Are car manufacturers on the way to reduce CO emissions?

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Highlights

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Are car manufacturers on the way to reduce CO_2 emissions?: A DEA approach

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- We test the ability of car manufacturers to meet emission targets.
- A DEA-Malmquist model is estimated using panel data between 2004 and 2010.
- With post-2007 technical change, the vast majority of companies beat the 2015 target.
- 27% of the market meets the 2020 target, and 3% meets the 2025 target.
- More stringent regulation is needed to meet the goals set by the European Authorities.

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Supplementary material.

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Are car manufacturers on the way to reduce CO_2 emissions?: A DEA approach

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ABSTRACT

One of the pillars of the fight against climate change is reducing the amount of greenhouse gases that are emitted into the atmosphere. In that regard, curtailing CO_2 emissions from transport activities is a major objective. In its attempts of "decarbonising" transport, the European Commission set in 2009 different emission limits on the vehicles sold in Europe. With this background, this paper aims to test the ability of the major car manufacturers to meet these present and future targets with the existing technological trends. To that end, we provide an in-depth analysis on the temporal evolution of emission efficiencies in the Spanish car market. The well-known DEA-Malmquist method is applied over a large sample of car models sold in Spain between 2004 and 2010. A second-stage regression allows us to identify the main drivers of efficiency, catch-up and technical change over the period. Finally, the estimated trends are extrapolated to predict future emission levels for the car manufacturers. Using post-regulation rates of technical change, results show that the vast majority of companies would meet the 2015 target, 27% of the current market would meet the 2020 target, and around 3% would be able to comply with the 2025 target. Thus, since all targets are technologically feasible, stricter regulation is the recommended approach to encourage manufacturers to meet the goals set by the European Commission.

1. Introduction

The apparent threat of global warming has led governments to put in place a diversity of regulations aimed at combating climate change. The United Nations' Conference on Climate Change is a clear example of the importance that environmental policies are taking on the political agenda. Within the set of sectors that make up the economy, road transport is a significant contributor to total greenhouse gas emissions, such as carbon dioxide (CO_2). According to the statistics of *Instituto para la Diversificación y Ahorro de Energía* (IDEA) for 2004, transport contributed 25% of total CO_2 emissions in the European Union.

In regards to public policy, two main approaches have been implemented to treat this negative externality[2]: pigouvian taxes, both to car sales and to gasoline prices[3]; and emission thresholds to new car production. In regard to the first, Ryan et al. (2009) show how both fiscal instruments reduce car sales in European Union in the period 1995–2004.

This paper, however, is more interested in the second course of action, which pursues to improve energy efficiency of internal combustion vehicles. To that end, in 1999 the European Commission (EC) signed a voluntary agreement with the European Automobile Manufacturers Association (ACEA)[4] to reduce CO_2 emissions for new cars. This agreement established a target of 140 g CO_2/km in 2008, with an intermediate target of 165–170 g CO_2/km for 2003. The Japan Automobile Manufacturers Association (JAMA)[5] and the Korean Automobile Manufacturers Association (KAMA)[6] also signed the agreement.

In 2007, with the expectation that the voluntary agreement did not achieve its objectives,[7] the EC defined a global strategy to reduce emissions to 120 g CO_2/km in 2012 (COM, 2007). In 2009, the European Commission (EC) again prioritized the "decarbonization" of road transport in Europe. EC's own research indicates that, in order to reduce the

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[2] CO_2 emissions are not exclusively a governmental concern. Koo et al. (2012) do an empirical study in South Korea to conclude that consumers consider energy efficiency when they decide to buy a new car.

[3] See Clerides and Zachariadis (2008) to compare the impact of fuel standards and fuel taxation over new car fuel economy. Recently, Karplus et al. (forthcoming) use a general equilibrium model to investigate the effect of combining a fuel economy standard with an economy-wide greenhouse gas emission constraint in the US.

[4] ACEA is composed by BMW AG, Daimler-Benz AG, Fiat Auto S.p.A., Ford of Europe Inc., General Motors Europe AG, F. Porsche AG, PSA Peugeot Citröen, Renault SA, Rover and Volkswagen AG. It also includes brands as Audi, Opel, Saab, Seat, Skoda and Volvo.

[5] JAMA is composed by: Daihatsu, Honda, Isuzu, Mazda, Nissan, Mitsubishi, Subaru, Suzuki and Toyota.

[6] KAMA is composed by Hyundai, Daewoo and Kia.

[7] In a recent report, the EC stated that ACEA had fallen short of meeting the target of 140 g CO_2/km in 2008, while JAMA and KAMA were about to accomplish in 2009 (EC, 2010).

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average temperature by 2 º C, the EU should reduce its emissions by 70% by 2050, using the 1990 levels as baseline[8] (EC, 2010). As a result of aforementioned strategy, the EU adopted Regulation 443/2009 to introduce mandatory CO_2 emission standards for new passenger cars.[9] These targets are 130 g CO_2/km by 2015,[10] and a long-term target of 95 g CO_2/km by 2020. In addition, the regulation also states that non-compliant manufacturers must pay "excess emissions premium" (EEA, 2011).

The introduction of these limits has sparked opposite reactions: In 2010, the EU declared unlikely that the objective of 120 g CO_2/km will be achieved in 2012 (COM, 2010), despite reduced emissions from new passenger cars during 2009.[11] According to Fontaras and Samaras (2010), car efficiency did not improve between 2003 and 2007, concluding that internal combustion vehicles had reached their technical limit, and therefore, meeting the requirement of 130 g CO_2/km in 2015 was impossible. On the contrary, Berggren and Magnusson (2012) conclude that the EC should set even stricter limits, proposing levels of 70–75 g CO_2/km in 2025 and of 50–55 g CO_2/km in 2030. Furthermore, in 2007, the European Parliament favored a target of 70 g CO_2/km by 2025, a proposal that the EC is still studying. In support of that, the analysis of Berggren and Magnusson (2012) found a 5.1% increase in car efficiency during 2009, which can be linked to car makers anticipating the new legislation and setting new strategic priorities that materialized in specially branded low-emission models.[12] Similarly, Sprei and Karlsson (forthcoming) found that, after 2007, Swedish car manufacturers started prioritizing fuel-saving technological advancements instead of consumer amenities. However, the authors did not make predictions about technical change, arguing that new regulations can alter the dynamics of the industry.

With this background, this paper aims to test the ability of the major car manufacturers to meet the present and future EC emission targets with the existing technological trends. To that end, we provide an in-depth analysis on the temporal evolution of technical efficiencies in the Spanish car market.[13] The well-known DEA-Malmquist method is applied over a large sample of car models sold in Spain between 2004 and 2010. Using balanced panel data allows us to obtain not only a static measure of car efficiency for each sample period, but also the dynamic measure of total efficiency change disaggregated into its two components: technical change and efficiency catch-up. A second-stage regression is used to identify the main drivers of efficiency, catch-up and technical change over the period. Finally, the estimated trends are extrapolated to predict future emission levels for the car manufacturers. In this way we can know if they are on track to achieve the emission targets set by the EC or otherwise require any technological step-change to meet these regulatory limits. Besides the evident contribution to environmental policy and regulation, this paper provides the first panel data efficiency analysis for the car market.

The rest of the paper is structured as follows: Section 2 presents a review of the academic literature on the estimation of car efficiency, as well as the technical literature on the reduction of engine emissions. Section 3 presents the car database and the data sources as well as the different estimation methodologies used in this study. Section 4 presents our results and discusses the main policy conclusions. Finally, Section 5 concludes.

2. Literature review

Despite the importance of the automotive sector in the European economy[14] and the popularity of the DEA methodology to measure the efficiency of different production sectors, we do not found a large number of studies analyzing the level of efficiency in the car sector. The number of studies is even smaller if we consider those that take into account CO_2 emissions as an undesirable output of internal combustion vehicles.

One of the first papers that studied car efficiency was Papahristodoulou (1997). The author divided the car sample in three classes depending on engine capacity (1.4 *l*–1.6 *l*, 1.6 *l*–2.0 *l*, and 2.0 *l*–3.5 *l*). The non-parametric DEA model found no significant efficiency differences between European and Japanese manufacturers, which, however, scored significantly lower than Korean producers. This study also found that vehicles with larger engines are the least efficient, and also that no significant relationship between efficiency and acceleration rates exists. Finally, it should be noted that efficiency scores vary widely among different brands. Some, such as the Korean Daewoo and Hyundai, the Spanish Seat or the Japanese Nissan, have a greater number of models with high efficiency scores.

Fontaras and Samaras (2007) analyze the evolution of CO_2 emissions per vehicle in Europe in the period 1992–2005. Their objective was to assess the commitment made by car manufacturers using independent data. They employed the ARTEMIS[15] database, made by the EC to harmonize emission measurements for all transport modes. Their descriptive approach leads to the following results: i) the data shows no significant improvement in fuel efficiency for individual car segments between 1992 and 2003; ii) CO_2 emissions from new registrations appear to decrease (compared to those of 1992), due to both changes in market shares and dieselization; and, iii) they found that in order to meet the 140 g CO_2/km target, emissions must be reduced by 22.5% with respect to the 2003 level.

For the U.S. car industry, Cheng and Zhang (2009) also analyzed the evolution of energy efficiency. The authors note the absence of significant efficiency improvements during the 80's and 90's, as the most efficient firms did not introduce any major advancements, even showing signs of technical regress. This gave inefficient firms the opportunity to catch up with the technological frontier. For the authors the factor that holds back technological progress is the trade-off between vehicle weight and energy efficiency.

Oh et al. (2010) focused on technical and allocative efficiencies[16] in the Korean automobile market. Authors use a combination of DEA and discrete choice models that allow them to take account the consumer preferences. The results show that the vast majority of vehicles have a very high level of technical efficiency, and low levels of allocative efficiency.

Finally, it is worth noting the unpublished study by Hampf and Krüger (2010), which incorporates CO_2 as an undesirable output of combustion engines. The authors note that the introduction of CO_2-emissions in the analysis reduced the technical efficiency estimates for the different car models in 1.7%, on average, while the trade-off between technical improvements and the decline in emissions is 7.4%. They also found that: i) compact vehicles are more efficient

[8] However, emissions increased by 26% from 1990 to 2010, so that the objective may be compromised.

[9] Until 2015, the electric vehicle counts as zero-emissions vehicles. So it is an incentive for manufacturers to promote it. We have also to note that the EU Fuel Quality Directive (FQD, 2009/30/EG) forces fuel suppliers to improve the well-to-wheel CO_2 emissions of their fuels by 6% in 2020.

[10] This value is defined as the average value for the fleet of newly registered passenger cars in the EU.

[11] Note that part of the reductions in 2008 and 2009 might have been due to the financial crisis and the design of scrappage schemes.

[12] Examples for this are: Mercedes Blue Efficiency, Volkswagen BlueMotion, BMW Efficient Dynamics, Ford Econetic, and Volvo DRIVe.

[13] The European car market is fairly homogeneous across countries, as we can see in different EC competition reports, e.g. http://ec.europa.eu/competition/sectors/motor_vehicles/prices/report.html. Thus, the choice of Spain does not preclude a generalization of the results for all of Europe.

[14] According to the Spanish Ministry of Industry, manufacture of automobiles and bicycles in Spain during 2009 accounted for 11.5% of total production and 7.2% of employment in all manufacturing sectors.

[15] Assessment and Reliability of Transport Emission Models and Inventory Systems database.

[16] This refers to the fit between product quality and consumer preferences.

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than larger ones. ii) European vehicles are more efficient than their U.S. or Asian counterparts. iii) SUVs (Sport Utility Vehicles) are, on average, less efficient than the rest. And iv) the results surprisingly show that vehicles powered with natural gas are also below average efficiency.

As seen in this section, the existing economic literature has made no dynamic analysis of car efficiency using panel data on a worldwide car sample, which allows for estimates of technical development in this industry to be obtained. Secondly, there is no econometric estimation on the drivers of car efficiency. Finally, there are no quantitative appraisals on the ability of the car manufacturers to comply with regulations imposed by the EC or the European Parliament. Our paper aims to fill these gaps in the literature.

3. Data and methodology

In order to achieve the proposed objectives, a large vehicle database was compiled from various sources. It contains data on retail prices and technical characteristics of 732 model variants sold in Spain between 2004 and 2010 by 41 major car manufacturers (with a grand total of 18,029 observations). Data on prices and technical characteristics was obtained from the National Motor Vehicle Retailers Association (GANVAM[17]), which provides information on the cars' dimensions, mass, performance, and equipment.

The presence of important asymmetries in the data required us to perform several aggregations in order to obtain the balanced panel required for the estimation of DEA-Malmquist models. First, the 732 variants were consolidated into 281 unique models by removing duplicated records that only differ in non-relevant variables, such as optional equipment (airbag, etc.). In order to facilitate comparisons across different manufacturers, these unique models were clustered in 21 categories that combine 4 body styles[18] and 8 car segments as defined by the European Commission[19] (EC, 1999). Thus, a hatchback in the C-segment (e.g. Ford Focus) is labeled as "H-C" (See Appendix 1 for a complete list of all defined categories).

The seven years of the original sample were consolidated into four time periods[20] in order to obtain the largest possible balanced panel. Finally, firm- and category-specific averages were taken for every time period, leading to final samples of 94 firm-models (376 observations) and 61 firm-models (244 obs.) for gasoline and diesel, respectively (See Appendices 2 and 3).

In order to characterize car technology, a simplified input–output structure is proposed. We assume that cars provide the necessary power (output: engine power) and capacity to accommodate persons and goods (output: volume[21]) for transportation to a certain distance (output: range). In order to achieve that, the vehicle needs to be adequately equipped (input: mass) and fuelled (input: fuel consumption).

Previous studies on this subject (Hampf and Krüger, 2010; Papahristodoulou, 1997) considered alternative variables, such as retail price (input), top speed and acceleration (outputs). While the latter are important performance indicators, they are highly correlated with engine power and hence, did not add to the estimation of the technological frontier. Retail prices, on the other hand, do not have any significant technological meaning. However, they are used in the second-stage analysis as one of the determinants of efficiency and technical change in the car market, along with the car's origin (Europe, United States, Japan, or Korea) and the price of unrefined oil (period average).

Data on CO_2 emissions, an undesirable output of car transportation, is also available. However, its inclusion in the DEA production frontier is not advised since emissions and fuel consumption are fully codetermined by fixed emission factors from the chemical equations of gasoline and diesel fuel combustion processes.[22] No efficiency gains can be obtained in that regard and car manufacturers can only strive to increase fuel efficiency by e.g. improving aerodynamics. This type of efficiency is the one measured by our model.

Finally, mixing technologies will only lead to misleading conclusions as diesel engines are systematically less polluting and more fuel efficient than gasoline engines. Hence, separate models for diesel and gasoline cars will be specified.

Table 1 below provides some descriptive statistics of the car sample. Note the significant variability in all relevant characteristics. Indeed, the database converse a wide range of car models, from compact cars to luxury 4 × 4 vehicles. As expected, the estimation of separate DEA frontiers for diesel and gasoline cars is justified by the important differences in average engine power, range, consumption and emissions. Regarding this last variable, it is worth noting that the percentage of models that achieve the 130 g/km emission target set by the EU increases, between 2004 and 2010, from 7% to 11% of gasoline models and from 33% to 50% of diesel models.

3.1. DEA-Malmquist model

Technical efficiency of the different car manufacturers that operate in Spain will be measured against an industry-wide technological frontier. This frontier can be formalized by the upper boundary of a production possibility set $y(x)$ that comprises all feasible output combinations (y) that can be obtained from a given quantity of inputs (x). According to Färe et al. (2007), for $y(x)$ to represent an actual production process, it should satisfy the axioms of inactivity,[23] compactness [24] and free-disposability of inputs.[25] These mathematical assumptions, in combination with the observed data (x_i, y_i), can be easily implemented in a set of linear optimization programs to obtain a non-parametric approximation to the technological frontier. This method, proposed by Charnes et al. (1978), is known as Data Envelopment Analysis (DEA) and it has been widely used in the empirical literature to measure the efficiency of decision making units. In a sample with n firms, m outputs and s inputs, the standard input-oriented DEA problem can be written as follows:

$$\min \theta; s.t.\theta x_i \geq X\lambda, y_i \geq Y\lambda, \lambda \geq 0, \sum\lambda = 1, \qquad (1)$$

where X is the $s \times n$ input matrix, Y is the $m \times n$ output matrix, and λ is an $n \times 1$ vector of firm-specific weights that add to 1 in order to allow for variable returns to scale (VRS). θ denotes the factor by which the evaluated firm could potentially scale down its input vector while holding the output constant. Thus, $\theta \in [0,1]$ can be interpreted as the indicator of technical efficiency. In order to determine this parameter, the optimization program finds the best-performing "peer", or linear combination of them, in the sample. Imposing VRS facilitates that these "peers" be similar to the evaluated firm-model combination by explicitly accounting for the importance of size in car performance. Finally, the input-orientation was considered the best alternative given the environmental framework of this research. Car manufacturers are assumed to try to minimize

[17] Asociación Nacional de Vendedores de Vehículos a Motor, Reparación y Recambios.

[18] These body styles are: sedan, station wagon/hatchback, 4 × 4/SUV, and minivan.

[19] EC's car segments are not formally defined as they combine dimensions, price, and performance variables. These segments are: A (mini), B (small), C (medium), D (large), E (executive), F (luxury), and S (sport). S-cars are further disaggregated into roadster/convertible, sportscar, grand tourer, and supercar.

[20] These periods are: 2004/2005 (period 1), 2006/2007 (2), 2008/2009 (3), and 2010 (4).

[21] Our database did not provide information on the vehicle's usable space. Hence, this variable was proxied by the volume delimited by the car's height, width, and wheelbase.

[22] Gasoline engines produce approximately 2.3 kg of CO_2 per liter of fuel, diesel engines' emission factor is approximately 2.6 kg CO_2 per liter (EPA, 2005).

[23] It is always feasible to produce zero quantity of outputs for any given input set.

[24] For each finite input set one could obtain a finite output level.

[25] It is feasible to increase input usage and keep the output level constant.

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Table 1
Overview of the car sample.
Source: GANVAM, ANIACAM, own elaboration.

GASOLINE	Engine power (HP)	Capacity (m3)	Range (km)	Fuel consumption (*l*/100 km)	Mass (kg)	CO_2 emissions (g/km)	Retail price (EUR)
Average	185.1	6.9	711.6	8.8	1872.7	207.2	45,869.9
Maximum	593.3	12.8	1031.8	21.0	3197.7	483.3	[illegible]0,515.3
Minimum	58.0	4.3	447.7	4.5	969.9	106.2	8078.5
Standard dev.	125.1	1.0	99.5	3.4	375.5	80.1	57,154.5
DIESEL	Engine power (HP)	Capacity (m3)	Range (km)	Fuel consumption (*l*/100 km)	Mass (kg)	CO_2 emissions (g/km)	Retail price (EUR)
Average	126.5	7.2	995.8	5.8	1969.3	153.6	26,383.5
Maximum	313.0	11.2	1315.6	11.3	7484.2	326.9	113,617.5
Minimum	41.0	4.3	647.1	3.3	970.1	86.2	11,178.2
Standard dev.	42.7	1.2	117.4	1.5	514.1	41.2	14,217.3

consumption rates (and hence, emissions) without sacrificing power, range, or capacity.[26]

The availability of panel data also allows us to study technical change and "catch-up" effects in the car industry, as the manufacturers may be incentivized, by regulation or otherwise, to reduce their performance gaps with respect to the state of technology at a given moment. The idea of comparing the firms' performance across different time periods was first proposed by Malmquist (1953) and then formalized by Caves et al. (1982) in the Malmquist Productivity Index. Färe et al. (1994) showed that, if panel data is available, a firm's Malmquist index of total productivity change between two time periods ($m_i^{t,t+1}$) can be estimated using a non-parametric DEA approach. Its input-oriented version can be written as follows:

$$m_i^{t,t+1} = \left(\frac{\theta_i^t \left(y_{t+1}, x_{t+1} \right)}{\theta_i^t (y_t, x_t)} \cdot \frac{\theta_i^{t+1} \left(y_{t+1}, x_{t+1} \right)}{\theta_i^{t+1} (y_t, x_t)} \right)^{0.5}, \quad (2)$$

where $\theta_i^t(y_t, x_t)$ denotes input-oriented technical efficiency of firm *i* in time period *t*, considering the technology of period *t*. The rest can be deduced by analogy, leading to the conclusion that the Malmquist index is a geometric average of simple efficiency ratios calculated under alternative technologies. A value of $m_i^{t,t+1} > 1$ indicates an increase in total productivity between *t* and *t + 1*. The computation of $m_i^{t,t+1}$ under CRS requires solving four different linear programs, i.e.

$$\min \theta_i^t (y_t, x_t); s.t. \theta x_i^t \geq X^t \lambda, y_i^t \geq Y^t \lambda, \lambda \geq 0 \quad (3)$$

$$\min \theta_i^t (y_{t+1}, x_{t+1}); s.t. \theta x_i^{t+1} \geq X^t \lambda, y_i^{t+1} \geq Y^t \lambda, \lambda \geq 0 \quad (4)$$

$$\min \theta_i^{t+1} (y_t, x_t); s.t. \theta x_i^t \geq X^{t+1} \lambda, y_i^t \geq Y^{t+1} \lambda, \lambda \geq 0 \quad (5)$$

$$\min \theta_i^{t+1} (y_{t+1}, x_{t+1}); s.t. \theta x_i^{t+1} \geq X^{t+1} \lambda, y_i^{t+1} \geq Y^{t+1} \lambda, \lambda \geq 0. \quad (6)$$

Besides, the introduction of VRS requires reestimating problems (3) and (6) with the additional convexity restriction $\Sigma\lambda = 1$. Once the different efficiencies have been obtained, Färe et al. (1994) also developed a method to disaggregate total productivity change in its two major components: "catch-up"/technical efficiency change (EFFCH) and technical change (TECHCH), i.e.

$$m_i^{t,t+1} = \frac{\theta_i^{t+1} (y_{t+1}, x_{t+1})}{\theta_i^t (y_t, x_t)} \cdot \left(\frac{\theta_i^t (y_{t+1}, x_{t+1})}{\theta_i^{t+1} (y_{t+1}, x_{t+1})} \cdot \frac{\theta_i^t (y_t, x_t)}{\theta_i^{t+1} (y_t, x_t)} \right)^{0.5} = \text{EFFCH} \cdot \text{TECHCH}. \quad (7)$$

According to Coelli et al. (2005), the Malmquist index is not able to identify all sources of productivity change under the assumption of VRS, including those related to changes in scale efficiency (Balk, 2001). These magnitudes, however, are not expected to be significant for the car market as car models do not tend to converge to an optimal size that may likely be a characteristic of a different market segments. Thus, the proposed decomposition remains valid (Coelli et al., 2005; p. 73). The well-known software DEAP 2.1 (Coelli, 1996) was used in the estimation. Among other features, it features in-built support for DEA-Malmquist models, including the Färe et al. (20[illegible]4) decomposition of total productivity change. Coelli's (1998) multi-stage method is employed to solve the linear programs. This ensures that units are benchmarked against actual frontier points[27] and also that efficiency results will be invariant to units of measurement, which are of critical importance due to the nature of our data (See Table 1). Q8

3.2. Second-stage analysis

In order to gain more insight on the determinants of car efficiency and technical development, a second-stage regression analysis on the estimated productivity indices will be carried out. Traditionally, a censored Tobit model has been the preferred regression method, featuring in a large number of empirical studies. However, Simar and Wilson (2007) recently proved that the Tobit model is not a valid approach for second-stage analysis due to the existence of serial correlation among the non-parametric efficiency estimates. Instead, they argue for the suitability of truncated regressions (removing efficient observations), which is the method we use to model the static measure of technical efficiency (TE) across the four sample periods. For the dynamic measures, catch-up/efficiency change (EFFCH) and technical change (TECHCH), a simple OLS model will be estimated.

Both gasoline and diesel second-stage regressions feature the same set of exogenous variables, including retail prices, the car's country of origin, a time trend and additional dummies representing the major car categories.[28] Retail prices are expected to be one of the most obvious determinants of car efficiency and technical change

[26] In that regard, one would argue that the most appropriate model to analyze car efficiency would be a directional output distance function (DODF), as in Hampf and Krüger (2010), which takes into account both the expansion of desirable outputs and reduction of undesirable outputs (CO_2) in the measure of efficiency. Since this output-oriented approach keeps inputs constant (e.g. consumption), the codetermination between both variables, as argued in Section 3.1, makes any reduction of CO_2 emissions unfeasible.

[27] In other words, both radial and slack movements are considered when determining the efficiency measure.

[28] Dummy variables for the largest brands will not be included because the estimating sample is not comprehensive at a brand-model level. Thus, there is a risk of producing misleading results, especially if a brand is represented only by its most/less polluting models.

Table 2
Gasoline DEA results (average efficiency by car category).

Category	TE	EFFCH				TECHCH			
	4	2	3	4	Sample	2	3	4	Sample
S-A	0.964	1.056	0.993	1.006	1.018	0.942	1.012	1.036	0.995
S-B	0.925	1.076	1.002	1.010	1.029	0.941	1.017	1.023	0.993
S-C	0.904	1.045	1.014	0.999	1.019	0.987	1.013	1.033	1.011
S-D	0.897	0.993	1.018	1.000	1.003	1.014	1.008	1.035	1.019
S-E	0.894	1.045	1.034	0.979	1.019	1.000	1.006	1.031	1.012
S-F	0.917	1.046	1.024	0.967	1.011	1.019	1.011	1.036	1.021
Av. Sedan	0.917	1.048	1.011	0.999	1.018	0.976	1.013	1.031	1.006
H-B	0.940	1.072	1.011	0.997	1.026	0.933	1.022	1.023	0.991
H-C	0.909	1.063	1.009	0.998	1.022	0.963	1.020	1.042	1.008
H-D	0.861	1.065	1.003	0.984	1.016	0.936	1.007	1.022	0.988
Av. Hatchback	0.899	1.066	1.007	0.993	1.021	0.948	1.016	1.032	0.998
4-B	0.906	1.218	0.986	1.008	1.066	0.850	1.031	1.009	0.960
4-C	0.950	1.073	1.013	1.011	1.031	0.911	1.004	1.024	0.978
4-D	0.977	1.071	1.024	1.042	1.044	0.964	1.004	1.023	0.996
4-E	1.000	1.178	1.031	1.024	1.075	0.942	1.043	1.136	1.037
4-F	1.000	1.068	1.058	1.055	1.061	0.953	1.003	1.028	0.994
Av. 4 × 4/SUV	0.961	1.114	1.018	1.023	1.050	0.919	1.015	1.040	0.990
SP-GT	0.958	0.951	1.019	0.969	0.979	1.053	1.017	1.063	1.044
SP-R	0.844	0.997	1.006	0.988	0.996	1.007	1.011	1.052	1.023
SP-S	0.929	0.978	1.009	0.996	0.994	1.037	1.013	1.082	1.043
Av. Sport	0.916	0.974	1.011	0.985	0.990	1.034	1.014	1.068	1.038
Grand average	0.921	1.051	1.011	1.000	1.020	0.970	1.014	1.037	1.006

as the revenue perspective may incentivise the company to invest in research and development.[29] In spite of that, high-end car customers may not be specially concerned about consumption and mileage, leading to reduced fuel efficiency in comparison with economy models. Thus, the sign of the price interaction remains, a priori, undetermined.

Regarding the car's origin, our database comprises cars from US, Japanese, Korean and European manufacturers, the latter serving as reference category. This variable is expected to characterize the impact of domestic preferences and regulatory approaches on car design and efficiency. A quadratic time trend (t) is also introduced in order to test if the dynamics of car performance have been influenced by the recent economic downturn (periods 3 and 4) or the rise in oil prices. In that regard, it is expected that the worst performers may have benefited from deceleration to catch-up with the industry. A negative impact on technical change is also expected. Finally, the model is completed with a set of four dummy variables labelling different car categories, these are: Sedan-A (in order to test if the competition from electric cars has led to better performance than other segments), Hatchback, 4 × 4, and Sport (all segments). Sedan cars from segments B to F are defined as the reference category. The final specification can be written as follows:

$$Y = \alpha + \beta_1 \cdot Price + \beta_2 \cdot Japan + \beta_3 \cdot Korea + \beta_4 \cdot US + \beta_5 \cdot t + \beta_6 \cdot t^2 + \\ + \beta_7 \cdot S - A + \beta_8 \cdot H + \beta_9 \cdot SP + \beta_{10} \cdot 4 \times 4 + v, \quad (8)$$

where Y represents TE, EFFCH or TECHCH as dependent variables, v is statistical white noise, and α, β are the coefficients to be estimated.[30]

3.3. Actual and predicted average emissions

Our estimates can also be used to estimate average emission levels per car manufacturer in order to analyze compliance to regulatory emission targets set for 2015, 2020, and 2025, under different scenarios of technological progress. While we recognize that observed technical change may not be a precise proxy for future technological potential, as manufacturers may have a number of "shelved" projects and technologies, this exploratory analysis can indicate if there is need for further acceleration, facilitated by a technical or regulatory step-change, in order to achieve the EC limits.

To that end, there is need to combine our database of technical characteristics with sales data. Total car sales during 2010 of 27 major car manufacturers operating in Spain were compiled from "Asociación Nacional de Importadores de Automóviles, Camiones, Autobuses y Motocicletas (ANIACAM)".

Firstly, all car models in the sales database were classified in segments for the sake of consistency. If a particular brand-segment pair is included in the DEA-Malmquist database, the specific efficiencies will be assigned, using the static TE estimate of period 4, and the dynamic measures of technical change (TECHCH) for period 2 (change between 2004 and 2007), period 4 (between 2008 and 2010), and over the whole sample period (2004–2010). This leads to alternative scenarios for technical change that can be used to obtain additional insights on the impact of recent regulations on car efficiency. If the brand-segment in the sales database is not included in the DEA-Malmquist sample, probably as a result of incomplete time-series, segment-average estimated efficiencies will be assigned with the same conditions as above.

Next, efficient emission values for 2010, still at a brand-segment level, are simply calculated by multiplying current emissions by the TE estimate for period 4. These values are sequentially projected to 2015, 2020, and 2025 by dividing by the 2010 efficient level by the different estimates of technical change compounded to 5 years in each step. Finally, average emissions per manufacturer (actual and efficient for 2010, and projected values for 2015, 2020, and 2025) under the different TECHCH scenarios are simply calculated as the sales-weighted mean of the respective emissions at a car segment level. Final results are benchmarked across manufacturers and against the regulatory emission targets defined by the EU, which are set at 130 g/km in 2015, 95 g/km in 2020, and 70 g/km in 2025.

4. Results

Tables 2 and 3 summarize the estimation results for the gasoline and diesel DEA-Malmquist models. This includes the most recent technical

[29] Previous research (Greene, 2010) shows that consumers place high value on fuel efficiency when making purchasing decisions.

[30] The model was estimated using Bayesian inference. The dependent variable was assumed to be normally distributed, with the expression in Eq. (8) as the mean and a constant variance σ_v^2. Non-informative priors were assigned to all coefficients. Prices were normalized between [0,1] in order to ease the interpretation of the estimated coefficients.

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Table 3
Diesel DEA results (average efficiency by car category).

Category	TE	EFFCH				TECHCH			
	4	2	3	4	Sample	2	3	4	Sample
S-A	0.965	0.994	1.000	1.006	1.000	1.006	1.043	1.021	1.023
S-B	0.965	0.991	0.983	1.016	0.996	1.015	1.031	1.026	1.024
S-C	0.961	0.996	0.993	1.025	1.004	1.036	1.034	1.039	1.036
S-D	0.913	0.988	0.977	0.976	0.980	1.058	1.046	1.045	1.050
S-E	0.921	0.949	0.977	0.986	0.970	1.054	1.019	1.013	1.028
S-F	1.000	1.000	1.000	1.000	1.000	0.985	1.038	1.066	1.029
Av. Sedan	0.955	0.991	0.988	1.010	0.996	1.028	1.035	1.034	1.032
H-B	0.979	1.013	0.952	1.049	1.003	1.020	1.031	1.022	1.024
H-C	0.922	0.982	0.986	1.034	1.000	1.043	1.032	1.021	1.032
H-D	0.916	0.970	0.989	1.004	0.988	1.031	1.019	1.021	1.023
H-E	0.916	0.946	0.984	0.987	0.972	1.057	1.016	1.013	1.029
Av. Hatchback	0.931	0.980	0.980	1.021	0.993	1.035	1.025	1.020	1.027
MV	1.000	1.010	0.963	0.991	0.988	0.987	1.010	1.009	1.002
4-B	0.930	1.019	0.987	0.969	0.991	0.985	1.001	1.014	1.000
4-C	0.909	1.012	0.993	0.999	1.001	0.990	1.003	1.014	1.002
4-D	1.000	0.927	0.985	1.109	1.004	1.050	1.021	1.026	1.032
4-E	0.862	0.975	0.988	1.015	0.993	0.982	1.000	1.020	1.001
4-F	1.000	0.992	1.024	1.045	1.020	0.994	1.003	1.035	1.010
Av. 4 × 4/SUV	0.931	0.993	0.995	1.019	1.001	0.997	1.005	1.020	1.007
Grand average	0.991	1.005	1.016	1.057	0.997	1.039	1.057	1.072	1.027

efficiency estimate (TE) for period 4, the decomposition of total productivity change in periods 2, 3, and 4 with respect to the previous period, and also over the entire sample period (2004–2010). For ease of reference, only average values are reported (category-specific). Full details are provided in Appendices 2 and 3 for gasoline and diesel, respectively.

A first relevant conclusion is that diesel cars are significantly more efficient than their gasoline counterparts (99% vs 92%) and experience more technological development (2.7% vs. 0.6% annual rate). This result seems reasonable when you consider that, in general, consumers of diesel vehicles usually place more importance on fuel efficiency than the users of gasoline cars. On the other hand, gasoline cars have improved their efficiency by an average 2% each year in order to catch up with the technological frontier. This result agrees with Cheng and Zhang (2009) in which the lack of strong technical development allows inefficient manufacturers to get closer to the best practices in the industry.

Looking at Tables 2 and 3, it is clear that there is a negative relationship between efficiency and car size in the Sedan and Hatchback segments, while the opposite applies to 4 × 4's. Again this result seems logical; indeed Hampf and Krüger (2010) indicated that compact cars were more efficient than those of middle and upper class. In the gasoline industry, catch-up indicators are very strong during the second period, matching the absence of technical progress, but manufacturers are unable to keep up with the state of technology after that. Note that only sportscars experience consistent technical progress between 2004 and 2010. The same applies to all diesel car segments, which, in addition, have been able to maintain their very high efficiency levels.

Second-stage results are shown in Tables 4 and 5. Truncated samples for the technical efficiency (TE) equations are 305 (71 efficient) and 200 (63 efficient) for gasoline and diesel, respectively. Reduced samples were also used for the dynamic equations, since catch-up/efficiency change (EFFCH) and technical change (TECHCH) estimates are not available for period 1.

The first conclusion from the second-stage analysis is that there appears to be a positive relationship between price and technical efficiency for gasoline cars, while the opposite applies to diesel cars. A possible explanation is that consumers of diesel vehicles have different income elasticities than gasoline users.[31] Unfortunately, the necessary income data to test this hypothesis is not available to the authors.

In spite of that, we believe that the negative price impact on diesel car efficiency deserves further analysis. Since diesel prices in our sample are not normally distributed, the price effect may not be homogeneous across different price segments. In order to investigate this, the second-stage diesel equations were re-estimated by splitting the sample in two price groups (above and under EUR 15,000[32]). Results are shown in Table 6. Diesel vehicles priced under EUR 15,000 have the expected positive price coefficient in the technical efficiency equation. On the contrary, diesel vehicles priced over EUR 15,000 still present a negative and significant price interaction. This result provides a deeper understanding on the relationship between engine type, consumer preferences, and technical efficiency, also complementing what was discussed above. Indeed, it is likely that consumers of low-price diesel cars are more concerned about consumption (and therefore emissions) than low-price gasoline vehicle consumers. On the high-end side, we argue that the revenue perspective boosts innovation and fuel efficiency improvements much more intensely in the gasoline segment, where larger emission reductions can be achieved, than in the diesel one.

In view of this evidence, one might ask why high-income consumers choose to buy very expensive diesel vehicles, which appears to be less efficient, instead of an expensive gasoline one. We must take into account two aspects. First, regardless of the price impact, diesel vehicles are, on average, more efficient than gasoline ones, see Tables 2 and 3. Second, even if high-end diesel vehicles turn up as less efficient than high-end gasoline vehicles because of the price impact (which cannot be automatically inferred from our second-stage results), one should take into account the significant tax difference between the two fuel types in Spain and the rest of Europe. Lower diesel taxes may end up compensating for any hypothetical consumption inefficiency with respect to gasoline cars.

The second conclusion is that gasoline cars from US have lower technical efficiency than European ones (as in Hampf and Krüger, 2010). No significant efficiency differences with respect to European manufacturers are found for Japanese or Korean gasoline cars. Moving now to diesel, the US coefficient is positive and significant only for vehicles over EUR 15,000, while in the lower-price segment Korean cars can be expected to be significantly more efficient. These results agree with Papahristodoulou (1997).

[31] We thank an anonymous referee for suggesting this explanation.

[32] The price distribution is bi-modal, with the largest frequency just below EUR 15,000 and a second mode around EUR 26,000. In addition, the 15,000 breakpoint leaves out all 4 × 4s from the lower-price model, allowing for sharper differentiation between car samples as per previous results from Tables 2 and 3.

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Table 4
Second-stage gasoline results.

Coefficient	EFF-TRUNC Mean	EFF-TRUNC Std	EFFCH-OLS Mean	EFFCH-OLS Std	TECHCH-OLS Mean	TECHCH-OLS Std
Constant	**0.7773**	**0.0200** (**)	**1.2173**	**0.0514** (**)	**0.8257**	**0.0385** (**)
Price	**0.0658**	**0.0369** (*)	**−0.0288**	**0.0175** (*)	**0.0414**	**0.0154** (**)
Japan	0.0072	0.0092	**−0.0138**	**0.0079** (*)	**0.0111**	**0.0065** (*)
Korea	−0.0018	0.0118	−0.0020	0.0090	−0.0011	0.0057
US	**−0.0355**	**0.0132** (**)	0.0022	0.0123	**−0.0225**	**0.0086** (**)
Time	**0.0903**	**0.0182** (**)	**−0.1087**	**0.0336** (**)	**0.0889**	**0.0249** (**)
Time^2	**−0.0145**	**0.0036** (**)	**0.0140**	**0.0052** (**)	**−0.0094**	**0.0039** (**)
S-A	**0.0509**	**0.0182** (**)	−0.0024	0.0115	−0.0096	0.0090
Hatch	−0.0137	0.0107	−0.0003	0.0077	−0.0040	0.0058
SP	−0.0219	0.0156	**−0.0223**	**0.0101** (**)	**0.0171**	**0.0090** (*)
4 × 4	−0.0159	0.0110	**0.0325**	**0.0115** (**)	**−0.0215**	**0.0091** (**)
R-squared	0.2214		0.2494		0.4293	

Bold indicates significant coefficients at 90% (*) and 95% (**) confidence levels.

Table 5
Second-stage diesel results.

Coefficient	EFF-TRUNC Mean	EFF-TRUNC Std	EFFCH-OLS Mean	EFFCH-OLS Std	TECHCH-OLS Mean	TECHCH-OLS Std
Constant	**1.0190**	**0.0204** (**)	**1.0963**	**0.0374** (**)	**1.0058**	**0.0262** (**)
Price	**−0.2616**	**0.0538** (**)	−0.0014	0.0158	**0.0296**	**0.0157** (**)
Japan	−0.0036	0.0081	**−0.0214**	**0.0060** (**)	0.0021	0.0033
Korea	0.0069	0.0088	0.0070	0.0094	−0.0023	0.0038
US	**0.0597**	**0.0187** (**)	**−0.0240**	**0.0085** (*)	**−0.0150**	**0.0075** (**)
Time	−0.0191	0.0151	**−0.0825**	**0.0265** (**)	0.0133	0.0177
Time^2	0.0029	0.0029	**0.0157**	**0.0045** (**)	−0.0020	0.0028
S-A	−0.0144	0.0144	−0.0023	0.0080	−0.0058	0.0091
Hatch	−0.0068	0.0074	−0.0016	0.0062	−0.0054	0.0036
SP						
R-squared	0.2426		0.1787		0.1999	

Bold indicates significant coefficients at 90% (*) and 95% (**) confidence levels.

Regarding efficiency change (catch-up) and technological progress, Japanese cars show reduced catch-up linked to faster technological development, which makes difficult for the inefficient firms to get closer to the top-performing manufacturers. Finally, our equation indicates that price affects positively to technical change in gasoline and diesel cars, though without significant coefficients for the fragmented diesel equations. This result implies that the most expensive cars are the most developed by the companies. This would call for further regulation, as it is necessary that improvements in fuel efficiency be enforced in the low-price models, which account for the lion's share of the market.

Finally, we extrapolated the estimated technological trends to calculate both current and future emission levels to determine whether the manufacturers in our sample will achieve the targets demanded by the EC under the observed rates of technical change. Unfortunately, the available sales data does not cover all models and variants for each brand. Representativity of sales data is shown in Table 7.

As seen in Table 7, we include those brands for which we have more than 80% of their total sales, thus covering more than 92% of the car market in Spain. This allows for our conclusions to be reasonably accurate for the specific manufacturers, and also generalizable to

Table 6
Second-stage diesel equations (price-disaggregated).

Price segment	EFF-TRUNC				EFFCH-OLS				TECHCH-OLS			
	<15,000		>15,000		<15,000		>15,000		<15,000		>15,000	
Coeff.	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Constant	**0.670**	**0.089** (**)	**1.020**	**0.024** (**)	**1.293**	**0.091** (**)	**1.081**	**0.044** (**)	**0.821**	**0.084** (**)	**1.062**	**0.029** (**)
Price	**2.526**	**0.714** (**)	**−0.295**	**0.065** (**)	**−1.041**	**0.503** (**)	0.004	0.018	0.321	0.295	0.015	0.017
Japan	0.018	0.016	−0.001	0.009	**−0.034**	**0.009** (**)	**−0.020**	**0.007** (**)	−0.002	0.004	0.003	0.004
Korea	**0.043**	**0.015** (**)	0.001	0.010	**−0.025**	**0.009** (**)	0.020	0.013	0.002	0.007	−0.004	0.005
US			**0.065**	**0.018** (**)			**−0.024**	**0.008** (**)			**−0.016**	**0.007** (**)
Time	−0.041	0.026	−0.016	0.017	**−0.120**	**0.055** (**)	**−0.072**	**0.031** (**)	**0.108**	**0.040** (**)	−0.021	0.019
Time^2	0.005	0.005	0.002	0.003	**0.022**	**0.009** (**)	**0.014**	**0.005** (**)	**−0.017**	**0.007** (**)	0.003	0.003
S-A	**0.034**	**0.018** (*)	−0.002	0.043	−0.016	0.014	**−0.025**	**0.008** (**)	0.007	0.014	**−0.024**	**0.003** (**)
Hatch	−0.012	0.017	−0.007	0.008	0.018	0.027	−0.005	0.007	−0.004	0.007	**−0.008**	**0.004** (**)
SP												
4 × 4			−0.010	0.010			−0.004	0.008			**−0.032**	**0.005** (**)
R-sq	0.306		0.226		0.354		0.198		0.278		0.280	

Bold indicates significant coefficients at 90% (*) and 95% (**) confidence levels.

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Table 7
Representativity of sales data.

Manufacturer	Sales 2010 sample	Sales 2010 total	Share of total sales (%)	Market share (%)
AUDI	38,652	40,857	94.60	4.23
BMW	28,662	32,386	88.50	3.35
CHEVROLET	18,694	22,960	81.42	2.38
CITROEN	75,967	81,162	93.60	8.40
DACIA	21,387	21,387	100.00	2.21
FIAT	19,671	23,705	82.98	2.45
FORD	74,530	77,942	95.62	8.07
HYUNDAI	25,908	31,353	82.63	3.25
LAND ROVER	5108	5117	99.82	0.53
MERCEDES	25,036	28,377	88.23	2.94
MINI	8716	8718	99.98	0.90
NISSAN	37,580	41,471	90.62	4.29
OPEL	71,657	71,976	99.56	7.45
PEUGEOT	79,372	82,231	96.52	8.51
RENAULT	74,069	81,496	90.89	8.44
SEAT	88,283	89,361	98.79	9.25
SKODA	17,474	19,747	88.49	2.04
TOYOTA	44,271	48,737	90.84	5.05
VOLKSWAGEN	81,846	83,334	98.21	8.63
SUBTOTAL	836,883	892,317		92.38
Excluded Manufacturers				
HONDA	7711	12,063	63.92	1.25
KIA	11,488	18,379	62.51	1.90
LEXUS	527	1689	31.20	0.17
MAZDA	1947	9385	20.75	0.97
MITSUBISHI	6528	8763	74.50	0.91
PORSCHE	849	1354	62.70	0.14
SSANGYONG	1820	4109	44.29	0.43
SUZUKI	4563	8541	53.42	0.88
VOLVO	3216	9350	34.40	0.97
SUBTOTAL	38,649	73,633		7.62
TOTAL	875,532	965,950		100.00

the Spanish and European car markets. Average actual, efficient, and projected emission levels per car manufacturer, under different technological scenarios, are shown in Table 8.

If the average technical change over the whole sample period (2004–2010) is used for the calculations, the brands that are predicted to meet the 2015 target (130 g CO_2/km) would account for 79.61% of total sales in Spain (considering that market shares were to remain constant in the long-run). Under the same conditions no firm is expected to meet the 2020 and 2025 emission levels.

While the above-mentioned results do not look promising, it is worth remembering that emission regulations did not become relevant within the EU until 2007, when the serious discussions about legally-binding emission targets commenced. The resulting legislation, as well as other factors such as rising fuel prices or the resurgence of electrical

Table 8
Actual, efficient and predicted average emissions per manufacturer (2010–2025).

Manufacturer	Units sold	Sales-weighted average CO2 emissions (g/km)										
		Actual	TE	2004–2010 tech change			2004–2007 tech change			2008–2010 tech change		
		2010	2010	2015	2020	2025	2015	2020	2025	2015	2020	2025
AUDI	38,652	149.9	142.2	**120.9**	103.4	88.9	**116.0**	96.2	81.2	**112.7**	**90.5**	73.5
BMW	28,662	156.4	149.3	133.3	120.3	109.8	**122.0**	110.7	111.7	**121.8**	100.5	83.7
CHEVROLET	18,694	156.4	149.2	137.1	127.0	118.6	175.0	235.6	358.4	130.1	113.6	99.2
CITROEN	75,967	129.6	123.2	**109.0**	97.2	87.3	**122.0**	127.7	142.4	**109.1**	96.8	86.0
DACIA	21,387	142.0	137.5	136.4	136.2	137.0	214.5	384.5	758.8	133.4	130.2	128.0
FIAT	19,671	118.2	110.6	**110.2**	110.1	110.4	181.1	323.1	611.4	**102.5**	**95.0**	88.1
FORD	74,530	139.6	133.2	**123.4**	115.5	109.1	137.2	149.3	171.7	**120.5**	109.3	99.4
HYUNDAI	25,908	134.4	127.1	**116.8**	108.2	101.1	132.8	140.9	152.1	**110.2**	95.7	83.2
LAND ROVER	5108	233.7	223.1	213.1	204.9	198.4	230.6	252.2	298.3	198.4	176.6	157.4
MERCEDES	25,036	163.1	149.9	**128.0**	109.9	94.8	**127.9**	111.7	100.4	130.1	113.7	100.0
MINI	8716	123.5	116.5	**113.3**	110.9	109.0	**114.5**	113.4	113.1	**96.1**	**79.7**	**66.5**
NISSAN	37,580	147.3	135.4	135.5	136.1	137.2	154.6	183.4	228.1	**125.1**	115.5	106.7
OPEL	71,657	138.6	131.0	**116.9**	105.2	95.6	**127.7**	130.2	139.3	**113.5**	98.4	85.5
PEUGEOT	79,372	134.6	125.3	**114.9**	106.2	99.2	**120.8**	119.5	121.6	**108.1**	**93.5**	81.0
RENAULT	74,069	148.8	140.2	**125.0**	112.2	101.6	130.3	123.0	118.0	**119.8**	102.5	88.0
SEAT	88,283	128.7	119.0	**107.5**	97.8	89.9	**120.3**	131.3	154.7	**99.6**	**83.6**	70.3
SKODA	17,474	131.2	119.7	**111.5**	104.7	99.1	**123.0**	134.7	157.1	**96.6**	**78.6**	**64.3**
TOYOTA	44,271	147.8	135.7	**123.5**	113.3	104.9	138.6	146.3	160.1	**120.5**	107.5	96.3
VOLKSWAGEN	81,846	149.4	137.3	**120.8**	107.3	96.4	**129.7**	128.1	132.9	**114.0**	95.1	79.8
Emission target				130.0	95.0	70.0	130.0	95.0	70.0	130.0	95.0	70.0

Bold indicates that the manufacturer meets the emission target.

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cars, can be expected to have a positive impact on technical change (as noted Berggren and Magnusson, 2012; Sprei and Karlsson, forthcoming) that has been partially explained by our second-stage results. Thus, additional calculations were done by splitting the sample period and using pre- and post-regulation technical change estimates, i.e. 2004–2007, and 2008–2010, respectively. As expected, pre-2007 technical change leads to worse results: only 55.70% of sales would meet the 2015 target and no brand would meet the 2020 and 2025 targets. These results can be interpreted as worst-case scenario for future emission levels in the absence of stringent regulation. On the contrary, post-2007 technical change leads to improved results. 84.31% of sales would reach the 2015 target (not surprising since it is legally mandated), with 27.38% compliance for 2020 and, most significantly, a 2.94% of the market would already be on the right track to meet the 2025 goal.

While a positive impact of regulation on car efficiency can be inferred from these results, the most important conclusion is that the objectives of 2020 and 2025 do not seem technologically unfeasible. Thus, we argue that the implementation of stricter regulation (such as making long-term emission targets mandatory rather than recommended, or introducing new tax regimes to incentivise sales of low-emitting vehicles) can push companies to increase research and development (R&D) investments (or move forward with "shelved" models and technologies), with the objective to boost technical change and improve the chances of complying with the emission limits. This could be achieved by either modifying different characteristics of internal combustion engines, e.g. developing high-powered ignition systems (see Kageson, 2005) or just moving to more fuel-efficient engine types, such as in hybrid and electric vehicles.

The estimates in Table 8 can also be used to benchmark the major multinational conglomerates. For example, if we take into account 2008–2010 technical change, Volkswagen Group and PSA Group placed almost all their brands[33] in a position to meet the 2020 target and are the closest to the proposed 70 g CO_2/km in 2025. In the other extreme we find the Renault Group where none of the three brands[34] meet the 2020 target and are well over of the 2025 target. These results suggest the influence of strategic policy at a group level, including the coordination of R&D investments and transference of knowledge between the different brands, in order to help achieve the environmental targets set by the EC.

5. Conclusions

Road transport is a significant contributor to total greenhouse gas emissions. In 2009, the EC prioritized the "decarbonization" of road transport in Europe and introduced mandatory CO_2 emission standards for new passenger cars. These targets are 130 g CO_2/km by 2015, and a long-term target of 95 g CO_2/km by 2020. This paper aims to test the ability of the major car manufacturers to meet the present and future EC emission targets with the existing technological trends. To that end, we provide an in-depth analysis on the temporal evolution of technical efficiencies in the Spanish car market.

The well-known DEA-Malmquist method is applied over a large sample of car models sold in Spain between 2004 and 2010. Using balanced panel data allows us to obtain not only a static measure of car efficiency for each sample period, but also the dynamic measure of total efficiency change disaggregated into its two components: technical change, and efficiency catch-up. A second-stage regression is used to identify the main drivers of efficiency, catch-up and technical change over the period. Finally, the estimated trends are extrapolated to predict future emission levels for the car manufacturers.

[33] Volkswagen Group predictions for 2025: Audi (73.50), SEAT (70.30), Volkswagen (79.80) and Skoda (64.30). For the PSA Group: Citroen (86) and Peugeot (81).

[34] Renault group predictions: Renault (88), Dacia (128) and Nissan (106.7).

The static analysis of car efficiency largely agrees with the existing literature, indicating that diesel and compact vehicles are the most efficient. We found that American and Japanese vehicles have lower and higher rates of technological progress than European cars, respectively. The second-stage regression shows that the price level has a direct relationship with technical change. This result, meaning that the most expensive cars are the most developed by the companies, would call for further regulation, as it is necessary that improvements in fuel efficiency be enforced in low-price models, which account for the lion's share of the market.

Using post-regulation rates of technical development, results show that the vast majority of companies beat the 2015 target, 27% of the market meets the 2020 target, and around 3% are able to reach the 2025 target. While a positive impact of regulation on car efficiency can be inferred from these results, the most important conclusion is that the objectives of 2020 and 2025 do not seem to be technologically unfeasible. Thus, we argue that the implementation of stricter regulation can incentivise manufacturers to increase R&D investment, with the objective to boost technical change and improve the chances of complying with future emission targets.

Finally, we can also conclude that there are business groups with overall efficiency levels significantly closer to the emission limits than others. These results suggest the influence of strategic policy at a group level, including the coordination of R&D investments and transference of knowledge between the different brands, in order to help achieve the environmental targets set by the EC and the European Parliament.

6. Uncited reference

EU, 2009

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Appendix A. Supplementary data

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