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The Relevance of the Local Context for Assessing the Welfare Effect of Transport Decarbonization Policies. A Study for Five Spanish Metropolitan Areas

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The relevance of the local context for assessing the welfare effect of transport decarbonization policies. A study for 5 Spanish metropolitan areas

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Abstract

The effectiveness and efficiency of policies that try to reduce carbon emissions in the transport sector may depend significantly, at least in the short term, on the availability of options to shift away from diesel and gasoline private cars. This paper uses a detailed model, and a carefully-constructed dataset, to show how a fuel tax reform affects differently Spanish metropolitan areas based on their fleet composition, share of public transport, and urban vs suburban distribution. We find that those areas with the largest share of diesel and with the highest penetration of public transport are able to reduce more their carbon emissions and energy use, at a lower welfare loss. We also find that the reductions obtained are not large, thus requiring additional measures.

Keywords: Fuel tax reform, Metropolitan transport, Decarbonization, Welfare

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1. Introduction

The relationship between transport and sustainability has been long since under the scrutiny of the scientific community (Proost and Van Dender, 2012) and policy makers (European Commission, 2011b), because of its importance and its complexity. On the one hand, transport plays a very relevant role supporting economic development and also leisure; and, on the other hand, its has a substantial impact on the environment, both at the local (Friedrich and Bickel, 2001) and global levels (International Energy Agency, 2009), and also on congestion or accidents.

For example, in Spain (considered in this paper as representative of many developed countries) the impact of the transport sector on climate change is very relevant, contributing to a 30% of the total carbon emissions coming from energy consumption. Mendiluce and Schipper (2011) and Sobrino and Monzón (2014), using a Laspeyres Index decomposition, analyse the causes of the CO_2 emissions in the Spanish transport sector, identifying, along with freight and industrial activity, diesel and private transport as among the main drivers. Both authors propose the introduction of additional fiscal and administrative policies to improve the sustainability of the sector and, particularly, to curb the widespread reliance on private transport which is behind many of these trends.

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However, well-meant transport policies may bring unexpected outcomes. As an example, diesel cars, until very recently, have been promoted in Europe with lower taxes Mayeres and Proost (2001); Burguillo-Cuesta et al. (2011); Sobrino and Monzón (2014); Schipper and Fulton (2009) because of their higher efficiency and lower CO_2 emissions. However, this did worsen problems like congestion and local air quality. Mayeres and Proost (2011), for instance, compared the actual, optimal, and efficient taxation for car usage in Belgium, taking into account elements such as congestion charges or fuel taxes. In both cases, they concluded that diesel should be taxed more than gasoline, provided the differences in efficiency and the emission of atmospheric pollutants. The complexity illustrated in this example requires policy makers to tackle all these issues from a wider perspective, but with the required detail. For this reason, a tool able to assess the variety of effects that a fiscal policy applied to the transport sector can yield is not only recommended, but also needed in order to capture and quantify the interactions between demand for mobility, the ways to supply it and its consequences on welfare and the local and global environment, as stressed out in Schäfer et al. (2009).

In the academic literature, the estimation of the impacts on the economy and sustainability of transport policies has relied on adapted energy models. The first models that represented transport as an energy service rather than just a fuel demand were Schäfer and Jacoby (2006) and Loulou and Labriet (2008); yet, only later examples (E3Mlab, 2008; Schäfer and Jacoby, 2006; Proost et al., 2009) increased the complexity in picturing transport and mobility, developing non-linear relationships that describe better demand and supply in the sector. A correct estimation of the impact of transport policies requires taking into account time and location, as well as the diversity of transportation modes available.

A particularly relevant place to look at is metropolitan areas, where many different transport options are possible, and also where most of the population lives. According to the World Bank, the population living in urban areas accounts for 54% of the total (World Bank, 2017b), with one fourth of it residing in the metropolitan areas that exceed 1 Million inhabitants (World Bank, 2017a). These areas are the ones in which much of the economic activity is generated, (e.g. representing 80% of global GDP), but also where 60-80% of all energy demand and 75% of all carbon emissions take place (Swilling et al., 2013). This presents a challenge between preserving the environment and keeping welfare levels unaffected. Also, not all metropolitan areas are the same regarding alternative transport modes or demand for mobility. Observing the mobility in 52 European cities, Albalate and Bel (2010) notice the links between city characteristics and urban transportation, including size, location, and socio-economic factors as the drivers of the use and the magnitude of urban transportation. Thus, decarbonization policies affecting the transport sector in different metropolitan areas will probably have different outcomes.

However, we are not aware of any study that looks in detail at how these policies would affect welfare in different metropolitan areas depending on their different configurations. In Spain, for example, these estimations have been done mostly at the national level, e.g. Sobrino and Monzón (2013), who adopted the TREMOVE model (Ceuster et al., 2007) to estimate the increase of greenhouse gases in the period 2000-2006. Studying only the case of Madrid, Guzman et al. (2014) simulated the introduction of a congestion toll (similar to the congestion charge in London), applying system dynamics techniques to evaluate the effects on social welfare over a 40 years span. But again, their results cannot be compared to those obtained in other places because of different methodolologies. Therefore, the first research gap identified in our review is the need to compare, with the same methodology, the effect of a certain transport policy on different metropolitan areas, so that we may understand the different outcomes and the drivers behind them.

Therefore, in this paper we propose a model able to compare these issues in different metropolitan areas in Spain. We simulate the impacts of a tax reform for liquid fuels on five Spanish metropolitan areas, and estimate changes in welfare, environmental impacts, and transport modes for each of them, then contrasting the different results obtained with their particular characteristics, and hence providing clues for adapting transport policies to these characteristics.

The reform of fuel taxes has already drawn the attention of many institutions. Here we follow the proposal of Labandeira (2011) who, following the lines included in European Commission (2010) and European Commission (2011a), updates a previous work in Labandeira and López Nicolás (2002) and analyses a tax proposal that would involve a broader energy tax reform, thus including both transport fuels, electricity, and heating. The reform proposes the substitution of the current fiscal structure with one directly linked to the energy and the CO_2 content of the fuel. Along with other implications, this would reduce the current difference that exists between gasoline and diesel, as proposed in Mayeres and Proost (2001). Furthermore, it could help alternative fuel sources, such as biodiesel and ethanol, to be more competitive with traditional fossil fuels.

Previous works have estimated the effects of the reform on tax revenues from private transportation in Labandeira (2011) and on energy consumption and CO_2 emissions in Danesin and Linares (2015). Both papers analyze the outcome at the national level using previous econometric results, finding positive effects of its implementation on economic, energy and carbon emissions. On the one hand, Labandeira finds that the tax reform would provide an additional 12,000 million Euros in fiscal revenues from the energy sector, with the transport sector representing an important share of the increase. On the other hand, Danesin and Linares show that the reform could lead in the long run to an overall reduction of energy consumption in transport of up to 480 million GJ, while cutting CO_2 emissions by 29 million tons.

However, both assessments cited come short in that they do not include all the elements that characterise transport, in particular in a metropolitan context. The interaction between private and public modes, as well as their availability, can deeply affect the results and should be taken into account when evaluating the impact of such a proposal. This is the second research gap that we have identified, and the reason why we were so keen at including in our model different transport modes, and the elasticity of substitution between them, calibrated for the current situation.

By comparing the outcomes of the same fuel tax policy applied to different metropolitan areas and including in our model the possibility to change modes of transport, we can identify the factors that drive the outcome of the policy, and the extent to which this policy may be effective or not, depending on the local context.

Section 2 presents the model developed, while Section 3 describes the significant challenges regarding data, and how they have been overcome. Section 4 shows the results, and Section 5 offers some conclusions.

2. The model

The model we developed is a partial equilibrium model fitted to a metropolitan area, where consumers choose how to allocate resources for using transport services, while, on the supply side, transport providers decide the quantities, given the available technology and associated cost function. Finally, a (central) government affects the market prices through taxation. For each resulting equilibrium we calculate welfare (including external costs), as well as CO_2 emissions and energy consumption, and total tax revenues, as can be seen in the diagram in figure 1.

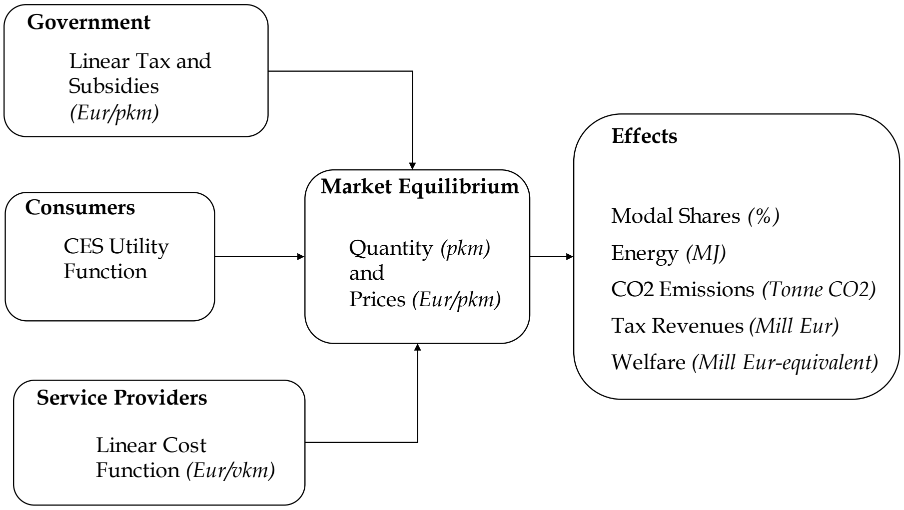

Fig. 1. Modular representation of the model.

The model used here takes inspiration from other well-established models such as TRENEN (Proost and Van Dender, 2001) and TREMOVE (Ceuster et al., 2007). While the second is designed to model with a high level of detail a whole region or nation, and introduces the dynamic dimension of the transport system, the first is a static partial equilibrium model aiming to optimise welfare in local areas, such as cities or small regions. We therefore follow the structure of TRENEN, and we adopt from it the utility and cost function design, as well as the use of the Marginal Utility of Income (MUOI, hereafter) to monetarize the utility and so construct the welfare function.

However, the model presented here differs from the previously presented models. The lack of data and the scope of the study led us to the construction of an apropos configuration. The objective of the model is to evaluate how policies affecting transport have an effect on local transport systems and the associated welfare. For this, we use a comparative static approach. We also had to drop some characteristics, given e.g. the difficulty to gather information about travelling time in metropolitan areas. Hence, a congestion function is not included, thus allowing for an easier description of time-dependent patterns.

Specifically, the maximization problem of the consumer is as follows (equation (1)), where x_l is the transport mode consumption and x_{NT} is the non-transport good consumption:

$$\max_{x_l, x_{NT}} U(x_l, x_{NT}), \tag{1}$$

subject to the budget constraint in equation (2), where p_l and p_{NT} are respectively transport-modes and non-transport prices, τ_l is the linear tax level associated with a particular mode (a subsidy when taking negative values), and Y is the available income.

$$p_l(1+\tau_l)x_l + p_{NT}x_{NT} \leq Y. \tag{2}$$

In a nutshell, the consumer chooses the consumption bundle of both a non-transport good (x_{NT}) and the specific transport modes (x_l) that maximizes her utility under the budget constraint, which states that the total expenditure must not exceed the available income, taking income, market prices, and taxes as given (Y, p, and τ respectively),

The nested-CES utility function U (Keller, 1976) is a model representation of consumption that allows allocating between different modes, thus representing modal shifting in transport. For each metropolitan area, we distinguish each mode by the location of the demand (inside the main municipality vs. outside), the time of the day (peak vs. off-peak), the service provider (public versus private) and the vehicle used (for example diesel car versus two wheels). Quantities are expressed in passenger-km (or pkm) while prices are in Euros per passenger-km. The parameters of this function are partially obtained from the literature (for example elasticities) but mostly calculated through a calibration process, which is primed by a real-data-fueled reference scenario.

The diagram of the nested structure is presented in figure 2.

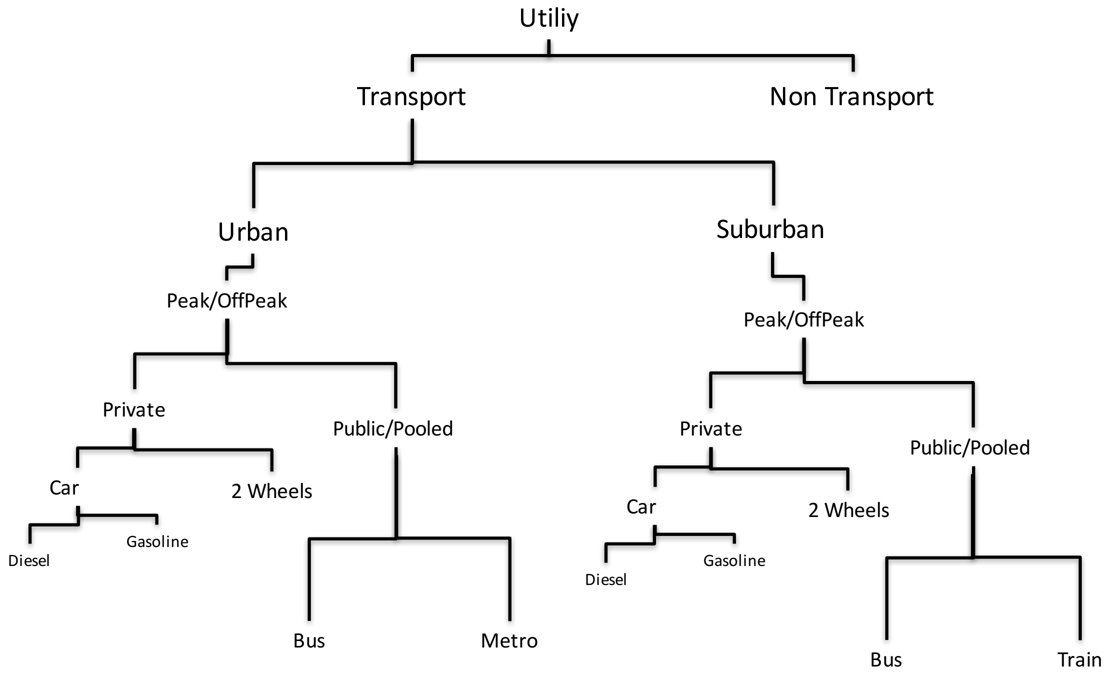

Fig. 2. Nested structure of the demand.

To model supply, we adopt a linear cost function that takes into account the cost of fuel, of vehicle operation and maintenance, insurance and the per-km cost of depreciation of the vehicle. Also to represent the fleet limitations, we adopt for each fuel-technology combination a constraint, and also another constraint for the usage of each technology.

Each quantity supplied and cost refer to a particular vehicle type and fuel, with quantity measured in vehicle-km (or vkm) and cost in Euro per vkm. Technology, in our example, represents the vehicle type that is used for transport, which can be diesel bus, metro train or gasoline car, while fuel (diesel, electricity or gasoline) is the type of energy used during transport.

We also include constraints characterising fleet availability and utilisation rates of the vehicles, being, for example, much higher in public transport.

The occupancy rate (pkm/vkm), exogenous in this model, connects transport demand with the supply side. So, being $v_{m,k,f}$ the vehicle-km supplied by each specific mode m, using technology k and fuel f, and c its associated variable cost, we develop the transport service provider problem as follows in equation (3):

$$\min_{v_{m,k,f}} \sum_{m,k,f} c_{m,k,f} v_{m,k,f}, \tag{3}$$

With the minimisation problem subject to the technology and fuel constraints $\bar{k}$ and $\bar{f}$ as in equations (4) and (5):

$$\sum_{f \in k} v_{m,k,f} \leq \bar{k}_{m,k}, \; \forall (m,k) \tag{4}$$

$$v_{m,k,f} \leq \bar{f}_{m,k,f}, \; \forall (m,k,f) \tag{5}$$

In simple words, the supplier provides certain levels of transport v while minimising total costs, and respecting the technological and fuel constraints ($\bar{k}$ and $\bar{f}$).

Market clearing determines prices and quantities at equilibrium, stating that the demanded quantity has to be at most equal to the quantity supplied, weighted by the exogenous occupancy rate o_m as in equation (6):

$$x_m \leq o_m \sum_{k,f \in m} v_{m,k,f}. \tag{6}$$

To evaluate the simulated effects of the introduction of a certain transport policy, along with the resulting prices, the differences in overall fuel consumption (and associated energy use and CO_2 emissions), the model also estimates a particular measure of welfare. The value includes both a quantitative metric for utility, weighing it with the already cited MUOI (μ in equations), plus the external costs coming from vehicle use (local and global pollution, and time use). The welfare change W in each scenario s is then calculated as in equation (7), where e is the external cost per vkm of each mode-technology-fuel combination:

$$\Delta W = \frac{1}{\mu}(U^s - U^{ref}) - \sum_{m,k,f} e_{m,k,f}(v^s_{m,k,f} - v^{ref}_{m,k,f}) \tag{7}$$

In a nutshell, the exogenous variables include costs and availability on the supply side, occupancy rate and tax rates and, for the demand side, elasticities and other parameters determined by the calibration process and detailed in the appendices. This methodological framework allows for a quantitative assessment of the introduction of a certain transport policy in metropolitan areas, provided there is enough data to build the model. This significant challenge is discussed in the following section.

3. Building the dataset

Since one of the goals of this paper is to compare how the same policy may perform in different metropolitan areas, a homogeneous and reliable dataset in essential for a meaningful comparison. Whereas in examples like Gibbons and O'Mahony (2002) and De Borger et al. (1997), the dataset used was specific for the area studied, we decided to build a comprehensive dataset general enough to include different Spanish metropolitan areas, and which would therefore allow us to meet the goal of our research.

3.1. Source Description

The Observatory for Metropolitan Mobility (OMM, Monzón et al. (2014)) provides a large and reliable set, collecting the information from local transportation authorities and transport service providers. However, the lack of information about time-of-the-day choices, and more importantly, the use of private vehicles, made integration with other sources necessary. For this, we included the 2006 survey on urban mobility Movilia Ministerio de Fomento (2007), the Spanish General Directorate of Traffic (DGT, Dirección General de Tráfico (2016)), and the Spanish Observatory for Transport and Logistics (OTLE, Ministerio de Fomento (2016)) for its information on the running costs of private vehicles, complemented by regional fuel prices found in the Energy Market Authority, (CNMC, Comisión Nacional de los Mercados y la Competencia (2016)) and finally INE (INE, 2012a,b) for economic and demographic data.

The first step is to identify and assess the data sources, acknowledging the limits beneath the raw data, and, for this, we list and analyse some of the aspects we are looking for to complete the input needs of the model. Figure 1 enumerates the sources that have been included in the study and evaluates them according to the information they provide.

The "Demand for public transport table (Tab. 6)" in OMM (in Figure 1), represents the most detailed table about public transport, measured in passenger-km and with enough information to distinguish between different modes and locations.

The time of use, used to discriminate peak and off-peak travel, is covered only in the Movilia database Ministerio de Fomento (2007), where time patterns for each province can help to identify the peak and off-peak of different areas, along with the modal share. Unfortunately, data are expressed in number of trips, limiting the potential to fill the information needs. Data for price and fleet, along with costs for fuel, capital and other variable costs are gathered from OMM for public transport, while for private transportation we lean on the data found on CNE, INE and OMM.

The integration of all the information collected has to deal with a wide range of issues. While some of the figures are in pkm or vkm, others are in trip number or just ratios. For this, a variety of assumptions provide the links between the different data; the result is a complete measure for each modal combination (area, location, time of use, vehicle) which eventually describes the demand in each area. However, in order to ensure the consistency of our data, it should be remarked that we never take absolute values from databases that do not belong to our base year (2012). When data is needed from a database with other reference year, we only use ratios or shares. Of course, we understand that these shares or ratios may vary with time, but, given the lack of alternative data, we find that this assumption may be reasonable enough.

3.2. Integrating the data sources

To better represent both the assumptions, the selected sources, and their alternatives, we focus on four main subjects: public transport, private transport, their modal shares, and the time of use.

Table 1
Information summary and data review.

Provider	Year	Table name	statistic	Trips	pkm	eur	Oth	Area	Loc	Time	Privat	Public
OMM	2012	General charact.	Area				**	**	**			
			Population				**	**	**			
			Constr Area				**	**	**			
OMM	2012	Socioec. charact.	Household Size				*	**				
			Activity Rate				*	**				
			Unemployment rate				*	**				
			GDP per capita			**		**				
OMM	2012	Motorization Index	Car ownership				**	**	**		*	
			Motorbike/Moped ownership				**	**	**		*	
OMM	various	Mobility characterstics	Workday trips	*				**				
			Average trip time				**	**		*		
			Average trip length	*	*		**	**				
			Intermodal trip rate	*			*	**			*	*
OMM	various	Modal Share	Work Purp.	*				**			*	*
			Other Purp.	*				**			*	*
			All Purp. (whole met. area)	*				**			*	*
			All Purp. (Capital City)	*				**	**		*	*
			All Purp. (Outside Capital City)	*				**	**		*	*
			All Purp. (in between CC and outside)	*				**	**		*	*
OMM	2012	N. of trips, publ. trans.	Number of Trips	**				**	*			**
OMM	2012	Demand of publ. trans.	Demand		**			**	*			**
OMM	2012	Tariffs	Prices of public transport			**		**	*			**
OMM	2012	Tickets sold	Number of Tickets used			**		**	*			**
OMM	2012	Economic results	Revenues			**		**	*			**
			Subsidies			**		**	*			**
DGT	2012	vehicle fleet	registered vehicles per fuel, per town				**	**	*		**	*
MOVILIA	2006	trip starting time	weekdays on the mode	*						**	*	**
MOVILIA	2006	trip starting time	weekend days on the mode	*						**	*	**
MOVILIA	2006	trip starting time	weekdays on the province	*				*		**		
MOVILIA	2006	trip starting time	weekend days on the province	*				*		**		
MOVILIA	2006	trip starting time	weekdays on the size of the munic.	*						**		
MOVILIA	2006	trip starting time	weekend days on the size of the munic.	*					*	**		
CNMC	2012	CNE fuel prices	average fuel prices			**		*				
CNMC	2012	CNE fuel cons./em.	fuel consumption				*	*				
FOMENTO	2012	Main roads trans	pass. transport on the main road network		*						*	*

blank	*characteristic missing*
*	*characteristic available and providing some evidence*
**	*characteristic available and providing strong evidence*

Column reference

Provider	*Information Provider and source*
Year	*reference year*
Table name	*name of the table in the reference source*
statistic	*Information Provided*
Trips	*information linked to trips*
pkm	*information linked to passenger-km*
eur	*economic information*
Oth	*other information (demographic, fleet composition)*
Area	*information linked to specific metropolitan area*
Loc	*information specific for urban-suburban zones*
Time	*Information specific for Time of travel*
Private	*information linked to private transportation*
Public	*information linked to public transportation*

As seen previously, data for public transportation is gathered from the OMM database. The assumption, kept throughout the analysis, is that certain modes do coincide with the geographical location. Metro trains and urban bus are limited to the principal municipality of the area, while metropolitan train and inter-urban buses are assumed to be outside of it. Although alternatives such as the surveys conducted by the same Public Transport Authorities (PTAs) and included in the OMM add some detail to the location, they would lose all the essential information about trip length and specific share.

These surveys are also used to obtain some measure of private transport in metropolitan areas, where sources like Fomento or Movilia cannot provide any local information. The OMM surveys provide an overall measure of the number of trips for private vehicle users, which should be adjusted using the average trip length for to obtain the total demand in passenger-km. As mentioned before, we only take relative shares from these surveys, to try to make results more consistent with the base year from OMM.

The next step is to define the private modes further. To differentiate between diesel and gasoline car usage, as well as two-wheel vehicles, we rely on the vehicle fleet data provided by DGT. Here, the modal share in private consumption is defined by the number of vehicles on the road, weighted by a parameter that represents the average number of km driven with each vehicle. This strong assumption is far less demanding compared to the one involving fuel consumption, which data, as shown before, are far less specific.

The estimation of this average km per vehicle relies on data and studies that tackle specifically the demand for private transportation. For the difference in use between the gasoline and diesel fleet we use previous econometric analyses on this specific topic (González and Marrero, 2012; Danesin and Linares, 2015; Mendiluce and Schipper, 2011), while a study on the usage of motorized two wheels in France (de Solere, 2010) served to overcome the lack of data on the usage of motorized two wheels in metropolitan Spain, given the similarities between the two contexts. It has to be reminded that these data are not used for total demand, but just to specify the fleet use compared to the overall demand for private transport.

Movilia survey data was the only resource available to construct the time of use (peak/off-peak demand). The main assumptions are related to the measure of data (in number of trips); the definition of modes and areas, as they do not always coincide with those in OMM; and finally, the reference year, which is different. Yet, the lack of alternatives required to adapt our scenario to the information available.

In particular, the different reference year available in the sources can be compared in table 2 and, as can be noticed, most of the sources are available for 2012. The few exceptions, Movilia and Public Transport Authorities' reports, are based on surveys, which for their high costs are not carried out on a yearly basis. For instance, the general mobility survey Movilia has not been updated since the 2006-2007 edition, while just some of the local surveys have been updated since. For this reason, we decided to rely on this information for just a few, although important details, like the public/private and peak/off-peak mobility shares, thus avoiding information for absolute values such as total demand or fleet composition. The summary of the whole process described in this section is presented in the diagram in figure 3.

3.3. Putting everything together

Provided the assumptions stated before, we can construct the dataset to be used by the calibration process and, to formally represent this construction, we introduce some parameters and indices. Demand, to be measured in passenger-km (pkm) and named x, is defined by the metropolitan area

Table 2
Information and references to data sources.

Information	Source	Area	Year of reference
Demography/Economy	INE	All	2012
Public Mobility	OMM on PTA data	All	2012
Public/Private Shares	OMM on PTA surveys	Madrid	2004
		Barcelona	2011
		Valencia	2009
		Malaga	2010
		Girona	2006
Peak/Off Peak Shares	Movilia	All	2006
Public Fleet	OMM on PTA data	All	2012
Private Fleet	DGT	All	2012
Oil Prices	CNMC	All	2012

a (Madrid, Barcelona, for example), the location l (Intra and Extra-Urban), time of use t (Peak and Off-Peak), and mode m (diesel- and gasoline-car, urban bus, train, for example). The particular demand for a mode will be then $x_{a,l,t,m}$.

Metropolitan Areas (presented as a in equations) included in this paper are the ones presented in OMM, dropping the ones with important gaps in data coverage. Namely, the areas are Madrid, Barcelona, Valencia, Málaga, and Girona. To further define the demand geographically, we introduce the *location* as l in equations. These can be intra- or extra-urban, defining trips that take place within the main municipality or not, respectively. *Time* (t) can be either peak and off-peak and for modes, the set PU contains the public ones (metro, train, intra- and extra-urban bus) while the set PR the private ones (gasoline and diesel cars, two-wheelers).

OMM provides the demand in passenger-km for each mode, providing the data for $x_{a,l,m\in PU}$. The surveys, also in OMM, provide the aggregate measure for private transport in trips, together with public ones, which is then used to obtain the overall private travelled passenger-km. Defining $\mathbf{shr}_{a,m,PR}$ and $\mathbf{shr}_{a,m,PU}$ as the modal shares of the private and public transport from OMM, we get the overall demand for private modes:

$$\sum_{m\in PR} x_{a,l,m} = \frac{\mathbf{shr}_{a,m,PR}}{\mathbf{shr}_{a,m,PU}} \cdot \sum_{m\in PU} x_{a,l,m}. \tag{8}$$

To obtain the precise demand for each private mode, we introduce the relative fleet component $flt_{a,l,m\in PR}$ and the weight $a_{m\in PR}$ that relates the different modes (diesel and gasoline cars) to their different usage. While the $flt_{a,l,m\in PR}$ component is measured in vehicles, the weight $a_{m\in PR}$ is here measured in annual vehicle-km (vkm) per vehicle. The final result will be the relative mileage of a specific mode, compared to all the fleet:

$$x_{a,l,m\in PR} = \frac{\mathbf{flt}_{a,l,m\in PR} \cdot a_{m\in PR}}{\sum_{m\in PR} \mathbf{flt}_{a,l,m\in PR} \cdot a_{m\in PR}} \cdot \sum_{m\in PR} x_{a,l,m}. \tag{9}$$

Finally, we introduce the time of use through the parameter $\mathbf{tm}_{a,t,m}$, derived from the Movilia surveys (as mentioned, in relative terms), thus completing the parameter definition of the demand model input:

$$x_{a,l,t,m} = \mathbf{tm}_{a,t,m} \cdot x_{a,l,m}. \tag{10}$$

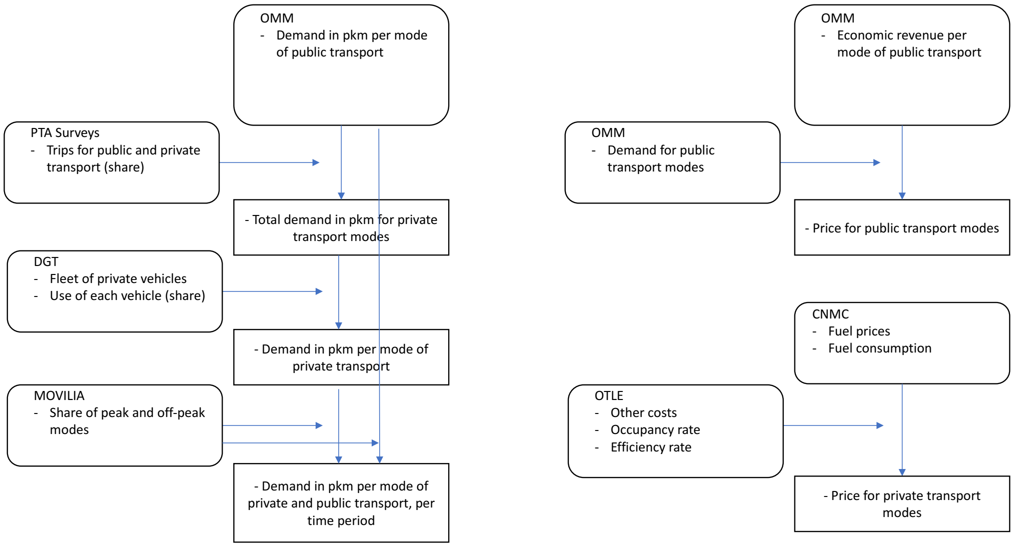

Fig. 3. The construction of the dataset

Along with quantities, the price represents the central aspect of the model input and is measured in euros per passenger-km (or pkm). Once again, the wish to rely on official data makes necessary a thorough assessment of the available sources.

For both public and private modes, the lack of a published *per-pkm price* leads us to combine different sources that have already been shown in table 1. Then, the resulting assumptions and the alternatives are compared to check whether the information obtained is robust enough to be used as input.

For public transport, the various sources that can bring information about pricing are all included in OMM and come from the official public service providers. The pricing scheme together with the number of trips sold and the average trip length can be a viable option. The shortcoming of this alternative is the impossibility to determine which mode (bus or metro, for instance) has been used and paid. Moreover, multiple and seasonal passes can be used in different occasions (and so modes) making it difficult to determine how much is spent for each trip.

The chosen alternative is the use of the economic revenues for each mode, together with the total passenger-km figures coming from the demand side. This allows for knowing the trip price per transport mode. The limits, as before, reside in the impossibility to determine the different distribution of revenues across peak and off-peak.

Recalling the notation in (3.2) we introduce some parameters for the information included in the tables just considered above: first the revenues collected in OMM are defined as $\mathbf{Y}$, while final price is called $\mathbf{p}$ instead. Recalling $\mathbf{x}_{a,l,m\in U}$ as the demand for public transport modes, we derive the equation for the prices for public transport modes in equation (11):

$$\mathbf{p}_{a,l,m\in PU} = \frac{\mathbf{Y}_{a,l,m\in PU}}{\mathbf{x}_{a,l,m\in PU}}. \tag{11}$$

Determining the price of private modes usage is trickier, due to the lack of an accounting system as for public transport. The indirect measure of this, as has been done extensively in the literature (De Borger and Proost, 2001; Mayeres et al., 1996; Schäfer, 2012), is to consider the private cost per use of the vehicles, and adopt an average occupancy rate.

The construction of the cost of private vehicle usage depends on the fuel component and others such as the maintenance and insurance costs. While the first depends on vehicle efficiency and the type of fuel, the other two are rather similar across the fleet. Values of the private vehicle efficiency are taken from the corrected official values of a reference car model. The correction is the 15% of the laboratory tests, a measure in line with the recent literature Mock et al. (2014). IAE databases (International Energy Agency, 2006) provide the energy content for fuels and the relative conversions.

The source of the fuel prices is the already covered CNMC dataset, while the source of the other costs is the DG Ground Transportation of the Spanish Ministry of Public Works through the Observatory Of Transport and Logistics of the same Ministry. The price will be computed as follows, with occupancy rate being $\mathbf{o}$ (in passenger-km/veh-km), efficiency rate $\mathbf{e}$ (in toe/veh-km), fuel price being $\mathbf{f}$ (in eur/toe), and $\mathbf{c}$ other complementary costs (in eur/vkm):

$$\mathbf{p}_{a,l,m\in PR} = \frac{(\mathbf{e}_{m\in PR} \cdot \mathbf{f}_{a,m\in PR}) + \mathbf{c}_{m\in PR}}{\mathbf{o}_{m\in PR}}. \tag{12}$$

Having already discussed the impossibility of discriminating prices without taking into account users' cost of time, the final relation will provide the price for all the modes, being equal in both peak ($peak$) and off-peak (off) situations, as follows:

$$\mathbf{p}_{a,g,t,m} = \mathbf{p}_{a,g,\mathbf{peak},m} = \mathbf{p}_{a,g,\mathbf{off},m} = \mathbf{p}_{a,g,m}. \tag{13}$$

All these equations provide the full framework for the dataset required by the model, leading to the reference scenario, used for the parametric calibration of the model and the comparison with the simulation results.

In summary, the exogenous variables of the model include the availability of transport and the per-km cost of them, the fiscal structure, and the elasticity of the demand. The reference scenario, as presented in this section, leads to the definition of the last exogenous variable, i.e. the Keller's Alphas.

4. Comparing the effects of a fuel tax reform on different metropolitan areas

Provided the model and the data frame previously discussed, in this section we will assess the effects of implementing a fuel tax reform in metropolitan areas in Spain, comparing the results obtained in the different areas.

4.1. Metropolitan areas studied

Data availability allows for the inclusion of the two biggest areas as Madrid and Barcelona, medium-size areas like Valencia and Málaga, and finally small areas, as Girona, thus covering a wide spectrum of the metropolitan situation across Spain. This allows us for addressing how different areas may respond to a common fuel tax policy, based on their initial conditions. The effects analysed will be those on total mobility (measured in passenger-km or pkm) and modal shares, variations in welfare and fiscal revenues (in Euros), and the savings in energy (in Megajoules) and CO_2 emissions (tCO2), each differentiated for each metropolitan area, mode and location.

But before getting into the simulation results, it is useful to describe the different starting conditions of the metropolitan areas analyzed, which will also help understand the different outcomes.

As may be seen in Table 3, Madrid and Barcelona are the areas with the largest passenger mobility, with over 23,000 and 15,000 million pkm respectively, with figures for smaller areas lying between 7,000 million pkm (Valencia) and 640 million pkm (Girona).

Table 3
General Metropolitan Area characteristics (2012, based on INE, OMM, TPA).

	Population	GDP, Mill. Euros	Tot. Mobility, Mill pkm
Madrid	9732087	187847	23335.47
Barcelona	6673000	137596	15087.17
Valencia	2602143	37326	7324.04
Malaga	1589188	17268	2786.04
Girona	352490	5402	634.27

It is interesting to highlight how these passenger-km are distributed across modes. In Madrid and Barcelona the rate of public mobility is about 51%, while in other areas public transport is less of an alternative: Valencia features around 29% and Málaga around 17%, and, finally, in Girona, around 13%, underlying the disparity in the demand (and provision) of public transport services between larger and smaller areas, as can be seen in more detail in figure 4.

Table 4 presents estimates for energy consumption and CO_2 emissions for metropolitan mobility in 2012, obtained by multipling the mobility figures (3) by reference values for efficiency and for energy content and emissions of the different fuels and technologies (International Energy Agency, 2006). There, it can be observed how the different mobility patterns translate into energy consumption and carbon emissions. Overall energy consumption in the metropolitan transport sector shows that bigger areas are also the largest energy users and carbon emitters, with figures lying between 35 million GJ in Madrid and 1.5 million GJ in Girona. It can also be observed how the relative energy consumption and carbon emissions differ among areas, following the share of public transport but also the composition of the fleet (e.g. Málaga features an energy intensity and carbon emissions similar to those of Girona, in spite of the larger share of public transport in the former).

Table 4
Energy consumption and CO_2 emissions, 2012.

	Energy Consumption		CO_2 Emissions	
	(total, Mill. GJ)	(relative, MJ/pkm)	(total, thou. tCO_2)	(relative, gCO_2/pkm)
Madrid	34.47	1.48	2431.20	104.18
Barcelona	22.00	1.46	1534.38	101.70
Valencia	14.70	2.01	1043.34	142.45
Malaga	6.32	2.27	458.49	164.57
Girona	1.45	2.28	105.52	166.37

It is interesting to look closer at the differences between the two largest areas, Madrid and Barcelona. Although Madrid features a highly developed public transportation,users' preferences

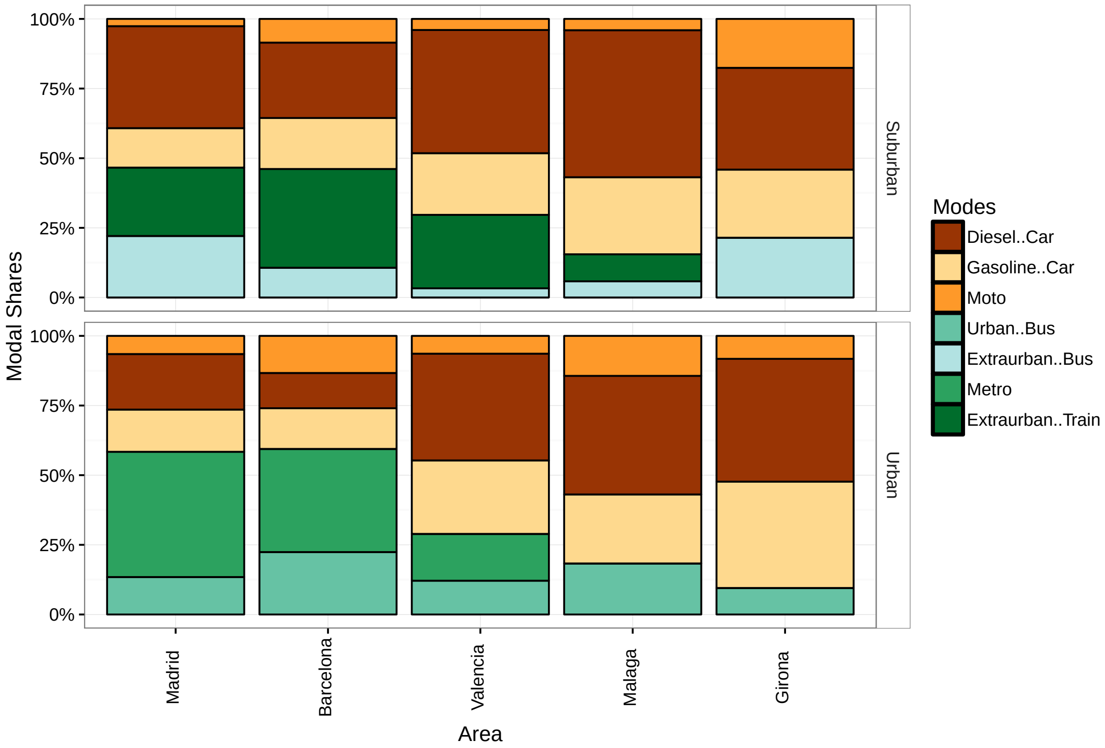

Fig. 4. Modal shares, 2012.

lean toward diesel cars, reaching 37% of all mobility in the suburban context. Barcelona, in turn, has one of the largest shares of two-wheel personal transportation across all areas, leading the usage of other private modes, at least in the urban context. As for public transportation, the metro represents the first choice in both areas, but in the suburban context, metropolitan regional train is preferred to extra-urban bus only in Barcelona, while in Madrid the shares are similar.

While gasoline vehicles are more common in the urban context, in suburban locations the typical private vehicle is a diesel car. Quantitatively, the dieselization rate of private mobility in the main municipality is about 43% in Madrid, 31% in Barcelona, 53% in Valencia, whereas in suburban areas it is 69% in Madrid, 50% in Barcelona and 63% in Valencia as shown in figure 5. The cause of this pattern can be associated to the different car choices. The longer trips and lower public transport density, common outside the main municipality, leads consumers to choose diesel vehicles, with lower running costs, as extensively shown in (Schipper et al., 2002).

Energy shares of diesel lie between 63% in Madrid and 48% in Barcelona, connected to both private (diesel cars) and public (buses) transportation. Gasoline, representing the consumption of gasoline cars and motorized two wheelers, features lower shares through all the areas, being as high as 47% in Girona and just 30% in Madrid. Electricity consumption, used only in metro and regional trains, is always below 10%.

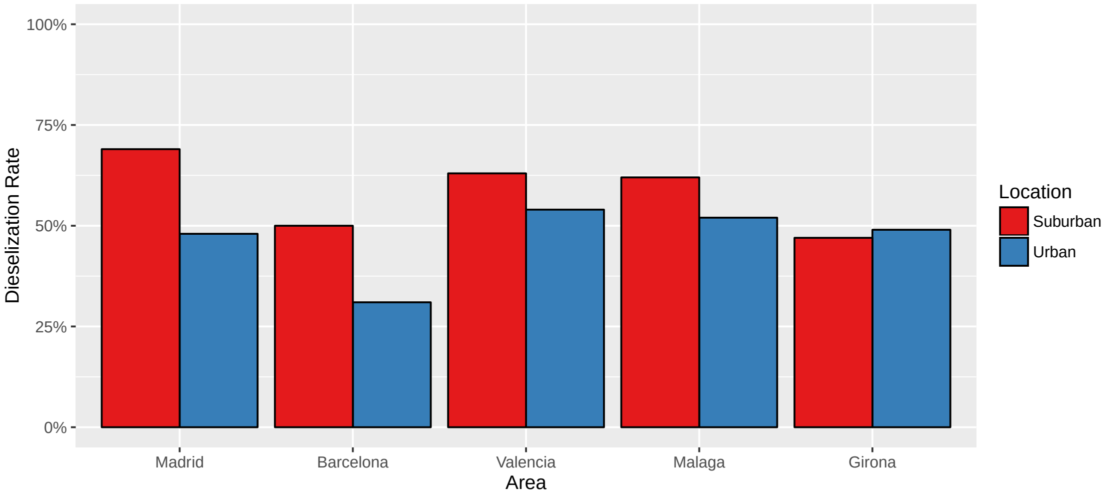

Fig. 5. Dieselization rates of private mobility, 2012.

4.2. A fuel tax reform as an example of a decarbonisation policy for transport

The context presented in the previous section highlighted a high dependence on private transportation, especially in the smaller areas, and a noticeable use of diesel. As already mentioned in the introduction, this situation affects particularly metropolitan areas, worsening both air quality and traffic flows.

The main reason for this large use of diesel resides in its competitive price compared to gasoline, in turn based on lower taxation rates. This situation is indeed widespread in Europe, as clearly shown in figure 6. Regarding Spain, fuel taxes are even lower than in neighbouring countries, providing cheaper access to gasoline and especially diesel fuel.

Therefore, we have chosen as an example of a decarbonisation policy for the transport sector in metropolitan areas a fuel tax reform along the lines of the proposal by the European Commission to amend Directive 2003/96/EC for the taxation of energy products and electricity (European Commission, 2011a). This proposal aims at the harmonization of the taxation of fuels across the European countries and across fuels, reducing the distance between fuel prices. The European Commission proposal states that fuel taxes should be based on CO_2 emission factors and on the net calorific value of the different fuels. It also revises minimum levels of taxation, based on minimum taxes for carbon emissions energy content. In practical terms, that means that diesel taxes will increase compared to gasoline taxes, and that both prices may also increase as a result of the minimum taxation levels.

Based on the minimum tax levels proposed by the European Commission, Labandeira et al. (2004), later updated in Labandeira (2011), create two scenarios for a potential implementation of the proposal in Spain. The first scenario (reform A) only includes the energy tax component, while the second (reform B) adds the carbon emissions tax component.

Table 5 summarizes the effects of the two possible reforms on the final price of each fuel compared to the 2012 reference year.

Although decided at the national level, this fuel tax reform might prove to be very relevant for metropolitan areas, given the already mentioned large share of diesel and private transport. By

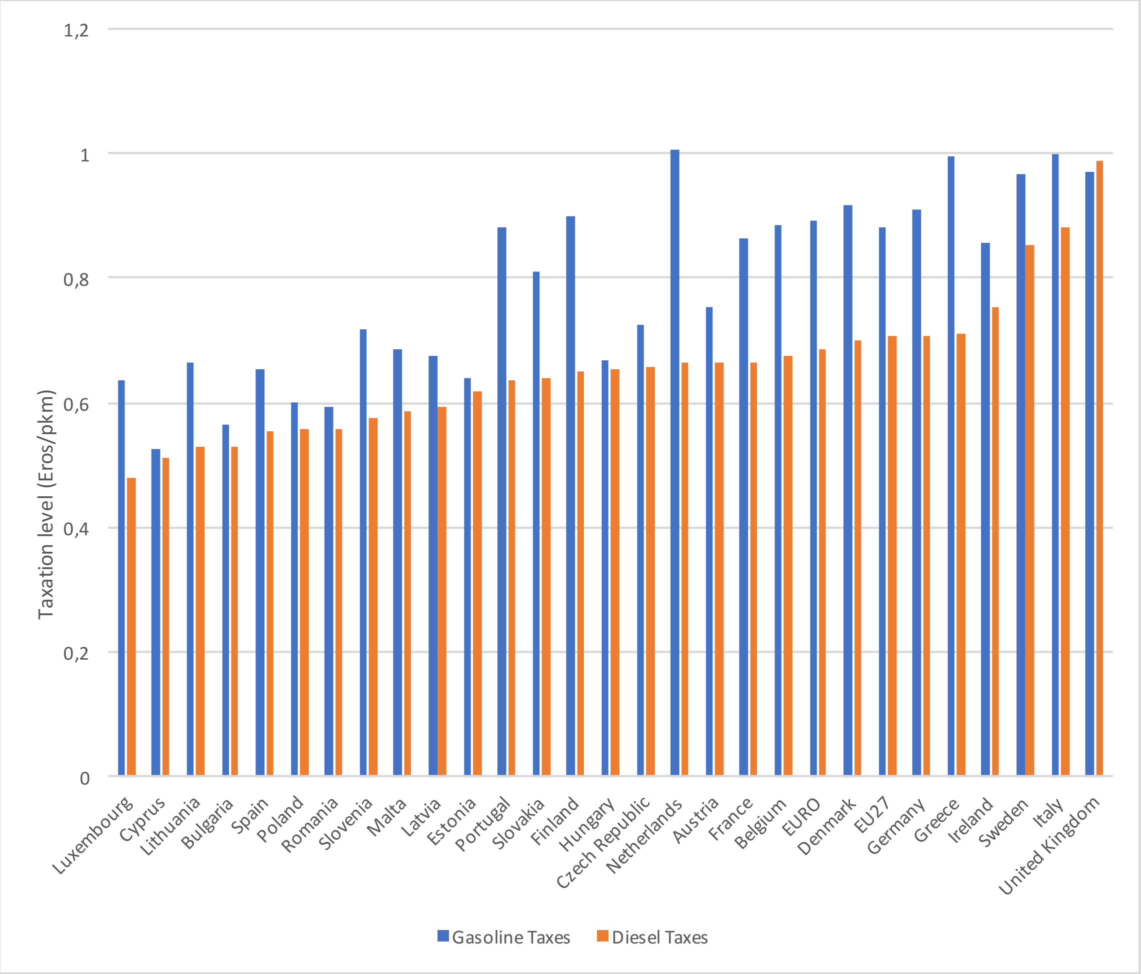

Fig. 6. Tax levels for gasoline and diesel in European countries, January 2012.

increasing both the relative price of diesel and also fuel prices, the reform could reduce the demand for private transport in these areas, and hence energy consumption and carbon emissions. The fuel price is a large part of the total cost of using private transport, so we should expect significant changes in demand, but only as long as there are alternatives such as public transport or cleaner fuels for private transport. Therefore, we consider it a very good example to test the extent in which the same transport policy could have different consequences in different metropolitan areas. This is what we do in the following section.

4.3. Simulation results

We now proceed to simulate the impact of the fuel tax proposal described before on the demand for transport in metropolitan areas, and on the share of the different transport modes.

In section 3.3 we already illustrated how the information collected translates into a precise

Table 5
Reform scenario specification.

	Reference (2012)		Reform A		Reform B	
	gasoil	gasoline	gasoil	gasoline	gasoil	gasoline
Price (Eur/l)	1.38	1.44	1.56	1.42	1.65	1.50
(% change)			(+12.65%)	(−1.70%)	(+19.56%)	(+4.05%)
Tax (eur/l)	0.59	0.69	0.76	0.67	0.86	0.75
(% change)			(+29.76%)	(−3.55%)	(+46.01%)	(+8.44%)

consumption bundle for transport for each of the metropolitan areas, determining the consumption (and price) for each mode, time of the day, and location. Then, together with the exogenous elasticities, and through the calibration process described in the Appendix Appendix A, we are able to determine all the parameters necessary to picture the whole diagram in Figure 2, through the basic assumption that the representative consumer is maximizing her utility in the reference scenario.

The fiscal reform proposal affects indirectly the market prices of mobility, especially private mobility. These changes in the market prices of mobility result in turn in a new market equilibrium, following the model structure pictured in Figure 1.

The results following the simulation of the reform provide interesting insights. Comparing these results with economic theory and previous literature, they seem sensible: there is an overall decrease in the demand for mobility following the increase in the cost of the fuel. As shown in table 6, this decrease ranges from 0.22% (in Barcelona) to 1.37% (in Málaga) in the case of reform A, with the gap widening to 0.54% and 2.70% for the same areas in reform B. In economic terms, this means that the overall price for transport increases when adopting the reforms, hence shifting consumption away from transport, even in the case of reform A, where mixed tax changes could have led to an overall rise in demand.

Table 6
Overall transport demand changes with respect to Reference Scenario 2012

	Reference	Reform A		Reform B	
	Total value (Mill pkm)	Total value (Mill pkm)	rel. change (%)	Total value (Mill pkm)	rel. change (%)
Madrid	23335	23236	-0.43 %	23170	-0.71 %
Barcelona	15087	15054	-0.22 %	15006	-0.54 %
Valencia	7324	7269	-0.76 %	7210	-1.55 %
Malaga	2786	2748	-1.37 %	2712	-2.67 %
Girona	634	628	-1.02 %	619	-2.35 %

As for energy and emissions, the results share the signs already seen for mobility, with a decrease after implementing reform A of 2.6% in Madrid, 1.3% in Barcelona and 1.7% in Valencia, and with the decrease increasing to 4.3% in Madrid, 2.9% in Barcelona, and 3.3% in Valencia in the case of reform B.

In absolute terms, the reduction in energy consumption and carbon emissions following reform A is around 900 thousand GJ and 68 thousand tCO_2 in Madrid, and 300 thousand GJ and 22 thousand tCO_2 in Barcelona. As for reform B, the reduction in energy consumption is almost 1.5 million GJ in Madrid and 112 thousand tCO_2, while in Barcelona is more than 600 thousand GJ and 49 thousand tCO_2. Figure 7 shows these reductions in per capita terms, also including changes in fuel use. The figure shows indeed an overall reduction, with electricity and gasoline increasing their shares in both simulated reforms. It is worth noting the figures for Valencia, where the energy use in mobility per inhabitant is almost double than in Barcelona, for instance. This is basically due to the high per capita mobility rate: users in Valencia travel 4 thousand kilometers per year, which is one third larger than Barcelona (3 thousand pkm/inh) and 50% greater than Málaga (2730 pkm/inh). However, this anomaly affects the starting point, but not the relative effects of the fuel tax reforms.

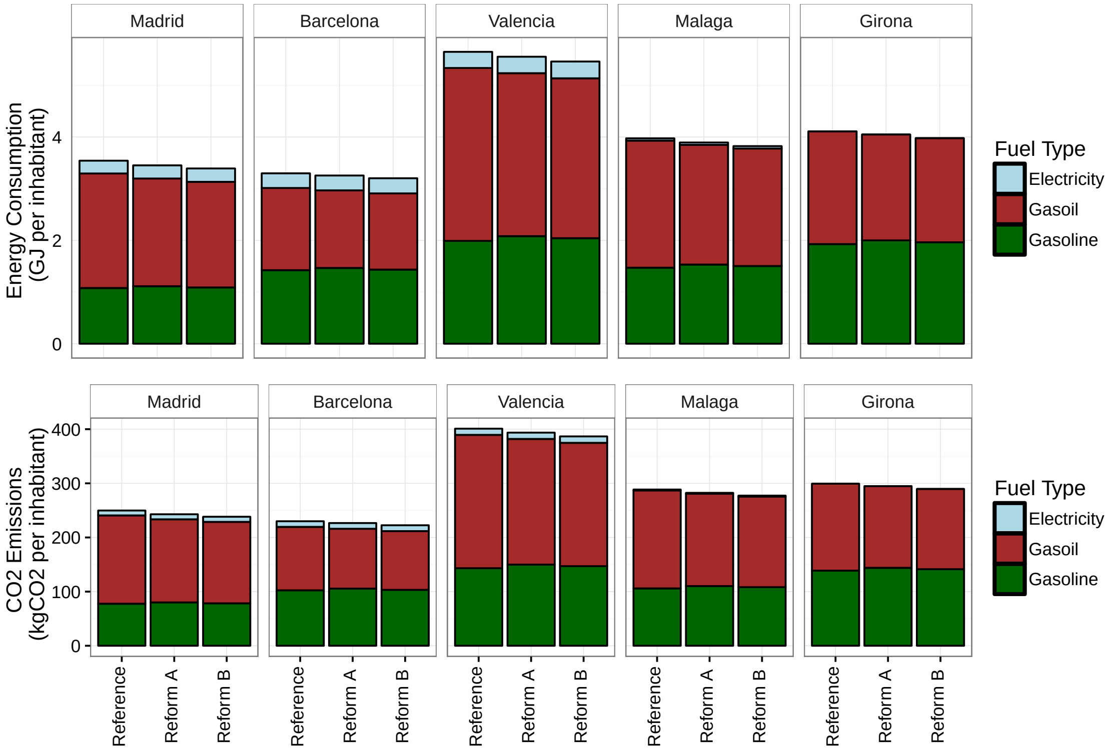

Fig. 7. Changes in per-capita energy consumption and CO_2 emissions.

Overall, these reductions may be considered modest, at least when compared with local carbon emission reduction plans.[1] As an example, our reference case accounts for 30% of carbon emissions compared to the official CO_2 Madrid regional emission inventory for 2012 (Comunidad de Madrid, 2016). According to the Madrid Regional Plan for emission reductions and air quality *Plan Azul +* (Comunidad de Madrid, 2014), the emission reduction proposal in the transport sector would need to be, for a 2020 horizon, of about 1,500 thousand tCO_2. Therefore, even the more ambitious reform B would only address 7.5% of the total reductions intended, thereby underlining the need

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[1] It has to be reminded that for the purpose of this paper, only metropolitan personal transport has been considered, leaving out long trips and all freight transport

to include other measures to reduce carbon emissions in metropolitan areas.

Results for Spain in Danesin and Linares (2015) show values for CO_2 savings around 1.3 million Tonnes (reform A) and 4.3 million Tonnes (reform B), far from the figures presented here, with simulated emission reductions in Madrid representing just less than 3% of the ones at the national level. However, the different setting (urban transport vs. national-level transport) and the different model lead to different results, probably also because of a better representation of the rebound effect and also due to allowing for shifting to alternative modes in the urban areas where total mobility is less elastic to changes in prices.

4.4. Differences between metropolitan areas

As may be seen in the previous section, there are large differences in the effects of the same policy when applied to different areas, even within the same size.

An example is the relative change of mobility under reform A, which is twice as large in Madrid as in Barcelona. These areas feature similar shares of public transport, as well as energy and carbon intensity. However, in Barcelona the energy share of diesel is smaller than in Madrid (48% vs 63%). Reform A, which de facto incentivizes the use of gasoline vehicles, has a higher impact on the overall mobility in those areas where diesel is more used, as in Madrid versus Barcelona.

In other areas, it is the lack of public transport that mostly influences results. The lack of options to shift away from diesel cars results in a larger reduction in mobility. For example, comparing simulation results for Barcelona and Valencia we find a larger mobility reduction in Valencia, in both relative and absolute terms.

This lack of flexibility is also seen in the reductions obtained in energy intensity. Table 7 provides a graphical representation of the energy intensity index for each area and the simulated changes after the reform. In this table, it is easily to notice that larger areas perform better also in energy intensity terms. After the implementation of the reforms, the improvements are lower in smaller areas such as Valencia (even less in Málaga or Girona), where the energy intensity of mobility goes from 2.00 MJ/pkm to 1.97 MJ/pkm (-2%), while in Barcelona it goes from 1.46 MJ/pkm to 1.42 MJ/pkm after reform B (-2.7%) and in Madrid the same measure goes from 1.48 MJ/pkm to 1.42 MJ/pkm (-4.1%).

Table 7
Changes in energy intensity

	Reference Total value (MJ / pkm)	Reform A Total value (MJ / pkm)	rel. change (%)	Reform B Total value (MJ / pkm)	rel. change (%)
Madrid	1.48	1.45	-2.03 %	1.42	-4.05 %
Barcelona	1.46	1.44	-1.37 %	1.42	-2.74 %
Valencia	2.01	1.99	-1 %	1.97	-1.99 %
Malaga	2.27	2.25	-0.88 %	2.24	-1.32 %
Girona	2.28	2.27	-0.44 %	2.26	-0.88 %

Here it can be seen that the flexibility that public transport provides, as well as a large share of diesel, make the fuel tax reform much more effective in the Madrid area than in the rest. As an example, in scenario B, diesel car usage decreases by 9% in Barcelona, similar to Madrid, while gasoline car usage increases by 1.8% in Madrid and 2% in Barcelona. Yet, in Madrid bus ridership increases by 4.6%, compared to just 2% in Barcelona; also, train usage shows a larger increase in

Madrid (+3.3%) than in Barcelona (+2.6%). In Valencia, however, the decrease of diesel car use is around 8% and gasoline increases by 3.3%, and while the use of buses and train grows by 2 and 4% respectively, their share is still just above 30%, making their contribution to the improvement in energy intensity not as effective as in Barcelona and Madrid.

Overall, changes in modal shares (table 8) follow the previous evidence: public transport grows equally for train, metro, and and bus, while the general decrease in private transport is inconsistent across modes, reflecting the different changes in fuel prices.

Table 8
Modal shares simulation results.

	Bus	Train/Train	Tot. Public	Gas. Car	Die. Car	Moto	Tot. Private
Madrid							
Reference	18.86%	32.13%	51.00%	14.54%	30.40%	4.06%	49.00%
Reform A	19.45%	32.88%	52.33%	15.20%	28.42%	4.05%	47.67%
Reform B	19.87%	33.42%	53.29%	14.90%	27.82%	3.99%	46.71%
Barcelona							
Reference	15.07%	36.03%	51.10%	16.92%	21.67%	10.31%	48.90%
Reform A	15.23%	36.50%	51.73%	17.71%	20.24%	10.33%	48.27%
Reform B	15.47%	37.18%	52.65%	17.36%	19.82%	10.17%	47.35%
Valencia							
Reference	6.97%	22.39%	29.36%	23.90%	41.76%	4.98%	70.64%
Reform A	7.09%	22.98%	30.07%	25.36%	39.54%	5.03%	69.93%
Reform B	7.23%	23.66%	30.89%	25.08%	39.05%	4.99%	69.11%
Malaga							
Reference	11.34%	5.41%	16.75%	26.39%	48.26%	8.61%	83.25%
Reform A	11.63%	5.65%	17.28%	28.10%	45.88%	8.75%	82.72%
Reform B	11.92%	5.88%	17.80%	27.92%	45.54%	8.73%	82.20%
Girona							
Reference	13.81%	−−	13.81%	33.23%	41.36%	11.60%	86.19%
Reform A	14.12%	−−	14.12%	35.13%	39.02%	11.73%	85.88%
Reform B	14.56%	−−	14.56%	34.95%	38.78%	11.71%	85.44%

One interesting result is that, as a result of reform B, the total share for Madrid public transport (53.3%) is larger than in Barcelona (52.7%), reverting the result for the reference scenario (51.0% in Madrid and 51.1% in Barcelona). This again highlights the importance of the initial conditions in the application of the reforms. Otherwise results show consistency, suggesting a shift toward public transport and gasoline-powered vehicles, with changes being as large as 3 percentage points, therefore indicating a small impact on mobility patterns. Moreover, the relative changes are lower in smaller areas, due to the scarce availability of alternatives.

Finally, simulation results also reveal important differences between urban and suburban areas. The general patterns described above are more evident in suburban locations, where the shift towards public transport and gasoline appears to be at least 4 times larger with respect to the urban case. The increase in use of urban public transport (metro and buses) in Madrid (reform A) is just under +0.5%, while for suburban public transport (buses and train) it reaches +3.5%. Reform B show similar results, with the increase in suburban public transport being larger than 5% in Madrid, Málaga, and Valencia, compared to changes around 1% in the urban context. This evidence can be easily related to the fleet composition, different in the urban and suburban contexts, as observed in Asensio (2002) and mentioned earlier.

4.5. Implications for welfare

Welfare change results also show how the impact of the reform varies across metropolitan areas. First, it has to be reminded that the welfare measure includes a monetary measure of the consumers' utility, and the internal and external costs associated to it, the latter including emissions of local pollutants and CO_2, accidents and time loss, all linear with respect to the provision of the service. In Madrid, the absolute variation is a loss of about 52 million Euros-equivalent for reform A, and a loss of 91 million for reform B. In Barcelona the loss is lower, being around 16 and 40 million Euros, respectively. Valencia shows figures close to Barcelona, with a loss of 16 million Euros in reform A, and 33 in reform B. The relative change, however, is small in all the cases, less than 0.03% of GDP.

Interestingly, and in line with our earlier comments about the flexibility of transport modes, welfare loss is not necessarily related to emissions reductions or reductions in mobility. For example, the largest relative losses correspond to Valencia, which is not the area with the largest reductions in mobility or emissions. This is a sign of the little flexibility of this area to accommodate the changes induced by the fuel tax reform. In turn, Barcelona features a very small welfare loss, at the same time being able to reduce its carbon emissions even more than Valencia.

Table 9
Changes in welfare

	Reform A Abs. variation, Mill. EU (rel. %)	Reform B Abs. variation, Mill. EU (rel. %)
Madrid	-52.11 (-0.03%)	-91.38 (-0.05%)
Barcelona	-16.03 (-0.01%)	-40.39 (-0.03%)
Valencia	-14.42 (-0.04%)	-32.80 (-0.09%)
Malaga	-7.53 (-0.04%)	-15.44 (-0.09%)
Girona	-0.90 (-0.02%)	-2.50 (-0.05%)

It is interesting to note that this estimation of welfare is largely influenced by a probably overlooked fact: that public transport is heavily subsidized. Therefore, under a static analysis, an increase in public transport usage will also increase public subsidies.

Table 9 shows how the positive effects of the reform regarding economic and fiscal revenues are mitigated by the modal shift towards public transportation. As an example, the results for Madrid (reform B) show an increase of about 550 million Euros in net tax revenues. But, breaking down this result, it is easy to observe that the additional revenues from diesel and gasoline (+692 million Euros) are reduced by the additional subsidies necessary to cover the increased demand in public transport that, in this case, reach 141 million Euros. Comparing the metropolitan areas of Barcelona and Valencia, it is interesting to observe that the increase in tax revenues from fuel is somehow similar: +120 million Euros in Barcelona and +121 million Euros in Valencia, according to reform A. However, considering the same reform, the increase in subsidies is markedly different, being +25 million Euros in Barcelona, due to the larger availability in public transport, versus only +2 million Euros in Valencia. Again, we see that the initial conditions regarding fleet composition and availability of public transport determine to a large extent the results for welfare. Of course, this might not be the case if the larger use of public transport improves its profitability and reduces the need for subsidies.

Previous research such as Proost et al. (2002) shows how far are current transport pricing schemes in urban areas from efficiency, with examples for London, Brussels, Dublin, and Amsterdam. There, an efficient policy (that would include tax revenues) would result in an improvement from 0.5% to 1.3%, with revenues increasing in the range between 108 million ECUs (London) and 171 ECUs (Amsterdam). The different sign of the welfare change on our results relates to both the purpose of policy (local vs. national level) the direct inclusion of tax revenues and the better representation of the congestion effect.

Another example for the Spanish context, and in particular for Madrid, is the experiment of the implementation of a congestion charge in Guzman et al. (2014). The welfare changes, which are positive, include the toll revenues and the land use changes, as well as the time savings. The model, which is dynamic, shows how the timeframe for implementing a congestion charge is important as, in their experiment, the overall welfare gains reached +120 Million Euros per year (after 25 years of implementation) although in the short term it shows a welfare loss (-20 Million Euros), similar to the results of this paper.

Table 10
Simulation effects on taxation.

	Fuel Tax Change		Subsidies Change		Net Tax Change	
Met. Area	Reform A	Reform B	Reform A	Reform B	Reform A	Reform B
Madrid	+401.67	+692.22	−81.50	−141.05	+320.18	+551.17
Barcelona	+119.69	+303.65	−24.23	−60.96	+95.46	+242.69
Valencia	+121.50	+260.46	−1.99	−4.58	+119.51	+255.88
Malaga	+61.90	+123.30	−1.26	−2.58	+60.64	+120.72
Girona	+10.36	+24.93	−0.49	−1.24	+9.87	+23.69

Finally, we should also mention that our results are quite robust to the specification of the elasticities in the model. As suggested by other authors Schäfer (2012) we run the model for changes in demand elasticities between +50% and -9% of the original ones.

According to this sensitivity analysis, the total reduction in mobility in the Madrid metropolitan area lies between -0.4% and -0.59% under reform A, or between -0.66% to -0.96% under reform B. In Barcelona the range lies between -0.2% and -0.31% for reform A and -0.5% and -0.75% for reform B. For CO_2 emissions the range is a bit wider: the emission savings in Madrid vary from 62 thousand tCO_2 when assuming a less elastic demand to 99 thousand tCO_2 when assuming a more elastic demand, with the difference widening to 62 thousand tCO_2 in reform B (-102 to -164 thousand tCO_2).

5. Conclusions and policy implications

The transport sector is critical for achieving carbon emission reduction goals. However, given its relevance for social welfare, a careful analysis of the implications of the policies required to achieve these reductions is crucial. Indeed, this consideration of social welfare may not only have a positive effect on the efficiency of the emissions reductions but can also improve the public acceptability of these policies, thus easing their implementation. Local conditions here become essential, since the characteristics of local fleets, the availability of public transport, and other issues, may have a large influence on welfare changes and therefore on the effectiveness and acceptability of transport policies.

In this paper, we have assessed the impacts on mobility, energy use, carbon emissions, and welfare of a fiscal reform that would increase tax rates for gasoline and diesel. In particular, we study the effects on metropolitan areas, due to their prominent role in this regard, and also to assess the dependence of the impacts on the local configuration.

Our results show that this reform can achieve reductions in carbon emissions and energy use, but at a certain cost in terms of welfare. Another very relevant conclusion is that, as suspected, the costs and benefits of the policy will depend on the characteristics of the metropolitan area, and more specifically, on the fleet composition and the public transport availability.

The higher taxes simulated induce a decrease in transport demand that lies between -0.22% and -2.70% depending on the area and the strength of the tax reform. Modal shares also change: diesel cars reduce their share and the use of gasoline cars and public transport increases. As a result, energy use and carbon emissions are also reduced. However, the reduction in energy use depends again on the metropolitan area. Madrid, highly reliant on diesel, and with a significant availability of public transport, shows a total decrease of 4.3% when applying the stronger reform, while Barcelona, with a similar share of public transport, but a lower penetration of diesel cars, only achieves 2.9%. In smaller areas, this reduction is less pronounced, mostly due to the lower share of public transport. This lack of flexibility results in both a larger reduction in mobility (given that shifts to public transport are not an option) and also in less improvement in energy and carbon emissions intensity.

The results also show increased tax revenues, up to 550 million Euros in Madrid, but lower consumers' welfare, approximately 90 million Euro-equivalent in Madrid and 40 million Euro-equivalent in Barcelona. This comes partly from the fact that the increased revenues coming from the increased gasoline and diesel taxes are sensibly counteracted (by over 20%), by the higher subsidies implied by the increase in public transport.

Again, the lack of energy-efficient options (such as public transport) in smaller metropolitan areas is revealed: these areas feature larger welfare losses for smaller reductions in carbon emissions and energy use, even considering that less public transport also means lower subsidies to add to maintain the same service level.

These results may be applicable to similar metropolitan areas, although of course only if they are similar in terms of energy and carbon intensity and of transport modal shares to the ones studied here. However, we believe that the central messages and conclusions of this research are broadly applicable, given the different contexts we have analyzed in our research.

A first general message is that this reform will be more effective the more options are available to shift away from diesel vehicles. That means mainly public transport modes, particularly those fueled by electricity (e.g. metro). Of course, the larger the share of diesel, the larger are the expected reductions in energy use. And finally, welfare losses are lower the more flexibility there is in the metropolitan area regarding transport modes.

However, it is important to notice that the simulated reform will do little to reduce environmental impacts, and may result in lower welfare for consumers. Our results show that this tax increase would only address around 7.5% of the total reductions required. Therefore, even in the metropolitan areas more receptive to it, other measures and policies will be required.

These measures and policies could indeed be complementary: for example, creating more public transport alternatives could facilitate shifting between modes, hence reducing emissions with lower impacts on overall mobility. Other measures would need to cover other aspects: for example, careful urban planning could reduce the demand for car mobility or substitute it with walking or bicycles; incentives for renewing the car fleet could also reduce overall emissions. Probably all of these measures, and then some, will be required to cut significantly emissions in urban environments.

Of course, our analysis has certain limitations that should be highlighted. We have not considered the dynamic effects that this reform may induce in the fleet composition and the introduction of new technologies. We are not able either to represent the interactions of these policies with a wider energy sector framework, which could be achieved by integrating our model into a more comprehensive energy model.

However, our major messages regarding the policy implications of our study remain valid. First, the stringency of fuel tax reforms or other price mechanisms to reduce the use of diesel cars should be carefully adapted to the availability of options in each urban area. When these options are not readily available, the welfare costs of the policies may become significant, hence affecting their public acceptability. Therefore, other policies that increase sustainable transport options should be prioritised before tax reforms implementation. Second, the effectiveness of fuel tax reforms is limited, in that they can only produce a small fraction of the carbon emissions reductions required. Again, other policies may be required to achieve the desired objectives.

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Appendix A. Model Description

Appendix A.1. Notation

Indices.

k	technology
f	fuel type
m	transport mode
NT	non-transport good
i_0	commodities, including both l and NT
i **and** j	utility component index, such that, if $i \in l$ the utility component i is associated with the final mode l
n	utility component level, with $n \in \{0, \ldots, N\}$ and $n = 0$ level of commodities, and $n = N$ the level of the overall utility.

Parameters.

$\alpha_{n-1,j}$	share between closely associated components, takes values between 0 and 1, and such that $\sum_{j\in i}\alpha_{n-1,j}=1$.
$\sigma_{n,i}$	elasticity of substitution, takes only positive values
$\rho_{n,i}$	transformation of σ, namely $(\sigma_{n,i}-1)/\sigma_{n,i}$
Y	total income [eur]
p_{NT}	exogenous price of non-transport good used as a numeraire
τ_m	tax rate (if negative, considered as subsidy)
o_m	occupation rate [pkm/vkm]
$c_{m,k,f}$	variable internal cost [eur/vkm]
$e_{m,k,f}$	variable external cost [eur/vkm]
$\bar{k}_{m,k}$	technology upper boundary [vkm]
$\bar{f}_{m,k,f}$	tech-fuel upper boundary [vkm]

Decision variables.

$v_{m,k,f}$	supply level for each fuel-tech combination [vkm]
x_m	transport demand for each mode [pkm]
x_{NT}	non-transport demand

Auxiliary variables.

p_m	pre-tax market prices [eur/pkm]
$q_{n,i}$	utility component value
$\phi_{n,i}$	aggregate price associated with the utility component

Dual variables.

$\nu^{\hat{k}}_{m,k}$	associated with the technology constraint
$\nu^{\hat{f}}_{m,k,f}$	associated with the fuel-tech constraint
ν^{x}_{m}	associated with the demand fulfilment
λ^{y}	associated with the budget constraint

Appendix A.2. Supply

Appendix A.2.1. Objective function

Here follows the cost minimisation objective function faced by the producers:

$$\min_{v_{m,k,f}} \sum_{m,k,f} c_{m,k,f} \cdot v_{m,k,f} \tag{A.1}$$

Appendix A.2.2. Constraints

In this section we present the constraints affecting the provision of transport goods. The first depend on the fleet composition and on the infrastructure that can handle certain amounts of traffic and travel. The second is affected by the fuel availability and its storage, as for plug-in electric hybrid vehicles. the last constraint tell the producer to provide at least the quantity demanded in the market. This is a reasonable constraint if we want to resemble a profit-maximization environment without introducing it in the problem.

$$\sum_{f \in k} v_{m,k,f} \leq \bar{k}_{m,k}, \; \forall (l,k) \tag{A.2}$$

$$v_{m,k,f} \leq \bar{f}_{m,k,f}, \; \forall (l,k,f) \tag{A.3}$$

$$x_m \leq o_m \sum_{(k,f) \in l} v_{m,k,f}. \forall l \tag{A.4}$$

Appendix A.2.3. Lagrangian for supply

Dual variables in section Appendix A.1 are associated with equations (A.2), (A.3), and (A.4). Together with the minimization problem in (A.1), we construct the supply problem lagrangian $\mathcal{L}_S$ as follows:

$$\mathcal{L}_S : \sum_{m,k,f} c_{m,k,f} \cdot v_{m,k,f} + \nu^{\hat{k}}_{m,k} (\sum_{f \in k} v_{m,k,f} - \bar{k}_{m,k}) + \nu^{\hat{f}}_{m,k,f} (v_{m,k,f} - \bar{f}_{m,k,f}) + \nu^{x}_{m} (x_m - o_m \sum_{(k,f) \in l} v_{m,k,f}). \tag{A.5}$$

Appendix A.3. Demand

Appendix A.3.1. Objective function

The aggregate consumer's problem is to maximise her utility, facing market prices p_m. The problem is developed hereafter, with the structure of $U(x_m, x_{NT})$ as in section Appendix A.3.4

$$\max_{x_m, x_{NT}} U(x_m, x_{NT}). \tag{A.6}$$

Appendix A.3.2. Budget Constraint

The only constraint affecting the consumer is the budget constraint, that limit the overall expenditure to the exogenous income and profits from the producing firms, here supposed to be owned by the consumer. It is worth noting that market prices faced by the consumer is constructed from the pre-tax prices p_m faced by the producers, corrected by the exogenous tax rate τ_m. Moreover the producing firms are owned by the same consumers, that receive the profits, thus increasing their budget.

$$p_{NT} x_{NT} + \sum_m (1 + \tau_m) p_m x_m \leq Y + \sum_{k,f \in l} (o_m \cdot p_m - c_{m,k,f}) v_{m,k,f}. \tag{A.7}$$

Appendix A.3.3. Lagrangian for demand

After associating the multiplier λ^y to the budget constraint in (A.7), we then construct the lagrangian $\mathcal{L}_D$ as follows:

$$\mathcal{L}_D : -U(x_m, x_{NT}) + \lambda^y \big[p_{NT} x_{NT} + \sum_m (1+\tau_m) p_m x_m - Y - \sum_{k,f \in l} (o_m \cdot p_m - c_{m,k,f}) v_{m,k,f} \big]. \quad \text{(A.8)}$$

Appendix A.3.4. Auxiliary equations

Utility function presented in section Appendix A.3.1 follows the nested CES presented in Keller (1976), and hereafter developed:

Utility Function.

$$U(x_m, x_{NT}) = q_{N,i}, \quad \text{(A.9)}$$

$$x_m = q_{0,i \in l}, \quad x_{NT} = q_{0,i \in NT}, \quad \text{(A.10)}$$

$$q_{n,i} = \Bigg[\sum_{n-1,j} \alpha_{n-1,j}^{(1-\rho_{n,i})} q_{n-1,j}^{\rho_{n,i}} \Bigg]^{1/\rho_{n,i}}. \quad \text{(A.11)}$$

Aggregate prices and expenditure.

$$\phi_{n,i} q_{n,i} = \sum_{j \in i} \phi_{n-1,j} q_{n-1,j} \quad \text{(A.12)}$$

with,

$$(1+\tau_m) p_m = \phi_{0,i \in l}, \quad p_{NT} = \phi_{0,i \in NT} \quad \text{(A.13)}$$

Deriving the Utility Function.

$$U'_{x_{NT}} = \frac{\partial U}{\partial x_{NT}} = \frac{\partial q_{N,NT}}{\partial q_{0,NT}} = \frac{\partial q_{N,NT}}{\partial q_{N-1,NT}}, \quad \text{(A.14)}$$

$$U'_{x_m} = \frac{\partial U}{\partial x_m} = \frac{\partial q_{N,l}}{\partial q_{0,l}} \quad \text{(A.15)}$$

$$= \frac{\partial q_{N,l}}{\partial q_{N-1,l}} \cdot \frac{\partial q_{n-1,l}}{\partial q_{n-2,l}} \cdots \frac{\partial q_{1,l}}{\partial q_{0,l}} \quad \text{(A.16)}$$

$$= \prod_{n=1}^{N} \frac{\partial q_{n,l}}{\partial q_{n-1,l}}, \quad \text{(A.17)}$$

that, deriving from the (A.11), will lead to:

$$\frac{\partial q_{n,l}}{\partial q_{n-1,l}} = q'_{n-1,l} = \left(\frac{\alpha_{n-1,j}}{q_{n-1,j}} \right)^{1-\rho_{n,i}} \Bigg[\sum_{n-1,j} \alpha_{n-1,j}^{(1-\rho_{n,i})} q_{n-1,j}^{\rho_{n,i}} \Bigg]^{\frac{1-\rho_{n,i}}{\rho_{n,i}}}. \quad \text{(A.18)}$$

Appendix A.4. The Market Clearing

Under this setting, market clearing condition state that pre-tax market prices p_m will equal the marginal costs for providing one more unit in mode l, represented by dual variable ν_m^x:

$$p_m = \nu_m^x \quad \text{(A.19)}$$

Appendix A.5. The Mixed Complementarity Model

Stationary Conditions and associated complentary slackness:. Finding the market equilibrium implies deriving the production and the consumption bundles and market prices $(v^*_{m,k,f}, x^*_m, x_{NT}, p^*_m)$ such that the problem for the both producers and consumer are solved, and market is cleared. This imply first that decision variables are perpendicular to their respective problems, as stated in the stationary conditions that follow:

$$0 \le v^*_{m,k,f} \perp \frac{\partial \mathcal{L}_S}{v^*_{m,k,f}} : c_{m,k,f} + \nu^{\hat{k}}_{m,k} + \nu^{\hat{f}}_{m,k,f} - o_{m\ni(l,k,f)} \cdot \nu^{x}_{m\ni(l,k,f)} \ge 0. \tag{A.20}$$

$$0 \le x^*_{NT} \perp \frac{\partial \mathcal{L}_D}{x^*_{NT}} : -U'_{x^*_{NT}} + \lambda^y p^*_{NT} \ge 0, \tag{A.21}$$

$$0 \le x^*_{m} \perp \frac{\partial \mathcal{L}_D}{x^*_{m}} : -U'_{x^*_{m}} + \lambda^y (1-\tau_m) p^*_{m} \ge 0 \tag{A.22}$$

Feasibility and associated complementary slackness:. Feasibility of the bundles in both consumption and production is a necessary condition for the equilibrium and, for this, constraints presented in sections Appendix A.2.2 and Appendix A.3.2 must hold, and so perpendicularity of the dual variables associated to these constraints (complementary slackness). The last condition is the market clearing, leading to prices equal to the marginal cost of each final mode l.

$$0 \le \nu^{\hat{k}}_{m,k} \perp \frac{\partial \mathcal{L}_S}{\nu^{\hat{k}}_{m,k}} : \bar{k}_{m,k} - \sum_{f\in l,k} v^*_{m,k,f} \ge 0, \tag{A.23}$$

$$0 \le \nu^{\hat{f}}_{m,k,f} \perp \frac{\partial \mathcal{L}_S}{\nu^{\hat{f}}_{m,k,f}} : \bar{f}_{m,k,f} - v^*_{m,k,f} \ge 0, \tag{A.24}$$

$$0 \le \nu^{x}_{m} \perp \frac{\partial \mathcal{L}_S}{p^*_{m}} : o_m \cdot \sum_{(l,k,f)\in l} v^*_{m,k,f} - x^*_m \ge 0. \tag{A.25}$$

$$0 \le \lambda^{Y} \perp \frac{\partial \mathcal{L}_D}{\lambda^{Y}} : Y - p^*_{NT} x^*_{NT} - \sum_{m} (1 + tau_m) p^*_m x^*_m + \sum_{k,f\in l} (o_m \cdot p_m - c_{m,k,f}) v_{m,k,f}; \tag{A.26}$$

$$0 \le p^*_m \perp p^*_m = \nu^x_m. \tag{A.27}$$

Appendix A.6. Assessing Welfare

To quantitatively assess welfare W, we first identify the components that sum up, that are consumer's utility U and the external costs. The Utility is reduced to monetary terms dividing it by μ, that is the marginal utility of income. The value of μ is derived within the algorithm by applying marginal changes to income. Profits are not included and neither are the revenues from taxation.

$$W = 1/\mu \cdot U(x_m, x_{m,k,f}) - \sum_{m,k,f} e_{m,k,f} \cdot v_{m,k,f} \tag{A.28}$$