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Abstract

This paper estimates the role that technological change and car characteristics have played in the rate of fuel consumption of vehicles over time. Using data from the Spanish car market from 1988 to 2013, we estimate a reduced form equation that relates fuel consumption with a set of car characteristics. The results for the sales-weighted sample of vehicles show that energy efficiency would have improved by 30% and 42% for petrol and diesel cars respectively had car characteristics been held constant at 1988 values. However, the shift to bigger and more fuel-consuming cars reduced the gains from technological progress. Additionally, using the results of the fuel equation we show that, besides a natural growth rate of 1.1%, technological progress is affected by both the international price of oil and the adoption of mandatory emission standards. Moreover, according to our estimations, a 1% growth in GDP would modify car characteristics in such a way that fuel consumption would increase by around 0.23% for petrol cars and 0.35% for diesel cars.

Keywords: fuel efficiency, technological change, car characteristics

1. Introduction

Technological advances have brought about a continuous improvement in the fuel economy of vehicles over time. At the same time, car manufacturers have used more powerful engines in order to satisfy consumers' preferences for bigger and faster cars. As a consequence, the potential efficiency gains from technological progress have been partially offset by a shift to more fuel-consuming vehicles. A clear example of this is the increasing penetration of four-wheel drive vehicles in the composition of the passenger car fleet. Recently, due to concerns regarding environment and energy dependence, a number of countries have adopted mandatory limits for fuel consumption or CO_2 emissions of new registered cars[1]. For instance, this is the case of the regulation adopted by the European Union in 2009 (EC, nº 443/2009) which set a CO_2 emission target of 130 g CO_2/km to be met by 2015. This policy has forced car manufacturers to take additional actions to further increase the efficiency in fuel consumption.

The aim of our work is twofold. In the first stage, we estimate the role that technological change and car characteristics have played in the observed rate of fuel consumption of new registered cars over time. Using data from the Spanish car market from 1988 to 2013, we estimate a reduced form equation that relates fuel consumption with a set of explanatory variables, among them, car characteristics. We run separate estimations for petrol and diesel cars. From the estimated equations, we construct an index of technological progress and an index of the contribution of changes in car characteristics to fuel consumption for the sales-weighted sample of cars. The indexes show that energy efficiency would have improved by 30% and 42% for petrol and diesel cars respectively had the weight and engine size been held constant at 1988 values. However, the shift to bigger and more fuel-consuming cars reduced the gains from technological progress, mainly for diesel cars. It is important to note that since 2008 the car characteristics of new registered cars have moved in the opposite direction, mainly as a reaction by Spanish households to a severe economic crisis. Additionally, we provide evidence on the trade-off between fuel consumption and car characteristics -weight and engine size- as well as on the differentiated impact of four-wheel drive and similar types of vehicles. The results are robust to the assumptions made with respect to the specification of technological change.

In the second stage, we use the results of the fuel equation to regress the estimated technological change and the estimated contribution of car characteristics to fuel consumption with respect to its main determinants. The results show that, besides a natural growth rate of around 1.1%, technological progress is affected by both the international price of oil and the adoption of mandatory emission standards.

[1] The amount of CO_2 increases linearly with the amount of fuel consumed. Thus, setting a limit on CO_2 emissions is equivalent to setting a limit on fuel consumption per kilometer driven.

Moreover, the GDP appears as the main determinant of car characteristics. According to our estimations, a 1% growth in GDP would modify car characteristics in such a way that fuel consumption would increase by around 0.23% for petrol cars and 0.35% for diesel cars.

There is a large and growing body of literature that analyses the changes in the fuel economy of cars from different perspectives. Firstly, there is a line of research that focuses on the analysis of consumer preferences for fuel efficiency and car characteristics[2]. A second line of research aims at studying how technology has contributed to improving fuel efficiency as well as the technical trade-off between energy efficiency and other car characteristics. Related to this second line, there are a growing number of papers which, using different methodologies, investigate the response of the car industry to the adoption of new fuel economy standards[3].

Our work relates to those by Newell, Jaffe and Stavins (1999) and Knitell (2011) which provide an adequate framework for estimating the role that technological progress and product characteristics have played in the energy consumption of energy-using products. Knitell (2011) uses a reduced form equation to model fuel economy as a function of car characteristics using US data. His results reveal that if weight, horsepower, and torque were maintained at their 1980 levels, fuel economy could have increased by 58% between 1980 and 2006. He also finds that the rate of technological progress is correlated with the real gasoline price and the percentage change in the United States Corporate Average Fuel Efficiency (CAFE) standards[4]. Moreover, he uses his estimates to discuss the strategies available to achieve the most recent CAFE standards adopted in US. Recently, there has been a growing amount of research focused on evaluating the response of car manufacturers to public policies aimed at reducing fuel consumption and/or CO_2 emissions from passenger cars. Bento et al. (2015), using a sample of vehicles sold in the US market between 1975 and 2011, investigate how historical changes in the fuel economy standards impacted technological innovation in the automobile industry and estimate the changes in the rate of innovation in response to the changes in the standards. Reynaert (2015) evaluates the effect of emission standards on the European car market using panel

[2] See, Busse et al. (2013); Greene (2010) for a review, and Galarraga et al. (2014) for the Spanish car market.

[3] This literature suggests that manufacturers may respond to new fuel economy standards in three different ways: modifying the relative prices of high and low emission vehicles, trading off fuel efficiency for other vehicles' characteristics and improving technology. Some of the papers related to this topic are: Goldberg (1998); Klier and Linn (2012); Whitefoot, Fowlie and Skerlos (2013); Klier and Linn (2015); Reynaert (2015) and Bento et al. (2015).

[4] The US Corporate Average Fuel Economy (CAFE) standards were introduced for passenger cars in 1978. CAFE standards target the sales-weighted average of the fuel economy of automobiles in all manufacturers that run business in the US. For passenger cars, CAFE standards were tightened in 2007 and 2009 in such a way that the limits to be met by 2016 were about 40% higher than 10 years before.

data covering 1998-2011 for seven European countries[5]. He finds that the 14% reduction in emissions observed between 2007 and 2011 is fully explained by advances in technology. Klier and Linn (2015) investigate manufacturers' response to the recent changes in US and European emission standards[6]. The authors find evidence that both US and European standards affected the rate of technology adoption and the direction of technology adoption by reducing light truck torque in the United States and both vehicle weight and horsepower in Europe.

The contributions of this paper to the literature can be summarized as follows. Firstly, we propose a methodology that makes it possible to decompose the changes observed in fuel consumption into two components: technological progress and vehicle characteristics. Secondly, we do so for a period of time long enough to account for two economic and oil price cycles. Thirdly, we report significant differences between petrol and diesel cars regarding both technological progress and car characteristics. Finally, we provide an estimation of the elasticities of technological progress and changes in car characteristics with respect to their main determinants.

After this introduction, the paper is organised as follows. Section 2 describes the data, section 3 discusses the methodology and empirical approach, section 4 discusses the econometric approaches, section 5 provides the estimation results and findings related to the changes in fuel efficiency, section 6 estimates the main determinants of technological progress and changes in car characteristics. Finally, section 7 concludes the paper.

2. Data

The data set contains a panel of new car models sold in the Spanish market from 1988 to 2013. We collect data for all models available in each of these 26 years, except for those with very low sales[7]. Our sample represents at least 95% of total registrations in a given year. Sales are only available at model level so our unit of analysis is car model and the vehicle characteristics refer to the mid-range version of the model for each year. Our analysis distinguishes between petrol and diesel cars. This distinction is important since the share of new registered diesel cars rose from 15% in 1988 to almost 70% at the end of the period. On the contrary, we do not consider hybrid vehicles since the sales of this type of vehicles were not significant until the final years

[5] The paper by Reynaert (2015) also evaluates the welfare effects of the European regulation by estimating a structural model.

[6] Klier and Linn (2015) extend previous analysis by matching engine data to vehicle model production data. Additionally, they estimate separate frontiers by engine, model and model-year.

[7] We exclude models with less than 1000 units sold in a given year.

of our sample[8]. The sample includes only cars with manual transmission. The final data contains 4,842 observations.

The characteristics and fuel consumption of the car models are obtained from specialized magazines. It is important to note that the data on fuel consumption corresponds to the data reported by the manufacturers. In other words, the results are obtained in laboratory conditions. However, some studies argue that the improvements reported via laboratory tests are not a reliable match for everyday driving. For instance, Tietge et al. (2015) maintain that not only is there no such match, but also that the gap between the laboratory-tested vehicle emissions and the real world on the road is widening. An increasing discrepancy between laboratory and everyday figures over time would certainly affect our results. If this occurred, the estimated fuel consumption improvement would be overstated. However, the magnitude of this effect is difficult to ascertain. The lack of a standard definition of real-world driving conditions means that the results of fuel consumption will depend on the specific circumstances of each measurement. Hence, we acknowledge that the technical change estimated for recent years in the sample can be upward biased, although the full magnitude of this effect cannot be determined for certain.

Table 1 provides the summary statistics for the main car characteristics for the years 1988 and 2013. We report data referring both to the average across vehicles in the sample and the weighted average according to sales. Fuel consumption is measured as a weighted average of urban and interurban consumption and has been calculated in a homogenous way over time. The main car characteristics included in the equation are vehicle engine size (displacement, specified in cc) and curb weight (the weight of the vehicle unloaded). Although in the preliminary estimations horsepower was included as a car characteristic, multicollinearity problems prevented including both horsepower and engine size in the estimated equation.

Regarding the dependent variable, we observe large differences in fuel consumption between 1988 and 2013. The unweighted figures show that litres of fuel per kilometre for petrol-powered cars decreased by 22%, while diesel cars showed a higher gain in efficiency with a fall of 32%. The percentage changes for the sales-weighted sample were very similar. Looking at the evolution over time, Figure 1 shows that fuel consumption remains almost constant until 1995 and from that point on there is a clear and continuous improvement in fuel efficiency. It subsequently falls sharply from 2007. The pattern is similar for diesel and petrol cars; however, on average, the drop is higher for diesel than for petrol cars. Besides, the drop for the average of both kinds of cars is even higher due to the constant replacement of petrol for diesel cars. This

[8] The sales of hybrid cars increased from 2,534 units in 2007 to 10,223 in 2013. It should also be noted that this market is highly concentrated; in 2013, the three models sold by Toyota represented 75% of total hybrid sales. Regarding electric cars, their sales reached a maximum of 832 units in 2013.

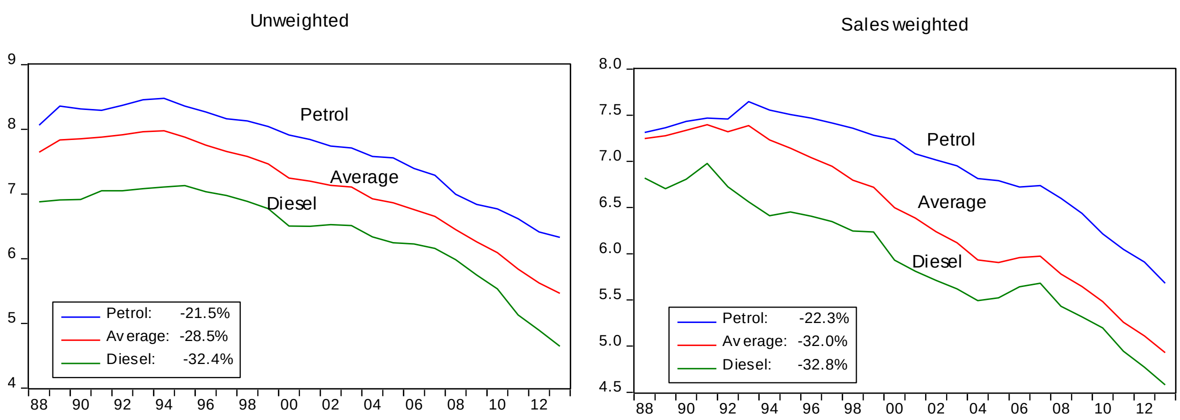
replacement can also be observed in the fact that the trend for average consumption becomes increasingly similar to that of diesel cars. Regarding the weighted figures, we also observe a decreasing trend in fuel consumption, although it is a bit more irregular. For instance, there is a surprising increase in 2005 and 2006. Nonetheless, the trend between unweighted and weighted figures for recent years is very similar.

Table 1. Descriptive statistics (annual means)

	Unweighted			**Sales-weighted**		
	1988	**2013**	**Change**	**1988**	**2013**	**Change**
Petrol						
Fuel consumption (l/100km)	8.1	6.3	-21.5%	7.3	5.7	-22.3%
Engine size (cc)	1660	1586	-4.4%	1428	1366	-4.3%
Weight (kg)	995	1308	31.4%	872	1138	30.5%
FWD and SUVs	0.0%	23.1%	23.1	0.0%	9.2%	9.2
Minivans	1.6%	11.0%	9.4	0.1%	5.8%	5.8
Diesel						
Fuel consumption (l/100km)	6.9	4.6	-32.4%	6.9	4.5	-34.8%
Engine size (cc)	1968	1774	-9.8%	1927	1731	-10.2%
Weight (kg)	1111	1401	26.1%	1076	1384	28.7%
FWD and SUVs	8.8%	24.0%	15.1	11.2%	23.7%	12.6
Minivans	2.9%	11.5%	8.5	0.1%	12.7%	12.6

Note: FWD refers to Four-Wheel Drive and SUV to Sport Utility Vehicle

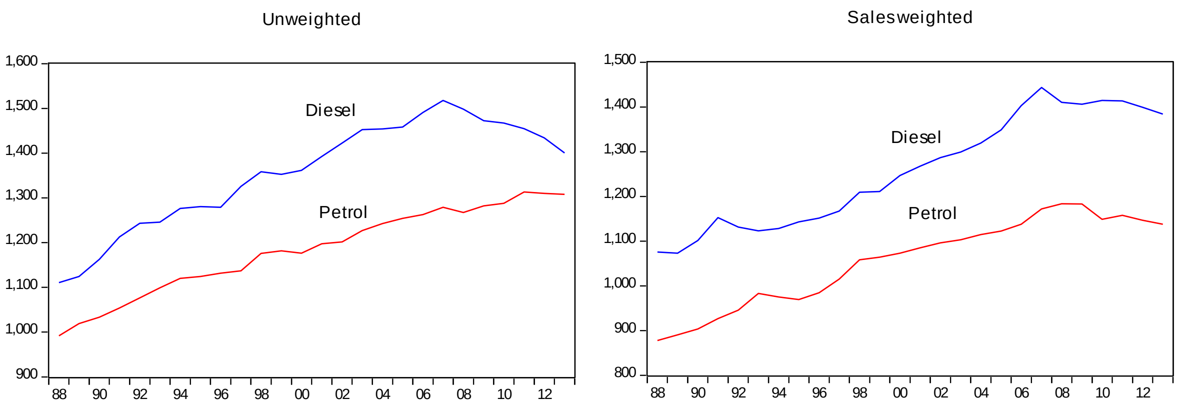
Figure 1. Fuel consumption of new registered cars (litres/100kms)



One of the main determinants of fuel consumption is car weight. Table 1 shows that between the first and the last year in the sample average car weight increased by 31% for petrol cars and 26% for diesel cars; when cars are weighted by sales the rise is around 30% for both types of cars. Looking at Figure 2, it can be observed that weight increased steadily until 2007, but then tended to level off for petrol cars and decreased sharply for diesel cars. The pattern followed by the sales-weighted figures mitigates the fall of car weight for diesel cars and, otherwise, accentuates the slowdown for petrol cars. Overall, weight is flat from 2007. The sharp decline for diesel cars in the unweighted sample is explained by the drop in sales of four-wheel drive vehicles as a consequence of the economic crisis.

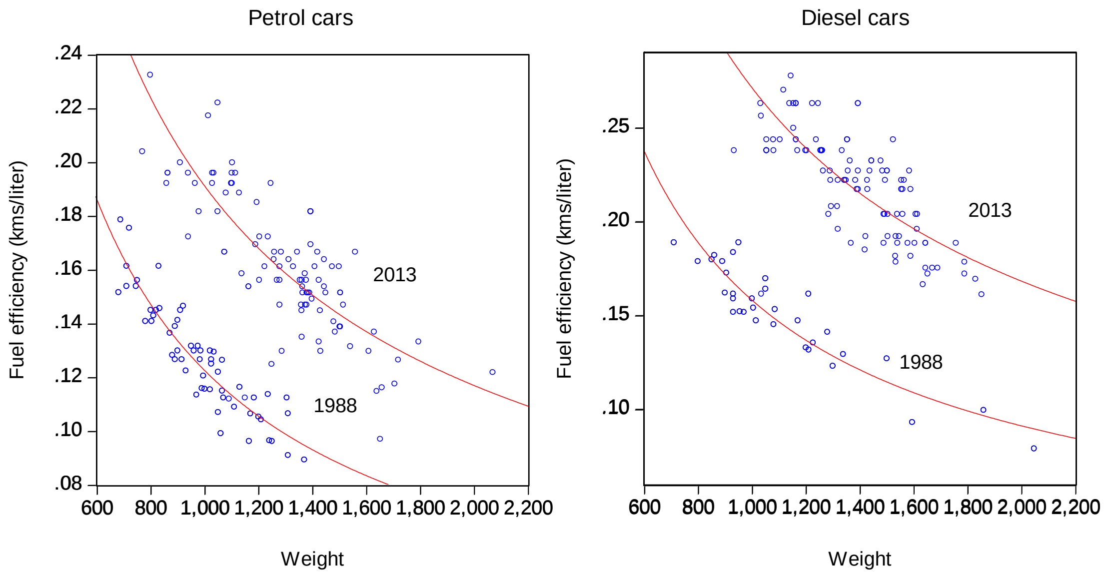
The improvements in fuel efficiency together with the increase in car weight suggest that the technological progress has had a significant impact on the car industry. To illustrate this, Figure 3 plots efficiency against car weight for the cars sold in 1988 and 2013[9]. A regression line, with variables in logarithms, is fitted through the data. The figure shows that for the same weight, cars were much more efficient in 2013 than in 1988. The gains in efficiency are very similar for all the car weight values and are higher for diesel than for petrol cars.

Figure 2. Curb weight of new registered cars (kilograms)



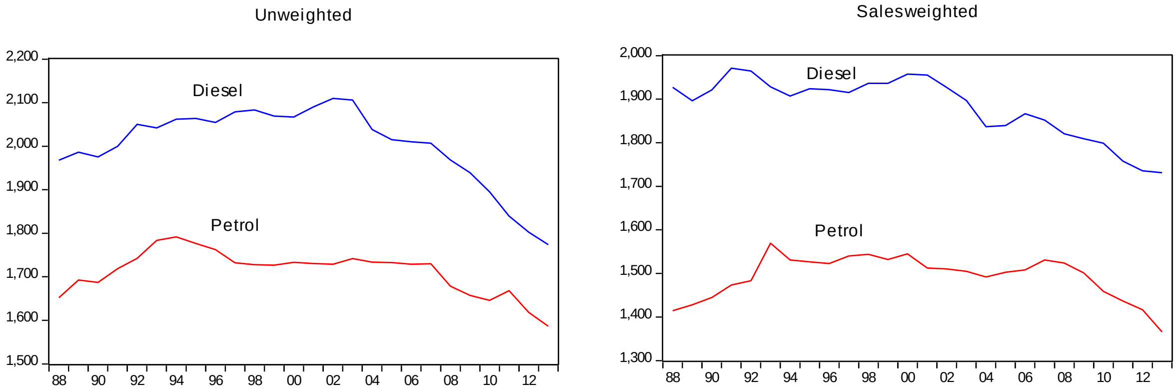
[9] This figure replicates Figure 3 from the paper by Knitell (2011).

Figure 3. Trade-off between fuel efficiency and car weight



Moreover, we observe that engine size falls by roughly 4.4% for petrol cars and 10% for diesel cars between the first and the last year in the sample. Nonetheless, Figure 4 shows different paths over time. Regarding the sample, engine size for diesel cars increased until 2003 and then started a falling trend that became accentuated in 2007. For petrol cars, the increase in engine size is only observed until the mid-nineties; it then remains stable until 2007. From that year, the variable also displays a drop which must be related to the outbreak of a severe economic crisis. The sharper decline in diesel cars is explained by the intense reduction of Four-Wheel Drive (FWD) and big Sport Utility Vehicle (SUV) sales. For instance, between 2007 and 2013, the units of AUDI-Q7 sold fell from 5139 to 431; the units of Porsche Cayenne declined from 1337 to 96 and those of Volkswagen Touareg from 4354 to 434.

Figure 4. Engine size of new registered cars (cc)



Finally, a major feature in the composition of the Spanish vehicle fleet is the increasing presence of FWD, SUV and Minivan vehicles. Table 1 reports the percentage of new car registrations corresponding to these types of vehicles. In 2013, FWD and SUVs represented 23% of the sample of new petrol cars and 24% of diesel cars. However, weighting by total sales, the percentage for petrol cars falls to 9.2%, whereas for diesel cars it remains approximately the same. It should be noted that in the last years of the sample, big SUV vehicles have been replaced by smaller more efficient SUV models.

3. Methodology and empirical specification

Engineering studies show that there is a trade-off between some car attributes, such as weight or engine power, and fuel consumption. Based on this trade-off, Knitell (2011) develops a framework that makes it possible to estimate the technological improvements in fuel consumption over time. Specifically, he assumes a marginal cost function for producing vehicles that is additive separable in the car attributes related to fuel consumption and the other car characteristics. Holding marginal production costs constant, fuel consumption can be expressed as a function of car attributes. In this regard, Knitell (2011) specifies a reduced form equation with fuel consumption being a function of product characteristics. If it is assumed that technological progress is input neutral, the equation to be estimated is:

$$f_{it} = T_t * f(X_{it}, u_{it}) \qquad (1)$$

Where f_{it} is fuel consumption, measured as litre per kilometre.
T_t are the time-fixed effects that capture the technological progress.
X_{it} is a vector of car attributes related to fuel consumption.
u_{it} is the error term.
i and *t* refer to car model and time period, respectively.

Knitell (2011) himself points out as a drawback of this formulation that omitting expenditures on technology from the empirical model may bias the results. If firms have increased or reduced expenditures on technology, the time-fixed effects will reflect both technological progress and the change in the amount spent on these technologies over time. However, this does not affect our results as long as we interpret the estimated coefficients as capturing both types of effects.

Regarding the empirical specification, the first issue is to select the set of car attributes that are related to fuel consumption. Following the literature, fuel consumption is mainly related to car weight and engine power. So the first variables to consider were curb weight, engine size (measured as engine displacement in cc) and horsepower. As explained in section 2, the high level of correlation between displacement and horsepower prevented us from including both variables in the equation. Based on the goodness of fit we selected engine size as the explanatory variable, although similar results were obtained when horsepower was used. Certainly, along with engine technology, there are other factors -such as advances in transmission, low rolling resistance of tyres, combustion improvement and advances in aerodynamics- which contribute to the improvement of fuel efficiency[10]. Including additional attributes in the equation depends on the set of characteristics we want to make conditional inference. Our approach has been to restrict the car characteristics to weight and engine size. Therefore, our results show how much more efficient a car is in 2013 compared with a car bought in 1988 with the same weight and engine size. The time-fixed effect coefficients absorb improvements in engine technology as well as any other technological changes addressed to reduce fuel consumption.

Nonetheless, a second model specification includes a set of dummy variables to account for different classes of vehicles. Since our sample includes vehicles that can serve different purposes it might be interesting to quantify improvements in fuel efficiency conditional on the type of vehicle. Specifically, we distinguish between passenger cars, FWD, SUVs and Minivans. We divide SUVs into two categories: small, compact and medium SUVs (SUV_1) and full-size SUVs (SUV_2). As a second separate vehicle category, we include Minivan vehicles divided into two categories: small and compact (Minivan_1) and full size (Minivan_2). Finally, we include manufacturer fixed effects to capture unobservable attributes related to fuel efficiency that are constant across car manufacturers.

We assume a Cobb-Douglas functional form where all continuous variables have been transformed taking logs[11]:

$$f_{it} = T_t + \beta' X_{it} + \gamma' Z_{it} + u_{it} \qquad (2)$$

Where f_{it} is fuel consumption.
T_t are the time-fixed effects that capture technological change.
X_{it} is a vector of car attributes related to fuel consumption.
Z_{it} is a vector of dummy variables including the type of vehicle and car manufacturers.
β, γ are the parameters to be estimated.
u_{it} is the error term.

We estimate separate equations for diesel and petrol cars to account for different technologies. The hypothesis of equal coefficients for the characteristics was clearly rejected by the data[12].

[10] See Knitell (2011) for a review of the main changes.
[11] Based on the value of the log-likelihood functions, the log-linear functional form was preferred to the linear equation.
[12] The calculated F-statistic is 14.5, while the critical value for the corresponding degrees of freedom at a significance level of 5% is 1.52.

4. Estimation approaches

As a first alternative, we estimate equation (2) under the assumption that the trade-off coefficients between fuel consumption and car characteristics are constant over time. This pooled equation includes a set of annual dummy variables that capture the technological change year by year. The estimated coefficients for such variables can be interpreted as the average change in fuel consumption across all vehicles in the sample due to technological change.

Alternatively, we use a second approach consisting of estimating single year equations. This alternative allows for the variation of the coefficients year by year and hence relaxes the assumption of technology being input neutral. Also, the single year estimation makes it possible to compute the contributions of car characteristics and technology improvements to the changes in fuel consumption according to the weighted average of car characteristics for each year in the sample. Following the standard practice in econometrics, we estimate an unweighted specification of the fuel economy equation[13]. The estimation results represent the set of vehicles available in the market. However, we might be interested in the fuel consumption performance of the actual fleet of new registered vehicles. In this case, it would be necessary to weight car characteristics according to sales. Estimating single year equations allows for *a posteriori* weighting procedure.

In order to simplify notation, we consider only the explanatory variables related to car characteristics, X. Following equation (2), the estimated equation for year "t" can be written as follows:

$$f_{it} = \beta_t' X_{it} + u_{it} \qquad (3)$$

And for year "t+1":

$$f_{it+1} = \beta_{t+1}' X_{it+1} + u_{it+1} \qquad (4)$$

By averaging over all individual observations, we obtain the arithmetic mean for each variable:

$$f_t = \beta_t' X_t \qquad (5)$$

$$f_{t+1} = \beta_{t+1}' X_{t+1} \qquad (6)$$

Taking differences:

$$\underset{\substack{\text{Variation}\\ \text{of average}\\ \text{consumption}}}{\overline{df_t}} = \underset{\substack{\text{Variation explained}\\ \text{by characteristics}}}{\hat{\beta}_t' d\bar{X}_t} + \underbrace{d\hat{\beta}_t' \overline{X}_t}_{\substack{\text{Variation explained}\\ \text{by technology}}} + \underbrace{d\hat{\beta}_t' d\bar{X}_t}_{\substack{\text{Variation explained}\\ \text{by mixed effects}}} \qquad (7)$$

[13] For a discussion of the role of weights see Solon et al. (2015).

Equation (7) decomposes the variation of the average fuel consumption for the car models available in the market in years "t" and "t+1".

Furthermore, if our interest lies in the actual fleet of new registered cars, we can proceed by weighting the characteristics according to the number of vehicles sold by make and model. In this case, we have:

$$f_t = \beta_t' X_t + u_t \tag{8}$$

$$f_{t+1} = \beta_{t+1}' X_{t+1} + u_{t+1} \tag{9}$$

$$\underset{Observed}{df_t} = \underset{Characteristics}{\hat{\beta}_t' d\tilde{X}_t} + \underbrace{d\hat{\beta}_t' \tilde{X}_t}_{Technology} + \underbrace{d\hat{\beta}_t' d\tilde{X}_t}_{Mixed} + \underset{Unexplained}{d\tilde{u}_t} \tag{10}$$

It must be noted that the weighted average of OLS residuals can be different from zero. That is why an unexplained residual effect is added to the so called mixed effects.

Equations (7) and (10) enable us to construct a set of indexes that reflect changes in fuel consumption, in characteristics and in technology over time, both for the available and the actual fleet of vehicles.

Therefore, firstly we estimate equation (2) assuming that the trade-off coefficients are constant over time and secondly we estimate single year equations to allow for different coefficients.

5. Results

5.1. Pooled equations

Table 2 reports the estimation results of the pooled regression approach for both petrol and diesel cars[14]. For each fuel type we estimate three different models that differ in the number of explanatory variables. Model 1 includes only weight and engine size; model 2 adds a set of dummies for the types of cars, and model 3 also includes manufacturing-fixed effects. Overall, the estimated coefficients for the various characteristics have the expected signs and reasonable magnitudes. Regarding petrol cars, a first issue we want to highlight is that the magnitudes of the estimated coefficients are very similar between the three specifications. Including the set of dummies for the different types of cars slightly diminishes the coefficient for the weight variable, whereas the coefficients are not essentially modified when manufacturer-fixed effects are added. However, for diesel cars some differences appear. In this case, not controlling for the type of car increases the coefficient for the weight variable. This result implies that a higher trade-off between fuel efficiency and

[14] Tables in the text omit the year and manufacturer-fixed effects. The full estimation results are presented in Table A.1 in the Annex.

weight is possible when the type of car is not held constant. Again, the estimated coefficients only vary slightly when we control for car make.

Since all continuous variables are in logs, the estimated trade-off coefficients correspond to elasticity values. The elasticities mentioned hereafter correspond to those appearing in Model 3. Regarding car weight, the elasticity is around 0.36 for petrol cars and 0.31 for diesel cars; this magnitude is consistent with available evidence. Knitell (2011) estimates a value of 0.42 for a sample of US passenger cars, whereas Bento et al. (2015) provide a value of 0.38 for a sample of European vehicles sold in the US market. Klier and Linn (2015) find elasticity values equal to 0.34 and 0.31 for the US and European market, respectively. Finally, Reynaert (2015) reports a somewhat higher value, 0.66, using data for seven European countries. Nonetheless, the elasticity values and the comparisons with other evidence have to be taken with caution since they are conditional on the covariates included in the equation.

We also find that a 10% increase in engine size causes a 0.3% increase in petrol consumption and a 0.4% increase in diesel consumption. For the same weight and engine size, a four-wheel drive vehicle increases the litres consumed by 100 kilometres by more than 30%. The impact of SUV is higher for diesel than for petrol cars and highest for the biggest SUVs. The fuel efficiency of Minivans is only slightly lower than other passenger cars except for high powered diesel Minivans.

Table 2. Estimation results for fuel consumption equations (litres per 100 km**)**

	Petrol cars			Diesel cars		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
ln(weight)	0.427***	0.365***	0.362***	0.715***	0.324***	0.313***
	(26.61)	(25.62)	(24.35)	(34.764)	(17.922)	(17.341)
ln(engine size)	0.283***	0.278***	0.317***	0.243***	0.332***	0.403***
	(19.81)	(25.19)	(26.58)	(12.58)	(23.14)	(26.05)
Four-wheel drive	-	0.290***	0.320***	-	0.326***	0.280***
		(20.77)	(24.76)		(36.45)	(21.68)
SUV_1	-	0.111***	0.113***	-	0.178***	0.146***
		(16.32)	(16.44)		(26.708)	(20.81)
SUV_2	-	0.136***	0.129***	-	0.230***	0.220***
		(9.96)	(9.01)		(23.83)	(21.62)
MPV_1	-	0.031***	0.024***	-	0.051***	0.044***
		(4.851)	(3.74)		(7.56)	(6.70)
MPV_2	-	0.069***	0.050***	-	0.152***	0.128***
		(7.22)	(4.29)		(15.28)	(12.23)
Constant term	-2.953***	-2.486***	-2.722***	-4.927***	-2.895***	-3.310***
	(-50.14)	(-46.74)	(-41.52)	(-56.346)	(-39.976)	(-37.664)
Year-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer-fixed effects	No	No	Yes	No	No	Yes

R-squared	0.8342	0.8834	0.9033	0.8066	0.9012	0.9162
Observations	2531	2531	2531	2311	2311	2311

*note: *** p<0.01, ** p<0.05, * p<0.1; robust t-statistics in parenthesis*

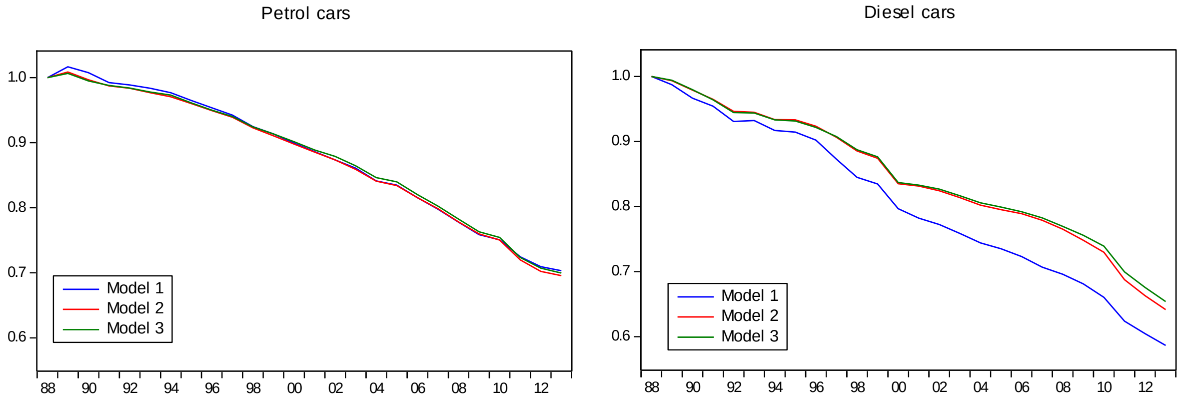
Table A.2 in the annex presents the same estimations but with standard errors clustered at the manufacturer level in order to account for possible correlation across models and within manufacturer. As can be observed, clustering involves a reduction in the value of t-statistics which might provide evidence of correlation between error terms within manufacturers. But, on the other hand, as Nichols and Schaffer (2007) point out, the cluster-robust standard error estimator converges to the true standard error as the number of clusters approaches infinity. These authors consider that with a number of clusters well below 50, or very unbalanced cluster sizes, inference using the cluster-robust estimator may be incorrect more often than when using the OLS estimator. In our case, we have 35 clusters that are clearly unbalanced. For instance, for diesel cars the size of the clusters ranges from 4 to 164. Based on the previous arguments, we have preferred to maintain OLS standard errors in the text[15]. Nonetheless, all coefficients remain statistically significant when standard errors are clustered at manufacturer level.

Technological change

From the estimates of the annual fixed effects in each of the three previous models, we have constructed an accumulative index of technological change that takes value 1 for the first year in the sample. The index reflects the drop in fuel consumption due to technological improvements. The indexes are plotted in Figure 5, whereas their specific values are reported in Table A.3 in the annex. For petrol cars, the results are robust to including the dummies for the types of vehicles and the manufacturer-fixed effects, whereas for diesel cars those regressions that include dummy variables for four-wheel drives, SUVs and Minivans show a lower improvement in efficiency.

[15] In Annex 2 we provide the results of a simulation exercise which shows that in our case where the number of clusters is low and highly unbalanced the estimation of cluster standard errors can generate unreliable estimates.

Figure 5. Index of technological change in fuel consumption (litres per km)



As we can observe, technological progress entails a clear declining trend in fuel consumption. Overall, our analysis reveals that between 1988 and 2013 technological change has improved fuel efficiency by around 30% for petrol cars and 41% for diesel cars, yet, for the latter the percentage drops to 35% when we condition on the type of car. Comparing our results to other available evidence, Knitell (2011) finds that, maintaining weight and power characteristics at their 1980 levels, fuel economy for passenger cars could have increased by 58% between 1980 and 2006. This percentage is higher than ours, but we have to take into account, firstly, that technological progress in Knitell's sample was higher during the early 1980s –a sample period we do not observe. Secondly, his sample includes both diesel and petrol cars, and between 19% and 27% of the gains in efficiency correspond to the contribution of diesel technology. Since we run separate regressions for petrol and diesel engines, our estimations do not include such a factor.

5.2. Yearly equations

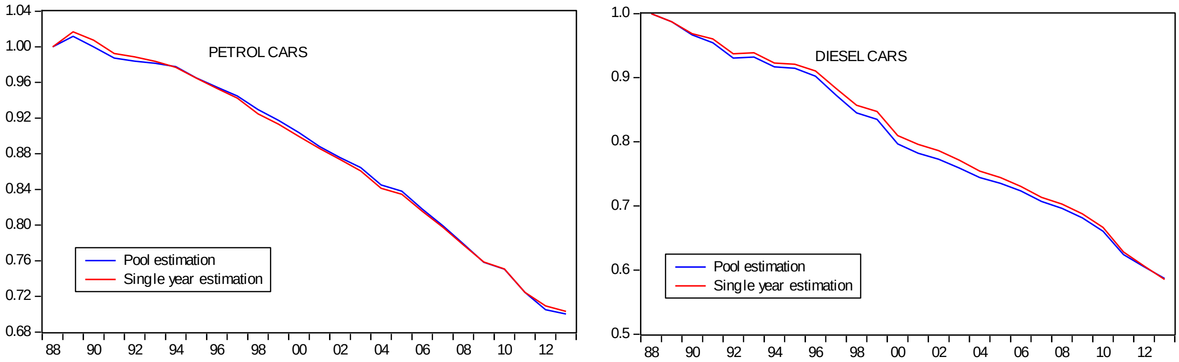
As a second approach, we have estimated single year equations in order to relax the assumption that the trade-off coefficients remain constant over time. Table A.4 in the annex presents the estimation results for Model 1 and 2[16]. According to equation (7), we have decomposed the variation in fuel consumption into three components: technological progress, changes in car characteristics and mixed effects. In order to present the results, we constructed an accumulative index for the three components which, as before, takes the value 1 for 1988 (see Table A.5). All the results presented in this section refer to Model 1; that is, they are conditioned only on weight and engine size. The reason for this is that we are interested in observing the effect of variations in car characteristics on fuel consumption. Since one of the main drivers of

[16] Since for a given year the number of available models by firm could be very low, including manufacturer-fixed effects was not advisable; therefore, Model 3 has not been estimated.

changes in characteristics is the purchasing of SUV and similar cars, we decided not to condition on the types of vehicle[17].

Firstly, Figure 6 compares the indexes of technological progress estimated from the pooled and the single year equations. As can be observed, the two approaches provide almost identical results both for petrol and diesel cars. Therefore, we can conclude that our results are robust to the hypothesis made regarding whether technological change is input neutral or not.

Figure 6. Index of technological change estimated from the pooled and single year equations



Note: the indexes correspond to Model 1 in Table A.3 and the technological index in Table A.5.

Decomposition of changes in fuel consumption weighted by car sales

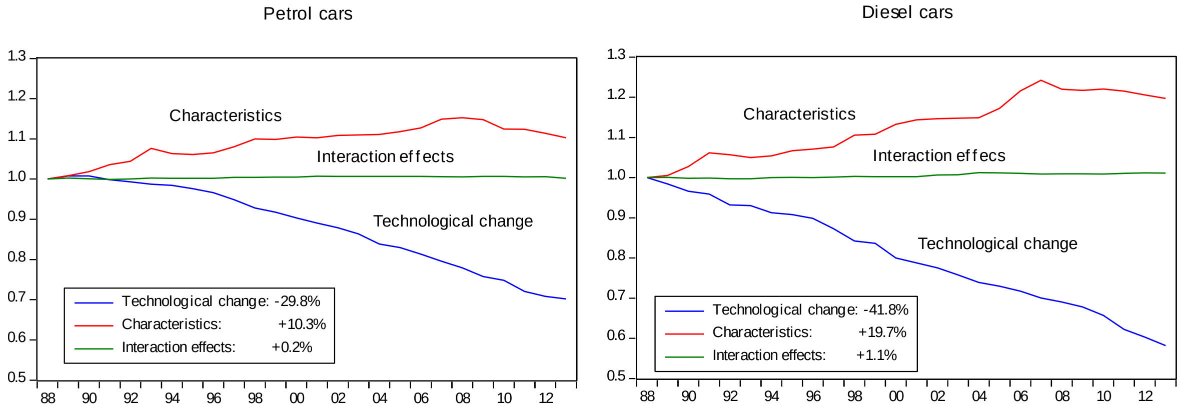
Secondly, the estimated equations can be used to disentangle the role that technological progress and car characteristics have played on the rate of change of the fuel consumption of new registered cars. At this point, since our aim is to measure how the characteristics of the cars actually sold in the market have influenced fuel consumption over time, weighting by car sales is necessary in order to make the analysis sample representative of the target population. Hence, following Equation 10, we have computed the contribution of technology and car characteristics to fuel consumption by weighting the characteristics according to the number of vehicles sold by make and model.

Figure 7 shows the decomposition for petrol and diesel cars; the vertical axis plots the index that takes value 1 in 1988. The full set of indexes is presented in Table A.6. First of all, we observe that fuel efficiency improves due to technological change over the entire period. For petrol cars, technological progress contributed to a decrease in fuel consumption of 30%, whereas for diesel cars this percentage reached almost 42%. It should be noted that those indexes do not essentially differ from those computed from the unweighted sample. For both type of fuels, consumers' preferences for larger cars have partially offset the technical gains. Specifically, for diesel cars the increase in

[17] We constructed the same indexes using the estimation results of Model 2. As occurred in the pooled equation, no significant differences appeared regarding petrol cars. With respect to diesel cars, we observed a lower gain in fuel efficiency and a flatter pattern for car characteristics.

weight and engine size has reduced the gains in efficiency by 20%. This percentage doubles that of petrol cars and must be related to a higher penetration of four-wheel drives and SUVs in the diesel market. Nonetheless, it is important to point out that the slope of the contribution of characteristics changed from 2008. From that year, the decrease in fuel consumption is also explained by the registration of smaller cars. The severe crisis that has hit the Spanish economy since 2008 not only reduced the number of new registrations but also involved a sharp decrease in the engine size of new vehicles. A comparison of our results with those of Reynaert (2015) may illustrate the effect of the deeper economic crisis suffered by Spain on the car market, in comparison with the average of the European countries on his sample[18]. Reynaert concludes that technology adoption is fully responsible for the observed increase in fuel efficiency between 2007 and 2011. He estimates that between 2008 and 2011 technology improves by an average pace of 4.3%. According to our estimations, for the same period and the Spanish sample, technology has improved at an annual rate of 2.6% and 3.4% for petrol and diesel cars, respectively. However, the downsizing of the new fleet has contributed to fuel efficiency at an annual rate of 0.8% and 0.2% for the two types of engines[19].

Figure 7. Decomposition of changes in fuel consumption



6. Determinants of technological change and car characteristics

In the second stage of the research, we use the estimated indexes of technological progress and changes in car characteristics in order to identify the effects of their main potential determinants. Specifically, for technological changes we consider three explanatory variables. Firstly, we include an annual trend that captures the average technological change over time. The second explanatory variable is the international

[18] The countries included are Belgium, France, Germany, Italy, Great Britain, The Netherlands and Spain.

[19] For European cars, Klier and Linn (2015) report that technological progress has improved fuel efficiency by a rate of 1.7% per year between 2005 and 2007 and 2.9% per year between 2008 and 2010, holding constant all vehicle characteristics.

price of oil (Europe Brent spot price, deflated by OECD-Europe CPI-energy). Finally, we include a dummy variable to account for the effects of the European Regulation (EC, 443/2009) that introduced mandatory CO_2 emission performance standards for new passenger cars. The regulation was adopted in 2009, with a phasing-in period that started in 2012 and finished in 2015. The regulation sets a cap on the average emissions of new vehicle sales, yet, it is based on vehicle characteristics, in such a way that the emission target varies with vehicle weight[20]. However, the extent of our data does not allow us to account for the effects of the regulation regarding car weight. The estimated coefficient for the dummy variable measures the effect of the new cap on fuel consumption across all cars, regardless of their weight. Thus, the conclusions related to the effect of this policy should be taken as an approximation.

The price of Brent and the dummy variable enter the equation as a first order polynomial distributed lag. For both variables the number of lags was determined on statistical grounds.

The coefficients estimated for the trend variable show that manufacturers would improve their technology over time at a rate of around 1.1% in the petrol market and 1.8% in the diesel market when we do not control for the type of cars; however, when we do control for the type of car the effect is similar in both markets, around 1.1% and 1.2% respectively. These percentages should be interpreted taking into account that the dependent variable is the technological progress when weight, engine size and vehicle type are held constant. That is, technical change would reduce fuel consumption by around 1.1% annually if car characteristics were held constant. This finding is very similar to that of Bento et al. (2015). These authors estimate an annual natural growth rate of innovation in technology equal to 1.19% for a sample of passenger cars sold in the US market between 1975 and 2011.

[20] For passenger cars, the regulation sets a CO_2 emission target of 130g CO_2/km by 2015, defined as the average value for the fleet of newly registered passenger cars in the EU. Average specific emissions are calculated as a weighted average of the manufacturer's fleet registered in a particular year. A phasing-in schedule is applied when calculating specific emissions. For passenger cars, only 65% in 2012, 75% in 2013 and 80% in 2014 of the best performing registered cars were taken into account in determining the performance of manufacturers.

Table 3. Determinants of technological change (1988-2013)

Dep. Var: ln(index technological change)

	Petrol-1	**Petrol-2**	**Diesel-1**	**Diesel -2**
Constant	0.3215***	0.2911***	0.2897***	0.2667***
	(8.83)	(10.90)	(7.05)	(5.35)
Trend	-0.0109***	-0.0107***	-0.0178***	-0.0121***
	(-22.52)	(-31.87)	(-11.27)	(-6.20)
ln(Brent price)	-0.0246***	-0.0214***	-0.0154**	-0.0183**
	(-5.43)	(-6.85)	(-2.30)	(-2.65)
ln(Brent price (-1))	-0.0184***	-0.0161***	-0.0115**	-0.0137**
	(-5.43)	(-6.85)	(-2.30)	(-2.65)
ln(Brent price (-2))	-0.0123***	-0.0107***	-0.0077**	-0.0092**
	(-5.43)	(-6.85)	(-2.30)	(-2.65)
ln(Brent price (-3))	-0.0062***	-0.0054***	-0.0038**	-0.0046**
	(-5.43)	(-6.85)	(-2.30)	(-2.65)
Sum of lags	**-0.0615*** **	**-0.0536*** **	**-0.0384** **	**-0.0458** **
	(-5.43)	(-6.85)	(-2.30)	(-2.65)
D2009	-0.0169***	-0.0196***	-0.0177**	-0.0259**
	(-3.09)	(-4.44)	(-2.12)	(-2.42)
D2009 (-1)	-0.0127***	-0.0147***	-0.0132**	-0.0194**
	(-3.09)	(-4.44)	(-2.12)	(-2.42)
D2009 (-2)	-0.0085***	-0.0098***	-0.0088**	-0.0129**
	(-3.09)	(-4.44)	(-2.12)	(-2.42)
D2009 (-3)	-0.0042***	-0.0049***	-0.0044**	-0.0065**
	(-3.09)	(-4.44)	(-2.12)	(-2.42)
Sum of lags	**-0.0423*** **	**-0.0491*** **	**-0.0441** **	**-0.0647** **
	(-3.09)	(-4.44)	(-2.12)	(-2.42)
AR(1)	0.4789*	0.3275	0.5280**	0.6814***
	(1.63)	(1.41)	(2.01)	(3.10)
SIGMASQ	0.0001**	0.00004**	0.0001**	0.0001**
	(2.13)	(1.85)	(2.59)	(2.54)
Adjusted R-sq	0.9950	0.9958	0.9954	0.9911
S.E. regression	0.0086	0.0076	0.0109	0.0117
Durbin-Watson	1.6671	1.7209	1.7841	1.5356

Note: Petrol-1 and Diesel-1 correspond to the indexes derived from Model 1 (without controlling on the type of car), while Petrol-2 and Diesel-2 correspond to the indexes derived from Model 2 (controlling on the type of car); t- statistics in parenthesis

Additionally, our data confirms that the energy price spurs technical progress. The aggregate effect amounts to 5.4% and to 4.6% for petrol and diesel vehicles when controlling on the type of cars. This result is consistent with other empirical evidence that finds that energy prices affect innovation. Newell et al. (1999) find that energy prices affected the energy efficiency of air conditioners. Regarding the automobile industry, Knitell (2011) shows a positive correlation between gasoline price and technological progress.

The introduction of the European regulation on emissions for new cars fostered technological change by 4%. However, once we control for the type of cars, the impact of the regulation on car manufacturers rises to 5%. This is an expected result given that when controlling for the type of car, the effect of a change in the mix of type of cars to fulfil the emission constraint is held constant. As regards the lag structure of the impact, we obtain that manufacturers would react quickly and intensively to the adoption of the new regulation. The estimated coefficient decreases over time and drops to zero in 2013. This result is in accordance with both the available literature[21] and the evolution of CO_2 emissions from new passenger cars in Spain. According to the European Environment Agency's technical report (2015), the target established for 2015 was already reached in 2012. Nonetheless, we would like to point out that a dummy variable is a crude instrument to account for the impact of regulation on innovation. Thus, the quantitative results should be taken with caution as the dummy can act as a proxy for other factors that took place in the same period. However, recent papers by Bento et al. (2015), Reynaert (2015) and Klier and Linn (2015) also confirm that emission standards have a significant effect on the rate of innovation.

Finally, we estimate an equation that relates the contribution of car characteristics to fuel consumption with respect to some possible determinants. Changes in car characteristics depend both on consumer preferences and on manufacturers' decisions, yet, our analysis cannot distinguish between these two sources of variation[22]. Since the index has been computed weighting car characteristics by sales, in our view, the effect of consumers' decisions will be predominant. Therefore, we select as the main explanatory variables those that capture demand behaviour. Specifically, we include GDP, energy price and a dummy variable that accounts for the change in the registration tax implemented in Spain in 2008[23]. Nonetheless, we also test if the adoption of the EC regulation in 2009 could have had any effect on characteristics through manufacturers' decisions, without finding any significant effect.

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[21] Reynaert (2015) and Klier and Linn (2015) also find that technology adoption changed quickly after the standards were announced.

[22] On the one hand, consumers decide about the type of car to buy according to their tastes, income and the price of car characteristics, among others. On the other hand, manufacturers can influence the mix of car sales both by changing the price of characteristics and by changing the type of cars they offer. in the market. For instance, Klier and Linn (2012) and Whitefoot et al. (2013) confirm that car manufacturers react to the introduction of new emissions targets by releasing smaller but more efficient vehicles.

[23] In 2008 a new registration tax was introduced based on CO_2 emissions. The tax rate ranges from 0% for vehicles with CO_2 emissions lower than 120g/km to 14.75% for vehicles with emissions larger than 200g/km. It is a low purchase tax compared with other European countries, but it is sensitive to CO_2, although the threshold is rather high.

Table 4. Determinants of contribution of car characteristics (1988-2013)

Dep. Var: ln(index of contribution of characteristics)

	Petrol-1	**Petrol-2**	**Diesel-1**	**Diesel -2**
Constant	-1.2171***	-1.1545***	-1.9802***	-0.5221
	(-8.42)	(-7.73)	(-6.57)	(-1.40)
Ln(GDP)	0.2323***	0.2203***	0.3549***	0.0912
	(7.75)	(7.29)	(6.69)	1.35
Ln(Brent price)	-0.0252*	-0.0234*	-0.0062	0.0033
	-1.84	-1.85	-0.57	0.21
D2008	0.0015	0.0019	-0.0114	-0.0091
	0.14	0.17	-0.92	-0.60
AR(1)	0.5184	0.5544*	0.7041***	0.6424**
	1.66	1.84	3.11	2.20
SIGMASQ	0.0001***	0.0001***	0.0001***	0.0001***
	4.35	4.42	2.98	3.06
Adjusted R-sq	0.9367	0.9362	0.9778	0.6933
S.E. regression	0.0099	0.0095	0.0100	0.0111
Durbin-Watson	1.8002	1.8001	1.6265	1.5261

Note: Petrol-1 and Diesel-1 correspond to the indexes derived from Model 1 (without controlling on the type of car), while Petrol-2 and Diesel-2 correspond to the indexes derived from Model 2 (controlling on the type of car; t-statistics in parenthesis.

The estimation results show that GDP is the main determinant of car characteristics. Although the price of Brent has a negative sign in three of the four equations, it is only marginally significant for petrol cars. That is to say, the economic recession that has affected Spain from 2007 is the main explanation for the demand for less consuming cars. Similarly, the new registration tax does not show a significant effect on consumer decisions. The lack of precision in the estimation of the adoption of a new tax regime can be explained by the difficulties in disentangling the effect of tax reform from the fall in GDP. Moreover, the Spanish government introduced several car scrapping programmes favouring low-consuming cars that cannot be evaluated in our analysis[24].

In any case, we want to stress that consumers do react to changes in GDP. For petrol cars, a 1% increase in GDP modifies car characteristics in such a way that this translates into a 0.23% increase in petrol consumption. For diesel cars this percentage increases up to 0.35% when we do not control for the type of car, showing that the consumers shift to larger and more powerful cars, such as four-wheel drives and SUVs, when there is an increase in GDP. In other words, consumers' reaction in expansion periods can

[24] We want to note that several papers find that fuel price has a significant effect on consumers' decisions regarding fuel economy when buying a car. See, for instance, Busse et al. (2013). Similarly, there is evidence that fiscal policies on CO_2 emission in Europe do affect consumer decisions (see Mabit, 2014 and Gerlagh et al., 2015).

offset, at least partially, the improvements in vehicle efficiency as a result of technological progress.

7. Conclusions

This paper provides evidence that there is a clear trade-off between fuel consumption and car characteristics, such as weight and engine size. Specifically, for petrol cars, increasing car weight and engine size by 1% would reduce fuel efficiency by 0.36% and 0.32%, respectively. By decomposing the observed change in fuel consumption, our study shows that technological progress would have improved fuel efficiency by around 30% for petrol cars and 42% for diesel cars had the weight and engine size been held constant at their 1988 values. However, the shift to bigger and faster cars has contributed to an increase in fuel consumption of around 10% for petrol cars and 20% for diesel cars. The higher percentage for diesel cars must be related to the replacement of traditional passengers' cars with four-wheel drive vehicles and alike. The results are robust to the hypothesis made regarding technological change.

The study estimates a natural annual growth rate of technological progress of around 1.1%. Moreover, we show that rising energy prices prompts the rate of innovation and that the introduction of mandatory emission standards encourages energy-saving technologies. On the contrary, consumers positively react to increases in GDP by buying larger and more powerful cars. For petrol cars, a 1% increase in GDP modifies car characteristics in such a way that this translates into a 0.23% increase in petrol consumption. For diesel cars, this percentage rises to 0.35% when not controlling for the type of car. Accordingly, consumers' reactions in expansion periods can partially offset the improvements in energy efficiency as a result of technological progress.

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Annex 1: Tables

Table A.1. Estimation results for the pooled equation

	Petrol cars			Diesel cars		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
ln(weight)	0,427***	0,365***	0,362***	0,715***	0,324***	0,313***
	(26,610)	(25,617)	(24,345)	(34,764)	(17,922)	(17,341)
ln(engine size)	0,283***	0,278***	0,317***	0,243***	0,332***	0,403***
	(19,805)	(25,193)	(26,575)	(12,575)	(23,144)	(26,049)
Four-wheel drive		0,290***	0,320***		0,326***	0,280***
		(20,767)	(24,759)		(36,454)	(21,681)
SUV_1		0,111***	0,113***		0,230***	0,220***
		(16,319)	(16,437)		(23,826)	(21,624)
SUV_2		0,136***	0,129***		0,178***	0,146***
		(9,962)	(9,009)		(26,708)	(20,808)
Minivan_1		0,031***	0,024***		0,051***	0,044***
		(4,851)	(3,734)		(7,565)	(6,702)
Minivan_2		0,069***	0,050***		0,152***	0,128***
		(7,216)	(4,248)		(15,275)	(12,228)
D1989	0,017	0,009	0,006	-0,013	-0,007	-0,006
	(1,296)	(0,732)	(0,569)	(-0,570)	(-0,377)	(-0,286)
D1990	0,007	-0,003	-0,005	-0,034	-0,021	-0,020
	(0,576)	(-0,307)	(-0,506)	(-1,539)	(-1,302)	(-1,057)
D1991	-0,008	-0,013	-0,012	-0,047**	-0,036**	-0,037*
	(-0,646)	(-1,170)	(-1,231)	(-2,150)	(-2,207)	(-1,945)
D1992	-0,011	-0,017	-0,016	-0,072	-0,055	-0,057
	(-0,956)	(-1,534)	(-1,633)	(-3,252)	(-3,390)	(-3,079)
D1993	-0,016	-0,024**	-0,023**	-0,070***	-0,057***	-0,058***
	(-1,403)	(-2,259)	(-2,352)	(-3,357)	(-3,747)	(-3,368)
D1994	-0,023**	-0,030***	-0,027***	-0,087	-0,068	-0,069
	(-1,967)	(-2,848)	(-2,859)	(-4,039)	(-4,560)	(-4,035)
D1995	-0,036***	-0,041***	-0,040***	-0,089***	-0,069***	-0,071***
	(-2,965)	(-3,853)	(-4,055)	(-4,153)	(-4,599)	(-4,113)
D1996	-0,048***	-0,052***	-0,051***	-0,103	-0,079	-0,082
	(-3,911)	(-4,905)	(-5,225)	(-4,749)	(-5,285)	(-4,873)
D1997	-0,059	-0,063	-0,062	-0,136**	-0,098**	-0,097*
	(-4,994)	(-5,907)	(-6,216)	(-6,729)	(-6,577)	(-5,832)
D1998	-0,078	-0,081	-0,079	-0,168	-0,122	-0,120
	(-6,570)	(-7,483)	(-7,860)	(-8,367)	(-7,565)	(-6,879)
D1990	-0,091	-0,094	-0,090	-0,180***	-0,134***	-0,132***
	(-7,434)	(-8,622)	(-8,925)	(-8,754)	(-8,399)	(-7,635)
D2000	-0,106	-0,108**	-0,104**	-0,227	-0,180	-0,178
	(-8,564)	(-9,784)	(-10,127)	(-10,953)	(-11,327)	(-10,293)
D2001	-0,121**	-0,122***	-0,118***	-0,246***	-0,185***	-0,183***
	(-10,480)	(-11,445)	(-11,907)	(-12,251)	(-11,846)	(-10,609)

D2002	-0,135***	-0,135***	-0,129***	-0,258	-0,193	-0,190
	(-11,637)	(-12,665)	(-12,855)	(-13,443)	(-12,736)	(-11,162)
D2003	-0,150***	-0,152***	-0,146***	-0,276**	-0,206**	-0,202*
	(-13,132)	(-14,664)	(-14,825)	(-14,439)	(-13,853)	(-11,988)
D2004	-0,173	-0,173	-0,167	-0,295	-0,220	-0,216
	(-15,590)	(-16,465)	(-16,630)	(-16,516)	(-15,296)	(-12,930)
D2005	-0,181	-0,182	-0,175	-0,307***	-0,229***	-0,224***
	(-16,083)	(-17,042)	(-16,990)	(-17,514)	(-16,067)	(-13,508)
D2006	-0,204	-0,204	-0,198	-0,324	-0,237	-0,233
	(-17,935)	(-18,466)	(-18,944)	(-18,725)	(-16,769)	(-14,125)
D2007	-0,226	-0,225**	-0,220**	-0,347***	-0,250***	-0,245***
	(-18,759)	(-18,894)	(-19,747)	(-19,956)	(-17,526)	(-14,742)
D2008	-0,251**	-0,251***	-0,245***	-0,362	-0,268	-0,262
	(-20,540)	(-20,752)	(-21,794)	(-20,153)	(-18,526)	(-15,600)
D2009	-0,276***	-0,275***	-0,271***	-0,384**	-0,290**	-0,280*
	(-22,582)	(-23,032)	(-24,747)	(-21,114)	(-19,787)	(-16,588)
D2010	-0,287***	-0,287***	-0,282***	-0,415	-0,315	-0,302
	(-23,147)	(-23,710)	(-25,485)	(-21,958)	(-20,652)	(-17,427)
D2011	-0,322	-0,329**	-0,324**	-0,471***	-0,374***	-0,357***
	(-25,473)	(-28,174)	(-29,636)	(-25,383)	(-24,291)	(-20,434)
D2012	-0,344**	-0,354***	-0,347***	-0,503	-0,411	-0,392
	(-24,942)	(-26,994)	(-28,132)	(-26,215)	(-25,964)	(-21,958)
D2013	-0,352***	-0,363***	-0,358***	-0,533***	-0,443***	-0,425***
	(-25,775)	(-27,790)	(-29,446)	(-28,452)	(-27,570)	(-23,737)
Alfa Romeo			(dropped)			(dropped)
Audi			-0,058***			-0,096***
			(-5,014)			(-7,656)
BMW			-0,090***			-0,103***
			(-8,557)			(-9,042)
Chrysler			-0,048***			-0,027
			(-3,452)			(-1,453)
Citroen			-0,025**			-0,038***
			(-2,432)			(-3,312)
Chevrolet			0,011			-0,003
			(0,847)			(-0,201)
Dacia			0,106***			-0,001***
			(7,761)			(-0,061)
Daewoo			0,022***			
			(1,612)			
Fiat			-0,010**			-0,019
			(-0,969)			(-1,439)
Ford			-0,054***			-0,052***
			(-5,131)			(-4,312)
Galloper			0,088***			-0,081
			(4,893)			(-1,858)

Honda	-0,072***	-0,123***
	(-6,127)	(-9,711)
Hyundai	-0,048**	0,006
	(-4,347)	(0,374)
Jeep	-0,167	-0,059***
	(-6,222)	(-3,424)
Kia	-0,063***	-0,028*
	(-4,578)	(-1,956)
Lancia	-0,030***	-0,038***
	(-2,577)	(-2,369)
Land Rover	-0,078**	-0,025
	(-1,523)	(-1,400)
Mazda	-0,057***	-0,054***
	(-4,523)	(-3,304)
Mercedes	-0,045***	-0,081
	(-4,075)	(-7,203)
Mini	-0,121***	-0,128***
	(-5,194)	(-5,151)
Mitsubishi	-0,118**	-0,015
	(-6,681)	(-0,820)
Nissan	-0,074	-0,013
	(-6,499)	(-1,045)
Opel	-0,056***	-0,032***
	(-5,680)	(-2,823)
Peugeot	-0,042***	-0,032***
	(-4,133)	(-2,853)
Porsche	0,012**	-
	(0,581)	
Renault	-0,040***	-0,037***
	(-3,959)	(-3,293)
Rover	-0,019***	-0,105
	(-1,747)	(-7,916)
Saab	0,010***	-0,048***
	(0,883)	(-3,099)
Seat	-0,028**	-0,096
	(-2,469)	(-7,941)
Skoda	-0,041	-0,071***
	(-3,771)	(-4,457)
Suzuki	-0,021***	0,039
	(-1,658)	(2,494)
Toyota	-0,067***	-0,032
	(-6,594)	(-2,708)
Volkswagen	-0,032**	-0,080***
	(-3,161)	(-6,581)
Volvo	-0,053***	-0,046***
	(-4,726)	(-3,609)

Smart			-0,020**			-0,030
			(-1,029)			(-1,000)
Lexus			-			-0,023
						(-1,099)
Ssangyong			-			0,005***
						(0,291)
_cons	-2,953***	-2,486***	-2,722***	-4,927***	-2,895***	-3,310***
	(-50,141)	(-46,736)	(-41,515)	(-56,346)	(-39,976)	(-37,664)
R-squared	0,8342	0,8834	0,9033	0,8066	0,9012	0,9162
Observations	2531	2531	2531	2311	2311	2311

Note: *** p<0.01, ** p<0.05, * p<0.1; Robust t-statistics in parenthesis

Table A.2. Estimation results for the pooled equation with S.E. clustered at manufacturer level

	Petrol cars			**Diesel cars**		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
ln(weight)	0,427***	0,365***	0,362***	0,715***	0,324***	0,313***
	(10,568)	(12,559)	(9,685)	(11,646)	(8,892)	(7,879)
ln(engine size)	0,283***	0,278***	0,317***	0,243***	0,332***	0,403***
	(6,367)	(11,015)	(12,859)	(3,833)	(10,191)	(10,274)
Four-wheel drive		0,290***	0,320***		0,326***	0,280***
		(7,325)	(12,984)		(16,457)	(8,591)
SUV_1		0,136***	0,129***		0,230***	0,220***
		(6,370)	(6,439)		(11,043)	(8,589)
SUV_2		0,111***	0,113***		0,178***	0,146***
		(6,524)	(7,188)		(13,285)	(11,372)
Minivan_1		0,031**	0,024**		0,051***	0,044***
		(2,511)	(2,044)		(3,579)	(2,954)
Minivan_2		0,069***	0,050**		0,152***	0,128***
		(3,215)	(1,980)		(7,315)	(6,305)
D1989	0,017*	0,009	0,006	-0,013	-0,007	-0,006
	(1,887)	(1,359)	(0,912)	(-1,158)	(-0,744)	(-0,711)
D1990	0,007	-0,003	-0,005	-0,034**	-0,021	-0,020
	(0,562)	(-0,539)	(-0,821)	(-2,088)	(-1,583)	(-1,465)
D1991	-0,008	-0,013*	-0,012*	-0,047***	-0,036**	-0,037**
	(-0,693)	(-1,738)	(-1,689)	(-2,828)	(-2,421)	(-2,489)
D1992	-0,011	-0,017*	-0,016*	-0,072***	-0,055***	-0,057***
	(-0,918)	(-1,853)	(-1,835)	(-3,274)	(-2,960)	(-2,862)
D1993	-0,016	-0,024**	-0,023**	-0,070***	-0,057***	-0,058***
	(-1,170)	(-2,209)	(-2,202)	(-3,137)	(-2,962)	(-2,751)
D1994	-0,023	-0,030***	-0,027**	-0,087***	-0,068***	-0,069***
	(-1,577)	(-2,634)	(-2,467)	(-3,986)	(-3,635)	(-3,408)
D1995	-0,036**	-0,041***	-0,040***	-0,089***	-0,069***	-0,071***

	(-2,412)	(-3,489)	(-3,522)	(-3,958)	(-3,744)	(-3,568)
D1996	-0,048***	-0,052***	-0,051***	-0,103***	-0,079***	-0,082***
	(-3,424)	(-4,987)	(-4,934)	(-3,958)	(-3,592)	(-3,379)
D1997	-0,059***	-0,063***	-0,062***	-0,136***	-0,098***	-0,097***
	(-4,786)	(-6,790)	(-6,611)	(-4,757)	(-3,893)	(-3,504)
D1998	-0,078***	-0,081***	-0,079***	-0,168***	-0,122***	-0,120***
	(-5,678)	(-7,623)	(-7,000)	(-5,383)	(-4,177)	(-3,781)
D1990	-0,091***	-0,094***	-0,090***	-0,180***	-0,134***	-0,132***
	(-5,634)	(-8,001)	(-7,532)	(-5,374)	(-4,488)	(-4,060)
D2000	-0,106***	-0,108***	-0,104***	-0,227***	-0,180***	-0,178***
	(-6,342)	(-8,921)	(-8,567)	(-7,050)	(-6,195)	(-5,713)
D2001	-0,121***	-0,122***	-0,118***	-0,246***	-0,185***	-0,183***
	(-7,640)	(-9,883)	(-9,404)	(-7,944)	(-6,314)	(-5,884)
D2002	-0,135***	-0,135***	-0,129***	-0,258***	-0,193***	-0,190***
	(-8,309)	(-10,538)	(-9,717)	(-8,797)	(-7,056)	(-6,396)
D2003	-0,150***	-0,152***	-0,146***	-0,276***	-0,206***	-0,202***
	(-10,005)	(-12,261)	(-11,444)	(-9,427)	(-7,876)	(-6,951)
D2004	-0,173***	-0,173***	-0,167***	-0,295***	-0,220***	-0,216***
	(-13,278)	(-14,663)	(-13,352)	(-10,517)	(-8,388)	(-7,314)
D2005	-0,181***	-0,182***	-0,175***	-0,307***	-0,229***	-0,224***
	(-13,752)	(-14,327)	(-12,897)	(-10,933)	(-8,739)	(-7,614)
D2006	-0,204***	-0,204***	-0,198***	-0,324***	-0,237***	-0,233***
	(-15,176)	(-15,494)	(-13,834)	(-11,708)	(-9,091)	(-7,889)
D2007	-0,226***	-0,225***	-0,220***	-0,347***	-0,250***	-0,245***
	(-13,836)	(-14,563)	(-13,052)	(-12,773)	(-9,823)	(-8,494)
D2008	-0,251***	-0,251***	-0,245***	-0,362***	-0,268***	-0,262***
	(-12,659)	(-13,951)	(-12,356)	(-12,489)	(-10,239)	(-8,861)
D2009	-0,276***	-0,275***	-0,271***	-0,384***	-0,290***	-0,280***
	(-14,135)	(-15,267)	(-14,014)	(-11,935)	(-10,716)	(-9,083)
D2010	-0,287***	-0,287***	-0,282***	-0,415***	-0,315***	-0,302***
	(-14,313)	(-15,302)	(-14,237)	(-12,415)	(-11,273)	(-9,622)
D2011	-0,322***	-0,329***	-0,324***	-0,471***	-0,374***	-0,357***
	(-14,644)	(-16,652)	(-15,266)	(-13,209)	(-13,416)	(-11,380)
D2012	-0,344***	-0,354***	-0,347***	-0,503***	-0,411***	-0,392***
	(-14,616)	(-16,304)	(-15,054)	(-13,921)	(-14,917)	(-12,796)
D2013	-0,352***	-0,363***	-0,358***	-0,533***	-0,443***	-0,425***
	(-14,875)	(-16,686)	(-15,666)	(-14,464)	(-14,933)	(-13,054)
Alfa Romeo			(dropped)			(dropped)
Audi			-0,058***			-0,096***
			(-14,040)			(-13,888)
BMW			-0,090***			-0,103***
			(-20,663)			(-14,691)
Chrysler			-0,048***			-0,027
			(-3,744)			(-1,572)
Citroen			-0,025***			-0,038***

	(-5,826)	(-8,433)
Chevrolet	0,011	-0,003
	(1,325)	(-0,363)
Dacia	0,106***	-0,001
	(8,598)	(-0,087)
Daewoo	0,022***	-
	(4,784)	
Fiat	-0,010*	-0,019***
	(-1,663)	(-3,768)
Ford	-0,054***	-0,052***
	(-13,085)	(-10,682)
Galloper	0,088***	-0,081***
	(3,569)	(-2,903)
Honda	-0,072***	-0,123***
	(-16,702)	(-19,388)
Hyundai	-0,048***	0,006
	(-10,403)	(1,095)
Jeep	-0,167***	-0,059**
	(-5,736)	(-2,109)
Kia	-0,063***	-0,028***
	(-10,318)	(-4,204)
Lancia	-0,030***	-0,038***
	(-7,750)	(-5,760)
Land Rover	-0,078***	-0,025*
	(-4,265)	(-1,715)
Mazda	-0,057***	-0,054***
	(-12,245)	(-11,791)
Mercedes	-0,045***	-0,081***
	(-13,213)	(-10,485)
Mini	-0,121***	-0,128***
	(-16,973)	(-15,305)
Mitsubishi	-0,118***	-0,015
	(-30,051)	(-0,987)
Nissan	-0,074***	-0,013
	(-19,907)	(-1,214)
Opel	-0,056***	-0,032***
	(-36,674)	(-5,270)
Peugeot	-0,042***	-0,032***
	(-11,845)	(-8,602)
Porsche	0,012	-
	(0,674)	
Renault	-0,040***	-0,037***
	(-8,903)	(-7,273)
Rover	-0,019***	-0,105***
	(-9,788)	(-35,698)

Saab			0,010**			-0,048***
			(2,414)			(-8,425)
Seat			-0,028***			-0,096***
			(-6,662)			(-21,910)
Skoda			-0,041***			-0,071***
			(-10,043)			(-17,430)
Suzuki			-0,021			0,039***
			(-1,628)			(2,889)
Toyota			-0,067***			-0,032***
			(-14,344)			(-3,655)
Volkswagen			-0,032***			-0,080***
			(-12,444)			(-19,168)
Volvo			-0,053***			-0,046***
			(-15,656)			(-9,567)
Smart			-0,020			-0,030*
			(-1,561)			(-1,782)
Lexus			-			-0,023**
						(-2,262)
Ssangyong			-			0,005
						(0,349)
_cons	-2,953***	-2,486***	-2,722***	-4,927***	-2,895***	-3,310***
	(-20,273)	(-15,511)	(-15,866)	(-13,908)	(-14,449)	(-14,528)
R-squared	0,8342	0,8834	0,9033	0,8066	0,9012	0,9162
Observations	2531	2531	2531	2311	2311	2311

Note: *** p<0.01, ** p<0.05, * p<0.1; Clustered t-statistics in parenthesis.

Table A.3 Index of technological change

	Petrol cars			Diesel cars		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
1988	1	1	1	1	1	1
1989	1,01676	1,00866	1,00643	0,98715	0,99343	0,99402
1990	1,00749	0,99662	0,99473	0,96658	0,97882	0,97974
1991	0,99237	0,98735	0,98785	0,95435	0,96498	0,96412
1992	0,98885	0,98361	0,98391	0,93065	0,94643	0,94462
1993	0,98377	0,97660	0,97768	0,93212	0,94500	0,94380
1994	0,97687	0,97059	0,97301	0,91696	0,93389	0,93330
1995	0,96487	0,96013	0,96105	0,91459	0,93333	0,93162
1996	0,95339	0,94929	0,95006	0,90235	0,92373	0,92173
1997	0,94245	0,93898	0,94016	0,87290	0,90641	0,90759
1998	0,92466	0,92262	0,92416	0,84499	0,88539	0,88736
1999	0,91318	0,91041	0,91350	0,83499	0,87445	0,87647
2000	0,89933	0,89775	0,90153	0,79675	0,83521	0,83694
2001	0,88600	0,88543	0,88870	0,78218	0,83146	0,83304
2002	0,87360	0,87343	0,87887	0,77272	0,82443	0,82681
2003	0,86082	0,85897	0,86429	0,75896	0,81400	0,81678
2004	0,84116	0,84090	0,84621	0,74431	0,80231	0,80603
2005	0,83461	0,83387	0,83986	0,73528	0,79552	0,79922
2006	0,81547	0,81551	0,82002	0,72326	0,78914	0,79227
2007	0,79757	0,79849	0,80257	0,70687	0,77910	0,78281
2008	0,77781	0,77831	0,78257	0,69626	0,76525	0,76981
2009	0,75868	0,75952	0,76280	0,68135	0,74836	0,75592
2010	0,75068	0,75034	0,75414	0,66063	0,72974	0,73940
2011	0,72463	0,71976	0,72344	0,62414	0,68782	0,69992
2012	0,70921	0,70187	0,70697	0,60497	0,66308	0,67589
2013	0,70309	0,69540	0,69940	0,58674	0,64179	0,65395

Table A. 4. Single year estimations

PETROL CARS												
Model 1	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
	coef/se	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**
ln(engine size)	0,304***	0,092	0,141	0,297***	0,240***	0,354***	0,396***	0,336***	0,336***	0,290***	0,330***	0,302***
	(0,093)	(0,101)	(0,101)	(0,077)	(0,076)	(0,070)	(0,069)	(0,073)	(0,071)	(0,071)	(0,057)	(0,055)
ln(weight)	0,391***	0,703***	0,560***	0,344***	0,428***	0,304***	0,248***	0,286***	0,285***	0,386***	0,387***	0,406***
	(0,128)	(0,136)	(0,132)	(0,105)	(0,101)	(0,093)	(0,090)	(0,093)	(0,090)	(0,091)	(0,072)	(0,076)
Constant term	-2,861***	-3,428***	-2,816***	-2,489***	-2,648***	-2,641***	-2,566***	-2,402***	-2,396***	-2,776***	-3,099***	-3,040***
	(0,360)	(0,349)	(0,361)	(0,323)	(0,292)	(0,272)	(0,275)	(0,280)	(0,292)	(0,297)	(0,294)	(0,301)

Model 2	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
	coef/se	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**
ln(engine size)	0,308***	0,154*	0,213***	0,199***	0,145**	0,241***	0,271***	0,274***	0,259***	0,244***	0,289***	0,287***
	(0,094)	(0,087)	(0,072)	(0,064)	(0,065)	(0,057)	(0,053)	(0,054)	(0,053)	(0,059)	(0,047)	(0,044)
ln(weight)	0,382***	0,574***	0,429***	0,442***	0,517***	0,379***	0,332***	0,304***	0,314***	0,377***	0,363***	0,351***
	(0,130)	(0,120)	(0,096)	(0,086)	(0,087)	(0,075)	(0,069)	(0,070)	(0,068)	(0,080)	(0,064)	(0,065)
Four-wheel drive	(dropped)	0,243***	0,288***	0,246***	0,255***	0,258***	0,261***	0,302***	0,316***	0,301***	0,311***	0,330***
		(0,048)	(0,036)	(0,044)	(0,042)	(0,035)	(0,034)	(0,040)	(0,040)	(0,043)	(0,046)	(0,048)
SUV_1	(dropped)	(dropped)	(dropped)	(dropped)	0,054	0,094	0,112**	0,136**	0,120**	0,106*	0,117*	0,152**
					(0,062)	(0,059)	(0,056)	(0,057)	(0,058)	(0,064)	(0,065)	(0,068)
SUV_2	(dropped)	(dropped)	0,211***	0,218***	0,223***	0,227***	0,225***	0,168***	0,181***	0,175***	0,160***	0,176***
			(0,061)	(0,059)	(0,057)	(0,056)	(0,053)	(0,039)	(0,039)	(0,042)	(0,037)	(0,034)
Minivan_1	(dropped)	-0,041	-0,012	-0,002	0,002	0,009	(dropped)	(dropped)	(dropped)	(dropped)	-0,098	-0,032
		(0,065)	(0,061)	(0,059)	(0,057)	(0,056)					(0,063)	(0,048)
Minivan_2	0,038	0,022	0,052	0,061	0,055	0,076*	0,087**	0,069**	0,083**	0,065*	0,080**	0,114***
	(0,070)	(0,066)	(0,061)	(0,059)	(0,058)	(0,041)	(0,039)	(0,033)	(0,034)	(0,034)	(0,032)	(0,031)
Constant term	-2,829***	-3,001***	-2,454***	-2,454***	-2,576***	-2,333***	-2,241***	-2,077***	-2,047***	-2,385***	-2,641***	-2,554***
	(0,367)	(0,315)	(0,264)	(0,262)	(0,246)	(0,219)	(0,210)	(0,217)	(0,223)	(0,258)	(0,255)	(0,253)

Note: *** p<0.01, ** p<0.05, * p<0.1

PETROL CARS (Continuation)

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se
0,307***	0,230***	0,265***	0,284***	0,305***	0,290***	0,280***	0,281***	0,285***	0,213***	0,274***	0,316***	0,162**	0,303***
(0,056)	(0,059)	(0,060)	(0,054)	(0,050)	(0,053)	(0,059)	(0,067)	(0,066)	(0,064)	(0,067)	(0,062)	(0,076)	(0,088)
0,396***	0,472***	0,415***	0,430***	0,459***	0,497***	0,480***	0,465***	0,412***	0,528***	0,475***	0,446***	0,556***	0,431***
(0,077)	(0,082)	(0,083)	(0,073)	(0,069)	(0,073)	(0,076)	(0,083)	(0,081)	(0,077)	(0,079)	(0,078)	(0,086)	(0,095)
-3,017***	-2,998***	-2,870***	-3,131***	-3,516***	-3,682***	-3,513***	-3,437***	-3,115***	-3,432***	-3,518***	-3,660***	-3,331***	-3,477***
(0,308)	(0,275)	(0,280)	(0,248)	(0,235)	(0,249)	(0,238)	(0,264)	(0,277)	(0,265)	(0,278)	(0,282)	(0,345)	(0,371)

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se
0,267***	0,277***	0,311***	0,310***	0,318***	0,293***	0,299***	0,323***	0,304***	0,221***	0,271***	0,307***	0,189**	0,342***
(0,045)	(0,048)	(0,049)	(0,041)	(0,043)	(0,046)	(0,057)	(0,072)	(0,066)	(0,064)	(0,068)	(0,057)	(0,075)	(0,087)
0,394***	0,373***	0,324***	0,335***	0,351***	0,393***	0,397***	0,356***	0,342***	0,457***	0,419***	0,346***	0,443***	0,294***
(0,064)	(0,069)	(0,071)	(0,058)	(0,064)	(0,068)	(0,080)	(0,100)	(0,083)	(0,079)	(0,084)	(0,074)	(0,090)	(0,099)
0,345***	0,375***	0,387***	0,403***	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)
(0,049)	(0,064)	(0,064)	(0,057)										
0,154**	0,195***	0,213***	0,163***	0,177***	0,179***	0,111***	0,090*	0,031	0,034	0,007	0,109	(dropped)	(dropped)
(0,069)	(0,048)	(0,048)	(0,030)	(0,032)	(0,033)	(0,036)	(0,046)	(0,048)	(0,056)	(0,055)	(0,071)		
0,179***	0,118***	0,115***	0,113***	0,119***	0,110***	0,100***	0,064*	0,083***	0,083***	0,078***	0,118***	0,087***	0,086***
(0,034)	(0,025)	(0,025)	(0,022)	(0,021)	(0,021)	(0,026)	(0,033)	(0,029)	(0,026)	(0,027)	(0,020)	(0,023)	(0,024)
-0,024	0,037	0,044	0,052*	0,016	0,003	-0,010	0,017	0,035	0,041	0,024	0,050**	0,053*	0,071**
(0,049)	(0,034)	(0,030)	(0,030)	(0,024)	(0,023)	(0,024)	(0,028)	(0,028)	(0,027)	(0,026)	(0,024)	(0,030)	(0,031)
0,074*	0,129***	0,027	0,038	0,027	0,026	0,003	0,034				0,050	0,068	
(0,042)	(0,046)	(0,066)	(0,059)	(0,062)	(0,064)	(0,073)	(0,083)				(0,068)	(0,083)	
-2,727***	-2,661***	-2,584***	-2,668***	-2,863***	-2,987***	-3,075***	-2,983***	-2,763***	-3,000***	-3,108***	-2,899***	-2,746***	-2,817***
(0,254)	(0,237)	(0,245)	(0,217)	(0,234)	(0,253)	(0,268)	(0,335)	(0,302)	(0,298)	(0,325)	(0,284)	(0,360)	(0,386)

Note: *** p<0.01, ** p<0.05, * p<0.1

DIESEL CARS

Model 1	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
	coef/se	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**
ln(engine size)	-0,094	-0,114	0,243	0,436***	0,266	0,251	0,067	0,526***	0,614***	0,499***	0,484***	0,438***
	(0,142)	(0,178)	(0,187)	(0,154)	(0,176)	(0,155)	(0,199)	(0,179)	(0,177)	(0,137)	(0,147)	(0,149)
ln(weight)	0,869***	0,949***	0,651***	0,540***	0,657***	0,708***	0,825***	0,557***	0,494***	0,556***	0,603***	0,597***
	(0,128)	(0,167)	(0,148)	(0,114)	(0,124)	(0,115)	(0,143)	(0,132)	(0,138)	(0,107)	(0,113)	(0,116)
Constant term	-3,453***	-3,872***	-4,508***	-5,198***	-4,760***	-5,004***	-4,457***	-6,049***	-6,282***	-5,873***	-6,124***	-5,746***
	(0,493)	(0,656)	(0,742)	(0,682)	(0,774)	(0,680)	(0,764)	(0,733)	(0,703)	(0,644)	(0,671)	(0,680)

Model 2	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
	coef/se	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**	**coef/se**
ln(engine size)	0,121	0,231	0,384***	0,529***	0,560***	0,416***	0,352***	0,465***	0,468***	0,410***	0,526***	0,546***
	(0,137)	(0,150)	(0,132)	(0,095)	(0,120)	(0,099)	(0,124)	(0,104)	(0,109)	(0,100)	(0,132)	(0,125)
ln(weight)	0,484***	0,342*	0,244*	0,127	0,035	0,208**	0,272**	0,156*	0,197**	0,219**	0,190	0,139
	(0,156)	(0,177)	(0,127)	(0,091)	(0,114)	(0,094)	(0,109)	(0,089)	(0,087)	(0,090)	(0,117)	(0,112)
Four-wheel drive	0,232***	0,355***	0,372***	0,352***	0,418***	0,357***	0,360***	0,378***	0,367***	0,344***	0,289***	0,329***
	(0,066)	(0,072)	(0,058)	(0,047)	(0,052)	(0,039)	(0,037)	(0,036)	(0,036)	(0,036)	(0,045)	(0,040)
SUV_1	(dropped)	(dropped)	0,162*	0,121*	0,275***	0,214***	0,210***	0,244***	0,239***	0,232***	0,241***	0,285***
			(0,087)	(0,073)	(0,066)	(0,059)	(0,058)	(0,056)	(0,056)	(0,059)	(0,077)	(0,079)
SUV_2	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	(dropped)	0,327***	0,261***	0,260***	0,277***
									(0,070)	(0,054)	(0,059)	(0,053)
Minivan_1	(dropped)	-0,068	-0,057	-0,062	-0,036	-0,033	(dropped)	(dropped)	(dropped)	(dropped)	0,030	0,057
		(0,081)	(0,073)	(0,064)	(0,072)	(0,068)					(0,096)	(0,072)
Minivan_2	0,081	0,091	0,107	0,119*	0,153**	0,126*	0,130***	0,146***	0,154***	0,110***	0,178***	0,207***
	(0,070)	(0,081)	(0,071)	(0,062)	(0,071)	(0,067)	(0,050)	(0,050)	(0,044)	(0,041)	(0,048)	(0,047)
Constant term	-2,412***	-2,271***	-2,747***	-3,035***	-2,649***	-2,775***	-2,752***	-2,795***	-3,116***	-2,844***	-3,542***	-3,346***
	(0,519)	(0,623)	(0,607)	(0,539)	(0,570)	(0,497)	(0,472)	(0,516)	(0,539)	(0,522)	(0,675)	(0,574)

Note: *** p<0.01, ** p<0.05, * p<0.1

DIESEL CARS (Continuation)

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se
0,394***	0,406***	0,275**	0,267***	0,167**	0,180***	0,201***	0,242***	0,269***	0,190***	0,235***	0,146**	0,028	0,001
(0,132)	(0,118)	(0,116)	(0,104)	(0,076)	(0,068)	(0,060)	(0,054)	(0,068)	(0,069)	(0,077)	(0,070)	(0,078)	(0,069)
0,614***	0,590***	0,713***	0,764***	0,881***	0,857***	0,815***	0,765***	0,721***	0,746***	0,675***	0,623***	0,655***	0,686***
(0,118)	(0,114)	(0,108)	(0,101)	(0,086)	(0,077)	(0,067)	(0,061)	(0,074)	(0,078)	(0,087)	(0,081)	(0,088)	(0,086)
-5,576***	-5,512***	-5,412***	-5,740***	-5,848***	-5,789***	-5,661***	-5,624***	-5,525***	-5,129***	-4,986***	-4,000***	-3,387***	-3,443***
(0,564)	(0,505)	(0,465)	(0,433)	(0,310)	(0,284)	(0,236)	(0,246)	(0,287)	(0,301)	(0,370)	(0,354)	(0,404)	(0,399)

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se	coef/se
0,458***	0,480***	0,480***	0,428***	0,317***	0,318***	0,251***	0,310***	0,309***	0,233***	0,275***	0,264***	0,137**	0,078
(0,102)	(0,089)	(0,092)	(0,079)	(0,061)	(0,055)	(0,049)	(0,043)	(0,051)	(0,053)	(0,059)	(0,064)	(0,069)	(0,065)
0,162	0,187**	0,196**	0,268***	0,435***	0,446***	0,533***	0,426***	0,388***	0,445***	0,327***	0,343***	0,381***	0,466***
(0,105)	(0,095)	(0,098)	(0,090)	(0,082)	(0,073)	(0,064)	(0,059)	(0,065)	(0,067)	(0,077)	(0,083)	(0,087)	(0,090)
0,355***	0,326***	0,308***	0,333***	0,292***	0,273***	0,257***	0,284***	0,317***	0,333***	0,420***			
(0,038)	(0,036)	(0,034)	(0,030)	(0,030)	(0,029)	(0,028)	(0,032)	(0,034)	(0,035)	(0,051)			
0,336***	0,293***	0,287***	0,251***	0,191***	0,182***	0,178***	0,234***	0,244***	0,179***	0,288***	0,131**	(dropped)	(dropped)
(0,076)	(0,055)	(0,049)	(0,042)	(0,035)	(0,032)	(0,027)	(0,031)	(0,036)	(0,042)	(0,061)	(0,057)		
0,320***	0,280***	0,253***	0,235***	0,193***	0,185***	0,158***	0,163***	0,189***	0,156***	0,181***	0,135***	0,128***	0,103***
(0,051)	(0,045)	(0,038)	(0,034)	(0,025)	(0,022)	(0,020)	(0,021)	(0,021)	(0,021)	(0,024)	(0,021)	(0,020)	(0,020)
0,046	0,032	0,103**	0,125***	0,051*	0,045*	0,013	0,025	0,033	0,039	0,065**	0,054**	0,064**	0,054**
(0,057)	(0,056)	(0,048)	(0,039)	(0,029)	(0,025)	(0,021)	(0,021)	(0,023)	(0,024)	(0,029)	(0,026)	(0,028)	(0,026)
0,193***	0,211***	0,192***	0,197***	0,168***	0,160***	0,094***	0,107***	0,110***	0,125***	0,184***	0,083*	0,129***	0,141*
(0,046)	(0,041)	(0,040)	(0,035)	(0,031)	(0,028)	(0,024)	(0,025)	(0,034)	(0,042)	(0,049)	(0,044)	(0,044)	(0,073)
-2,891***	-3,235***	-3,308***	-3,439***	-3,812***	-3,907***	-4,029***	-3,725***	-3,465***	-3,317***	-2,814***	-2,889***	-2,250***	-2,459***
(0,479)	(0,419)	(0,402)	(0,361)	(0,309)	(0,280)	(0,246)	(0,258)	(0,277)	(0,281)	(0,348)	(0,360)	(0,380)	(0,401)

Note: *** p<0.01, ** p<0.05, * p<0.1

Table A. 5. Decomposition of changes in petrol consumption (unweighted sample)

	Petrol cars			Diesel cars		
	Technological change	Change in characteristics	Mixed effects	Technological change	Change in characteristics	Mixed effects
1988	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000
1989	1,01173	1,01823	1,00336	0,98733	1,01448	1,00118
1990	1,00002	1,02793	1,00122	0,96854	1,04307	0,99168
1991	0,98752	1,04215	0,99978	0,96029	1,07103	0,98985
1992	0,98405	1,05412	1,00076	0,93724	1,09820	0,98827
1993	0,98142	1,06931	1,00089	0,93878	1,10082	0,98859
1994	0,97780	1,07734	1,00000	0,92281	1,12116	0,98943
1995	0,96508	1,07463	1,00065	0,92097	1,12657	0,98841
1996	0,95487	1,07379	1,00065	0,91064	1,12512	0,98788
1997	0,94475	1,06901	1,00190	0,88331	1,15682	0,98868
1998	0,92948	1,08227	1,00181	0,85682	1,17554	0,98984
1999	0,91764	1,08409	1,00191	0,84742	1,16783	0,99020
2000	0,90352	1,08336	1,00198	0,80975	1,16782	0,99054
2001	0,88808	1,09043	1,00345	0,79606	1,19043	0,99009
2002	0,87586	1,09200	1,00322	0,78622	1,21022	0,99141
2003	0,86444	1,10362	1,00366	0,77149	1,22761	0,99250
2004	0,84506	1,10832	1,00394	0,75422	1,21488	0,99656
2005	0,83797	1,11275	1,00430	0,74439	1,21515	0,99636
2006	0,81799	1,11576	1,00421	0,73040	1,23586	0,99540
2007	0,79933	1,12282	1,00402	0,71329	1,25269	0,99445
2008	0,77900	1,10862	1,00437	0,70297	1,23539	0,99450
2009	0,75819	1,11002	1,00666	0,68769	1,21727	0,99527
2010	0,75054	1,11079	1,00601	0,66662	1,21074	0,99449
2011	0,72451	1,12526	1,00602	0,62813	1,20126	0,99679
2012	0,70513	1,11348	1,01050	0,60624	1,18940	0,99835
2013	0,70014	1,10875	1,00787	0,58522	1,17161	0,99812

Note: The indexes have been computed using the estimations of Model 1

Table A. 6. Decomposition of changes in petrol consumption (weighted sample)

	Petrol cars			Diesel cars		
	Technological change	Change in characteristics	Mixed effects	Technological change	Change in characteristics	Mixed effects
1988	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000
1989	1,00807	1,00843	1,00249	0,98441	1,00538	1,00057
1990	1,00773	1,01865	1,00104	0,96585	1,02776	0,99850
1991	0,99852	1,03596	0,99907	0,95870	1,06158	0,99863
1992	0,99334	1,04427	1,00039	0,93212	1,05706	0,99708
1993	0,98719	1,07623	1,00252	0,92994	1,04969	0,99716
1994	0,98431	1,06369	1,00192	0,91250	1,05377	0,99980
1995	0,97624	1,06092	1,00187	0,90800	1,06676	1,00061
1996	0,96628	1,06555	1,00185	0,89873	1,07110	0,99992
1997	0,94851	1,08044	1,00437	0,87258	1,07628	1,00105
1998	0,92796	1,09956	1,00451	0,84243	1,10573	1,00266
1999	0,91741	1,09863	1,00486	0,83635	1,10782	1,00262
2000	0,90380	1,10459	1,00482	0,79993	1,13242	1,00262
2001	0,89051	1,10254	1,00732	0,78748	1,14346	1,00220
2002	0,87907	1,10853	1,00664	0,77511	1,14648	1,00638
2003	0,86372	1,10959	1,00662	0,75748	1,14765	1,00701
2004	0,83852	1,11101	1,00668	0,73887	1,14914	1,01235
2005	0,82982	1,11826	1,00682	0,72989	1,17251	1,01187
2006	0,81302	1,12754	1,00654	0,71710	1,21560	1,01047
2007	0,79573	1,14895	1,00610	0,70035	1,24241	1,00866
2008	0,77913	1,15259	1,00558	0,69013	1,21995	1,00916
2009	0,75737	1,14778	1,00659	0,67782	1,21701	1,00941
2010	0,74818	1,12456	1,00643	0,65705	1,22034	1,00873
2011	0,72076	1,12393	1,00558	0,62224	1,21536	1,01057
2012	0,70850	1,11395	1,00635	0,60278	1,20590	1,01161
2013	0,70205	1,10255	1,00202	0,58202	1,19735	1,01134

Note: The indexes have been computed using the estimations of Model 1

Annex 2

False clusters, superfluous heteroscedasticity correction and effects on the estimated standard errors of coefficients

As is known, using the option "cluster standard errors" provides a consistent estimate of the standard population errors when the number of clusters tends to infinity. When the number of clusters is small and the size of the clusters very unbalanced, inference using the cluster-robust estimator may be incorrect more often than when using the OLS estimator as Nichols and Schaffer (2007) have shown. In our case, we have 35 clusters (number of car brands) that are clearly unbalanced, with size ranging from 4 to 164. Therefore, the problem stated by Nichols and Schaffer (2007) clearly applies to our sample. In order to shed some light on the potential consequences on the estimated standard errors derived from forming false clusters in our database, we have carried out a simulation exercise.

The starting point in the simulation process is Model 3 in Table 2 of the main text:

$$y = X\beta + u \qquad \text{(a.1)}$$

where the dependent variable is the log of fuel consumption of petrol cars and the explanatory variables are car characteristics and vehicle types (seven variables), temporal dummies from 1989 to 2012 (twenty four variables) and car brand dummies (thirty five variables). Using the OLS estimation of the $\beta = \hat{\beta}$ parameters and of the standard error of disturbances $\sigma_u = \hat{\sigma}_u = 0.05974$, we generate a new dependent variable y^s as:

$$y^s = X\hat{\beta} + u^s \qquad \text{(a.2)}$$

where u^s has been generated as a normal independent random number distribution with a zero mean and a standard deviation of $\hat{\sigma}_u = 0.05974$.

Since the random disturbances verify the standard hypothesis of the regression model, the population matrix of variances and covariances of the estimated coefficients is obtained by:

$$\text{cov}\left(\hat{\beta}\right) = (0.05974)^2 \cdot \left(X'X\right)^{-1} \qquad \text{(a.3)}$$

Once the simulated dependent variable - y^s - has been generated, we estimate the equation with errors clustered at car brand level. It must be pointed out that, by definition, in the equation with the simulated dependent variable, we are dealing with false clusters. The new estimated covariance matrix is defined as:

$\text{cov}\ \tilde{\beta}$

This strategy enables the comparison of the population covariance matrix $\text{cov}\ \hat{\beta}$ with the estimated covariance matrix $\text{cov}\ \tilde{\beta}$ when false clusters are defined. This process was repeated 10,000 times.

For each standard error of the coefficient, we calculate the percentage of error defined by:

$$\text{Percentage of error for coefficient}_j = \left[\frac{\sqrt{\text{var}\ \tilde{\beta}_j} - \sqrt{\text{var}\ \hat{\beta}_j}}{\sqrt{\text{var}\ \hat{\beta}_j}} \right] \cdot 100$$

By way of comparison, we have repeated the same simulation process using the heteroscedasticity correction option suggested by White. The estimations of the covariance matrix are denominated “robust”. As in the previous case, when using simulated values, the robust correction is superfluous or unnecessary but the issue to investigate is the potential harmful effects of making such corrections in our database.

In order to facilitate the presentation of the results, the percentage of errors has been grouped into three headings: *characteristics* (10,000 replications and 7 estimated coefficients make 70,000 percentage of errors), *years* (10,000 replications and 24 coefficients make 240,000 percentage of errors) and *car brands* (10,000 replications and 34 car brands make 340,000 percentage of errors). A way to summarize this huge amount of information is through a kernel distribution as shown in Figure A.1. The upper part of this figure shows the cluster correction and the bottom part the robust correction.

Regarding *characteristics*, in the case of erroneous clusters, the distribution of the percentage of errors has an average near to -15%, and the average of the absolute values of the errors is almost 25%. On the other hand, introducing a superfluous robust correction has no effects in terms of bias, and the average of the absolute values of the errors is around 5%.

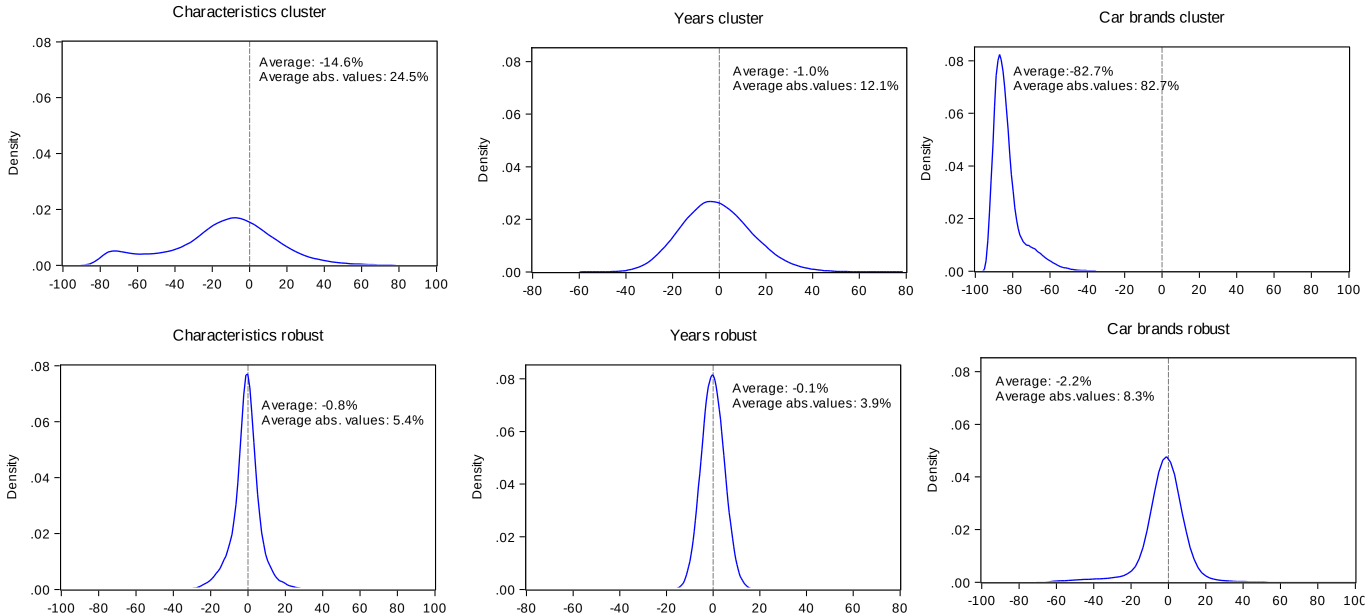
Going to yearly dummies, no cluster or robust seems to have any important effect on bias, but the cluster option leads to an average of the absolute values of errors of 12% compared to 4% for robust.

The most worrying results for the cluster option are those related to car brands. The cluster option implies a clearly negative bias, with an average of the distribution of errors equal to -83%, while the robust option seems to be free from bias. Also, the respective percentage of error referring to the absolute values is 83% for cluster and 8% for robust.

The simulation exercise reveals that in our database a blind application of cluster standard errors can be misleading. So, an eclectic approach consisting of considering both types of standard errors is the strategy followed in the main text. “False cluster” can have an important cost, while “superfluous robust” are almost free of any cost. But the other side of the coin is the negative consequences of employing the robust option when errors are actually clustered at the brand level. These are the reasons why we decided to maintain both the robust and the cluster options. Nonetheless, our conclusions in terms of the statistical significance of the coefficients are invariant to the option selected.

Figure A.1

False cluster, superflous heteroscedasticity correction and effects on estimated standar errors



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