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

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Motivation

- Diesels became the dominant engine choice in Europe in a very short period of time:
  - 10% penetration in 1990.
  - 70% penetration by 2000 (in some popular segments).
- Even today diesels are only produced by European firms or the European divisions of some American automobile manufacturers ⇒ *Any evaluation of diffusion policy involves a trade dimension*.
- Generality of diesel technology: It is easily imitated but interestingly, *only by some other European automakers*.
- Unintended consequences of public policies: great initial conditions (*Energy Tax Directive*) and during the early phase of diffusion (*Emission Policy*).

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- How did the spread of diesel vehicles impact prices, quantities, firm profits, emissions, and, more importantly, market share of imports in Europe?
- What was the value of TDI for different agents? (VW, other European and foreign automakers as well as consumers) How much of the innovation rents was VW able to capture?
- Can the lenient European NO_x emission policy help explaining the successful diffusion of diesel automobiles? What would the trade implications of such policy be?

Answering these questions is difficult:

- The automobile industry is not perfectly competitive.
- Vehicles are horizontally differentiated.
- Many relevant product characteristics are most likely unobservable (durability, reliability, torque).
- Demand, supply, and market structure vary across time.
- Fast changing product attributes questions the wisdom of the usual *BLP* identification strategy for this application.

◂ Ownership Structure

Empirical Approach

- Estimate a discrete choice model for horizontally differentiated products (à la BLP95):
  - Price, quantity, product attributes, and demographic data in Spain during the 1990s.
  - Estimation links heterogeneous price responses for different products to demographics and product attributes (Demand).
  - Estimation uses profit-maximization equilibrium conditions to identify marginal costs and markups (Supply).
  - We allow firms to **compete in prices and product attributes** to better account for the evolution of unobserved product features that drive the increasing demand for diesels.
  - Conduct multiple meaningful counterfactuals to address our research questions.

Some Highlights

Results

- *Using optimal IV is time-consuming but produces far more significant estimates, particularly of random coefficients: demand more responsive to prices and attributes than with BLP estimates.*
- *Unobserved product characteristics are not only important in explaining the diffusion of diesel automobiles but also the low market penetration of Asian imports.*
- *Volkswagen captured at least 32% of TDI potential innovation rents.*
- *Imposing US-style emissions standards substantially increases imports. ⇒ Non-EU market share increases from 11% to 19% if diesels did not exist.*
- *We conclude that EU emissions regulation amounted to a significant non-tariff trade barrier. ⇒ Equivalent to a 20% import duty for Spain.*

What is TDI?

Turbo Charged, Direct Injection, Diesel Engine (Audi-WV, 1989):

- The most efficient internal combustion engine available.
- It combines a direct injection pump, a turbo charger, and an intercooler to increase the power while reducing fuel consumption and therefore emissions per gallon.
- Increased performance and higher torque than gasoline engines at low r.p.m. (measurable but not directly observed by potential consumers).
- High durability and reliability, zero smell, and quite low clattering (unobservable to drivers and econometricians).
- An innovation *surprising ignored* by economists.

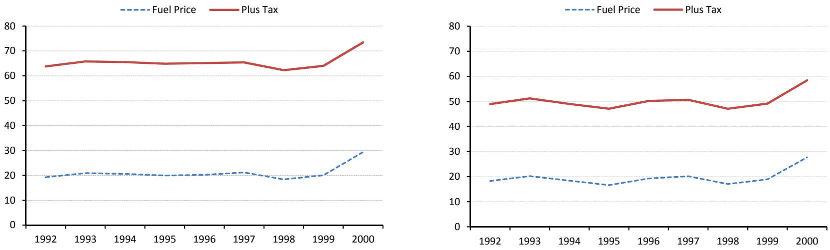
What Made the Diffusion of Diesels Possible?

Almost everything derives from the European Fuel Tax Directive of the 1970s:

- Fuel is taxed by volume and not by energetic content.
- Tax rate of diesels is somewhat lower than gasoline.
- Diesel achieves a market niche by mid 1980s of about 10% mostly among large passenger cars and small commercial vehicles.
- Diesel pumps are available in every gas station.
- There are sufficiently trained mechanics available.
- European did not have catastrophic experiences with early diesels.
- *However* the innovation happens at a time of historically low fuel prices.

Fuel Prices

Figure 2: Fuel Prices Gross and Net of Taxes (1994 Eurocents/liter)



(a) Gasoline (b) Diesel

The Spanish Economy in the 1990s

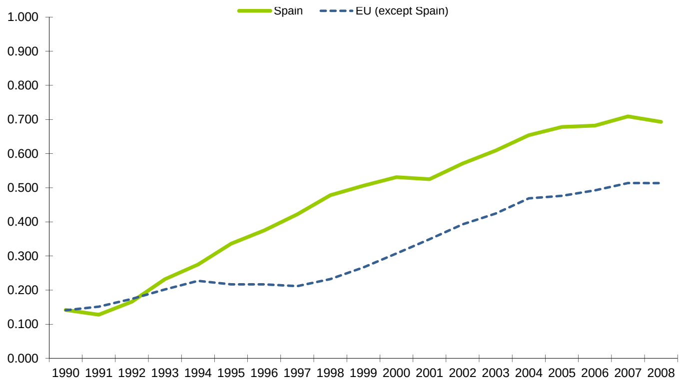
- Transition period of accession to the EU is ending in 1992.
- Strong recession in years 1992 – 1995.
- Unemployment reached 24% in 1994.
- Very strong growth in the second half of 1990s.

The Spanish Automobile Industry in the 1990s

- Fifth largest in the world by output.
- Largest exporting industry in the country.
- Second largest contributor to GDP.
- Important links to other sectors such as automobile components.
  - The component industry is so diversified that it attracted Asian manufacturers to open manufacturing plants in Spain after the automobile market was liberalized.
  - And yet, market penetration of Asian automobiles in Spain is similar to other European markets with the exception of France.

Europe and Spain

Figure 1: Market Share of Diesel Automobile Sales

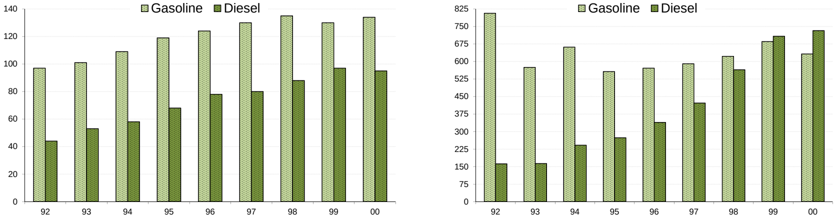


- Diffusion of diesel automobiles is similar than in the rest of Europe.

By Country

Evolution of the Automobile Market in Spain

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



(a) Models Available

(b) Sales (thousands of vehicles)

- A large number of models was already available just two years after the introduction of TDI.
- Yet, the domestic market was small relative to the European market $\Rightarrow$ Model introduction can be assumed exogenous to the Spanish market conditions.

Our Data

Spanish automobile registrations (1992-2000):

- We observe number of registrations and price by type of engine.
- Unbalanced panel with 1,869 model-year observations.
- The number of models increases over time.
- Relative to gasoline models diesel vehicles are heavier, less powerful, more expensive, and have better mileage.
- Automobiles become larger, more powerful and heavier over time.

Automobile Characteristics by Fuel/Origin

Table 1: Car Model Characteristics by Origin and Engine Types

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

◂ Characteristics by Segment ◂ Distribution Differences

Utility Function

- Discrete-choice model for differentiated products (BLP 1995).
- Consumer chooses one among many automobiles available or the outside option of not buying a car.

$$u_{ijt} = x_{jt}\beta_i^* - \alpha_{it}^* p_{jt} + \xi_{jt} + \epsilon_{ijt}\ ,$$
$$\text{where } \ i = 1, \ldots, I_t; \quad j = 1, \ldots, J_t.$$

x_{jt}: observed automobile characteristics ($J_t \times K$).
p_{jt}: price of automobiles (to the consumer).
$\alpha_{it}^* = \alpha / y_{it}$, where y_{it} consumer i's income.
β_i^* consumer i's preferences over characteristics.
ξ_{jt}: vector of unobserved (to the econometrician) characteristics.
ϵ_{ijt}: consumer i's unobserved taste for product $j \sim$ i.i.d. GEV.

Predicted Market Shares

- Define δ as tastes common to all consumers:

$$\delta_{jt} = X_{jt}\beta + \xi_{jt}$$

- Define μ as tastes idiosyncratic to consumer i:

$$\mu_{ijt} = \alpha \times \frac{p_{jt}}{y_{it}} + \sum_k \sigma^k \nu_i^k X_{jt}^k$$

- For consumer i, GEV (Logit) assumption implies product choice probabilities of:

$$s_{ijt} = \frac{\exp(\delta_{jt} + \mu_{ijt})}{1 + \sum_{r \in J_t} \exp(\delta_{rt} + \mu_{irt})}$$

- Integration generates purchase probabilities:

$$s_{jt} = \int_\nu \int_D s_{ijt} dP^*_{D_t}(D) dP^*_\nu(\nu)$$

Supply Under Oligopoly

Bertrand multi-product oligopoly model with horizontally differentiated products and tariffs $\tau_{jt} \geq 0$.

- Profit Maximization Condition:

$$\frac{p}{1+\tau} = mc + \underbrace{\Delta^{-1}(p, x, \xi; \theta) s(p, x, \xi; \theta)}_{\text{endogenous markups}} .$$

- Ownership Structure:

$$\begin{aligned} \Delta_{rj}(p, x, \xi; \theta) &= \begin{cases} \dfrac{\partial s_r(p, x, \xi; \theta)}{\partial p_j^{\tau}}, & \text{if } (r, j) \text{ produced by the same firm}, \\ 0 & \text{otherwise}. \end{cases} \\ \text{where } p_j &= p_j^{\tau} \times (1 + \tau_{jt}) \end{aligned}$$

- Pricing Equation:

$$\begin{aligned} \ln(mc) &= \ln\left[\frac{p}{1+\tau} - \Delta^{-1}(p, x, \xi; \theta) s(p, x, \xi; \theta)\right] \\ &= z\gamma + \omega . \end{aligned}$$

Identification Assumptions

- Data limitations lead most of the literature to assume product characteristics are exogenous:

$$E[\xi(\theta)|X] = 0$$

- But then we're assuming that firms can't (don't) respond to changes in ξ.
  $\Rightarrow$ the usual argument is that price is *more* endogenous than characteristics.

- We document important and changes in product attributes during the decade.

Estimation Strategy I

- We allow for partial endogeneity of product characteristics similar to Petrin and Seo (2014).
- Each year firms simultaneously choose characteristics and price.
- Equilibrium concept is Nash in product characteristics and prices.

Estimation Strategy II

A multi-product firm f chooses product characteristics X_j^k to solve:

$$\max_{X_j^k} E\left[\sum_{r\in\mathcal{F}_f}(p_r - c_r)\times s_r(\cdot)|\Omega_f\right]$$

which yields the following FOC:

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

where

$$\frac{\partial s_r}{\partial X_j^k} = \begin{cases} \int_i(\beta^k + \sigma^k\nu_i^k)\times s_{ij}(1-s_{ir})di + \sum_{m\in\mathcal{F}_f}\frac{\partial s_r}{\partial p_m}\frac{\partial p_m}{\partial X_j^k}, & r = j, \\ -\int_i(\beta^k + \sigma^k\nu_i^k)\times s_{ij}s_{ir}di + \sum_{m\in\mathcal{F}_f}\frac{\partial s_r}{\partial p_m}\frac{\partial p_m}{\partial X_j^k}, & \text{otherwise} \end{cases}$$

Estimation Strategy III

- Define θ as the vector of demand and supply coefficients.
- Solve for mean utilities $\delta(\theta)$ and marginal costs $c(\theta)$.
- Construct the structural error ε_j^k defined as

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

then profit-maximization implies $\forall j, k$

$$E[\varepsilon_j^k(\theta)|X, Z, \omega] = 0.$$

where:

- X is both observed and unobserved product characteristics (ξ),
- Z is a matrix of "observed" cost shifters,
- ω is a matrix of unobserved cost shifters.

Optimal Instruments

- Chamberlain (1987) shows the "optimal" (*i.e.*, most efficient) instruments are:

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

- Also used in BLP(1999) and Reynaert and Verboven(2013).

- Estimate θ via GMM:

$$\min_{\theta} G(\Theta)' A^{-1} G(\Theta)$$

where $G \equiv E[H \otimes \varepsilon]$.

- Update instruments H and weighting matrix A^{-1} via Iterative GMM.

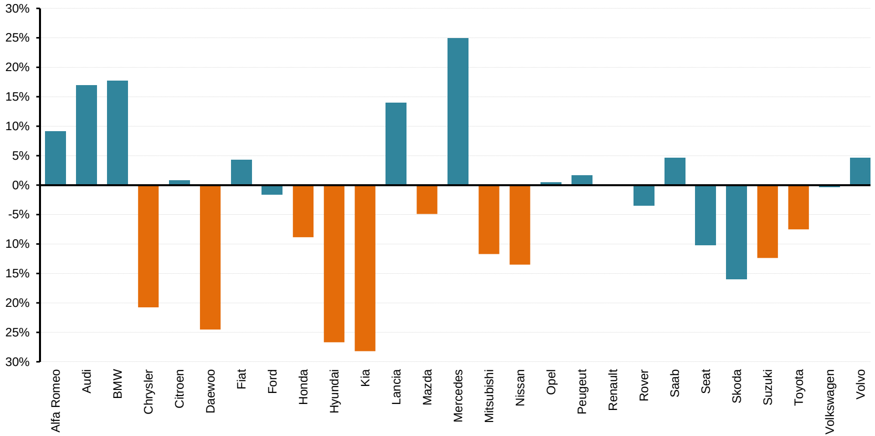
TABLE: Demand Estimates

Variable	Coefficient	Rob. SE	Variable	Coefficient	Rob. SE
Mean Utility (β)			SD (σ)		
KPE	0.2679	(0.3290)	KPE	3.1142***	(0.2649)
SIZE	-13.2042***	(0.6000)	SIZE	1.4304	(0.9971)
HPW	1.5288***	(0.4961)	HPW	1.4671***	(0.5383)
CONSTANT^b	5.7410***	(0.2243)	CONSTANT	2.8582***	(0.0274)
DIESEL^b	-2.3586***	(0.5275)	DIESEL	2.1196***	(0.0493)
DIESEL^b_{93}	0.7559	(0.6620)			
DIESEL^b_{94}	2.2892***	(0.6524)	Interactions (Π)		
DIESEL^b_{95}	2.0952***	(0.6377)	Price/Income	-16.8963***	(0.8800)
DIESEL^b_{96}	3.0923***	(0.6308)			
DIESEL^b_{97}	3.7642***	(0.6389)			
DIESEL^b_{98}	2.3827***	(0.6428)			
DIESEL^b_{99}	3.5044***	(0.6495)			
DIESEL^b_{00}	2.2448***	(0.6684)			
NON-EU^b	-1.5035***	(0.1882)			

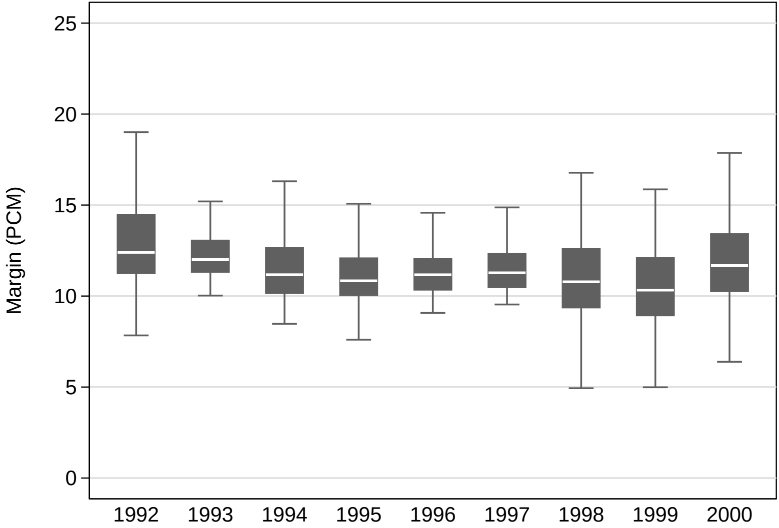
Table: Cost Estimates

Variable	Coefficient	Rob. SE
γ_{lnc90}	0.1311***	(0.0260)
γ_{LnSize}	0.8429***	(0.0497)
γ_{LnHPW}	0.3558***	(0.0187)
γ_{Xi}	0.0428***	(0.0014)
γ_{Diesel}	0.1948***	(0.0087)
γ_{const}	0.3964***	(0.0761)
γ_{Trend}	0.0137***	(0.0013)

Production Cost Differences Across Brands relative to Renault



Estimated Price-Cost Margins

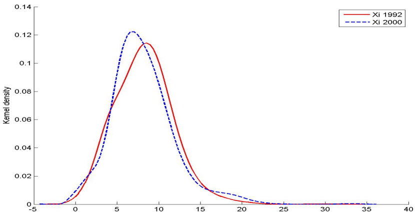


Orthogonal Attributes?

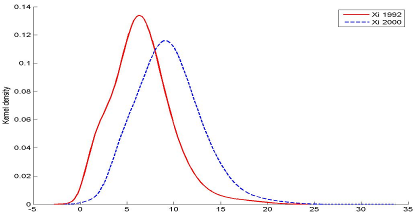
Table 3: Are Product Characteristics Correlated?

	KPE	SIZE	HPW	ξ
KPE	1.0000 -			
SIZE	-0.3215 (0.0276)	1.0000 -		
HPW	-0.5955 (0.0303)	0.3921 (0.0187)	1.0000 -	
ξ	-0.2997 (0.0273)	0.8337 (0.0098)	0.5222 (0.0166)	1.0000 -

Change in the Distribution of Unobserved Attributes



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



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

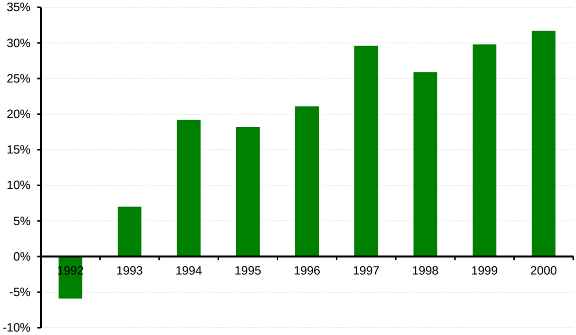
Was TDI Profitable for VW?

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

	No TDI	Benchmark	Monopoly
Prices (€Thousand)	15.84	16.14	17.42
- Diesel	-	16.72	18.42
- Gas	15.84	15.24	15.66
Quantity (Thousand)	199.83	319.79	401.09
- Diesel	0.00	194.31	255.23
- Gas	199.83	125.47	145.86
Market Share (%)	20.30	23.43	37.00
- Diesel	-	26.53	100.00
- Gas	20.30	19.84	17.60
Markup (%)	14.51	13.73	17.95
- Diesel	-	13.29	19.04
- Gas	14.51	14.40	16.05
Profit (€Million)	432.25	679.13	1,211.84
- Diesel	0.00	418.36	863.54
- Gas	432.25	260.78	348.29

- If diesels are not allowed, profitability of gasoline models increases but overall VW's profits are lower by about m€247.
- If only VW sells diesel vehicles profits are higher because of sales of TDI models and because gasoline vehicles are also more profitable. Maximum innovation rents m€779.
- VW would keep at least 32% of its potential monopoly rents.

Was TDI Profitable for VW?



- The Figure shows the share of VW's rent capture across the decade.
- VW succeeded to capture larger shares of potential profits despite the introduction of many diesel models by competing firms.
- Predatory effects on gasoline models present only in early stage.

Excluding Diesel Products

Table 5: Value of Diesels to Different Regions

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

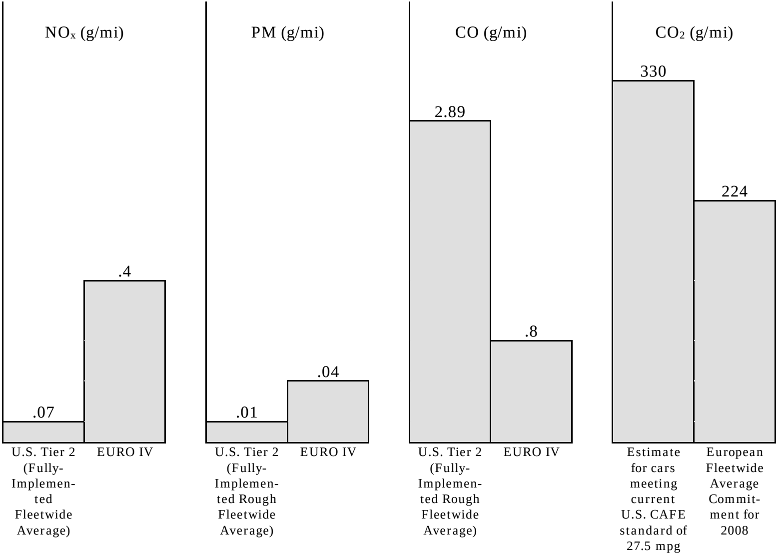
"Base" refers to benchmark equilibrium in the data while "CF" refers to the equilibrium without diesels cars. "Price" is the average price faced by consumers (in thousands of 1994 Euros), including tariffs. "Share" is the percent of vehicles sold in the category. "Markup" is the price-cost markup defined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

- Europeans lose market share and imports increase substantially by the end of the decade.

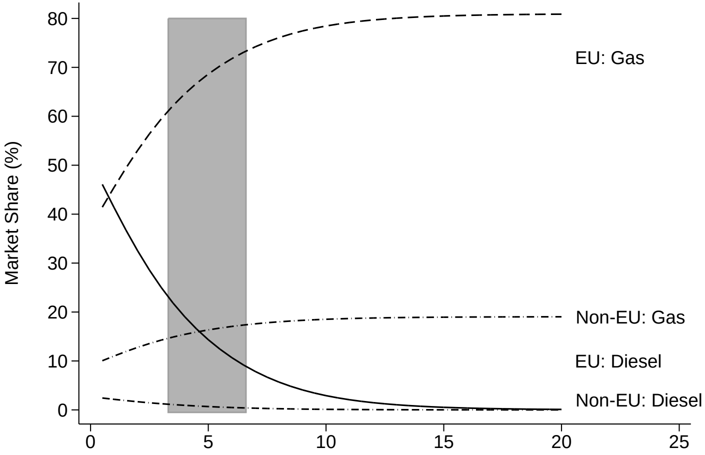
Stringent Environmental Policy

- Could diesels have not been viable in *some* plausible scenario?
- Approval of CAAA in 1991 led EPA to impose stringent emission standards on NO_x starting in 1994.
- European manufacturers withdrew their diesel models from the U.S. markets immediately after.
- The U.S. regulation happened in the early diffusion stage of diesel vehicles.

EU vs. US Emissions Standards



Responses to Stringent Environmental Policies: Retrofitting



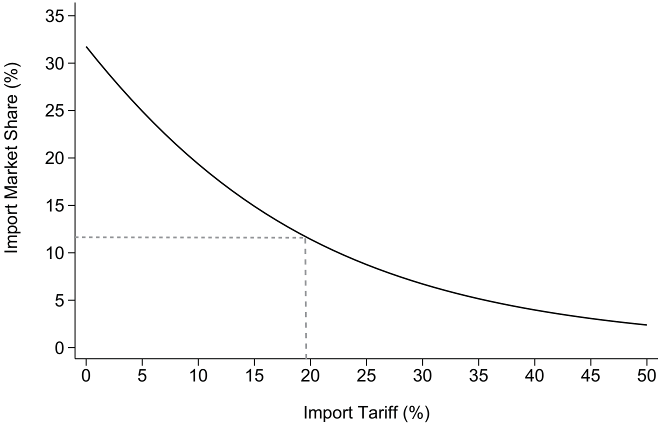
- At what "retrofitting" charge do diesel engines become prohibitively expensive? ⇒ Even today, diesels will not be commercially viable.

Environmental Policy as a Non-tariff Trade Barrier

- Targeting CO_2 allowed EU firms to retain substantial a market share although radically changing their product offering.
- How "big" is this non-tariff barrier? $\Rightarrow$ The following approach allows using equilibrium models to measure frictions common in gravity models of trade.
- Counterfactual: remove diesels and compute the equivalent import tariff that generates the market share of imports observed in the original equilibrium.
  - For 2000, the equivalent import tariff for Spain was 19.6% (actual was 10.3%).

Counterfactual

Was TDI Profitable for VW?



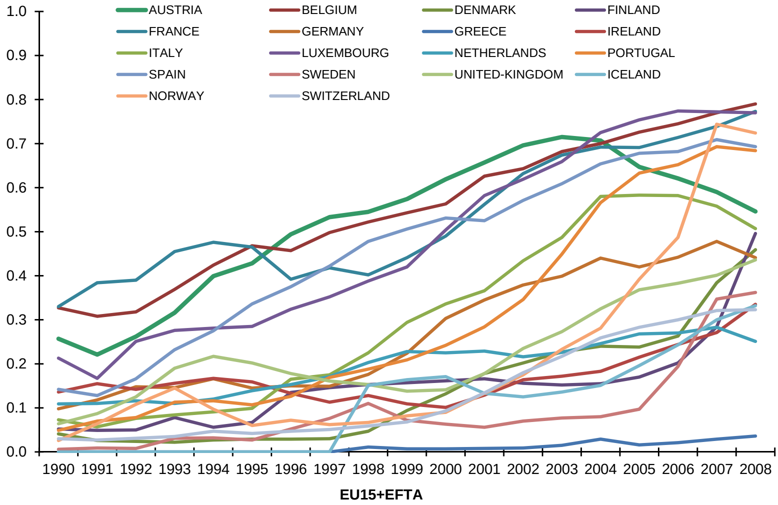
- Import tariffs are quite effective in reducing market penetration of foreign manufacturers.
- Further reductions of foreign presence would require rather large increases in import tariffs.

Summary

The analysis of the Spanish automobile market in the 1990s may shed some light on our current evaluation of new technologies:

- Diffusion of diesel engines follow a change in preferences.
- There is some evidence consistent with diesel vehicles being an experience good.
- Other institutional details, such as mergers, trade liberalization policies, or low diesel fuel taxation have negligible effects.
- Despite being a very general technology, VW was able to capture a substantial share of TDI's innovation rents.
- The European emissions policy allowed *de facto* Europeans keep control of their domestic market by successfully introducing a new product that non-Europeans were not capable of produce competitively.
- Environmental regulation turn out to be a key factor explaining the differential adoption of diesel technology across markets and a powerful non-tariff trade barrier against Asian automobile manufacturers.
- Was all this effect of environmental regulation intended? Most likely no.

Diffusion of Diesels in Europe



Return

Several Mergers

Table 3: Automobile Groups: 1992 vs. 2000

	Year 1992			Year 2000		
Automaker	Gasoline	Diesel	Owner	Gasoline	Diesel	Owner
ALFA ROMEO	5,038	64	ALFA ROMEO	2,941	3,983	FIAT
AUDI	16,689	1,982	VW	15,273	24,184	VW
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	VW	58,072	109,447	VW
SKODA	724	–	SKODA	5,003	10,385	VW
SUZUKI	2,058	–		3,250	486	
TOYOTA	4,425	–		16,827	3,584	
VOLKSWAGEN	50,561	5,471	VW	47,125	50,296	VW
VOLVO	10,179	–	VOLVO	7,379	3,566	FORD

Return

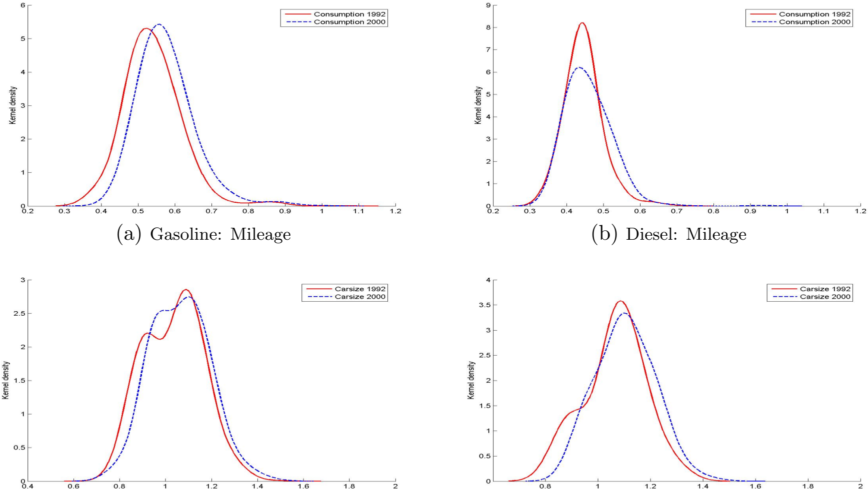
Automobile Characteristics by Segment

Table 2: Car Model Characteristics Across Segments

SEGMENT	PRODUCTS	SHARE	PRICE	KM/EURO	SIZE	HP/WT
1992						
Compact	31	35.8	11.0	38.8	74.3	39.8
Intermediate	39	22.3	14.3	36.6	80.1	42.6
Luxury	39	5.8	24.0	31.1	87.1	48.4
Minivan	4	0.3	17.3	29.3	81.7	37.9
Small	28	35.8	8.0	42.3	62.5	36.5
All	141	100.0	11.4	39.1	72.2	39.7
2000						
Compact	56	34.4	14.9	22.9	76.5	35.9
Intermediate	52	26.0	19.5	22.3	81.9	36.3
Luxury	40	3.7	34.5	16.4	89.7	51.7
Minivan	32	3.1	20.8	18.3	83.5	31.6
Small	49	32.8	10.4	22.3	66.4	31.8
All	229	100.0	15.5	22.2	75.3	35.1

Return

Automobile Characteristics



(a) Gasoline: Mileage

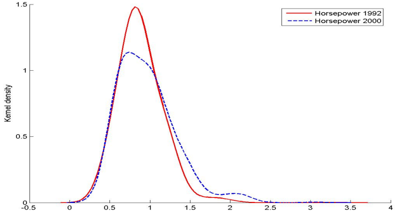
(b) Diesel: Mileage

(c) Gasoline: Car Size

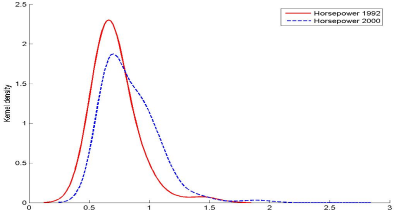
(d) Diesel: Car Size

Return

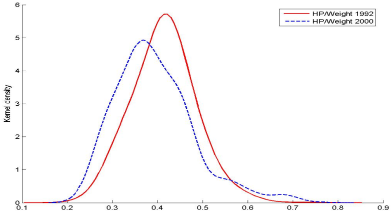
Automobile Characteristics



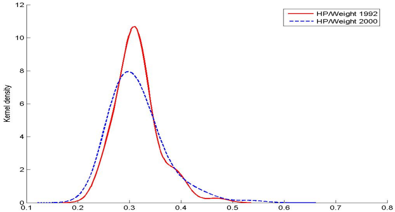
(e) Gasoline: Horsepower



(f) Diesel: Horsepower



(g) Gasoline: Horsepower/Weight



(h) Diesel: Horsepower/Weight

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Environmental Policy as a Non-tariff Barrier - Detailed

Table 7: Effects of Imposing Equivalent Import Tariffs (2000)

Scenario	Models	CAFE	Price	Quantity	Markup	Share	Profits
Benchmark							
EU: DIESEL	75	51.75	16.19	695.37	12.98	50.95	1,404.01
EU: GASOLINE	84	41.43	14.93	508.70	13.96	37.28	987.12
NON-EU: DIESEL	20	43.45	17.20	36.97	11.12	2.71	63.12
NON-EU: GASOLINE	50	38.52	13.66	123.65	13.41	9.06	191.77
Equilibrium without Diesels							
EU: GASOLINE	84	41.12	15.51	796.78	14.13	80.96	1,613.93
NON-EU: GASOLINE	50	38.18	14.24	187.40	13.69	19.04	307.82
Import Tariff of 19.6%							
EU: GASOLINE	84	41.10	15.56	837.80	14.24	88.23	1,715.18
NON-EU: GASOLINE	50	38.61	14.62	111.76	13.39	11.77	171.24

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

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