

## SINCEREST FORM OF FLATTERY? PRODUCT INNOVATION AND IMITATION IN THE EUROPEAN AUTOMOBILE INDUSTRY\*

JEFF THURK<sup>†</sup>

I study the impact of imitation on the returns to technological innovation when products are differentiated. Using data that capture Volkswagen's introduction of the TDI diesel engine and the technology's imitation by rival European firms, I estimate a discrete choice, oligopoly model of horizontally differentiated products. Imitation benefited consumers by increasing product variety and reducing prices but also limited Volkswagen to 14% of potential profits from the TDI. Volkswagen's ability to differentiate its diesel models made the TDI a worthwhile investment nonetheless. This indicates firms can mitigate imitation risk by bundling easy-to-copy technological advancements with difficult-to-copy product characteristics including brand.

### I. INTRODUCTION

ECONOMIC GROWTH DEPENDS ON THE WILLINGNESS of firms to invest in developing new technologies (Schumpeter [1942]; Lucas [1988]; Romer [1990]), while the ability of rivals to easily imitate new technology (Mansfield, Schwartz and Wagner [1981]) limits the incentive to innovate potentially leading to sub-optimal investment (Aghion, Harris, Howitt and Vickers [2001]). When goods are differentiated, however, a firm may be able to minimize the effects of imitation by leveraging other characteristics of its product (Petrin [2002]).

I study this trade-off in the context of the European automobile industry where the introduction of the turbocharged direct injection (TDI) diesel engine by Volkswagen in 1989 took diesel passenger automobiles from a niche product category to the dominant European engine choice in less than a decade – a dramatic transformation which has largely failed to

\*I thank the Editor, and two anonymous referees for helpful suggestions which improved the manuscript. I also thank Kenneth Hendricks, Tom Holmes, Eugenio Miravete and Maria J. Moral as well as audiences at various seminar and conference presentations. This research was supported in part by the Notre Dame Center for Research Computing and the Institute for Scholarship in the Liberal Arts. I am solely responsible for any errors.

<sup>†</sup>Author's affiliations: Department of Economics, University of Notre Dame, 3047 Nanovic Hall, Notre Dame, Indiana, U.S.A.  
*e-mail: jthurk@nd.edu*

attract the interest of innovation economists.<sup>1,2</sup> These new turbodiesel engines were significantly quieter, cleaner (i.e., no black smoke), and more reliable than their predecessors while maintaining superior fuel efficiency and torque relative to comparable gasoline models.<sup>3</sup> While Volkswagen did patent technology associated with the TDI, the quick introduction of turbodiesels by rival European firms such as PSA and Renault indicates the technology's generality was difficult to defend.<sup>4</sup> Using automobile registration data from Spain – a country which exhibited diesel adoption rates representative of Europe as a whole – I ask two questions: What was the impact of imitation on equilibrium prices and profits? Did imitation of the TDI make this new technology an *ex post* poor investment?

I answer these questions by estimating an equilibrium discrete choice oligopoly model to study an industry which is far from competitive and where products are horizontally differentiated. The structural demand-side model provides for flexible substitution patterns across automobile characteristics and segments while accounting for product characteristics known to consumers and firms but not to the researcher. The addition of a Bertrand-Nash pricing equilibrium not only increases the identification of product elasticities (Reynaert and Verboven [2013]) but also allows for the analysis of alternative counterfactual equilibria.

In this framework consumers consider a variety of product characteristics when making their purchase decisions leading to greater competition among firms with similar product sets (in characteristic space). Consequently, the model allows for greater competition in the diesel segment after the introduction of turbodiesels by rival European firms while the rich substitution patterns extend competition to the gasoline segment as well. The estimated model, therefore, disciplines the answers to the above questions by modulating the degree to which product differentiation mitigates imitation risk.

I find that rival firms' introduction of diesel models equipped with turbodiesel engines based on the same technology as the TDI limited Volkswagen to capture only 14% of the potential innovative rents associated with the

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

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

<sup>3</sup> I use the term 'TDI' to refer specifically to Volkswagen group diesel models which use the TDI technology, and the term 'turbodiesel' to refer more generally to any diesel vehicle which features a turbocharger plus cylinder-direct fuel injection.

<sup>4</sup> It is the generality of this technology which allowed it to be imitated and reused easily by other manufacturers. See Bresnahan [2010].

TDI during the sample though the impact of imitation varied significantly across firms. For instance, the introduction of turbodiesels by PSA and Renault generated substantial losses for Volkswagen as these firms both introduced a large number of turbodiesels and had product portfolios which competed heavily with Volkswagen automobiles. In contrast, the introduction of turbodiesels by FIAT and Ford had a much smaller effect on Volkswagen profits. This indicates that Volkswagen was able to differentiate its diesel fleet from these competitors but not from PSA or Renault.

It would be tempting to conclude that imitation made the TDI a poor investment. Using a simple model of innovation and imitation, I show just the opposite as consumer demand for the TDI increased overall market size while Volkswagen's ability to differentiate its diesel models enabled the firm to generate substantial profits from its turbodiesels. Over the course of the decade, Volkswagen's diesel vehicles generated €3.6 billion in profit for the firm and their importance to VW's bottom line grew over the sample, accounting for 10.5% of profits in 1992 when the TDI was new and 61.1% of profits by the year 2000 when customer adoption had reached its steady-state. When I account for cannibalization of gasoline models as well as the replacement of pre-existing diesel engines based on the legacy technology, Volkswagen's benefit from the TDI ranges from €2.1 billion to €2.6 billion in the Spanish market alone.

The story of the TDI, therefore, is one in which the innovator generated a lot of profit from this new technology despite widespread imitation while consumers benefited from increased variety and low retail prices. Thus, the market equilibrium simultaneously delivered both dynamic (i.e., a new product) and static (i.e., low prices) efficiencies leading to an unambiguous increase in welfare as both firms and consumers benefited from the technology. Moreover, it did so for a technology in which patents – the most common public policy tool to encourage innovation – proved to be ineffective. This is significant since patent protection itself creates a distortion by promoting dynamic over static efficiencies. Business trade groups and government policy-makers often cite intellectual property protection as an important issue towards fostering innovation but surprisingly there exist few if any reliable estimates as to the magnitude of the effect of imitation on firm profits. To my knowledge this is the first paper to use a structural equilibrium model to do so.

A further contribution of this paper is to find empirical evidence that economic innovation requires much more than just technological advancement – an idea which dates back to Schumpeter [1934]. For Schumpeter, new goods, brands, or firms were the embodiment of many things and 'economic development,' as he put it, occurred precisely because of new combinations of resources in which technological progress was only a component. We see this effect in the case of the TDI as Volkswagen integrated the easy-to-copy TDI technology into its difficult-to-copy Volkswagen brand which enabled

the firm to appropriate profits from the technology. Just as Schumpeter also argued that the role of dynamic efficiencies (i.e., new goods and firms) are more important than static inefficiencies (i.e., market power), my results indicate that in mature industries economists should think of product differentiation specifically, or brands more generally, as an important and perhaps necessary component of technological progress.

The remaining paper is organized as follows. I review this paper's contribution to relevant literature in Section II and discuss Volkswagen's introduction of the TDI innovation, its imitation by European auto makers, and summarize the main features of the Spanish market for diesel automobiles in Section III. In Section IV, I describe the equilibrium model of discrete choice demand for horizontally differentiated products as well as the corresponding supply-side pricing model. Section V describes the estimation approach, discusses identification and reports the estimation results. In Section VI, I use a series of counterfactual experiments to measure the effect of imitation on equilibrium prices and profits. Finally, Section VII summarizes the results and contribution as well as discussing avenues for future research. Details of the estimation, additional results, data sources, and institutional details of the Spanish automobile market are documented in the Appendix.

## II. RELATED LITERATURE

In this paper, I study the impact of imitation on dynamic and static efficiency. As such, it contributes to a large literature on competition, innovation and imitation which dates back to Schumpeter [1942] who argued that temporary market power was needed to encourage innovation.<sup>5</sup> He theorized that the long run benefits of new ideas (e.g. new products, better processes) generate dynamic efficiencies which swamp any temporary static inefficiencies due to market power.<sup>6</sup>

Mansfield *et al.* [1981] use firm-level survey data to show that the cost of imitating a new technology is 65% the research & development cost originally required to develop it. Thus, successful technologies are often easily imitated and imitation of a new technology by rival firms, consequently, extracts surplus from the innovating firm. In a rational expectations equilibrium, the innovator internalizes this risk leading to low levels of equilibrium research and development – a point addressed by Aghion *et al.* [2001].

<sup>5</sup>In his 1934 'The Theory of Economic Development' Schumpeter espoused the belief that all firms were capable of innovation and discovery. Later in 'Capitalism, Socialism and Democracy,' he modified his theory to focus on large firms endowed with market power as the engines of growth.

<sup>6</sup>See Gilbert [2006] and Cohen [2010] for a comprehensive literature review.

Patent systems therefore provide a state-sanctioned monopoly to guarantee temporary rents to the innovator (i.e., a static inefficiency) in hope of increasing equilibrium levels of research.

Whether imitation does actually impede innovation is fundamentally a quantitative issue. My finding that imitation and innovation can coexist even when the former is significant adds to a growing concern that modern patent systems do more harm than good.<sup>7</sup> Waldfoegel [2012] documents that increased imitation in digital music was more than offset by reductions in the cost of bringing new music to market so the equilibrium effect of imitation was to generate a net *increase* in the quality of music available to consumers. Boldrin and Levine [2008] argue the first-mover advantage inherent in the innovative process is sufficient to drive research. In my data, however, there appears to be little if any first mover advantage as imitation is nearly contemporaneous with the introduction of the TDI. Instead, I identify a new channel for innovation under imitation risk as I show the introduction of a new product can grow the size of the pie while product differentiation enables firms to each secure their piece.

Miravete, Moral and Thurk [2018] show that European fuel taxes and vehicle emissions policy lowered the retail prices of diesel vehicles and increased their fuel economy, leading price-sensitive consumers to shift consumption away from inexpensive, fuel-efficient gasoline-powered Asian imports and towards brands which offered diesel vehicles, largely domestic automakers. The policies therefore incentivized the adoption of the diesel among consumers and amounted to a significant trade policy. In this paper I take these policies as given and evaluate competition among European automakers as rivals such as Renault and Peugeot introduce their own turbodiesel vehicles to compete with the Volkswagen TDI.

Bronnenberg, Dubé, Gentzkow, and Shapiro [2015] study the purchase of branded and non-branded products in homogenous good categories. They find the existence of information asymmetries among seemingly identical goods which generate price dispersion. For example, branded and generic drugs are required by law to be biologically-equivalent and therefore homogenous yet the authors find that uninformed consumers (e.g., consumers not employed in health care) are more likely to purchase a branded product such as Bayer aspirin. In equilibrium, firms which offer a branded product leverage these asymmetries to charge higher prices. In my setting, products continue to be heterogenous after imitation since the final good a consumer purchases amounts to a bundle of characteristics and the imitated technology is only one component. Hence, I demonstrate that an effective method to mitigate the effects of imitation is for a firm to leverage other

<sup>7</sup> See Hall [2009] for a review

characteristics of its product set which may include the consumers' valuation of its brand.

Petrin [2002] uses the random coefficients model of Berry, Levinsohn and Pakes [1995] – a workhorse model in the empirical literature – to show Chrysler's introduction of the minivan generated significant profits for the firm despite imitation by GM and Ford. Moreover, he finds only minor effects from imitation since GM and Ford built their minivans on downsized versions of full-sized van platforms. The consequence was that their rear-wheel drive vehicles were difficult to maneuver whereas the front-wheel drive Chrysler minivan handled similarly to a passenger car. Chrysler was therefore able to protect its minivans via product differentiation – a similar conclusion to the one presented here. My contribution, therefore, is to show that product differentiation can be an effective tool even when effects of imitation are large.

It is perhaps more appropriate to think of the automobile industry as a dynamic game where manufacturers choose investment, imitation, and product characteristics in an initial stage and then choose price conditional on their product portfolios. While appealing, incorporating both dynamic and static effects in a tractable empirical framework is difficult since doing so requires the researcher to address issues of endogenous firm beliefs and multiple equilibria, both of which are exacerbated when goods are differentiated. Petrin and Seo [2016] consider a two-stage game where firms simultaneously choose vehicle characteristics (e.g., fuel efficiency) and then choose equilibrium prices. Though firms may have different beliefs regarding competitors' attribute choices, they understand that their attribute choices influence equilibrium prices of automobile manufacturers through own and cross-price effects.

Other authors evaluate the dynamics of innovation using models with little product differentiation. A recent paper by Rust, Gillingham, Iskhakov, Munk-Nielsen and Schjerning [2016] studies dynamics within the Danish automobile industry but the authors simplify static competition significantly to make the model tractable.<sup>8</sup> Goettler and Gordon [2011] use a quality-ladder model to show that competition by AMD led to lower innovation rates by the industry leader Intel while Igami [2017] studies the dynamic effects of innovation in the hard drive industry – an industry with sufficient product homogeneity that he models firm competition as Cournot. Interestingly, he also finds that patent protection decreases firm innovation and overall welfare.

<sup>8</sup> Specifically, cars differ only in their type (i.e., diesel or gas engine) and age.

Answers to the research questions posed here, however, depend critically on the impact of imitation on both dynamic and static efficiency, or equivalently on the prices facing consumers both with and without imitation. I therefore focus my efforts on a feasible extension of the Berry *et al.* [1995] framework to generate realistic substitution patterns among differentiated goods taking Volkswagen's decision to introduce the TDI as well as its imitation by other firms as given. I then evaluate the impact of imitation by comparing the estimated equilibrium to counterfactual equilibria where I vary competition in the diesel segment – an approach similar to Berry and Jia [2010] who address the equilibrium effects of low cost carriers in the airline industry. This places greater emphasis on effectively measuring the impact of imitation on retail prices and static profits. The issue of dynamic efficiency then centers on addressing whether the TDI was a worthwhile investment for Volkswagen given the imitation risk posed by its rivals. This in turn requires the researcher to make plausible assumptions as to how the industry would have evolved absent the introduction of the TDI technology. My results, therefore, amount to an *ex post* analysis of the incentive to innovate under imitation risk in differentiated goods markets.

### III. THE EUROPEAN MARKET FOR DIESEL AUTOMOBILES

In the late 19th century, Rudolf Diesel designed an internal combustion engine in which heavy fuel is injected into a cylinder and self-ignites due to levels of compression much greater than a gasoline engine. However, it was only in 1927, many years after Diesel's death, that the German company Bosch built the injection pump that made the development of the engine for trucks and automobiles possible. The first diesel vehicles sold commercially followed soon after: the 1933 Citroën Rosalie and the 1936 Mercedes-Benz 260D. Large passenger and commercial diesel vehicles became common in Europe in the late 1950's, while preferential fuel taxation beginning in 1973 enabled diesel passenger cars to maintain a small but stable market share.<sup>9</sup>

In 1989, Volkswagen introduced the turbocharged direct injection (TDI) diesel engine in its Audi 100 model.<sup>10</sup> The TDI engine was an improvement on the existing technology as it was the first to combine a turbocharger with a fuel injector.<sup>11</sup> The turbocharger increases the amount of air going

<sup>9</sup> See Miravete *et al.* [2018] for a more thorough discussion of initial market conditions behind the diesel's success.

<sup>10</sup> The 1987 FIAT Croma was actually the first diesel passenger car to be equipped with turbo direct-injection. Whereas the Audi 100 controlled the direct injection electronically, the FIAT Croma was mechanical. The difference proved crucial for commercial success as electronic controls improved both emissions and power.

<sup>11</sup> Alfred Büchi invented the turbocharger in 1905 and noted in his patent that such a technology would prove particularly useful to diesel engines as it increases compression in the cylinder. A turbocharger was, however, not incorporated into a passenger diesel vehicle until 1979 when Peugeot introduced the Model 604.

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. The addition of fuel injection enables the engine to spray fuel directly into the combustion chamber of each cylinder which increases fuel atomization. The combination of the two was a diesel-powered engine that was significantly quieter, cleaner (i.e., no black smoke), and more reliable than its predecessors while maintaining superior fuel efficiency and torque relative to comparable gasoline models.<sup>12</sup> For the average driver, greater torque makes the driving experience more enjoyable by increasing the responsiveness of the car. For rival automakers, introducing their own version of the TDI (i.e., introducing their own ‘turbo-diesel’) only required developing an engine which combined these two established and general technologies.

### III(i). *Evolution of Automobile Characteristics*

The data include yearly car registrations by manufacturer, model and fuel engine type in Spain between 1992 and 2000. Retail prices and vehicle characteristics are from *La guía del comprador de coches* (ed. Moredi, Madrid) where I aggregate trim types within a model by selecting the price and characteristics of the mid-range trim version of each model, i.e., the most popular and commonly sold. I further segment the cars into SMALL, COMPACT, SEDAN, MINIVAN, and LUXURY where the last includes sports cars.<sup>13</sup>

After removing observations with extremely small market shares (mostly LUXURY vehicles) the sample is an unbalanced panel comprising 99.2% of all car registrations in Spain during the 1990’s.<sup>14</sup> Spain was the fifth largest automobile manufacturer in the world during the 1990’s and also the fifth largest European automobile market by sales after Germany, France, the United Kingdom and Italy. In the sample, automobile sales range from 968,334 to 1,364,687 units sold annually.

Figure 1 documents the evolution and composition of European automobile sales during the 1990’s. In particular, we see that European diesel penetration, defined as the share of new vehicles sold with diesel engines, steadily increased across the 1990’s.<sup>15</sup> Spain, the country of interest, exhibited

<sup>12</sup> See the 2004 report ‘Why Diesel?’ from the European Association of Automobile Manufacturers (ACEA).

<sup>13</sup> See ‘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.

<sup>14</sup> See Appendix for further details.

<sup>15</sup> There is variance in the adoption of diesels across countries, however, as smaller countries such as Denmark were slow adopters while France, led by Peugeot, adopted diesels earlier than Spain.



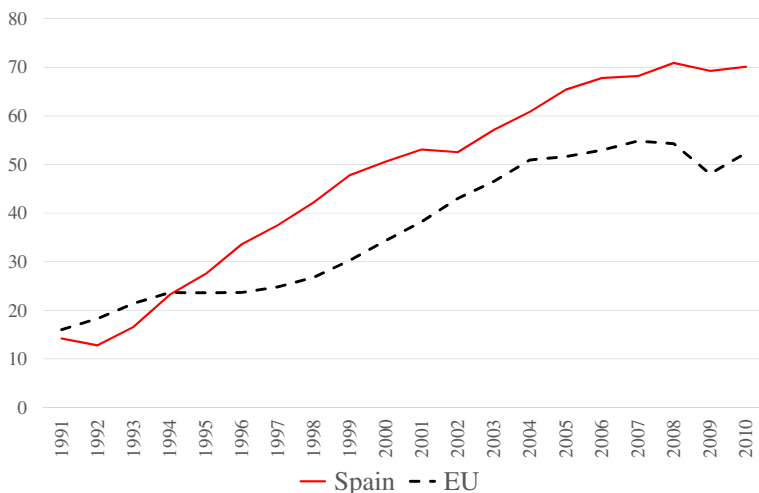


Figure 1  
Growth of Diesels (% New Vehicle Sales)

Notes: Figure plots the growth in the percent of new car sales which have a diesel engine. Author's calculations. New passenger car registration data from *Association Auxiliaire de l'Automobile (AAA)*. In panel (a), European diesel penetration (dashed line) constructed gross domestic product as weights (source: World Bank Development Indicators). Countries included: Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Portugal, and the United Kingdom. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

growth representative of the continent as a whole or even served as a leading indicator.<sup>16</sup>

It is common to see slow consumer adoption after the introduction of a new technology. Schumpeter [1950 p.98] theorized that this was due to consumers waiting for incremental improvements in the technology. This idea was later formalized by Balcer and Lippman [1984] and was used by Manuelli and Seshadri [2014] to explain the half a century time span needed for the diffusion of tractors – an important technological advancement for the agriculture industry. In contrast, the incredible pace of adoption of diesel automobiles suggests that the TDI proved to be a significant technological advance and consumers gained little from waiting for additional incremental improvements.

<sup>16</sup> Initially in 1992, diesels represented only 16% of total sales but by the end of the decade diesels represented 54% of the market, growing from 161,667 to 732,334 units sold in years 1992 and 2000, respectively. Sales of gasoline models were flat in 1993 and 1995, about 573,000, despite a scrappage program in 1994, when they temporarily increased by 15%. While the sales of gasoline models has grown steadily since, it pales in comparison to the growth of diesels.

TABLE I  
EVOLUTION OF DIESEL SUPPLY

	1992	1994	1996	1998	2000
All Gasoline Engines	97	109	124	135	134
All Diesel Engines	44	58	78	88	95
Volkswagen	9	9	14	16	21
FIAT	6	10	12	13	13
PSA	8	9	13	13	10
Ford	4	6	8	6	7
GM	5	4	4	6	6
Mercedes	3	4	4	5	6
Renault	4	6	6	5	5
Nissan	1	2	2	4	4
Rover	2	4	5	4	4
BMW	2	2	3	3	3
Mazda	0	0	1	3	3
Mitsubishi	0	0	2	2	3
Toyota	0	1	2	3	3
Honda	0	0	1	2	2
Hyundai	0	0	0	2	2
Chrysler	0	1	1	1	1
Kia	0	0	0	0	1
Suzuki	0	0	0	0	1
Daewoo	0	0	0	0	0
Total Offered	141	167	202	223	229

*Notes:* Automaker ownership groups sorted in descending order by number of diesel models offered in 2000. The Volkswagen group includes brands Audi, SEAT, Skoda, and Volkswagen.

The substantial growth in diesel sales was aided by an increase in supply.<sup>17</sup> Table I shows that by 1992 a consumer wishing to purchase a diesel had 44 models to choose from, or equivalently 31% of all new cars models were equipped with diesel engines. At this point market share of diesels in Spain amounted to 16.7% of total new car sales, up only slightly from 14.2% when Volkswagen introduced the TDI in 1989. Of the 44 diesel models available to consumers only nine were produced by the Volkswagen group, with the remainder being largely offered by rival European firms.

<sup>17</sup> In 'Theory of Economic Development' Schumpeter theorized that it was supply and demand that generated growth.

As the decade progressed, rival European auto makers, particularly FIAT and PSA, increased the number of diesels in their portfolios.<sup>18</sup> Asian automakers were slower to adopt the new technology and only began to enter the space at the end of the decade.<sup>19</sup> This suggests a low cost of imitation – a trait which characterizes all ‘general technologies’ (e.g. Bresnahan [2010]) – due to the fact the technology can be easily modified or reverse-engineered.<sup>20</sup> Further, the turbodiesel technology could be licensed from European automakers. Toyota and other Asian firms chose this route and outfitted their turbodiesel models with diesel engines purchased from European firms.<sup>21</sup>

Automobiles may differ in several different dimensions. Since the diesel and gasoline version of a particular car model share the same chassis, a consumer contemplating the purchase of an Audi A4 gas or diesel car bases her decision on differences in engine performance and not on car size. Diesel vehicles are about 10% heavier than similar gasoline versions; have 15% to 20% less horsepower; and are between one and two thousand euros more expensive. They are also more fuel efficient as they consume 20%–40% less fuel than a comparable gasoline model enabling a diesel to attain better fuel economy as they travel about 63% farther on a euro’s worth of fuel.

Of course, engine type is not the only characteristic consumers consider when they purchase a new car. From Table II we observe that most purchases are in the COMPACT, SMALL, and SEDAN segments though there is growth in the MINIVAN segment across the decade largely driven by an increase in vehicle choices in the segment. SMALL vehicles tend to be less expensive and more fuel efficient (i.e., low C90) while LUXURY cars and MINIVAN s are just the opposite. SEDANs and LUXURY cars also

<sup>18</sup> Outside of the Volkswagen group, the data do not allow me to rigorously identify whether a specific diesel model is equipped with turbodiesel technology, though there is evidence that automakers incorporated the turbodiesel technology in their new diesel models and replaced the old Perkins technology in their existing diesel models. For example, in 1993 Peugeot introduced the technology in its 205 and 405 STDT (special trim diesel turbo) vehicles. Since turbodiesels offer many advantages over the old Perkins technology, an assumption which underlies much of the analysis is that firms incorporated the new technology in their diesel fleet, particularly in new vehicles.

<sup>19</sup> Asian imports include Daewoo, Honda, Hyundai, Kia, Mazda, Mitsubishi, Nissan, Suzuki, and Toyota.

<sup>20</sup> Is this experience unique? Using firm-level survey data, Mansfield *et al.* [1981] document that 60% of *patented* technologies are imitated within four years of introduction indicating that patent protection alone is insufficient to protect a firm’s intellectual property. Put differently, their finding suggests that many technologies are indeed ‘general technologies.’

<sup>21</sup> A natural question is why these Asian firms did not offer their own turbodiesels. One possibility is that the popularity of diesels was largely a European phenomenon so European auto makers chose to invest in the technology since a significant portion of their profits came from European consumers whereas Europe was a small market for Asian auto makers. The per cent of revenue from the European market for BMW, PSA, Renault and Volkswagen was 65%, 93%, 84%, and 74%, respectively, while for Honda, Mazda, and Toyota the shares are substantially smaller: 11%, 10%, and 8%, respectively (source: company 10-K SEC filings).

TABLE II  
VEHICLE CHARACTERISTICS AVAILABLE TO CONSUMERS

Segment	Model	Share	Price	C90	KPE	Size	HPW
1992							
<i>By Fuel Type</i>							
Diesel	44	16.70	12.27	4.45	46.37	73.87	3.14
Gasoline	97	83.30	11.23	5.41	29.52	71.80	4.14
<i>By Segment</i>							
Compact	31	35.79	10.96	5.33	32.07	74.34	3.98
Luxury	39	5.77	24.01	6.49	25.75	87.07	4.84
Minivan	4	0.32	17.28	6.93	24.21	81.66	3.79
Sedan	39	22.31	14.26	5.69	30.27	80.10	4.26
Small	28	35.82	7.98	4.68	35.00	62.51	3.65
Total	141	100.00	11.40	5.25	32.33	72.15	3.97
2000							
<i>By Fuel Type</i>							
Diesel	95	53.66	16.24	4.59	37.90	76.63	3.15
Gasoline	134	46.34	14.68	5.76	23.95	73.78	3.93
<i>By Segment</i>							
Compact	56	34.43	14.86	5.00	32.53	76.54	3.59
Luxury	40	3.72	34.53	6.72	23.31	89.72	5.17
Minivan	32	3.13	20.80	6.39	25.91	83.47	3.16
Sedan	52	25.97	19.45	5.26	31.60	81.92	3.63
Small	49	32.75	10.42	4.86	31.61	66.36	3.18
Total	229	100.00	15.52	5.13	31.43	75.31	3.51

Notes: Share is the market share as defined by automobiles sold. Price is denominated in the equivalent of thousands of 1994 euros and includes value added taxes and import tariffs. C90 is a measure of ‘Fuel Efficiency’ and is the fuel consumption (in liters) required to cover 100 kilometers at a constant speed of 90 kilometers per hour. A car becomes more fuel efficient as C90 decreases. KPE is a measure of ‘Fuel Economy’ and is the distance, measured in kilometers, traveled per euro of fuel. SIZE is length × width measured in square feet. HPW is the performance ratio of horsepower per hundred pounds of weight. Figure C.2 presents the distributions of these characteristics across engine type.

tend to be more powerful (i.e., horsepower/weight, or HPW) than vehicles in other segments. Such qualitative differences across segments tend to persist across the decade though magnitudes change. There are also common trends in the market as vehicles in 2000 were 36.1% more expensive, 4.4% larger (SIZE), 11.6% less powerful (HPW), 2.3% more fuel-efficient (C90), and attained 2.8% better fuel economy (KPE) than at the beginning of the decade.

## IV. AN EQUILIBRIUM OLIGOPOLY MODEL OF THE AUTOMOBILE INDUSTRY

In this section I present a structural equilibrium model of demand and supply where utility-maximizing heterogeneous consumers choose among a variety of car models each year and vehicle prices are set among multi-product firms in a pure strategy Bertrand-Nash equilibrium. Since consumers consider a variety of product characteristics when making their purchase decisions, there exists greater competition among firms with similar product sets (in characteristic space). The introduction of turbodiesels by rival European firms, therefore, leads to greater competition which erodes Volkswagen's market power and profits. Volkswagen's ability to differentiate its vehicles from the competition mitigates this effect, however.

IV(i). *Demand*

Consumer demand is represented by a random coefficients nested logit (RCNL) discrete choice framework of Grigolon and Verboven [2014]. Demand can be summarized as follows: consumer  $i$  derives an indirect utility from buying vehicle  $j$  at time  $t$  that depends on price and characteristics of the car:

$$(1) \quad u_{ijt} = x_{jt}\beta_i^* - \alpha_i^* p_{jt} + \xi_{jt} + \bar{\epsilon}_{ijt},$$

where  $i = 1, \dots, I_t$ ;  $j = 1, \dots, J_t$ ;  $t = \{1992, \dots, 2000\}$ .

where I define a product  $j$  as a model-engine type pair. This Lancasterian approach makes the payoff of a consumer depend on the set of characteristics of the vehicle purchased, which includes a vector of  $K$  observable vehicle characteristics  $x_{jt}$  such as engine type, car size, or fuel efficiency as well as others that remain unobservable for the econometrician,  $\xi_{jt}$  (e.g., reliability, leather interior) plus the effect of unobserved tastes of consumer  $i$  for vehicle  $j$ ,  $\bar{\epsilon}_{ijt}$ .

An important component of (1) is that consumers have heterogeneous responses to changes in vehicle prices and characteristics:

$$(2a) \quad \alpha_i^* = \Pi D_{it}$$

$$(2b) \quad \beta_i^* = \beta + \Sigma \eta_{it}$$

Consumer  $i$  in period  $t$  is characterized by a  $d$  vector of observed demographic attributes,  $D_{it}$ , as well as a vector of random tastes,  $\eta_{it}$  distributed i.i.d. with cumulative distribution function  $F$  commonly assumed to be standard normal.  $\Pi$  is a  $(n + 1) \times d$  matrix of coefficients that measures the effect of a consumer's demographics (e.g., income) on her valuation of an automobile's characteristics, including price. Similarly,  $\Sigma$  measures the covariance in unobserved preferences across characteristics. A useful decomposition is to separate the deterministic portion of the consumer's

indirect utility into a common part shared across consumers,  $\delta_{jt}$ , and an idiosyncratic component,  $\mu_{ijt}$ , given by:

$$(3a) \quad \delta_{jt} = x_{jt}\beta + \xi_{jt},$$

$$(3b) \quad \mu_{ijt} = p_{jt}\Pi D_{it} + (x_{jt}) \times (\Sigma \eta_{it}).$$

I assume the idiosyncratic product  $j$  period  $t$  consumer valuations ( $\bar{\epsilon}_{ijt}$ ) follow the distributional assumptions of the nested logit literature, thereby increasing the valuations of products within the same ‘group’ or ‘nest.’ Suppose there are  $g = 0, 1, \dots, G$  groups for which each car can be assigned to only one (i.e., segment) and define group zero as the outside good. I can then write the idiosyncratic valuation as

$$(4) \quad \bar{\epsilon}_{ijt} = \zeta_{igt} + (1 - \rho)\epsilon_{ijt}$$

where  $\rho \in [0, 1]$ ,  $\epsilon$  is assumed i.i.d. multivariate type I extreme value distributed, and  $\zeta_{igt}$  has the unique distribution for the group  $g$  to which product  $j$  belongs such that  $\bar{\epsilon}_{ijt}$  is extreme value – an assumption which is useful in constructing the purchase probabilities for each agent. I call  $\rho$  the ‘nesting parameter’ as its value modulates the importance of the nests in explaining consumer purchases. As  $\rho$  goes to one consumers view products within a group as perfect substitutes while  $\rho$  converging to zero drives within-group correlation to zero. Plugging (4) into (1) yields:

$$(5) \quad u_{ijt} = x_{jt}\beta_i^* - \alpha_i^* p_{jt} + \xi_{jt} + \sum_{g=1}^G \mathbb{1}_{jgt} \zeta_{igt} + (1 - \rho)\epsilon_{ijt}$$

where  $\mathbb{1}_{jgt}$  is an indicator variable equal to one when  $g$  is the group corresponding to product  $j$ . From Equation (5) we can see the model’s flexibility. When  $\Sigma = 0$  and  $\rho > 0$  the model collapses to nested logit. Alternatively, when  $\rho = 0$  but  $\Sigma > 0$  the model collapses to the random coefficients model of Berry *et al.* [1995]. When both  $\Sigma = 0$  and  $\rho = 0$  the model returns the simple multinomial logit.

I define the potential market as the number of households in Spain. In each period  $t$ , the head of each household (i.e., consumer  $i$ ) chooses the product  $j = 0, 1, \dots, J_t$  which provides him/ her the most utility. Inclusion of the outside good ( $j = 0$ ) in the consumer’s consideration set allows him/ her to choose not to purchase a new car in period  $t$ . The model is silent as to whether a consumer who chooses the outside option purchases a used car or holds off his/ her new car purchase for a later period.

Define the set of individual-specific characteristics leading to the optimal choice of car  $j$  as:

$$(6) \quad A_{ijt}(x_{.t}, p_{.t}, \xi_{.t}; \theta) = \{ (D_{it}, \eta_{it}, \epsilon_{ijt}) \mid u_{ijt} \geq u_{ikt} \quad \forall k = 0, 1, \dots, J_t \},$$

with  $\theta$  summarizing all model parameters. The extreme value distribution of the random shocks then allows us to integrate over the distribution of  $\epsilon_{ijt}$  to obtain the probability of observing  $A_{ijt}$  analytically where the probability ( $\Pi$ ) that consumer  $i$  purchases automobile model  $j$  in period  $t$  is:

$$(7) \quad \pi_{ijt} = \frac{\exp\left(\frac{\delta_{jt} + \mu_{ijt}}{1-\rho}\right)}{\exp\left(\frac{I_{igt}}{1-\rho}\right)} \times \frac{\exp(I_{igt})}{\exp(I_{it})},$$

where  $I_{igt} = (1-\rho) \ln \left[ \sum_{m=1}^{J_g} \exp\left(\frac{\delta_{mt} + \mu_{imt}}{1-\rho}\right) \right]$

$$I_{it} = \ln \left( 1 + \sum_{g=1}^G \exp(I_{igt}) \right).$$

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

$$(8) \quad s_{jt}(x_t, p_t, \xi_t; \theta) = \int_{\eta_t} \int_{D_t} \pi_{ijt} dP_{D_t}(D_t) dP_{\eta_t}(\eta_t),$$

with  $s_{0t}$  denoting the market share of the outside option. Solving (8) can be expensive in practice when the dimension of  $\eta$  or  $D$  is large (see Skrainka and Judd [2011]). The advantage of the RCNL discrete choice model is to provide analytical integrals over the nested group (e.g., car segment) as in the nested logit model while enabling the researcher to include random coefficients to avoid the Independence of Irrelevant Alternatives (IIA) property of cars with varying observable characteristics within each group.

#### IV(ii). Pricing

In this section I append supply-side costs and pricing to the RCNL discrete choice demand model. This serves two objectives. First, Reynaert and Verboven [2013] show the addition of the supply-side pricing decision increases precision for the demand-side parameters, particularly the price coefficient. Second, including a supply-side pricing decision enables computation of counterfactual equilibrium prices – a component which will be crucial for measuring both the static and dynamic implications of imitation.

Equilibrium prices are found as the solution to a non-cooperative pure strategy Bertrand-Nash game among the competing auto makers. Specifically, static profit-maximization by each firm  $f$  implies that equilibrium prices ( $p^m$ ) can be written as a nonlinear function of the product characteristics ( $X$ ), market shares  $s(x, p, \xi; \theta)$ , retail prices ( $p$ ), and markups:

$$(9) \quad p_{jt}^w = mc_{jt} + \underbrace{\Delta_t^{-1}(p, x, \xi; \theta) s_{jt}(p, x, \xi; \theta)}_{b_{jt}(p, x, \xi; \theta)},$$

where  $p_{jt} = p_{jt}^w \times (1 + \tau_{jt})$  and  $\tau_{jt}$  is the import duty applicable to model  $j$  in period  $t$ , if any. The vector of equilibrium markups  $b_{jt}(\cdot)$  depends on market shares  $s_{jt}(\cdot)$  and the matrix  $\Delta_t(\cdot)$  with elements:

$$(10) \quad \Delta_t^{rj}(x, p, \xi; \theta) = \begin{cases} -\frac{\partial s_{jt}(x, p, \xi; \theta)}{\partial p_{jt}} \times \frac{\partial p_{jt}}{\partial p_{jt}^w}, & \text{if products } \{r, j\} \in J_t^f, \\ 0 & \text{otherwise.} \end{cases}$$

where  $J_t^f$  is the set of products offered by firm  $f$  in period  $t$ . Equilibrium prices are then a function of consumer demand, import tariffs, and the portfolio of products offered by each firm.

In estimating marginal costs, I make a common assumption that firms have Cobb-Douglas cost functions of the following (log-linear) form:

$$(11) \quad \log c = Z\gamma + \omega.$$

where  $Z$  are logged observable characteristics and  $\omega$  are cost components known to firms but unobserved by the researcher.

V. ESTIMATION

I define structural parameters of the model as  $\theta = [\beta, \Sigma, \Pi, \gamma, \rho]$ , the demand-side structural error as  $v^D(\theta) = \xi$ , and the supply-side structural error as  $v^S(\theta) = \omega$ . Under the common assumption that the product set (and the corresponding set of characteristics) is exogenous, demand and supply parameter estimates  $(\beta, \Sigma, \Pi, \gamma, \rho)$  are recovered via a generalized method of moments (GMM) estimator (Hansen 1982) using observable product characteristics as basis functions to construct identifying instruments ( $H$ ). The GMM estimator exploits the fact that at the true value of parameters ( $\theta^*$ ), the instruments  $H$  are orthogonal to the structural errors  $v^D(\theta^*), v^S(\theta^*)$  so that the GMM estimates solve:

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}} \left\{ g(\theta)' HWH' g(\theta) \right\},$$

where  $g(\theta)$  is a stacked vector of the demand and supply-side structural errors and  $W$  is the weighting matrix, representing a consistent estimate of  $E[H'gg'H]$ .<sup>22</sup>

<sup>22</sup> In constructing the optimal weighting matrix, I first assume homoskedastic errors and use  $W = [H'H]^{-1}$  to derive initial parameter estimates. Given these estimates, I solve the model and use the resulting structural errors ( $v^D, v^S$ ) to update the weight matrix.



I construct the structural errors as follows. I solve for the mean utilities  $\delta(\theta)$  via a contraction mapping which connects the predicted purchase probabilities in the model to observed shares in the data for a given value of  $\theta$  (see Grigolon and Verboven [2014]). The demand-side structural error then follows from (3a). Observed prices, ownership structure, and tariff rates plus Equation (9) generate marginal costs as a function of the parameter guess. The supply-side structural error then follows from (11).

Knittel and Metaxoglou [2014] and Dubé, Fox and Su [2012] point out that finding a global solution to the estimator is difficult since the objective function is highly non-linear so any line, gradient or simplex search will likely only result in a local solution. To increase the likelihood of achieving a global minimum, I set the fixed-point tolerance in the mean utility contraction to  $1e-14$  and employ a state-of-the-art minimization algorithm (Knitro Interior) starting from several different initial conditions – a strategy shown by Dubé *et al.* [2012] to generate the global solution in Monte Carlo simulations.<sup>23</sup>

#### V(i). *Specification*

Bringing the model to the data requires the researcher to make explicit assumptions about what characteristics consumers value when they purchase a new vehicle as well as the set of potential supply-side shocks faced by firms. Consumer demand (both mean and idiosyncratic) includes measures of automobile performance: horsepower divided by weight (HPW), exterior dimensions (SIZE), the cost of driving (KPE), and engine type (Diesel) where the inclusion of Diesel as a random coefficient allows for different substitution patterns within the diesel segment. I also include a constant random coefficient (Constant) to capture changes in substitution patterns due to the increasing product set and a linear diesel trend (Diesel trend) in mean utility which I found helpful in explaining the increasing popularity of diesel vehicles among consumers. I define the product nests as car segments (i.e., small, compact, sedan, luxury, and minivan) thereby allowing for valuations of products within a segment to be correlated. I limit the demographic interactions ( $\Pi$ ) to be just the interaction between price and income where I follow Berry, Levinsohn and Pakes [1999] and model the price coefficient as  $\alpha_{it} = \frac{\alpha}{y_{it}}$  where  $y_{it}$  is the year  $t$  income of consumer  $i$ . I simulate individual income  $y_{it}$  using yearly census data to account for changes in the income distribution over time. Finally, the inclusion of a linear time trend (TREND) accounts for any variation in the remaining relative valuation of the outside option over time.

<sup>23</sup> Relaxing the fixed-point tolerance to  $1e-12$  yielded similar results whereas limiting the number of initial conditions often resulted in the estimation algorithm, finding inferior (i.e., higher J-statistic) local solutions.

The supply-side largely mirrors the demand-side with a couple modifications. First, I include logged values of the continuous observed characteristics (e.g., HPW). Second, I replace KPE, which includes the effect of fluctuations in fuel price, with a measure solely based on fuel-efficiency, C90. Consequently, Audi's choice of fuel-efficiency for a gasoline model A4 impacts its cost directly as measured by C90, but demand for A4's will also be influenced by changes in the price of gasoline due to economic factors outside of Audi's control. Hence, I include KPE in demand but (log) C90 supply. Similarly, I allow for increasing steel prices to impact the cost of producing larger, heavier cars by multiplying car weight and size by an index for the price of steel. This leads to shifts of HPW and SIZE in supply but not demand. I also include brand (e.g., Audi, BMW, Volkswagen) and segment (e.g., COMPACT) dummies to account for differences in marginal cost across these dimensions. Finally, I assume reductions in the import tariff rate and changes in firm ownership due to mergers and acquisitions are both exogenous. The former impacts the difference between retail price  $p$  and wholesale price  $p^w$  for foreign firms, while the latter impacts the  $\Delta$  matrix and ultimately estimated marginal costs through Equation (9).<sup>24</sup>

#### V(ii). *Parameter Identification*

The parameter estimates are pinned down in the GMM estimation via the instruments  $H$ . The intuition into how data variation (via  $H$ ) identifies different components of  $\theta$  is as follows. Mean utility parameters  $\beta$  and cost parameters  $\gamma$  are recovered using the linear projection outlined in Nevo [2000] using Equations (3a) and (11). Consequently, the mean utility vector  $\beta$  is identified by correlations between market shares and observable product characteristics. The identification of  $\gamma$  follows from variations in observable product characteristics and implied marginal costs where the latter depends on variation in price and market shares (via the price coefficient,  $\alpha$ ) plus the shocks to fuel price and steel prices. Hence, the components of  $X$  and  $Z$  are sufficient instruments for these parameters.

The price coefficient ( $\alpha$ ) is identified by changes in quantity sold, retail prices and consumer income. Much of this variation is across time where I discussed variation in quantity sold and retail prices in Section III. In Figure 2, I present variation in consumer income over the decade. Dots in the figure correspond to the average consumer (head of household) income in each year and the bars correspond to the interquartile range, i.e., the distance between the 75th and 25th quartiles also known as the middle 50%. From the figure we see that (real) consumer income decreases slightly during the beginning of the decade immediately following Spain's accession

<sup>24</sup> See Appendix for details on acquisitions and mergers in the European automobile industry during the 1990's.

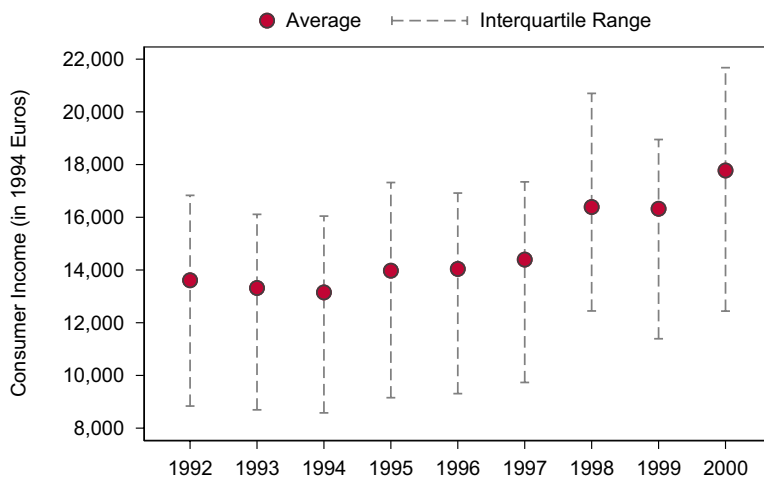


Figure 2  
Identification of the Price Coefficient

Notes: *Encuesta Continua de Presupuestos Familiares*. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

into the European Union in 1992. After 1994, incomes begin to rise slowly at first and then significantly at the end of the decade. The distribution of income around the average is fairly stable with the exception of 1998 and 2000 when the prevalence of high income earners increases.

I identify the remaining parameters ( $\Sigma$ ,  $\rho$ ) using variation in the product set and the distributions of distances in product characteristic space. I construct instruments for the constant and Diesel random coefficients using the total number of products and diesel vehicles accounting for differences in firm portfolios. Thus, the random coefficient for diesel vehicles is identified by the correlation between changes in the number of diesel vehicles in the product set and changes in purchase shares of diesel vehicles. A similar relationship holds for the constant random coefficient and gasoline-powered cars. I construct an instrument for the nesting parameter  $\rho$  as the number of other vehicles in a car's segment after accounting for variation in firm product portfolios.

I construct instruments for the HPW and KPE random coefficients by approximating the 'optimal instruments' of Chamberlain [1987] using 'differentiation IVs' introduced by Gandhi and Houde [2015].<sup>25</sup> The idea is to use the distributions of product characteristics to identify  $\Sigma$  by constructing cdf's for each continuous characteristic based on the distances in the

<sup>25</sup> See Reynaert and Verboven [2013] and Gandhi and Houde [2015] for a further discussion on instruments and identification in random coefficient logit demand systems.

corresponding product space. For example, I can construct a cdf for a 1995 Audi A4 in KPE space by looking at the distance between that model's fuel efficiency and the fuel efficiency of other models in that year. The addition or subtraction of fuel-efficient models over time then impacts this distribution. When consumers value fuel efficiency, orthogonality between  $v^d(\theta)$  and this cdf is achieved by increasing the KPE random coefficient – a similar intuition to the instruments used in Berry *et al.* [1995].

I operationalize this approach by replacing the large-dimensional cdf's with sample statistics. Specifically, the period  $t$  instrument for product  $j$  and characteristic  $k$  is

$$(12) \quad H_{jt}^{k,\lambda}(\hat{\theta}) = x_{j,t}^k \times \left( \sum_{r \neq j}^{J_t} 1(d_{rj,t}^k < c_\lambda) \times x_{r,t}^k \right)$$

where  $c_\lambda$  designates a cut-off in the cdf in which to construct the instrument and  $d_{rj,t}^k$  is the absolute distance in product characteristic space  $k$  defined as  $|x_{r,t}^k - x_{j,t}^k|$ . By interacting the characteristic of product  $j$ , the instrument is able to account for differences in the correlation between product distance and market share across different positions in the product characteristic space. In practice, I chose  $c_\lambda$  for each characteristic such that the bins are evenly-distributed and set  $\lambda = 3$ , or equivalently four identifying instruments for each of these continuous product characteristics.

### V(iii). *Estimation Results*

Estimation results are presented in Table III. Overall, the estimates are reasonable, statistically significant, and congruent with the descriptive evidence of the industry from Section III. Significant parameter estimates for both the nesting parameter  $\rho$  and the random coefficients ( $\sigma \in \Sigma$ ) allow me to reject all three of the nested models common in the empirical literature: logit, nested logit, and random coefficients, or equivalently the RCNL of demand fits the data better than these alternative models.

The results indicate that diesels are more expensive to manufacture than gasoline models. The marginal costs of production are also higher for larger, more powerful, and less fuel-efficient cars.<sup>26</sup> The insignificant trend variables indicate there are no important efficiency gains occurring during the decade in the production of either gasoline or diesel engines.

<sup>26</sup> 'Fuel Economy' in Table III corresponds to KPE in consumer demand ( $\beta, \Sigma$ ) and 'Fuel Efficiency' corresponds to C90 in the cost function ( $\gamma$ ). The positive coefficient for C90 therefore indicates marginal cost is increasing in the amount of fuel required to cover 100 kilometers at a constant speed of 90 kilometers per hour (i.e., cost is increasing as 'fuel efficiency' decreases).

TABLE III  
DEMAND AND SUPPLY ESTIMATES

	Demog. Interaction ( $\alpha$ )					
	Mean Utility ( $\beta$ )			Random Coefficients ( $\Sigma$ )		
	Coefficient	Rob. SE	Rob. SE	Coefficient	Rob. SE	Rob. SE
Price/Income						
HP/Weight	1.4683	1.9604	(0.2065)	-1.8236	(0.4329)	0.0716
Size	5.3089	(0.8916)		2.4665		(0.1720)
Fuel Economy	0.8180	(1.0179)		3.3593	(0.4271)	
Fuel Efficiency						
Diesel	-13.4983	(1.9979)		3.8745	(0.4687)	(0.0728)
Diesel-x-Trend	0.6263	(0.0592)				(0.0377)
Constant	-12.9327	(1.1927)		0.0547	(0.2805)	(0.0042)
Trend	0.0170	(0.0167)				(0.1532)
Non-Euro	-0.9532	(0.1554)				(0.0035)
SEAT	0.5671	(0.2385)				
Nest ( $\rho$ )	0.2759	(0.0858)				
<i>Statistics</i>						
Avg. SW Elasticity		3.6				
Avg. SW Margin		33.2				
Number of obs.		1,740				
J-Statistic		124.5				

Notes: Estimates based on Monte Carlo simulation using 1,300 simulated consumers each year. Heteroskedasticity robust standard errors in parentheses. 'Fuel Economy' is KPE for consumer demand ( $\beta\Sigma$ ) while 'Fuel Efficiency' is C90 in the cost function ( $\gamma$ ). Fixed effects for brand and segment not reported. 'Margin' is the Lerner index defined as  $100 \times \frac{p - c}{p}$  where price excludes import tariffs, if applicable. Statistics for average 'Elasticity' and 'Margin' are weighted by quantity sold ('SW'). Equilibrium prices account for year-specific ownership structure as reported in Appendix VII.

The estimation also accounts for differences in marginal costs by brand (e.g., Audi), which I report in Figure 3 relative to the Spanish market leader, Renault. Results are very reasonable as German upscale brands Audi, BMW, and Mercedes, are among the most expensive to produce while Chrysler and Asian imports such as Daewoo, Hyundai, Kia, and Mitsubishi are relatively less expensive to produce. European manufacturers with lower unit costs of production than Renault, include the Czech brand Skoda and the Spanish brand SEAT, both of which were acquired by Volkswagen to sell streamlined versions of their vehicles targeting lower income customers. Another interesting case of relatively low cost of production is Ford which produces most of its smaller European models in a large plant located in Valencia, Spain.

The estimated demand curves are all downward slopping and elastic; amounting to an average sales-weighted estimated (absolute) price elasticity of 3.6 and an average 33.2% estimated margin (Lerner index), both of which are consistent with other estimates of the European automobile industry around this time (e.g., Goldberg and Verboven [2001]; Moral and Jaumandreu [2007]; Grigolon and Verboven [2014]). There is however substantial heterogeneity across products as the standard deviation for the price elasticities and price-cost margins are 1.28 and 8.80, respectively,

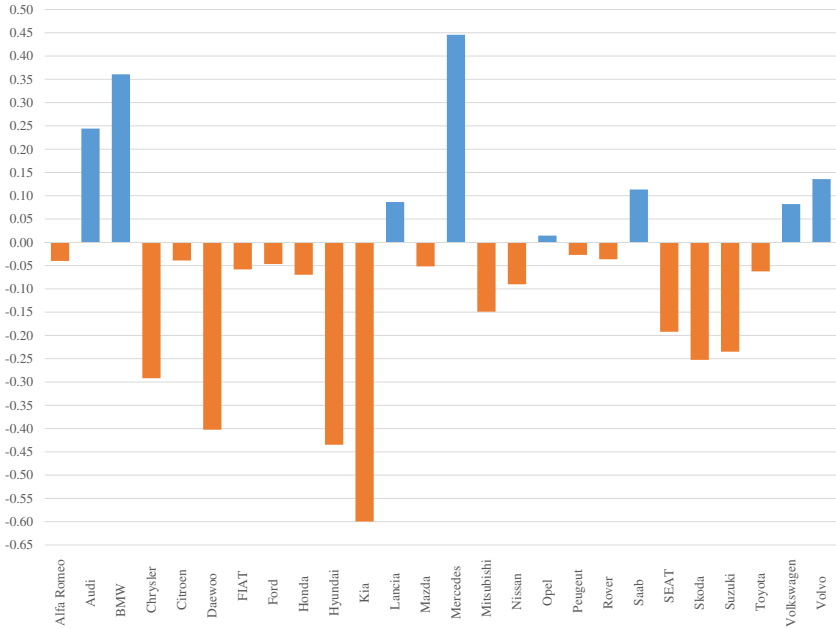


Figure 3  
 Production Cost Differences Across Brands (Reference: Renault) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

reflecting the large degree of horizontal-differentiation in the industry as price competition occurs in local areas of product characteristic space. Elasticities and margins, both of gasoline and diesel vehicles, remain quite stable over the decade (Figure 4) despite the evolution of vehicle characteristics and consumer preferences combined with increasing product variety.

Estimates of Table III indicate that, all else equal, drivers favor gasoline over diesel engines at the beginning of the sample ( $\hat{\beta}_{Diesel} < 0$ ) but consumer attitudes towards diesels improve across the decade ( $\hat{\beta}_{Diesel \times Trend} > 0$ ) due either to consumers' learning about these new turbodiesels or improvements in the technology. The small and insignificant estimate for the linear time trend (TREND) indicates that variation in overall market size is sufficiently captured by the time-series variation in household income (Figure 2). Consumers also prefer larger cars (positive coefficient for SIZE) after controlling for segment and other observable product characteristics such as price. The average consumer is indifferent about performance and fuel economy (insignificant coefficients for HPW and KPE in mean utility) though the significant random coefficients for both characteristics indicate a great deal of heterogeneity. I also find a large and statistically significant

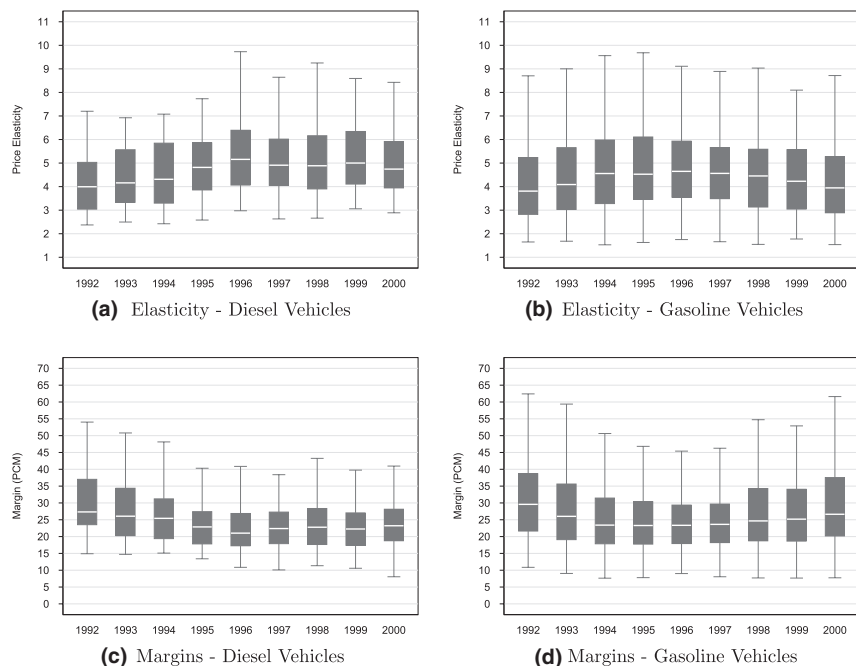


Figure 4

Evolution of Estimated Market Power

Notes: 'Elasticity' in panels (a) and (b) is the absolute value of the estimated demand elasticity. 'Margin' in panels (c) and (d) is the Lerner index, or Price-Cost margin, defined as  $100 \times (p_{it}^w - \hat{c}_{it}) / p_{it}^w$

value for the diesel random coefficient indicating that the substitution patterns between diesel cars are significantly different than between a diesel and gasoline-powered car even after controlling for differences in fuel economy. This suggests that other product characteristics such as torque differentiate diesel cars from their gasoline-powered competition.

The negative and significant estimate for NON-EU combined with the positive and significant estimate for the domestic brand, SEAT, indicates a 'home bias' for domestic brands – an empirical regularity in the international trade literature.<sup>27</sup> Since the focus here is on a specific industry rather than a set of bilateral trade flows across many sectors, I can provide a more detailed interpretation than is commonly provided in that literature. At this time, Asian imports were first sold in the European market and were considered lower quality, more fuel-efficient alternatives to European gasoline-powered vehicles but they lacked both brand recognition as well as a widespread network of dealerships for maintenance. Thus, the negative sign of NON-EU is not surprising. Meanwhile, the domestic brand SEAT was owned by the Volkswagen group thus it could be that the positive estimated coefficient is picking up demand characteristics brought to the company via Volkswagen but not observed to the econometrician.

The estimated model also generates reasonable substitution patterns (Figure 5). Panels (a)–(c) document how the random coefficients  $\Sigma$  for continuous characteristics such as HPW impact the cross-price elasticities. I do this by first solving for the distance between each pair of products in a particular characteristic (e.g., HPW). I then divide the product-pairs into deciles where the first decile correspond to pairs which are most alike. The last step is to compute the average cross-price elasticity for each bin. For all of the characteristics considered in the estimation, substitution between similar products is much more likely than for products far apart in characteristic space. The histogram for SIZE (panel b) is interesting because the estimation does not include a random coefficient for this characteristic yet we see greater substitution among products with similar dimensions. This is due to correlations of product size with other observable characteristics, including segment.<sup>28</sup> Since diesel is a discrete variable, I show the average cross-price elasticity within and across fuel types (panel d). Again, consumers are much more likely to substitute within fuel type.

Panels (e) and (f) document the impact of the nesting parameter  $\rho$  on cross-price elasticities across segments. In panel (e) we see that the cross-price elasticity within compact cars is roughly double the cross-price elasticity between a compact car and the other segments. In panel (f) we see

<sup>27</sup> See Cosar, Grieco, Li and Tintelnot [2018] for estimates of cross-country home bias in the automobile industry.

<sup>28</sup> Including a random coefficient for SIZE generated a small and statistically-insignificant value.



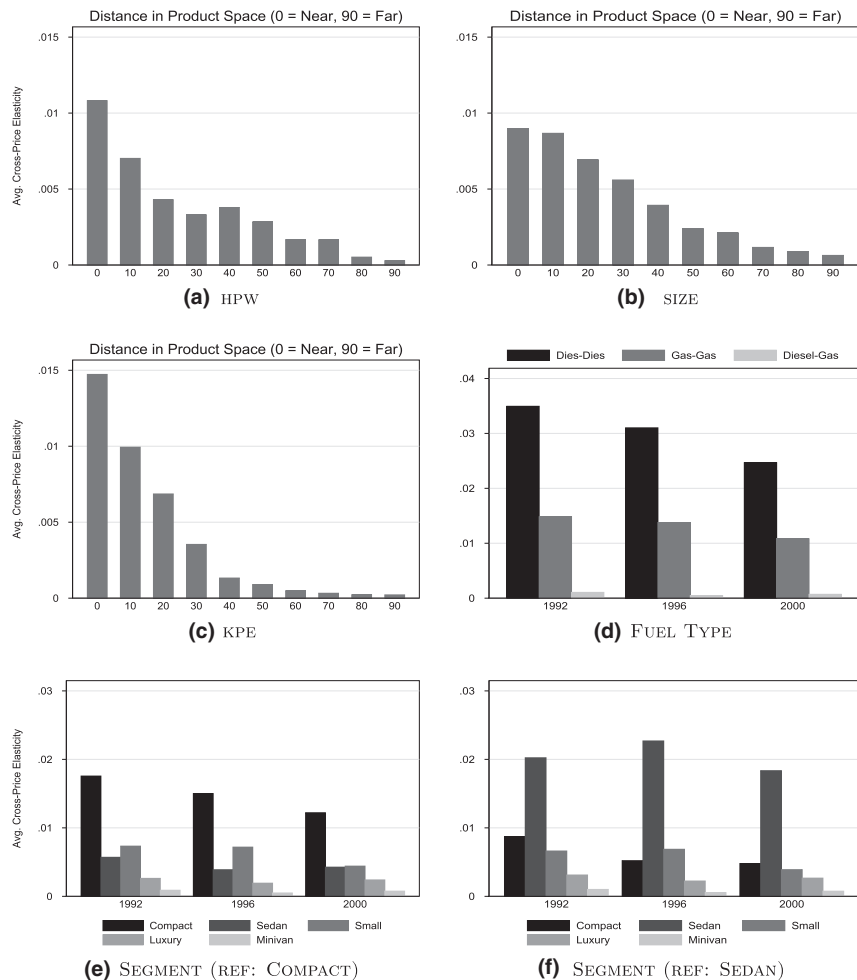


Figure 5

Substitution Patterns

Notes: Panels (a)-(c) present average cross-price elasticity on product characteristic space where two products are 'close' when the observed product characteristic is similar (i.e., distance between is small). Panel (d) compares the average cross-price elasticities across engine fuel types. Panels (e) and (f) compare average product elasticities within and across segments using different reference segments.

the same is true for sedans though the magnitude is greater and, of course, similar results hold for the remaining car segments as well.

VI. MEASURING THE IMPACT OF IMITATION

With robust estimates of demand and supply in hand, the objective in this section is to measure the implications of imitation on static and dynamic

efficiency. First, I show that imitation led to significant price competition among European automakers though the effect on Volkswagen profits varied significantly across firms. Second, I show that while imitation enabled rivals to steal a substantial amount of potential business from the TDI, Volkswagen's ability to horizontally-differentiate its diesel models enabled the firm to generate a lot of profit from its innovation. Hence, the TDI remained a worthwhile investment for the firm. This suggests that imitation, though significant, still provided for a dynamically efficient outcome.

#### VI(i). *Imitation, Prices and Profits*

I begin with an evaluation of the static implications of imitation on Volkswagen equilibrium pricing and profits by comparing the estimated equilibrium with two plausible counterfactual equilibria where I vary importance of the TDI technology. I construct these equilibria by taking advantage of two facts: (a) diesel penetration at the beginning of the sample was close to the penetration rate prior to the TDI's introduction ( $\approx 14\%$ ), and (b) demand estimates indicate a positive trend for diesel models ( $\hat{\beta}_{\text{Diesel}-x-\text{Trend}} > 0$ ). Point (a) indicates that consumer demand for diesels in 1992 looked similar to demand for diesels equipped with the old Perkins technology while point (b) suggests that consumers learned about the new turbodiesel technology as the decade progressed.<sup>29</sup> Setting  $\hat{\beta}_{\text{Diesel}-x-\text{Trend}} = 0$  eliminates this mechanism and forces consumers to make decisions based on their perceptions of the old diesel technology.

In my first counterfactual equilibrium I set  $\hat{\beta}_{\text{Diesel}-x-\text{Trend}} = 0$  and recompute the pricing equilibrium for each year. By reducing the popularity of diesels to the level observed at the beginning of the sample, I simulate a world in which diesels operate with the old Perkins technology. I call this experiment 'No TDI.' In the second counterfactual I simulate the equilibrium where Volkswagen successfully defends its patent rights. I do so by setting  $\hat{\beta}_{\text{Diesel}-x-\text{Trend}} = 0$  for all diesel vehicles not manufactured by Volkswagen. In this equilibrium consumers observe that the TDI technology enables Volkswagen diesel models to be more reliable, cleaner, and quieter than the competition (e.g., Renault) as diesels sold by these rival firms

<sup>29</sup> Alternatively, it could be that the technology underlying the turbodiesel increased steadily across the decade. I can identify only one significant improvement during this period. In 1997 the Alfa Romeo 156 2.4 JT D and Mercedes-Benz C-Class W202 both incorporated 'common rail fuel injection' which enabled detailed electronic control over both fuel injection time and volume. The higher pressure of the common rail technology also increased fuel atomization, making ignition more efficient. Since there is a steady increase in consumer demand for diesels (Figure 1) over the decade, it seems reasonable that consumer learning related to turbodiesels played at least a significant part in the growth of diesels.

can only be equipped with the old Perkins technology. I call this experiment ‘No Rival TDI.’<sup>30</sup>

These equilibria therefore amount to end points of a spectrum where on the one hand the TDI technology is never invented while on the other Volkswagen is able to limit the technology’s imitation by rival firms. The task then is to assess whether the observed equilibrium is closer to one in which Volkswagen is able to differentiate its innovation from the competition and is therefore largely unaffected by imitation (as in Petrin [2002]) or whether imitation materially reduced the innovative rents of the TDI. In Table IV I compare the estimated equilibrium to these counterfactual equilibria at the beginning and end of the decade.<sup>31</sup>

I find the estimated equilibrium is much more similar to the ‘No TDI’ equilibrium than the ‘No Rival TDI’ equilibrium. Imitation by rival firms applied downward pressure to Volkswagen prices and margins. Had Volkswagen been able to maintain monopoly power over the TDI, retail prices for automobiles would have been 1.3% higher at the beginning of the sample and 58.2% higher at the end – a sizable difference. Most of this increase is due to price increases in the diesel segment where the average retail price for a diesel car increases 2.3% and 78.1% in 1993 and 2000, respectively. The equilibrium at the end of the decade would have therefore looked much different for Volkswagen shareholders as monopoly power over the TDI technology would have enabled the firm simultaneously to increase its margins (i.e., from 33.4% to 53.2%) and its overall market share (i.e., from 22.3% to 43.4%) while dominating the diesel segment by accounting for 92.8% of all new diesel vehicle sales.

I estimate that Volkswagen profits in 1993 would have been 8.5% larger (€44.7 million) than the estimated equilibrium had the company been able to maintain dominance of the diesel segment by leveraging the positive attributes associated with the TDI technology. By the end of the decade, I estimate the firm would have earned profits roughly four-times the amount it earned in the data, or €4.4 billion – a sizable difference. The introduction of turbodiesels by rival firms therefore reduced Volkswagen profits significantly.

To illustrate the effects of imitation on Volkswagen profits, I define the share of potential TDI profits which Volkswagen was able to capture as:

$$(13) \quad \text{“Rent Capture”} \equiv \frac{\pi_t^{\text{Benchmark}} - \pi_t^{\text{No TDI}}}{\pi_t^{\text{No Rival TDI}} - \pi_t^{\text{No TDI}}}.$$

<sup>30</sup> In the Appendix I quantify the value of the TDI using counterfactual equilibria where diesel vehicles disappear from the marketplace due to either regulation or competition from the TDI. Results are qualitatively similar to those presented in the main text.

<sup>31</sup> My analysis begins in 1993 because the estimated and counterfactual equilibria are equal in 1992 by construction.

TABLE IV  
VALUE OF TDI TECHNOLOGY TO VOLKSWAGEN

	1993			2000		
	No TDI	Data	No Rival TDI	No TDI	Data	No Rival TDI
<i>Prices</i> (€ Thousand)	12.68	12.73	12.89	16.21	16.30	25.79
Diesel	14.20	14.16	14.49	18.25	16.87	30.04
Gas	12.47	12.48	12.48	15.41	15.44	15.47
<i>Market Share</i> (%)	18.16	17.83	19.91	21.24	22.31	43.35
Diesel	12.06	12.12	21.94	29.58	25.11	92.84
Gas	19.46	19.45	19.45	19.12	19.05	18.89
<i>Margin</i> (%)	34.49	34.30	34.30	34.78	33.35	53.15
Diesel	28.50	28.77	30.38	32.98	31.94	60.33
Gas	35.28	35.28	35.30	35.48	35.50	35.70
<i>Profit</i> (€ Million)	504.20	522.05	566.71	889.96	1,510.03	5,862.87
Diesel	57.59	77.03	120.46	275.72	922.99	5,258.29
Gas	446.61	445.02	446.25	614.23	587.04	604.58

<sup>a</sup> Notes: 'Price' is in thousands of 1994 euros. 'Market Share' is the per cent share of cars sold in the respective category. 'Margin' is the Lerner margin defined as  $(p - \hat{c})/p$  where  $\hat{c}$  is the estimated marginal cost and price ( $p$ ) includes any applicable import tariffs. 'Profit' is measured in millions of 1994 euros. See Figure 4 for the evolution of estimated price-cost margins across the decade. Statistics are weighted by quantity sold where relevant and correspond to the Volkswagen group and therefore include the brands Audi, SEAT, Skoda, and Volkswagen. 'No TDI' and 'No Rival TDI' counterfactual equilibria are described in the text.

where  $(\pi_t^{\text{No TDI}}, \pi_t^{\text{No Rival TDI}}, \pi_t^{\text{Benchmark}})$  are the period  $t$  Volkswagen profits when all firms which offer diesel vehicles use the old diesel technology, rival firms which offer diesels are restricted to use the old diesel technology but Volkswagen diesels use the TDI technology, and the estimated equilibrium, respectively. From Table IV we observe that  $\pi_t^{\text{No TDI}} < \pi_t^{\text{Benchmark}} < \pi_t^{\text{No Rival TDI}}$  so as this fraction converges to one (zero), the conclusion is that Volkswagen was able to capture all (none) of the potential profits from the TDI. This metric therefore provides a simple measuring stick to evaluate the impact of imitation on firm profits.

I plot 'rent capture' across the decade in Figure 6. When the TDI technology was new in 1993, Volkswagen was able to capture 28.6% of the potential profits from the TDI. Entry of turbodiesel models by FIAT, PSA, Ford, Renault, and Rover in 1994 (Table I), however, increased competition among diesel vehicles and eroded VW's rent capture significantly (from 28.6% to 16.9%). By the end of the decade, Volkswagen was only able to capture 12.5% of potential profits. Thus, competition brought on by the market entry of rival turbodiesels dominated growth in consumer demand for diesels (via  $\hat{\beta}_{\text{Diesel-x-Trend}} > 0$ ) and consumer income (Figure 2). When I recompute rent capture using total equilibrium profits across decade, I estimate that Volkswagen was able to capture only 13.8% of the potential profits from its technological innovation. I conclude that imitation by rival

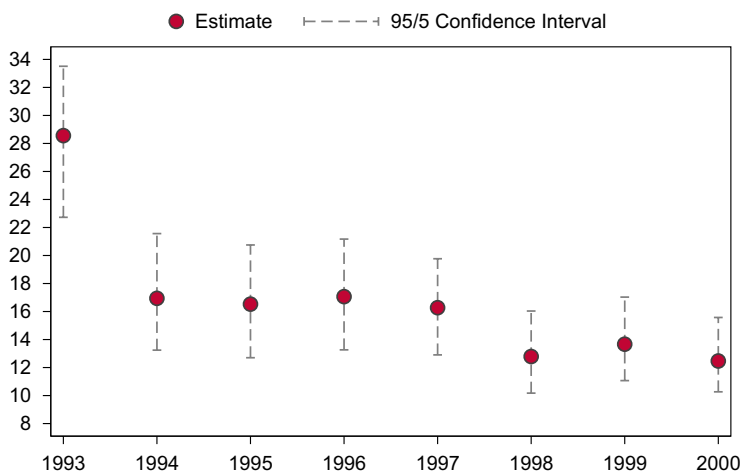


Figure 6

#### Volkswagen Rent Capture across the Sample

Notes: Figure presents 'rent capture' over the sample using definition (14). Rent capture is not defined in 1992 (i.e.,  $\pi_{t=1992}^{\text{No Rival TDI}} = \pi_{t=1992}^{\text{No TDI}}$ ) and has been therefore excluded. Confidence intervals (dashed lines) based on bootstrap simulation (N = 1,000) following the procedure outlined in Appendix VII. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

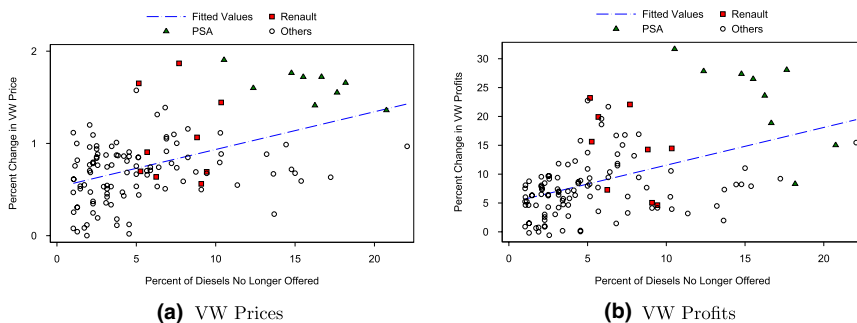


Figure 7

Imitation, Business Stealing, and Static Efficiency

*Notes:* Panels (a) and (b) present the change in VW average retail price and profit, respectively, as a function of the diesel offerings of rival firms. For each observation I begin from the observed product portfolios, remove a rival firm’s line of diesel automobiles, and recompute the pricing equilibrium. The x-axis is the per cent reduction in diesel models available to consumers. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

firms limited TDI profits significantly and this effect increased steadily over the decade.

When goods are differentiated and firms are heterogenous the impact of imitation likely varies significantly across firms. I evaluate this hypothesis by looking at the impact of firm-level imitation on Volkswagen profits where for each rival firm I remove the firm’s diesel fleet in a given year and recompute the pricing equilibrium. I present the equilibrium effect of firm-level imitation on Volkswagen prices (panel a) and profits (panel b) in Figure 7.

From panel (a) we observe that removing a random rival firm’s diesel portfolio decreases options for consumers and would have enabled Volkswagen to increase retail prices 0.77% on average though the impact varies widely across firms. Imitation by PSA and Renault had much larger effects on Volkswagen price (1.63% and 1.05%, respectively) than imitation by FIAT and Ford (0.71% and 0.90%, respectively) while the introduction of turbodiesels by Asian automakers had negligible effects. In terms of profits (panel b), we again see that firms which invested heavily in turbodiesels (largely European automakers) tended to have a larger negative impact on Volkswagen’s profits though again there is significant variation across firms. I estimate that removing a PSA diesel vehicle from the marketplace in 1992 would have increased Volkswagen profits €1.6 million, or roughly twice the average impact of removing a Renault turbodiesel model (€880 thousand).<sup>32</sup> As the popularity of turbodiesels grew across the decade, so did the impact of imitation: removing a PSA turbodiesel in 2000 would

<sup>32</sup> See Figure C.3 in the Appendix.

have, on average, increased Volkswagen profits by €5.6 million while removing a Renault turbodiesel would have increased Volkswagen profits €2.6 million on average. Interestingly, firms like FIAT and Ford which both had large turbodiesel portfolios (Table I) but I find that their products had relatively small impacts on Volkswagen profits. Thus, Volkswagen was able to differentiate its turbodiesel fleet from these competitors but not from PSA or Renault. Similarly, those Asian manufacturers which did invest in diesels had negligible impacts on Volkswagen's bottom line.

#### VI(ii). *Imitation and Dynamic Efficiency*

Thus far I have demonstrated that imitation had a significant negative effect on Volkswagen profits but this does not necessarily mean that imitation made the TDI an *ex post* poor investment. In this section I build a simple model of innovation to fix ideas about the trade-off facing an innovating firm as well as to test whether the TDI was still a good investment for Volkswagen despite this significant level of imitation.

Define  $\Pi(x,s)$  as profits of a firm which sells a product of quality  $x$  and faces competitors who sell products of quality  $s = \{s_1, \dots, s_{F-1}\}$  where  $F$  is the total number of firms. I assume  $\Pi$  is increasing in  $x$  (i.e., the product quality produced by the innovating firm) and decreasing in the product quality of the competition.<sup>33</sup> The innovating firm can choose to invest in a new technology  $x' > x$  but doing so requires a one-time development cost of  $\kappa > 0$ . Similarly, a rival firm  $f$  can invest to imitate the innovating firm's technological innovation so that  $s'_f > s_f$ . The pay-offs for the innovating firm which decides whether to innovate ( $V^I$ ) or not ( $V^N$ ) are

$$(14) \quad V^I(x,s) = \pi(x',s) + \delta \int V(x',s') dH(s'|x',s)$$

$$(15) \quad V^N(x,s) = \pi(x,s) + \delta V(x,s),$$

where  $V(x,s)$  is the innovating firm's continuation value discounted by  $\delta > 0$  and  $H$  is the imitation risk which the innovating firm perceives. In (14) there are two important forces. First, there is a first-mover advantage for the innovating firm, via  $\pi(x',s)$ , which increases the returns to the innovation. On the other hand, imitation risk (via  $H$ ), the second force, drives down the firm's future profits. If the firm chooses not to undertake the project (Equation 15), I assume product qualities do not change, so period profits are fixed. The innovating firm chooses to undertake the project if and only if

<sup>33</sup> For example, under Dixit-Stiglitz preferences the product qualities of the competition collapses into a single measure of competition, the price index, so when the competition increases the quality of their products, the price index falls leading to less profits for the innovating firm.

$$(16) \quad V^I(x,s) - \kappa \geq V^N(x,s)$$

so the innovating firm also accounts for the cannibalization of profits under its current technology. Equation (16) demonstrates that firms undertake projects which generate sufficient net profit to cover the cost of research and development. Thus, a product may face significant risk of imitation leading to reductions in  $V^I$  and a low ‘rent capture’ statistic but is nonetheless a worthwhile investment.

The project is valued by society (under marginal cost pricing) when

$$(17) \quad CS^I(s) - \kappa \geq CS^N(s)$$

where  $CS(s)$  corresponds to aggregate consumer surplus under industry state ( $s$ ).<sup>34</sup> I call an equilibrium *dynamically efficient* when a project valued by society (Equation 17) is undertaken (Equation 16). Consider the case when a project is valued by society. Dynamic efficiency is attained whenever an innovator believes it can extract sufficient surplus from its innovation to make the project worthwhile. Conversely, a project may not be undertaken but nonetheless be valued by society (i.e., a dynamically inefficient equilibrium) when the firm cannot extract sufficient rents from its innovation due to the firm’s perceived imitation risk by its rivals (i.e.,  $H$ ).

I use the estimated model to generate *ex post* estimates for  $V^I$  and  $V^N$  in order to test whether the TDI amounted to a good investment, at least *ex post*. I begin with the estimate of the *ex post* value of the TDI technology to Volkswagen,  $V^I$ . In Figure 8, I document the growing importance of diesels to Volkswagen and the European rivals who imitated the technology. From panel (a) there is significant growth in diesel profits for all firms across the decade. I estimate that Volkswagen profits from diesel vehicles amounted to €923 million in 2000, or roughly 13x the profit generated by diesels in 1992. Over the decade, I estimate the Volkswagen group generated €3.6 billion in profit from its diesel portfolio alone.

While some of this is due to growth in the Spanish market overall, in panel (b) I document that diesels also become the dominant profit source for both Volkswagen and its rival European firms by the end of the decade. This indicates that not only did both diesel and overall profits increase as the market grew but also that the growth of the diesel segment proved an important driver for that growth.

Pinning down a value for  $V^N$ , the profits Volkswagen would have achieved had it not introduced the TDI, is difficult since this requires the researcher to take a stand on what the product set would have looked like in this alternative reality. As the model is static and there are several possibilities to

<sup>34</sup> In principle, changes in consumer surplus from an innovation could account for externalities (e.g., vehicle emissions) and taxation required to fund preferential taxes or R&D subsidies given to firms.



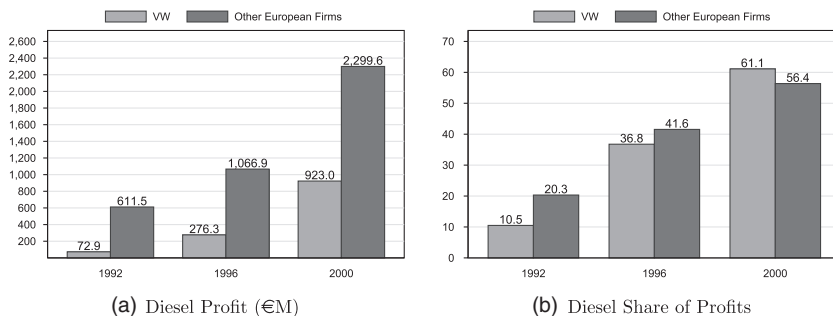


Figure 8  
Importance of Diesels

consider, I consider two reasonable counterfactual equilibria. In the first counterfactual equilibrium I eliminate all diesel vehicles and recompute the pricing equilibrium each year. I call this equilibrium ‘No Diesels’ and argue that it is a good approximation for  $V^N$  in the event that without the TDI technology diesel vehicles would have disappeared from the marketplace perhaps due to their inability to compete profitably with the quieter, reliable, and fuel-efficient gasoline-powered imports produced by Asian automakers. In the second counterfactual equilibrium, I use the ‘No TDI’ counterfactual equilibrium from earlier which is a good approximation for  $V^N$  in the event firms would have chosen to increase the number of diesel vehicles independent of the TDI technology, presumably to take advantage of preferential fuel taxes and vehicle emissions policies.<sup>35</sup>

I compare Volkswagen profits in the estimated equilibrium ( $V^I$ ) to Volkswagen profits had the TDI never existed ( $V^N$ ) in Table V. *Ex post*, the TDI was a very successful innovation for Volkswagen despite the large scale imitation by its rivals. When I eliminate diesels altogether, total Volkswagen profits fall by €2.6 billion over the decade (i.e.,  $V^I - V^{\text{No Diesels}}$ ). Constraining consumer demand for the engines but maintaining growth in the number of diesels with the old Perkins technology implies that Volkswagen profits would have fallen €2.1 billion during the period (i.e.,  $V^I - V^{\text{No TDI}}$ ). In both scenarios, I observe the profits attributable to the TDI grew over the decade despite the corresponding growth in rival turbodiesels.

I therefore estimate the value of the TDI (i.e.,  $V^I - V^N$ ) to be €2.1 to €2.6 billion in the Spanish market alone. Moreover, the tight 95/5 confidence intervals (in brackets) in Table V indicate the estimated value is robust to estimation errors in demand and supply. Extending the analysis to the rest

<sup>35</sup> See Miravete *et al.* [2018] for estimates of the value of pro-diesel fuel taxation and vehicle emissions policies to European firms.

TABLE V  
VALUE OF TDI TECHNOLOGY

Year	$V^I$	$V^N$	
		No Diesels	No TDI
1992	694.23 [579.33, 783.55]	654.45 [548.63, 733.97]	694.23 [579.33, 783.55]
1993	522.05 [435.87, 588.57]	490.37 [429.69, 535.97]	504.20 [420.89, 569.76]
1994	617.51 [511.00, 698.86]	532.02 [463.37, 580.16]	570.52 [471.39, 647.08]
1995	653.25 [543.22, 737.33]	537.10 [481.02, 579.33]	566.62 [468.78, 641.38]
1996	751.51 [624.40, 847.41]	620.42 [594.42, 637.19]	597.85 [494.65, 676.7]
1997	919.99 [768.65, 1037.2]	582.20 [530.21, 621.2]	655.92 [543.76, 744.65]
1998	1,164.65 [974.27, 1312.88]	710.20 [671.69, 742.11]	810.59 [676.24, 914.09]
1999	1,376.52 [1154.57, 1555.53]	758.43 [700.93, 805.9]	868.51 [725.42, 981.07]
2000	1,510.03 [1262.07, 1705.14]	696.88 [619.00, 762.03]	889.96 [734.14, 1007.15]
Total	8,209.74 [6856.85, 9254.10]	5,582.06 [5054.66, 5981.78]	6,158.40 [5112.93, 6952.07]

Notes:  $V^I$ ,  $V^N$  correspond to the total estimated profits (diesel plus gasoline models) to the Volkswagen group measured in millions of 1994 euros in the estimated equilibrium and counterfactual environment without the TDI, respectively. 95/5 confidence intervals [in brackets below corresponding estimate] are based on bootstrap simulation ( $N = 1,000$ ) following the procedure outlined in Appendix VII.

of Europe would only increase the TDI’s estimated value as would increasing the time horizon. Thus, I conclude the TDI was a successful technology, at least *ex post*, provided the fixed cost of development ( $\kappa$ ) was not enormous.<sup>36</sup>

How was Volkswagen able to recover its investment in the TDI despite significant imitation? In Figure 9, I present the total number of vehicles sold in Spain across the three equilibria considered in Table V. The figure

<sup>36</sup> I am unaware of fixed cost estimates for Volkswagen to develop the TDI. As a point of reference, however, the estimated fixed cost to build CERN’s Large Hadron Collider, the largest and most complex machine ever built, is €4.6 billion (source: *Agence Science-Presse*. ‘LHC: Un (très) petit Big Bang.’ Lien Multimédia. December 7, 2009).

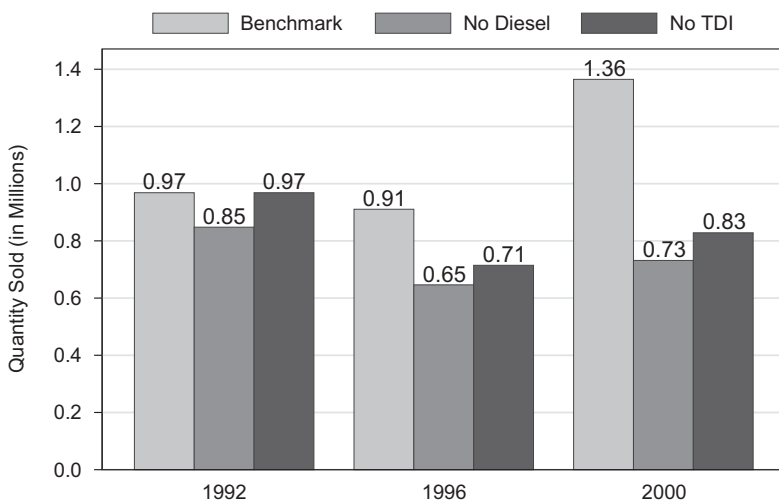


Figure 9  
Imitation and Market Size

Notes: Statistics represent total new vehicle sales in the Spanish auto industry (in millions). 'Benchmark' corresponds to the data. The 'No Diesel' and 'No TDI' counterfactual equilibria correspond to the equilibria from Table V.

clearly shows that total market size shrinks under both counterfactual equilibria. The TDI's introduction therefore increased the size of the Spanish new car market as turbodiesels increased consumers' willingness to buy new vehicles even after controlling for changes in incomes.<sup>37</sup> Thus, the market was able to support both innovation and significant levels of imitation because the TDI increased the size of the pie while product differentiation enabled firms to each secure a sufficient piece. More generally, the results suggest that differentiated goods markets may still be dynamically efficient (i.e., promote investment in new goods) even with significant imitation risk as these markets provide the innovator an opportunity to secure future profits by differentiating its products horizontally.

Finally, it is important to note that (14) does not constrain the relationship between firm's perceptions ( $H$ ) and the data generating process; therefore perceptions need not be 'correct' (Pakes, Porter, Ho and Ishii [2015]). Consequently, my analyses (and conclusions) allow for Volkswagen's investment in the TDI to be a poor decision *ex post*, or equivalently just observing innovation is not sufficient to conclude it was a worthwhile investment *ex ante*. This means that my results can be interpreted in two ways. First, if Volkswagen did indeed correctly perceive the imitation of the TDI by its

<sup>37</sup> One could also evaluate the TDI's welfare implications for consumers as in Petrin [2002] for the minivan. Akerberg and Rysman [2005], however, point out that such calculations over-estimate the value of new goods in models with unobserved product differentiation.

rivals, my results would indicate that innovation occurred in this industry even though rampant imitation was expected. On the other hand, if the scale of imitation caught Volkswagen management by surprise, the popularity of the innovation was sufficient to benefit all firms. In my case, these stories are indistinguishable but understanding the implications of each is an important research area – particularly for the role of business uncertainty and innovation (e.g., Bloom [2009]).

## VII. CONCLUDING REMARKS

The objective in this paper was to evaluate the impacts of imitation to dynamic and static efficiency in a differentiated goods market. I do so via the study of a new diesel engine technology in the European auto industry – the TDI. The estimated model of consumer demand for differentiated products allows for flexible substitution patterns while the oligopoly pricing model increases identification of price elasticities. As the estimated model generates reasonable estimates and substitution patterns, I use it to evaluate the equilibrium effects of imitation on firm pricing, profits, and consumer demand via a series of counterfactual experiments.

I find that widespread imitation of the TDI by European auto makers due to the technology's generality led to significant price competition. The amount of business stolen by these firms was substantial and limited Volkswagen to capturing only 14% of the potential profits from the TDI. I also find that the firm's ability to differentiate its diesel models horizontally enabled it to generate a significant amount of profit, likely making the R&D investment required to introduce the TDI worthwhile. Thus, imitation benefited consumers by simultaneously increasing the number of products in the consideration set and decreasing retail prices while product differentiation enabled the innovator to carve out a sufficient market niche to maintain significant profits for its innovation. I conclude that, at least for the TDI, the market delivered an equilibrium which was both dynamically and statically efficient without government intervention (i.e., without the aid of patents). Moreover, my results indicate that in mature industries such as automobiles, economists should think of product differentiation specifically, or a brand more generally, as an important component of technological progress.

My results suggest two interesting avenues for future research. First, it would be interesting to see whether my results – an *ex post* analysis of a particular innovation – extend more generally to other differentiated goods markets. Second, the mere fact that Volkswagen undertook the investment in the TDI indicates the firm believed the TDI was a worthwhile investment *ex ante*. As my results indicate the innovation's value was worthwhile *ex post* despite widespread imitation, it would be interesting to investigate the

set of firm beliefs about the evolution of the market consistent with investing in the TDI. Doing so, however, would require modeling the automobile industry as a dynamic game among competing multi-product firms – a difficult task.

#### APPENDIX A

This appendix presents the different sources of data used in the estimation and discusses why the sales of most Asian vehicles during the 1990's are considered imports despite some being partially built in Europe.

##### *A.1. 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.<sup>38</sup> The outside option varies significantly during the 1990's due to the important recession between 1992 and 1994 and the very fast growth of the economy and population (immigration) in the second half of the decade. I also use these consumer surveys to set the size of the outside option for each year in our sample which I compute as the total number of households minus the total number of new car registrations. Starting with 1992, the outside market share  $s_{0t}$  is: 0.92, 0.94, 0.93, 0.93, 0.93, 0.92, 0.91, 0.89, and 0.89, respectively.

I also obtained fuel prices from INE. I use Spanish steel prices, SPI, from the 2001 edition of *Iron and Steel Statistics – Data 1991-2000* published by the European Commission (Table VIII.I).

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

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

<sup>38</sup> See <http://www.ine.es/jaxil/menu.do?L=1&type=pcaxis&path=/t25/p458&file=inebase> for a description of these databases.

APPENDIX TABLE A1  
 JAPANESE MODELS PRODUCED IN THE E.U

Toyota*	Nissan	Nissan	Honda	Mitsubishi**
(UK)	(UK)	(Spain)	(UK)	(Netherlands)
Carina (1992-1996)	Primera (1992-2000)	Patrol (1992-2000)	Accord (1992-2000)	Carisma (1992-2000)
Avensis (1997-2000)	Micra (1992-2000)	Terrano (1992-2000)	Civic (1994-2000)	Space Star (1998-2000)
Corolla (1997-2000)	Almera (1998-2000)	Serena (1997-2000)		
		Almera (1999-2000)		
		Other Light Vehicles		

Notes: (\*) Production in France started in 2001; (\*\*) Mitsubishi also produced in Spain but only manufactured trucks and engines. In the Netherlands, Mitsubishi produced in a joint venture with Volvo. Source: Japan Automobile Manufacturers Association.

levels. European imports paid tax duty of 4.4% in 1992, and nothing thereafter. Non-European manufacturers had to pay 14.4% and 10.3%, respectively. Thus, for the estimation of the equilibrium random coefficient discrete choice model of Table III I distinguish between prices paid by consumers ( $p$ ) and those chosen by manufacturers ( $p^m$ ).

The other relevant factor that changes during the 1990's is the ownership structure of automobile firms. During this decade *Fiat* acquired Alfa Romeo and Lancia; Ford acquired Volvo; and GM acquired Saab. BMW acquired Rover in 1994 but sold it in May, 2000 (with the exception of the 'Mini' brand) so these are treated as separate firms. Table C.I describes the ownership structure at the beginning and end of the decade.

### *A.2. Japanese Automobile Sales in Europe*

In the analysis I treat all Japanese production as imported even though some models were produced in the E.U. even before the beginning of our sample. Thus, for instance, Nissan established in the U.K. in 1984 and Toyota and Honda in 1989. There are three observations: (i) Most Japanese vehicles sold in the European automobile market during the 1990's were imported from Japan, (ii) Out of those produced in Europe, many were light trucks not included in the sample, and (iii) those produced in Europe could not avoid paying import tariffs because local value added was considered too low to qualify as domestic production by European rules until year 2000.

During the 1990's Japanese automakers tried to avoid EU import tariffs through the establishment of factories in the U.K. and later in partnership with other manufacturers in a strategy known as 'Transplant Japanese Production.' To avoid import tariffs, Japanese firms had to demonstrate that their models contained a sufficient amount of 'local content.' In France, Italy, Portugal, and Spain this amounted to 80% of value added that had to be from European sources – a stringent standard set at the request of European automakers.<sup>39</sup> In the U.K. and Germany, a threshold of 60% was accepted as appropriate. Seidenfuss and Kathawala [2010] document that these demanding requirements were active until 1999.

Table A.I presents car models manufactured by Toyota, Nissan, Honda, and Mitsubishi, the most important Japanese firms in Europe at the time, e.g. Kato [1997]. The UK was the country where more Japanese passenger models were produced. As the UK Government was less demanding in the application of the 'local content' requirement, most of the production was also sold there. Before year 2000, when these models were sold in Spain, they had to face the European import tax duty rate – generally 10.3%

<sup>39</sup> This local content commitment by Japanese firms in the E.U. is far higher than corresponding amount in the U.S.A., see Hyun [2008].

during the sample. In any case, the share of Japanese produced vehicles in Europe is very small – see [Miravete *et al.* [2018], Appendix A].

APPENDIX B

In this appendix I outline the algorithms I use to solve for the equilibrium prices in each counterfactual experiment and the confidence intervals.

*B.1. Solving for Counterfactual Automobile Prices*

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

$$(18) \quad \max_{\{p_j^w\}} \sum_{j \in J^f} (p_j^w - c_j) \times Ms_j,$$

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

$$(19) \quad s_j + \sum_{r \in J^f} (p_r^w - c_r) \times \frac{\partial s_r}{\partial p_j^w} = 0.$$

Optimality requires that Equation (19) holds for all products in period  $t$ . I express the set of firm  $f$  first-order conditions in matrix notation as:

$$(20) \quad s + \Delta \times (p^w - c) = 0,$$

where an element of the matrix  $\Omega$  is defined as:

$$(21) \quad \Omega_{jr} = \begin{cases} -\frac{\partial s_j}{\partial p_r^w}, & \text{if } \{j,r\} \subset J^f, \\ 0 & \text{otherwise.} \end{cases}$$

For a given vector of marginal costs  $c$ , I Use (20) to find the fixed point to the system of equations – a common practice in the literature dealing with this class of models. To my knowledge there exists no proof of convergence or uniqueness for this contraction operator and fixed point in models with multi-product firms. My experience (as is common) is that convergence is monotonic and proceeds quickly. Further, starting from different starting values yields an identical result.

*B.2. Confidence Intervals*

I constructed the 95% confidence intervals in Section VI via bootstrap simulation using the point estimates and standard errors for the demand and



cost parameters (Table III) to construct a random sample ( $N = 1,000$ ) of demand and cost estimates. To ease computation, I restricted the bootstrap to be over the nonlinear parameters  $\{\alpha, \Sigma, \rho\}$ . For each bootstrap sample  $n = 1, \dots, 1000$ ; I begin with a set of parameters drawn from the empirical distributions defined by Table III. Define  $\tilde{\theta}_n = \{\alpha_n, \Sigma_n, \rho_n\}$  as the bootstrap parameters for sample  $n$  where I restrict the vector of random coefficients ( $\Sigma_n$ ) to be greater than zero. I then recover the remaining parameters  $\{\beta_n, \gamma_n\}$  following the solution method outlined in Section V.<sup>40</sup> Consequently, each bootstrap simulation  $n$  generates predicted market shares which match the data by construction.

For each sample  $n$  and year  $t$  I then repeat each counterfactual experiment (e.g., ‘No TDI’) using the parameter vector  $\{\alpha_n, \Sigma_n, \rho_n, \beta_n, \gamma_n\}$ . The final product is a large set of equilibria which vary by experiment and beginning parameter vector:  $\{\alpha_n, \Sigma_n, \rho_n, \beta_n, \gamma_n\}$ . The confidence intervals presented are based on computing the relevant statistic for each counterfactual equilibrium considered where I construct the 95% confidence interval for each year as the range between the 2.5% and 97.5% quartiles, i.e., the middle 95%.

#### APPENDIX C

In this appendix I present additional results referenced in the paper.

##### *C.1. Additional Descriptive Statistics*

Figure C.1 presents quantity sold of diesel and gasoline vehicles by different brands.

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

The other relevant factor that changes during the 1990’s, as previously mentioned, is the ownership structure of automobile firms. During this decade FIAT acquired Alfa Romeo and Lancia; Ford acquired Volvo; and GM acquired Saab. BMW acquired Rover in 1994 but sold it in May, 2000 (with the exception of the ‘Mini’ brand) so these are treated as separate firms. Table C.I describes the ownership structure at the beginning and end of the decade.

<sup>40</sup> First solve for the mean utilities  $\delta(\tilde{\theta}_n)$  such that bootstrap sample  $n$  generates predicted shares equal to those observed in the data. I then recover mean utility demand  $\beta(\theta_n)$  and cost  $\gamma(\theta_n)$  parameters via linear projection.

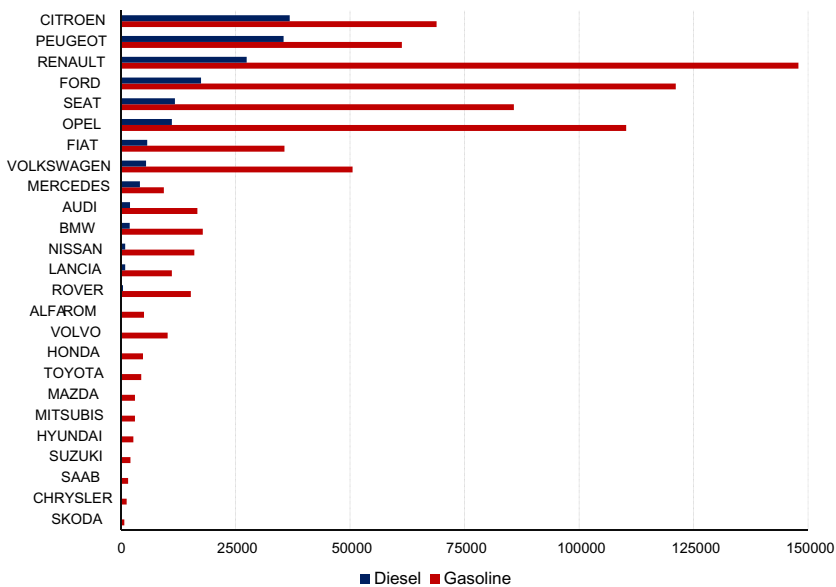
APPENDIX TABLE CI  
AUTOMOBILE GROUPS: 1992 vs. 2000

Firm	Year 1992			Year 2000		
	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	-	Volkswagen	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

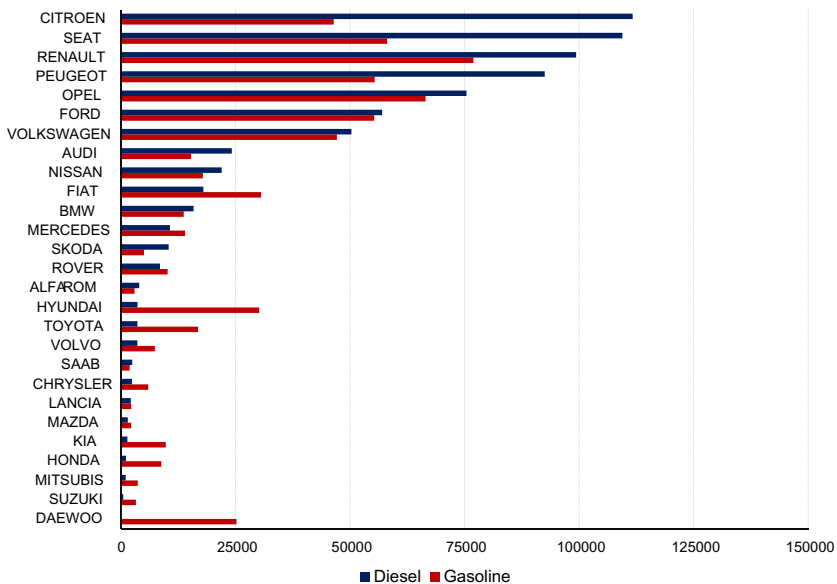
Notes: Sales of vehicle by manufacturer and fuel type. ‘Owner’ indicates the name of the automobile group with direct control over production and pricing. Those without a group are all non-European manufacturers and defined as NON-EU in the analysis.

*C.2 An Alternative Value of the TDI*

In this section I repeat the analysis of Section VI but replace the ‘No TDI’ and ‘No Rival TDI’ counterfactual equilibria where diesel vehicles disappear from the marketplace due to either regulation or competition from the



(a) Year 1992



(b) Year 2000

Figure C1

Sales by Firm and Type of Engine [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

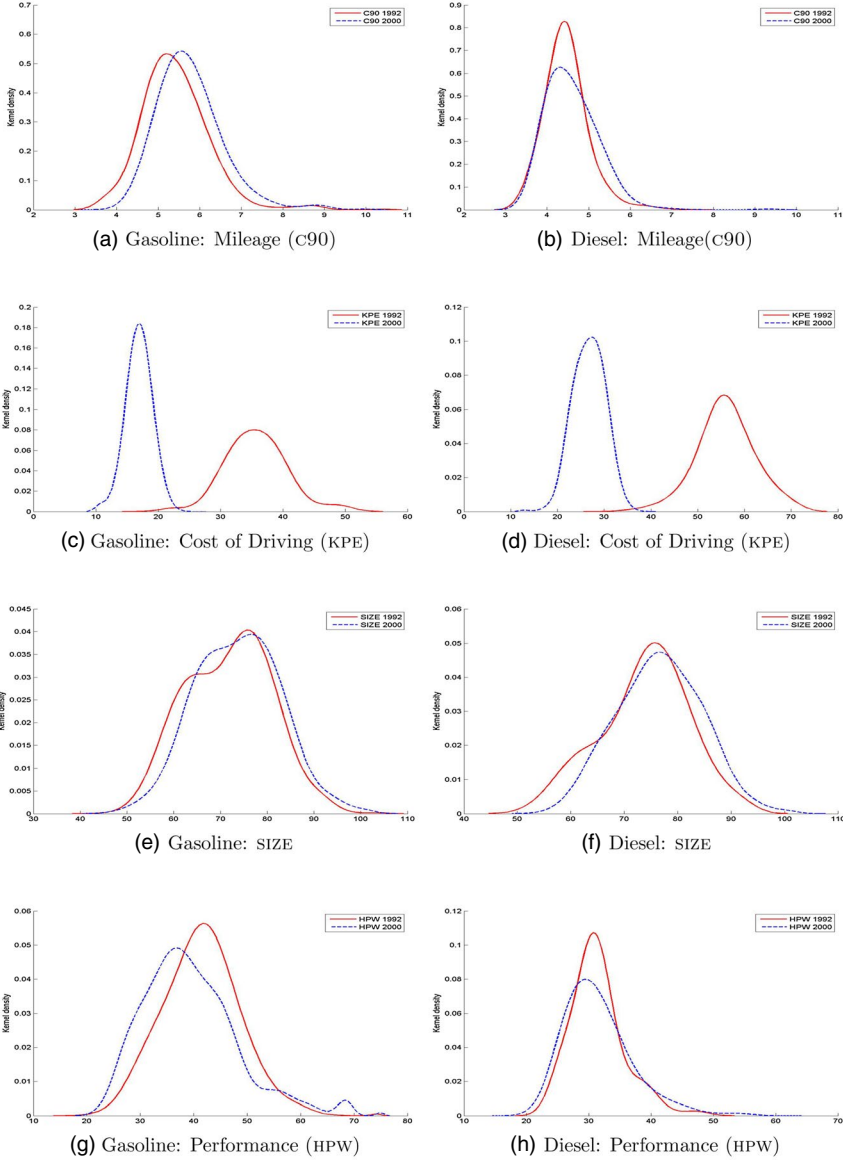


Figure C2  
Change in the Distribution of Automobile Attributes [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

TDI. In the first experiment I consider the equilibrium where diesels are either not allowed by regulators or were simply never developed by any automobile manufacturer.<sup>41</sup> I call this experiment ‘No Diesel’ and use it to evaluate the value of diesels in general. Interestingly, in this experiment the European auto market comes closest to replicating market shares in the North American market where diesel vehicles maintained a negligible market share during this period. I consider this equilibrium a more extreme version of the ‘No TDI’ equilibrium presented in the main text.

In the second experiment, I consider the equilibrium in which Volkswagen successfully defends its intellectual property and remains the sole producer of this next generation technology. For simplicity I assume that other automakers choose to remove their legacy diesel passenger cars entirely from the product choice set since the advancements of the TDI in terms of performance made these vehicles uncompetitive.<sup>42</sup> Volkswagen (including its affiliate brands) is therefore the sole provider of diesel vehicles. These results are presented in the column labeled ‘Monopoly.’ I consider this equilibrium a more extreme version of the ‘No Rival TDI’ equilibrium presented in the main text.

From Table C. II we see that the qualitative results line-up with those presented in Section VI, though the magnitudes are of course larger. Similar to the main text, define period  $t$  rent capture as

$$(22) \quad \text{Rent Capture} \equiv \frac{\pi_t^{\text{Benchmark}} - \pi_t^{\text{No Diesel}}}{\pi_t^{\text{Monopoly}} - \pi_t^{\text{No Diesel}}}$$

where  $(\pi_t^{\text{No Diesel}}, \pi_t^{\text{Monopoly}}, \pi_t^{\text{Benchmark}})$  are the period  $t$  Volkswagen profits when diesels disappear from the market; Volkswagen is the only firm which sells diesels, and the estimated equilibrium, respectively. Rent capture under this definition is 13.4% across the decade and follows a similar pattern as Figure 6.

### C.3. Firm-Level Imitation

In Figure C.3 I present the increase in Volkswagen profits from removing a diesel vehicle from the PSA and Renault portfolios.

In Figure C.4 I evaluate firm-level imitation using the counterfactual environment in which Volkswagen is the sole provider of diesel vehicles as benchmark. There exists a strong linear relationship (dashed blue line) and a large degree of heterogeneity across firms, led by PSA and Renault. Firm-level imitation of the TDI leads to a 1.84% average decline in Volkswagen price with Renault (4.33%) and PSA (5.60%) again playing the role of

<sup>41</sup> For example, due to strict standards regarding nitrogen oxide emissions. See Miravete *et al.* [2018].

<sup>42</sup> While this assumption may be strong, I remind the reader that diesel passenger cars were a niche product in the European marketplace before the introduction of the TDI.

APPENDIX TABLE CII  
VALUE OF TDI TECHNOLOGY TO VOLKSWAGEN

	1992				2000			
	No Diesel	Data	Monopoly	No Diesel	Data	Monopoly	No Diesel	Monopoly
<i>Prices</i> (€ Thousand)	11.56	11.71	12.99	14.80	16.30	27.81		
Diesel	-	12.86	17.68	-	16.87	33.78		
Gas	11.56	11.56	11.62	14.80	15.44	15.49		
<i>Market Share</i> (%)	18.99	17.79	22.87	19.14	22.31	41.98		
Diesel	-	11.90	100.00	-	25.11	100.00		
Gas	18.99	18.97	18.67	19.14	19.05	19.11		
<i>Margin</i> (%)	40.46	39.57	42.62	37.03	33.35	55.06		
Diesel	-	32.78	48.94	-	31.94	63.81		
Gas	40.46	40.42	40.78	37.03	35.50	37.01		
<i>Profit</i> (€ Million)	654.45	694.23	1,002.11	696.88	1,510.03	6,370.43		
Diesel	-	72.88	364.12	-	922.99	5,696.73		
Gas	654.45	621.36	637.98	696.88	587.04	673.70		

*Notes:* 'Price' is in thousands of 1994 euros. 'Market Share' is the per cent share of cars sold in the respective category. 'Margin' is the Lerner margin defined as  $(p - \hat{c})/p$  where  $\hat{c}$  is the estimated marginal cost and price ( $p$ ) includes any applicable import tariffs. 'Profit' is measured in millions of 1994 euros. See Figure 4 for the evolution of estimated price-cost margins across the decade. Statistics correspond to the Volkswagen group and therefore include the brands Audi, SEAT, Skoda, and Volkswagen.

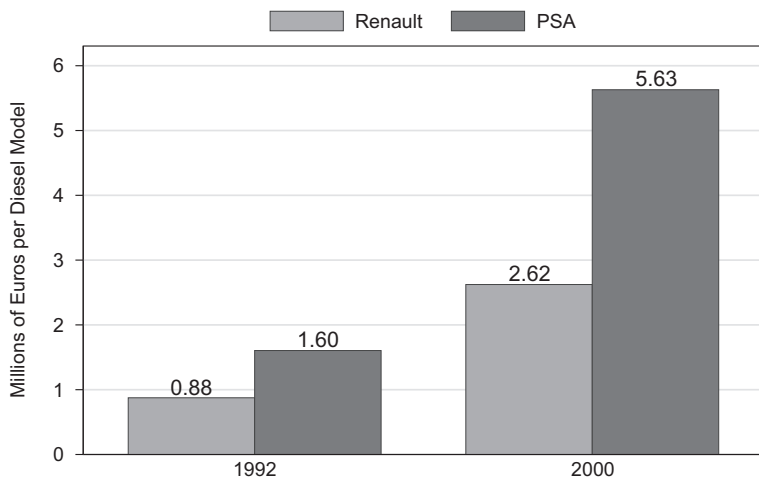


Figure C3  
Business Stealing by EU Firms

Notes: Statistics correspond to the value of foregone Volkswagen profits (in 1994 euros) per diesel model introduced by the Renault and PSA. The reported statistic is the increase in Volkswagen profits divided by the total number of diesel vehicles removed.

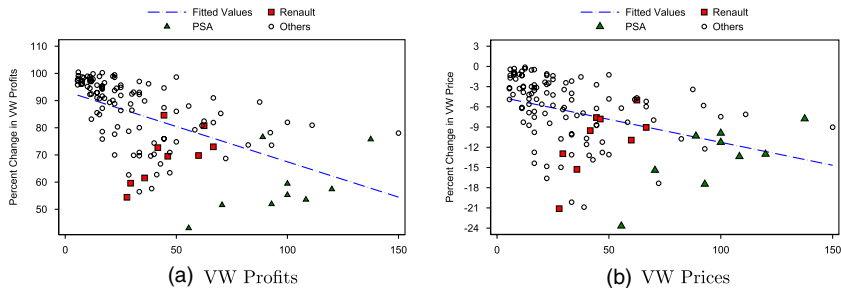


Figure C4

#### Imitation, Business Stealing, and Static Efficiency

Notes: Panels (a) and (b) present the change in VW profits and average retail prices, respectively, as a function of the diesel offerings of rival firms. For each observation I begin from the counterfactual world in which VW has a monopoly and add the corresponding rival firm's observed diesel models. The x-axis is the per cent increase in the total number of diesel vehicles available to consumers. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

outlier. In comparison to Figure 7, the impact on Volkswagen profits and retail prices are much larger. This indicates a decreasing marginal impacts of imitation where the largest impact on equilibrium prices and profits occurs with the initial imitators.

## REFERENCES

- Akerberg, D. A. and Rysman, M., 2005, 'Unobserved Product Differentiation in Discrete-Choice Models: Estimating Price Elasticities and Welfare Effects,' *RAND Journal of Economics*, 36 (4), pp. 771–788.
- Aghion, P.; Harris, C.; Howitt, P. and Vickers, J., 2001, 'Competition, Imitation and Growth with Step-by-Step Innovation,' *Review of Economic Studies*, 68, pp. 467–492.
- Balcer, Y. and Lippman, S. A., 1984, 'Technological Expectations and Adoption of Improved Technology,' *Journal of Economic Theory*, 34, pp. 292–318.
- Berry, S. and Jia, P., 2010, 'Tracing the Woes: An Empirical Analysis of the Airline Industry,' *American Economic Journal: Microeconomics*, 2, pp. 1–43.
- Berry, S.; Levinsohn, J. and Pakes, A., 1995, 'Automobile Prices in Market Equilibrium,' *Econometrica*, 63, pp. 841–890.
- Berry, S.; Levinsohn, J. and Pakes, A., 1999, 'Voluntary Export Restraints on Automobiles: Evaluating Strategic Trade Policy,' *American Economic Review*, 89, pp. 400–430.
- Bloom, N., 2009, 'The Impact of Uncertainty Shocks,' *Econometrica*, 77, pp. 623–685.
- Boldrin, M. and Levine, D. K., 2008, *Against Intellectual Monopoly* (Cambridge University Press, Cambridge, England).
- Bresnahan, T. F., 2010, 'General Purpose Technology,' in Hall B. H. and Rosenberg N. (eds.), *Handbook of the Economics of Innovation*, Volume II, (North-Holland Press, Amsterdam, The Netherlands).
- Bronnenberg, B. J.; Dubé, J.-P.; Gentzkow, M. and Shapiro, J. M., 2015, 'Do Pharmacists Buy Bayer? Informed Shoppers and the Brand Premium,' *The Quarterly Journal of Economics*, 130, pp. 1669–1726.
- Chamberlain, G., 1987, 'Asymptotic Efficiency in Estimation with Conditional Moment Restrictions,' *Journal of Econometrics*, 34, pp. 305–334.
- Chug, R.; Cropper, M. L. and Narain, U., 2011, 'The Cost of Fuel Economy in the Indian Passenger Vehicle Market,' *Energy Policy*, 39, pp. 7174–7183.
- Cohen, W. M., 2010, 'Fifty Years of Empirical Studies of Innovative Activity and Performance,' in Hall B. H. and Rosenberg N. (eds.), *Handbook of The Economics of Innovation*, Vol. 1, pp. 129–213, (North-Holland Press, Amsterdam, The Netherlands).
- Cosar, A. K.; Grieco, P. L.; Li, S. and Tintelnot, F., 2018, 'What Drives Home Market Advantage?' *Journal of International Economics*, 110, pp. 135–150.
- Dubé, J.-P.; Fox, J. T. and Su, C.-L., 2012, 'Improving the Numerical Performance of Static and Dynamic Aggregate Discrete Choice Random Coefficients Demand Estimation,' *Econometrica*, 80, pp. 2231–2267.
- Gandhi, A. and Houde, J.-F., 2015, 'Measuring Substitution Patterns in Differentiated Products Industries,' (University of Wisconsin-Madison and Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania, U.S.A.).
- Gilbert, R., 2006, 'Looking for Mr. Schumpeter: Where Are We in the Competition-Innovation Debate?,' in Jaffe, A. B., Lerner J. and Stern S. (eds.), *Innovation Policy and the Economy*, Volume 6, (MIT Press, Cambridge, Massachusetts, U.S.A.).
- Goettler, R. L. and Gordon, B. R., 2011, 'Does AMD Spur Intel to Innovate More?,' *Journal of Political Economy*, 119, pp. 1141–1200.
- Goldberg, P. K. and Verboven, F., 2001, 'The Evolution of Price Dispersion in the European Car Market,' *Review of Economic Studies*, 68, pp. 811–848.
- Greenwood, J., 1997, *The Third Industrial Revolution: Technology, Productivity and Income Inequality* (AEI Press, Washington, D.C., U.S.A.).
- Grigolon, L. and Verboven, F., 2014, 'Nested Logit or Random Coefficients Logit? A Comparison of Alternative Discrete Choice Models of Product Differentiation,' *The Review of Economics and Statistics*, 96, pp. 916–935.



- Hall, B. H., 2009, 'The Use and Value of Patent Rights,' (Intellectual Property Office, U.S. patent & Trademark Office, Alexandria, Virginia, U.S.A.).
- Hansen, L. P., 1982, 'Large Sample Properties of Generalized Method of Moments Estimators,' *Econometrica*, 50, pp. 1029–1054.
- Hyun, J. H., 2008, 'A Comparative Analysis of Transplants and Industrial Location of Japanese and Korean Automotive Industries in Europe,' *International Journal of Business*, 13, pp. 215–235.
- Igami, M., 2017, 'Estimating the Innovator's Dilemma: Structural Analysis of Creative Destruction in the Hard Disk Drive Industry, 1981–1998,' *Journal of Political Economy*, 125, pp. 798–847.
- Kato, M., 1997, 'Japanese Automakers Struggle in Europe,' (NLI Research Institute, Chiyoda-Ku, Tokyo, Japan).
- Knittel, C. R. and Metaxoglou, K., 2014, 'Estimation of Random Coefficient Demand Models: Two Empiricists' Perspective,' *Review of Economics and Statistics*, 96, pp. 34–59.
- Lucas, R. J., 1988, 'On the Mechanics of Economic Development,' *Journal of Monetary Economics*, 22, pp. 3–42.
- Mansfield, E.; Schwartz, M. and Wagner, S., 1981, 'Imitation Costs and Patents: An Empirical Study,' *The Economic Journal*, 91 (364), pp. 907–918.
- Manuelli, R. and Seshadri, A., 2014, 'Frictionless Technology Diffusion: The Case of Tractors,' *American Economic Review*, 104, pp. 1368–1391.
- Miravete, E. J.; Moral, M. J. and Thurk, J., 2018, 'Fuel Taxation, Emissions Policy, and Competitive Advantage in the Diffusion of European Diesel Automobiles,' *RAND Journal of Economics*, 49 (3), pp. 504–540.
- Moral, M. J. and Jaumandreu, J., 2007, 'Automobile Demand, Model Cycle and Age Effects,' *Spanish Economic Review*, 9, pp. 193–218.
- Nevo, A., 2000, 'Mergers with Differentiated Products: The Case of the Ready-to-Eat Cereal Industry,' *RAND Journal of Economics*, 31, pp. 395–421.
- Oster, S., 1982, 'The Diffusion of Innovation among Steel Firms: The Basic Oxygen Furnace,' *Bell Journal of Economics*, 13, pp. 45–56.
- Pakes, A.; Porter, J.; Ho, K. and Ishii, J., 2015, 'Moment Inequalities and Their Application,' *Econometrica*, 83, pp. 315–334.
- Petrin, A., 2002, 'Quantifying the Benefits of New Products: The Case of the Minivan,' *Journal of Political Economy*, 110, pp. 705–729.
- Petrin, A. and Seo, B., 2016, 'Identification and Estimation of Discrete Choice Models when Observed and Unobserved Product Characteristics are Correlated,' manuscript (University of Minnesota, Minneapolis, Minnesota, U.S.A.).
- Reynaert, M. and Verboven, F., 2013, 'Improving the Performance of Random Coefficients Demand Models: The Role of Optimal Instruments,' *Journal of Econometrics*, 178, pp. 83–98.
- Romer, P. M., 1990, 'Endogenous Technological Change,' *Journal of Political Economy*, 98, pp. S71–102.
- Rose, N. L. and Joskow, P. L., 1990, 'The Diffusion of New Technologies: Evidence from the Electric Utility Industry,' *RAND Journal of Economics*, 21, pp. 354–373.
- Rust, J.; Gillingham, K.; Iskhakov, F.; Munk-Nielsen, A. and Schjerning, B., 2016, 'Nonstationary Equilibrium in the Auto Market: Structural Estimation Using Danish Register Data,' working paper (Georgetown University, District of Columbia, U.S.A.).
- Schumpeter, J. A., 1934, *The Theory of Economic Development* (Harvard University Press, Cambridge, Massachusetts, U.S.A.).
- Schumpeter, J. A., 1942, *Capitalism, Socialism, and Democracy* (Harper & Row, New York, New York, U.S.A.).

- Schumpeter, J. A., 1950, *Capitalism, Socialism, and Democracy* (3rd ed.). (Harper & Row, New York, New York, U.S.A.).
- Seidenfuss, K.-U. and Kathawala, Y., 2010, 'Voluntary Export Restraint (VER) without Market Restraints? The Case Study of the Monitoring Agreement (1991-1999) between the Japanese Car Manufacturers and the European Union,' *European Business Review*, 17, pp. 217–231.
- Skrainka, B. S. and Judd, K. L., 2011, 'High Performance Quadrature Rules: How Numerical Integration Affects a Popular Model of Product Differentiation,' working paper, (The Hoover Institution on War, Revolution and Peace, Stanford University, Stanford, California, U.S.A.).
- Waldfogel, J., 2012, 'Copyright Protection, Technological Change, and the Quality of New Products: Evidence from Recorded Music since Napster,' *The Journal of Law & Economics*, 55, pp. 715–740.