Working papers series

WP ECON 15.11

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JEL Classification: E13, H22, Q43, Q54, R40

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September 16, 2015

*The authors acknowledge the financial support from *Ministerio de Economía y Competitividad* of Spain through project ECO2013-48884-C3-3-P, and from *Junta de Andalucía* through project SEJ-1512. The basic ideas of this paper originated while Jesús Rodríguez was visiting the University of Minnesota in 2009, during fruitful conversations with Víctor Ríos-Rull. Of course, any other error is of our entire responsibility. Appart from Víctor's comments, we also thank the ideas and suggestions from Antonia Díaz, Gonzalo Fernández de Córdoba, Luis Puch, Laura Riesgo, José Luis Torres, and María José Trigueros. This paper has been presented and discussed in the following meetings: FUNSEAN workshop on Energy Economics (May 9th 2014), Seminar of Departamento de Teoría e Historia Económica at Universidad de Málaga (June 11th 2014), X Congress of the Spanish Association of Energy Economics (Santa Cruz de Tenerife, January 29th 2015), Seminar of IPTS (European Commission, Seville February 27th 2015), and Departamento de Análisis Económico at Universidad de Alicante (Alicante, June 5th 2015).

Abstract. The stock of diesel motor cars has been growing during the last decades in Europe and nowadays accounts for nearly 40% of automobile fleet. Two issues helps explain this process. Firstly, fuel efficiency (liters/km) of diesel cars is about 20% higher than that of gasoline cars on average; secondly European governments have implemented tax policies lenient with diesel fuel, thus generating an extra stimulus to use diesel motor cars. We build on an dynamic general equilibrium model that makes distinction of diesel motor and gasoline motor vehicles, and calibrate it for main European countries. The model reproduces the vehicle fleet dieselization, the rebound effects in kilometers driven, the demand for fuel, and CO_2 emissions dynamics. From a normative view, the model recommends a tax discrimination according to the carbon content of each fuel, and not according to the fuel efficiency of the engine. Given that such a content is 15% higher for diesel relative to gasoline, tax rates should reflect this point: 1.40 cents of Euro per liter of diesel, and 1.22 cents per liter of gasoline. This is equivalent to imposing a tax of 19 Euros per ton of carbon. Yet Pigouvian sale taxes on new cars are useless to internalize the costs of externalities. Both recommendations are radically different to the existing fuel tax design in most OECD countries, except in Australia, Switzerland, UK and the US.

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1 Introduction

The profile of passenger cars fleet has been soundly transformed in Europe during the last decades. Diesel motor cars accounted for a minor part of the fleet at the beginning of the eighties and nowadays represent more than 40% of the total EU fleet, a process referred to as *dieselization*. Regarding durable goods consumption, this process is likely to be the most important program in terms of quantities and expenditures held in Europe during the last decades.

The choice between a gasoline versus a diesel car is a crucial element in European consumers' car-purchasing decisions. For certain important vehicle attributes, such as speed, safety, size, design, or horsepower, there are not substantial differences between the two types of vehicles. But for the fuel efficiency embedded, on average, diesel motor cars consume about 20% less fuel per kilometer than gasoline cars. This appealing property has a crucial incidence when consumers confront the dilemma on the type of motor that will engine the car they plan to purchase (Verboven, 2002).

An additional aspect likely behind the dieselization of the European passenger vehicle fleet is related to the fuel tax policy conducted by most European Governments. Since the oil price shocks of the seventies, most European governments have been more lenient with diesel fuel, generating an extra stimulus to use diesel motor cars (see among others, Verboven, 2002; Rietveld and Van Woudenber, 2005; and Zervas, 2010). Although relative (gasoline/diesel) fuel taxation has smoothed over time, diesel drivers still enjoy an operating cost per kilometer considerably lower than that of gasoline cars. Very often, sale taxation on new cars (value added tax and registration fees) has been addressed at inducing the purchase choice towards diesel vehicles. European governments have usually adduced two arguments to defend this discrimination policy, apparently backed by the higher fuel efficiency of diesel cars. Firstly, the gains in energy savings by owning and using diesel motor cars; secondly, the expected reduction of emissions. Early studies in Transport Economics (among many others, those by Schipper et al. 2002, and Sullivan et al. 2004), connected dieselization with reductions in CO_2 emissions as a consequence of the larger fuel efficiency of diesel engines. Alternatively, Miravete, Moral and Thurk (2015) find that behind such a tax practice is hidden a non tariff barrier against foreign imports.

In this paper, however, we start showing empirical evidence that casts some doubts about the success of dieselization in abating CO_2 pollution from passenger cars. Using data for a selected group of EU countries (the EU14 group) between 1998 to 2011, we estimate a dynamic panel data model and find robust evidence that the dieselization process has been detrimental for carbon emissions from cars, and such relationship holds a significant correlation with policy measures aimed at prompting the utilization of diesel vehicles. Early explanations of this finding point to an actually regularity observed in European road traffic: diesel cars are driven much more than gasoline cars. Thus, dieselization would generate a rebound effect, that is, an increase in the use of the overall fleet (total kilometers driven) because diesel cars show lower operating costs due to larger fuel efficiency combined with the lenient taxation of diesel.[1]

We address two additional issues in this paper. The first one is positive and deals with consumers' choices on the new car they purchase, the utilization of cars and the subsequent generation of CO_2 emissions. We propose an aggregate dynamic stochastic general equilibrium (DSGE) model to understand the interaction among these variables.[2] We build on a neoclassical framework with a representative household, whose utility hinges on leisure, consumption of non-durable goods, and the services provided by two types of automobiles: diesel-motor and gasoline-motor. Both automobiles are powered with their corresponding (non substitutable) fuels. These fuels are produced in a single refinery combining crude oil and capital. The model is calibrated for EU14, and its solution characterizes how cars ownership and use affect the local EU14 economy and global warming. The model generates different short-run and long-run price elasticities of fuel consumption, ranging within the region of plausible estimates in the empirical literature. Simulations show also that our market equilibrium is reasonably consistent with both cyclical and long run properties of EU14. Using the DSGE model, the tax policies earlier described can account for the replacement of gasoline by diesel automobiles (dieselization process), the increase in total kilometers driven and fuel consumed (rebound effect), and the particular recent evolution of CO_2 emissions from passenger cars in EU14.

The second aspect addressed in this paper is normative and deals with the optimality of the tax policy implemented in Europe. Parry, Walls and Harrington (2007) identify several vehicles externalities: noise, congestion, accidents, local pollution and global warming. Under these externalities, market prices fail to provide information on their external costs and, consequently, car users tend to drive their automobiles non optimally. With the exception of global warming, these externalities do not provide a fundamental to make a different tax treatment: diesel cars are not less noisy, nor cause fewer congestions than gasoline cars, and cars insurance policies do not contain different

[1] The success of the dieselization as a measure to control CO_2 emissions has been recently questioned by many authors in the Transport Literature: Schipper and Fulton (2013), Schipper (2011) and González and Marrero (2012). For a survey of the rebound effect in energy consumption see Greening et al. (2000).

[2] González and Marrero (2012) outlined the need to build theoretical models that consider the most important reciprocities among economic agents, energy incentives and road traffic, to fully understand the relationship between dieselization, fuel consumption and emissions in the road transport sector.

premiums informing drivers about a higher accident propensity of gasoline motor cars. The most important attribute determining local pollutants emissions (carbon monoxide, CO, nitrogen oxides, NO_x, and hydrocarbons, HC) is the age of the vehicle, and these emissions present a downward trend thanks to technological progress of fuel combustion (Parry, Walls and Harrington, 2007). Roughly, the age of the car and the technological progress are common to both type of vehicles. Thus, emissions of greenhouse effect gases and global warming do justify a different tax treatment between diesel and gasoline cars. This is the focus we choose to explore in the normative part of this paper. According to the U.S. Environmental Protection Agency (EPA, 2011), CO_2 emissions per liter of fuel combusted depend on the carbon content per liter of fuel. After combustion, most of the carbon content is emitted as CO_2 and, in a minor proportion, as other pollutants (HC, CO). The EPA estimates 2.689 kg. of CO_2 per liter of diesel, and 2.348 kg. of CO_2 per liter of gasoline. Therefore, the higher carbon content per liter of diesel (15% more) partially offsets the fuel efficiency in diesel powered cars (20% more).

Solving the planning problem allows to convey an expression for the social planner solution that internalizes the damage of fuel combustion. This socially optimal solution is confronted to the market equilibrium allocations, characterizing the Pigouvian taxation of each type of fuel and taxation of new cars acquisitions. This solution recommends, on the one hand, setting the fuel tax rates proportionally to the amount of carbon emissions of the fuel, which is about a 15% higher for diesel than for gasoline, and not according to fuel efficiency, which would lead to the opposite conclusion (about 20% lower for diesel). Thus, according to our calibration and this normative finding, tax rates should reflect this point and taxed by 1.40 cents of Euro per liter of diesel, and 1.22 cents per liter of gasoline, which is equivalent to imposing a tax of 19 Euros per ton of carbon. On the other hand, Pigouvian taxation sets a nil sale tax on new purchases of cars. Both results are at odd to the dieselization policy implemented during the last decades in most OECD countries, except in Switzerland, Australia, Switzerland, UK and the US. Thus, we find that the replacement of gasoline by diesel cars has been sub-optimal, generating an excessive rebound impact in terms of fuel consumption and CO_2 emissions in the car sector, which has largely compensated the fuel efficiency gain of substituting gasoline by diesel powered cars.

To our knowledge, this is the first paper addressing all these issues related to dieselization using both an empirical analysis and a DSGE model. Wei (2013) is probably an exception in using a similar theoretical framework, analyzing the consequences of Corporate Average Fuel Economy (CAFE) standards on gasoline consumption and miles driven in the US. By contrast, in our paper we take fuel economy for granted and focus on the diesel-gasoline dilemma. Our model is also linked to a wide branch of topics. Given that we deal with the externality of global warming, we extend some ideas from Golosov, Hassler, Krusell and Tsyvinski (2014) concerning the carbon cycle, and adapt them to CO_2 emissions from passenger vehicles in Europe, and derive similar equations to carbon (Pigouvian) taxation. A more traditional carbon cycle is the one proposed by Nordhaus (2008) for optimal carbon taxation. However, we borrow the cycle given in Golosov et al. (2014) as it reflects different global warming damage depending on emissions persistency.

The article by Parry and Small (2005) shares with ours a common interest of optimal (gasoline) taxation. However, while they account for a wider range of automobile externalities, such as congestions, accidents, pollution and global warming, we incorporate in our setting relevant general equilibrium and dynamic aspects which are crucial to understand and analyze driving decisions of agents and vehicle accumulation, and the subsequent fuel consumption and carbon dynamics.

The DSGE model is also useful to study automobile pricing. Verboven (2002) documents price differences, ranging from 10% to 15%, for gasoline and diesel new cars in France, Belgium and Italy. Similar price differences are also reported by Miravete, Moral and Thurk (2015) for Spain. Using a competitive monopolistic framework, Verboven concludes that between 75% and 90% of these differences can be explained by mark-up differences. By contrast, averaging the tax practice in EU14, our calibration leads to a relative price for new cars 9% higher for diesel. However, our explanation relies on fuel efficiency and fuel tax discrimination, under a fully competitive framework.

Finally, our paper is also connected with the literature on energy economics and transport economics (see references in footnote 1 and 2): we bring forth a comprehensive analysis relating dieselization, fuel consumption, replacement, rebound effect and CO_2 emissions in passenger cars.

The paper is structured as follows. The second section presents some evidence describing the evolution of the vehicle fleet, fuel consumption, and CO_2 emissions in Europe. We combine several sources of data and report estimated results from a dynamic panel data model. The dynamic model with diesel and gasoline cars is set up in the third section. In the fourth section, the market equilibrium is solved. In the fifth section, the model is calibrated for an aggregate economy of fourteen European countries, and the market equilibrium is analyzed through impulse response functions and a sensitivity analysis of steady state values. The sixth section is rather normative and solves for the social planner allocation. Pigouvian rules are obtained for fuels and cars sales taxation. A steady state study completes this normative section. Conclusions are summarized and presented in the last section.

2 Empirical evidence

In this Section we show some empirical evidence illustrating the correlation between dieselization and CO_2 emissions from road transport (passenger cars) in Europe. This analysis is based on collected information from fourteen European countries (henceforth, EU14) during the last twenty years: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, and United Kingdom.[3]

2.1 Dieselization, fuel efficiency and rebound

Figure 1 shows the evolution of the percentage over the total of the stock of diesel passenger cars, diesel consumption of cars and new registrations in EU14 countries from 1991 to 2011. It clearly reflects an intensive transformation process in the European car fleet. For example, the percentage of diesel cars increased from 11% in 1991 to almost 38% in 2011. With the exception of Greece, this ratio has raised in all EU14 countries during this period. For example, Austria, Belgium, France, Portugal, Spain or Italy, currently holding the highest proportion of diesel cars, have shifted from ratios of between 9% and 17% in 1991 to others between 40% and 59% in 2011 (Table A6 in Appendix A shows details by countries for 1999 and 2011). Similar patterns are observed when looking at the ratios of cars' fuel consumption and the ratio of new cars registrations. These trends are clear indicatives of the intensive dieselization process taken place in Europe during that period.

Two facts may help explain the origin of this dieselization process. First, there is an advantage in fuel efficiency of diesel motor cars with respect to gasoline motor cars. Figure 2 evinces the average number of liters of fuel needed per 100 kilometer for diesel and gasoline car (i.e., the inverse of fuel efficiency) from 2000 to 2011. While a diesel motor car burns around 6.8 liters of diesel fuel per 100 kilometers, a gasoline motor car burns 7.96 liters on average, i.e. 17% more. Moreover, as can be seen in the Figure, a common downward trend (i.e., maybe due to a common technological improvement) is observed for both series.

Second, most European Governments have practiced a diesel incentive fuel tax policy. Figure 3 shows the evolution of the EU14 average of gasoline and diesel prices (with and without taxes) from 1998 to 2011. While prices of both fuels (net of taxes) have basically evolved evenly during

[3] Throughout this section, data on fuel consumption (million tonnes of oil equivalent), stock of cars and new sales of cars (millions of units), kilometers driven (km-travelled/car-year), fuel efficiency (liters/100 km.) and CO_2 emissions (Mt. CO_2) come from the Odyssee-Mure database:

http://www.indicators.odyssee-mure.eu/online-indicators.html

This database allows a distinction between diesel and gasoline.

this period, the price of diesel turns clearly higher than that of gasoline (about 20% higher on average for the whole period) when taxes are included. Moreover, on average, taxation accounted about 55% for diesel and 65% for gasoline of their respectively final fuel prices.[4] Energy saving is the argument often used to justify this discriminating taxation in favor of the diesel fuel, given that diesel powered vehicles are more efficient than those combusting gasoline. During the 90s, Transport Economics research eagerly defended the dieselization process as a way to reduce CO_2 emissions from road transport (see Rietveld and Van Woudenber (2005), and Zervas (2010), among others). Miravete et al. (2015) find that this tax practice hides a non tariff barrier against foreign imports.

A more recent literature, however, has alerted about the weakness of this result. In particular, this new branch of research finds robust evidence about the existence of certain facts that could offset the short-run efficiency impact of substituting a gasoline car by a diesel motor car. We highlight two of them, which will be considered in the model presented in Section 3. First, the higher carbon content per liter of diesel partially offsets the fuel efficiency in diesel powered cars (EPA, 2011). On average, the emissions generated by the consumption per liter of diesel is about 2.689 Kg. of CO_2, which is about a 14.5% higher than that generated per liter of gasoline, which is 2.348 Kg. of CO_2. Thus, on average, CO_2 emissions per kilometer driven in a diesel car is just a 5.5% lower than in a gasoline car, which is clearly below than the efficiency gains (in liters per kilometers) of the diesel commented above.[5] Second, the dieselization process implies also a rebound in total kilometers driven. Precisely, provided that diesel cars are more efficient (in terms of liters per km. driven) and the diesel price (tax included) is cheaper (in terms of euros per liter), diesel cars are driven more intensely than gasoline cars, which is the final cause of the rebound impact. Figure 4 reports the kilometers driven by diesel cars, by gasoline cars and its ratio, averaged over a set of countries.[6] From 2000 to 2011, the average kilometers driven by gasoline cars were 11,356 while by diesel cars were 18,737, and the ratio exhibits an upward trend with values well above one (in the 1.67-1.87 interval) for the entire sample.[7]

[4] Most OECD countries follow a similar practice (Knittel, 2012). Two exceptions are Switzerland and the US, where the tax rate on gasoline is lower. In Australia and the UK both fuels are equally taxed. See Table A7 in Appendix A which presents details of these tax ratios for EU14 countries in 1999.

[5] Further details can be viewed at the U.S. Energy Information Administration:
http://www.eia.gov/oiaf/1605/coefficients.html#tbl2

[6] Due to data availability, Figures 2 and 4 are constructed using data from a reduced number of countries: Austria, Denmark, France, Germany, Ireland, Netherlands, Portugal and Spain.

[7] Verboven (2002) reports similar figures for France, Belgium and Italy. Although there is no controversy on the fact that diesel cars are driven more intensively, a word of caution should be said around the magnitude of the series of data on kilometers driven, as these are generally obtained from non-homogeneous estimation methodologies across years and countries (for a discussion, see Small and Van Dender, 2007). Schipper (2011) reports that

Finally, Figure 5 shows the evolution from 1998 to 2011 of total CO_2 emissions coming from all final consumers (including electricity) and those only coming from passenger cars. Data were aggregated for main EU14 countries.[8] While both series have decreased for the entire sample (10% for final consumers and 3.8% for passenger cars), carbon emissions coming from passenger cars have become more important (the ratio was 15.7% in 1998 and 18.7% in 2011).

Given all previous arguments, the relevant question is: has the dieselization policy favored this CO_2 evolution or, on the contrary, has it been harmful? To properly analyze the global impact of the dieselization policy over CO_2 emissions in the sector, we must figure out whether the rebound impact has (or not) offset the benefits on emissions induced by the replacement of gasoline cars by the more efficient diesel cars.

[**Figures 1 through 5 here**]

2.2 Evidence on dieselization and CO_2 emissions

We use an incomplete panel of EU14 countries from 1998 to 2011 to explore the link between dieselization and CO_2 emissions growth in passenger cars.[9] For country $i = 1, ..., 14$, let $\left(E_{i,t}^{cars}, GDP_{i,t}^{pc}, Q_{i,t}^{pc}\right)$ respectively denote CO_2 emissions from passenger cars, real GDP, and stock of vehicles, all expressed in per capita terms. We estimate the following regression for the growth rate of $E_{i,t}^{cars}$:

$$\Delta \ln E_{i,t}^{cars} = \rho_i + \overline{\rho} + \rho_0 \cdot t + \xi_0 \cdot \ln E_{i,t-1}^{cars} + \xi_1 \cdot \Delta \ln GDP_{i,t}^{pc} + \xi_2 \cdot \Delta \ln Q_{i,t}^{pc} + \lambda \cdot \Delta D_{it} + \varepsilon_{it}, \quad (1)$$

with $\varepsilon_{i,t} \sim iid$, and Δ denoting the first difference operator; ρ_i denotes a country-specific effect, $\overline{\rho}$ and ρ_0 reflect a constant and a linear trend, common to all countries. GDP^{pc} and Q^{pc} are used to control for the degree of development and the scale of the fleet. Finally, D_{it} abstracts a variety of measures of dieselization. Three proxies of dieselization are considered, $D_{i,t}$, which are included in (1) separately in order to avoid colinearity problems.

- The diesel-to-gasoline stock of passenger vehicles ratio, as a first measure of dieselization, albeit uninformative for the usage of the fleet.

individual km. traveled in European countries is between 35% to 45% lower than in the US.

[8] Belgium and Finland are excluded due to incomplete CO_2 data.

[9] After required transformation, the number of observations is 137, for 13 countries (Belgium is excluded from the sample because its fuel consumption series do not distinguish between diesel and gasoline cars). Data of Finland from 1998 to 2003 are missing.

- The diesel-to-gasoline fuel consumption ratio, which is more contrived as it captures the stock together with the flow of utilization (kilometers driven), and aggregate fuel efficiency.

- The relative fuel price, fuel taxes included, as a key factor behind the decision of vehicle replacement and of usage.

The estimates of equation (1) are presented in Table 1.[10] The linear trend for CO_2 emissions per capita, ρ_0, is always negative and statistically significant, indicating fuel-efficiency gains from dieselization. The dynamic term ξ_0 is non-significant in all specifications, showing the lack of conditional convergence; the growth rate of GDP per capita is positively correlated with the growth rate of emissions (parameter ξ_1), albeit it is not statistically significant; the growth rate of the stock of passenger cars is positively correlated (parameter ξ_2), and statistically significant at 5% in all cases (the size of the fleet matters for per capita emissions).

The key parameter, λ, associated to $D_{i,t}$, is positive and significant at 10% for the three specifications considered. The first specification of $D_{i,t}$ (columns (a) and (a') in Table 1) suggests that a change in the composition of the fleet can account between one fifth and one half of any 1% increase in CO_2 per capita emissions. The second specification of $D_{i,t}$ (columns (b) and (b')) indicates that a change in the rebounding usage paired with the composition effect can account between one fourth and one sixth of any 1% increase in emissions. Finally, the third specification of $D_{i,t}$ (columns (c) and (c')) points out to the crucial role of fuel taxation on emissions through the channels on fleet dieselization and automobile utilization: lenient tax policies have favored the use of diesel fuel and prompted for further CO_2 emissions. Thus, this evidence highlights that the rebound effect dominates the efficiency gains induced by the replacement effect in EU14 countries.

The empirical evidence presented so far points out to a limited success of dieselization in reducing CO_2 emissions from passenger cars. However, in order to characterize whether the dieselization policy has been the right one, we must rely on a dynamic general equilibrium model which put together all required pieces to handle optimal policy issues.

[**Table 1 here**]

[10] Since pooled-OLS estimator suffers from endogeneity problems when estimating a dynamic model like (1), we also consider the system-GMM estimator proposed by Arellano and Bover (1995) and Blundell and Bond (1998) which properly handles the endogeneity problem in this sort of models. We also follow Roodman (2009) recommendations to overcome additional estimation problems in macro panel models, and reduce the number of instruments in the System-GMM approach by collapsing the matrix of instruments.

3 A DSGE model

We build on a neoclassical DSGE model with a representative agent and durable goods (cars), distinguishing between diesel and gasoline motor cars. Special attention is given to the services from automobiles, and the indirect effects that they generate through their use and the externality due to CO_2 emissions. We assume the presence of a government that levies a variety of fiscal tools that affect the decision of acquisition of new cars and the decision of driving. We carry out the convention that aggregate variables are denoted with capitals letters and individual variables with lower case letters; time subscript is omitted if not necessary, with v' denoting the one-period ahead value of variable v. Diesel attribute is subindexed with $j = 1$, and gasoline attribute with $j = 2$.

This Section starts with a description of the general setting and defining some key equations related with preferences and the benefits and cost of using vehicles (Section 3.1); the technology of the three kind of goods produced in the economy (Section 3.2): final consumption good, motor vehicles (diesel and gasoline) and fuel (diesel and gasoline); the budget constraint of the different agents in the economy (Section 3.3); the resource constraints (Section 3.4); finally, the carbon cycle and the generation of CO_2 emissions in the passenger cars sector (Section 3.5).

3.1 Preferences, automobiles and operating costs

The economy is inhabited by an infinitely lived, representative household with time-separable preferences in terms of consumption of a final non-durable good, c, direct services from cars, s, and hours worked, h. Preferences are represented by a strictly concave utility function,

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u\left(c_t, s_t, h_t\right), \tag{2}$$

where $\beta \in (0, 1)$ is the discount factor and $\mathbb{E}_0$ is the expectation operator conditional on information available at time 0. We pose a separable utility function of the form:

$$u\left(c, s, h\right) = \ln\left(c\right) + \psi_s \ln\left(s\right) - \psi_h \frac{h^{1+1/\nu}}{1 + 1/\nu}, \tag{3}$$

where $\psi_s > 0$ accounts for the willingness to drive a car (the higher, the more willing); $\psi_h > 0$ represents the (un-)willingness to work (the higher it is, the higher the propensity for leisure); and $\nu > 0$ is the Frisch elasticity of labor. The concavity of this utility function guarantees that households adequately diversify their asset portfolios and consumption plans. For vehicle services s, the logarithmic function makes consumers design a bundle of vehicles fueled with either gasoline or diesel. Services accruing to vehicles depend on the ownership and utilization of diesel and gasoline.

For $j = 1, 2$, q_j is the stock of vehicles j, $\tilde{n}_j$ represents the kilometers driven in a car of type j, and s_j denotes the services from vehicles powered with fuel j, which is given by:

$$s_j = \tilde{n}_j^{\varsigma} q_j, \tag{4}$$

with $0 < \varsigma < 1$ showing that using cars too intensely has diminishing returns and it is better to use cars of type j less intensely by having more cars. Total services accruing to the fleet of passenger vehicles (q_1, q_2) are aggregated using a CES average:

$$s = [\chi_1 s_1^{\rho} + \chi_2 s_2^{\rho}]^{1/\rho}, \tag{5}$$

where $\chi_1 + \chi_2 = 1$, and $\rho \leq 1$, which is the elasticity of substitution between the services of both diesel and gasoline vehicles. For the particular case $\rho = 1$, the services of both vehicles are perfect substitute. In general a certain degree of substitutability, as we guess it is the case, can be allowed for the range $0 \leq \rho \leq 1$, where substitution effects dominate income effects. More details about this parameter is shown in Section 5 (Calibration).

The stock of cars evolves according to a geometrical law of motion:

$$q_j' = (1 - \alpha_j)\, q_j + x_j, \tag{6}$$

with x_j being the flow of new cars purchases, and $\alpha_j \in (0, 1)$ being the geometrical rate of depreciation, thus $\alpha_j q_j$ is a proxy for scrapped vehicles.

The use of the fleet requires consuming additional resources: fuel (F_j), maintenance and repair the vehicle (MR_j):

$$\begin{aligned} F_j &= f_j \tilde{n}_j q_j, & (7) \\ MR_j &= m_j \tilde{n}_j q_j, & (8) \end{aligned}$$

for $j = 1, 2$, where, f_j denotes liters of fuel j per kilometer in a car of type j, with $f_1 < f_2$ (recall from the facts described in Section 2); m_j refers to the quantity of maintenance and repair services needed per kilometer.[11] While F_j and MR_j are proportional to the amount of kilometers driven, $\tilde{n}_j q_j$, other costs just depend on the ownership, such as the insurances and tolls, TI:

$$TI = (q_1 + q_2)\, p_{TI}, \tag{9}$$

where p_{TI} represents the amount of resources (in units of the final consumption good) required for this concept per vehicle.

Finally, in the aggregate level, total vehicles kilometers driven (TKD) are given by:

$$TKD = Q_1 \tilde{N}_1 + Q_2 \tilde{N}_2. \tag{10}$$

3.2 Sectors

The supply side of the economy consists in three sectors: a sector producing a final consumption good Y, is used as a numeraire in the rest of activities; an automotive industry producing two type of cars, gasoline and diesel powered cars, $\mathcal{X}_j$, $j = 1, 2.$; and a refinery which produces two fuels (diesel and gasoline), $\mathcal{F}_j$, $j = 1, 2$, needed by households to drive their cars. We assume that these two last industries (automotive and refinery) are capital intensive and, by simplicity, we disregard labor as a productive factor in these two last sectors.

The final consumption good Y is produced according to a Cob-Douglas production function, which employs physical capital, K_Y, and effective hours worked, $\widetilde{H}$, under constant returns to scale. The production frontier is impulsed by aggregate total factor productivity (TFP) A, which is damaged by the CO_2 concentrated in the atmosphere, Z, in excess to that of preindustrial era which we take as 581 Gts (Golosov et al., 2014):

$$Y = e^{-\gamma(Z-581)} A \cdot \widetilde{H}^{\theta} K_Y^{1-\theta}, \tag{11}$$

where $\gamma > 0$ is the damage factor.[12] The accumulation process of CO_2, Z, will be described later. The (log of) TFP follows an autorregresive process (see details in Section 4). We impose a certain

[11] $\{f_j, m_j\}$ are assumed to be exogenous, though they can be affected by technology. For instance, improvements in energy efficiency reduces f_j, or a quality improvement of cars may reduce m_j. Aghion et al. (2012) show evidence that automotive industry tend to innovate relatively more in fuel efficiency under tax-adjusted fuel prices increases. Wei (2013) uses a vintage capital within a DSGE model to incorporate innovations in fuel economy. We opt to take fuel efficiency (f_i) as a parameter.

[12] See Golosov et al. (2014) for a discussion of the reliability of this assumption. According to these authors, damages to utility, production and to capital can all be synthesized into the form we consider here.

degree of complementarity between aggregate cars services (durables consumption), S, and the supply of labor (Fisher, 2007), such that the amount of hours measured in efficiency units, $\widetilde{H}$, are given by:

$$\widetilde{H} = H^{\mu} S^{1-\mu}, \tag{12}$$

with $\mu \in [0,1]$.[13] Such a complementarity between vehicle services and hours worked responds to the idea that cars can be viewed as work tolls and are not mere consumption durable goods. In this respect, we follow Fisher (2007) and assume that the utilization of automobiles affects productivity and increases hours worked in efficiency units.

The representative firm in the automobile sector is assumed to manufacture a bundle of a single model of cars but with two different engines: diesel and gasoline combustion motors. It only uses capital, $K_{X,j}$,

$$\mathcal{X}_j = A \; a_j \; K_{Xj}^{1-\theta_X}, \; j = 1, 2, \tag{13}$$

with $0 < \theta_X < 1$, and technology which is embedded in $a_j > 0$. Aggregate TFP affects also to this sector.

Finally, fuel is produced in a single plant of a refinery which combines crude oil, o, and capital, $K_{F,j}$, under a constant return to scale technology:

$$\mathcal{F}_j = A \; b_j \; o_j^{\theta_F} K_{Fj}^{1-\theta_F}, \; j = 1, 2, \tag{14}$$

where $b_j > 0$ denotes technological parameters in the production of diesel and gasoline, respectively. Again, aggregate TFP A affects this sector.

Other activities in this economy, such as repair services, insurance services, or the extraction of crude oil, are assumed to be exogenously produced and supplied in a perfect elastically way.

3.3 Government and household's budgets

Let $\mathbf{p}$ denote the vector of prices (relative to that of the numeraire final good Y) related to vehicles ownership and use:

$$\mathbf{p} = (p_{X1}, p_{X2}, p_{F1}, p_{F2}, p_{MR}, p_{TI}),$$

[13] Standard RBC models suppose $\mu = 1$, implying that effective hours worked equal hours devoted to non-leisure activities. However, this case makes consumption of durables decrease in response to a positive shock to TFP, a prediction not supported by the data. Assuming, instead, $\mu < 1$ helps the standard model to reconcile with the data (Fischer, 2007).

where p_{Xj} denotes the acquisition price of a brand new vehicle j, p_{Fj} is the fuel j price, p_{MR} is the real price of one unit of maintenance and repairs services (we assume it is the same for $j = 1$ and $j = 2$), and p_{TI} is the price of a set of fixed costs per vehicle, such as car insurances and tolls. For cars insurances, we implicitly assume that these contracts are actuarially fair and that the risk covered by them occurs with probability one, i.e. the cost of cars insurances fully translates into consumption. The three raw inputs in this economy, labor, capital and oil, are traded in competitive markets at prices (W, R, p_o), denoting wage, rental price of capital and the real exchange rate (in units of the final consumption good) of crude oil. Real prices p_o, p_{MR} and p_{TI} are taken as exogenous because, as commented above, repair services, insurance services, and the extraction of crude oil are supplied in a perfect elastically way.

The government uses four taxes and distort agents' decisions: (i) a taxation $\{\tau_{X1}, \tau_{X2}\}$ that affect the price new vehicles of type j: $(1 + \tau_{Xj})\, p_{Xj}$; (ii) taxes on fuel $\{\tau_{F1}, \tau_{F2}\}$ that affect the operating cost of cars: $(p_{Fj} + \tau_{Fj})$. Tax revenues are fully rebated to the household every period via a lump sum transfer TR. Therefore, the public budget is balanced period by period:

$$\sum_{j=1,2} (\tau_{fj} f_j \tilde{n}_j q_j + \tau_{xj} p_{Xj} x_j) = TR. \tag{15}$$

Household's budget can be written as:

$$c + i + \sum_{j=1,2} \left[(1 + \tau_{x,j})\, p_{Xj} \cdot x_j + (\overline{mc}_j \tilde{n}_j + p_{TI})\, q_j \right] = \widetilde{h}\, W + k\; R + \Pi + TR, \tag{16}$$

where Π are profits from the automotive sector in the economy; i denotes individual gross investment in a physical capital asset k. The term $\overline{mc}_j$ denotes the operating (marginal) cost per kilometer driven $\tilde{n}_j$, and collects expenditures of fuel (including taxes) and maintenance and repairs services:

$$\overline{mc}_j \equiv (p_{F,j} + \tau_{F,j})\, f_j + p_{MR} m_j. \tag{17}$$

Car insurances and tolls in (16) implies a a fixed cost p_{TI} per vehicle regardless the number of kilometers driven.

3.4 Automobile externalities, CO_2 emissions and the carbon cycle

The use of vehicles can affect the economy and the environment in many ways: global warming, pollution of local air and water quality, congestion, accidents, or noise. Surveys of potential externalities from automobile use include Delucchi (2000), Parry, Walls and Harrington (2007), Knittel (2011), and Delucchi and McCubbin (2010). These studies find that the external cost of air pollution is greater than the cost of climate change. For instance, in Delucchi's (2000) survey, the cost of climate change due to CO_2 emissions from automobile accounts between 7 and 13 percent of total external environmental costs of U.S. automobile use (in 1990 U.S. dollars), congestion excluded. According to Parry and Small (2005), the external cost of global warming would represent only a minor fraction of total external costs. They find that congestion may explain the higher taxation of gasoline fuel in the U.K. relative to the U.S. More recently, Delucchi and McCubbin (2010) estimate that accident and congestion costs likely represent the largest part of these external costs, followed by air pollution and climate change costs.

Market prices do not contain information on these external costs and the operating costs of driving make motorists use their automobiles non optimally. The lenient tax treatment of diesel should be based on at least one of these arguments. Car insurance contracts do not reflect different premiums informing drivers about a higher accident propensity of gasoline cars. Diesel cars are not less noisy, nor do congest less than gasoline cars. Until the nineties, however, diesel powered cars were commonly perceived more noisy. Local pollutants such as carbon monoxide, CO, nitrogen oxides, NO_x, volatile organic compounds VOC, tend to increase with the age of a vehicle (Beydoun and Guldmann, 2006), and cannot be associated to the engine. Indeed, emissions of local pollutants exhibit a downward trend due to technological progress (Parry et al., 2007). Michaelis (1995) finds that diesel cars emits less CO than gasoline cars, the same VOC, and more NO_x. When considering urban air quality, Crawford and Smith (1995) emphasized that the social costs of using diesel cars have some clear disadvantages, which tend to exacerbate under traffic congestion. Overall, the net cost-benefit evaluation of these externalities is unclear and do not help justify a tax discrimination. Albeit global warming costs represent a minor fraction of these external costs, we focus our attention on these costs given that it is the main factor which can justify a different tax treatment of diesel and gasoline.

Let E be the world flow of CO_2 emissions, represented according to the following structure:

$$E = E^{RW} + E^{other} + E^{cars}, \tag{18}$$

where E^{cars} denotes the emissions due to passengers vehicles in Europe, E^{other} is the flow of European emissions other than those emitted by European cars, and E^{RW} are emissions from the rest of the world. E^{cars} mainly depends on the carbon content of the fuel. After combustion, most of the carbon content is emitted as CO_2 and, in a minor proportion, as other pollutants (HC or CO). Thus, we can assume that cars emissions is a by-product of fuel consumption, F_1 and F_2 (EPA, 2011):

$$E^{cars} = \phi_1 F_1 + \phi_2 F_2, \tag{19}$$

where ϕ_j is the amount of TonsCO2 per liter of fuel $j = 1, 2$, with $\phi_1 > \phi_2$ and its ratio ϕ_1/ϕ_2 being approximately equal to 1.145 as already discussed in Section 2.

The stock of CO_2, Z, evolves according to the carbon cycle proposed by Golosov et al. (2014) and references therein. Using related studies, these authors assume that a 20% ($\varphi_L = 0.2$) of CO_2 emissions, denoted by Z_1, remains in the atmosphere for thousands of years. The remaining fraction ($1 - \varphi_L = 0.8$), a percentage φ_0 has a half life of 300 years in the atmosphere (this part is denoted by Z_2), and a percentage $1 - \varphi_0$ exists in the surface of the oceans and in the biosphere, with a half life of about one decade, denoted by Z_3. Z_1, Z_2 and Z_3 can be represented by a geometrical law of motion with decays $\delta_1 = 0$, δ_2 and δ_3, respectively, with $\delta_3 > \delta_2 > 0$. Given that Golosov *et al.* (2014) focus on long run implications of CO_2 concentration, they only consider Z_1 and Z_2. We adapt this state equation to our business cycle frequency and take Z_3 into account. Thus, the aggregate stock Z is governed by the following law of motion:

$$Z = Z_1 + Z_2 + Z_3, \tag{20}$$

$$Z_1' = Z_1 + \varphi_L E, \tag{21}$$

$$Z_2' = (1 - \delta_2) Z_2 + (1 - \varphi_L) \varphi_0 E, \tag{22}$$

$$Z_3' = (1 - \delta_3) Z_3 + (1 - \varphi_L)(1 - \varphi_0) E. \tag{23}$$

In subsequent representations, this cycle will be outlined through the following state-space form:

$$Z' = \mathcal{Z}(Z, E). \tag{24}$$

Another carbon cycle is the one proposed by Nordhaus (2008) for optimal carbon taxation, where the interaction between atmosphere and surface oceans are considered. We opt to use the cycle given in Golosov et al. (2014) as it provides an accurate representation of emissions persistency, which is crucial to determine optimal carbon taxation.

3.5 Resource constraints

Given these ingredients, the resource constraint for Y is given by:

$$Y = C + I + \sum_{j=1,2} \left(p_o \cdot o_j + p_{MR} \cdot m_j Q_j \tilde{N}_j + p_{TI} \cdot Q_j \right). \tag{25}$$

The left hand side is the total amount of resources available at period t (output Y produced), and the right hand side denotes the use of these resources (consumption, investment, crude oil, repair and maintenance of cars and insurances and tolls of cars ownership). Analogously, as for fuels and new cars, the feasibility constraints can be expressed as follows:

$$f_j \tilde{N}_j Q_j = \mathcal{F}_j, \quad \text{for } j = 1,2, \tag{26}$$

$$X_j = \mathcal{X}_j. \quad \text{for } j = 1,2. \tag{27}$$

The law of motion for aggregate physical capital K is given by

$$K' = (1 - \delta) K + I, \tag{28}$$

where $\delta \in (0,1)$ is the capital depreciation rate. This aggregate capital is allocated across the alternative sectors:

$$K = K_Y + \sum_{j=1,2} (K_{Xj} + K_{Fj}). \tag{29}$$

4 Market equilibrium

We characterize market equilibrium allocations in terms of prices and policy variables. These conditions allow us to analyze in the next section positive issues related with fuel taxation, dieselization or emissions damage. The agents living in this economy are households, firms (final goods, cars and fuel producers) and a government.

4.1 Households

The representative household considers a set of state variables $\zeta^H = (K, Q_1, Q_2, A, p_o)$, and does not internalize the costs of CO_2 concentration. The representative household problem can be written as follows:

$$V\left(\zeta^H, k, q\right) = \max\left\{u\left(c, s, h\right) + \beta\mathbb{E}\left[V\left(\zeta^{H\prime}, k', q'\right)\right]\right\}, \tag{30}$$

with respect to $\left(c, h, i, , k', \{x_j, \tilde{n}_j, q'_j\}_{j=1,2}\right)$, subject to the budget constraint (16), the state equations for capital (28) and vehicle accumulation (6), and non-negaivity constraints. The wage W, the (net) rental rate of capital R, the government transfer TR, and the dividends from the automotive industry Π are assume to be given. All remaining prices $\left(\{p_{Xj}, p_{Fj}\}_{j=1,2}, p_{MR}, p_{TI}\right)$ and taxes $\{\tau_{Fj}, \tau_{Xj}\}_{j=1,2}$ are also assumed to be given to the household.

First order conditions of the households are the following. First, the standard intertemporal Euler equation

$$u_c = \beta\mathbb{E}\left[u'_c\left(R' + 1 - \delta\right)\right], \tag{31}$$

which determine the amount of investment in physical asset k. Second, the intratemporal choice between c and h,

$$0 = W\mu\left(s/h\right)^{1-\mu}u_c + u_h. \tag{32}$$

The third set of conditions produces the decision of purchasing a brand new car of type j:

$$\begin{aligned}(1 + \tau_{x,j})\, p_{Xj} u_c \;=\; & \beta\mathbb{E}\Big\{\chi_j\left(\tilde{n}'_j\right)^{\varsigma\rho}\left(q'_j\right)^{\rho-1}\Omega' - \left(\overline{mc}'_j\tilde{n}'_j + p'_{TI}\right)u'_c \\ & + (1 - \alpha_j)\left(1 + \tau'_{Xj}\right)p'_{Xj}u'_c\Big\}.\end{aligned} \tag{33}$$

where Ω denotes

$$\Omega \equiv \frac{\psi_s}{s^\rho} + (1 - \mu)\, W\frac{h^\mu}{s^\mu}u_c. \tag{34}$$

The term $\{(1 - \mu)\, W'\left(h'/s'\right)^\mu u'_c\}$ collects the productivity gains from owning and using vehicles, due to its complementarity with capital. Condition (33) determines the amount of new cars investment for each type $j = 1, 2$. Expression (33) is a forward looking pricing relation for new vehicles: the price of a new car of type j reflects the future stream of services minus the future stream of its opportunity cost, expressed in utility units. Using a sequential notation, it is illustrative to iterate forward on this expression and rewrite it in relative terms:

$$\frac{(1 + \tau_{X1,0})\, p_{X1,0}}{(1 + \tau_{X2,0})\, p_{X2,0}} = \frac{\mathbb{E}_0\sum_{t=1}^{\infty}\beta^t\left(1 - \alpha_1\right)^t\left[\chi_1\tilde{n}_{1,t}^{\varsigma\rho}q_{1,t}^{\rho-1}\Omega_t - \left(\overline{mc}_{1,t}\tilde{n}_{1,t} + p_{TI,t}\right)u_{c,t}\right]}{\mathbb{E}_0\sum_{t=1}^{\infty}\beta^t\left(1 - \alpha_2\right)^t\left[\chi_2\tilde{n}_{2,t}^{\varsigma\rho}q_{2,t}^{\rho-1}\Omega_t - \left(\overline{mc}_{2,t}\tilde{n}_{2,t} + p_{TI,t}\right)u_{c,t}\right]}. \tag{35}$$

Following a decrease in the price of diesel vehicles (relative to the price of gasoline vehicles), household's optimal choice moves resources from the services of gasoline cars to those of diesel cars. Given concavity of preferences, the marginal rate of substitution between both types of cars must also decrease.

Finally, we have the condition for the mileage demand of each car, $\tilde{n}_j$, (the marginal benefit of driving must equalize its marginal cost every period):

$$\varsigma\Omega\ \chi_j \tilde{n}_j^{\varsigma\rho-1} q_j^{\rho-1} = \overline{mc}_j u_c. \tag{36}$$

Given the state q_j, the short-run elasticity of $\tilde{n}_j$ with respect to the operating cost $\overline{mc}_j$ is $-1/\left(1-\varsigma\rho\right)$. Holding constant all other variables, for $\rho < 1$, any change in q_j would be reflected in a reduction of $\tilde{n}_j$: having more cars implies driving existing cars less intensively. As we will show in Section 5.3, this situation can be motivated by a change in taxation τ_{X_j}.

Dividing this expression for $j = 1$ and $j = 2$, we obtain the condition for relative vehicle utilization, $\tilde{n}_1/\tilde{n}_2$:

$$\frac{\tilde{n}_1}{\tilde{n}_2} = \left(\frac{q_2}{q_1}\right)^{(1-\rho)/(1-\varsigma\rho)} \times \left[\frac{\chi_1}{\chi_2}\frac{\overline{mc}_2}{\overline{mc}_1}\right]^{1/(1-\varsigma\rho)}. \tag{37}$$

The relative mileage $\tilde{n}_1/\tilde{n}_2$ depends on the relative marginal cost $\overline{mc}_2/\overline{mc}_1$, which contains the prices of the two type of fuel (taxes included) and the price of maintenance and repairs. The relative stock q_2/q_1 also affects the relative decision of driving when s_1 and s_2 are not perfectly substitutive: if diesel cars are scant, their marginal utility would be high relative the marginal utility of abundant gasoline cars, which produces an increase in relative mileage use. In summary, this relative mileage increases when the relative utility χ_1/χ_2 increases, the relative marginal cost $\overline{mc}_1/\overline{mc}_2$ decreases, and the relative stock q_2/q_1 increases. Finally, notice that the short-run elasticity of substitution between the relative mileage driven and the relative marginal costs is also given by $-1/\left(1-\varsigma\rho\right)$.

4.2 Firms

All sectors are tradable and competitive. Thus, they maximize their time period profits taking prices and technology as given, and optimal conditions equalizes marginal costs to marginal profits. The representative firm in the final good sector solves

$$\max_{\left(\widetilde{H},K\right)} \left(Y - W\cdot\widetilde{H} - R\cdot K\right),$$

given (W, R) and S, and hires capital and labor equating the marginal products to their respective rental prices

$$W = \theta \frac{Y}{\widetilde{H}}, \tag{38}$$

$$R = MPK_Y = (1-\theta)\frac{Y}{K_Y}. \tag{39}$$

Using (13) for the production function of cars $\mathcal{X}_j$, $j = 1, 2$, and taking r and (p_{X1}, p_{X2}) as given, the representative firm in the car sector solves

$$\max_{(k_{X1}, k_{X2})} \sum_{j=1,2} \left(p_{Xj}\mathcal{X}_j - Rk_{Xj}\right).$$

First order conditions imply that the relative supply of vehicles must be given by the following expression:

$$\frac{p_{X1}}{p_{X2}} = \left(\frac{a_2}{a_1}\right)^{1/(1-\theta_X)} \left(\frac{\mathcal{X}_1}{\mathcal{X}_2}\right)^{\theta_X/(1-\theta_X)}, \tag{40}$$

where $\left(\theta_X^{-1} - 1\right) > 0$ denotes the elasticity of supply. As long as the technology in this sector presents decreasing returns to scale, there is a fraction $(1 - \theta_X)$ of profits that are not rebated to the proprietor of capital. This fraction is transferred to the household in the form of profits, Π, as long as they are the ultimate owners of the firms.

The third sector is the refinery. Given the prices of oil, p_o, the rental price of capital, R, the prices of fuels (p_{F1}, p_{F2}) and technologies (14) for $\mathcal{F}_j$, $j = 1, 2$, the refinery employs crude oil and capital in order to maximize profits:

$$\max_{(o_1, o_2, k_{F1}, k_{F2})} \sum_{j=1,2} \left(p_{Fj}\mathcal{F}_j - p_o o_j - RK_{Fj}\right).$$

First order conditions are:

$$p_o = p_{F1}\theta_F \frac{\mathcal{F}_1}{o_1} = p_{F2}\theta_F \frac{\mathcal{F}_2}{o_2}, \tag{41}$$

$$R = p_{F1}(1-\theta_F)\frac{\mathcal{F}_1}{k_{F1}} = p_{F2}(1-\theta_F)\frac{\mathcal{F}_2}{k_{F2}}. \tag{42}$$

From these conditions, fuel pricing relations are given by the following relations:

$$p_{F1} = \frac{1}{\theta_F^{\theta_F}(1-\theta_F)^{1-\theta_F}} \frac{p_o{}^{\theta_F} R^{1-\theta_F}}{b_1}, \tag{43}$$

$$p_{F2} = \frac{1}{\theta_F^{\theta_F}(1-\theta_F)^{1-\theta_F}} \frac{p_o{}^{\theta_F} R^{1-\theta_F}}{b_2}. \tag{44}$$

The final prices increase after an increase in p_o or in R, or under a technological involution (b_1, b_2). Importantly, the relative price of fuels solely depends on technology:

$$\frac{p_{F1}}{p_{F2}} = \frac{b_2}{b_1}. \tag{45}$$

This means that variations in the price of crude oil, or in the rental price of capital, are transmitted to the final prices (p_{F1}, p_{F2}) in exactly the same proportion.

There are three markets whose behavior is taken as exogenous in this model: the market for maintenance and repairs services, the market for car insurances and tolls, and the market for crude oil.

4.3 Equilibrium

Definition 1 *Given a government policy, $\{\tau_{X,1}, \tau_{X,2}, \tau_{F,1}, \tau_{F,2}, TR\}$, a recursive equilibrium is a set of decision rules,*

$$\left\{c(\zeta), \{x_j(\zeta), \tilde{n}_j(\zeta)\}_{j=1,2}, h(\zeta), k'(\zeta)\right\},$$

aggregate choices,

$$\left\{C(\zeta), \left\{X_j(\zeta), \tilde{N}_j(\zeta)\right\}_{j=1,2}, H(\zeta), K'(\zeta)\right\},$$

prices for fuel, new vehicles, maintenance and repairs, and tolls and cars insurances

$$\left\{\{p_{Xj}(\zeta), p_{Fj}(\zeta)\}_{j=1,2}, p_{MR}, p_{TI}\right\},$$

and factor prices

$$\{W(\zeta), R(\zeta), p_o\},$$

such that

1. *Given the government policy and factor prices, households' decisions solve (30), subject to*

the budget constraint (16), the state equations for capital (28), vehicle accumulation (6), and non-negaivity constraints..

2. *All factors (hours, capital and crude oil) are hired at their marginal productivities: (38), (39), (40), (41) and (42).*

3. *The government satisfies its budget constraint (15) every period.*

4. *Markets clean: labor demand is equal to labor supply; condition (29) holds for physical capital; for $j = 1, 2$, $\mathcal{X}_j = X_j$ for cars and $\mathcal{F}_j = F_j$ for fuel; and, consequently, condition (25) for the final consumption good sector also holds.*

5. *The representative agent condition holds, i.e. aggregate choices coincide with individual ones when the latter is representative: $K'(\zeta) = k'(\zeta)$, $Q'_j(\zeta) = q'_j(\zeta)$, $H(\zeta) = h(\zeta)$, $C(\zeta) = c(\zeta)$, and $X_j(\zeta) = x_j(\zeta)$, for $j = 1, 2$.*

5 Calibration and results

In this section the market equilibrium is numerically solved. First, we calibrate the market stationary equilibrium. Second, we show impulse response functions (IRF) induced by technology and oil price shocks. The IRF allows us to analyze the consistency of our market equilibrium solution with business cycle regularities. Third, we carry out some numerical exercises analyzing how particular dieselization measures impact the replacement of diesel and gasoline cars, the rebound impact and carbon emissions.

5.1 Calibration

This sub-section summarizes the calibration exercise. See Appendix A for further details.[14] The model is calibrated for the EU14 countries described in Section 2. The unit of time is quarter, although some moments and parameters are given in yearly terms. Year 1999 is chosen as the pivotal moment, as it is not unrealistic to consider that EU14 economies were sited relatively close to their balanced growth path by this year.[15].

[14] http://www.upo.es/econ/rodriguez/index_archivos/Diesel/Appendix_A.pdf

[15] The average GDP growth rate is 2.4% for 1995-2007 (just before the Great Depression), while it is 1.5% when we account until 2014, i.e., for 1995-2014. The growth rate was 2.3% in 1999, which encounters the average growth before the Great Depression.

We need to assign values for 42 parameters, collected in Tables 2a and 2b. A total of 22 parameters (Table 2a) are justified according to precise sources, documented in the last column of the table or using own regressions. The remaining 20 parameters are calibrated from average moments for EU14 countries to target certain steady state conditions of the market equilibrium (Table 2b). The rest of this section is devoted to summarize how the choice of these parameters have been made. Throughout this section, the steady state position of a variable is denoted by a starring superindex $(^*)$.

We start assigning values to those 22 parameters that can be determined ex-ante (Table 2a). We retrieve series of capital and Value Added (VA) from the EU KLEMS data set for main EU14 countries (Figure A1, Appendix A), and calculate an average ratio of $K^*/GNP^* = 3.56$ for 1993-2007, which serves as reference to set the steady-state real interest rate (39) and to calibrate the subjective time discount rate β according to the intertemporal Euler equation (31). Due to logarithmic utility for consumption, the time discount rate must meet $\beta = (1+r^*)^{-1}$, where r^* is the stationary real interest rate, which is selected to 0.0106 (4.29% in yearly terms) to match the target $K^*/GNP^* = 3.55$. This yields $\beta = 0.9896$. After application of accounting identities, we set $Y^* = 0.951$, which offers a reliable measure of this final good sector in EU14 countries (Table A13, Appendix A).

The Frisch elasticity of labor supply in the utility function (3), v, is set equal to 0.72 (Heathcote *et al.*, 2010). The output elasticity with respect to hours worked in the final good sector Y, θ in (11), is chosen according to the labor income share in European National Accounts (averaged over 1991-2007 from EU KLEMS) and is set to 0.658. The elasticity θ_F in the refinery sector (14) is equal to 0.827 resulting from a log-linear regression of the first order conditions (43)-(44). The elasticity θ_X for the automotive industry is discussed below. The parameters related with the carbon cycle (i.e., those included in (21)-(23)) are borrowed from Golosov et al. (2014) and references therein (see Section 3.4 and Appendix A for further explanations).

The average global warming damage parameter γ in (11) is set to be 2.379 $(\times 10^{-5})$ (IPCC, 2007; Golosov et al., 2014). This implies that a concentration of $Z = 802$ Gt, in excess of the preindustrial level 581 Gt, produced a 0.52% damage on 1999 output, i.e., $1 - e^{-\gamma(802-581)} = 0.0052$. Finally, following standard estimates (EPA, 2011), the carbon content per litter of diesel, ϕ_1, is 2.689 Kg.CO_2/liter, while that for gasoline, ϕ_2, is 2.348 Kg.CO_2/liter. The ratio is therefore $\phi_1/\phi_2 = 1.1455$, as discussed in Section 2.

The rest parameters in the carbon concentration dynamic ((21)-(23)) are selected following

Golosov et al. (2014): $\varphi_L = 0.2$ (20% of total emissions remain in the atmosphere forever), $(1-\delta_2)^{4\times300} = 0.5$ (carbon concentration Z_2 has a half life of 300 years), $\delta_3 = \frac{1}{4\times10}$ (Z_3 has a residence time of one decade following a geometric decay). The percentage φ_0 is calibrated to ensure that total emissions confront a half life of 200 years:

$$1 - 0.5 = \varphi_L + (1-\varphi_L)\left[\varphi_0 (1-\delta_2)^{4\times200} + (1-\varphi_0)(1-\delta_3)^{4\times200}\right].$$

This produces $\varphi_0 = 0.595$ (Golosov et al. (2014) estimate $\varphi_0 = 0.393$, in a model structured under a te-year frequency).

As of 1999, average fuel prices were $p_{F_1} = 0.330$ euros per liter of diesel, and $p_{F_2} = 0.357$ euros per liter of gasoline. Taxation was remarkably lenient with diesel fuel: $\tau_{F_1} = 0.812$ euros per liter of diesel *versus* $\tau_{F_2} = 1.111$ euros per liter of gasoline (see Table A7 in the Appendix A for details). From information extracted from the European Automobile Manufacturers Association (ACEA), we take a 20% sale tax for new cars common for both type of vehicles, and set $\tau_{X_1} = \tau_{X_2} = 0.20$. The price of maintenance and repairs p^*_{MR} is normalized to 1.

We take several magnitudes relative to the EU14 GNP countries from Eurostat (see Appendix A, Table A5). For calibration purposes, the GNP as of 1999 for EU14 is normalized to 1. This normalized steady state GNP is distributed reflecting the relative magnitudes (see Table 2a and 2b): investment, I^*, is 0.20; new cars investment, $(p^*_{X1}X^*_1 + p^*_{X2}X^*_2)$, is 0.0438; fuel expenditure, $(p^*_{F1}F^*_1 + p^*_{F2}F^*_2)$, is 0.0302; maintenance and repairs expenditure, $p^*_{MR}\cdot\left(m_1\tilde{N}^*_1 Q^*_1 + m_2\tilde{N}^*_2 Q^*_2\right)$, is 0.0195; and the expenditure in cars insurances (fixed costs), $p^*_{TI}\cdot(Q^*_1 + Q^*_2)$, is 0.012; consumption, net of previous concepts, C^*, completes the remaining fraction, and amounts to 0.6945.

Diesel motor cars accounted for 18.2% of the stock of passenger cars in 1999 (Table A6, Appendix A). In steady state, we normalize $Q^*_1 + Q^*_2 = 1$, and then set $Q^*_1 = 0.182$ and $Q^*_2 = 0.818$. The ratio of diesel to gasoline fuel consumption, F^*_1/F^*_2, was 0.288 in 1999 (Table A2, Appendix A). Moreover, we showed in Section 2 that $f_1/f_2 = 0.831$. Using these moments and the definition of fuel consumption (7), we obtain:

$$\frac{F^*_1}{F^*_2} = 0.288 = \frac{\tilde{N}^*_1}{\tilde{N}^*_2}\frac{Q^*_1}{Q^*_2}\frac{f_1}{f_2} = \frac{\tilde{N}^*_1}{\tilde{N}^*_2}\frac{0.182}{0.818}0.831 \Rightarrow \frac{\tilde{N}^*_1}{\tilde{N}^*_2} = 1.56.$$

Hence, our steady-state condition is that diesel motors cars are driven 56% more intensively than gasoline powered vehicles, on gross average.[16]

[16] As commented in Section 2, data for kilometers driven should be used cautiously. This ratio is rather low

Using the levels of fuel prices commented above, we can recover the resultant steady state levels of F_1^* and F_2^* by solving the following system of equations:

$$\begin{aligned} F_1^* &= 0.288{\cdot}F_2^*, \\ p_{F_1}^* F_1^* + p_{F_2}^* F_2^* &= 0.0302, \end{aligned}$$

leading to $F_1^* = 0.0192$ and $F_2^* = 0.0668$.

Consistent with previous moments, we can calibrate f_1, f_2, m_1, m_2, the marginal costs of driving $\overline{mc}_1$ and $\overline{mc}_2$, and the price p_{TI}^*. If we normalize to one the km. driven of a gasoline car, $\tilde{N}_2^* = 1$, and use the definition of fuel consumption (7), we obtain $\tilde{N}_1^* = 1.56$, $f_1 = 0.0679$ and $f_2 = 0.0817$.[17]

In a similar manner, concerning the expenditures of maintenance and repairs, using steady-state levels of $\tilde{N}_j^*$ and Q_j^*, and assuming that $m_1 = m_2$ (i.e. both cars have the same needs of repair services), $p_{MR}^* = 1$ and given that these expenditures account for 1.95% of the GNP, we can easily recover m_1 and m_2 from

$$m_1 = m_2 = \frac{0.0195}{\tilde{N}_1^* Q_1^* + \tilde{N}_2^* Q_2^*} = 0.0177.$$

The marginal costs of a kilometer driven in a car of type j are obtained from:

$$\begin{aligned} \overline{mc}_1 &= \left(p_{F1}^* + \tau_{F1}^*\right) f_1 + p_{MR}^* m_1 = 0.0952, \\ \overline{mc}_2 &= \left(p_{F2}^* + \tau_{F2}^*\right) f_2 + p_{MR}^* m_2 = 0.1376. \end{aligned}$$

Note that this implies that operating costs of gasoline cars exceed 44.5% those of diesel cars: $\overline{mc}_2/\overline{mc}_1 = 1.445$.[18]

compared with that reported in Section 2 for 1999, which was 1.73. Notwithstanding, this calibrated moment, $\tilde{N}_1^*/\tilde{N}_2^* = 1.56$, might provide an accurate idea. For Belgium, France and Italy, Verboven (2002) reports ratios varying with the vehicle weight (1.65 on average). As of 2008, the *Encuesta de Hogares y Medio Ambiente* by the Spanish National Institute of Statistics (INE), reports an estimate of mileage per diesel car that exceeds by 40% that of gasoline cars. When controling for the family size, the ratio goes from 60% for single households to 32% for families with 4 or more components.

[17] A more realistic structure should include a dependence of fuel efficiency (f_j) on market fundamentals. For example, automakers can respond innovating on fuel efficiency (i.e. reducing f_j) in the wake of a permanent fuel prices increase. Aghion et al. (2012) reports for evidence on this aspect. Wei (2013) internalizes the choice of fuel efficiency (f_j) in attention to the CAFE standards.

[18] In the U.K., where traditionally there are no substantial discrimination between the fuel tax rates on both fuels ($\tau_{F1} \simeq \tau_{F2}$), the U.K. Automobile Association reports differences in operating costs that favors the use of diesel

Finally, the (fixed) costs, which include cars insurances, parking fees and tolls, can be estimated from the national accounts (Table A5, Appendix A), and using $(Q_1^* + Q_2^*) = 1$, we obtain:

$$p_{TI}^* (Q_1^* + Q_2^*) = p_{TI}^* = 0.0120.$$

For the depreciation rate of cars, we assume $\alpha_1 = \alpha_2$, or equal average lifespan for both type of vehicles (Table A6, Appendix A). We take a 12 year lifespan: $\alpha_j = 1/48$, i.e. 8.33% in yearly terms. Using this information, the stationary new cars investment is given by (neglecting growth components):

$$\begin{aligned} X_1^* &= \alpha_1 \cdot Q_1^* = 0.0038, \\ X_2^* &= \alpha_2 \cdot Q_2^* = 0.0170. \end{aligned}$$

The value for μ in (12) and θ_X in (13) are selected to meet the simulated correlation of Y and new cars investment, and they are $\mu = 0.8$ and $\theta_X = 0.55$. Further arguments on the choice of these parameters are given in Appendix A.

The parameters or steady-state values for $p_{X_1}^*$, $p_{X_2}^*$, φ_s, χ_1, ς and ρ are calibrated by solving the following set of steady-state market equilibrium conditions:

$$p_{X_1}^* X_1^* + p_{X_2}^* X_2^* = 0.0438, \tag{46}$$

$$(1 + \tau_{X_1}) p_{X_1}^* = \frac{\beta}{\varsigma} \frac{(1-\varsigma)\overline{mc}_1 \tilde{N}_1^* - \varsigma p_{IT}^*}{1 - \beta(1 - \alpha_1)}, \tag{47}$$

$$(1 + \tau_{X_2}) p_{X_2}^* = \frac{\beta}{\varsigma} \frac{(1-\varsigma)\overline{mc}_2 \tilde{N}_2^* - \varsigma p_{IT}^*}{1 - \beta(1 - \alpha_2)}, \tag{48}$$

$$\varsigma \varphi_s C^* + \varsigma \theta (1 - \mu) Y^* = \sum_{j=1,2} \overline{mc}_j \tilde{N}_j^* Q_j^*, \tag{49}$$

$$\frac{\tilde{N}_1^*}{\tilde{N}_2^*} = \left[\frac{Q_2^*}{Q_1^*}\right]^{(1-\rho)/(1-\rho\varsigma)} \left[\frac{\chi_1}{\chi_2} \frac{mc_2}{mc_1}\right]^{1/(1-\rho\varsigma)}, \tag{50}$$

$$\varphi_h = \theta \mu \frac{Y^*}{C^*} \frac{1}{(H^*)^{1+1/v}}, \tag{51}$$

$$ES^* = \frac{1}{1 - \varsigma\rho} = 1.1. \tag{52}$$

---

powered vehicles (www.theaa.co.uk). As of 2014, for five categories, labeled from A (lowest price) to E (highest price), these cost differences are 9.6%.

Equation (46) is the accounting condition of new cars investment commented above. The next two (47) and (48) are the stationary expression of new cars investment (33): the price of a new car is the present discounted sum of current and all futures net benefits accruing to an automobile buyer. Equations (49) and (50) are the steady-state representations of the market conditions that determine the absolute and relative decisions of driving, (36) and (37). Expression (51) is the steady-state version of condition (32), representing the static trade-off between consumption and leisure. The willingness to work parameter φ_h in (3), after assigning a fraction $H^* = 0.31$ of hours (Prescott, 2002) devoted to labor activities, and consumption $C^* = 0.6945$, and given μ, θ and v, is calibrated to be $\varphi_h = 11.8275$.

The last expression (52) denotes the short-run elasticity of vehicle usage with respect to the operating costs $\overline{mc}_j$ (recall from Section 4.1). This elasticity is set to be 1.1 in the baseline calibration. From Section 3.1, recall that diesel and gasoline vehicles behave as substitutes for $0 < \rho \leq 1$. By contrast, for $\rho < 0$, the services from both cars complement. Bento et al (2009) estimate that the elasticity of TKD with respect to operating costs is $ES^* = -0.74$, which in our terms requires assuming complementarity for the car services (note $0 < \varsigma < 1$), but that situation seems unrealistic in our case. Thus, to accommodate this inconvenience, we use the following strategy: first, notice that, using the first order condition (36), the short run price elasticity of fuel, $\epsilon^{F_f}_{p_{F_j}+\tau_{Fj}}$, can be written as,

$$\epsilon^{F_f}_{p_{F_j}+\tau_{Fj}} = \frac{\left(p_{F_j} + \tau_{Fj}\right) f_j}{\left(p_{F_j} + \tau_{Fj}\right) f_j + p_{MR} m_j} \frac{-1}{1 - \varsigma\rho}, \tag{53}$$

which implies that fuel demand is more inelastic than vehicle utilization, $1/\left(1 - \varsigma\rho\right)$; second, bearing in mind this expression, we then select a level of ρ that meets the estimates of this elasticity in the empirical literature, and we chose it to be -0.8, which is consistent with $ES^* = 1.1$, and then set ρ accordingly.[19]

Solving (46)-(51), and given all other previous steady-state values and calibrated parameters, we obtain: $p^*_{X_1} = 2.2544$, $p^*_{X_2} = 2.0686$, $\varphi_s = 0.0662$, $\chi_1 = 0.224$, $\varsigma = 0.6048$ and $\rho = 0.1494$.

[19] Blundell, Horowitz and Parey (2012) have found a long run value of -0.92 for the price elasticity, using standard time series methods. They report other estimates of the fuel price elasticity ranging within the [-1.13, -0.3], on average. The papers surveyed by these authors include: Hausman and Newey (1995), Schmalensee and Stoker (1999), Yatchew and No (2001), and West (2004). See also the survey by Goodwin, Dargay and Harly (2003). Differences between these estimates can be due to the period and countries considered, the type of data (time series, cross-section, micro-data), the frequency of data, or the methodology they employed. The review of current and earlier literature suggests that price elasticity has increased over time (Espey, 1998; Goodwin, Dargay and Harly, 2003).

Note that our resultant steady state for the relative price of cars is $p^*_{X_1}/p^*_{X_2} = 1.09$, i.e. 9% higher for diesel cars. As of 2000, Miravete, Moral and Thurk (2015), documents this same relative price for new cars in Spain. They argue that the Spanish case is indeed a representative case in the automotive market. For the same period, Verboven (2002) reports similar relative prices that range from 1.10 for Italy, to 1.15 for France. Verboven's (2002) average price for Belgium, France and Italy is $p_{X_1}/p_{X_2} = 1.13$. He concludes that 75-90% of this price difference can be accounted for by monopolistic competition strategies in the automotive industry. By contrast, using moments from a wider set of countries and similar average fuel efficiency, our calibration produces nearly the same relative prices under the assumption of competitive markets (see expressions (47) and (48)). Hence, models with a competitive structure can also generate observed relative prices for new cars.

In order to determine technology parameters $\{\delta, A, a_1, a_2, b_1, b_2\}$ and the subsequent equilibrium resource allocations $\left[K^*_Y, \left\{K^*_{Xj}, K^*_{Fj}, o^*_j\right\}_{j=1,2}\right]$, we use the stationary expression of the capital law of motion (28), the feasibility condition for capital across sectors (29), and the first order conditions of the different firms' profit optimization problems, (39), (40), (42) and (41). Further details are given in Appendix A.

Finally, for the two exogenous shocks, we assume that both TFP, A_t, and the international crude oil price, $p_{o,t}$, are governed by an AR(1) process (both series are log-transformed). We estimate persistency parameters $\pi_A = 0.897$, $\pi_o = 0.979$, with a volatility of their respective fundamental shocks $\sigma_A = 0.003$ and $\sigma_o = 0.121$, (Tables A9 and A11, Appendix A).

[**Tables 2a and 2b here**]

5.2 Impulse-response analysis

Using impulse-response functions (IRF), we analyze the reaction of main macroeconomic variables to two structural shocks: a shock to the neutral technological progress, A, and a shock to the crude oil price, p_o. In both cases, we assume that both processes are governed by AR(1) structure. Figures 6a-6c display the IRF. In each figure, the left column reports the responses to a 1% shock to TFP, while the right column shows the analogous reaction to a 1% crude oil price shock.

In Figure 6a, we show the IRF of main aggregate variables: output, consumption, investment and government transfers. It displays the standard reactions described under a neoclassical framework: in response to a 1% transitory shock to TFP, GDP, consumption, investment and transfers increase, while a 1% shock to the crude oil price generates the opposite reaction. Figure 6b reports the IRF of several variables related to vehicles utilization: kilometers driven per vehicle ($\tilde{N}_1$ and $\tilde{N}_2$), traffic intensity (measured by the TKD), and CO_2 emissions from cars, E^{cars}. All these variables increase in response to a positive TFP shock, while they decrease in response to an oil price shock. It is worth noting that CO_2 emissions tend to be more inelastic than any other variable related to road traffic.

Finally, Figure 6c presents the IRF of fuel prices and fuel consumption. Prices (net of taxes) of both type of fuels decrease following a positive TFP shock, while they are positively correlated with a crude oil price shock. The consumption of both fuels increases in response to TFP shocks, but they reduce in response to a positive shock to the oil price.

[**Figures 6a through 6c here**]

5.3 CO_2 emissions sensitivity

Here we study how stationary carbon vehicle emissions alter in response to a particular dieselization policy, say a change in τ_{Xj} or τ_{Fj}. Note that vehicles emissions E^{cars} given in (19) can be written in the following form, using the definition of total kilometers driven TKD (10),

$$E^{cars} = \left[\left(\phi_1 f_1 - \phi_2 f_2\right) \Omega_1 + \phi_2 f_2\right] \times TKD, \tag{54}$$

where $\Omega_1 = \tilde{N}_1 Q_1 / TKD$ is the share of total kilometers driven by diesel cars. Notice that $\phi_1 f_1 - \phi_2 f_2 < 0$, according calibrated parameters. A positive change in Ω_1, $\Delta\Omega_1 > 0$, has two effects on E^{cars}, moving in opposite directions,

$$\Delta E^{cars} = \underbrace{\left(\phi_1 f_1 - \phi_2 f_2\right) TKD \times \Delta\Omega_1}_{\text{Fuel efficiency effect}} + \underbrace{\frac{E^{cars}}{TKD} \cdot \frac{\partial TKD}{\partial \Omega_1} \Delta\Omega_1}_{\text{Rebound effect}}. \tag{55}$$

First is the *fuel efficiency effect*, which implies a reduction in E^{cars} after an increase in Ω_1. Second is the *rebound effect*, a raise in Ω_1 would generally be transmitted into an increase in TKD, i.e., $\partial TKD / \partial \Omega_1 > 0$, because diesel cars are driven more intensely, as discussed in Section 2. Thus, emissions E^{cars} will be reduced depending on whether the fuel efficiency effect dominates the rebound effect. As we illustrate below, according to our parametrization, the rebound effect has offset the gains from the efficiency effect, and emissions have increased. This helps explain the findings outlined of the regressions in Table 2.

We take our previous calibration as the benchmark case, thus $\tau_{X_1} = \tau_{X_2} = 0.20$ for the sale tax, with diesel cars accounting for 18% of total passenger vehicles stock. Next, the level of τ_{X_1} is changed, ceteris paribus, holding constant all other parameters. Since results are sensitive to the elasticity of substitution between the services of both types of vehicles (s_1, s_2), we perform a sensitivity analysis for three alternative levels of ρ: i) a value of $\rho = 0.95$, meaning that vehicles services (s_1, s_2) are strongly substitutive, with elasticity 2.5); ii) a value of $\rho = 0.14$, positive and small ρ, the baseline case, with elasticity of substitution 1.1; iii) and a negative ρ, meaning that (s_1, s_2) are complementary, with elasticity of substitution 0.74 as in Bento et al. (2009).

Results for $\rho = 0.95$ are reported in Figure 7a. As can be seen in this figure, a reduction in the sale tax on diesel cars τ_{X1} (shadowed area) generates a sensible vehicle replacement. Every 10% points of reduction in τ_{X_1} causes, on average, an increase of diesel cars of about 6.5%, which is almost compensated by a reduction in the stock of gasoline cars of similar magnitude. Consequently, the Q_1/Q_2 ratio shows an important increase. At the same time, according to the relative mileage in (36), the increase of the diesel fleet leads to drive each diesel car less intensely, which implies a reduction of $\tilde{N}_1$. However, in spite of this reduction, $\tilde{N}_1$ is still significantly higher than $\tilde{N}_2$. Thus, under this circumstance (i.e. $\tilde{N}_1 > \tilde{N}_2$), the replacement implies a rebound impact in TKD, which offsets the fact that diesel are less polluting per kilometer traveled (recall, $f_1\phi_1/f_2\phi_2 \simeq 0.95$). In general, we find that, following a reduction in τ_{X_1}, the rebound effect dominates the fuel efficiency gains. Hence, the only way to reduce emissions from cars is to hold constant, or even reduce, total traffic intensity (TKD in (10)).

Notwithstanding, this situation only occurs when the replacement is very small, which implies a low degree of substitution between s_1 and s_2. This idea is illustrated in Figure 7b for $\rho = 0.15$ (baseline case) and, more clearly, in Figure 7c for $\rho = -0.5773 < 0$ (complementarity), corresponding to elasticities of substitution of 1.1 and 0.74, respectively. In these two cases, the replacement of gasoline by diesel cars is less intense (as can be seen by the lower negative slope of the Q_1/Q_2 line), and the resultant rebound effect is clearly smaller. However, it is only in the latter case, which represents a non realistic situation of $\rho = -0.5773 < 0$, where stationary CO_2 emissions from cars suffer a reduction (although very small) following a reduction in τ_{X_1} (notice that the Q_1/Q_2 line now shows a positive slope with τ_{X_1}).

In a second exercise we consider a reduction in the diesel fuel tax τ_{F_1}, holding constant the remaining parameters at their baseline levels. Figures 8a through 8c illustrate this situation. Reported results are conclusive about the failure of using lenient taxation on diesel fuel as a way to reduce CO_2 emissions. A reduction in τ_{F_1} does not only imply a replacement of gasoline by diesel cars (when $\rho > 0$) - thus we observe an increase in the Q_1/Q_2 ratio -, but it also implies an increase in $\tilde{N}_1$, given the smaller operating cost of driving a diesel car. Contrasting with the previous exercise when τ_{X_1} was reduced, a reduction of the diesel fuel tax rate also generates an increase in their kilometers driven, which amplifies the rebound impact. For example, according to Figure 8b (baseline case), every 10% reduction of τ_{F_1} implies an average increase in CO_2 emissions per car of about 2.4%; when $\rho = 0.95$ (Figure 8a), the average increase of emissions per car is about 8.5%. Even when $\rho = -0.5773$ (Figure 8c), where now a reduction of τ_{F_1} implies an opposite impact on Q_1/Q_2 (now this ratio shows a positive relationship with τ_{F_1}), TKD and CO_2 emissions still raise (1.6% on average every 10% reduction of τ_{F_1}). The reason is that the lack of replacement does not compensate the important increase of $\tilde{N}_1$ due to a lenient taxation on diesel.

[**Figures 7a-7c and Figures 8a-8c here**]

6 Is Europe taxing fuel and new cars purchases optimally?

This section addresses the question of whether the dieselization policy and the resultant emissions path is socially optimal. First, we solve the planning problem, which sets how to optimally allocate resources over time taking into account how cars ownership and use affects the economy and global pollution. Second, we compare key conditions with those from the market equilibrium, and characterize the Pigouvian taxes, for both diesel and gasoline (fuel and cars): $\tau^+_{F_1}$, $\tau^+_{F_2}$, $\tau^+_{X_1}$ and $\tau^+_{X_2}$. Finally, we use our model to compare the performance of the EU fuel tax policy with the Pigouvian in terms of carbon emissions, replacement and rebound impact.

6.1 The planner and the social cost of CO_2

From the solution of the planner problem, it is easy to show that potential sources of inefficiencies in the market equilibrium arise from the accumulation and utilization of cars (conditions (33) and (36) for the market equilibrium, respectively). We describe next the set of optimal conditions to calculate the Pigouvian taxes.

The vector of aggregate state variables for the social planner, $\zeta^{SP} = (K, Q_1, Q_2, A, p_o, Z)$, now includes the stock of CO_2 concentration into the atmosphere, Z, whose dynamic is described in expressions (20) through (23). The social planner maximizes the present value function

$$V\left(\zeta^{SP}\right) = \max\left\{u\left(C, S, H\right) + \beta \mathbb{E} V\left(\zeta^{SP\prime}\right)\right\}, \tag{56}$$

with respect to $\left(C, H, K', K_Y, \left\{\tilde{N}_j, K_{Xj}, K_{Fj}, o_j\right\}_{j=1,2}\right)$, subject to the following constraints:

$$\begin{aligned}
e^{-\gamma(Z-581)}\mathcal{Y}\left(A, K_Y, \widetilde{H}\right) &= C + I + \sum_{j=1,2}\left[p_o o_j + \left(m_j \tilde{N}_j + v_{TI}\right) Q_j\right], && (57)\\
f_j \tilde{N}_j Q_j &= b_j o_j^{\theta_F} K_{Fj}^{1-\theta_F}, \quad \text{for } \; j = 1, 2, && (58)\\
Q_j' &= a_j K_{Xj}^{1-\theta_X} + (1 - \alpha_j) Q_j, \quad \text{for } j = 1, 2, && (59)\\
K' &= (1 - \delta) K + I, && (60)\\
K &= K_Y + \sum_{j=1,2} (K_{Xj} + K_{Fj}), && (61)\\
Z' &= \mathcal{Z}(Z, E), && (62)
\end{aligned}$$

and the nonnegativity constraints, given the state variables in vector ζ^{SP}. Equation (57) represents the feasibility constraint in the final good sector, which is the only one that produces the savings to finance the investment I of capital goods needed in the economy; expressions (58)-(59) define the feasibility restrictions in the refinery and in the automotive sector; (60) shows the accumulation process of physical capital; (61) is the feasibility constraint for capital; and (62) summarizes the CO_2 concentration ((20)-(23)).

The optimal intertemporal allocation for investment and the static condition for labor are given by:

$$\begin{aligned}
u_C &= \beta \mathbb{E}\left[u_C' \left(1 - \delta + MPK_Y'\right)\right], && (63)\\
u_H &= -\mu\theta \frac{Y}{H} u_C, && (64)
\end{aligned}$$

where MPK_Y the marginal product of capital employed in sector Y. None of these two expression are distorted by the externality due to CO_2 concentration, and do not differ from those given in the equilibrium solution (31) and (32), provided that capital and hours will be hired at their marginal productivities.

The third condition defines the optimal acquisition of new vehicles of type j, X_j:

$$
\begin{aligned}
u_C \frac{MPK_Y}{MPK_{Xj}} \quad = \quad & \mathbb{E}\left\{ \chi_j \left(\tilde{N}_j'\right)^{\varsigma\rho} \left(Q_j'\right)^{\rho-1} \left[\frac{\psi_s}{(S')^{\rho}} + u_C' \left(1-\mu\right) \theta \frac{Y'}{S'}\right] \right. \\
& \left. -u_C' \left[p_{MR}' m_j \tilde{N}_j' + p_{TI}' + \frac{MPK_Y'}{MPK_{Fj}'} f_j - \left(1-\alpha_j\right) \frac{MPK_Y'}{MPK_{Xj}'}\right] \right\} \\
& +\beta \; \phi_j \; f_j \; \tilde{N}_j \; \mathbb{E}\left[V_Z'\right],
\end{aligned} \tag{65}
$$

where MPK_ℓ denotes the marginal product of capital in the production of good ℓ, for $\ell = Y$, X_1, F_1, X_2, F_2. The terms MPK_Y/MPK_{Xj} and MPK_Y/MPK_{Fj} represent the marginal rates of transformation of the numeraire good into cars of type j, and into fuel of type j, respectively. The final term $\mathbb{E}\left[V_Z'\right]$ expresses the expected social marginal cost of CO_2 concentration. To determine this condition, note that we assume that certain real prices are also exogenously taken by the social planner: (p_{MR}, p_{TI}, p_o).

Condition (65) means that the current marginal cost of assigning a j car in terms of the final consumption good (the lhs) must equalize their future net social benefits (the rhs). The first term in the rhs represents the positive benefits in terms of the flow of services accruing to the owner, including a positive impact through effective labor. The second term represents the utilization cost of a j-type car (maintenance, tolls and insurances, fuel) and the last term indicates the social damage of using cars in terms of global warming, which was absent in the competitive counterpart expression (33).

The fourth optimal condition is the social optimal decision of driving:

$$
\varsigma \chi_j \tilde{N}_j^{\varsigma\rho-1} Q_j^{\rho-1} \left[\frac{\psi_s}{S^{\rho}} + \left(1-\mu\right) \theta \frac{Y}{S} u_C\right] = \left(f_j \frac{MPK_Y}{MPK_{Fj}} + m_j p_{MR}\right) u_C - \phi_j f_j \beta \mathbb{E}\left[V_Z'\right], \tag{66}
$$

which shows that the marginal social benefit of driving (the lhs term) must equalize the social marginal cost (the rhs), which also includes the environmental damage of an extra kilometers traveled, i.e. the term $\beta\mathbb{E}\left[V_Z'\right]$. Again, this social marginal cost was not considered in the competitive counterpart expression (36).

Finally, the last condition sets an expression for the marginal social cost of CO_2 concentration, V_Z:

$$
V_Z \equiv \varphi_L V_{Z_1} + \left(1-\varphi_L\right) \varphi_0 V_{Z_2} + \left(1-\varphi_L\right)\left(1-\varphi_0\right) V_{Z_3}, \tag{67}
$$

with,

$$V_{Z_n} = -\varphi u_C Y + (1-\delta_n)\beta \mathbb{E}\left[V'_{Z_n}\right], \tag{68}$$

for $n = 1, 2, 3$ and taking into account that $0 = \delta_1 < \delta_2 < \delta_3 < 1$. The first term $-\varphi u_C Y < 0$ denotes the instant marginal damage of an extra CO_2 molecule.[20]

Forward iteration on V_Z provides an alternative manner to interpret this social marginal cost:

$$V_{Z_n,0} = -\varphi \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t (1-\delta_n)^t u_{C,t} Y_t < 0, \tag{69}$$

that is, $V_{Z_n,0}$ can be seen as the discounted value of future marginal damages from global warming, with $(1-\delta_n)\beta < 1$ being the discount factor for each component of CO_2 concentration, Z_n, for $n = 1, 2, 3$, and $\delta_1 = 0$.

6.2 Pigouvian taxes

In this section, we determine the tax scheme for $(\tau_{F_1}, \tau_{F_2}, \tau_{X_1}, \tau_{X_2})$ that must be set in a market economy in order to implement the social planner allocations: (63), (64), (65) and (66).

For this scheme to be implemented, two circumstances are called for:

- As stated in the competitive equilibrium condition, aggregate choices need to meet individual ones when the household is representative.
- Market equilibrium prices are equal to the marginal rates of transformation:

$$\begin{aligned} p_{Xj} &= \frac{MPK_Y}{MPK_{Xj}} = \frac{(1-\theta)\,Y/K_Y}{(1-\theta_X)\,\mathcal{X}_j/K_{Xj}}, \\ p_{Fj} &= \frac{MPK_Y}{MPK_{Fj}} = \frac{(1-\theta)\,Y/K_Y}{(1-\theta_F)\,\mathcal{F}_j/K_{Fj}}, \end{aligned}$$

  for $j = 1, 2$, where MPK denotes the marginal product of capital (see (39)); wages are given by the marginal product of labor (represented in (38), and the three prices (p_{MR}, p_{TI}, p_o) are also exogenous to the social planner.

[20] As in Golosov et al. (2014), we find that an increase in output has two effects of opposite sign over $\varphi u_C Y$: one is positive provided that this cost is proportional to final output, while the other is negative since marginal utility u_C is inversely proportional to final output. For log-utility function, these offsetting effects cancel out.

In view of these conditions, we derive two normative propositions. The first one is related with fuel taxes,

Proposition #1 *The Pigouvian tax on fuel j that internalizes the cost of global warming is given by*

$$\tau_{F_j}^{+} = -\phi_j \frac{\beta \mathbb{E}\left[V_Z'\right]}{u_C} > 0, \tag{70}$$

where $E\left[V_Z'\right]$ is the social marginal costs of CO_2, defined by (67).

Proof #1 Subtracting the condition for optimal vehicle utilization (66) with the decision of driving undertaken by a representative household in a decentralized economy (36) produces the tax rule (70)□

The taxation rule in (70) implies that car users internalize the cost of CO_2 concentration by paying a tax proportional to the marginal social cost $\mathbb{E}\left[V_Z'\right]$ (an equivalent taxing rule is given in Golosov et al. 2014, eq. (27)). This proportion is given by the carbon content per liter of fuel j, ϕ_j, regardless the fuel efficiency of the fuel motor cars, f_j. The relative Pigouvian tax rate (diesel versus gasoline) can be expressed as:

$$\frac{\tau_{F_1}^{+}}{\tau_{F_2}^{+}} = \frac{\phi_1}{\phi_2}. \tag{71}$$

Thus, given that $\phi_1/\phi_2 = 1.145$, the Pigouvian fuel tax ratio must be higher than one, which contrasts with the tax practice implemented in European countries during the last decades. If we look at the fuel tax ratio (in cents of Euros per liter) from the Oil Bulletin of the European Commission for 2013, we find that none of the EU14 countries has a τ_{F_1}/τ_{F_2} higher than one. On average, this ratio is 0.767, and just for the UK the ratio approaches to 1.[21] However, this behavior is not restricted to Europe. As emphasized by Knittel (2012), most OECD countries follow a similar practice, with only two exceptions which are Switzerland and the US, where the tax rate on gasoline is lower than that of diesel. As in the UK, in Australia both fuels are equally taxed.[22] It is illustrative to represent the fuel tax (70) as the present discounted sum of the marginal social

[21] The lowest ratios are shown for Greece (0.60), the Netherlands (0.658) and Portugal (0.712), while the highest ratios correspond to UK (0.954), Sweden (0.904) and Austria (0.877).

[22] From the American Petroleum Institute for 2014, we can obtain data for the τ_{F_1}/τ_{F_2} by geographical areas in the U.S., and this ratio is always higher than 1, averaging around 1.127, which is in line with our Pigouvian fuel tax ratio result.

damage in (67)

$$\tau^{+}_{F_{j,t}} = \beta\gamma\phi_j \mathbb{E}_t \sum_{n=1}^{\infty} \beta^n \left[\varphi_L + (1-\varphi_L)\varphi_0 (1-\delta_2)^n + \right. \tag{72}$$
$$\left. + (1-\varphi_L)(1-\varphi_0)(1-\delta_3)^n\right] \frac{u_{C,t+n}}{u_{C,t}} Y_{t+n}.$$

This condition implies that the marginal social cost and the optimal tax are higher the bigger the scale of emissions from fossil fuel combustion by cars ϕ_j, the larger the residence time of CO_2 in the atmosphere (the closer to zero δ_2 and δ_3 are), the lower the discount rate (the closer to one the β is), and the higher the damage parameter γ. In steady-state (i.e., setting $u_{C,t} = u^*_C$ and $Y_t = Y^*$ for all t), the Pigouvian tax takes the following form:

$$\tau^{+,*}_{F_j} = \gamma\beta\phi_j \left[\frac{\varphi_L}{1-\beta} + \frac{(1-\varphi_L)\varphi_0}{1-\beta(1-\delta_2)} + \frac{(1-\varphi_L)(1-\varphi_0)}{1-\beta(1-\delta_3)}\right] Y^*, \tag{73}$$

from where it is easy to show that the steady state tax rate $\tau^{+,*}_{F_j}/Y^*$ depends only on the discount rate, the damage parameter and parameters related with the carbon cycle.

The second proposition sets the Pigouvian sale tax on the purchase of new vehicles:

Proposition #2 *If the fuel tax is set according to rule (70), $\tau_{F_j} = \tau^{+}_{F_j}$, the Pigouvian sale tax on the purchase of new vehicles for all period t is nil:*

$$\tau^{+}_{Xj,t} = 0. \tag{74}$$

Proof #2 Confronting the decision of purchasing a brand new car of type j (33), in a decentralized equilibrium, with the optimal acquisition of new vehicles of type j (65), one obtains:

$$\tau_{X,j,t} p_{Xj,t} u_{C,t} = \beta (1-\alpha_j) \mathbb{E}_t \left[\tau_{X,j,t+1} p_{X,j,t+1} u_{C,t+1}\right].$$

For any initial period t_0, iterating forward on this expression we reach

$$\tau_{X,j,t_0}\ p_{X,j,t_0}\ u_{C,t_0} = \lim_{t\to\infty} \beta^t (1-\alpha_j)^t \mathbb{E}_{t_0} \left[\tau_{X,j,t}\ p_{Xj,t}\ u_{C,t}\right] = 0.$$

For this expression to be truth, the Pigouvian sale tax must be nil as (74) *whenever* the fuel taxes are fixed according to a Pigouvian criterion (70)□

The rule in (74) entails that a policy maker should refrain from using sale taxes (i.e., VAT) or registration fees to internalize the costs from global warming, and that fuel taxes are sufficient to correct for the social damage generated from fuel combustion if they are set according to (70). This result also contradicts the tax policy taken place in Europe during the last decades, where governments had tended to reduce the VAT to incentive more fuel efficient vehicles, regardless of the type of fuel these vehicles are combusting.[23]

6.3 Carbon taxation

Using the parameters calibrated in Section 5, we next quantify the Piguvian tax rate per liter of fuel implied by our model. A real interest rate of 4.29% meets the observed capital to output ratio of 3.56. This implies a time discount rate of $\beta = 0.9896$. A crucial part in the numerical evaluation hinges on this subjective discount rate (see Nordhaus, 2008, or Golosov et al., 2014 for a discussion).[24] For our baseline calibration, the model implies pigouvian fuel tax rates of 1.4 cents of Euro per liter of diesel and 1.2 cents of Euro per liter of gasoline (note the ratio meets $\phi_1/\phi_2 = 1.145$). The reason why these tax rates may seem low compared with observed rates is that we abstract in this paper from other externalities (road congestion, accidents or pollution), whose costs account for the bulk of automobiles externalities (recall discussion in subsection 3.4). In terms of Euros per ton of carbon, these rates are equivalent to pay 20 Dollars per ton of carbon.[25]

In order to compare our result with those given in other studies, Table 3 presents several estimates from alternative scenarios following our previous calibration. Thus, using the same parametrization than that described for EU14 countries in Section 5.1, the different columns are calculated for alternative interest rates - and resultant discount factors. In the last row, Euros have been converted to US Dollars using the 1999 average EUR/USD exchange rate (0.9387 Euros per 1 Dollar). Case in column (i) corresponds to an upper bound for a 5% interest rate, where the capital-output ratio would meet that of US economy (around 3.0). Case (ii) is our benchmark scenario, using an interest rate of 4.29%. Case (iii) represents an intermediate scenario with 3%

[23]In Spain, new car purchases are levied through a registration tax (Impuesto de Matriculación). By Law 51/2007, the tax depends upon CO_2 emissions per kilometer (for a survey, see Trigueros-Martín, 2014). Our previous findings, however, shows that this tax rule, although aimed at reducing *potential* emissions, can have the opposite undesired effects increasing *de facto* emissions.

[24]The model produces arbitrary quantities in many respects, including the flow of CO_2. This scale problem is adjusted by multiplying the carbon content of each fuel ϕ_j by a factor 3.24, which represents the ratio of observed to simulated CO_2 emissions (as of 1999, World emissions were 23.3 Gt).

[25]The atomic mass of carbon is 12, while the atomic mass of CO_2 is 44. Therefore, to convert from tonnes of carbon to tonnes of CO_2, one should multiply by 44/12. Hence, 1 gigatonne of carbon equals 3.67 gigatonnes of carbon dioxide.

interest, often used in a Neoclassical framework. The resultant tax implies 6 cents per gallon of gasoline, which meets the rate considered in Parry and Small (2005) to internalize the costs of climate change (27$ per ton of carbon).[26] The two last columns (iv) and (v) in Table 3 present the interest rates discussed in Nordhaus (2008) and Stern (2007), respectively. Nordhaus (2008) estimates a cost of 30 Dollars per ton of Carbon using an interest rate 1.5%. Our model, using the carbon dynamics proposed by Golosov et al. (2014), implies a cost of 50 Dollars per ton of Carbon. Finally, for the Stern's (2007) case, using a real interest rate of 0.1%, our model yields almost 400 Dollars per ton of carbon, a cost between that estimated by Stern (250$) and that estimated by Golosov et al. (2014) using this discount rate (500$). In these two last cases, notice that our model produces unplausible capital to output ratios.

[**Table 4 here**]

6.4 Steady state analysis

We conclude our normative analysis with a numerical exercise which compares carbon emissions and other key variables generated under the current EU tax policy versus the Pigouvian rule. As discussed in the Introduction, we only consider a particular automobiles externality, that from global warming. Other forms of pollution, accidents or road congestion are excluded from our exercise. This externality is indeed important in terms of one motivating a tax discrimination between gasoline and diesel fuel consumption.

In the following exercise, we assume that the observed tax rate on gasoline fuel is optimal ($\tau_{F_2} = 1.11$), in the sense that it internalizes the social cost of global warming. We scale the coefficients ϕ_1 and ϕ_2 accordingly (73).[27] Next we solve numerically the steady state at market equilibrium under alternative situations. Results are reported in Table 4. The first column shows the results under this Pigouvian scenario:.

$$\begin{aligned} \tau_{F_2}^{+,*} &= 1.11, \\ \tau_{F_1}^{+,*} &= \frac{\phi_1}{\phi_2}\tau_{F_2}^{+,*} = 1.271, \\ \tau_{X_1}^{+,*} &= \tau_{X_2}^{+,*} = 0. \end{aligned}$$

[26] The framework in Parry and Small (2005) is somewhat static, although it considers several externalities. The capital to output rate is well above stylized facts levels for both European countries and the US.

[27] Using an scale of 281, the resultant level of $\tau_{F_2}^{+,*}$ meets 1.11, and $\tau_{F_1}^{+,*} = \frac{\phi_1}{\phi_2}\tau_{F_2}^{+,*} = 1.271$.

In the second column, we take these Pigouvian tax rates on fuel but we set the sale tax to $\tau^*_{X_1} = \tau^*_{X_2} = 0.20$. The third column shows the percentage change with respect to the Pigouvian situation. Finally, the fourth and fifth columns reflect the EU14 case earlier discussed with $\tau^*_{X_1} = \tau^*_{X_2} = 0.20$, $\tau^*_{F_1} = 0.812$, $\tau^*_{F_2} = 1.11$, where $\tau_{F_1}/\tau_{F_2} = 0.731$ is the average of this ratio for EU14 countries in 1999.

In view of Table 4, we highlight the following results. Moving from the Pigouvian scenario towards actual EU14 case always increases fuel consumption and CO_2 emissions (columns 1st and 4th). Such an increase is related to the existence of a rebound effect which implies a more intensive use of cars $\left(\tilde{N}_1, \tilde{N}_2\right)$, and more intensive road traffic, TKD. If we compare the Pigouvian situation (1st column) with the baseline (4th column), there is a difference of almost 36.77% of fuel consumption and 6.45% of carbon emissions. These differences are caused by an increase of diesel vehicles with respect to gasoline vehicles, Q_1/Q_2, and an obvious rise in relative kilometers driven, $\tilde{N}_1/\tilde{N}_2$, which provokes road traffic, TKD, to increase 6.73%.

Comparing the Pigouvian case in 1st columns with 2nd column, it is worth noticing that all ratios (Q_1/Q_2, $\tilde{N}_1/\tilde{N}_2$, and F_1/F_2) remain unchanged when the sale tax on new cars increases uniformly. However, total road traffic, TKD, and emissions, E^{cars}, increase. The total stock of cars decreases and people tend to drive existing cars more intensely (see FOC for kilometers driven in (36)). Thus, the increase in $\tilde{N}_1/\tilde{N}_2$ more than compensates the drop in Q_1/Q_2.

Finally, comparing percentage increases of fuel consumption and emissions, columns 2nd and 4th, CO_2 emissions are more sensible to deviations of fuel taxation than deviations of sale taxation, with respect to the Pigouvian case. The reason is that fuel taxation affects vehicles operating costs, which helps internalize the externality costs. This supports our early results in Table 1.

[**Table 4 here**]

7 Conclusions

Tax policies have been favoring diesel versus gasoline during the last decades in most European countries. This action has been justified on the grounds of energy saving and reducing oil dependence. European automobile makers have been successful in producing diesel powered cars which are more fuel efficient than gasoline cars. Early in the eighties, these automotive firms took advantage of these innovations and the stock of diesel vehicles rapidly grew in Europe.

This paper provides empirical evidence that contradicts initial beliefs of European countries: dieselization did not help to reduce CO_2 emissions of passenger cars. In spite of the positive effect of using a more efficient motor cars, the smaller operational cost of diesel induces a more intensive use of diesel cars, and the replacement of gasoline by diesel vehicles generates a rebound on kilometers traveled and, as a consequence, on fuel consumption and CO_2 emissions. This finding has been addressed using a dynamic general equilibrium model.

The benchmark model in this paper helps to understand the dynamics behind these items: kilometers driven, fuel consumption, cars sales, and CO_2 emissions from cars. The model has been calibrated for a group of 14 countries (EU14), and the market equilibrium has been solved numerically. We show that setting incentives to diesel (through cars purchases and, specially, through fuel consumption) leads to a significant increase of mobility and CO_2 emissions per cars, this increase is more significant the higher is the degree of substitution between diesel and gasoline cars.

A second finding in this paper indicates that the design of these tax practices has been flawed and lacks consistent public finances grounds. A socially optimal taxation must correct all negative externalities coming from ownership and use of automobiles, such as pollution, congestion, noise, accidents, and oil imports dependence (Parry et al., 2007). As long as these externalities depend exclusively on the use of cars, optimal taxation should focus on those tax instruments affecting automobiles operating costs (through fuel consumption or, instead, through kilometers driven), but not on the purchase of new automobiles. Moreover, correcting congestion, noise and accidents does not serve to justify a distinct tax favor treatment of diesel with respect to gasoline.

In this paper, we have argued that global warming via CO_2 emissions from cars justifies a different tax treatment between diesel and gasoline cars. Focused on global warming, the optimal fuel tax ratio is independent on fuel efficiency (in terms of liters per km.) and it should be set according to the carbon content of each fuel, which is about 14.5% higher for diesel fuel with respect to gasoline: 1.40 cents of Euro per liter of diesel, and 1.22 cents per liter of gasoline. This is equivalent to imposing a tax of 19 Euros per ton of carbon, which is comparable with other studies. This result also challenges the optimality arguments underlying the fuel tax policies implemented by most OECD countries during the last decades. With the exception of Australia, Switzerland, US and UK, the rest of OECD countries are more lenient with the use of diesel fuel. Overall, current tax design in EU14 countries has proved useless reducing greenhouse effects gases from automobiles and for energy saving.

8 References

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Tables: Dieselization, CO2 emissions and fuel taxes in Europe

Table 1: Dependent variable: CO2 per capita emissions from cars (growth rate), 1998-2011

	Pooled-OLS			System-GMM, 1 step, collapse instruments		
	(a)	*(b)*	*(c)*	*(a')*	*(b')*	*(c')*
Constant term	0.0279	0.0686	-0.00951	-0.0175	-0.0956	-0.0276
	(0.28)	(0.68)	(-0.09)	(-0.07)	(-0.70)	(-0.10)
Linear Trend	-0.00266***	-0.00289***	-0.00178*	-0.00374*	-0.00321***	-0.00154
	(-3.04)	(-3.40)	(-1.93)	(-1.80)	(-2.71)	(-1.64)
ln(Emissions(-1) per capita)	-0.00325	0.00225	-0.00712	-0.0125	-0.0233	-0.00884
	(-0.23)	(0.16)	(-0.49)	(-0.37)	(-1.19)	(-0.22)
Δln(GDP per capita)	0.0864	0.0691	0.206**	0.0119	0.0220	0.214
	(1.01)	(0.83)	(1.98)	(0.07)	(0.14)	(1.44)
Δln(Total stock of vehicles)	0.643***	0.664***	0.527***	0.499*	0.426*	0.529**
	(3.32)	(3.56)	(2.89)	(1.75)	(1.89)	(2.06)
Δ(Diesel/Gasoline vehicles stock)	0.218**			0.589*		
	(2.13)			(1.69)		
Δ (Diesel/Gasoline fuel consumption)		0.171***			0.249**	
		(3.38)			(2.44)	
Δ (Gasoline/Diesel fuel price, taxes included)			0.121***			0.0795**
			(2.86)			(2.45)
No. Obs.	161	161	137	161	161	137
R2	0.291	0.323	0.270			
Hansen test (p-value)				0.1000	0.172	0.341
No. countries in the sample	14	14	13	14	14	13
No. Instruments				10	10	10

Note: Figures into parentheses are t statistics. Significant at 10% (*), 5% (**), and 1% (***).
Sources: Eursotat, and Odyssee-Mure

Table 2.A: Targets and parameters

Parameter	Value	Definition	Source
A. Parameters determined ex-ante (22 parameters)			
Parameters associated to utility (1 parameter)			
ν	0.720	Frisch elasticity of labor supply	Heathcote, et al. (2010); Chetty et al. (2011)
Parameters associated to production (2 parameters)			
θ	0.658	Technology in final good sector Y	Labor income share (EU KLEMS)
θ_F	0.827	Technology in refinery sector F	Regression analysis
Carbon cycle: emissions, CO2 concentration and damage (7 parameters)			
φ_L	0.200	Fraction of emissions that remain forever	Golosov, Hassler, Krusell and Tsyvinski (2014)
φ_0	0.595	Fraction of emissions that remain 300 years	*Idem*
δ_2 ($\times 10^4$)	5.775	Persistency of $(1-\varphi_L)\varphi_0$ CO2 emissions	*Idem (half life 300 years, Archer (2005))*
δ_3	0.025	Persistency of $(1-\varphi_L)(1-\varphi_{0)}$ CO2 emissions	*Idem (residence time 10 years, IPCC (2007))*
γ ($\times 10^5$)	2.379	Global warming damage parameter	*Idem*
ϕ_1	2.689	Carbon content per litter of Diesel	Environmental Protection Agency, EPA (2011)
ϕ_2	2.348	Carbon content per litter of gasoline	Environmental Protection Agency, EPA (2011)
Stationary prices and taxes (8 parameters)			
p_{F1}	0.330	Price of diesel fuel	Energy Oil Bulletin, European Commission
p_{F2}	0.357	Price of gasoline fuel	Energy Oil Bulletin, European Commission
p_{MR}	1.000	Price of maintenance and repairs	Normalization
p_o	1.000	Price of crude oil	AR(1) regression for "North Sea Brent" oil price
τ_{F1}	0.812	Diesel fuel (ad valorem) tax rate	Energy Oil Bulletin, European Commission
τ_{F2}	1.111	Gasoline fuel (ad valorem) tax rate	Energy Oil Bulletin, European Commission
τ_{X1}	0.200	Sale tax on new diesel cars	European Automobile Manufacturers Association (ACEA)
τ_{X2}	0.200	Sale tax on new gasoline cars	European Automobile Manufacturers Association (ACEA)
Exogenous shocks (4 parameters)			
ρ_A	0.897	Persistency of TFP shocks	Regression analysis for TFP from EU KLEMS
σ_A	0.001	S.D. of TFP shocks	Regression analysis for TFP from EU KLEMS
ρ_o	0.979	Persistency of oil price shocks	Regression analysis for "North Sea Brent" oil price
σ_o	0.121	S.D. of oil price shocks	Regression analysis for "North Sea Brent" oil price

Table 2.B: Parameters that require solving the model (20 parameters)

Parameter	Value	Definition	Target
β	0.990	Time discount rate	Capital/Total Income, K/(WH + RK) = 3.55
δ	0.014	Depreciation rate of capital asset	Fraction of hours worked, H = 0.31
ψ_H	11.828	Willingness to work	Share of gross investment over GNP, I = 0.20
ψ_S	0.066	Willingness to drive	Share of new cars investment over GNP, $\Sigma p_{Xj} \cdot X_j = 0.0438$
χ_1	0.224	Utility weight of diesel cars	Share of fuel expenditures over GNP, $\Sigma p_{Fj} \cdot F_j = 0.0302$
ς	0.605	Substituibility diesel-gasoline km.	Share of maintenance and repairs over GNP, MR = 0.0195
ρ	0.150	Substitution of services of both type of cars	Share of car fixed costs over GNP, TI = 0.0120
θ_X	0.550	Technology in automotive industry	Fuel demand elasticity wrt operating costs = 1.10
μ	0.800	Fischer complementarity hours-cars	Correlation between Y and new cars investment
a_1	0.009	Diesel cars production function	Relative volatility Y to new cars
a_2	0.021	Gasoline cars production function	Relative fuel price, pF1/pF2 = 0.924
b_1	2.531	Diesel fuel production function	Fraction of diesel cars in 1999, $Q_1 = 0.188$
b_2	2.339	Gasoline fuel production function	Relative units of fuel consumed, $F_1/F_2 = 0.288$
A	0.778	Final good Y production function	Relative fuel efficiency = 0.831
f_1	0.068	Gallons per mile (diesel cars)	Assumption: $m_1 = m_2$
f_2	0.082	Gallons per mile (gasoline cars)	Avg. lifespan of vehicles = 12 years (48 quarters)
m_1	0.018	Maintenance need (diesel cars)	Static FOC, tradeoff consumption-leisure
m_2	0.018	Maintenance need (gasoline cars)	Dynamic FOC, intertemporal consumption substitution
α_1	0.0208	Depreciation rate of diesel vehicles	Relative static FOC, relative km. driven ñ1/ñ2
α_2	0.0208	Depreciation rate of gasoline vehicles	Relative dynamic FOC, new cars investment

Table 3: Pigouvian taxation on fuel and carbon

	(i)	(ii)	(iii)	(iv)	(v)
Interest rate (yearly), r	5,00%	4,29%	3,00%	1,50%	0,10%
Time discount rate (quarterly), β	0,9879	0,9896	0,9926	0,9963	0,9998
Capital-output (yearly), K/GNP	3,06	3,56	5,06	10,07	150,22
€-1999 per Liter of Diesel τ_{F1}	0,0122 EUR	0,0140 EUR	0,0190 EUR	0,0346 EUR	0,2740 EUR
€-1999 per Liter of Gasoline, τ_{F2}	0,0107 EUR	0,0122 EUR	0,0166 EUR	0,0302 EUR	0,2392 EUR
€-1999 per Ton of Carbon	16,69 EUR	19,05 EUR	25,96 EUR	47,20 EUR	373,53 EUR
$-1999 per Ton of Carbon	17,78 USD	20,29 USD	27,66 USD	50,28 USD	397,92 USD

Table 4: Steady-state Pigouvian taxation Vs. EU-14 baseline taxation

		1st	2nd	3rd	4th	5th
		Pigouvian taxation (fuel & cars sales taxes)	Fuel Pigouvian + baseline levels for τX1 & τX2	% change wrt Pigouvian case	Benchmark	% change wrt Pigouvian case
Diesel Fuel tax	τ_{F1}	1,273	1,273	0,00%	0,812	-36,20%
Gasoline Fuel tax	τ_{F2}	1,111	1,111	0,00%	1,111	0,00%
Relative tax	τ_{F1}/τ_{F2}	1,145	1,145	0,00%	0,731	-36,20%
Sale tax	τ_{X1}	0,000	0,200	-20,00%	0,200	-20,00%
Sale tax	τ_{X2}	0,000	0,200	-20,00%	0,200	-20,00%
Relative car prices	p_{X1}/p_{X2}	1,072	1,071	-0,05%	1,089	1,70%
Diesel veh. stock	Q_1	0,194	0,181	-6,94%	0,182	-6,38%
Gasoline veh. stock	Q_2	0,886	0,825	-6,90%	0,818	-7,66%
Relative stock	Q_1/Q_2	0,219	0,219	-0,04%	0,223	1,39%
Km. per diesel veh.	$\tilde{N}_1$	1,073	1,165	8,56%	1,556	45,15%
Km. per gasol. veh.	$\tilde{N}_2$	0,929	1,009	8,52%	1,000	7,59%
Relative km.	$\tilde{N}_1/\tilde{N}_2$	1,155	1,155	0,04%	1,556	34,91%
Diesel consumption	F_1	0,014	0,014	1,03%	0,019	35,89%
Gasoline consumption	F_2	0,067	0,068	1,03%	0,067	-0,65%
Relative consumption	F_1/F_2	0,211	0,211	0,00%	0,288	36,79%
Road Traffic, VKT	$\tilde{N}_1 Q_1 + \tilde{N}_2 Q_2$	1,032	1,043	1,03%	1,102	6,73%
CO2 veh. Emissions, E^{cars}	$\phi 1 \cdot F_1 + \phi 2 \cdot F_2$	0,196	0,198	1,03%	0,209	6,45%

Graphical Appendix: Dieselization, CO2 emissions and fuel taxes in Europe

Figure. 1. Dieselization in EU14: ratio of diesel cars, new registration diesel cars and diesel consumption with respect to the total

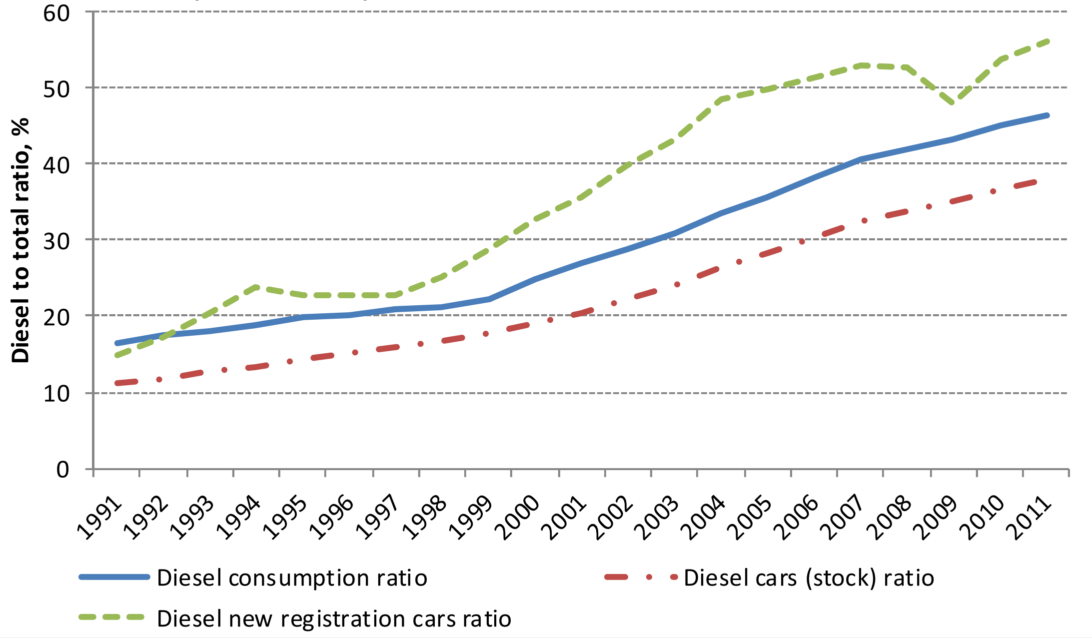

Figure 2. Fuel intensity for gasoline and diesel car fleet and relative fuel efficiency in Western European countries

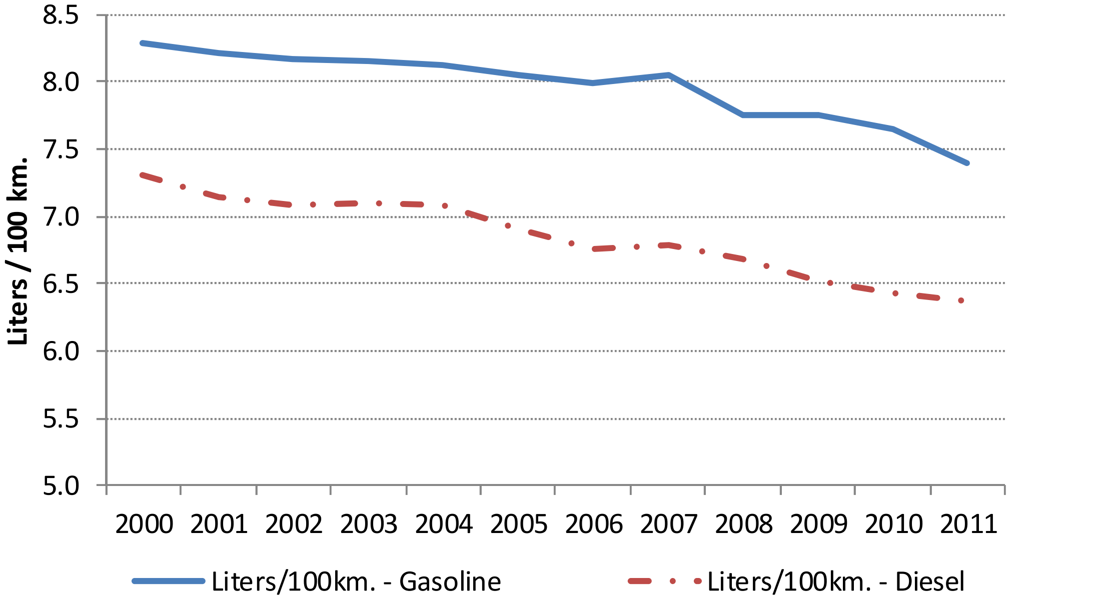

Figure 3. Fuel prices and taxes in EU14 (average values)

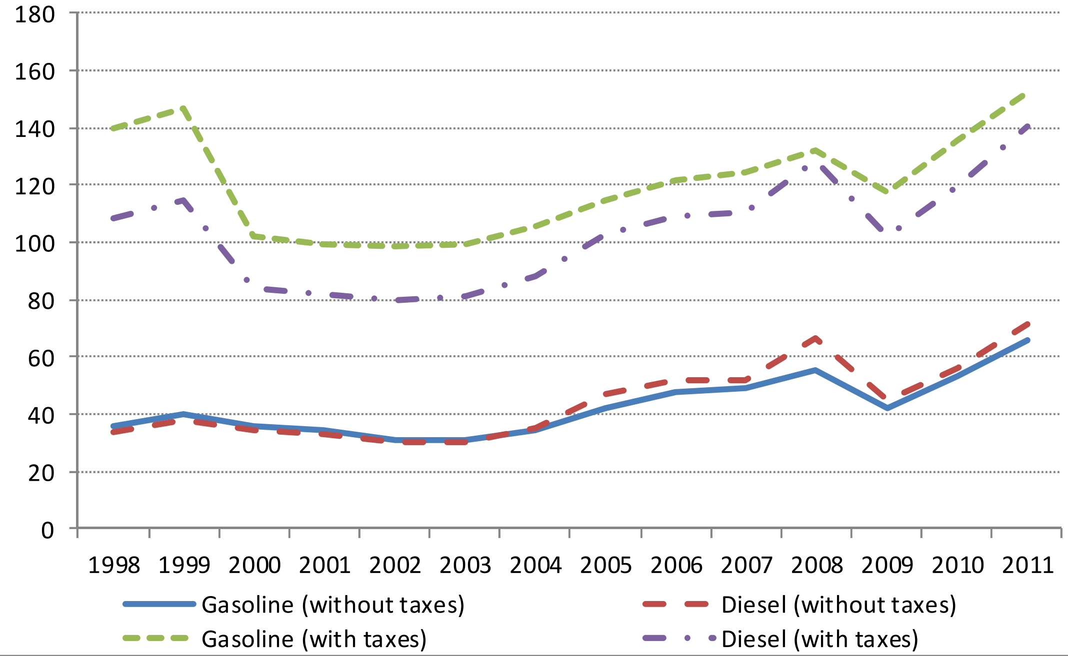

Figure 4. Average kms. traveled by diesel and gasoline car in main EU14 countries

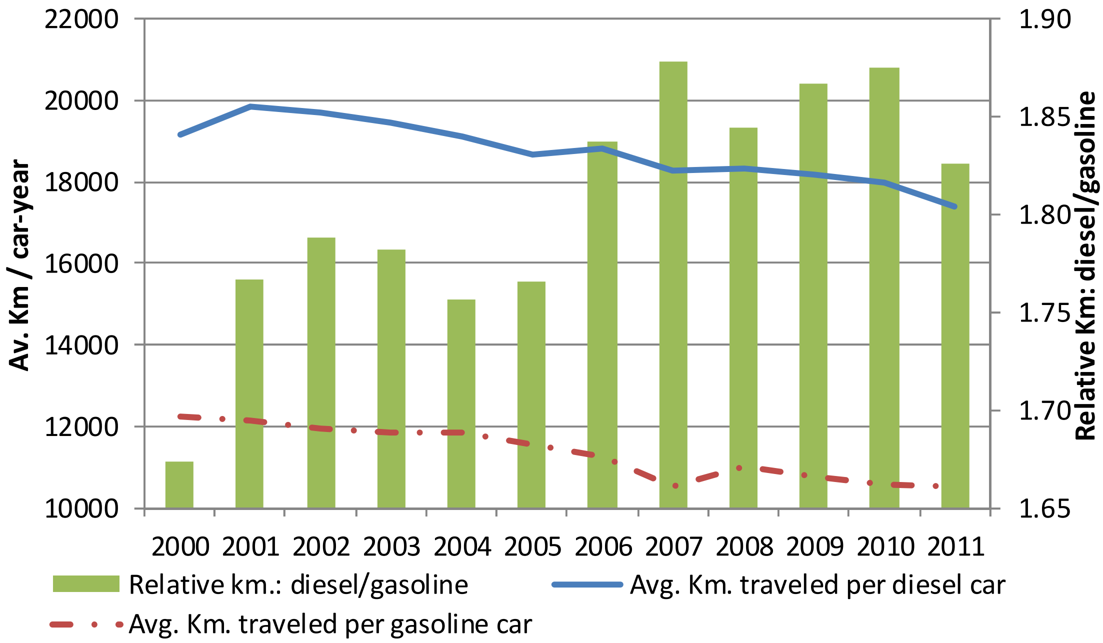

Figure 5: CO2 emissiones in EU14 from cars and final consumers

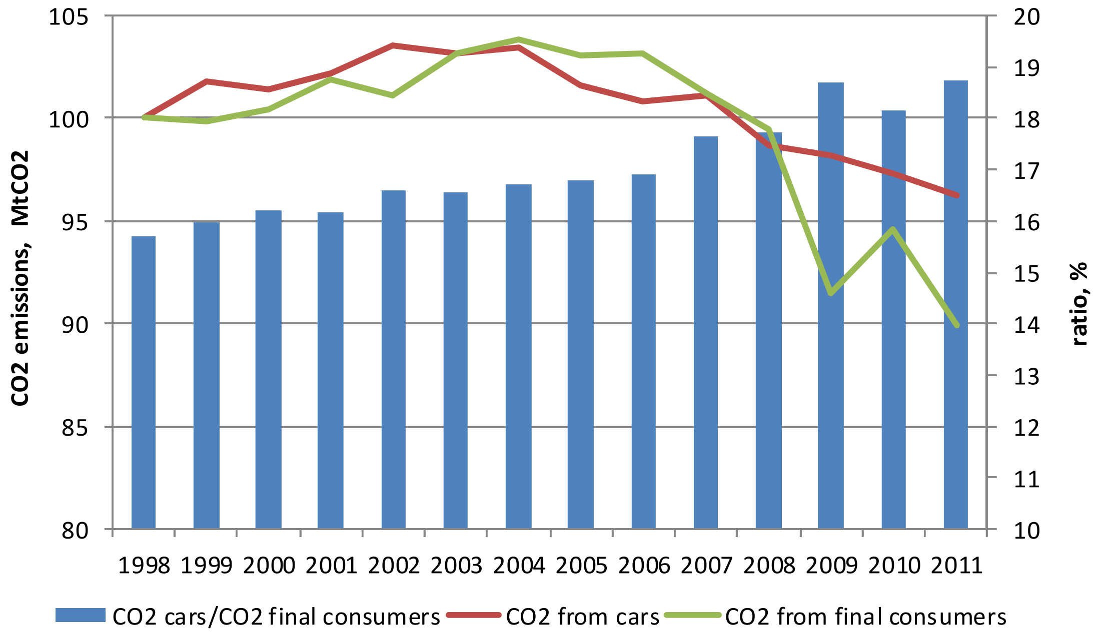

Figure 6.a. Impulse response function: Main aggregates

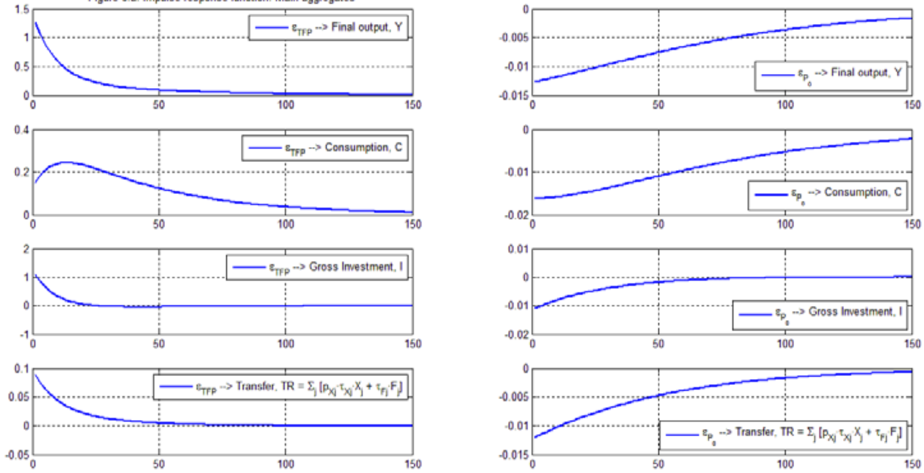

Figure 6.b. Impulse response function: Traffic aggregates

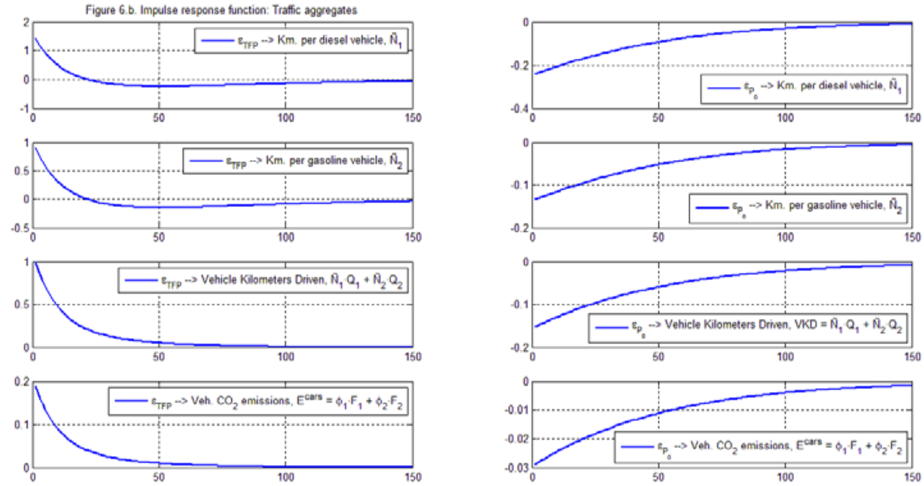

Figure 6.c. Impulse response function: Fuel uses and prices

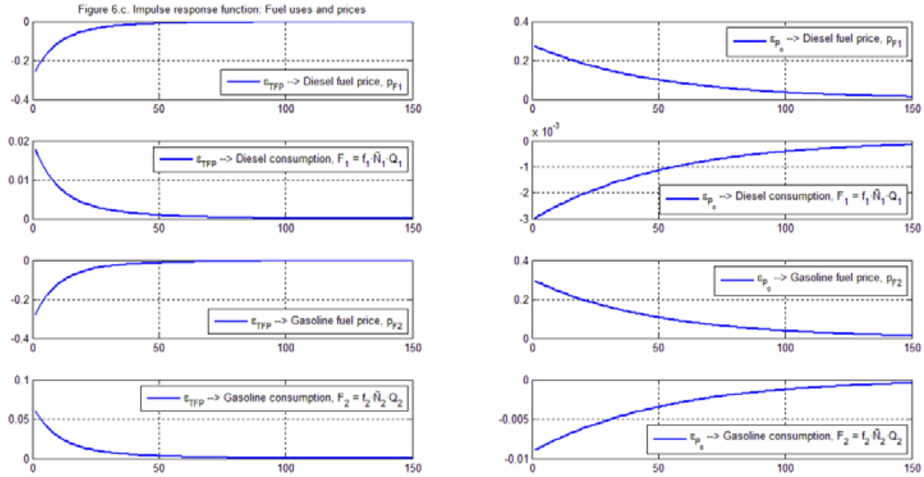

Figure 7.a. CO_2, replacement and rebound: change in $\tau X1$ (s1 & s2 strongly substitutes)

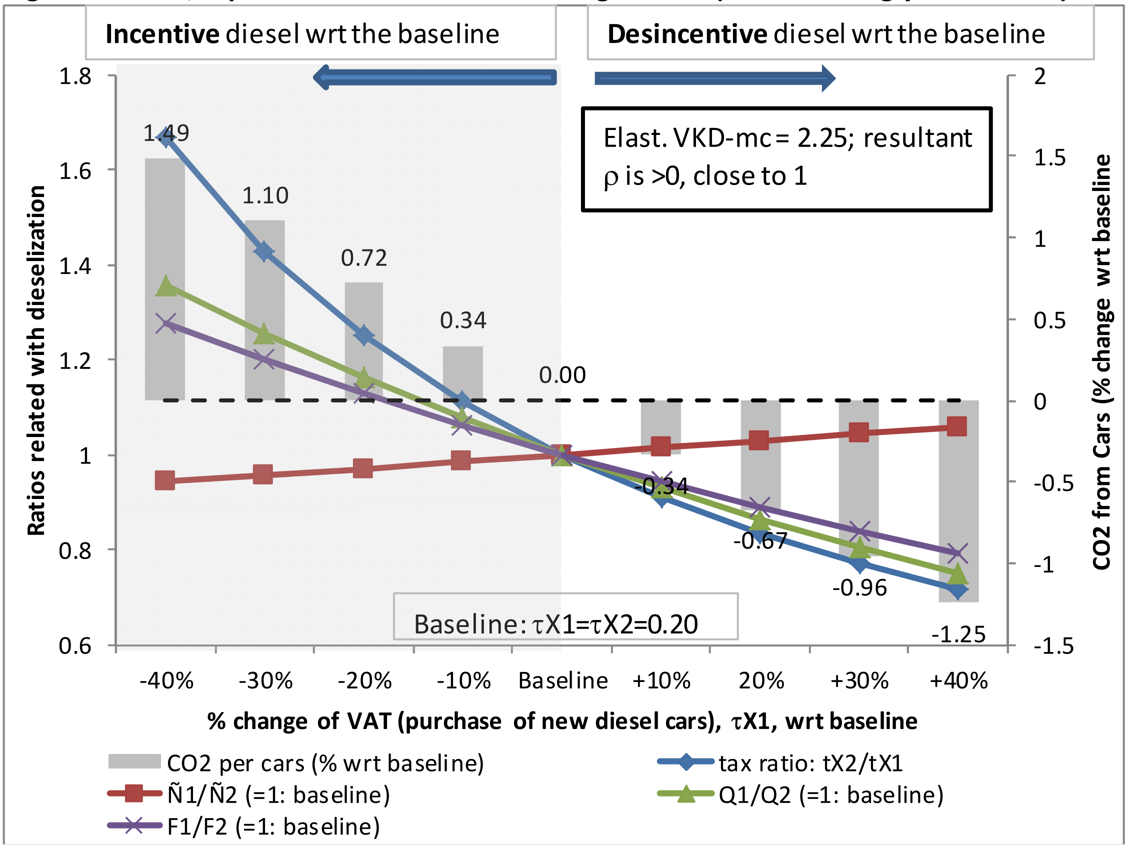

Figure 7.b. CO2, replacement and rebound: change in τX1 (s1 & s2 substitutes, baseline)

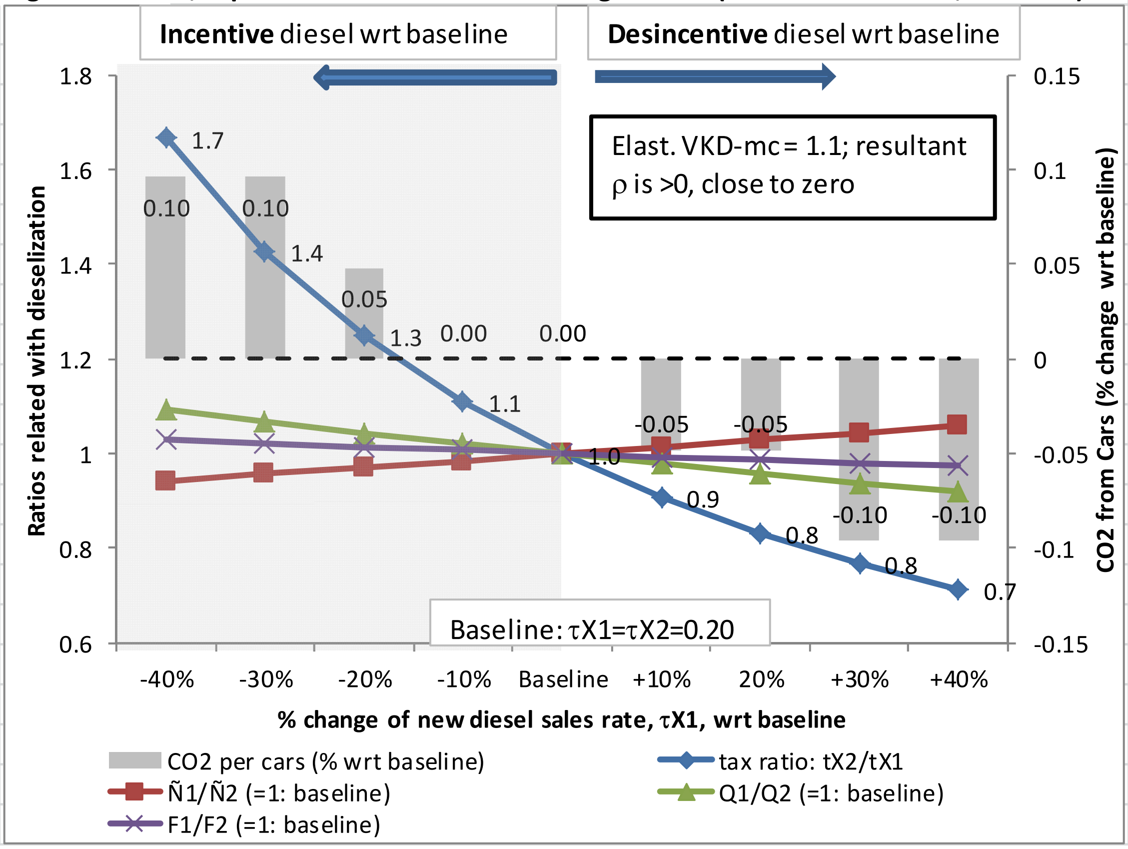

Figure 7.c. CO2, replacement and rebound: change in τX1 (s1 & s2 complementary)

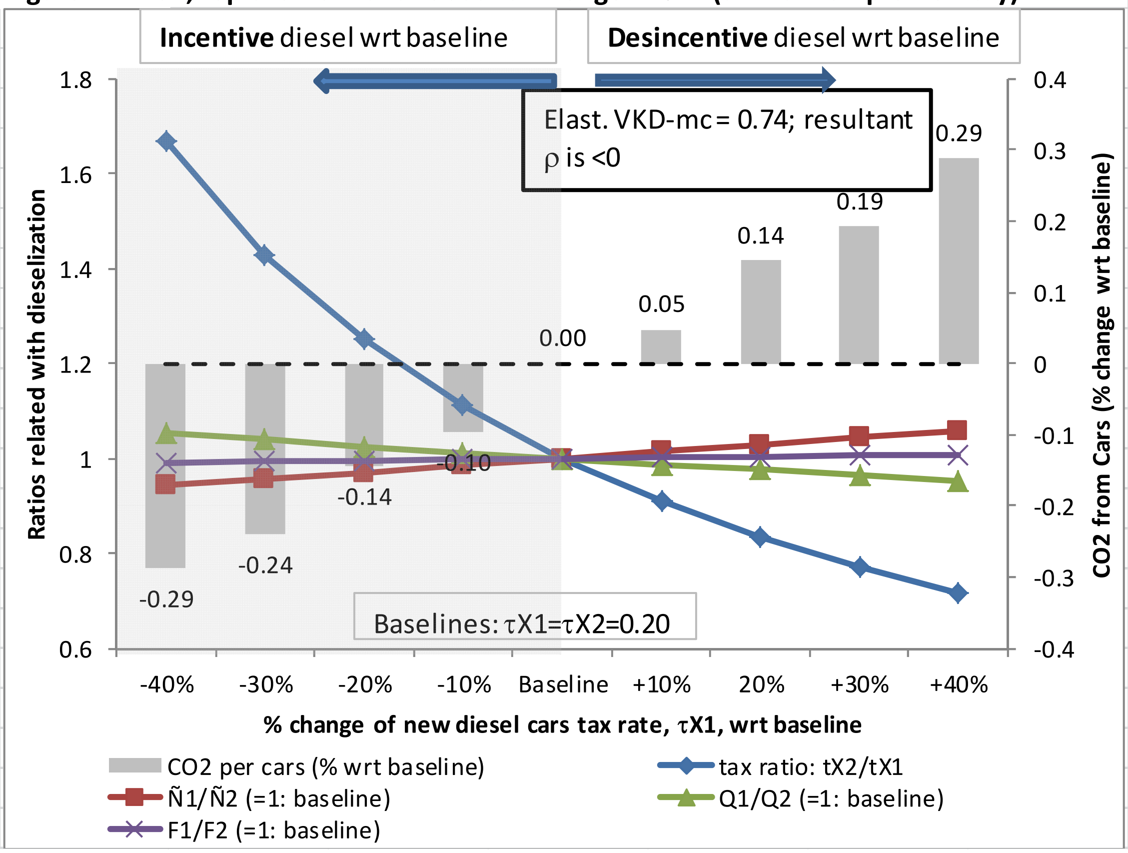

Figure 8.a. CO2, replacement and rebound: change in τF1 (s1 & s2 strongly substitutes)

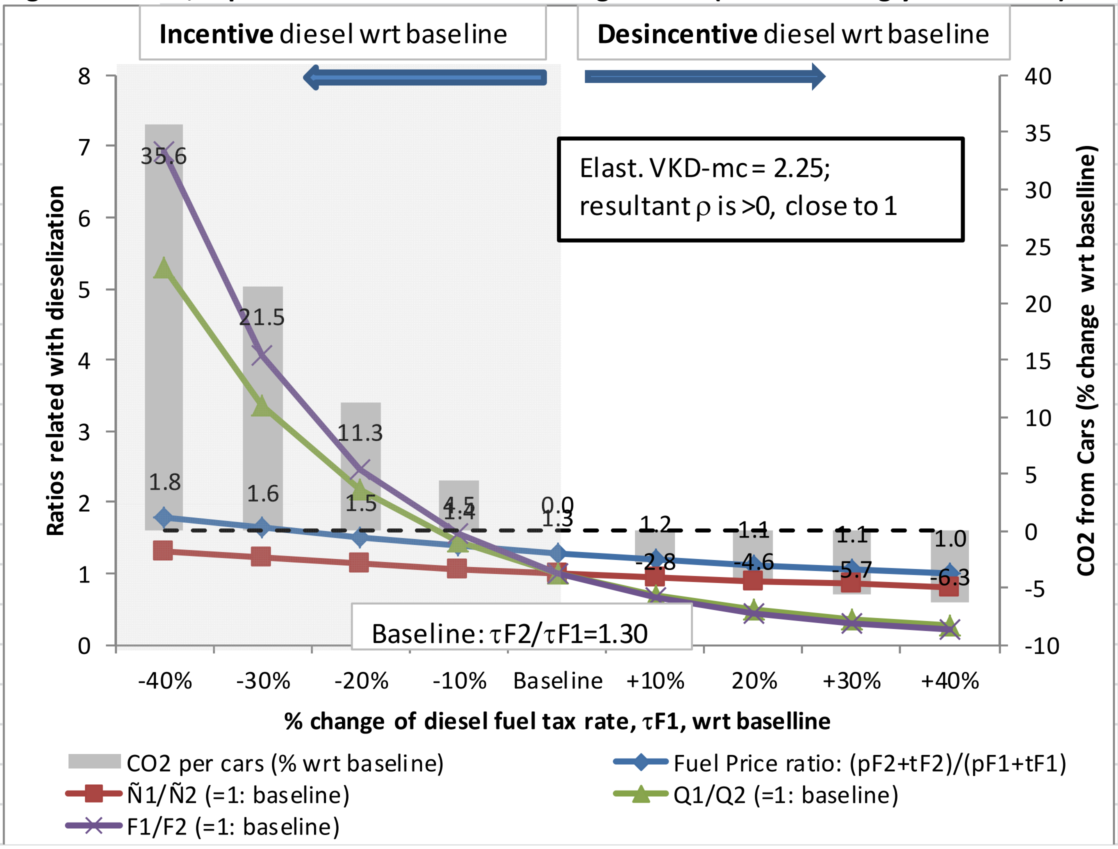

Figure 8.b. CO2, replacement and rebound: change in τF1 (s1 & s2 substitutes, baselline)

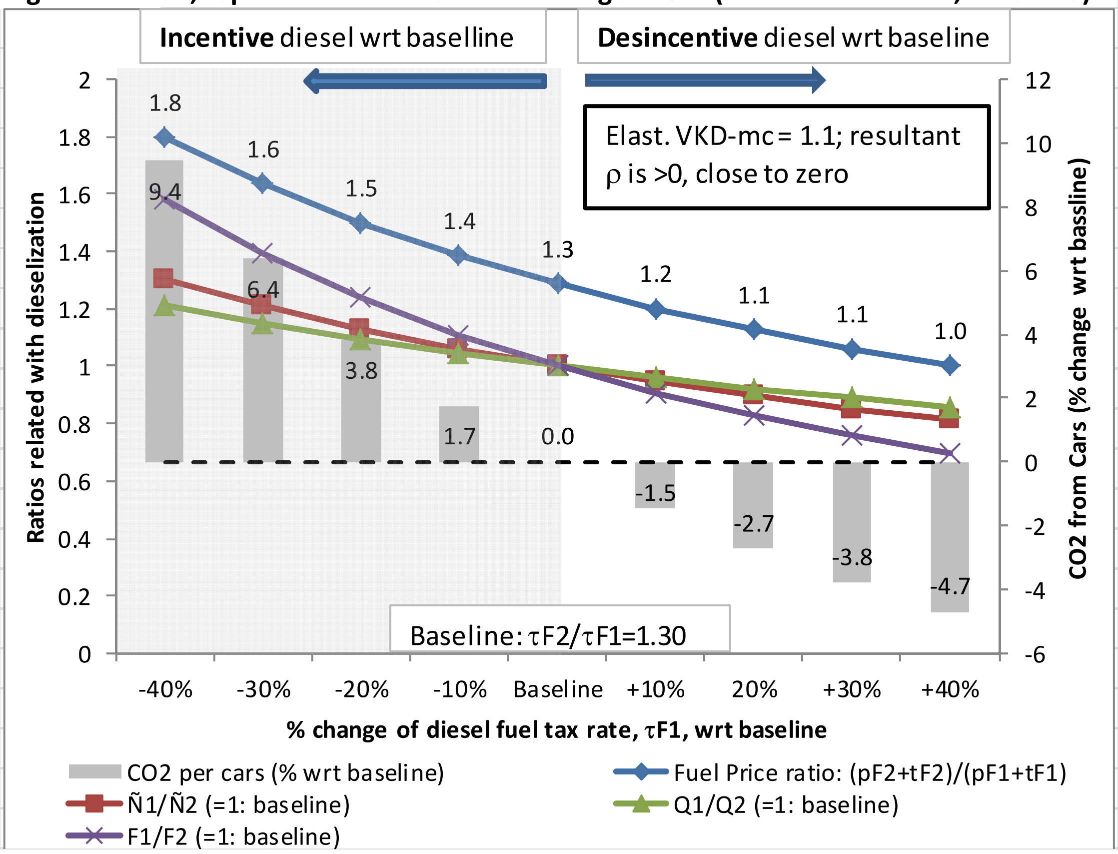

Figure 8.c. CO2, replacement and rebound: change in τF1 (s1 & s2 complementary)