

Analyzing CO₂ emissions from passenger cars in Europe: A dynamic panel data approach

Rosa Marina González^{a,*}, Gustavo A. Marrero^b, Jesús Rodríguez-López^c, Ángel S. Marrero^d

^a Universidad de La Laguna, IUDR, Tenerife, Spain

^b Universidad de La Laguna, CEDESOG, Tenerife, Spain

^c Universidad Pablo de Olavide, Sevilla, Spain

^d Universidad de La Laguna, Tenerife, Spain

ARTICLE INFO

Keywords:

Dieselization
Energy efficiency
Car CO₂ emissions
Dynamic panel models

ABSTRACT

Road transport accounts for 92 per cent of CO₂ emissions from all transport services, and car transport makes the largest contribution to the total. We examine the dynamic relationship between car CO₂ emissions in western European Union countries (EU-13) with the dieselization of the passenger vehicle fleet, technological progress, fuel efficiency, mobility indicator, economic activity and motorization rate. We take advantage of a panel data set of 13 EU countries between 1990 and 2015 and estimate a Dynamic Panel Data (DPD) model using alternative econometric methods. This approach allows us to estimate the effect on car CO₂ emissions of induced indirect channels involving the reaction of economic agents to changes in aforementioned explanatory variables. We provide evidence that CO₂ emissions have been benefited from global technological progress and changes in average fuel efficiency, while increases of economic activity, motorization rate and the dieselization process hold positive and significant relationship with car CO₂ emissions. These results are consistent with alternative model specifications and econometric methods.

1. Introduction

In recent decades, the share of carbon dioxide (CO₂) emissions emanating from the transport sector has risen in the European Union (EU) from 32% in 1990 to 45% in 2015.¹ Moreover, road transport accounts for 92% of CO₂ emissions from the transport sector, and between 1990 and 2015 CO₂ emissions from cars accounted for half of the road transport emissions. This means that car transport is a key sector for the proposal of strategies to curb the upward trend in CO₂ emissions in Europe.

Regarding CO₂ emissions in the transport sector, most of previous studies have focused on road transport, without distinction between passenger and freight transport (e.g. Marques et al., 2012; Saboori et al., 2014). However, passenger and freight transport modalities respond differently to economic and policy factors and, for that reason, mixing both series can lead to misleading conclusions. Our analysis takes care of this issue focusing exclusively on passenger car CO₂ emissions.

More concretely, the contribution of our study is twofold. First, we focus on analyzing the relationship between CO₂ emissions from passenger cars and variables related to technological progress, economic activity, fuel efficiency, mobility indicator, motorization rate and paying special attention on several measures of dieselization. Second, we use a Dynamic Panel Data (DPD) approach to estimate these relationships, considering their dynamic nature and to take advantage of panel data information from 1990 to 2015 for 13 main EU countries. To the best of our knowledge, no studies published to date have focused exclusively on CO₂ emissions of passenger cars in Europe using a DPD approach.

Policies promoting energy efficiency in passenger cars have been praised as effective measures for reducing energy consumption and for fighting climate change (Freire-González, 2017). Several research studies supported the idea that replacing gasoline cars by diesel cars as a way to reduce CO₂ emissions through the gains in energy efficiency (see, among others, Sullivan et al., 2004; Zachariadis, 2006; Zervas and Lazarou, 2007, or Fontaras and Samaras, 2007). Indeed, diesel motor

* Corresponding author. Departamento de Economía, Contabilidad y Finanzas, Facultad de Ciencias Económicas, Empresa y Turismo, Campus de Guajara, Universidad de La Laguna, La Laguna, 38071, Santa Cruz de Tenerife, Spain.

E-mail addresses: rmglzmar@ull.edu.es (R.M. González), gmarrero@ull.edu.es (G.A. Marrero), jrodlop@upo.es (J. Rodríguez-López), amarrerl@ull.edu.es (Á.S. Marrero).

¹ Data are available from <http://www.odyssee-mure.eu/>.

<https://doi.org/10.1016/j.enpol.2019.03.031>

Received 11 October 2018; Received in revised form 18 February 2019; Accepted 17 March 2019

Available online 25 March 2019

0301-4215/ © 2019 Elsevier Ltd. All rights reserved.

vehicles consume (on average) 12 per cent less fuel per kilometer driven than gasoline-fueled vehicles. Persuaded by this argument, European governments have applied lenient tax policies with regard to the use of diesel-fueled vehicles (Rietveld and van Woudenberg, 2005; Zervas, 2010). While the prices of both fuels (net of taxes) have evolved evenly during this period, the price of gasoline is on average 20% higher than that of diesel when taxes are included.

In this context, diesel drivers have benefited from considerably lower operating costs than gasoline drivers. As a consequence, diesel vehicles tend to be driven more than gasoline vehicles in Europe, generating what is referred in the literature as a *rebound effect*, increasing overall mobility and overall fuel consumption (Sorrell and Dimitropoulos, 2008). Thus, the expected gains in energy saving and emission reductions from the dieselization process have been lessened (Greening et al., 2000; Bonilla, 2009; Tovar, 2011; González and Marrero, 2012).

Although the effect of the dieselization on controlling emissions has been questioned by many authors, there are few empirical researches quantifying the forces that govern passenger car CO₂ emissions in Europe (Marques et al., 2012). Our paper contributes to fill this gap. Moreover, empirical studies are particularly necessary in the light of the increasing social sensitivity to car emissions and tax policies in Europe (e.g. the “yellow vest” protests in France).

Regarding the method of estimation, the use of panel data helps to obtain more efficient estimations because it jointly considers the time and the cross-section dimensions of the dataset. Furthermore, the dynamic nature of aggregate energy and emissions variables has been shown to be an important aspect to be considered in empirical applications. Since the seminal paper by Houthakker et al. (1974), and exploiting the panel information of databases, dynamic panel data (DPD) models have been widely used in many fuel demand applications (Baltagi et al., 2003; Sterner, 2007; Pock, 2010; González and Marrero, 2012, among many others), and to study the determinants of energy consumption and CO₂ emissions (Marrero, 2010). Dynamic models allow also to estimate the conditional effects of different control variables on emissions (i.e., their elasticities if the model is linear and variables are expressed in logs). Additionally, we use the system GMM approach (Blundell and Bond, 1998; Roodman, 2009) to correct for the potential endogeneity bias incurred by traditional DPD estimation methods, such the pooled-OLS, Within-Group or Random Effects estimates.

Specifically, we use a data set spanning the period from 1990 to 2015 for 13 EU countries: Austria, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden and the United Kingdom. Our dynamic reduced form is estimated using three alternative methods: i) a pooled panel regression estimated by ordinary least squares with time dummies; ii) a fixed effect dynamic panel, in order to check whether our results might be biased by the data pool; and iii) the system GMM approach to overcome problems of potential endogeneity, given the double-sense causality usually found between CO₂ emissions, economic activity and energy consumption (Atems and Hotaling, 2018).

In relation to the variables used in our models, we consider alternative measures of the dieselization process, said the diesel to gasoline car ratio and the diesel to gasoline fuel consumption ratio. We also use the diesel to gasoline fuel efficiency ratio and the diesel to gasoline price ratio and variables affecting dieselization. As additional control variables, we include private consumption per household, average fuel efficiency in passenger cars, the motorization rate (cars per capita), an indicator of car traffic and a linear trend as a proxy of global technological progress in the sector and in Europe.

Our main findings are that car CO₂ emissions have been benefited from global technological progress and changes in average fuel efficiency. By contrast, increases of economic activity, motorization rate and the dieselization process hold positive and significant relationship with car CO₂ emissions. We find that these results are consistent with

alternative model specifications and the different econometric methods used.

The remainder of the paper is organized as follows. Section 2 reviews the current literature on the subject and relates our contributions with those found in these papers. Section 3 presents the data set and a graphic summary of statistics. In Section 4, we introduce a specification of a growth-emissions dynamic panel data model and describe the alternative econometric methods for its estimation. Section 5 presents the results. Finally, Section 6 concludes and proposes a set of policy recommendations based on our results.

2. The literature on road transport emissions, fuel consumption and dieselization

Transport CO₂ emissions have been widely studied in the literature. One of the main objectives of these studies is to analyze policies aiming to reduce the negative environmental impact of the transportation sector (Hickman and Banister, 2007; Chapman, 2007; Nocera and Cavallero, 2011). Many of these studies have examined the relationship between economic growth, transport activity and environmental impact.

These issues have been addressed using a range of approaches: decomposition techniques, time series analysis, regression analysis and panel data models. The most popular approach involves the use of decomposition techniques, starting from the IPAT identity (Ehrlich and Holdren, 1971), which describes the human impact on the environment as the product of three factors: population, technology, and per capita consumption. This identity, specifically applied to CO₂ emissions, becomes the Kaya identity (Kaya and Yokobori, 1997), which breaks down the technology factor into carbon intensity and energy intensity (see also Timilsina and Shrestha, 2009; Lakshmanan and Han, 1997).

Using a time series analysis, Begum et al. (2015) estimated the impact of GDP, transport fuel consumption and population growth on CO₂ emissions. Similarly, Ackah and Adu (2014) found that transport demand is price inelastic, implying that continual fuel price subsidization is economically inefficient and that investment in productivity is able to restrain CO₂ emissions in the transport sector. Using a cross-section analysis, Xu and Lin (2015) investigated the effects of private vehicle inventory, GDP, urbanization and energy intensity on CO₂ emissions. Shu and Lam (2011) analyzed the impact of population, urban area, income and road density on CO₂ emissions from the transport sector. Saboori et al. (2014) focused on the road transport sector and examined the bi-directional long-run relationship between emissions, energy consumption and economic growth in the OECD countries over the period 1960–2008. They found that most energy consumption, rather than economic growth, accounts for the bulk in the dynamic of CO₂ emissions, suggesting that policies supporting a more efficient use of energy are crucial to attain emission reduction targets.

Using a partial and static approach, Sullivan et al. (2004), Zervas (2006), Zachariadis (2006), and Jeong et al. (2009) all concluded that an increase in the share of diesel vehicles would contribute to reducing CO₂ emissions. Shortly afterwards, this literature was thoroughly revised, incorporating a larger set of explanatory variables and the use of panel data specifications. For example, Ryan et al. (2008) focused on the relationship between fuel prices, vehicle taxes, income and population density in Europe. Yang et al. (2015) analyze transport sector emissions in China during the period 2000–2012. For European countries, Marques et al. (2012) found that the reduction in CO₂ emissions from diesel vehicles (due to the higher fuel efficiency) was outweighed by the increase in kilometers driven (due to the rebound effect). Finally, González and Marrero (2012) extended this panel data specification by incorporating a dynamic component concerning growth and CO₂ emissions. Using a sample of 16 Spanish regions between 1998 and 2006 they concluded that the (negative) impact of the rebound effect was greater than the (positive) effect of energy-efficiency gains.

The rebound effect reflects behavioral responses to changes in fuel

prices, income, and preferences. The literature on the subject can be divided into two categories depending on the methodological approach used. On the one hand, the rebound effect has been addressed using the efficiency elasticity of the demand for energy – that is, the elasticity of the distance travelled with respect to fuel efficiency (see, among others, Khazzoom, 1980; Berkhout et al., 2000; Sorrell, 2007; Sorrell and Dimitropoulos, 2008). On the other hand, it can be estimated using the price elasticity – that is, the elasticity of the distance travelled with respect to the fuel price. Using these price elasticities, several studies have estimated the direct rebound effect associated with private transport (Greene, 1997; West, 2004; Small and Van Dender, 2007; Frondel et al., 2012). Interestingly, the two elasticities are potentially different (Greene, 2012; Stapleton et al., 2017), suggesting that consumers do not respond in the same manner to improvements in fuel efficiency as to changes in fuel prices.

The last point to make in this literature review is that only a few studies have considered dynamic panel data models to analyze CO₂ emissions in the transport sector. Exceptions include Kasman and Duman (2015), Wang et al. (2015), and Zhang et al. (2015). The two latter works applied a dynamic panel quantile regression model to study the direct rebound effect for China's road passenger transport during 2003–2012. Moreover, these studies have concentrated on the whole transport sector or, specifically, on the road transport sector. In this paper, we focus on passenger cars only.

3. Dataset description and summary of statistics

This section presents a preliminary description of time series related to passenger cars from 1990 to 2015² for 13 EU member countries: Austria, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden and the United Kingdom. All data were retrieved from Odyssee-Mure (see footnote 2).

Fig. 1 represents the series of car CO₂ emissions and total CO₂ consumer emissions (total CO₂ emissions of final consumers, including electricity, in MtCO₂) for selected countries. To compare growth dynamics, their initial values have been normalized to 100. For the most part, CO₂ emissions from final consumers are decreasing, especially since the recession starting in 2008. These series contrast with CO₂ emissions from cars, which present an upward trend (with the exceptions of Greece, Sweden and the United Kingdom).

Analyzing the behavior of EU-13 in average, in Fig. 2 we can see that total CO₂ emissions are decreasing, while car CO₂ emissions are increasing, which contributes to raise the share of car emissions in total emissions between 1990 and 2015.

Table 1 compiles average moments related to dieselization: CO₂ emission factors per liter of fuel (Santos, 2017), car stock, fuel consumption, average liters per 100 km (the inverse of fuel efficiency), and the fuel price (including taxes). All these figures are presented in relative terms (diesel to gasoline ratio). We also present a set of variables that help to explain the CO₂ emissions from cars, namely: Private consumption per households (ppp) (k€2005p/hh), average specific fuel consumption (liters/100 km) of cars, the stock of cars per capita (cars pc.) and car traffic in terms of giga passenger-kilometer (Gpkm).³

Regarding CO₂ emission factors, although the carbon content varies from country to country, on average a liter of diesel fuel contains 10 per cent more carbon than a liter of gasoline (with a range from 4.6 per cent in Denmark to 17 per cent in the UK). Regarding the rest of the dieselization variables, France and Austria present the most dieselized vehicle fleet (on average, there is 0.8 diesel car per 1 gasoline car),

whereas Greece has the fewest diesel car ratio. The relative fuel consumption varies evenly with the relative car stock: the higher the relative stock, the higher the relative fuel consumption.

Fig. 3 presents the series for the relative stock of cars diesel/gasoline (dashed line), and the corresponding relative fuel consumption (solid line), for selected countries. Both series present upward trends in all countries with the exception of Greece. In Austria, France, Ireland, Portugal, Spain and probably Italy, fuel consumption ratios are higher than in the year 2000. Without exception, fuel consumption ratios grow in parallel with stock ratios, reflecting a rebound in the use of diesel. Comparing Figs. 1 and 3, the growing share of CO₂ emissions from cars is correlated with the strength of the dieselization process.

Back to Table 1, with regard to fuel efficiency, diesel vehicles are on average 12 per cent more efficient than gasoline vehicles in terms of liters of fuel per kilometer driven. In Fig. 4 we can see that the efficiency of both diesel and gasoline cars and also the difference between them (in favor of diesel cars) have been increased during the period. Note, however, that the higher carbon content per liter of diesel (an increase of 10 per cent) partially offsets the fuel efficiency in diesel-powered cars (an increase of 12 per cent).

With regard to fuel prices (including taxes), we should mention the more lenient tax treatment of diesel in these countries (with the exception of the UK). Fig. 5 displays the relative fuel prices from 1998 to 2015. Prices are represented net of taxes (dashed lines) and including fuel taxes (solid lines). The evolution of these series (with and without taxes) is very homogeneous across these European countries. Prices net of taxes have generally been higher for diesel fuel, peaking in 2008; in contrast, the final prices (including taxation) are lower for diesel fuel. The only exception is the UK, where gasoline prices have been 5% lower on average. It is also worth mentioning that, in general, the difference between both series has been, on average, relatively constant throughout the period considered and for most of the countries.⁴

The last columns of Table 1 present some descriptive statistics on economic activity. Italy has the highest stock of cars per capita (more than one car for every two people), while Greece, Spain and Portugal have the lowest (around one car for every three people). Car traffic reflects the total movement of passenger cars on a given network, and is strongly influenced by the population and the kilometers of the road surface network of each country. The last two columns present the average household consumption and the GDP per capita (relative income) of each country.

Finally, Fig. 6 plots the share of CO₂ car emissions versus relative diesel/gasoline consumption. In all cases, there is evidence that the share increases with one of our measures of dieselization (diesel to gasoline consumption ratio).

As a preliminary quantitative exercise, in Table 2 we regress the share of CO₂ emissions from cars over two elementary indicators of dieselization: the relative stock of vehicles (diesel/gasoline), and the relative consumption of fuel (diesel/gasoline). We use pooling OLS estimates and fixed effects OLS estimates. The correlation of both indicators with the share is positive, as expected, and statistically significant (although for the pooling-OLS case the relative vehicle stock value is not significant). In line with the plots presented in Fig. 5, the correlation with the ratio of fuel consumption is always statistically significant: a 1% increase in the relative fuel consumption increases the

⁴ Despite observing few changes in the temporal evolution of the diesel to gasoline price ratio, we observe significant differences between countries. For example, on average in the sample considered (1998–2015 for the case of fuel prices including taxes), the average ratio is 1.03 in UK, 0.90 in Spain, 0.83 in France, and 0.75 in The Netherlands. Using a panel data information (as we do in Section 5), we can estimate the impact of the relative fuel prices in European countries by looking at the cross-section dimension of the database. Precisely, this is an additional advantage when using panel information, since the estimates include both the within- and between-country relationship, and this allows obtaining more efficient estimates.

² Except for series related to fuel prices that are only available for 1998–2015.

³ “Passenger transport refers to the total movement of passengers using inland transport on a given network. Data are expressed in million passenger-kilometers, which represents the transport of a passenger for one kilometer” (OECD, 2019).

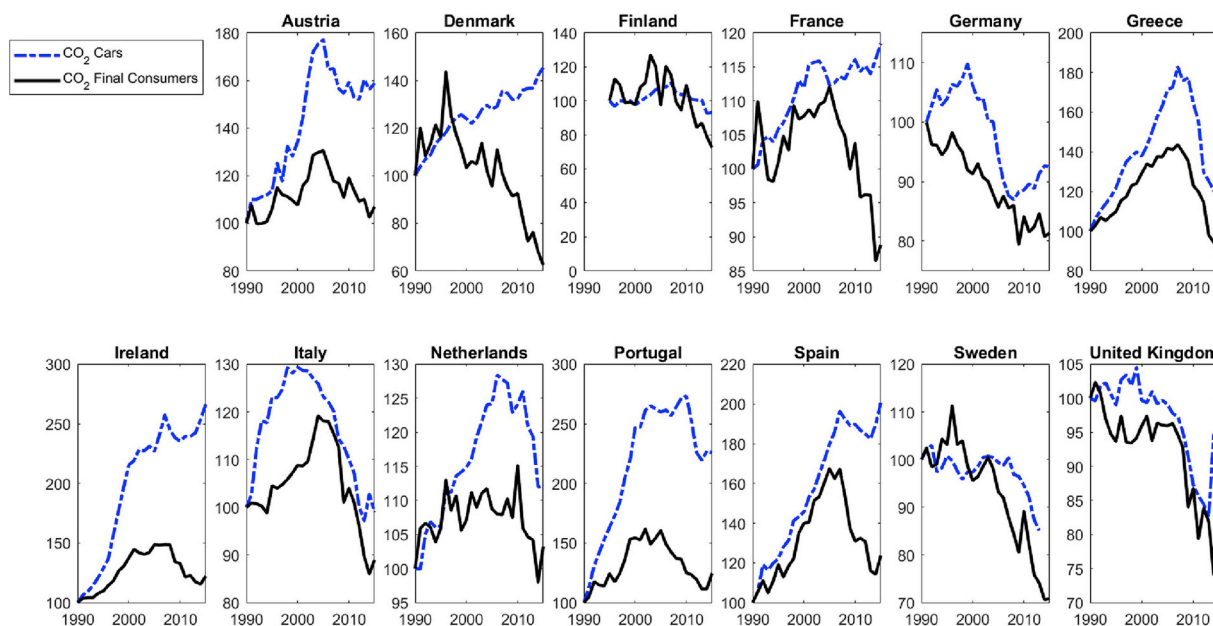


Fig. 1. CO2 emissions (Index 1990 = 100) in Europe, 1990–2015.

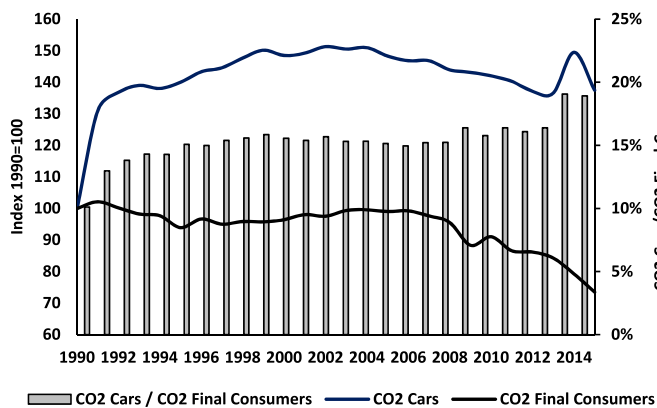


Fig. 2. CO2 emissions in Europe, EU-13 Average, 1990–2015.

share of CO2 cars emissions by 0.2%, on average. This correlation is robust to the method of estimation. On average, these two indicators of dieselization account for between a quarter and a third of the variability of the share, as indicated by the adjusted R^2 .

The descriptive statistics and preliminary regressions presented in this section point that CO2 emissions due to the usage of cars has been positively affected by the dieselized vehicle fleet in Europe. However, we also find that there is much to explain. For this reason, in the next section we propose a more complex model, including more explanatory variables than the dieselization, related to technological progress, fuel efficiency, mobility, economic activity and motorization rate.

Table 1

Explanatory variables, 1990–2015 (Averages over the period).

Source: Santos (2017), Odyssey-Mure and own calculations

	Diesel to gasoline ratio				Consump. per household (k€2005 p/hh)	Avg. Fuel Consump. per car (l/100 km)	Cars pc.	Traffic (Gpkm)	
	CO2 emission factor (KgCO2/liter)	Cars	Fuel Consump.	Fuel efficiency (l/km)					Fuel Price (with taxes) ^a
Austria	1.08	0.79	0.97	0.82	0.90	35.00	7.78	0.48	67.9
Denmark	1.05	0.17	0.31	1.22	0.83	27.00	8.42	0.37	50.48
Finland	1.08	0.16	0.30	0.93	0.80	26.66	7.86	0.45	58.17
France	1.10	0.81	1.29	0.82	0.83	32.06	7.30	0.47	622.87
Germany	1.11	0.25	0.36	0.83	0.84	32.46	8.10	0.49	857.36
Greece	1.13	0.02	0.04	0.89	0.89	33.82	8.02	0.34	71.43
Ireland	1.11	0.26	0.39	0.87	0.95	39.28	8.02	0.36	39.83
Italy	1.11	0.38	0.64	0.88	0.88	36.11	6.83	0.57	660.93
Netherlands	1.11	0.17	0.36	0.83	0.76	31.04	8.02	0.42	139.8
Portugal	1.08	0.48	1.01	0.95	0.80	31.47	7.72	0.35	90.33
Spain	1.09	0.61	0.99	0.85	0.90	34.99	7.56	0.33	275.46
Sweden	1.06	0.11	0.13	0.74	0.90	25.49	8.79	0.44	103.77
UK	1.17	0.25	0.35		1.03	56.61	8.07	0.42	640.49
EU-13	1.10	0.34	0.55	0.89	0.87	34.00	7.88	0.42	282.99

Note: Columns 2 to 8 present the specific explanatory variables used in the models below. We also present CO2 emission factor and GDP per capita for informative purposes.

^a Fuel prices are averaged over the period 1998–2015.

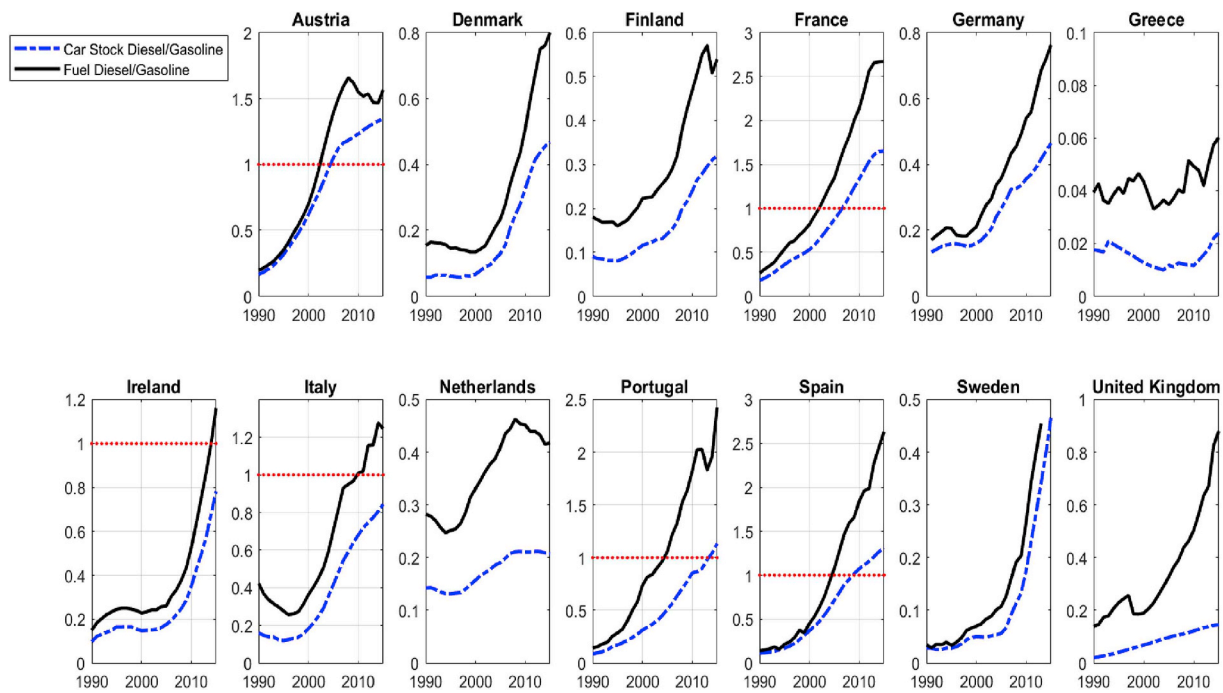


Fig. 3. Relative vehicle stock and fuel consumption (diesel to gasoline ratio) in.

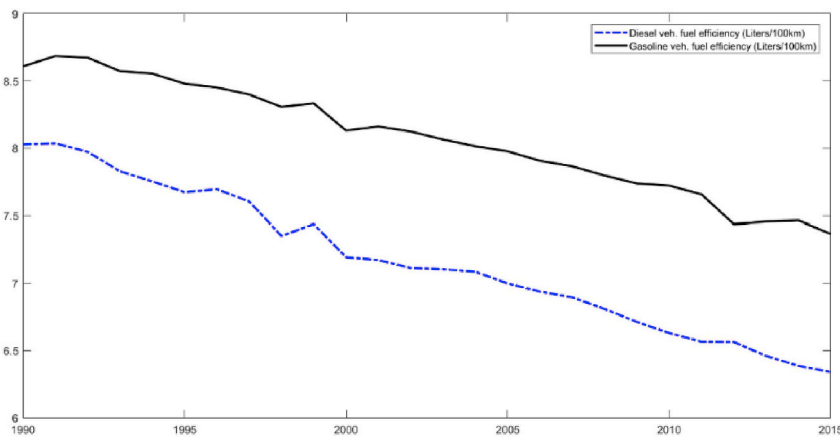


Fig. 4. Diesel and gasoline fuel efficiency in Europe, EU-13 Average, 1990–2015.

4. A growth-emissions dynamic panel data model

4.1. Specification

We first show a reduced form specification model relating the CO2 emissions from cars with a set of explanatory variables. This model is commonly used in the transport literature at the macroeconomic level. The reduced form is derived from a Neoclassical growth model which has been extended to incorporate other variables, such as urbanization, public transport and population density. We propose the following dynamic panel data specification, which includes the growth rate of car CO2 emissions as dependent variable:

$$\Delta \ln(Z_{i,t}) = \alpha + R_i + T_t + \beta \ln(Z_{i,t-1}) + \theta X_{i,t} + \lambda D_{i,t} + \varepsilon_{i,t}. \quad (1)$$

In this specification, the dependent variable $Z_{i,t}$ denotes passenger car CO2 emissions per capita for country i and year t (as long as this variable is logged and first-differenced, it can be read in growth terms) α , is a fixed factor, R_i and T_t are country- and time-specific effects. In order to control for initial technology and conditional convergence, the

lagged levels of passenger cars CO2 emissions per capita (capturing the convergence factor), $\ln(Z_{i,t-1})$ is included.

The term $\theta X_{i,t}$ encompasses the effect of technology and indicators of economic activity, with the following structure:

$$\theta X_{i,t} \equiv \theta_1 \Delta \ln(Y_{i,t}) + \theta_2 \Delta \ln(Q_{i,t}) + \theta_3 \Delta FFE_{i,t} + \theta_4 \Delta \ln(PAS_{i,t}) + \gamma t. \quad (2)$$

The first key term, $\Delta \ln(Y_{i,t})$, denotes the annual growth rate of private consumption per households (k€2005p/hh). Alternatively, we also consider $Y_{i,t}$ as GDP per capita, as an estimate of gross aggregate income. The second term, $\Delta \ln(Q_{i,t})$, denotes the annual growth rate of stock of passenger cars per capita, both diesel and gasoline. The third term $\Delta FFE_{i,t}$ denotes the annual change in average fuel efficiency of the car fleet, that is, kilometers travelled per liter of fuel (calculated as the inverse of specific consumption of the car, liters/100 kms, multiplied by 100). The fourth term $\Delta \ln(PAS_{i,t})$ denotes the annual change in passenger transport per kilometer of road network. Data are expressed in million passenger-kilometers. The last term, γt , is a linear deterministic trend.

The last component in equation (1), $D_{i,t}$, compiles several indicators

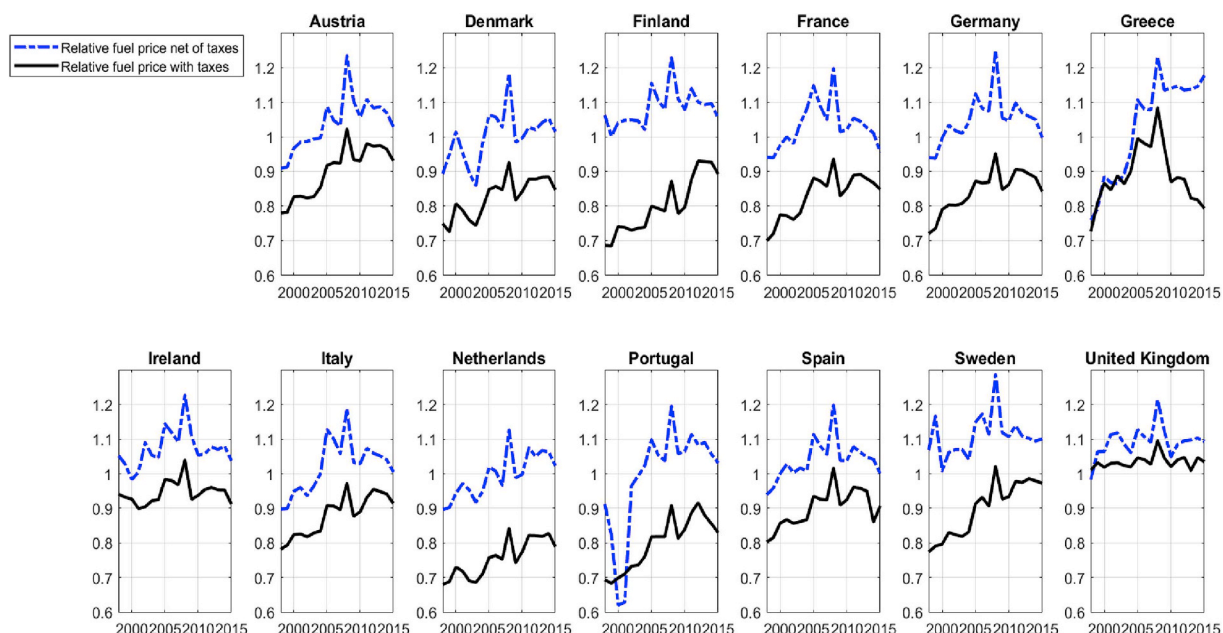


Fig. 5. Relative fuel prices (diesel to gasoline ratio) in Europe, 1998–2015.

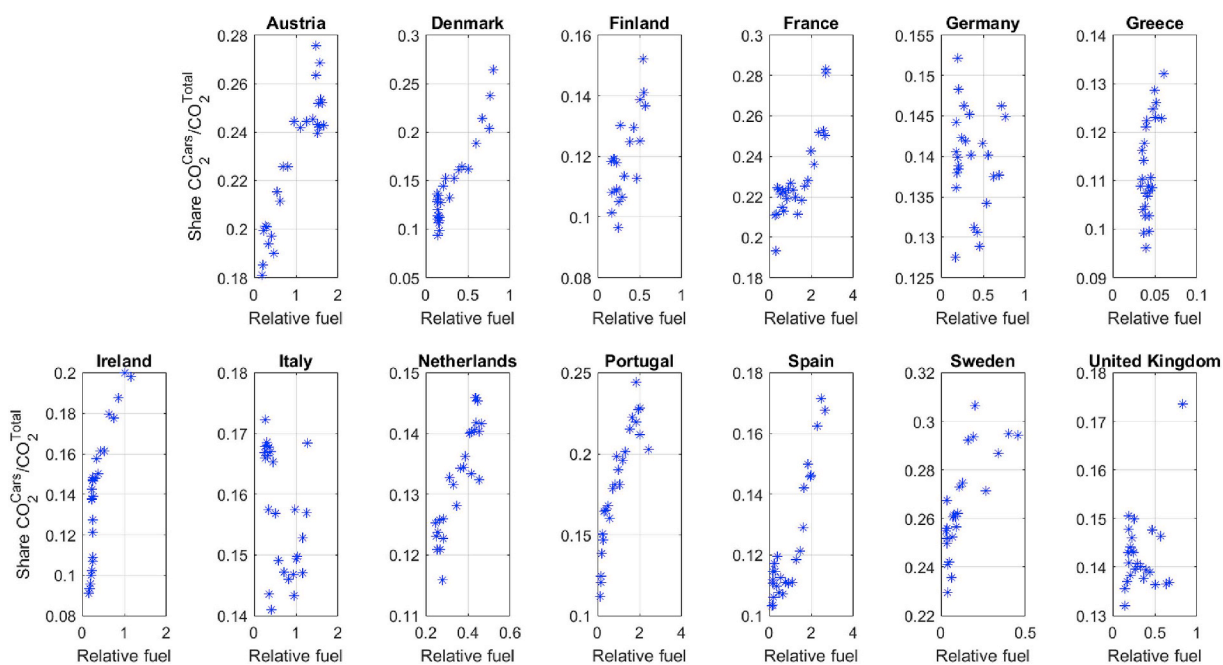


Fig. 6. Share of CO2 cars emissions versus relative fuel consumptions (diesel/gasoline) in Europe, 1990–2015.

related to dieselization (all expressed in annual changes)⁵: the relative stock of diesel to gasoline cars and the relative fuel consumption of diesel to gasoline cars. The evolution of these ratios is a reflection of many aspects affecting dieselization, such as final car prices, subsidies to car registration, expected use of the car, the discounted flow of future operating cost (including fuel taxes), individual preferences, etc. As other controls, we have also considered the diesel to gasoline liter/km

ratio and the relative price of gasoline/diesel fuel. All these controls are introduced sequentially in the model, in order to analyze their marginal impact on the growth rate in car CO2 emissions caused by the dieselization process taken place in Europe between 1990 and 2015.

For all specifications of (1), the set of variables (R_t , T_t , $\ln(Z_{i,t-1})$, $\Delta X_{i,t}$) is always included: *i.e.*, regional and time dummies, the lagged level of the dependent variable, and the change of $X_{i,t}$, $\Delta X_{i,t}$.

Finally, $\varepsilon_{i,t}$ encompasses effects of a random nature which are not considered in the model, and it is assumed to have a standard error component structure (see Arellano and Bond (1991) for these technical details).

⁵ A natural way to measure the dieselization is to use the diesel/gasoline kilometres-driven (per vehicle and total) ratio. However, these series are incomplete and many observations are missing in the Odyssee database. Alternatively, as González and Marrero (2012) did, we consider the diesel to gasoline ratio (fuel consumption and the stock of cars) to measure dieselization in Europe.

Table 2
Accounting CO2 emissions share.

Dependent variable: Share of CO2 emissions from cars				
	OLS	OLS	FE	FE
	(1)	(2)	(3)	(4)
Constant	−1.993*** (−103.46)	−1.989*** (−98.47)	−1.966*** (−188.37)	−1.966*** (−194.45)
Relative Car Stock Diesel/ Gasoline Growth	0.405*** (10.39)		0.323*** (13.05)	
Relative Fuel Consumption Diesel/ Gasoline Growth		0.235*** (9.35)		0.195*** (13.67)
No. Observations	329	329	329	329
R2 adjusted	0.246	0.208	0.324	0.347

Notes: This table reports pooling ordinary least squares (OLS) and fixed effects estimates. The dependent variable is the share of CO2 emissions from cars over total emissions. Figures in parenthesis denote t-statistics. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2. Econometric issues

Equation (1) is estimated first through pooled-OLS including controls for both regional and time dummies (Table 3). Next, we estimate them through fixed effect (FE) estimates (Table 4). With respect to pooled-OLS, the FE has the advantage of dealing with the existence of country-specific (and time-invariant) effects possibly correlated with regressors. However, authors such as Banerjee and Duflo (2003), Barro (2000) or Partridge (2005), have raised some caveats regarding the FE approach: it may produce inaccurate results for controls that mostly vary in the cross-section (such as the growth in emissions and energy efficiency in our case) since the method basically takes into account within-state variability.

Additionally, in dynamic models, pooled-OLS and FE estimates might be affected by an endogeneity bias, at least due to the lagged term included as a regressor in (1), $\ln(Z_{i,t-1})$. To address this problem in the absence of suitable external instruments (a standard limitation of dynamic panels), a GMM based approach is a natural alternative (Arellano and Bond, 1991; Arellano and Bover, 1995). The basic idea is to use equation (1), expressed in first differences, and then use the levels of the explanatory variables (lagged two or more periods) as natural instruments (i.e., $\ln(Z_{i,t-1})$, $X_{i,t-s}$, for $s \geq 2$), resulting in a first-difference GMM estimator (Arellano and Bond, 1991).

However, using the model only in the first-difference form may create an important finite sample bias when variables are highly persistent (Blundell and Bond, 1998), which is the case of variables like per capita CO2 emissions. An alternative to the first-difference GMM estimator is the system-GMM approach (Arellano and Bover, 1995; Blundell and Bond, 1998), which consists of estimating a system of equations in both first-differences and levels, where the instruments of the level equations are now suitable lags of the first difference variables.⁶ We consider standard errors with a variance-covariance matrix corrected by small sample properties to be robust (Windmeijer, 2005; Roodman, 2009). The results for the system GMM strategy are reported in Table 5.

The validity of the GMM instruments is tested using an over-identifying Hansen J-test. It is worth mentioning, though, that the proliferation of instruments (a common issue in system-GMM estimation) tends to produce problems of overidentifying, and this may require a reduction in the instrument (Roodman, 2009). In this situation,

⁶ Huang et al. (2008) and Marrero (2010), among many others, have emphasized the relevance of using system GMM when working with dynamic panel data growth models. For a similar exercise using the GMM approach, see Atems and Hotaling (2018).

the p-value of the Hansen J-test tends to be close to one. Bearing this in mind, in our baseline system GMM specification, we limit the number of instruments in the instruments matrix to one.

The Hansen's J-test suggests that the null hypothesis of joint validity of all instruments cannot be rejected in most cases. Moreover, we also compute a difference-in-Hansen test, which compares the efficiency of system GMM over first-difference GMM in each model (their p-values are always greater than 0.10, see Table 5). As a final caveat, it should be mentioned that system-GMM performs better when the number of cross-sectional observations (N) is large (i.e., consistency is obtained as N tends to infinity). When N is not very large and the data exhibit a high degree of persistence (which may lead to problems of weak instruments even in system GMM), as in our case, the system GMM estimators may also behave poorly (Binder et al., 2005; Bun and Sarafidis, 2015). Thus, in this situation, as in many macroeconomic applications, a GMM based approach may not be preferable to robust pooled-OLS (with regional and time dummies) or vice versa. In this situation, it is good practice to report both estimation results (as we do here), and to verify robustness.

5. Results

Tables 3–5 present the estimated results for pooled-OLS, FE and system GMM, respectively, of the proposed dynamic panel. The dependent variable is the growth rate of CO₂ emissions from cars. In all tables, column (1) only includes indicators of economic activity (i.e. $X_{i,t}$ in equation (1)). In the remaining columns (2) to (5), control variables for dieselization (i.e. $D_{i,t}$ in equation (1)), are introduced sequentially into the dynamic panel.⁷ The data in these tables suggests the following conclusions.

Firstly, with the exception of the conditional convergence term (as explained below), the results are fairly robust to the method of estimation: there are no remarkable differences among the estimated coefficients across tables. On average, the specification in (1) can account for around 40% of the variability of the growth in the CO₂ emissions from car. The value of coefficients does not vary substantially across the three econometric methods used.

Secondly, car emissions evolve around a quite flat, although downward-sloping, trend of -0.1% on a yearly basis (on average). The linear trend component is in most of the cases statistically significant. Controlling by all other factor, this finding is indicative of the existence of a global technological progress factor (common to all European countries) which is favoring CO₂ emissions reduction in passenger cars.

Thirdly, the rate of convergence (as indicated by the coefficient of the lagged car CO₂ emissions term) lies between almost 0% for the pooled-OLS estimate, which tends to generate downward bias estimates of this parameter in growth models (Islam, 1995; or Caselli et al., 1996), and 7% for the fixed effects estimates (generally upper-bias) and the more credible 4% of the system GMM estimates.

Fourthly, the two variables used as proxy of economic activity, i.e. the growth rates of private consumption per household (in purchasing power parity terms, PPP), and the stock of cars per capita, are positively correlated with emissions. A similar result was found by Abbes and Bulteau (2018) in relation to motorization rate effect in transport CO₂ emissions in Tunisia. Others authors found that the rapid growth of the economy and vehicle ownership were the most important factors for the

⁷ We have also considered the following set of variables, although they were not found significant in any specification: change of the share of population in urban areas; change of population density; change of public transportation share with respect to total (vehicles stock and traffic). These variables have been considered in other studies, for example, Su et al. (2011) showed that the proportion of bus travel had a significantly negative effect on CO₂ from transportation sector in China. Zhang and Zeng (2013) showed that urban areas had a positive impact on the transportation energy use and related emissions. In contrast to our country level approach, these studies focus on the regional or city level, thus capturing these effects at the aggregate level is more difficult.

Table 3
OLS estimates.

Dependent variable: Annual growth rate of passenger cars CO2 emissions per capita						
	(1)	(2)	(3)	(4)	(5)	
Constant	1.255** (2.48)	1.923*** (3.44)	1.921*** (3.45)	1.643*** (2.75)	0.910 (0.93)	
Linear Trend	-0.000704*** (-2.64)	-0.00106*** (-3.63)	-0.00104*** (-3.57)	-0.000881*** (-2.82)	-0.000494 (-0.96)	
Lag of passenger cars CO2 emissions per capita	-0.0132 (-1.37)	-0.0143 (-1.56)	-0.00898 (-0.94)	-0.0102 (-1.04)	-0.00498 (-0.43)	
Private consumption per households (Growth rate)	0.402*** (3.57)	0.410*** (3.88)	0.401*** (3.81)	0.461*** (4.08)	0.461*** (3.35)	
Stock of passenger cars per capita (Growth rate)	0.436*** (3.21)	0.478*** (3.66)	0.488*** (3.72)	0.449*** (3.27)	0.462*** (2.86)	
Car passengers per road km (Change)	0.150** (2.30)	0.150** (2.41)	0.165*** (2.67)	0.165*** (2.67)	0.143* (1.81)	
Fuel efficiency (km/liters) (Change)	-0.0448*** (-10.84)	-0.04709*** (-10.26)	-0.04268*** (-10.17)	-0.03673*** (-3.32)	-0.04451*** (-11.50)	
Diesel to gasoline passenger cars stock ratio (Change)		0.290*** (4.04)				
Diesel to gasoline fuel consumption ratio (Change)			0.139*** (3.53)	0.142*** (3.56)		
Diesel to gasoline fuel efficiency ratio liter/km (Change)				-0.0299*** (-2.87)		
Gasoline to diesel fuel prices (with taxes) ratio (Change)					0.130*** (3.46)	
No. Observations	269	269	269	247	196	
R2 adjusted	0.393	0.433	0.429	0.403	0.385	

Notes: This table reports pooling ordinary least squares (OLS). The dependent variable is the growth of CO2 emissions from cars. Figures in parenthesis denote t-statistics. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 4
Fixed effects estimates.

Dependent variable: Annual growth rate of passenger cars CO2 emissions per capita						
	(1)	(2)	(3)	(4)	(5)	
Constant	0.704 (1.02)	1.256 (1.77)	1.240 (1.75)	0.739 (1.11)	0.753 (0.65)	
Linear Trend	-0.000574 (-1.77)	-0.000891** (-2.54)	-0.000884** (-2.63)	-0.000656* (-2.13)	-0.000645 (-1.00)	
Lag of passenger cars CO2 emissions per capita	-0.0580** (-2.70)	-0.0652*** (-3.07)	-0.0657*** (-3.24)	-0.0766*** (-3.67)	-0.0708* (-2.01)	
Private consumption per households (Growth rate)	0.431*** (3.54)	0.425*** (3.58)	0.416*** (3.50)	0.477*** (3.66)	0.527*** (3.31)	
Stock of passenger cars per capita (Growth rate)	0.448*** (4.71)	0.457*** (4.85)	0.464*** (4.94)	0.427*** (5.15)	0.529*** (3.59)	
Car passengers per road km (Change)	0.128 (1.33)	0.136 (1.36)	0.143 (1.54)	0.139 (1.47)	0.141 (1.40)	
Fuel efficiency (km/liters) (Change)	-0.03968*** (-5.80)	-0.04199*** (-6.67)	-0.03763*** (-6.19)	-0.03312* (-1.91)	-0.03798*** (-5.53)	
Diesel to gasoline passenger cars stock ratio (Change)		0.260** (2.37)				
Diesel to gasoline fuel consumption ratio (Change)			0.127*** (3.62)	0.129*** (3.87)		
Diesel to gasoline fuel efficiency ratio liter/km (Change)				-0.00742 (-0.29)		
Gasoline to diesel fuel prices (with taxes) ratio (Change)					0.135*** (3.46)	
No. Observations	269	269	269	247	196	
R2 adjusted	0.428	0.443	0.448	0.420	0.457	

Notes: This table reports fixed effects (FE) estimates. The dependent variable is the growth of CO2 emissions from cars. Figures in parenthesis denote t-statistics. ***p < 0.01, **p < 0.05, *p < 0.1.

increased carbon dioxide emissions (see Lu et al., 2007, for Germany, Japan, South Korea and Taiwan during 1990–2002). In our case, our estimates indicate that CO2 emissions from cars are particularly sensitive to changes in household consumption, with an elasticity that ranges between 0.4 and 0.64 (depending on the model estimated). That is, an increase of 1% in household consumption has associated an increase in CO2 emissions in the car sector of about 0.4% and 0.64%.

Fifthly, we find that overall fuel efficiency (average kilometers

travelled by liters of fuel consumed) is an important factor that helps to reduce CO2 emissions in the car sector. This result is in line with empirical results reported in other studies suggesting that increases in fuel efficiency significantly influences CO2 emissions in the transport sector (Yan and Crookes, 2009; Ekins et al., 2011; Beuno, 2012; Mustapa and Bekhet, 2015). In our case, our results indicate that a 1 point increase in average fuel efficiency, for example, moving from the observed average of 12.6 km/l to 13.6 km/l (equivalent to change from 7.88 to 7.30/l

Table 5
System GMM estimates.

Dependent variable: Annual growth rate of passenger cars CO2 emissions per capita					
	(1)	(2)	(3)	(4)	(5)
Constant	0.860 (1.56)	1.691** (1.99)	1.590** (2.18)	1.491** (2.05)	0.339 (0.25)
Linear Trend	-0.000579* (-1.70)	-0.00103** (-2.14)	-0.000999** (-2.36)	-0.000944** (-2.30)	-0.000185 (-0.24)
Lag of passenger cars CO2 emissions per capita	-0.0361 (-1.36)	-0.0410** (-2.01)	-0.0466** (-2.12)	-0.0403** (-2.38)	-0.00177 (-0.03)
Private consumption per households (Growth rate)	0.626*** (4.03)	0.593*** (3.87)	0.631*** (4.25)	0.641*** (4.49)	0.743*** (3.63)
Stock of passenger cars per capita (Growth rate)	0.493** (2.03)	0.433* (1.75)	0.376 (1.61)	0.450** (2.17)	0.398 (1.40)
Car passengers per road km (Change)	0.0774 (0.69)	0.0683 (0.65)	0.0763 (0.70)	0.0593 (0.56)	0.0934 (0.85)
Fuel efficiency (km/liters) (Change)	-0.03659*** (-4.18)	-0.03973*** (-4.18)	-0.03431*** (-4.46)	-0.02186 (-1.19)	-0.04420*** (-5.71)
Diesel to gasoline passenger cars stock ratio (Change)		0.283 (1.11)			
Diesel to gasoline fuel consumption ratio (Change)			0.125* (1.73)	0.128* (1.81)	
Diesel to gasoline fuel efficiency ratio liter/km (Change)				0.0303 (0.49)	
Gasoline to diesel fuel prices (with taxes) ratio (Change)					0.140** (2.44)
No. Observations	269	269	269	247	196
Hansenp	0.686	0.793	0.405	0.750	0.510
ar1p	0.0285	0.0293	0.0317	0.0321	0.00310
ar2p	0.173	0.170	0.200	0.185	0.228

Notes: This table reports generalized method of moments (GMM) estimates. The dependent variable is the growth of CO2 emissions from cars. Figures in parenthesis denote t-statistics. ***p < 0.01, **p < 0.05, *p < 0.1.

100 km) implies a significant reduction of CO2 emissions in the car sector of about 3.4%–4%, depending on the model estimated.

Finally, when variables controlling for dieselization are included in the model, we find positive effects on car CO2 emissions growth in all cases. For instance, a 0.1 point increase in the relative vehicle car stock (e.g., from the observed average of 0.34–0.44) is associated with an increase between 2.6% and 2.9% (depending on the model) in car CO2 emissions (second column in Tables 3–5). Meanwhile, a 0.1 point increase of the relative fuel consumption (e.g., from the observed average of 0.55–0.65) has an average positive effect on cars CO2 emissions between 1.3% and 1.4% (third and fourth columns in Tables 3–5). Instead, when including the relative fuel prices (gasoline/diesel, and including taxes), reflecting the government tax incentive on diesel fuel to promote the use of diesel, our models estimate that a 0.1 point increase in relative fuel prices (e.g., from the observed average of 0.87–0.97) has an average positive effect on car CO2 emissions between 1.3% and 1.4%. This finding suggests that the existence of this diesel to gasoline price gap has contributed to the dieselization process (through reducing the operating cost of diesel cars compared to that of gasoline cars) and to higher CO2 emissions.

Our results contribute to the dieselization debate. The evidence found in the literature about the relationship between dieselization and CO2 emissions in the transport sector is contradictory. In general, former works have analyzed the relationship between dieselization and emissions focusing only on the direct and efficiency advantages of the diesel with respect to the gasoline (see, among others, Sullivan et al., 2004; Zervas and Bikas, 2005; Zervas, 2006; Zervas et al., 2006; Zachariadis, 2006; Zervas and Lazarou, 2007; and Fontaras and Samaras, 2007). These sets of papers conclude that the dieselization process reduces CO2 emissions in the transport sector. However, other papers (Schipper et al., 2002; Jensen, 2003; Hugrel and Joumard, 2001; González and Marrero, 2012, among others) argue that this literature is not properly capturing the overall effect of dieselization on emissions, because they are only measuring part of the impact. The analysis must also consider the existence of indirect and dynamic effects involving the

reaction of economic agents affecting the decision to use diesel versus gasoline cars, motivated by the improvement in fuel efficiency in favor of the diesel or the existence of tax incentives to purchase diesel cars.

Relating these results with the discussion on CO2 emissions presented in the Introduction, we conclude that the rebound effect of diesel cars has indeed been greater than the fuel efficiency introduced by the dieselization process. The literature suggests two opposite effects of dieselization. On the one hand, one could expect a negative signal to CO2 emissions given that, comparatively, diesel cars emit lower average CO2 per km. On the other hand, a positive signal could be expected due to the longer distances travelled by diesel cars, and so dieselization may increase emissions.⁸ This divergence in the contribution of dieselization to CO2 emissions makes it very important to identify whether the predominant effect is negative or positive. Our results show a negative global effect of dieselization, which is strongly robust to the alternative econometric techniques and model specifications used.

6. Conclusions and policy implications

In this paper, we have examined the dynamic relationship between passenger car CO2 emissions and several variables in Europe between 1990 and 2015. We provide evidence that CO2 emissions have benefited from global technological progress and changes in average fuel efficiency, while increases of economic activity, motorization rate and the dieselization process hold a positive and significant relationship. These results are robust to alternative model specifications and econometric methods.

Specifically, we have found that car emissions evolve around downward-sloping trend and that they are converging across European

⁸ Some authors, for example, Schipper and Fulton (2009) and Schipper (2009) found that diesel cars are driven about 42% more than gasoline cars. Moreover, Schipper (2009) pointed out the existence of a self-selection effect, as those who drive farther switch to diesel, while those who drive less opt for gasoline cars.

countries by a yearly 4%. We also found that car CO₂ emissions are sensitive to the stocks of cars and particularly to changes in household consumption and that improvements in fuel efficiency implies a significant reduction of CO₂ emissions in the car passenger sector. However, our evidence suggests that the rebound effect of diesel vehicles has been greater than the effect of fuel efficiency introduced by the dieselization process. Indeed, all variables related to dieselization hold positive significant correlations with the growth rate of CO₂ emissions. In the case of relative fuel price, reflecting the government tax incentive on diesel fuel to promote diesel cars, we estimate that a 0.1 point increase in the relative fuel price (gasoline/diesel) produces about a 1.4% increase in car CO₂ emissions in passenger cars. This result contributes to the dieselization debate about the fuel taxation policy implemented in Europe.

In general, our results are consistent with the idea that tax policies in favor of dieselization have contributed to increase CO₂ emissions in passenger cars in Europe, mainly due to rebound effect that deepened the impact on mobility. However, this effect could have been mitigated if dieselization policies had been accompanied by mobility management measures. At this respect, our findings suggest that transport policies in Europe must change and reduce the benefits to the purchase of diesel fuel and diesel vehicles. In general, these policies would shift consumer choices in the transportation sector in a way that can reduce CO₂ emissions. However, to implement these policies, they should be also socially and politically acceptable. Otherwise, they will not be sustainable in the mid- and long-term. In this situation, policymakers need to combine rigorous empirical analysis (as the one provided in this paper) with a theoretical framework to analyze the social and political applicability of such policies and make them socially acceptable.

Acknowledgments

The authors greatly acknowledge comments of three anonymous referees, and the financial support from the Ministerio de Economía y Competitividad (Spain) under project ECO2016-76818-C3-2-P, from Junta de Andalucía through project SEJ-1512 and from the Agencia Canaria de Investigación, Innovación y Sociedad de la Información through its doctoral thesis support program.

References

- Abbes, S., Bulteau, J., 2018. Growth in transport sector CO₂ emissions in Tunisia: an analysis using a bounds testing approach. *Int. J. Glob. Energy Issues* 41.
- Ackah, I., Adu, F., 2014. Modelling gasoline demand in Ghana: a structural time series approach. *Int. J. Energy Econ. Policy* 4 (1), 76–82.
- Arellano, M., Bover, O., 1995. Another look at the instrumental-variable estimation of error-components models. *J. Econom.* 68, 29–52.
- Arellano, M., Bond, S., 1991. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Rev. Econ. Stud.* 58, 277–297.
- Atems, B., Hotaling, C., 2018. The effect of renewable and nonrenewable electricity generation on economic growth. *Energy Policy* 112, 111–118.
- Baltagi, B.H., Bresson, G., Griffin, J.M., Piroette, A., 2003. Homogeneous, heterogeneous or shrinkage estimators? Some empirical evidence from French regional gasoline consumption. *Empir. Econ.* 28 (4), 795–811.
- Banerjee, A., Duflo, E., 2003. Inequality and growth: what can the data say? *J. Econ. Growth* 8, 267–299.
- Barro, R.J., 2000. Inequality and growth in a panel of countries. *J. Econ. Growth* 5 (1), 5–32.
- Begum, R.A., Sohag, K., Sharifah, S.A., Mokhtar, J., 2015. CO₂ emissions, energy consumption, economic and population growth in Malaysia. *Renew. Sustain. Energy Rev.* 41, 594–601.
- Berkhout, P.H., Muskens, J.C., Velthuis, J.W., 2000. Defining the rebound effect. *Energy Policy* 28 (6–7), 425–432.
- Beuno, G., 2012. Analysis of scenario for the reduction of energy consumption and GHG emission in transport in Basque country. *Renew. Sustain. Energy Rev.* 16, 1988–1998.
- Binder, M., Hsiao, C., Pesaran, H., 2005. Estimation and inference in short panel vector auto-regressions with unit roots and cointegration. *Econom. Theor.* 21, 795–837.
- Blundell, R., Bond, S., 1998. Initial conditions and moment restrictions in dynamic panel data models. *J. Econom.* 87 (1), 115–143.
- Bonilla, D., 2009. Fuel demand on UK roads and dieselisation of fuel economy. *Energy Policy* 37 (10), 3769–3778.
- Bun, M., Sarafidis, V., 2015. Dynamic panel data models. In: Baltagi, B.H. (Ed.), *The Oxford Handbook of Panel Data*. Oxford University Press, Oxford, pp. 76–110.
- Caselli, F., Esquivel, G., Lefort, F., 1996. Reopening the convergence debate: a new look at cross-country growth empirics. *J. Econ. Growth* 1, 363–389.
- Chapman, L., 2007. Transport and climate change: a review. *J. Transp. Geogr.* 15 (5), 354–367.
- Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth. *Science* 171 (3977), 1212–1217.
- Ekins, P., Anandarajah, G., Strachan, N., 2011. Towards a low-carbon economy: scenarios and policies for the UK. *Clim. Policy* 11 (2), 865–882.
- Fontaras, G., Samaras, Z., 2007. A quantitative analysis of the European Automakers' voluntary commitment to reduce CO₂ emissions from new passenger cars based on independent experimental data. *Energy Policy* 35 (4), 2239–2248.
- Freire-González, J., 2017. Evidence of direct and indirect rebound effect in households in EU-27 countries. *Energy Policy* 102, 270–276.
- Frondel, M., Ritter, N., Vance, C., 2012. Heterogeneity in the rebound effect: further evidence for Germany. *Energy Econ.* 34 (2), 461–467.
- González, R.M., Marrero, G.A., 2012. The effect of dieselization in passenger cars emissions for Spanish regions: 1998–2006. *Energy Policy* 51, 213–222.
- Greene, D.L., 1997. Theory and Empirical Estimates of the Rebound Effect for the U.S. Transportation Sector. ORNL.
- Greene, D.L., 2012. Rebound 2007: analysis of US light-duty vehicle travel statistics. *Energy Policy* 41, 14–28.
- Greening, L.A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy* 28, 389–401.
- Hickman, R., Banister, D., 2007. Looking over the horizon: transport and reduced CO₂ emissions in the UK by 2030. *Transport Pol.* 14 (5), 377–387.
- Houthakker, H.S., Verleger, P.K., Sheehan, D.P., 1974. Dynamic demand analyses for gasoline and residential electricity. *Am. J. Agric. Econ.* 56 (2), 412–418.
- Huang, B.N., Hwang, M.J., Yang, C.W., 2008. Causal relationship between energy consumption and GDP growth revisited: A dynamic panel data approach. *Ecol. Econ.* 67 (1), 41–54.
- Hugrel, C., Joumard, R., 2001. Passenger cars contribution to the greenhouse effect influence of the air-conditioning and ACEA's commitment (JAMA and KAMA included) on the CO₂ emissions. In: *Proceedings of the 10th International Symposium on Transport and Air Pollution*.
- Islam, N., 1995. Growth empirics: a panel data approach. *Q. J. Econ.* 110 (4), 1127–1170.
- Jensen, P., 2003. Potential limitations of voluntary commitments on CO₂ emission reductions in transport. IPTS Rep. 79.
- Jeong, S.J., Kim, K.S., Park, J.W., 2009. CO₂ emissions change from the sales authorization of diesel passenger cars: Korean case study. *Energy Policy* 37 (7), 2630–2638.
- Kasman, A., Duman, Y.S., 2015. CO₂ emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. *Econ. Modell.* 44, 97–103.
- Kaya, Y., Yokobori, K. (Eds.), 1997. *Environment, Energy, and Economy: Strategies for Sustainability*. United Nations University Press, Tokyo.
- Khazzoom, J.D., 1980. Economic implications of mandated efficiency in standards for household appliances. *Energy J.* 1 (4), 21–40.
- Lakshmanan, T.R., Han, X., 1997. Factors underlying transportation CO₂ emissions in the USA: a decomposition analysis. *Transport. Res. Transport Environ.* 2 (1), 1–15.
- Lu, I.J., Lin, S.J., Lewis, C., 2007. Decomposition and decoupling effects of carbon dioxide emission from highway transportation in Taiwan, Germany, Japan and South Korea. *Energy Policy* 35 (6), 3226–3235.
- Marques, A.C., Fuinhas, J.A., Gonçalves, B.M., 2012. Dieselization and road transport CO₂ emissions: evidence from Europe. *Low Carbon Econ.* 3 (03), 54.
- Marrero, G.A., 2010. Greenhouse gases emissions, growth and the energy mix in Europe. *Energy Econ.* 32 (6), 1356–1363.
- Mustapa, S.I., Bekhet, H.A., 2015. Investigating factors affecting CO₂ emissions in Malaysian road transport sector. *Int. J. Energy Econ. Policy* 5 (4), 1073–1083.
- Nocera, S., Cavallero, F., 2011. Policy effectiveness for containing CO₂ emissions in transportation. *Procedia Soc. Behav. Sci.* 20, 703–713.
- OECD, 2019. *Passenger Transport (Indicator)*. <https://doi.org/10.1787/463da4d1-en>, Accessed date: 15 February 2019.
- Partridge, M.D., 2005. Does income distribution affect U.S. State economic growth? *J. Reg. Sci.* 45 (2), 363–394.
- Pock, M., 2010. Gasoline demand in Europe: new insights. *Energy Econ.* 32 (1), 54–62.
- Rietveld, P., van Woudenberg, S., 2005. Why fuel prices differ. *Energy Econ.* 27 (1), 79–92.
- Roodman, D., 2009. How to do xtabond2: an introduction to difference and system GMM in Stata. *STATA J.* 9 (1), 86–136.
- Ryan, L., Ferreira, S., Convery, F., 2009. The impact of fiscal and other measures on new passenger car sales and CO₂: evidence from Europe. *Energy Econ.* 31 (3), 365–374 2009.
- Saboori, B., Sapri, M., bin Baba, M., 2014. Economic growth, energy consumption and CO₂ emissions in OECD (Organization for Economic Co-operation and Development)'s transport sector: a fully modified bi-directional relationship approach. *Energy* 66, 150–161.
- Santos, G., 2017. Road fuel taxes in Europe: do they internalize road transport externalities? *Transport Pol.* 53, 120–134.
- Schipper, L., 2009. Carbon in motion: fuel economy, vehicle, use and other factors affecting CO₂ emissions from transport (editorial). *Energy Policy* 37 (10), 3711–3713 2009.
- Schipper, L., Fulton, L., 2009. Disappointed by diesel? Impact of shift to diesels in Europe through 2006. *Transport. Res. Rec.: J. Transport. Res. Board* (2139), 1–10.
- Schipper, L., Marie-Lilliu, C., Fulton, L., 2002. Diesels in Europe: analysis of characteristics, usage patterns, energy savings and CO₂ emission implications. *J. Transp. Econ. Policy* (JTEP) 36 (2), 305–340.
- Shu, Y., Lam, S.N.N., 2011. Spatial disaggregation of carbon dioxide emissions from road

- traffic based on multiple linear regression model. *Atmos. Environ.* 45, 634–640.
- Small, K.A., Van Dender, K., 2007. Fuel efficiency and motor vehicle travel: the declining rebound effect. *Energy J.* 25–51.
- Sorrell, S., 2007. The Rebound Effect: an Assessment of the Evidence for Economy-wide Energy Savings from Improved Energy Efficiency. UK Energy Research Centre, London.
- Sorrell, S., Dimitropoulos, J., 2008. The rebound effect: microeconomic definitions, limitations and extensions. *Ecol. Econ.* 65 (3), 636–649.
- Stapleton, L., Sorrell, S., Schwanen, T., 2017. Peak car and increasing rebound: a closer look at car travel trends in Great Britain. *Transport. Res. Transport Environ.* 53, 217–233.
- Sternier, T., 2007. Fuel taxes: an important instrument for climate policy. *Energy Policy* 35 (6), 3194–3202.
- Su, T.Y., Zhang, J.H., Li, J.L., Ni, Y., 2011. Influence factors of urban traffic carbon emission: an empirical study with panel data of big four city of china. *Ind. Eng. Manag.* 16 (5), 134–138 (in Chinese).
- Sullivan, J.L., Baker, R.E., Boyer, B.A., Hammerle, R.H., Kenney, T.E., Muniz, L., Wallington, T.J., 2004. CO2 emission benefit of diesel (versus gasoline) powered vehicles. *Environ. Sci. Technol.* 38, 3217–3223.
- Timilsina, G.R., Shrestha, A., 2009. Transport sector CO2 emissions growth in Asia: underlying factors and policy options. *Energy Policy* 37 (11), 4523–4539.
- Tovar, M.A., 2011. An integral evaluation of dieselisation policies for households' cars. *Energy Policy* 39 (9), 5228–5242.
- Wang, L., Zhou, D., Wang, Y., Zha, D., 2015. An empirical study of the environmental Kuznets curve for environmental quality in Gansu province. *Ecol. Indic.* 56, 96–105.
- West, S.E., 2004. Distributional effects of alternative vehicle pollution control policies. *J. Public Econ.* 88 (3), 735–757.
- Windmeijer, F., 2005. A finite sample correction for the variance of linear efficient two-step GMM estimators. *J. Econom.* 126 (1), 25–51.
- Xu, B., Lin, B., 2015. Factors affecting carbon dioxide (CO2) emissions in China's transport sector: a dynamic nonparametric additive regression model. *J. Clean. Prod.* 101, 311–322.
- Yan, X., Crookes, R.J., 2009. Reduction potentials of energy demand and GHG emission in China's road transport sector. *Energy Policy* 37 (2), 658–668.
- Yang, W., Li, T., Cao, X., 2015. Examining the impacts of socio-economic factors, urban form and transportation development on CO2 emissions from transportation in China: a panel data analysis of China's provinces. *Habitat Int.* 49, 212–220.
- Zachariadis, T., 2006. On the baseline evolution of automobile fuel economy in Europe. *Energy Policy* 34 (14), 1773–1785.
- Zervas, E., 2006. CO2 benefit from the increasing percentage of diesel passenger cars. Case of Ireland. *Energy Policy* 34 (17), 2848–2857.
- Zervas, E., 2010. Analysis of the CO2 emissions and of the other characteristics of the European market of new passenger cars. 1. Analysis of general data and analysis per country. *Energy Policy* 38 (10), 5413–5425.
- Zervas, E., Bikas, G., 2005. CO2 changes from the increasing percentage of diesel passenger cars in Norway. *Energy Fuels* 19 (5), 1919–1926.
- Zervas, E., Lazarou, C., 2007. CO2 benefit from the increasing percentage of diesel passenger cars in Sweden. *Int. J. Energy Res.* 31 (2), 192–203.
- Zervas, E., Pouloupoulos, S., Philippopoulos, C., 2006. CO2 emissions change from the introduction of diesel passenger cars: case of Greece. *Energy* 31 (14), 2915–2925.
- Zhang, Y.J., Peng, H.R., Liu, Z., Tan, W., 2015. Direct energy rebound effect for road passenger transport in China: a dynamic panel quantile regression approach. *Energy Policy* 87, 303–313.
- Zhang, T.X., Zeng, A.Z., 2013. Spatial econometrics on china transport carbon emissions. *Urban Stud.* 20 (10), 14e20.