scenario	Fuel Tax	Models	CAFE	Price	Quantity	Markup	Share	Profits
Benchmark Diesel and Gas Excise Taxes								
EU: DIESEL	0.23	75	51.75	16.19	695.37	38.76	50.95	4,112.85
EU: GASOLINE	0.35	84	41.43	14.93	508.70	42.09	37.28	2,927.54
NON-EU: DIESEL	0.23	20	43.45	17.20	36.97	42.15	2.71	203.64
NON-EU: GASOLINE	0.35	50	38.52	13.66	123.65	48.54	9.06	614.14
TOTAL	0.29	229	45.83	15.52	1,364.70	40.98	100.00	7,858.16
Diesel and Gas Excise Taxes are the Same								
EU: DIESEL	0.35	75	51.42	16.37	572.38	38.72	44.35	3,417.16
EU: GASOLINE	0.35	84	41.48	14.82	552.64	42.02	42.82	3,155.08
NON-EU: DIESEL	0.35	20	43.03	17.35	32.60	42.18	2.53	181.23
NON-EU: GASOLINE	0.35	50	38.58	13.62	133.05	48.54	10.31	659.15
TOTAL	0.35	229	45.03	15.45	1,290.66	41.23	100.00	7,412.62
Diesel Excise Tax is Increased								
EU: DIESEL	0.38	75	51.35	16.41	551.27	38.72	43.11	3,298.06
EU: GASOLINE	0.35	84	41.48	14.81	560.79	42.00	43.86	3,197.18
NON-EU: DIESEL	0.38	20	42.95	17.38	31.81	42.18	2.49	177.15
NON-EU: GASOLINE	0.35	50	38.58	13.62	134.75	48.55	10.54	667.44
TOTAL	0.36	229	44.89	15.44	1,278.62	41.28	100.00	7,339.82

"Fuel Tax" is measured in 1994 Euros per liter and TOTAL is the sales-weighted average fuel excise tax. "CAFE" is the production-weighted harmonic mean fuel economy, expressed in miles per gallon, as commonly used in the U.S. to evaluate the fuel efficiency of a manufacturer's fleet. "Price" is the sales-weighted average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Quantity" is measured in thousands of cars. "Profits" is measured in the equivalent of millions of 1994 Euro. "Markups" and "Share" are reported as percentages.

Our first counterfactual (center panel of Table 4) eliminates the favorable tax treatment of diesel fuel by setting a common fuel tax equal to the higher gasoline excise tax. Comparing results to the benchmark case, we notice that sals of diesels would be 127,360 units lower in year 2000. These lower diesel sales will reduce automakers profits in the order of m€445, or about 5% of profits. Market penetration of diesel vehicles increased 37 points from 16.7% in 1992 to 53.7% in 2000. Being important, the favorable treatment of diesel fuels accounts only for a share of 6.78%, leaving a much larger 30% market penetration of diesel vehicles to be explained by other factors.

Interestingly, the increase in diesel fuel taxation has two other side effects following the reduction in demand for diesel vehicles: the worsening of the average mileage of vehicle sold and a 1% market share increase of imports. In other words, the distorting effect of a reduced diesel fuel tax rate was not only to help farmers and truckers but also the domestic automobile manufacturers by favoring the purchase of vehicles that foreign automakers could only produce at a much higher cost.[32]

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). The bottom panel of Table 4) shows that under the current system diesel fuels are more heavily taxed than gasoline.[33] 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 8.07% lower. Relative to the scenario of equal excise taxation across fuels based on volume, the difference is a negligible 1.29% lower market share penetration of diesels. Given this minimal impact of the nuew fuel taxation regime, it should not be surprising than confronting excessive levels of local pollution European authorities have recently suggested the use of subsidy schemes to scrap old diesel vehicles, or even the use of traffic bans of diesel vehicles in large cities.[34]

[32] For the American reader these mileage figures may seem exceedingly high, *e.g.*, the average fuel economy in 2008 for new cars and light trucks the U.S. was only 26.4 miles per gallon. However, the reported European mileage is in line with the common average consumption in Europe. It corresponds to 5.81 and 5.16 liters per 100km, respectively. There are two reasons that explain this large difference. First, European automobiles are smaller and more fuel efficient. Second, the way fuel consumption is measured in Europe exacerbates this difference as it only accounts for highway driving at a constant speed of 90km/h rather than the 40/60 U.S. mix of highway and city driving.

[33] Excise fuel taxes at the bottom panel of Table 4 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`

[34] See the "Charlemagne" section of *The Economist*, May 17th, 2014.

6 Dissipation of Innovation Rents

A natural question our model can address is whether the introduction of the TDI technology was profitable for VOLKSWAGEN. 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.[35] The counterfactual analysis summarized in Table 5 leaves little room for doubt that introducing the TDI technology was a profitable decision and that indeed VOLKSWAGEN captured a significant share of the potential innovation rents.

Table 5: Value of TDI Technology to Volkswagen (2000)

			TDI Monopoly	
	No TDI	Benchmark	Spillovers	No Spillovers
Prices (€Thousand)	15.13	16.14	17.11	16.50
- Diesel	-	16.72	17.83	17.40
- Gas	15.13	15.24	16.03	15.71
Quantity (Thousand)	208.12	319.79	392.06	327.08
- Diesel	0.00	194.31	235.57	153.54
- Gas	208.12	125.47	156.49	173.54
Market Share (%)	20.34	23.43	34.88	30.06
- Diesel	0.00	26.53	100.00	100.00
- Gas	20.34	19.84	17.61	18.57
Markup (%)	42.79	40.79	43.60	42.89
- Diesel	-	39.19	42.24	40.89
- Gas	42.79	43.28	45.65	44.65
Profit (€Million)	1,246.13	1,969.06	2,739.03	2,158.68
- Diesel	0.00	1,202.45	1,675.37	1,030.10
- Gas	1,246.13	766.61	1,063.66	1,128.58

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

To evaluate the profitability of TDI for VOLKSWAGEN, we make use of two counterfactuals. The "No TDI" counterfactual of Table 5 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 in Europe. Under this scenario VOLKSWAGEN's overall profits are m€722 lower

[35] 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).

despite the fact that profits from the gasoline division grow by almost m€500. 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 allow 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 two other counterfactuals where the TDI technology is assumed to be exclusive for VOLKSWAGEN and where competitors cannot come up with close substitutes in the diesel segment. Under the "TDI Monopoly, Spillovers" 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€2.7, or over m€770 higher. Thus, the maximum value of the innovation rents amount to bn€1.5, the difference between VOLKSWAGEN being a diesel monopolist and the scenario when diesels do not exists. 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.[36]

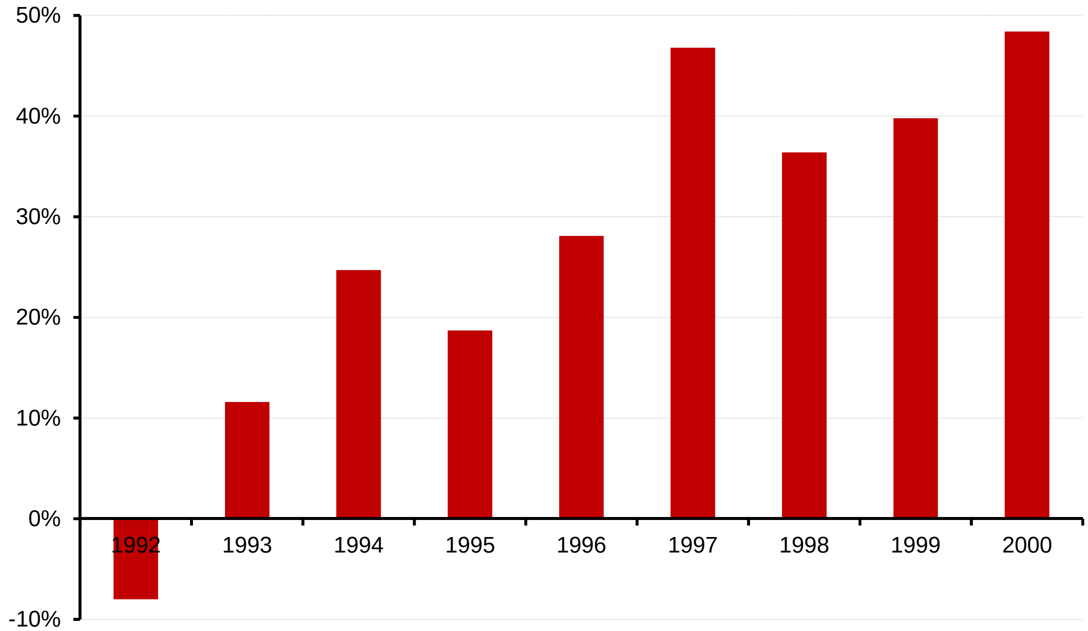
Therefore, starting from the "No TDI" scenario, we can compare the incremental profits of being a monopolist bn€2.7 – bn€1.2, with the incremental profits of the benchmark scenario bn€2 - bn€1.2, to conclude that VOLKSWAGEN is able to keep 48.4% of the potential rents of the TDI innovation under a much more strict patent protection or less easily reusable technology. Competition is thus responsible for the dissipation of more than half the innovation rents, which will benefit consumers in the form of lower prices and more products to choose from.

At the beginning of the 1990s VOLKSWAGEN was not the leader of the Spanish market neither in gasoline or diesel. RENAULT, FORD, and GM 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.[37] VOLKSWAGEN was a close second top diesel seller thanks to the early acquisition of the local producer SEAT. Because of this, Figure **??** 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.

[36] Relative to the current benchmark, under this second hypothetical scenario are larger not only because of the monopoly position in the sale of diesel vehicles (up m€473), but also because VOLKSWAGEN's profits associated to its increased sale of gasoline models are also larger (up m€298). This is due to the fact that many other other fuel efficient diesel vehicles of other manufacturers have now been removed to compute this new market equilibrium.

[37] See Figure W.3 in the Web Appendix.

Figure 6: Volkswagen's Rent Capture Across the Decade



One may be concerned that imitation of the TDI by competitors like MERCEDES, PEUGEOT, or RENAULT was an important component to facilitating drivers adoption of the diesel engine has they became more frequently in contact with other diesel vehicles. Consequently, adoption in a world in which VOLKSWAGEN maintains its monopoly rights would likely be smaller because of reduced spillovers, and our estimate of the degree to which VOLKSWAGEN captured the available rents would be biased downwards. To address this concern, last column of Table 5 conducts the "Monopoly, No Spillovers" counterfactual, where we restrict the time trend variables interacted with the DIESEL dummy to be zero. In the absence of spillovers from other manufacturers, the maximum innovation rents are only m€913 of which VOLKSWAGENstill captures m€723, *i.e.*, 79%.

In the end, whether VOLKSWAGEN is able to keep larger share of the potential innovation rents depends on the successful differentiation of their products and the ability to avoid being imitated by competitors. To this end, Table 6 presents the results of several counterfactuals in the same spirit than Chaudhuri et al. (2006). We recompute the market equilibrium of the Spanish market in 1999-2000 under scenarios that are increasingly more restrictive for the presence of diesel vehicles in order to explore how a more effective patent protection policy (or an environmental regulation against diesels) would affect the market share of domestic European manufacturers and the average mileage of vehicles sold.

The second panel considers the case where only European manufacturers sell diesel vehicles. This corresponds to the case where European manufacturers refuse to sell diesel engines to Asian automakers. Asian manufacturers did not sell any diesel vehicles. As they became popular, they

Table 6: Value of Diesel Automobiles (2000)

	Models	CAFE	Price	Quantity	Markup	Share	Profit
Benchmark							
EU: DIESEL	75	51.75	16.19	695.37	38.76	50.95	4,112.85
EU: GASOLINE	84	41.43	14.93	508.70	42.09	37.28	2,927.54
NON-EU: DIESEL	20	43.45	17.20	36.97	42.15	2.71	203.64
NON-EU: GASOLINE	50	38.52	13.66	123.65	48.54	9.06	614.14
Only European Firms Offer Diesels							
EU: DIESEL	75	51.74	16.22	707.24	38.84	52.35	4,201.81
EU: GASOLINE	84	41.42	14.97	517.03	42.17	38.27	2,988.83
NON-EU: DIESEL	0	-	-	-	-	-	-
NON-EU: GASOLINE	50	38.52	13.66	126.59	48.48	9.37	627.61
Only Volkswagen Offers Diesels							
EU: DIESEL	18	57.26	17.83	235.57	42.24	20.96	1,675.37
EU: GASOLINE	84	41.36	14.93	717.15	42.08	63.79	4,135.65
NON-EU: DIESEL	0	-	-	-	-	-	-
NON-EU: GASOLINE	50	38.47	13.85	171.44	48.71	15.25	866.24
No Diesels Offered							
EU: DIESEL	0	-	-	-	-	-	-
EU: GASOLINE	84	41.41	14.87	831.86	41.83	81.28	4,737.78
NON-EU: DIESEL	0	-	-	-	-	-	-
NON-EU: GASOLINE	50	38.46	13.97	191.57	48.92	18.72	981.58

"CAFE" is the production-weighted harmonic mean fuel economy, expressed in miles per gallon, as commonly used in the U.S. to evaluate the fuel efficiency of a manufacturer's fleet. "Price" is the sales-weighted average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Quantity" is measured in millions of cars. "Profits" is measured in the equivalent of millions of 1994 Euro. "Markups" and "Share" are reported as percentages. "Markups" include import duties paid by consumers.

bought diesel engines directly from European manufacturers to power their many new models being introduced in the gasoline segment. This raises the question of whether Europeans were not cannibalizing some of their own sales at a huge loss. Results show that European manufacturers lost about m€150 for selling diesel engines to Asian manufacturers while they gained m€190 for offering diesel vehicles. Evidently, most profits were accrued by the seller of these engines, BMW, but overall, European manufacturers did not suffer much from allowing Asians to turn the diesel segment more competitive. Indeed, they were able to capture most of Asians' incremental profits from offering diesels.

The third panel looks at the case where VOLKSWAGEN is the only manufacturer selling diesel vehicles analyzed before in Table 5. Overall, European manufacturers are worse off, with the exception of VOLKSWAGEN, while Asians increase their profits. Not being able to purchase or imitate diesel vehicles, they sell their competitive and fuel efficient gasoline to a larger share of customers that now cannot opt for a diesel unless they purchase the pricey VOLKSWAGENs. comparing the first and third panel we get an idea of the economic importance of the generality of the diesel technology that allowed imitation and entry in this market segment: the average price of diesels is €1,650 because of the increased competition; market share of diesel increased by 30%; and the share of imports (both gasoline and diesel) is 3.5% lower.

The last panel resembles a situation similar to that of the U.S. automobile market from the late 1990s to the early 2010s when diesel vehicles were essentially non-existing. Average mileage substantially worsens, from 46.48 to 40.86 miles per gallon, in the absence of diesel vehicles. Total profits are also a fraction of the benchmark scenario as diesel expands the market by increasing participation from fuel-efficient drivers. The only clear winners of not having the diesel technology available are Asian manufacturers, who increase they profits by 50%.

7 Trade Effects of Strict NO_x Emission Standards

So far we identify 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 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. In this section we put forward the hypothesis that this was due to the different goals pursued by the environmental policies in the U.S. and the E.U. While Americans were concerned mostly with reduction in emissions leading to acid rain, Europeans aimed at reducing green house emissions. The most novel result from this analysis is our use of the equilibrium oligopoly model of demand for differentiated products to show that environmental policies might have important trade effects and that in fact, the European green house emission policy amounted to a substantial non-tariff trade barrier equivalent to a 29% import tariff.

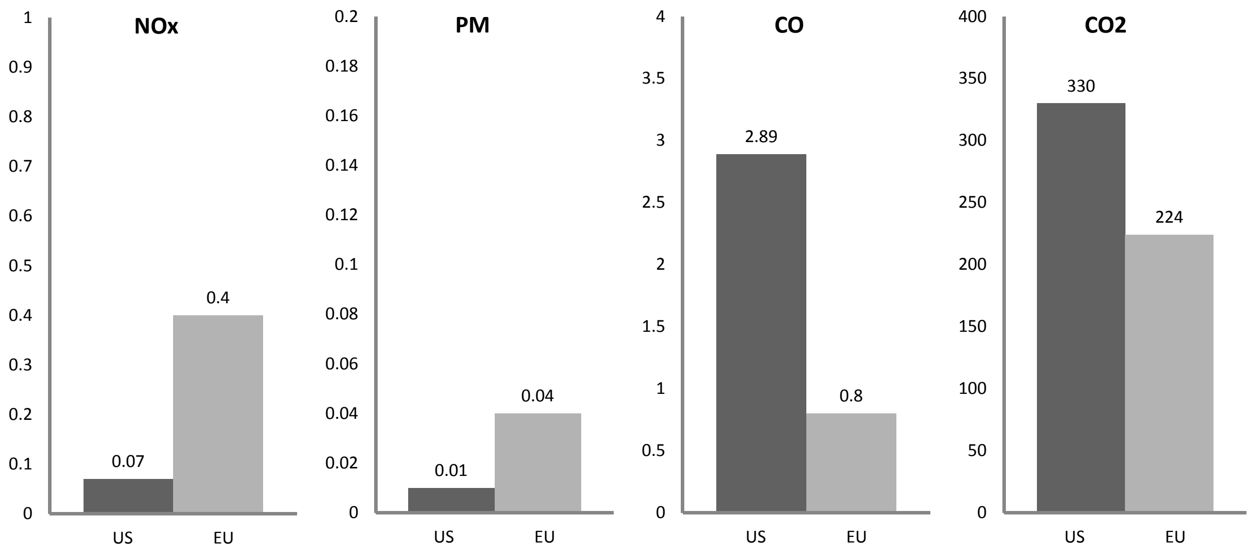
7.1 Vehicle Emissions Standards in the United States and Europe

Figure 7 illustrates the differences in emissions standards between the United States and Europe around year 2000.[38] 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

[38] European authorities set NO_x and particulates matter (PM) standards for each vehicle while U.S. authorities set at a fleet-wide limit. As for CO and CO_2 emissions, these depend on fleet average fuel consumption standards and are reported in Figure 7 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`.

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 7: 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.

European regulators took a different approach and chose a less stringent NO_x emission standard and a more demanding green house (CO, CO_2) targets. 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. On the contrary, Europeans set CO and CO_2 emissions targets that were 72% and 32% lower than those of the U.S. EPA. These lower green house emission standards were only attainable because of the successful diffusion of diesel vehicles in Europe.

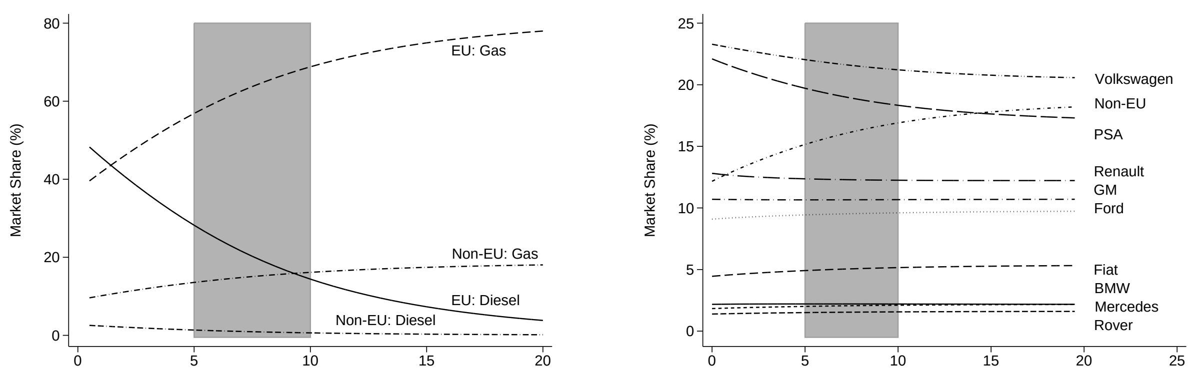
7.2 Retrofitting Costs

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 by focusing on the likely cost of retrofitting diesel engines in order to make them comply with the NO_x emission standards set by the EPA.

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 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.[39] This suggests 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?

For many years, a technology to successfully capture NO_x emissions at the tailpipe simply did not exist. And 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 requires specific exhaust temperatures for appropriate NO_x emission control performance, and on average they reduce emissions up to a maximum of 40%. Given this limited ability to capture NO_x emissions, both BMW and MERCEDES were finally certified to be sold in all 50 states of the U.S. 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.[40]

Figure 8: Market Shares and Retrofitting Costs



(a) €1,000 (b) €1,000

[39] 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.

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

Had this technology been available in the 1990s, retrofitting costs would have been even higher. Figures 8(a) and 8(b) plots the results of recomputing the market equilibrium for a wide range of retrofitting costs. The shaded area highlights the limits of the retrofitting cost region of the lean and selective catalysts. Figure 8(a) focuses on the impact of retrofitting on the market shares distinguishing by type of engine and geographical origin of manufacturers while Figure 8(b) reports the combined market shares (gasoline+diesel) of each automobile group.

At a retrofitting cost of €10,000, 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 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 €9,000, the market share of European diesel vehicles falls below the share of gasoline imports, who grow monotonically with the retrofitting costs although the production of European gasoline models grows much faster.

Figure 8(b) shows that, in terms of market shares, the only clear beneficiary of a 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 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 current 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 standards 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.

7.3 Import Tariff Equivalence of Environmental Regulation

Contrary to the U.S. strict NO_x reduction policy, the European policy in favor of green house emission reductions did not raise the cost of production of diesel vehicles and aligned the incentives of green house emission reduction and promotion of the European developed technology. Whether the emission policy was designed explicitly to promote sales of domestically produced diesel vehicles is inconsequential. In practice, that policy achieved precisely that objective and we now will quantify how important it was protecting the European automobile industry.

Table 7 reports the counterfactuals necessary to evaluate the tariff-equivalence of the lenient European NO_x emission policy during the 1990s. Starting at the second half of the table, we first

Table 7: Effects of Imposing Equivalent Import Tariffs

Scenario	Models	CAFE	Price	Quantity	Markup	Share	Profits
1992 EQUILIBRIUM							
Benchmark							
EU: DIESEL	43	52.86	12.26	160.76	42.99	16.60	772.52
EU: GASOLINE	73	43.64	11.05	769.32	41.73	79.45	3,210.01
NON-EU: DIESEL	1	44.38	13.76	0.91	44.80	0.09	4.01
NON-EU: GASOLINE	24	40.42	14.88	37.35	43.86	3.86	165.52
Equilibrium without Diesels							
EU: GASOLINE	73	43.66	11.14	867.60	42.11	95.33	3,682.99
NON-EU: GASOLINE	24	40.44	14.95	42.47	44.09	4.67	190.39
Import Tariff of 19.6%							
EU: GASOLINE	73	43.65	11.15	871.54	42.14	96.05	3,704.43
NON-EU: GASOLINE	24	40.52	15.64	35.85	47.07	3.95	164.08
2000 EQUILIBRIUM							
Benchmark							
EU: DIESEL	75	51.75	16.19	695.37	38.76	50.95	4,112.85
EU: GASOLINE	84	41.43	14.93	508.70	42.09	37.28	2,927.54
NON-EU: DIESEL	20	43.45	17.20	36.97	42.15	2.71	203.64
NON-EU: GASOLINE	50	38.52	13.66	123.65	48.54	9.06	614.14
Equilibrium without Diesels							
EU: GASOLINE	84	41.41	14.87	831.86	41.83	81.28	4,737.78
NON-EU: GASOLINE	50	38.46	13.97	191.57	48.92	18.72	981.58
Import Tariff of 29.3%							
EU: GASOLINE	84	41.42	14.87	874.76	41.91	88.23	4,992.72
NON-EU: GASOLINE	50	38.78	16.37	116.69	58.55	11.77	642.72

"CAFE" is the production-weighted harmonic mean fuel economy, expressed in miles per gallon, as commonly used in the U.S. to evaluate the fuel efficiency of a manufacturer's fleet. "Price" is the sales-weighted average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Quantity" is measured in millions of cars. "Profits" is measured in the equivalent of millions of 1994 Euro. "Markups" and "Share" are reported as percentages. "Markups" include import duties paid by consumers.

compare the 2000 benchmark with a hypothetical situation where TDI, and therefore modern diesel engines, never existed. The market share of Asian manufacturers jumps from 11.77% to 18.72% as they increase profits by almost 25% as they increase the price, markup, 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 recompute the equilibrium of our model for different import tariffs that change the relative prices of vehicles that consumers face. We repeat this analysis until the share of gasoline imports equals 11.77%, the combined share of imported diesel and gasoline automobiles sold in year 2000. We thus conclude that a 29.3% import tariff would limit Asian imports and lead to a similar market outcome than the pro-green emission reduction, non-tariff trade barrier that favors diesel vehicles. This effective level of protection is substantially higher than the nominal tariff of 10.3% charged at the time.[41]

At the top of Table 7 we repeat this same analysis but considering a different benchmark, 1992, when the diffusion of diesel vehicles was just starting, and where the presence of foreign automobile manufacturers in Europe was still rather limited, just a 3.95%. In such an environment European automobile manufacturers kept over 96% of the market and excluding the development of TDI and early adoption of diesel essentially leaves market shares unchanged: the market share of imports increases only by less than 1% but European profits shrank by m€300 (almost 8%) as profitable diesels are no longer sold and the available models do not suffice segment the market sufficiently. In this environment, a 19.6% import tariff (25.6% in France) is necessary to reduce the market share of imports just by 1% to bring it back to the level of the 1992 benchmark. Thus, even in the early stages of diffusion of the new technology, the pro-green house emission reduction policy was important although not that different from the explicit 14.4% tariff set by European authorities against automobile imports in the early 1990s. The tariff value equivalence of the European environmental policy non-tariff trade barrier is more important the larger the presence in the market of domestically produced diesel vehicles.

8 Concluding Remarks

Our analysis of the diffusion of diesel automobiles in Europe during the 1990s characterizes the very rich dynamics. We have shown that in its beginning, the diffusion of diesel vehicles had to overcome important concerns by European drivers who later embraced diesels massively as they learned of their performance and improved features. We also documented that while diesels and gasoline models increasingly became closer substitutes during the decade, unobservable product characteristics were more responsible for the small share of imports (both gasoline and diesels) than the overall market penetration of diesels in Spain. This evidence speaks in favor of consumers learning relatively quickly about unobservable product characteristics such as low clattering of high torque at low r.p.m. and Asian manufacturers lacking reputation, brand image, or a sufficiently large dealership network.

The fact that diesel technology is only commercialized by European manufacturers add the interesting twist that any policy proposal affecting diesel vehicles or diesel fuel carries important implications. Thus, contrary to the common belief, reduced fuel taxation was only responsible for a small fraction of diesel sales (7%) but resulted in a small reduction of imports (1%). Much

[41] Market penetration of Asian imports in Spain is similar to that of Europe overall. 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 62.1%.

more important for the diffusion of diesel vehicles than the favorable tax treatment of diesel is the generality of the technology that makes imitation and possible and allow competitors to offer improved alternatives in the diesel market segment. While VOLKSWAGEN was still able to capture a very large fraction of potential innovation rents (between 48% and 79%), generality of diesel technology allowed for the successful entry of many European manufacturers in this segment lowered the average diesel price by €1,650, increased the share of diesel penetration over 30%, and reduced the share of imports by 3.5%.

Perhaps the most novel result of our paper is to show that environmental policies may have important trade effects. Regardless of whether the European pro-greenhouse emission reductions was intended to favor the sales of domestically produced diesel vehicles or not, we first show that alternative NO_x reduction policies would have effectively halted the commercial success of diesel vehicles in the early 1990s, and second, that given the large market share of diesels by year 2000, this policy amounted to a large import tariff of 29/3% that cut Asian imports almost in half. This is, to the best of our knowledge, the first use of a structural equilibrium model of demand and industry oligopoly pricing to evaluate the trade effects of non-tariff trade barriers. We illustrate how that in an increasingly global economy, governments can effectively use 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.[42] 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.

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

	Year 1992			Year 2000		
Automaker	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.

[42] 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.

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. On the 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.

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.

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 (with the exception of the "Mini" brand) in May 2000 so these are treated as separate firms. Table A.1 describes the ownership structure at the beginning and end of the decade.

B Computing Domestic Automobile Prices

We provide computational details for the procedures we employ to find the profit-maximizing prices under each policy experiment. Each firm f produces some subset $\mathcal{F}_t^f$ of the $j = 1, \ldots, J$ automobile brands in each period t and chooses a vector of pre-tariff prices $\{p_{j,t}^{\tau}\}$ to solve:

$$\max_{\{p_{jt}^{\tau}\}} \sum_{j \in \mathcal{F}_t^f} \left(p_{jt}^{\tau} - c_{jt} \right) \times M_t s_{jt}(p_{jt}) \,, \tag{B.1}$$

where we have assumed that the consumer pays the import duty. The final price facing the consumer (p_{jt}) is defined as $p_{jt}^{\tau} \times (1 + \tau_{jt})$ where τ_{jt} is the import tariff (if applicable). The firm's first-order condition associated with profit maximization in period t is given by:

$$s_{jt}(p_t) + \sum_{r \in \mathcal{F}_t^f} (p_{rt}^{\tau} - c_{rt}) \times \frac{\partial s_{rt}(p_t)}{\partial p_{rt}^{\tau}} = 0 \,. \tag{B.2}$$

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

$$s(p_t) + \Omega(p_t) \times (p_t^{\tau} - c_t) = 0 \,, \tag{B.3}$$

where an element of the matrix Ω is defined as:

$$\Omega_{jr} = \begin{cases} \dfrac{\partial s_{jt}(p_t)}{\partial p^{\tau}_{rt}}\,, & \text{if } \{j,r\} \subset \mathcal{F}^f_t\,, \\ \\ 0 & \text{otherwise}\,. \end{cases} \tag{B.4}$$

For a given vector of period t marginal costs c_t, we find the fixed point to the system of equations defined in Equation (B.3) numerically. To this end, define the following operator in period t as:

$$T(p_t) = c_t - \Omega^{-1}(p_t) \times s(p_t)\,, \tag{B.5}$$

where the equilibrium prices are such that $p' = T(p)$. When $\|p' - p\|_\infty$ is sufficiently small, then the first-order condition defined in Equation (B.3) necessarily holds and p' contains the set of profit-maximizing retail prices in each market.

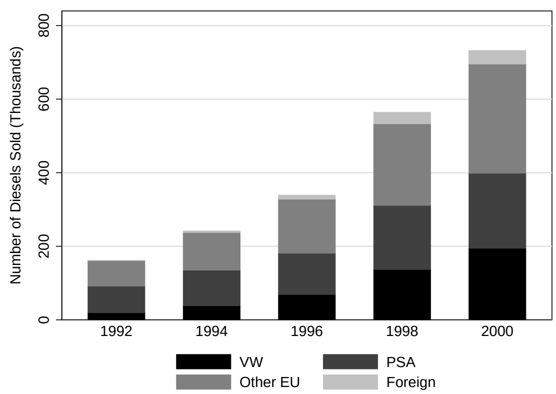
C Additional Results

Table C.1: Car Model Characteristics Across Engine Types

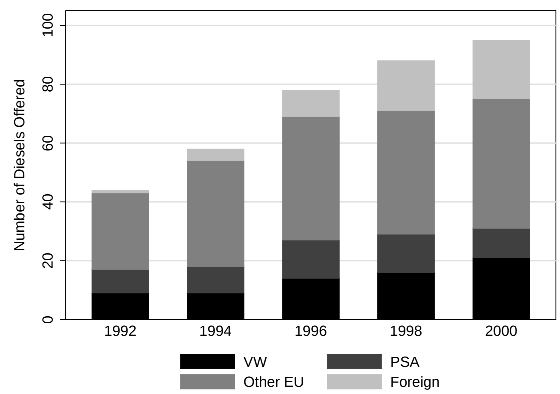
SEGMENT	MODELS	SHARE	PRICE	KPE	SIZE	HPW
1992						
SMALL	28	35.8	8.0	35.0	62.5	36.5
COMPACT	31	35.8	11.0	32.1	74.3	39.8
SEDAN	39	22.3	14.3	30.3	80.1	42.6
LUXURY	39	5.8	24.0	25.8	87.1	48.4
MINIVAN	4	0.3	17.3	24.2	81.7	37.9
ALL	141	100.0	11.4	32.3	72.2	39.7
2000						
SMALL	49	32.8	10.4	31.6	66.4	31.8
COMPACT	56	34.4	14.9	32.5	76.5	35.9
SEDAN	52	26.0	19.5	31.6	81.9	36.3
LUXURY	40	3.7	34.5	23.3	89.7	51.7
MINIVAN	32	3.1	20.8	25.9	83.5	31.6
ALL	229	100.0	15.5	31.4	75.3	35.1

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. KPEis 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.

Figure C.1: Evolution of Models and Sales by Origin



(a) Diesel Sales by Year



(b) Number of Diesel Models Offered by Year

Table C.2: Growth in Car Models Sold

FUEL TYPE	1992	1994	1996	1998	2000
DIESEL	44	58	78	88	95
BMW	2	2	3	3	3
FIAT	6	10	12	13	13
FORD	4	6	8	6	7
GM	5	4	4	6	6
MERCEDES	3	4	4	5	6
NON-EU: DIESEL	1	4	9	17	20
PSA	8	9	13	13	10
RENAULT	4	6	6	5	5
ROVER	2	4	5	4	4
VOLKSWAGEN	9	9	14	16	21
GASOLINE	97	109	124	135	134
Total	141	167	202	223	229

Web Appendix – Not for Publication

Table W.1: Robustness – Convergence

Alternative	Matlab / Tolerance	Objective Function
Algorithm:		
Ours: Nelder-Mead (simplex)	fminsearch.m	40.98
Quasi-Newton (gradient)	fminunc.m	41.09
Contraction Mapping:		
Less Demanding	1E-10	40.98
Ours (Dubé et al. (2012))	1E-14	40.98
More Demanding	1E-16	Not Converged
Objective Function:		
Less Demanding (Knittel and Metaxoglou (2013))	1E-03	40.98
Ours	1E-05	40.98
More Demanding	1E-08	40.98

Figure W.1: Distribution of Objective Function Estimates

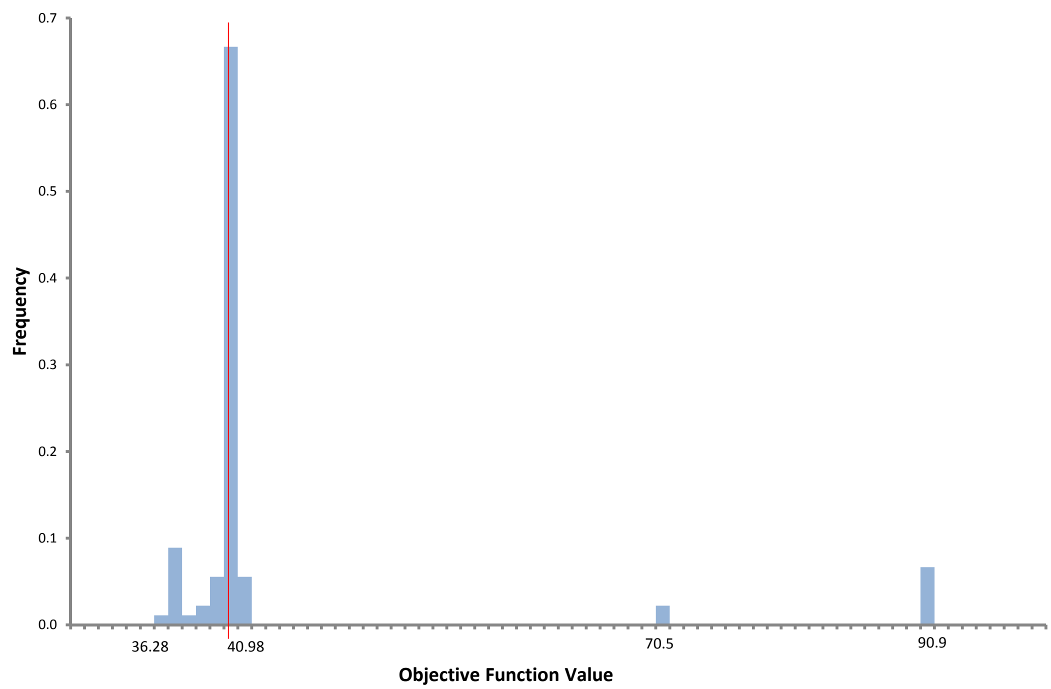
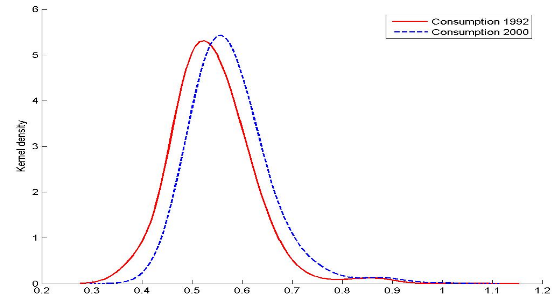
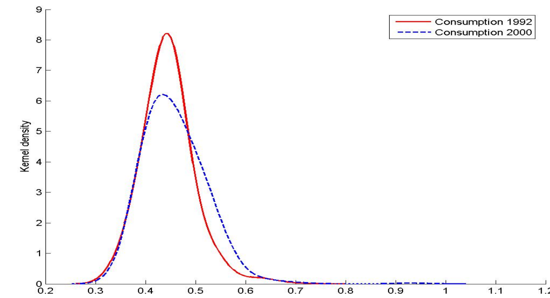


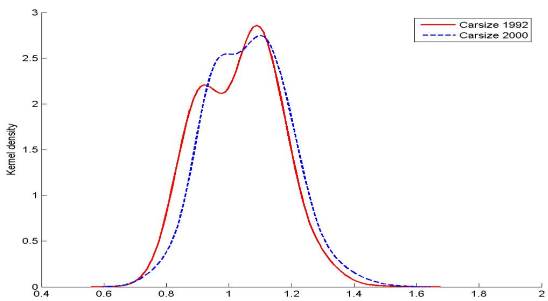
Figure W.2: Change in the Distribution of Automobile Attributes



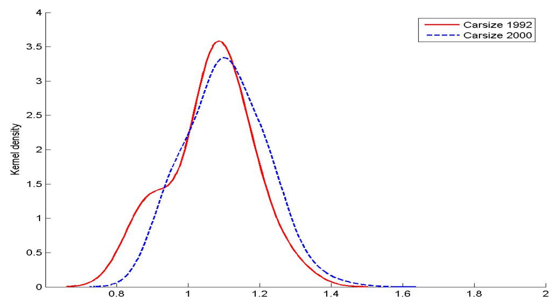
(a) Gasoline: Mileage



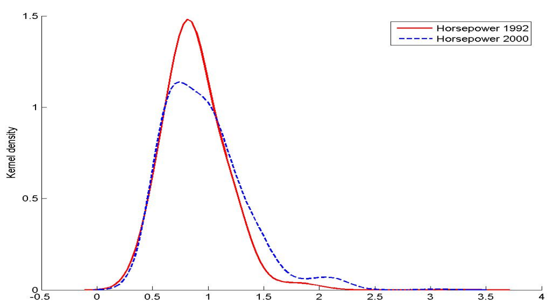
(b) Diesel: Mileage



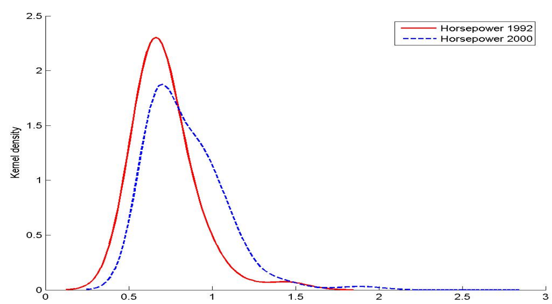
(c) Gasoline: Car Size



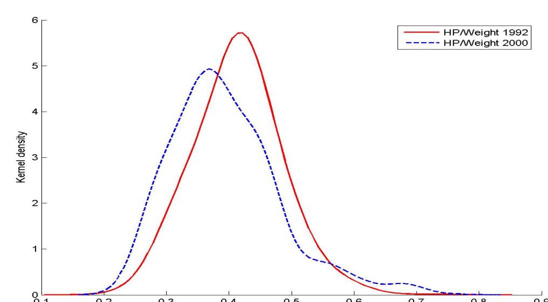
(d) Diesel: Car Size



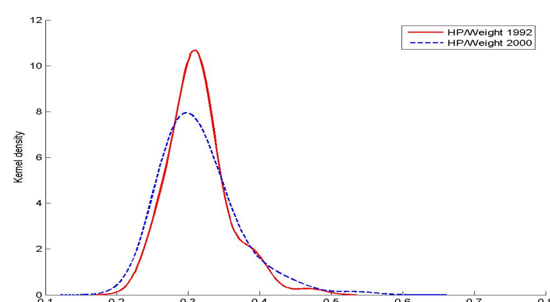
(e) Gasoline: Horsepower



(f) Diesel: Horsepower

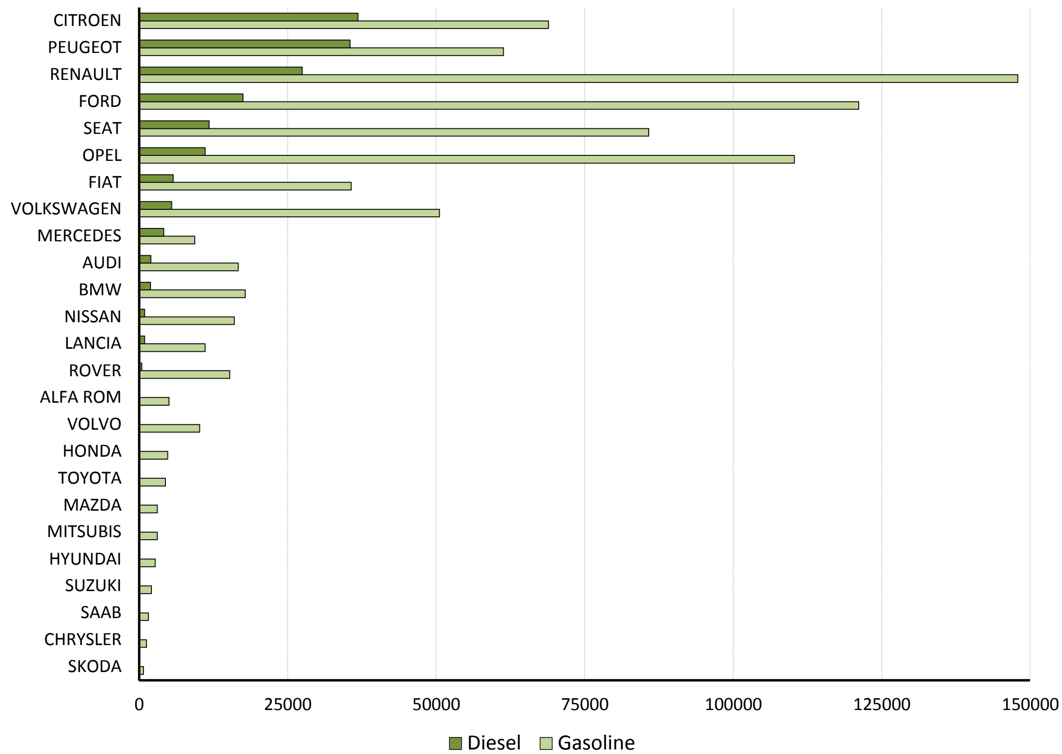


(g) Gasoline: Horsepower/Weight

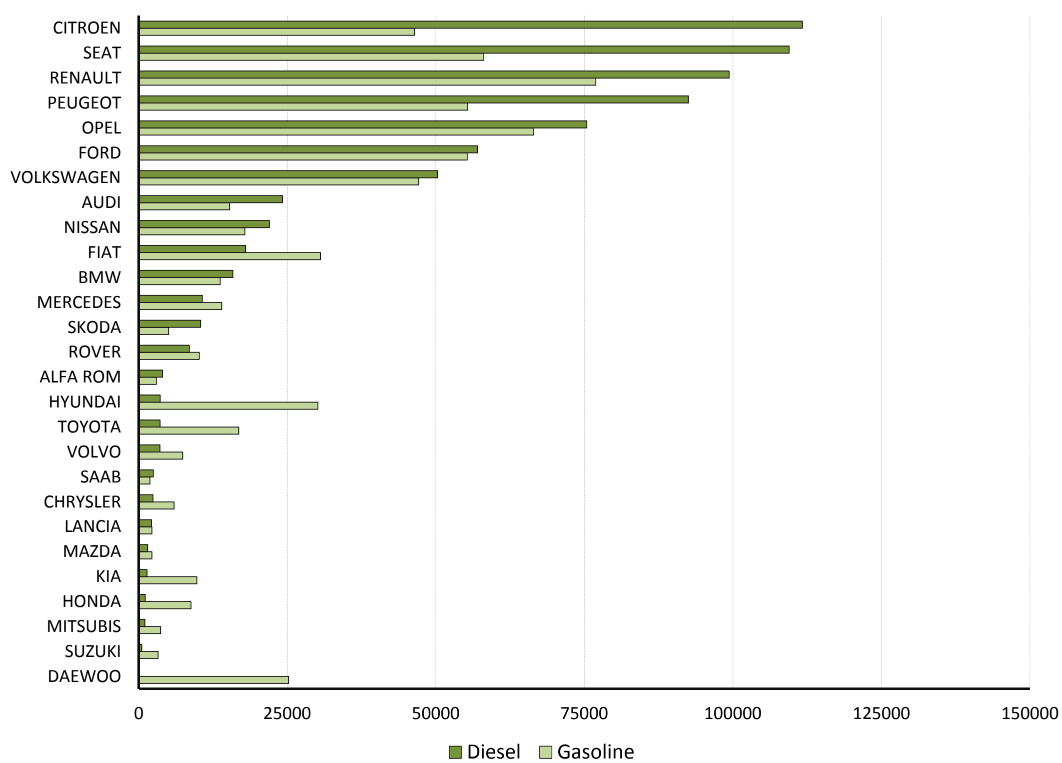


(h) Diesel: Horsepower/Weight

Figure W.3: Sales by Firm and Type of Engine

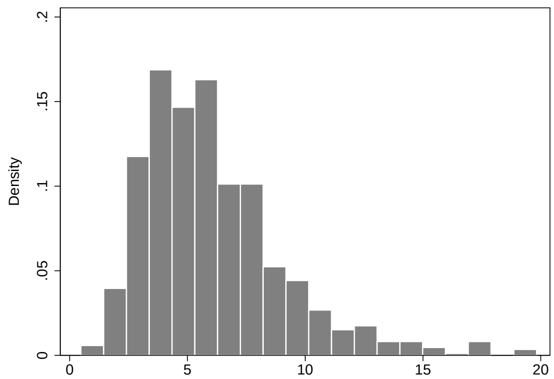


(a) Year 1992

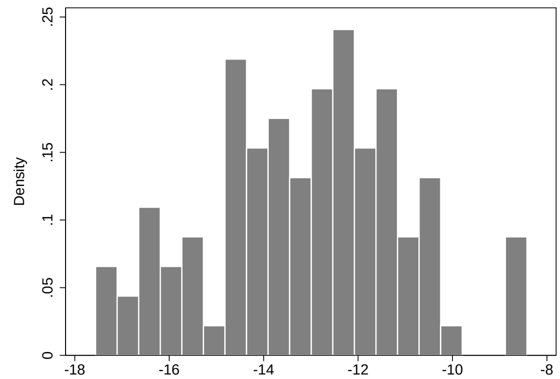


(b) Year 2000

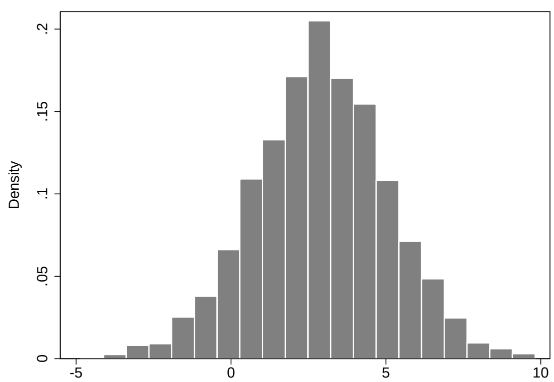
Figure W.4: Distribution of Taste Parameters



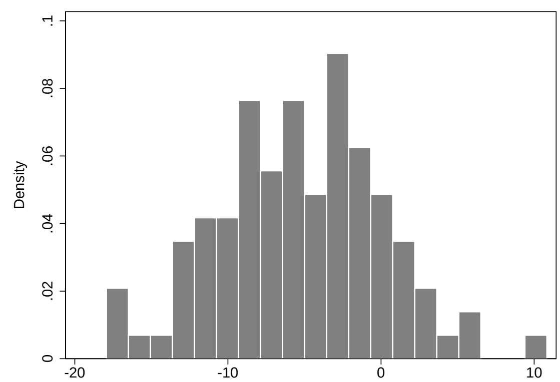
(a) Price Coefficient



(b) Constant

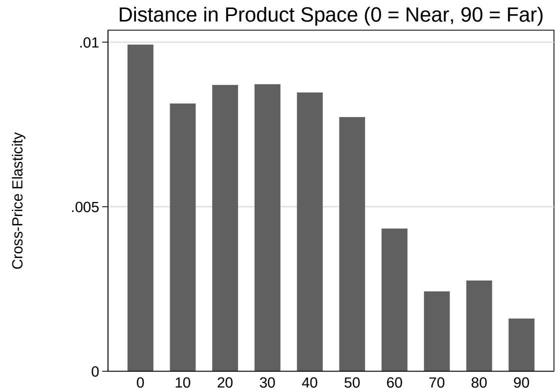


(c) Size

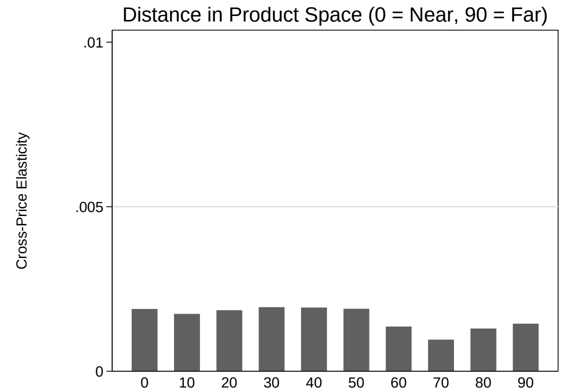


(d) Kilometers per Euro

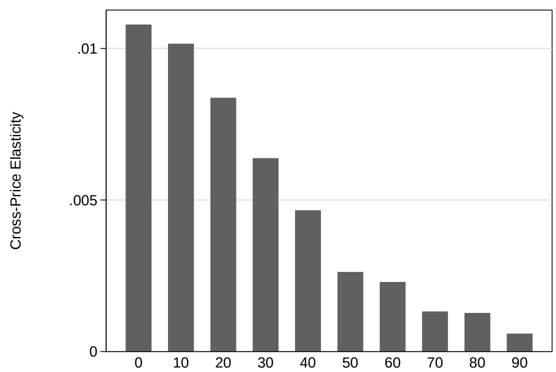
Figure W.5: Substitution Patterns due to Random Coefficients



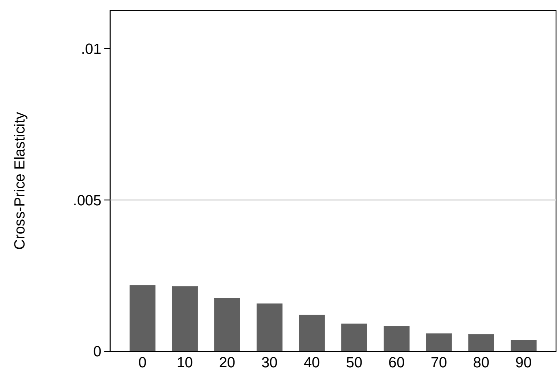
(a) Kilometers per Euro - Full Model



(b) Kilometers per Euro - $\nu = 0$



(c) Size - Full Model



(d) Size - $\nu = 0$