Electric vehicle diffusion in the Portuguese automobile market

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ABSTRACT
The present research focuses on electric vehicles as part of the Portuguese policy to make the transportation system more energy efficient and environmentally friendly. The main goal is to estimate the fleetwide energy consumption and corresponding carbon dioxide emissions up to 2030 and examine to what extent the introduction of electric vehicles will reduce those indicators. A system dynamics model of the Portuguese car fleet was developed that captures the interrelationships between the main drivers of the system while simulating the car owners’ behavior when selecting technologies. To analyze the evolution of energy consumption and carbon emissions, a scenario analysis is followed. In addition, a series of transportation policy instruments is tested in each scenario in order to analyze reduction effectiveness of emissions and increasing diffusion of electric vehicles. We concluded that a fast-growing economy is the best scenario to decrease energy consumption mostly due to the expected increase in fuel efficiency of the car stock deriving from a faster technological turnover of internal combustion engine vehicles. Regarding transportation policy instruments, the increase in the tax applied to fossil-fuel sales as well as applied to conventional vehicles’ sales are the most efficient policies to increase the diffusion of electric vehicles. Importantly, according to our results, the uptake of electric vehicles is expected to be rather low (less than 10% of new cars until 2030), regardless of the scenario or transportation policy analyzed.

1. Introduction

As defined by the Intergovernmental Panel on Climate Change, climate change refers to any change in the climate due to both natural variability and human activity (IPCC, 2007). Climate change is one of the major concerns today because it is an environmental, social, and economic threat to both the planet and humankind. The main cause of climate change, global warming, is triggered by the rapid increase of greenhouse gas (GHG) emissions to the atmosphere mainly from anthropogenic activities. According to the IPCC (2007), annual global CO2 emissions grew between 1970 and 2004 by about 80% and represented 77% of total anthropogenic GHG emissions in 2004.

As Portugal’s economy has grown in recent decades, so has energy demand and, consequently, GHG emissions. In 2010, Portuguese GHG emissions without land use, land use change, and forestry were estimated at about 70 Mt CO2eq, which represents an increase of 17% compared with 1990 levels, with carbon dioxide having the highest atmospheric concentration, representing 75% of total GHG emissions (expressed as global warming potential—GWP—weighted emissions). According to the Portuguese National Inventory Report on Greenhouse Gases 1990–2010 (APA, 2012), energy is the highest emitting sector, accounting for 70.3% of total GHG emissions in 2010. Energy-related activities are responsible for about 92% of the total CO2 emissions as, during the period 1990–2010, 83% of the primary energy consumed was produced from fossil-fuel combustion (APA, 2012). Energy supply industries and transport are the two most important sources inside the energy sector, corresponding to 47.8% of total emissions (67.5% of the energy sector’s emissions). The emissions of these sectors have grown steadily due to the continued increase in electricity demand, driven by residential and commercial buildings and the growth of mobility.

Transportation has had an 84% increase in exhaust GHG emissions (90.4% increase in CO2 emissions) since 1990 (APA, 2012). The increase in road traffic is mainly due to the rapid growth in private car ownership and road travel both associated with the increase in household income and supported by the strong development of road infrastructure.

The Kyoto Protocol (United Nations, 1998) introduced legally binding targets for developed countries to reduce their collective GHG emissions by at least 5.2% below their 1990 level by the first commitment period of 2008–2012 (8% collective European Union reduction).

The present research focuses on the transportation sector, and more specifically, on electric drive vehicles (EDVs)—both battery-electric and hybrid vehicles), as part of the Portuguese policy to make the transportation system more energy efficient and environmentally friendly. The main goal of this research is to analyze to what extent battery-electric vehicles (BEVs) are
expected to diffuse in the Portuguese car fleet and to estimate
the resulting fleet-wide energy consumption and corresponding
life-cycle carbon dioxide emissions up to 2030. Life-cycle analy-
sis includes “well-to-tank” and “tank-to-wheel” emissions and
excludes those from car production because these account for a
smaller amount of total emissions—less than 15% (Chester &
Horvath, 2008, 2009; Costa, 2012). Both energy consumption
and CO₂ emissions evolution are estimated through a system
dynamics model of the Portuguese car fleet that includes,
among others, the following variables: macro-socioeconomic
drivers (demography and GDP), motorization rate, modal
share, energy costs, vehicle costs, taxes and subsidies, techno-
logical structure of the fleet (concerning both vehicle and fuel
technologies) and the annual mileage of vehicles. We account
for CO₂ emissions only because they make up almost 100% of
the total road transport emissions (APA, 2012).

To analyze the evolution of energy consumption and carbon
emissions, a scenario analysis procedure is followed. Alternative
scenarios to assess the future are used in which a scenario is a
consistent version of the future. In the present research three
scenarios are studied: “Clean but not sparkling,” “Dynamic but
careless,” and “Bright skies.” Each scenario is defined by a state
in economic growth, directly linked with technological change,
and attitudes toward the global environment based on those
defined in the International Energy Agency’s report Energy to
2050: Scenarios for a Sustainable Future (IEA, 2003).

Furthermore, a series of transportation policy instruments
will be implemented in each scenario in order to observe which
is the most efficient in decreasing total emissions and increas-
ing the diffusion of BEVs. These policies are mainly applied to
the taxation system: tax on petroleum products increase, vehi-
cle purchase tax increase, and vehicle circulation tax increase.
Regarding the “Bright skies” scenario, two further policies will
be applied due to its assumptions: diffusion of fast charge sta-
tions for BEVs encouragement and an urban sprawl control
policy.

A differential analysis of energy and carbon intensities as
well as the structure of the vehicle fleet is performed for 2030,
by which we examine the effectiveness of each implemented
policy compared with the “do nothing” baseline scenario.

This paper is organized into six sections. The literature
review presented in section 2 overviews vehicle fleet and car
choice models, the main results and conclusions of several
transportation policy surveys, and how these can be modeled.
In section 3, a detailed description of the developed model is
presented followed by the model validation. Section 4 presents
a detailed description of the scenarios analyzed as well as the
transportation policy instruments tested here. The final results,
as well as their discussion, are presented in section 5. The final
conclusions are drawn in section 6.

2. Literature review

There are different methodological approaches to evaluate the
energy and environmental performance of the transport and
energy sectors. The TREMOVE model (Transport and Mobility
Leuven, 2007) studies the effects of transport and environmen-
tal policy instruments on the transport sector’s emissions. Other
approaches, such as general equilibrium models for
energy analysis, assume that energy demand for transportation
(and other sectors) is supplied by the best available technologies
(BAT) following a cost-effectiveness criteria and according to
the existing BAT capacity. These are generally optimization
models, where the objective is to minimize the total discounted
costs of the overall system in the long term. These do not con-
sider stochastic demand behavior issues in their methodological
approach. Some examples of such approaches are: MARKAL
(Loulou, Goldstein, & Noble, 2004), the integration of MAR-
KAL with TIMES (Loulou, Remn, Kanudia, Lehtila, & Gold-
stein, 2005), TIMES_PT (E.VALE and CENSE, 2010; Simões,
Cleto, Fortes, Seixas, & Huppes, 2008) and GAINS (IIASA,
2005).

The model developed in the present research focuses on the
evolution of the Portuguese passenger car fleet. Similarly to the
TREMOVE model, it aims to study the effects of several policy
instruments on the final technology distribution of the fleet.

2.1 Vehicle fleet modeling

Numerous researchers have approached car ownership modeling
from several viewpoints and therefore with different methods. The broad categories can be distinguished between:

- economic approaches, using financial parameters as
  explanatory variables;
- system dynamics that approach the problem in a causal-
  ity-driven and analytical manner; and
- engineering approaches, which being primarily based on
  empirical analysis, account only implicitly (if at all) for
  the influence of explanatory variables (e.g., financial) and
  usually are less sophisticated.

Jong, Fox, Pieters, Daly, and Smith (2004) performed a com-
prehensive literature review of existing car ownership models
for the Dutch Ministry of Transport, Public Works, and Water
Management. In the context of analyzing the dynamics of evo-
lution of technological change in transport, Grübler (1990)
reviews extensively the formal characteristics and properties of
various growth, diffusion, and substitution aggregate models.
Grübler’s approach focuses more on “biological models” that fit
into the more aggregate engineering approach referred to ear-
lier (and, thus, not detailing the types of technologies; for exam-
ple, he refers to “cars” generically and not to the numerous
models available). The following authors focus mainly on eco-
nomic approaches and detail the qualitative choice model (pos-
sibly, these authors are more interested in the “makes and
models” of cars).

Ben-Akiva and Lerman (1985) and Train (1986, 2003) pres-
ent methods of qualitative choice analysis and, more particu-
larly, Train (1986) suggests a car ownership model that
explores the consumer demand for automobiles. Likewise,
Ortúzar and Willumsen (2002) and Hensher and Button
(2000) present in their handbooks (“not so deep”) reviews of
the principal methods for modeling car ownership, while cover-
ning discrete choice mathematical methods applied to other
transport modeling problems (e.g., modal split). Apart from
these authors, many others have dedicated their research to
modeling car ownership since the 1960s, using single methodo-
logical approaches for specific case studies. For instance, Mog-
ridge (1967) developed an econometric model that relates car
ownership of households to income and uses national income distribution and its growth to predict future car stock evolution. More recently, many publications have addressed the issues of car ownership of alternative-fuel vehicles (including EDVs) from different perspectives, but generically using econometric modeling techniques (Brownstone & Train, 1998; Choo & Mokhtarian, 2004; Greene, 2001; McFadden & Train, 2000; Train & Winston, 2007; among others).

According to Jong et al. (2004), in aggregate time series models the development of car ownership over time (as a function of income or GDP) is modeled by a sigmoid-shape function (slow increase in the beginning followed by a steep rise and by the end approaches a saturation level). Static disaggregate car-type choice models forecast the composition of the car fleet and include discrete choice models that deal with the choice of car type of a household, given some car ownership.

Generically, we follow the methodological approach from Moura (2009) that combined an aggregate time series model with a static disaggregate car-type choice model to forecast the technological turnover of the car stock. Importantly, we include explicitly the EDV alternatives in the choice set of new cars, which Moura (2009) did not differentiate from other powertrain types. The choice of vehicle attributes, used to develop our static disaggregate car-type choice model, was based on the work of several authors presented in Table 1.

### 2.2 Transportation policies

Scrapage schemes are one of the main strategies to reduce emissions because they accelerate the removal of older vehicles from circulation. These schemes should be designed taking into account the pollutants targeted to be reduced. Kim, Ross, and Keoleian (2004) conclude that scrapage schemes are ideal to reduce regulated emissions (CO, NOₓ, NMHC) but not CO₂ emissions from a life-cycle emissions perspective. Regarding the implementation time, it is suggested that these schemes are only temporarily effective when there are many “dirty” vehicles (Kim et al., 2004) and so should be implemented as a “one-shot” program. Permanent scrapage schemes may even have negative environmental effects (OECD, 1999). Cash-for-scrapage schemes were found to be more efficient than cash-for-replacement ones because they do not have any obligations concerning the replacement choice (OECD, 1999).

An alternative is changing the structure of the taxation system (OECD, 1999). As stated in Cleaner Cars: Fleet Renewal and Scrapage Schemes (OECD, 1999), the German experience showed that the annual taxation of older vehicles according to their emissions characteristics can accelerate the replacement of old vehicles. Enhancing inspection and maintenance programs, particularly the environmental component, can also encourage the replacement of a vehicle if its operation becomes too costly. A final alternative is replacing vehicle parts that may be responsible for the low environmental performance of the vehicle instead of replacing it entirely (Moura & Viegas, 2009).

According to Eggers and Eggers (2011), there are limitations to the adoption of alternative fuel vehicles if there are no incentives or regulations that may include tax reductions, the development of public charging stations, and the education of vehicle buyers about environmental consciousness. Ohta, Fujii, Hishimura, and Kozuka (2013) conclude that providing information regarding eco-cars in Japan, namely their prevalence, has a significant positive effect on their acceptance. A feebate system to switch to more energy-efficient vehicles while keeping the same vehicle size was found to achieve a (3.1%–3.3% and a 2.8%–3.3%) reduction in fuel consumption and CO₂ emissions, respectively, without significant market disturbance (De Haan, Mueller, & Scholz, 2009). A 33% reduction in hydrocarbon emissions can be achieved when the combination of feebate systems with scrapage programs is implemented (BenDor & Ford, 2006). This research focuses only on hydrocarbon emissions but can be expanded to represent carbon dioxide emissions. Mabit and Fosgerau (2010) conclude that if BEV tax reductions were to be implemented, these vehicles could reach a market share similar to ICE vehicles. All implemented policies meant to introduce cleaner technologies must be strong and stay in force for extended periods of time in order to let them develop until they can compete with the conventional ones (Köhler et al., 2009).

There are also policies to reduce emissions involving lifestyle changes that include switching to public transports or even to slow modes such as cycling or walking, switching to homeworking (ICT), and creating mixed-zone developments, which decrease the demand for transport. Köhler et al. (2009) conclude that technological transitions are more likely to occur than lifestyle changes. Neither technical measures, modal shift to public transport, or any other transport policy measure are effective alone. A combined strategy is needed in order to fulfill the needs of sustainability, where multi-instrumentality has a high potential to enhance the success of transport policy implementation (Potter, 2007; Vieira, Moura, & Manuel Viegas, 2007).

### Table 1. Main attributes used to analyze car type choice.

| Probabilistic models | Other approaches |
|----------------------|------------------|
| Beggs and Cardell, 1981 | Lieven et al., 2011 |
| Ordered logit model | Eggers and Eggars, 2011 |
| Calfee, 1985 | Stated preferences survey |
| Probabilistic choice model | Critical factors |
| Mabit and Fosgerau, 2011 | Hidrue et al., 2011 |
| Mixed logit with random effects | |
| Lieven et al., 2011 | |
| Latent class random utility model | |
| Eggers and Eggars, 2011 | |
| Stated preferences survey | |
| Initial price, fuel cost, gasoline/battery powered, full tank/charge range, top speed, acceleration, number of seats, air conditioning, warranty | Price, maximum cruising range, environmental impact, performance, durability, convenience |
| Purchase price, capacity, top speed, daily range, operating costs, EV dummy | Purchase price, range, timing of the market entry, environmental evolution |
| Purchase price, annual cost, operation range, refueling frequency, acceleration time, service dummy | Driving range, charging time, fuel saving, pollution reduction, performance, price difference |
| Driving range, charging time, fuel saving, pollution reduction, performance, price difference | |
| Price, maximum cruising range, environmental impact, performance, durability, convenience | |
2.3 Policy analysis modeling

The literature suggests two main modeling techniques to tackle the problem that differ in the presumed aggregation of agents: a system dynamics modeling approach (SDM) and an agent-based modeling approach (ABM). In ABM, objects are individualized, their behavior rules stated and implemented, and their direct or indirect interaction takes place in a predetermined and designed environment. Despite its complexity, ABM has the advantage of representing the intricacies of policy structures in order to investigate the detailed structural changes in the consumer market stemming from such policies. In SDM, the information is aggregated in levels and the interaction between various elements is done through stock-and-flow diagrams and their respective feedback loops that will dictate the rate and direction of change in the system.

SDM has been used to simulate road fuel demand in the EU for different scenarios (Armenia, Baldoni, Falsini, & Taibi, 2010) and to simulate the transition from ICE to other technological alternatives (Struben & Sterman, 2008). ABM is extensively used to model product diffusion in the automobile market, be it from the consumers’ point of view (Kim, Lee, Cho, & Kim, 2011) or from a policy maker standpoint (Mueller & De Haan, 2009). The transition to a sustainable mobility has also been studied through a mixed-model approach (Köhler et al., 2009), combining agent-based modeling techniques to model a number of subsystems integrated in a system dynamics structure.

Here, we are inspecting the diffusion of electric drive vehicles on the aggregate car fleet in the Portuguese context. It intrinsically involves individual decisions by car owners. Therefore, we have to deal with two levels of analysis, making the problem suitable to be analyzed through a mixed-model approach using system dynamics modeling.

3. Methodology

Causal loop diagrams (CLD) help to visualize the interrelated variables and their effect on each other through a series of causal links between a number of elements. Causal links are positive when the direction of change is the same for the two linked elements and are negative when the direction of change is opposite for the two linked elements.

Figure 1 presents the CLD of the developed model. The final output is to forecast the total energy consumption and the resulting CO₂ emissions. The main drivers of this consumption are the travel demand per vehicle and the vehicle stock, including the corresponding technological composition. The vehicles’ fuel efficiency also influences directly the final emissions. These increase as the efficiency decreases (higher L/100 km).

The model was developed using the SDM approach and was implemented using Anylogic produced by XJ Technologies. A time step (dt) of one year was used and the calculations started in 1960 so that the 30-year-old vehicle fleet was complete by 1990 (base year for the Kyoto Protocol emission reduction program). The methodology adopted in the calculation of most of the variables is mostly based on the work by Moura (2009). The matrix variables have a combination of the following dimensions: fuel technology, vehicle type, and vehicle age. The fuel technology dimension has six classes: petrol, diesel, LPG (liquefied petrol gas), hybrid, diesel hybrid, and pure electric vehicles. Regarding the vehicle type, four classes were considered: city, utility, family cars, and SUVs. Finally, concerning the vehicle’s age, vehicles up to 30 years old were considered, divided into 30 one-year segments.

3.1 Vehicle stock module

The final output of this module is the calculation of the total vehicle fleet divided into its various classes (see Figure 2). The total vehicle stock is calculated based on the Portuguese motorization rate—MR—(number of vehicles for 1,000 driving license holders) given by a logistic curve (Grübler, 1990) and the population with driving license (Total Vehicle Fleet = (MR/1000) × Number of driving license holders). Based on vehicle data provided by ACAP (2008) and demographic data provided by INE (2007), the following logistic curve was calibrated for the period 1990 to 2009: \( MR(\text{year}) = 893/(1 + e^{-0.21894 \times \text{year} - 377.36}) \).
The vehicle stock is then divided into a three-dimension matrix: fuel technology, vehicle type, and vehicle age. This division is achieved through the calculation of the number of new vehicles each year.

New vehicles are given by the aggregate evolution of the vehicle fleet over time \( C(t) = C(t - 1) - S(t) + N(t) \) taking into account the total vehicle fleet each year \( C \) and the number of total scrapped vehicles \( S \). The number of new vehicles of each vehicle type and fuel technology class is obtained by multiplying the total number of new vehicles by the market share of each class. The number of vehicles in each of the remaining cohorts is calculated by subtracting the number of scrapped vehicles of the same class and age in that year from the number of vehicles of the same class, one year younger, that existed in the previous year. The number of scrapped vehicles is calculated by using a scrappage curve. A “modified Weibull” cumulative distribution was suggested (Zachariadis, Samaris, & Zierock, 1995) as the survival curve and its probability distribution function gives the percentage of the surviving vehicles over a certain age (the complementary percentage multiplied by the number of vehicles a year younger in the previous year \( t - 1 \) is used to determine the number of retired vehicles in year \( t \)) using the following expression: 

\[
S(k) = \exp\left[\left(-\frac{t}{\lambda}\right)^k\right]
\]

where \( k \) represents the vehicle age. The parameters \( \lambda \) and \( \beta \) are the age at which scrappage starts and the maximum life expectancy expressed in years, respectively. These were calibrated for the Portuguese fleet (ACAP, 2008) by which \( \lambda = 11 \) and \( \beta = 34 \), although some variation occurs depending on the vehicles’ model years.

### 3.2 Static disaggregate car-type choice models

The market share of new vehicles is used to calculate the distribution between fuel technology and vehicle-type classes and estimate the technological turnover of the automobile market of these specific vehicles; \( \beta_0 \) is the attribute’s coefficients; \( \beta_{\text{fuel}}, \beta_{\text{type}}, \beta_{\text{age}}, \beta_{\text{price}}, \beta_{\text{cost}}, \beta_{\text{range}}, \beta_{\text{range}} \) are alternative specific constants (ASC).

A series of discrete choice model specifications were made in order to calibrate the utility functions of the alternatives considered, using the econometrics software NLOGIT, based on data collected from a stated preferences (SP) survey for Portugal. This type of survey was chosen because it is the number of makes and models in the Portuguese automobile market of these specific vehicles; \( \beta_0 \) are the attributes’ coefficients; \( \beta_{\text{fuel}}, \beta_{\text{type}}, \beta_{\text{age}}, \beta_{\text{price}}, \beta_{\text{cost}}, \beta_{\text{range}}, \beta_{\text{range}} \) are alternative specific constants (ASC).

A web SP survey was conducted in January 2012 and 1,110 responses were collected, out of which 348 were validated. Most of the removed responses were incomplete, while a smaller portion was found to have inconsistencies throughout the survey. Each SP scenario had four vehicles to choose from: a city car, a utility car, a family car, or an SUV. Each of these vehicles was characterized by seven attributes: fuel technology, price, operational costs, number of makes and models in the market, maximum velocity, range, and refueling time. The levels of the attributes for each scenario were set according to a fractional experimental design that generated 20 blocks of four cards each. Each respondent was assigned one block randomly.

The survey also included a socioeconomic section. When comparing the survey sample with the population over age 18 of the 2011 Portuguese Census, it was found that it was biased toward more educated and younger people. This bias can lead to an overestimation of alternative fuel vehicles as they influence the calibration results presented below because younger and more educated people tend to be more prone to accepting new technologies, a priori. Therefore, the overall estimates could be criticized for being optimistic. However, our end results show that even so, BEVs fall short of expectations (refer to section 5).

The final car-type choice model specification was as follows:

\[

type = \begin{cases} 
\beta_0 + \beta_1 \text{price} + \beta_2 \text{OC} + \beta_3 \text{Charging} + \beta_4 \text{BEV} + \beta_5 \text{Range} \\
\beta_6 \text{price} + \beta_7 \text{OC} + \beta_8 \text{Charging} + \beta_9 \text{BEV} + \beta_{10} \text{Range} + \beta_{11} \text{MM} \\
\beta_{12} \text{fuel} + \beta_{13} \text{OC} + \beta_{14} \text{Charging} + \beta_{15} \text{BEV} + \beta_{16} \text{Range} + \beta_{17} \text{MM} \\
\beta_{18} \text{fuel} + \beta_{19} \text{OC} + \beta_{20} \text{Charging} + \beta_{21} \text{BEV} + \beta_{22} \text{Range} + \beta_{23} \text{MM}
\end{cases}
\]

where \( \text{CP} \) is the car price (€); \( \text{OC} \) captures the impact of operational costs (€/100 km); \( \text{Charging} \) corresponds to the charging time of battery-electric vehicles (not considered for other vehicles because it is not an issue). It corresponds to the difference between two categorical variables corresponding to two levels of charging time: higher than five hours or lower than 30 minutes; \( \text{BEV} \) is a binary variable that specifies whether the vehicle is a pure electric vehicle (1) or not (0); \( \text{Range} \) is a battery-electric vehicle specific variable and captures the impact of the driving range (kilometers). This attribute was only considered for this fuel technology because other technologies do not have constraints, since most of these cars can travel more than 500 kilometers without refueling; \( \text{MM} \) is specific for hybrid vehicles (0 for other vehicles) and it is the number of makes and models in the Portuguese automobile market of these specific vehicles; \( \beta_0 \) and \( \beta_5 \) are the attributes’ coefficients; \( \beta_{\text{fuel}}, \beta_{\text{type}}, \beta_{\text{age}}, \beta_{\text{price}}, \beta_{\text{cost}}, \beta_{\text{range}}, \beta_{\text{range}} \) are alternative specific constants (ASC).
using NLOGIT (refer to Table 3). Direct elasticities show how car price or operational costs affect demand for each car type while cross-elasticities show how they affect the demand of the remaining alternatives, that is, substitution effects. Our results suggest that the demand for both city and utility cars is relatively inelastic w.r.t. price (i.e., closer to zero), that is, when price increases, demand decreases at a slower rate, while family vehicles’ car price is almost elastic (closer to 1). Although price cross-elasticities of these vehicles are quite low, there may be some substitution between different car types when price changes. SUV vehicle demand is relatively elastic (i.e., higher than 1 in absolute terms) w.r.t. price as expected, because this is a higher value product. This means that when SUV car prices increase, demand will decrease faster and, as the cross-elasticity is almost zero, there will be fewer substitution effects. The same conclusions are applied to the operational costs attribute.

According to the U.S. EPA (2012), direct elasticities w.r.t. market price vary between −1.8 and −2.8 for small-size vehicles, from −1.3 to −3.5 for medium-size vehicles and, finally, from −2.8 to −4.5 for large-size vehicles. In the same vein, Cambridge Econometrics (EFTEC, 2008) estimated direct elasticities w.r.t. purchase price, which are within the same ranges as U.S. EPA (2012), as well as cross-elasticities of other car segments that vary between 0.001 and 0.571 (with a couple of exceptions). These authors also estimated direct and cross-elasticities w.r.t. fuel costs (variable costs of motoring), which present similar ranges of values as those for purchase price.

Although our cross-elasticities estimates are in accordance with the existing literature, direct elasticities present lower ranges (i.e., inelastic demand), with the exception of SUV (i.e., elastic demand). However, elasticities cited in the surveys mentioned above were estimated based on revealed preferences (RP)—car segment market share historical data—while our estimates result from stated preferences (SP) data, that is, individual choices in the face of hypothetical alternatives. Furthermore, respondents from our SP survey were required to choose one vehicle from each choice set. As such, the model did not include a “buy/no-buy” decision. The opportunity to choose not to buy a vehicle results in more elastic vehicle-type demands because, in reality, when price increases customers may choose not to buy instead of switching to another vehicle type.

In fact, other studies suggest that market price elasticity of new car type purchase was found to be approximately −1 (McCarthy & Tay, 1998) or lower, i.e. −0.87 (McCarthy, 1996). These studies are more prone to comparison here, because they both rely on SP household surveys where the “buy/no-buy” decision was not considered also. Additionally, direct elasticities increase as the car segment size increases, following the trend of previous studies, although the values are generically lower. Moreover, cross-elasticities were in line with all studies. In the end, we judge our results sensible.

Figure 3 compares 2009 car sales (ACAP, 2010) with the results obtained with our modeling approach. This comparison indicates that our estimates match sales statistics for Portugal according to fuel-type statistics. When taking into account car-type distribution, the model fitting is less satisfactory, with an overestimation of utility cars and underestimation of family cars, which can be explained by the bias in the survey sample toward younger people. We also tested for 2011 and 2012 when electric vehicles entered the Portuguese car market (ACAP, 2013), and our model also predicted their entrance, although car sales, are insipient overall (less than 0.1% of new car sales - both observed and predicted).

Dummy variables were introduced specifically for BEVs because it was found that consumers do not value the remaining fuel technologies differently, resulting in insignificant dummy variables for these technologies. In fact, BEVs have characteristics such as range, price, and horsepower that consumers find unappealing when compared with conventional fueled vehicles. The negative signal of the corresponding parameter and small p-values corroborates with the overall reluctance regarding BEV technologies under current and

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**Table 2. Attribute coefficients and ASCs for the final discrete choice model calibration.**

| Attribute          | Coefficient  | t-test  |
|--------------------|--------------|---------|
| ASC utility car    | 0.4280       | 5.371   |
| ASC family car     | 0.1386       | 1.1200  |
| ASC SUV            | −1.0308      | −5.2820 |
| Car Price (CP)     | −2.38E-05    | −6.0060 |
| Operational Costs (OP) | −0.1261    | −6.3910 |
| BEV Charging Time  | −0.2510      | −2.1510 |
| Battery-Electric Vehicle (BEV) | −2.0351 | −4.9090 |
| BEV Range          | 0.0035       | 1.2980  |
| Hybrid MM          | 0.0034       | 1.5160  |

Log Likelihood (base model): −2424.917
Log Likelihood: −1591.967
$P_2$: 0.3435
Sample size: 1392

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**Table 3. Direct and cross elasticities of car ownership w.r.t. price and operational costs.**

| Car price       | Attribute          | Direct | Cross | Operational costs | Direct | Cross |
|-----------------|--------------------|--------|-------|-------------------|--------|-------|
| City            | −0.314             | 0.159  | −0.438 | −0.226            |        |
| Utility         | −0.386             | 0.263  | −0.453 | −0.349            |        |
| Family          | −0.782             | 0.203  | −0.675 | 0.185             |        |
| SUV             | −1.363             | 0.055  | −1.175 | 0.042             |        |

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Figure 3. Comparison between estimated values and ACAP sales data from 2009 divided by fuel technology on the left and by vehicle size on the right.
near-future circumstances (assuming that car-buying behavior does not change on yearly basis if no disrupting technology occurs that would change the current paradigm). The literature corroborates with this understanding to give specific constants to these new technologies and differentiate them when compared to other standard technologies (refer to Brownstone & Train, 1999 and McFadden & Train, 2000, for example). This also applies to the “range” variable that was only considered for BEVs. Consumers do not differentiate between a 600 km—and an 800 km—range diesel vehicle because these values are high and refueling infrastructures are available everywhere. Furthermore, these range values are what consumers are used to. As such, it is only significant when the range is below these values.

The variable “makes and models” (MM) was introduced in order to reflect the unwillingness of consumers to purchase vehicles whose technology they perceive as not mature due to the few makes and models available in the market, although it has been around for quite some time. It was important to include in the model for hybrid vehicles because the progression in logit models is not linear. Instead, it is logarithmic and therefore shifting from a few MM (which is the case for hybrid vehicles today) to a few hundred MM will have an impact that is significantly more expressive than shifting from 1000 MM to 4000 MM, for instance (which is the case for mature technologies such as ICE vehicles). The same does not apply to BEVs (MM_BEVs), because these vehicles had been recently introduced on the market at the time the survey was conducted (there were less than 10 versions of BEVs available on the market). Train and Winston (2007) discuss the importance of MM variability in the market where they model vehicle choice behavior in the U.S. car market to analyze the declining share of U.S. car brands. Greene (2001) also included the number of makes and models available to assess market shares of transitional alternative fuel vehicles.

This discrete choice model is not used to calculate the number of new LPG vehicles because these vehicles result mostly from transformations of gasoline vehicles. The number of circulating LPG vehicles is assumed and not calculated.

### 3.3 Travel demand module

The main outputs of this module are the distance traveled per vehicle and the number of vehicle kilometers traveled, as shown in Figure 4. The latter is obtained from the total travel demand (in kilometers) which has a log-linear relationship with GDP per capita in the observed range of values and is calculated using the following equation: Total travel demand [million pkm] = \( \frac{240,000}{(1 + e^{-1.95956 - 9.2471 \times 10^{-5} \text{ GDPpc}})} \). The number of vehicle kilometers traveled is then given by dividing the total travel demand (for passenger cars only) by the average number of passengers per vehicle. The average kilometric cost per vehicle is included here because it influences the average number of passengers per vehicle (i.e., the increase in cost results in an increase in the number of passengers and in a decrease in vehicle kilometers). Finally, the average distance traveled by vehicle is calculated by dividing the number of vehicle kilometers traveled by the number of vehicles for each category.

### 3.4 Kilometric cost module

The average kilometric cost per vehicle is the sum of variable and fixed costs divided by the number of kilometers per vehicle. As the main output of the present module is an average kilometric cost per vehicle of the total vehicle fleet (see Figure 5), a weighted average is calculated taking into account the number of vehicles in each class and each age segment with regard to the total number of vehicles each year.

The variable costs include the maintenance costs and the fuel costs. The latter are calculated by multiplying the fuel price by the fuel efficiency. Maintenance costs are a percentage of the vehicle’s initial price and vary according to the vehicle’s age. The fixed costs include regulated circulation taxes, which vary according to the engine size and emissions per kilometer of the vehicle, insurance and toll costs, and, finally, the vehicle’s depreciation. The residual value (initial value minus the depreciation) of a vehicle is dependent only on its age and initial value and was estimated using the following inverted exponential depreciation curve: Residual value, \( R_k = \text{Initial price} \times e^{-0.3k} \), where \( k \) is the vehicle’s age (Storchmann, 2004, for the OECD countries seen in Moura, 2009).
3.5 Emissions module

The output of this module is the calculation of the total car passenger fleet carbon dioxide emissions (see Figure 6). This variable is directly obtained from the fuel consumption (in liters) of the total vehicle fleet by multiplying by the emission factor (gCO₂/L) for each fuel type. Fuel consumption, in turn, is calculated by multiplying fuel efficiency by the number of vehicle kilometers traveled (distance traveled per vehicle times the number of vehicles).

3.6 Indicators

The variables used as indicators were chosen in order to analyze how each scenario affects the vehicle fleet and its characteristics, as well as the final fuel demand. As such, the structure of the fleet, that is, the percentage that each fuel technology occupies in the market, was chosen as one indicator. This will demonstrate, for example, whether the innovative technologies penetrate the market. Furthermore, the energy intensity (EI) — the ratio between total consumption and GDP (see Equation 1) — is calculated for each scenario in order to measure the impact of the car stock technological evolution on the Portuguese economy. In this research, carbon intensity (CI) is the ratio between total emissions and total consumption and it quantifies the impact of BEV policies on the car stock overall intensity (see Equation 2).

\[
\text{Energy Intensity} \left[\frac{\text{toe}}{\text{10}^3 \text{€}}\right] = \frac{\text{Total fuel consumption}}{\text{GDP}}
\]

(1)

\[
\text{Carbon Intensity} \left[\text{ton CO}_2/\text{toe}\right] = \frac{\text{Total CO}_2 \text{ emissions}}{\text{Total fuel consumption}}
\]

(2)

3.7 Model validation

The validation of the developed model is crucial to determine the confidence of forecasting results. This process consists of the verification of the accuracy of the estimates made by the model by comparing them with existing data.

The aggregate vehicle fleet model has a high goodness of fit, as shown in Figure 7. Figure 8 depicts the distribution per age segment of the total fleet in three different years: 2008, 2010, and 2011. These estimates present a good fit to the existing data (provided by ACAP — Portuguese Car Sellers Association, 2013) and the discrepancies found can be due to the scrappage curve used.

Total fuel consumption, divided into petrol, diesel, and LPG, is compared with fuel sales data from DGEG in Figure 9, where it can be seen that petrol and LPG are well estimated (DGEG, 2010). The lower estimates of LPG sales can be due to an underestimation of total LPG vehicles in circulation. Estimated diesel consumption follows closely the consumption variation reported by National Authorities. The gap between estimated and reported consumption levels is due to the fact that reported diesel consumption included all road transportation, including light-duty vehicles and trucks, which correspond to approximately half of total consumption.

Total CO₂ emissions are presented in Figure 10, where a linear plot is shown due to the lack of data (only 1990 and 2010 emissions are available). Both plots have similar slopes, although there is a significant shift between them, which, again, is due to the inclusion of light-duty vehicles and trucks as well as buses and coaches in the data from APA (2012).

4. Scenario and policy analysis

Scenarios are conjectures about what can happen in the future based on our past and present experience of the world (IEA, 2003). Scenario planning uses alternative scenarios to assess the future, where each scenario is a plausible evolution of key factors, although nothing can be said about its likelihood of occurring. In Energy to 2050: Scenarios for a Sustainable future (IEA, 2003), the energy system is under investigation and the key factors that affect the system (i.e., main drivers that have a potentially high impact on the system) were identified based on existing knowledge: speed of technological change; attitudes and preferences toward the global environment; economic growth; population growth; globalization and degree of market openness; structure of power, and governance and global security issues.

In this research, only the first three are considered, although it is believed that the speed of technological change is closely related to economic growth because the latter is essential to
obtain the former. As such, economic growth/technological change and environmental concern were chosen as the axes along which the scenarios are characterized. The axis on economic growth varies from stagnation to fast growth and the environmental concern axis varies from unconcerned to concerned. An infinite number of scenarios can be studied, taking into consideration the two-dimensional space formed by the two axes. However, following the methodology used by IEA (2003), only the extreme cases will be studied (shown in Figure 11). “By focusing on the extreme cases we have a chance to explore the full range of uncertainties deriving from those factors/drivers,” as stated by IEA (2003, p. 59).

The qualitative directions of change of the key factors of the three scenarios presented in Figure 11, compared with those of the reference scenario, are presented in Table 4. These are applied only from 2010 onward, that is, until 2010, the methodology described in the previous section is applied. The baseline scenario considers current stagnation of the economy: current transportation policies regarding the taxation system are maintained up to 2030, ICE vehicle fuel efficiency increases over time by 1.5% per year, GDP has a constant growth rate of 0.5% per year from 2010 until 2030, and the motorization rate reaches a maximum of 893 vehicles per 1,000 driving license holders by 2030.

In the Clean but not sparkling (CS) scenario, there is a strong environmental concern in a slow-growing economy. The latter does not allow the investment in R&D, leading to limited technological progress. This is reflected in the increase of fuel efficiency of conventional vehicles (1.5% per year). In the first few years, CO₂ emission reduction goals are met through behavioral changes as travel demand decreases due to a negative GDP growth rate, that is, the decrease in GDP per capita leads to fewer kilometers driven (there is less money to purchase fuel), thus reducing fuel consumption and probably shifting those trips to public transportation or, less probably, to soft modes after changing residence and/or job locations. We note that the impacts of these transfers are not accounted for in the present research. Although later on GDP slowly starts to increase, environmental goals are put in second place as the focus is on encouraging economic growth.

In the Dynamic but careless (DC) scenario, environmental problems are a very low priority for both citizens and politicians, with the main priority being an unhindered economic growth. Low energy prices and security of supply are considered important conditions for economic growth. With such a fast-growing economy, there is high investment in technology, which is reflected in a higher fuel efficiency increase (2% per year). As progress is faster in fossil-fuel-based technologies, fossil-fuel demand grows rapidly, helping to maintain low prices (resulting from both higher travel demand per capita and higher motorization rate of 980 vehicles/1,000 driving license holders). As such, it is believed that rapid technological change is the answer to threats such as climate change with no need of further policy intervention in this area.

The Bright skies (BS) scenario is characterized by a fast-growing economy, and the resulting fast technological progress (3% per year increase in fuel efficiency), and a high concern for the global environment. The government agrees to take action to deal with the climate-change threat by reversing current GHG emission trends. Policies that encourage transport-related GHG emission reduction are designed and implemented, thus making the motorization rate decrease (maximum of 803 vehicles/1,000 driving license holders). There is also high investment in R&D of new technologies for climate change mitigation. Through these efforts, environmental goals are met.
Regarding the policy analysis, a series of transportation policy instruments, mainly applied to the taxation system, will be implemented in each scenario in order to analyze how effective they are in decreasing total emissions and increasing BEV diffusion. Increases in the tax on petroleum products (TPP), meant to encourage the purchase of either more fuel-efficient vehicles or even BEVs, the vehicle purchase tax (VPT) and vehicle circulation tax (VCT), to encourage the purchase of vehicles with lower emissions (g/km) or even zero emissions (BEV), will be studied. All of these taxes have a direct impact on the consumers’ vehicle choice (TPP and VCT on the operational costs and VPT on the car price). For each instrument, three levels of increase were implemented to check for any non-linearity in the effects: 10%, 50%, and 100%.

Regarding the “Bright skies” scenario, two further policies will be applied: a policy that encourages the diffusion of rapid charge points for BEVs because this is thought to accelerate the penetration of BEVs in the market, and an urban sprawl control policy where individuals are encouraged to change their lifestyles, decreasing the travel demand per capita.

5. Results and discussion

5.1 Baseline scenario (“Stagnation”)

The results presented in the following sections will be compared with the baseline scenario (“Stagnation”) using the indicators presented in section 3.5. The final year of simulation is 2030, the results of which are compared with those of 1990 (reference year of the Kyoto Protocol).

In the reference scenario, energy and carbon intensities decrease over time (shown in Figure 12), as expected, as fuel consumption decreases due to the introduction of hybrid vehicles and BEVs in the market. These vehicles reach 67% of the automobile market by 2030, out of which 60% are hybrids, making fuel consumption decrease rapidly. Carbon intensity decreases as the diffusion of BEVs in the market increases, reaching approximately 8% in 2030. As these vehicles have a much lower CO₂ life-cycle emission factor, CO₂ emissions decrease faster than total fuel consumption, thus decreasing CI over time.

5.2 Scenario analysis: Results and discussion

Table 5 presents the results of the scenario analysis described in the previous section (see section 4). These results are compared with those of the baseline scenario (“Stagnation”) which, as mentioned previously, is considered to be the reference scenario in this research. The number of LPG vehicles is not affected by any of the studied scenarios because it was assumed external to the model. However, its market percentages are affected by changes in the motorization rate, that is, in the DC scenario when the motorization rate increases, the market percentage of LPG vehicles decreases and the opposite occurs in the BS scenario.

Regarding the Clean but not sparkling (CS) scenario, the vehicle fleet structure has some slight fluctuations when compared with the baseline scenario, leading to an increase in all fuel technologies except diesel hybrid vehicles. The variation of the energy and carbon intensity indicators is negligible (less than 1% in both cases when compared with the baseline scenario). Energy intensity shows a smaller decrease due to the smaller GDP growth rate in the present scenario and the transfer from diesel hybrids to mostly petrol vehicles, which have lower fuel efficiencies. Carbon intensity decreases slightly more than in the baseline scenario because CO₂ emissions grow slower than fuel consumption due to a minor transfer to BEVs with a lower CO₂ life-cycle emission factor.

In the Dynamic but careless (DC) scenario, fuel efficiency of ICE vehicles improves more rapidly than in the baseline scenario and, as such, higher efficiencies from hybrid vehicles attenuates. As a result of this tighter competition, a transfer to conventional vehicles occurs and petrol and diesel vehicles increase 6% and 4%, respectively, when compared with the baseline scenario. EI decreases more than in the baseline scenario as GDP grows faster conversely to fuel consumption due to the higher vehicle fuel efficiency. A steeper decrease in CI also occurs as a result of fuel consumption growing slightly faster than CO₂ emissions. A closer look at the results showed

![Table 4. Explanatory scenarios—Qualitative directions of change.](image)

![Figure 10. Carbon dioxide emissions—Model validation.](image)

![Figure 11. Explanatory scenarios (based on IEA 2003).](image)
that this discrepancy is caused by an increase in kilometers driven by BEVs despite the reduction in the number of BEVs.

The lower motorization rate in the Bright skies (BS) scenario is compensated for by the increase in the kilometers driven per year per vehicle because travel demand is mainly dependent on GDP. The transfer to petrol and diesel vehicles, 11% and 7% respectively, is higher than in the DC scenario because technological progress allows a further 1% increase in ICE vehicles’ fuel efficiency (3% per year). Accordingly, EI decreases more than in both the baseline and the DC scenarios, despite the increase in the share of ICE vehicles. CI is higher than in the baseline scenario at first but by 2030 the opposite is true (CI has a steeper decrease than the baseline scenario). This is a result of a higher increase rate of CO₂ emissions over fuel consumption at first due to the market transfer of BEVs to ICE vehicles. By 2020, when the inversion occurs, fuel consumption has a higher increase rate than CO₂ emissions due to an increase in kilometers traveled by BEVs, despite the reduction in the number of BEVs (similar to the situation that occurred in the DC scenario).

5.3 Transportation policy instruments (TPI): Results and discussion

Table 6 presents the results obtained from the increase of 10%, 50%, and 100% of the tax on petroleum products regarding the reference scenario (“Stagnation”). Here we can see that as we increase the tax, the percentage of petrol and petrol hybrid vehicles decreases, while diesel hybrids and electric vehicles increase. Diesel vehicles remain approximately constant. Energy intensity also remains constant, while carbon intensity decreases compared with 1990 (percent-variation increases). These results show that different levels of tax increase lead to similar variations in terms of increase/decrease compared with 1990. Therefore, for the remaining TPIs, only the effect of a 50% increase will be examined for each scenario.

Table 7 presents the results of the application of TPIs in all studied scenarios. The results of each TPI will be compared with the no-intervention reference scenario, that is, without any TPI (e.g., TPP-CS compared with Ref-CS). The market percentage of LPG is not affected by any of the applied policies because the number of LPG vehicles is external to the model.

The increase in the tax on petroleum products (TPP) has a clear impact on the vehicle fleet structure in 2030, resulting in a decrease of petrol and petrol hybrid vehicles and an increase in diesel, diesel hybrids, and BEVs when compared with their corresponding references. BEVs increased on average 23% when compared with the results from the corresponding reference scenario. Both diesel and hybrid diesel vehicles increase because diesel is cheaper than petrol and the tax percentage in the final fuel price is lower. The lower CO₂ life-cycle emission factor of electricity results in a steeper decrease of CI in all the scenarios as the consumption transfer from petrol to electricity occurs. EI remains practically unchanged when compared with the reference scenarios as travel demand is transferred, making fuel consumption practically the same. In the BS scenario, the decrease in EI is more accentuated due to the higher fuel efficiency of ICE vehicles, which makes fuel consumption decrease.
The effect of the increase in the vehicle purchase tax (VPT) is not as big as the previous TPI because the relative increase of car price with the tax is small, affecting the car buyers’ choice-less. Conversely, the relative impact of TPP in the previous case is much bigger and clearly affects the options of car consumers. It results in a decrease of the 2030 market percentage of diesel vehicles and an increase in BEVs in all scenarios. There is no consistent pattern of variation regarding the remaining fuel technologies. Petrol vehicles are more competitive than diesel vehicles due to the lower vehicle purchase tax applied as well as their lower initial base price. In the BS scenario, these vehicles are even more competitive than hybrids due to their higher fuel efficiency, while maintaining their advantage in terms of upfront price. Both types of hybrid vehicles are not as affected by the increase in this tax because these vehicles only pay half of the applied tax, despite the higher upfront price. BEVs increase in all scenarios because these are completely exempted from the present tax. The increase in hybrid vehicles results in a steeper decrease in EI due to their higher fuel efficiency. The increase in BEVs results in a steeper decrease in CI. However, both of these reductions are quite small, that is, less than 2%.

A vehicle circulation tax (VCT) increase does not have a precise impact on the structure of the vehicle fleet because there is no consistent pattern of variations across scenarios. Diesel vehicles are the only ones that increase in all scenarios or remain the same in the DC scenario. Petrol cars increase in all scenarios except BS. Petrol hybrids increase only in the DC scenario, while diesel hybrids increase in CS and BS scenarios.

### Table 6. Sensitivity analysis for the increase of the tax on petroleum products (TPP).

| TPI   | Petrol | Diesel | LPG | Hybrid | Diesel Hybrid | Electric | EI   | CI   |
|-------|--------|--------|-----|--------|---------------|----------|------|------|
| Ref   | 13.31  | 18.79  | 0.58| 28.90  | 30.91         | 7.51     | 51.33| 5.00 |
| 10%   | 13.18  | 19.13  | 0.58| 28.35  | 30.88         | 7.88     | 51.33| 5.17 |
| –1%   | 12.04  | 18.94  | 0.58| 27.75  | 31.46         | 9.23     | 51.33| 5.70 |
| 50%   | 10.97  | 18.90  | 0.58| 25.77  | 32.69         | 11.09    | 51.29| 6.48 |

1Percentages in brackets correspond to percent-changes from the reference situation after TPI implementation.

The effect of the increase in the vehicle purchase tax (VPT) is not as big as the previous TPI because the relative increase of car price with the tax is small, affecting the car buyers’ choice-less. Conversely, the relative impact of TPP in the previous case is much bigger and clearly affects the options of car consumers. It results in a decrease of the 2030 market percentage of diesel vehicles and an increase in BEVs in all scenarios. There is no consistent pattern of variation regarding the remaining fuel technologies. Petrol vehicles are more competitive than diesel vehicles due to the lower vehicle purchase tax applied as well as their lower initial base price. In the BS scenario, these vehicles are even more competitive than hybrids due to their higher fuel efficiency, while maintaining their advantage in terms of upfront price. Both types of hybrid vehicles are not as affected by the increase in this tax because these vehicles only pay half of the applied tax, despite the higher upfront price. BEVs increase in all scenarios because these are completely exempted from the present tax. The increase in hybrid vehicles results in a steeper decrease in EI due to their higher fuel efficiency. The increase in BEVs results in a steeper decrease in CI. However, both of these reductions are quite small, that is, less than 2%.

A vehicle circulation tax (VCT) increase does not have a precise impact on the structure of the vehicle fleet because there is no consistent pattern of variations across scenarios. Diesel vehicles are the only ones that increase in all scenarios or remain the same in the DC scenario. Petrol cars increase in all scenarios except BS. Petrol hybrids increase only in the DC scenario, while diesel hybrids increase in CS and BS scenarios.

### Table 7. Fleet structure in 2030 and decrease in EI and CI from 1990 until 2030—Implementation of transportation policy instruments.

| Scenario                  | TPI   | Petrol | Diesel | LPG | Hybrid | Diesel Hybrid | Electric | EI   | CI   |
|---------------------------|-------|--------|--------|-----|--------|---------------|----------|------|------|
| Baseline ("stagnation")  | Ref   | 13.31  | 18.79  | 0.58| 28.90  | 30.91         | 7.51     | 51.33| 5.00 |
| TPP                       | 12.04 | 18.94  | 0.58  | 27.75| 31.46  | 9.23         | 51.33    | 5.70 |
| VPT                       | 13.34 | 18.43  | 0.58  | 28.55| 31.34  | 7.77         | 51.42    | 5.12 |
| VCT                       | 13.45 | 19.04  | 0.58  | 27.34| 30.73  | 7.46         | 51.33    | 4.98 |

1Percentages in brackets correspond to percent-changes from the reference situation in each scenario after TPI implementation.
BEVs increase in the DC and BS scenarios. In the CS scenario, EI has a steeper decrease and CI a lower decrease than in the corresponding reference scenario, while the opposite occurs in the DC and BS scenarios. In the baseline scenario, EI remains the same, while CI has a steeper decrease than in the corresponding no-intervention scenario. Circulation taxes are paid annually and vary with the engine size and CO2 emissions per kilometer. Here, this tax was added to the kilometric operational costs (OC). As such, it is divided by the annual travel distance per vehicle, which results in a smaller change to total annual OC. The end result is that it does not affect directly nor significantly the market share of new vehicles.

The investment in fast-charging points (FCP) for BEVs increases the probability of charging a BEV faster (less than 30 minutes), which is reflected in an increase of 6% in BEVs when compared with “BS-Ref.” All the remaining technologies decrease their market percentages by 2030 except diesel hybrids as the transfer to BEVs occurs. As a result, CI decreases more than in the BS reference, scenario. EI decreases less than in the reference BS scenario, which can be a result of a transfer of travel demand instead of a decrease, that is, despite the decrease in ICE vehicles as well as petrol hybrids, the travel demand previously met by these vehicles was transferred, and maybe even increased, and is now supplied by BEVs and diesel hybrids.

Finally, we analyzed the impact of reducing total travel demand by individuals instead of technological replacement with more efficient vehicles or even zero-emission ones. The reduction of individual annual travel distance could possibly derive from urban sprawl control (USC) measures through, for example, a combination of several measures: higher density of land uses, incentives to modal shifting to public transportation, tolls at the main road entrances of urban areas, higher parking fees near big trip generators/attractors, etc. Here, we tested the impact of such policy on travel demand only where it was assumed that this variable’s level by 2030 is the same as in 2005 (i.e., the maximum travel demand is achieved by 2010, after which it starts to decrease). As such, after 2010, total travel demand is calculated using the following equation: Total travel demand [million pkm] = –11,245log(GDPpc) + 202, 202. The observed fluctuations in the vehicle fleet in 2030 are not significant in this context because the impact is solely on travel demand. EI decreases steeply when compared with the corresponding reference BS scenario, with a further 40% decrease, because fuel consumption decreases due to the decrease in kilometers driven. CI decreases slightly more than in the reference BS scenario as BEVs increase by less than 1%.

6. Conclusions

This research aims to identify the extent to which electric vehicles can potentially diffuse in the Portuguese car fleet by analyzing the problem from the car demand perspective. As indicators of the overall car fleet performance variation, we estimated the resulting fleetwide energy consumption and corresponding carbon dioxide emissions up to 2030. A system dynamics model of the Portuguese car fleet was developed for this purpose. The final aggregate energy and carbon intensities and the BEV market diffusion were compared for several evolving scenarios against a baseline scenario.

According to our estimates, the diffusion of BEVs in the market will not be very high, reaching a maximum of 7.6% of the total vehicle fleet by 2030, whereas hybrid vehicles could reach up to almost 60%. This results in a decrease in energy intensity and carbon intensity of 51% and 5%, respectively, compared to 1990s levels. The reduction in EI is achieved due to the diffusion of hybrid vehicles, which have higher fuel efficiency, and the decrease in CI due to the penetration of BEVs. These results show that, despite the higher concern for the environment, people will hardly shift to BEVs.

From our scenario analysis (refer to Table 5), we conclude that a fast-growing economy is the best driver to a decrease in both energy and carbon intensity, even when there is no particular concern for the environment because it is expectable (and assumed here) that a faster technological development occurs accordingly. As expected, in a future where there is both fast economic growth and higher environmental concern (“Bright skies”), the reduction in energy consumption is higher. On the other hand, BEV diffusion decreases for both fast-growing economy scenarios. This is explained by the fact that conventional fossil-fuel vehicles become more competitive in the marketplace due to their higher fuel-efficiency evolution stemming from fast technological progress (according to our assumptions in both scenarios supported by the IEA report Energy to 2050: Scenarios for a Sustainable Future, 2003).

Regarding the TPIs applied, it was found that the increase in circulation taxes is not an effective instrument to decrease consumption and emissions because their impact on the consumers’ vehicle choice is very small and inconsistent. The increase in the vehicle purchase tax can be a reasonable way to increase BEVs and decrease emissions. This instrument would result in little market disturbance because cars are already expensive and an increase in their price would go more unnoticed than in other goods such as fuel. The increase in both the tax on petroleum products and vehicle purchase tax would be the best method to reduce energy consumption and corresponding carbon dioxide emissions because both result in a more important increase in BEVs share and use. However, as past and present experience shows, increasing fuel prices through increasing taxes has a very high impact on the market. Increasing the availability of rapid charging stations for BEVs increases the diffusion of these vehicles and decreases carbon intensity in comparison with the reference scenario (which in this case is the “Bright skies” scenario), although the final impact falls short of initial expectations. Finally, acting on the transport-land use interaction (“urban sprawl control”) produces much more effective results than acting on the technology side of the system, although its implementation takes much longer and requires strong and multi-instrumental enforcement procedures to make it really happen.

Importantly, one additional highlight from the present research is the demonstration that the methodological approach followed here is appropriate to test transport policy instruments in an aggregate way. The results yield important insights on the directions and magnitude of impacts that can be expected from transport policy interventions. Overall, and as highlighted before, current taxation on energy and vehicles fall short of expectations with regard to influencing energy and carbon efficiency of the overall car fleet. In the same vein,
Attempts to achieve higher energy and carbon efficiency using such TPis only, as a means to foster technological turnover of fleets, faces high inertia of the system. This inertia is due to the current technological turnover of car fleets, that is, new and more efficient technologies enter the stock through new car sales only. Additionally, car use elasticity with respect to operational costs is very low ($c = -0.3$) (Goodwin, Dargay, & Hanly, 2004), which somehow is an indicator of the resistance of citizens to change their mobility patterns. In fact, current Portuguese mobility is still very dependent on cars.

The diffusion of electric vehicles in the market is highly dependent not only on consumer behavior but also on vehicle manufacture innovations, the evolution of battery-charging technology, and the number and distribution of charging stations (both slow and fast charging). However, the discussion of these BEV’s critical factors is beyond the scope of this research.

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Appendix

Nomenclature

ABM  Agent-based modeling
ACAP  Associação Automóvel de Portugal
APA  Agência Portuguesa do Ambiente
ASC  Alternative specific constant
BAT  Best available technologies
BEV  Battery-electric vehicle
BS  Bright Skies
CENSE  Center for environmental and sustainability research
CI  Carbon Intensity
CLD  Causal loop diagram
CO  Carbon monoxide
CO$_2$  Carbon Dioxide
CO$_2$eq  Carbon Dioxide equivalent
CP  Car Price
CS  Clean but not Sparkling
DC  Dynamic but Careless
DCM  Discrete Choice Model
DGEG  Direção Geral de Energia e Geologia
EDV  Electric drive vehicles
EI  Energy intensity
ETSAP  Energy Technology Systems Analysis Program
EU  European Union
EV  Electric vehicle
FCP  Fast-charging points
GAINS  Greenhouse Gas and Air Pollution Interactions and Synergies
GDP  Gross Domestic Product
GDPpc  GDP per capita
GHG  Greenhouse gas
GWP  Global warming potential
ICE  Internal combustion engine
ICT  Information and communication technologies
IEA  International Energy Agency
IIASA  International Institute for Applied Systems Analysis
INE  Instituto Nacional de Estadística
IPCC  Intergovernmental Panel on Climate Change
LPG  liquefied Petroleum Gas
MM  Makes and Models
MM$_E$  Makes and Models of Electric Vehicles
MNL  Multinomial logit
MR  Motorization Rate
NMHC  Non-methan hydrocarbons
NO$_x$  Nitrogen oxides
OC  Operational costs
OECD  Organization for Economic Co-operation and Development
pkm  passenger kilometers
R&D  Research & Development
RUM  Rational Utility Maximization
SDM  System dynamics modeling
| Abbreviation | Description                  | Symbol | Definition               |
|--------------|------------------------------|--------|--------------------------|
| SP           | Stated Preferences           | U      | Utility                  |
| SUV          | Sport Utility Vehicle        | US     | United States            |
| TIMES        | The Integrated MARKAL-EFOM System | USC   | Urban Sprawl Control     |
| Toe          | Tonne of oil equivalent     | VCT    | Vehicle circulation tax  |
| TPI          | Transportation policy instruments | VPT   | Vehicle purchase tax     |
| TPP          | Tax on petroleum products    | w.r.t. | with respect to          |