Should BEVs be subsidized or taxed? A European perspective based on the economic value of CO_2 emissions

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ARTICLE INFO

Keywords:
CO_2 emissions
Well-to-Wheel analysis
Electric vehicles
European policies
European incentives

ABSTRACT

Battery Electric vehicles (BEVs) are generally considered as potentially contributing to the reduction of CO_2 emissions. Consequently, many countries have promoted (or are in the process of promoting) policies aimed at directly or indirectly subsidizing BEVs to accelerate their market uptake. The aim of this paper is to assess whether BEVs' subsidies are justified (and by what amount) with reference to the carbon component, distinguishing by car segments and countries. To address these research questions, a simulation model is developed, based on the most recent and reliable data available. The model estimates and monetizes the Well-to-Wheel CO_2 emissions of six car segments in 28 European countries. The monetary value of the difference of the CO_2 emissions between the non-BEVs and the BEVs ranges from −€1133 (tax) to +€3192 (subsidy), depending on the car segment and on the nation considered. These results are then compared to the policies about alternative fuels adopted by the single EU countries, suggesting in some cases the necessity to rethink such incentives.

1. Introduction

In 2014, transport was the largest energy-consuming sector, accounting for roughly one third of final energy consumption. This generated about 22% of global energy-related greenhouse gas (GHG) emissions (IEA, 2015). In comparison to the 1990 levels, a relevant increase of such emissions is evident (+23%; EU, 2014). This is in contrast with all international agreements against climate change, such as the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), which set the objective to limit global warming to less than 2 °C. This objective is difficult to achieve without a major contribution provided by the transport sector.

Carbon dioxide (CO_2) is the most important of GHGs, as it counts more than 78% of total anthropogenic GHG emissions (IPCC, 2014, p. 6). There are several ways to reduce CO_2 emissions from transport without curbing mobility (Bristow et al., 2004). They include the promotion of freight and passenger modal split towards less polluting systems, the adoption of technical and regulatory constraints (e.g., standards and prohibitions) and appropriate financial means (e.g., taxes, charges and tolls), as well as increasing the attractiveness of existing alternatives. Although it is not sufficient if applied alone, the improvement of the efficiency and the proliferation of vehicles powered by alternative sources can contribute to this aim (Dray et al., 2012). Aware of this potential, the Paris Declaration on Electro-Mobility and Climate Change envisions the global deployment of 100 million electric vehicles (EVs) by 2030 (UNFCCC, 2015).

As of December 2016, more than two million EVs have been sold worldwide, the most active markets being China and Europe.

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http://dx.doi.org/10.1016/j.trd.2017.07.017

This has been possible due to reduced costs and the application of incentives for the purchase and supply of EVs. As far as the first point is concerned, battery costs for the Chevrolet Bolt are estimated at $145/kWh and are expected to drop below the $100/kWh mark by 2022 (IEA, 2016). Regarding the incentives in the USA, EVs enjoy tax credits capped up to $7500 at the national level with states able to apply further purchasing incentives (AFDC, 2016). China applies an exemption from the purchase and excise taxes, normally based on engine displacement and sale price (Mock and Yang, 2014). The incentives range from $6000 to $10,000 (Lutsey et al., 2015).

Europe, which is committed to reduce its levels of GHG emissions by 40% by 2030 (EC, 2015), presents relevant differences with regard to the diffusion of EVs. Referring to the year 2015, in Norway the EV market share of new cars was close to 22.5% (almost 30% in 2016), the highest percentage globally (EEA, 2016). On the other hand, the dispersion of EVs was extremely limited in other countries, such as Latvia or Lithuania; in Bulgaria and Cyprus, no EVs were sold in 2015. Overall, the registration of EVs in the EU increased from 2000 in 2001 to about 150,000 vehicles in 2015. Despite this increase, the market share of new EVs was only 1.5% of new cars sold, with a total amount of EVs in circulation in Europe equal to 0.15% of all passenger cars.

The potential of EVs to reduce GHG emissions is related to the energy sources at the national level to produce the electricity necessary to power the vehicles. Also in this case, the EU countries present very different circumstances. Due to these policy and energy differences, the European situation is rather heterogeneous, making it difficult to reach the GHG targets previously agreed to. By considering the entire process of fuel and energy production and consumption, this paper aims to understand the contribution of EVs to the reduction of GHG emissions according to the specificities of the different EU countries, including their energy policies and the driving behaviours of their populations. Based on the economic valuation of GHG emissions that we have provided from previous papers (Nocera et al., 2015a,b), we compare the GHG contribution of EVs to other vehicles that would be optimal in each EU country. Furthermore, we calculate the incentives or the taxes (if emissions of EVs are found to be higher than those of traditional vehicles) that each EU country should apply to the purchase of EVs, in order to promote the reduction of GHG emissions.

The paper is structured as follows: Section 2 provides a literature review of the most important studies that deal with the issue of emissions caused by EVs and vehicles powered by traditional fuels. Section 3 presents a description of the methodology that we adopt to determine the social costs of CO_2 emissions caused by vehicles, separated by classes and fuel/technology, and analysis for each EU country. Sections 4 and 5 show the principal results of our analysis, expressed in terms of average emissions per class of vehicle by EU countries and the related CO_2 social costs and compare them to other studies. The conclusions illustrate the policy implications regarding subsidies or taxes for EVs in comparison to other types of vehicles.

2. Literature review

There are a large number of papers comparing the energy and environmental performance of vehicles powered by different fuels. Hawkins et al. (2012, 2013a) review 55 studies from peer-reviewed and grey literature, providing environmental, energy or material assessments. They find that very few studies report full Life Cycle Assessment, including both the fuels and the vehicle itself. Rusich and Danielis (2015, Table 1, p. 4) summarise the results presented in 35 recent papers comparing different vehicle technologies regarding the environmental impact only. They find that EVs generally emit lower CO_2 emissions than the conventional Internal Combustion Engine Vehicles (ICEVs). The result is, however, strongly dependent on how electricity is produced and distributed. If carbon intensive sources are used, CO_2 emissions produced by EVs are comparable or, in some cases, even worse than some advanced ICEVs. Regarding local pollutants, they track only two studies that attempt to differentiate between the effects of harmful pollutants linked to the location of emission: Huo et al. (2009) perform an assessment of local air pollutants (NO_x, PM_{10}, $PM_{2.5}$, CO, VOCs), focusing on North America. The National Petroleum Council (2012) confirms that EVs are a very promising instrument to reduce urban air pollution. No studies are reported for the European Union.

In the recent years, this literature further increased. We review four major contributions: Abdul-Manan (2015), UCS (2015), Holland et al. (2016) and Messagie et al. (2014).

Abdul-Manan (2015) deals with the uncertainty in estimating the potential reduction of GHG emissions. He performs an international analysis by examining the average carbon intensity for grid electricity from over 200 countries, by considering all vehicles models on sale in the USA, and by conducting a sensitivity analysis that measures the variability linking the efficiency of the vehicles, the driving cycles, and the intensity of emissions associated with power generation and supply. The overall conclusion is that in many instances EVs emit less GHG emissions than ICEVs but more than hybrid electric vehicles (HEVs). The main limitations of Abdul-Manan's (2015) contribution is the lack of documentation over the energy mix used, the failure to make explicit how uncertainty is modelled and to discuss the emissions related with battery production and disposal.

The Union of Concerned Scientists' report (UCS, 2015) focusses on global warming emissions in the USA. By recognizing the need to perform a spatially disaggregated analysis, they divide the US into 26 "grid regions". The issue of considering either marginal or average grid emissions (raised in some recent contributions such as Graff Zivin et al., 2014; Tamayao et al., 2015) is also discussed. The latter approach is chosen since it reflects changes that are occurring in non-marginal load generation. This choice permits comparison with future and past emissions and it captures the impact of ongoing changes to the electricity grid as a whole resulting from regulatory policy and other factors. The emissions connected with battery production and disposal are included in the analysis, although a high level of technological uncertainty is recognized. The emissions from extraction and transportation of fuels used in electricity production, the emissions from extraction, refining, and the transportation of the fuels to filling gasoline stations are also included. The analysis is limited to two Battery Electric Vehicles (BEVs; Nissan LEAF and Tesla Model S) and two comparable ICEVs (a midsize car with a fuel economy of 29 MPG and a vehicle weight of 3000 lbs). The main finding is that over its lifetime -from manufacturing to operation to disposal- a BEV generates about 50% fewer GHG emissions than a comparable gasoline car. No analysis of the local air pollutants is provided.

Holland et al. (2016) perform a very complex and detailed analysis, combining a theoretical discrete-choice model of vehicle purchases, an econometric analysis of electricity emissions, and the AP2 air pollution model to estimate the geographic variation in the environmental benefit from driving EVs. They include both global and local air pollutants (from driving and energy production, inclusive of the diffusion models), measured at county level and estimate the marginal emissions factors for each pollutant at each of the 1486 power plants considered due to an increase in regional electricity load. A set of EVs and equivalent gasoline vehicles are compared in terms of damages and environmental benefits. A scenario analysis is also performed. They find that: (a) the second-best EV purchase subsidy ranges from \$3025 in California to −\$4773 in North Dakota, with a mean of −\$742; and (b) that 90% of local environmental externalities from driving EVs in one state are exported to others, implying they may be subsidized locally, even when the environmental benefits are negative overall. The main criticisms raised are related with the not up-to-date energy mix coefficients, the lack of transparency in the model adopted for local air pollutants and the use of marginal emissions factors, not suited for medium to long term predictions.

Lastly, Messagie et al. (2014) analyse the European countries. They report the results of a full Life Cycle Assessment of petrol, diesel, fuel cell electric, compressed natural gas, liquefied petroleum gas, hybrid electric, electric battery, bio-diesel and bio-ethanol vehicles. They consider all the family cars registered in Europe in 2011. Their raw material production, transport, manufacturing, use, maintenance and end-of-life are considered. BEV is equipped with the lithium-manganese battery, as in the Nissan Leaf. The analysis is performed by assessing the Life Cycle Inventory. Results are then converted into environmental indicators. The following impact categories are estimated: climate change, air acidification, mineral extraction and respiratory effects (inorganics). Interval estimates are provided. The main findings are that: conventional vehicles using fossil fuels have the largest impact on climate change. Hybridization has a positive effect on climate change. Except for the bioethanol vehicle using fuel produced from sugar cane, BEVs are found to have the lowest impact on climate change. However, it is stressed that the energy source used to generate the electricity is of crucial importance. With regards to the respiratory effects and the impact on acidification, biofuels are found to have the largest impact, while BEVs and ICEVs have a similar impact. With regards to mineral resource depletion, fuel cell electric, hybrid vehicles and BEVs have the highest impact due to the use of specific materials in the fuel cell, the NiMH battery and the lithium battery. However, it is argued that recycling these components reduces such impact significantly. The selection of the vehicle segment has an influence on the environmental impact: segments dominated by larger, heavier vehicles have broader consequences.

As evident from the previous literary review, comparing the environmental impact of conventional and alternative vehicles within a Life Cycle Assessment approach is a challenging exercise. A large quantity of data sources need to be assembled and the relative uncertainties recognised. This requires a clear definition of the reference frame. This paper focuses on the CO_2 emissions in European countries, accounting for the differences in travelling habits and energy mixes. Disregarding local air pollutants excludes an important component of transport externalities, especially in relation to the densely populated European urban areas. However, such an approach was taken to avoid dealing with too many spatially complex issues at once, leaving it to future research efforts. Finally, a further methodological aspect must be emphasized. The paper endeavours to provide an economic evaluation of the CO_2 emissions as a basis for taxation\subsidizing policies. Since some parameters of the model used to estimate the cost of CO_2 emissions are characterized by a high level of uncertainty, they are specified as random parameters and a Monte Carlo simulation technique is used to estimate values. Consequently, the results presented in the following sections are given as intervals instead of point estimates.

3. Methodology

This section describes the methodology used to estimate the cars' CO_2 emissions and their economic value. It includes a simulation model whose graphical illustration is provided in Fig. 1.

3.1. Methods to calculate CO_2 emissions

First, a methodological definition of the framework must be provided. The methods adopted to evaluate the transport impact of CO_2 emissions are rather heterogenic, including different phases of the fuel production and the emission phase. In this section, we present different conceptual approaches: Life Cycle Assessment, Well-to-Wheel analysis, including the Well-To-Tank and Tank-To-Wheel phases, which can be also considered as independent.

Life Cycle Assessment (LCA) covers the entire life cycle of the product, process or activity, encompassing the extracting and the processing of raw materials, manufacturing, transportation and distribution, use, re-use and maintenance, recycling, and final disposal (Cass and Mukherjee, 2011).

Well-To-Wheel analysis (WTW) covers two phases: fuel production and vehicle use (Nocera and Cavallaro, 2017). WTW is described through specific energy pathways, which include the primary energy source, the energy required for its extraction, transformation, transportation, fuel production and characteristics of the vehicle using the fuel. Differently from LCA, the vehicle production and decommissioning phases are not counted. WTW can be divided into two main separate steps: Well-To-Tank (WTT) and Tank-To-Wheel (TTW), which can be considered also independently.

Well-To-Tank analysis (WTT) describes the energy pathway necessary for the process of producing, transporting, manufacturing and distributing fuels suitable for transport powertrains. In its most general terms, the process can be broken down into five main phases (Edwards et al., 2013): the production and conditioning of the energy, the transformation of the energy at source, the transportation to market, the transformation near the market and the conditioning and distribution of the finished fuels to the individual refuelling points.

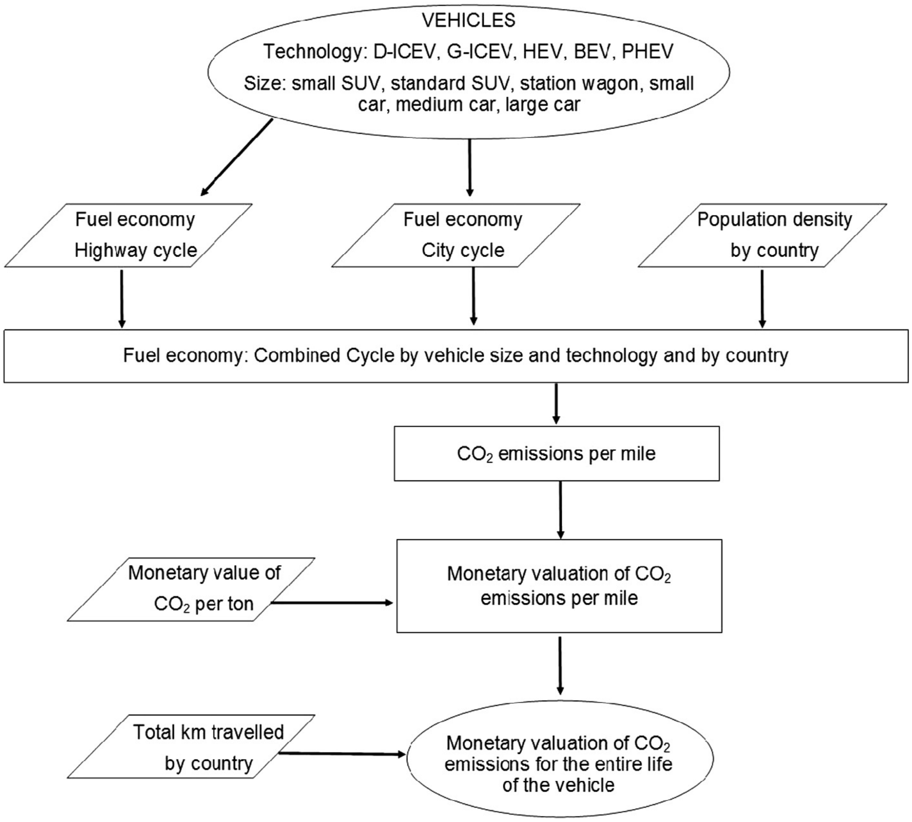

Fig. 1. Description of the methodology used.

Tank-To-Wheel analysis (TTW) quantifies the unitary energy expended and the unitary pollutant substances emitted by a vehicle during its driving cycle. It includes evaporative and tailpipe emissions during the operation of the vehicle. TTW is related to the efficiency of the vehicle and driving behaviour. Several studies consider only this phase in their CO_2 evaluation.

The choice of the most suitable method to adopt depends on the purpose of the study. By definition, LCA is a product-oriented approach, which implies a description of the process necessary to obtain industrial products by adopting estimated inventories and assuming uniform conditions. However, CO_2 cannot be assimilated to such products, because its emissions are highly dependent on territorial specifications. TTW presents a limited approach, which does not consider the production and distribution phases. For this reason, a WTW analysis seems an appropriate approach to assess the issues of alternative fuels and energy policies.

3.2. Vehicles

According to the taxonomy provided by Tie and Tan (2013), vehicles can be classified into three main groups: ICEVs, HEVs and EVs. ICEV has a combustion chamber to transform chemical energy to heat energy and kinetic energy to propel a vehicle. This class consists of two types of vehicles: conventional ICEV, which are powered by traditional fuels (diesel cars, D_ICEVs; gasoline cars, G_ICEVs), and micro-hybrid electric vehicles (micro-HEVs), which have an electric motor with low operating voltage 14 V (12 V) and power not higher than 5 kW.

HEVs are a combination of ICE and electric sources. Two main groups can be identified, the Mild-HEV and the Full-HEV. The Mild-HEVs are similar to micro-HEV but the electric motor in mild-HEV has an electric power of 7–12 kW with 150 V (140 V) operating voltage and can run the car together with ICE. Full-HEVs have a system characterized by a higher capacity of energy storage. According to the technologies adopted, we distinguish five types of Full-HEVs: the extended range electric vehicles, the parallel hybrid electric vehicles, the series hybrid electric vehicles, the complex hybrid electric vehicles and the plug-in hybrid electric vehicles (PHEVs).

EVs operate purely electrically. They use an electric motor for traction, and chemical batteries, fuel cells, ultra-capacitors, and/or flywheels for their corresponding energy sources (Ehsani et al., 2005). According to the technology adopted, EVs can be divided into Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs). This last category, which has been described in Nocera and Cavallaro (2016a), uses hydrogen and oxygen to create electricity by an electro-chemical process and is not analysed in this paper. BEVs adopt a battery as storage device: it consists of one or more electrochemical cells that convert the stored chemical energy into electrical energy. Five main types of batteries are available: Lead acid battery, Nickel battery, ZEBRA battery, Lithium battery and Metal-air battery. Due to the high efficiency (up to 95%), lithium-ion battery (which is a sub-class of Lithium battery) is the most

Table 1
Fuel economy and average emissions of the different vehicle classes.

	Fuel economy			TTW (combined)	Fuel economy			TTW (combined)
	City MPG (non BEV) kWh (BEV)	Highway MPG (non BEV) kWh (BEV)	Combined MPG (non BEV) kWh (BEV)	CO_2/mile	City MPG (non BEV) kWh (BEV)	Highway MPG (non BEV) kWh (BEV)	Combined MPG (non BEV) kWh (BEV)	CO_2/mile
Small cars					*Medium sized cars*			
D_ICEV	32	42	36	284	26	39	31	331
G_ICEV	21	29	24	391	24	33	27	344
HEV	42	41	41	221	42	42	42	219
BEV	3.69	3.00	3.36		3.25	2.77	3.02	
PHEV (charged)	101	99	100	94.9	96	87	92	103.6
PHEV (depleted)	56	58	56	168.5	39	38	39	245.5
Large cars					*Station wagon*			
D_ICEV	24	36	28	360	30	40	34	299
G_ICEV	20	29	23	407	23	31	26	348
HEV	34	35	51	180	44	40	42	211
BEV	2.85	2.93	2.90		3.45	2.70	3.04	
PHEV (charged)	71	79	77	123.3	95	95	95	99.9
PHEV (depleted)	45	50	52	184.3				
Small SUV					*Standard SUV*			
D_ICEV	26	33	29	363	22	29	24	421
G_ICEV	21	28	24	378	16	21	18	505
HEV	33	31	32	280	29	28	29	315
BEV	–	–	–		2.49	2.48	2.50	
PHEV (charged)	–	–	–		148	148	148	64.1
PHEV (depleted)	–	–	–		148	148	148	64.1

popular power source, but it is still rather expensive if compared to traditional ICEV. To overcome this critical aspect, van Essen and Kampman (2011) indicate that each battery generation is likely to be in production for at least four to five years to recoup capital investments and R & D costs.

According to the US Environmental Protection Agency database (EPA, 2016), cars can be distinguished, among other features, by vehicle class and by the fuel and\or type of engine used. EPA (2016) lists more than 2500 cars, specifying their technical characteristics, including fuel, vehicle class, fuel economy (city MPG, highway MPG, combined MPG) and combined CO_2 emissions. Of these, we selected 456 models, focusing on those on sale in Europe, and adding 5 BEVs on sale in Europe only. The final sample consists of 461 cars. Distinguishing the cars by vehicle class, adopting the EPA classification,[1] the sample consists of 197 small cars, 77 medium cars, 37 large cars, 68 small SUVs, 59 standard SUVs, 23 station wagons.[2] Distinguishing the cars by fuel used or engine technology, in the database there are 18 diesel cars (D_ICEVs), 402 gasoline cars (G_ICEVs), 15 HEVs, 13 BEVs, and 13 PHEVs. Classifying the cars both by "size" (σ) and by "fuel\engine technology" (η), 30 different car sub-segments are identified. In the simulation model, a car is specified as a uniformingly distributed discrete random variable $V_{\sigma\eta}$ (with $\sigma = 1,\ldots,6$; $\eta = 1,\ldots,5$).[3] An alternative, not yet implemented for lack of data, would be to consider the current European market share of each car model, and use it as the density probability function of the random variable.

3.3. Data on fuel economy and CO_2 emissions driving cycles

For most cars, the EPA database provides fuel economy estimates of the driving cycle (city, highway, combined) and of the combined TTW CO_2 emissions.[4] Table 1 shows the average values for each size class in terms of the miles per gallon for diesel cars, for petrol cars or for HEVs, in terms of miles per kWh for BEVs, and in terms of miles per gallon for PHEVs, distinguishing between the fuel economy with a charged or depleted battery. It can be noted that the efficiency level varies significantly by vehicle segment.

[1] There are numerous car classification schemes, developed by governments and private organizations for innumerable purposes including regulation, description and categorization. The EPA vehicle classification class is mainly based on size; the European one is based on A to J market segments.

[2] "Station wagon" (or "estate car") is an automobile with one or more rows of folding or removable seats behind the driver and no luggage compartment but an area behind the seats into which suitcases, parcels, etc., can be loaded through a tailgate.

[3] The index σ represents the 6 car segments: small cars, medium cars, large cars, small SUVs, standard SUVs, station wagons. The index η identifies the 5 engine technologies: D_ICEV, G_ICEV, HEV, BEV, PHEV.

[4] It is measured through the Corporate Average Fuel Economy (CAFE; Kühlwein et al., 2014), based on the assumption that the driving cycle consists of 55% city and 45% highway driving. We have decided to adopt the American rather than the European evaluation system due to accuracy reasons. Indeed, both systems are known to underestimate real life emissions. However, the European values are lower than the American ones and the lack of aggressive driving and high load conditions makes the European method particularly weak in diesel estimations. For these reasons, American standards have been preferred. When only European values were available, we have converted them to American ones by a specific software provided by ICCT (2016).

Table 2
Characteristics of European countries in terms of density and average annual distance travelled.

Country	Code	Population density ab/km^2	Annual distance travelled by a vehicle km	Country	Code	Population density ab/km^2	Annual distance travelled by a vehicle km
Austria	A	102	86,012	Italy	I	201	94,062
Belgium	B	367	92,422	Latvia	LV	31	63,652
Bulgaria	BG	65	57,540	Lithuania	LT	45	71,851
Croatia	HR	75	97,342	Luxembourg	L	218	106,435
Cyprus	CY	92	56,944	Malta	M	1363	42,932
Czech Republic	CZ	134	64,845	Netherlands	NL	407	73,193
Denmark	DK	132	86,012	Poland	PL	122	63,652
Estonia	EST	29	63,652	Portugal	P	112	64,248
Finland	SF	16	99,429	Romania	R	83	32,050
France	F	105	114,261	Slovakia	LK	111	45,615
Germany	D	227	92,571	Slovenia	SLO	102	97,342
Greece	GR	82	71,404	Spain	ES	92	63,354
Hungary	HU	106	57,839	Sweden	S	22	100,472
Ireland	IRL	66	81,093	United Kingdom	UK	261	86,758

3.4. An estimate of the combined fuel economy for the European countries

The EPA combined fuel economy estimates are based on the assumption that the driving cycle consists of 55% city and 45% highway driving. Because of the huge geographical differences between the USA and Europe and the heterogeneity within European countries, we have estimated a European country-specific combined cycle, E_CMB_{κ} (with $\kappa = 1, \ldots, 28$), using an adjustment factor based on the population density of each country (Table 2). In order to take into account the uncertainty connected with this estimate, this variable enters the model as a normally distributed random variable. The distance travelled on average by a vehicle for each European country is based on a study provided by the French national railway company (SNCF, 2013). Our analysis assumes a lifespan of a vehicle equal to 10 years.

Specific attention needs to be paid to PHEVs. EPA provides two fuel economy estimates, termed "charged" and "depleted", meaning the fuel economy that could be realized using a fully charged or a depleted battery. We combined the two estimates assuming that 40% of the trips are made with a charged battery. Our assumption may be too conservative since recent evidence suggests that PHEVs in Norway make use of the all-electric mode for about 55% of their mileage (Figenbaum and Kolbenstvedt, 2016). The uncertainty of this parameter is accounted for by specifying this variable as a normally distributed random parameter with a mean equal to 0.4 and a standard deviation equal to 0.1.

3.5. An estimate of the country-specific WTW CO_2 emissions for non-BEVs

The EPA estimate of the TTW combined cycle CO_2 emissions for each vehicle class, corrected by the ratio of the EPA estimated fuel economy over our estimate of the European country-specific fuel economy, allows us to estimate a European country-specific TTW CO_2 combined emission. Such estimate is performed for each size class and fuel\engine technology.

The estimate of the WTT CO_2 emissions associated with extraction, refining, distribution, storage and retail of the conventional fuels is based on the European value derived from Edwards et al. (2013), as explained in Nocera and Cavallaro (2016b). The values are equal to 2016 gCO_2 per gallon for diesel and 1694 gCO_2 per gallon for gasoline. The WTT CO_2 emissions per car sub-segment are obtained by dividing this value by the relative fuel economy.

The sum of the two variables, country-specific TTW CO_2 combined emissions and WTT CO_2 emissions, represents the country-specific WTW CO_2 combined emission variable, termed $nonBEV\_\Psi_{\sigma\eta\kappa}$.

3.6. An estimate of the country-specific WTW CO_2 emissions for BEVs

The starting point is the estimate of BEVs' CO_2 emissions per kWh for the 28 European countries provided by IEAA (EU Commission, DG ENER, 2016). Table 3 displays the data together with the 2014 country-specific energy mixes. In absolute terms, relevant differences can be noted: Sweden has the lowest value (128 gCO_2/kW h), since electricity is primarily produced by nuclear and renewable sources, while Greece has the highest value (1057 gCO_2/kW h).

The country-specific CO_2 emissions of BEVs by size class is then derived by applying the above described E_CMB_{κ} variable to the country-specific BEVs' CO_2 emissions per kWh. Such variable is specified as $BEV\_\Psi_{\sigma\eta\kappa}$. To account for the battery production and the disposal, an additional value of 30 g/CO_{2eq} per car has been included, drawing from Hawkins et al. (2013b).

By combining the non-BEV and the BEV estimates previously shown, one obtains the random variable $\Psi_{\sigma\eta\kappa}$ (with $\sigma = 1, \ldots, 6$; $\eta = 1, \ldots, 5$; $\kappa = 1, \ldots, 28$).

Table 3
Energy mixes of European countries.
Source: EU Commission, DG ENER, 2016.

	gCO_2/kW h	Coal (%)	Petroleum (%)	Gases (%)	Nuclear (%)	Renewables (%)		gCO_2/kW h	Coal (%)	Petroleum (%)	Gases (%)	Nuclear (%)	Renewables (%)
Austria	249	6	1	13	0	79	Italy	361	16	5	39	0	39
Belgium	472	4	0	28	51	16	Latvia	180	0	0	43	0	57
Bulgaria	722	44	1	5	32	17	Lithuania	180	0	4	47	0	44
Croatia	472	17	2	14	0	67	Luxembourg	326	0	0	49	0	49
Cyprus	713	0	92	0	0	8	Malta	765	0	98	0	0	2
Czech Republic	670	48	0	5	35	12	Netherlands	490	24	1	58	3	12
Denmark	300	41	1	10	0	46	Poland	719	84	1	4	0	11
Estonia	782	87	1	3	0	9	Portugal	808	23	3	14	0	59
Finland	257	20	0	10	33	36	Romania	498	29	1	16	20	35
France	593	4	0	3	74	18	Slovakia	361	11	2	10	55	23
Germany	636	45	1	13	15	25	Slovenia	713	30	0	3	33	34
Greece	1057	46	10	19	0	25	Spain	679	14	5	21	20	41
Hungary	464	21	0	19	51	9	Sweden	128	1	0	1	43	54
Ireland	584	25	1	51	0	23	United Kingdom	619	36	1	27	20	16

Table 4
Main descriptive statistics of GHG economic value.

Main descriptive statistics of GHG economic value	
	All sample (€/tCO_2)
Mean	56.78
Median	17.54
Std dev	137.27
N. obs.	699

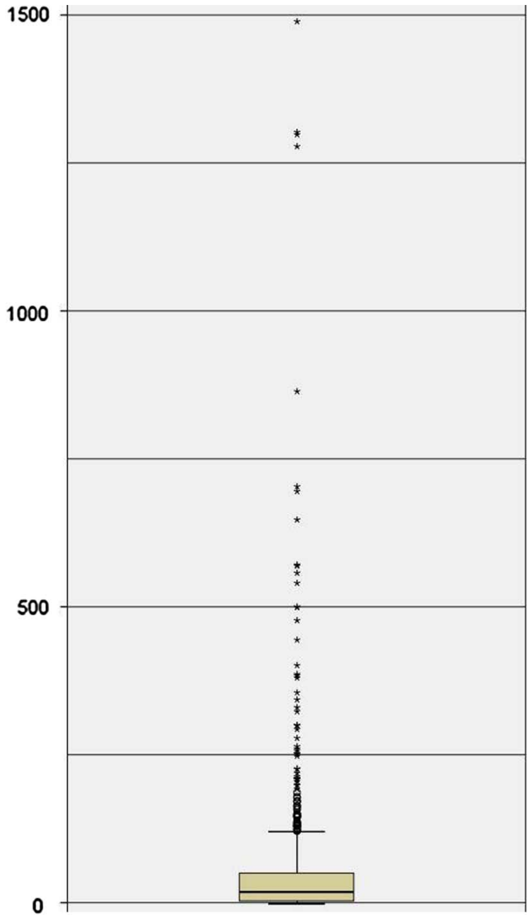

Fig. 2. Box plot of the observations about CO_2 economic values.

3.7. Estimates of the monetary value of a ton of CO_2

The estimates of the unitary economic value of CO_2 emissions proposed in the literature are quite numerous. Nocera et al. (2015a) have been able to track 699 estimates deriving from 60 studies (mostly published between 2004 and 2012). Originally expressed in $/tC, we have reported them in this paper to €/tCO_{2eq},[5] in order to make them coherent to the European scale selected in our analysis. The mean (Table 4) is €56.78/tCO_{2eq} (std. dev 137.27). The range varies from −€2.06 to €1488.83. The high standard deviation means that there is high variability in the economic values of climate change and that these values are spread out over a broad range (which is visible in Fig. 2). The negative values mean that climate change can initially have positive impacts on society and environment.

In order to account for the large heterogeneity of these estimates, the monetary value is quantified as a random variable u, characterized by a uniform distribution, meaning that each estimate is assigned the same probability of being the true one. This is due to the numerous objective and subjective uncertainties that we have discussed in Nocera et al. (2015a). Referring particularly to the

[5] The conversion from $/tC to $/$tCO_{2eq}$ can be made by adopting the relation: $1tC = 3.664 \times 1tCO_{2eq}$ (Metz, 2001). To report value from $ to €, we have adopted the official exchange rates provided by the Bank of Italy (2017).

latter, we can list the future level of emissions, concentrations and temperatures, climate impacts resulting from an increased CO_{2eq} concentration, physical impacts associated with climate change, economic damage, equity weight, discount rate, adaptation and mitigation. All these aspects make the selection of a single value complicated, if not arbitrary, thus confirming the appropriateness of the uniform distribution. An interesting enhancement, not yet applied, would be to provide an index reflecting the credibility of each estimate, based on some subjective or objective indicators. This would allow us to apply a non-uniform probability distribution.

3.8. *The monetary value of CO_2 emitted during the entire life of a car*

The WTW CO_2 emissions produced per mile travelled by size class, by fuel\vehicle technology and by country are then multiplied by the monetary value of CO_2 per gram, obtaining the monetary value of the CO_2 emissions produced per mile travelled by vehicle category in each country (formula (1)).

$$\Theta_{\sigma\eta\kappa} = \Psi_{\sigma\eta\kappa} \times \upsilon \tag{1}$$

where

Θ is the economic valuation of WTW CO_2 emissions per mile;
Ψ is the quantity of WTW CO_2 emissions per mile;
υ is the unitary value assigned to one ton of CO_2 emissions;
σ is the size of the car (distinguishing between small cars, medium cars, large cars, small SUVs, standard SUVs, station wagons);
η is the "fuel\engine technology" (distinguishing between D_ICEV, G_ICEV, HEV, BEV and PHEV);
κ is the European country object of the analysis.

This value is then multiplied by the number of miles travelled on average by a vehicle in each country over its entire life (Table 2), obtaining the monetary value of the total CO_2 emitted by each vehicle segment for each country over its entire lifetime (formula (2)):

$$\Upsilon_{\sigma\eta\kappa} = \Theta_{\sigma\eta\kappa} \times Z_{\kappa} \tag{2}$$

where

Θ, σ, η, κ are defined above;
Z is the average distance (expressed in mile) covered by a vehicle (see Table 2);
Y is the economic valuation of WTW CO_2 emissions of a vehicle over its entire life cycle.

To summarize, the sources of uncertainty accounted for are: the population density used to generate the country-specific combined driving cycle, the percentage of miles driven in electric mode by PHEVs, and the monetary value of CO_2. A Monte Carlo simulation is performed with 10,000 draws. Finally, the difference between the monetary value of CO_2 emitted by specific car and that of a BEV can be interpreted as the economically justifiable subsidy (if positive) or tax (if negative) that BEV can be attributed relative to another specific fuel\engine technology of the same size class (formula (3)):

$$Subsidy\backslash tax = non\text{-}BEV\,\Upsilon_{\sigma\eta\kappa} - BEV\,\Upsilon_{\sigma\eta\kappa} \tag{3}$$

4. Main findings

Since results are reported in 30 × 28 matrices, country-specific values are shown in Appendixes. In this section, the main considerations are presented at the aggregate European level. Table 5 displays the average CO_2 emissions per mile (in grams) for each car

Table 5
Average unitary CO_2 emissions (grams per mile).

	EU average	EU min	EU max	EU average	EU min	EU max	EU average	EU min	EU max
	Small cars			Medium-sized cars			Large cars		
D_ICEV	347	304	369	412	340	450	455	372	498
G_ICEV	479	405	517	417	360	447	502	418	546
HEV	262	260	266	260	259	261	155	153	156
BEV	187	69	352	205	73	386	213	74	395
PHEV	149	144	152	191	190	192	169	157	175
	Small SUV			Standard SUV			Station wagon		
D_ICEV	438	390	463	516	447	552	366	318	390
G_ICEV	460	402	490	611	536	650	425	368	454
HEV	333	326	346	368	365	374	252	246	262
BEV	–	–	–	243	82	456	201	73	381
PHEV	–	–	–	175	175	175	168	168	168

segment\engine technology. In the small car segment, G_ICEVs have the highest average CO_2 emissions, followed by the D_ICEVs. HEVs have much lower values. On average, PHEVs are slightly lower than BEVs, although, depending on the country, BEVs range from a very low average level (69 g/mile in Sweden; see Appendix A) to a very high level (352 g/mile, similar to the D_ICEVs, in Greece). The striking difference can be easily attributed to the different energy mixes (see Table 3). PHEVs show a much lower variation. In the medium-sized car segment, results are similar. However, the difference between G_ICEVs and D_ICEVs is smaller and BEVs are slightly better than PHEVs, although with a large variation. In the large car segment, PHEVs are again on average better than BEVs, with the extreme cases of Sweden and Greece. No comparison can be made in the small SUV segment for lack, so far, of available BEVs and PHEVs models. In the station wagon segment, the ranking is similar to the previous ones, with PHEVs slightly better than BEVs.

Table 5 reports the average CO_2 emissions per mile values across countries (values referred to the single Country are visible in Appendix B). The examination of the values for each country, keeping track of 10,000 simulation runs, reveals that D_ICEVs and G_ICEVs are always worse than BEVs in any European country. This outcome is in line with results deriving from Messagie et al. (2014), Abdul-Manan (2015) and UCS (2015).

On the converse, HEVs are better than BEVs:

- in the small car segment: in Estonia and Portugal (1% of the runs) and in Greece (100% of the runs);
- in the medium-sized car segment: in Bulgaria, Cyprus, Estonia, Greece, Poland, Portugal and Slovenia (100% of the runs);
- in the large car segment: in all countries, except for Austria, Denmark, Finland, Latvia, Lithuania, Luxembourg and Sweden (100% of the runs), Italy and Slovakia (73% and 16% of the runs, respectively);
- in the standard SUV car segment: only in Greece;
- in the station wagon car segment: in Bulgaria, Estonia, Greece and Portugal (100% of the runs); in other countries (Cyprus, Poland, Slovenia and Spain) most of the runs.

PHEVs are also superior to BEVs at least 80% of the runs for most countries and segments:

- in the small car segment: in 19 countries;
- in the medium-sized car segment: in 14 countries;
- in the large car segment: in 19 countries;
- in the standard SUV car segment: in 21 countries;
- in the station wagon car segment: in 18 countries.

In other countries, PHEVs are not always superior to BEVs: there are simulation runs in which the opposite is true. These findings are consistent with the results obtained by Doucette and McCulloch (2011), but in contrast with the evaluations of Thiel et al. (2010). However, these latter use emission coefficients referring to the year 2008, and do not specify the percentage of use of the electric mode, which is one of the major critical aspects in the evaluation of PHEV emissions (Marshall et al., 2013).

Figs. 3–7 and Table 6 display our main conclusions regarding the monetary value of CO_2 emissions between non-BEVs and BEVs, by car size. Such a difference might be interpreted as the amount of subsidies or taxes that are economically justified on the basis of the social costs of CO_2. The country-specific results are displayed in Appendixes C and D (in this case, minimum and maximum values are also provided). The average values range from −€1133 (tax) to +€3192 (subsidy), depending on the car segment and on the country considered.

In the small car segment (Fig. 3), BEVs should always be subsidised relative to D_ICEVs, G_ICEVs, and HEVs. However, the exact

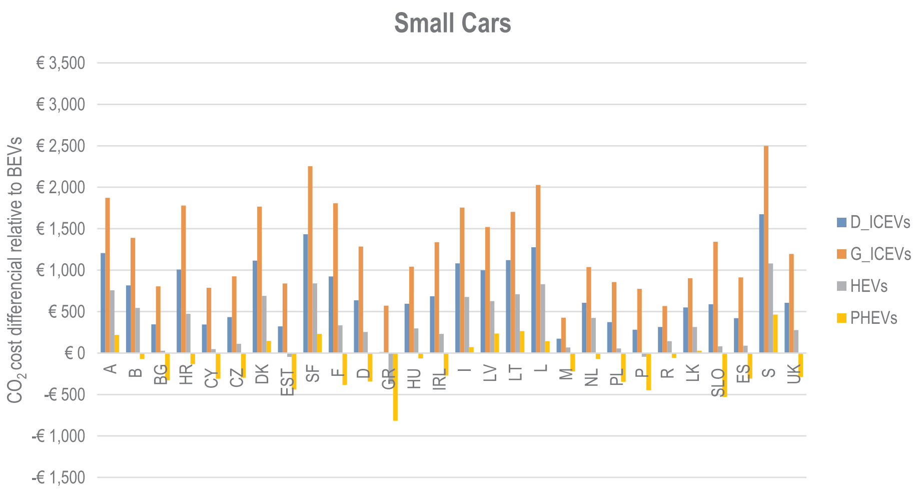

Fig. 3. Monetary value of the difference of CO_2 emissions between non-BEVs and BEVs, small cars.

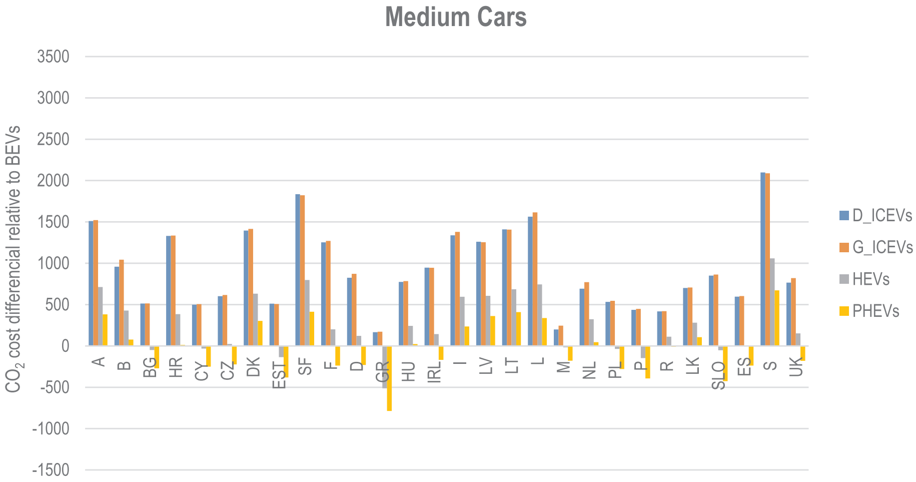

Fig. 4. Monetary value of the difference of CO_2 emissions between non-BEVs and BEVs, medium cars.

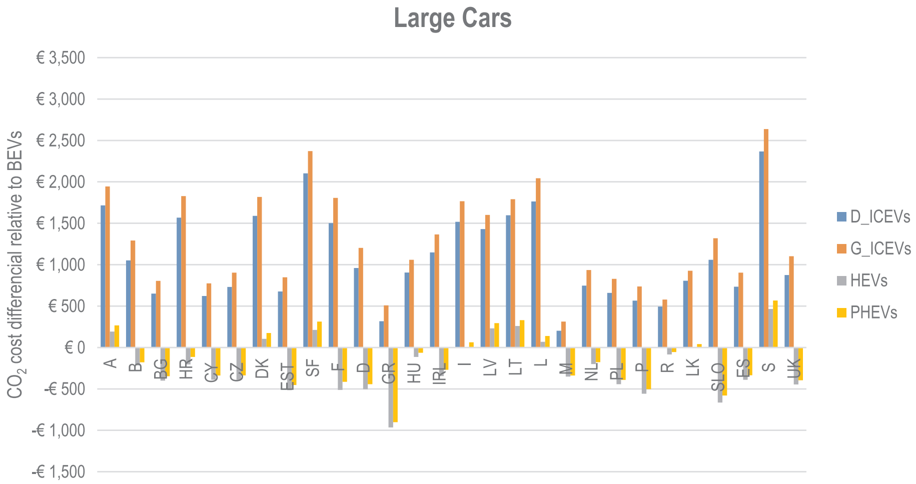

Fig. 5. Monetary value of the difference of CO_2 emissions between non-BEVs and BEVs, large cars.

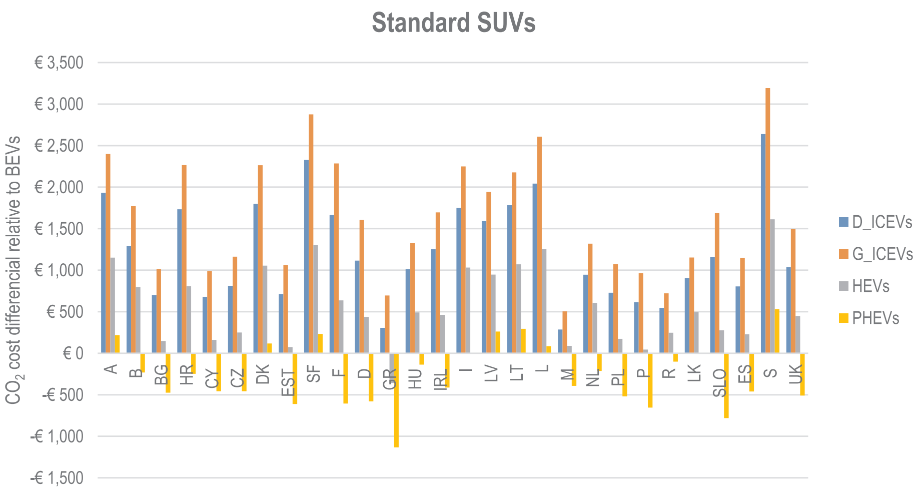

Fig. 6. Monetary value of the difference of CO_2 emissions between non-BEVs and BEVs, standard SUVs.

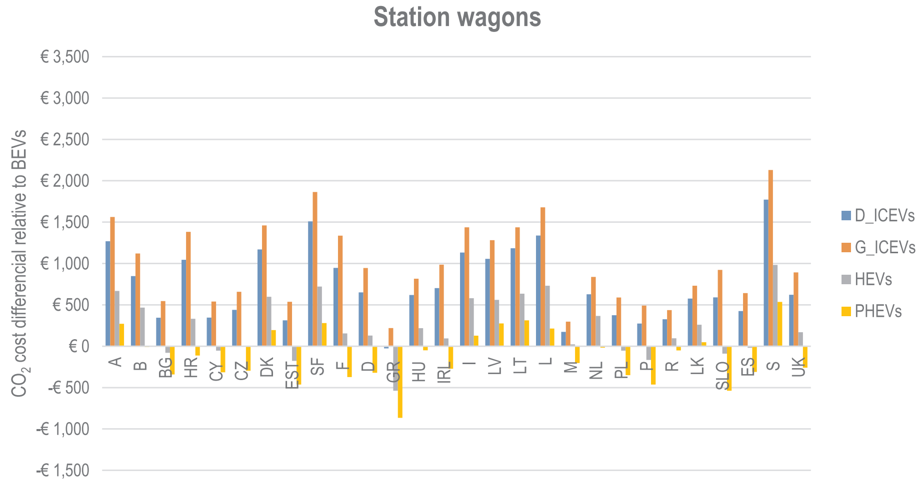

Fig. 7. Monetary value of the difference of CO_2 emissions between non-BEVs and BEVs, station wagons.

Table 6
Monetary value (€$_{2010}$) of the difference of CO_2 emissions between non-BEVs and BEVs at the European level.

	EU average	EU min	EU max	EU average	EU min	EU max	EU average	EU min	EU max
	Small cars			Medium-sized cars			Large cars		
D_ICEV	712	11	1674	928	166	2099	1084	202	2368
G_ICEV	1285	426	2500	946	172	2089	1286	313	2638
HEV	340	−371	1081	260	−512	1058	−220	−965	466
PHEV	−141	−817	463	−31	−787	672	−159	−901	568
	Small SUV			Standard SUV			Station wagon		
D_ICEV	–	–	–	1220	285	2638	737	−27	1772
G_ICEV	–	–	–	1630	504	3192	992	219	2129
HEV	–	–	–	569	−359	1613	236	−538	983
PHEV	–	–	–	−259	−1133	531	−120	−865	535

amount depends on the country, with large variations between the minimum and maximum values (see also Appendix D). Relative to D_ICEVs and G_ICEVs, the minimum values are obtained in Greece and the maximum values in Sweden. In Greece (but also in Portugal and in Estonia), BEVs should be taxed also relative to HEVs. Relative to PHEVs, BEVs' subsidies are justified only in some countries.

In the medium-sized car segment (Fig. 4), BEVs should be on average subsidised relative to all other fuel\engine technologies but with lesser amounts, except for PHEVs (in 14 Countries) and HEVs (these latter only in Bulgaria, Cyprus, Estonia, Greece, Malta, Poland, Portugal and Slovenia).

In the large car segment (Fig. 5), BEVs should be on average subsidised only relative to D_ICEVs and G_ICEVs, while in the majority of the countries they should be taxed relative to HEVs and PHEVs (exceptions are Austria, Denmark, Finland, Italy, Latvia, Lithuania, Luxembourg, Slovakia and Slovenia).

In the standard SUV segment (Fig. 6), BEVs should be, on average, subsidised relative to all segments but PHEVs and in some countries the subsidies should be substantial (up to more than €3000). Taxes are justified only if BEVs are compared to PHEVs.

Finally, in the station wagon segment (Fig. 7), BEVs should be, on average, subsidized relative to all other fuel\engine technologies, with the exception of PHEVs and HEVs (these latter only in few countries). The subsidies should however be smaller than in the other segments.

5. Discussion and policy implications

The results presented in the previous section and in the appendixes A-D show that the European panorama is rather varied. A specific technology cannot provide optimal results in terms of reduction of CO_2 emissions. Indeed, a distinction should be made according to the vehicle class and the country considered.

However, despite such differences, some general considerations can be made. First, ICEVs are found to be more carbon polluting than other vehicles powered by alternative fuels. Second, the energy mix is fundamental to determine the carbon efficiency of alternative fuels: in those countries where the energy mix is mostly based on traditional sources (e.g., petrol, coal), PHEVs (and in some cases even HEVs) are found to be less carbon emitting than BEVs – as is the case of Greece, Estonia, Slovenia and the United Kingdom. This is particularly valid for vehicles characterized by higher fuel consumption (i.e., SUVs and large cars), even if PHEVs

Table 7
Incentives for new EVs in EU countries.
Source: ACEA, 2016, modified.

Country	Year 2016		
	Purchasing incentives	Registration tax	Yearly incentives
Austria	Local incentives for EVs.	None	EVs: exemption from the fuel consumption tax and from the monthly vehicle tax
Belgium	Incentives for EVs and FCEVs	EVs and PHEVs: exemption from registration tax in the Flemish Region	EVs: minimum rate of the annual circulation. Company cars: 120% deductibility rate from corporate income of expenses for zero-emissions vehicles and 100% for vehicles emitting 1–60 g CO_2/km
Bulgaria	None	None	EVs: exemption from the annual circulation tax
Croatia	None	None	None
Cyprus	None	None	None
Czech Republic	None	None	EVs, HEVs, PHEVs: exemption from the road tax
Denmark	None	EVs: exemption from registration tax	None
Estonia	None	None	None
Finland	None	EVs: minimum rate of the CO_2 based registration tax	None
France	EVs, PHEVs, HEVs: €750 for vehicles emitting 61–110 g CO2/km; €1000 for vehicles emitting 21–60 g; €6300 for vehicles emitting 0–20 g	EVs, HEVs, CNG, LPG, and E85: option for an exemption from the registration tax (100% or 50%)	EVs: exemption from the company car tax. HEVs: exemption for the first two years after registration
Germany	Incentives up to €4000 for BEVs, up to €3000 for HEVs	None	EVs: exemption from the annual circulation tax (10 years validity)
Greece	None	EVs and HEVs: exemption from registration tax	EVs and HEVs: exemption from luxury tax EVs and HEVs up to 1549 cc: exemption from circulation tax
Hungary	None	EVs: exemption from registration tax	EVs and HEVs: exemption from annual circulation tax and company car tax
Ireland	BEVs and PHEVs: grant of up to €5000 on purchase	BEVs, PHEVs, HEVs: benefit from vehicle registration tax up to a maximum of €5000, €2500 and €1500, respectively	EVs: minimum rate (€120) of the road tax
Italy	None	None	EVs: exemption from the annual circulation tax (ownership tax) for 5 years. Afterwards, 75% reduction of the tax rate
Latvia	None	EVs: exemption from registration tax	EVs: minimum rate (€10) for the company car tax
Lithuania	None	None	None
Luxembourg	None	None	EVs: minimum rate (€30) for the annual circulation tax
Malta	None	None	None
Netherlands	None	EVs: exemption from registration tax	Vehicles emitting max. 50 g CO_2/km are exempt from the annual circulation tax
Poland	None	None	None
Portugal	None	EVs: exemption from registration tax	EVs: exemption from the annual circulation tax HEVs: payment of 25% of registration tax
Romania	None	EVs, HEVs: exemption from registration tax	EVs: exemption from the annual circulation tax
Slovakia	None	None	EVs: exemption from the annual circulation tax HEVs: 50% reduction of the annual circulation tax
Slovenia	None	None	None
Spain	None	None	EVs: 75% reduction of the annual circulation tax
Sweden	PHEVs: SEK20,000 EVs: SEK40,000	None	EVs, PHEVs: 5-year exemption from the annual circulation tax; reduction of company car taxation
United Kingdom	None	None	EVs, HEVs, PHEVs below 100 g/km: exemption from the annual circulation tax BEVs: exemption from the company car tax, HEVs, PHEVs $<$ 50 g/km: 5% discount for the car tax

appear also on the segment of small and medium cars (in 19 and 14 out of the 28 EU countries, respectively).

These facets have some relevant implications also in terms of national policies. At the EU level, every Country decides its approach autonomously. This national decision generates relevant differences (Table 7): in some cases (e.g. Croatia, Slovenia), no incentives are given. In other cases, they are limited to the exemption from the circulation tax (e.g. Czech Republic, Italy). In some other countries (e.g., Belgium, France, Sweden), besides the exemption from the circulation tax, also vehicle purchasing incentives and/or the exemption from the registration tax are provided.

The greatest incentives, either in terms of purchasing incentive impact or in terms of the impact of reduction/abolishment of the registration and circulation taxes, are provided for BEVs, while the contributions for other vehicles (HEVs, PHEVs) are normally lower. In some countries (e.g., Latvia, where BEVs are exempt from the registration tax), this choice is supported also by the results of the WTW analysis of CO_2 emissions presented in Section 4. However, in some other countries BEVs are not the least polluting solution. The case of Ireland is emblematic: here, the reduction of the vehicle registration tax can be up to a maximum of €5000, €2500 and €1500, respectively for BEVs, PHEVs, HEVs. Our evaluations have found that PHEVs are always less emitting than BEVs and, limited to large cars, also HEVs are less emitting. The Bulgarian case is similar: here, only BEVs are exempted from the annual circulation tax. However, Figs. 3–7 show that in this country, PHEVs are less emitting for each car segment.

On a policy level, incentives are the object of controversial discussions about their actual utility. Beresteanu and Li (2011) and Gallagher and Muehlegger (2011) find that they are positively correlated to HEV sales, but Zhang et al. (2013) identify only a very weak relationship between purchase subsidies and consumer willingness to buy EVs. Regarding BEVs, OECD (2011) is convinced that the rationale for subsidizing or otherwise promoting EVs in these instances cannot be principally for direct CO_2 mitigation but rather for developing a market in anticipation of the development of low carbon electricity production. Their analysis reveals that subsidies may be superfluous and that where they do not compare favourably, the bonus is on demonstrating that subsidies are economically justified. Prud'homme and Konig (2012) underline the mileage problems behind a fair evaluation of the subsidies. The idea that EVs could be a general substitute to ICEVs is not acceptable. It can only be, at best, a niche market. BEVs appear as a gamble on the part of producers and governments. Until massive cost and efficiency improvements are achieved, they require enormous subsidies. Sierzchula et al. (2014) find that fiscal incentives are significant and positively correlated to a country's EV market share, but the infrastructural ones seem to be more effective. Since these two factors are complimentary, the support of both measures could lead to higher market shares than focusing on either financial incentives or charging infrastructure alone.

By considering a broader temporal scale, a stronger diffusion of BEVs should redefine the approach about the subsidies, also in view of an adequate fiscal system. Tscharaktschiew (2015) affirms that fuel is likely to be undertaxed in many countries. However, as this is one large source of revenue generation for infrastructures, its reduction can cause relevant maintenance problems (Jenn et al., 2015). The emergence of electric mobility could contribute to a better definition of the current taxation, which several scholars consider economically inefficient (West and Williams, 2007; Parry and Timilsina, 2010; Mayeres and Proost, 2013). Recalling data about EVs as presented in the introduction, these issues can be referred to a broader temporal horizon, once that EVs have become a competitive alternative to traditional fuels.

6. Conclusions

The paper has assessed whether BEVs' subsidies in Europe are justified in terms of carbon reduction and by what amount, differentiating by car segments and countries. In order to answer these research questions, a simulation model was developed, based on the most recent and reliable data available. The model estimates the WTW CO_2 emissions of five car segments in 28 European countries and monetizes CO_2 emissions making use of the available CO_2 monetary evaluation studies. It was determined that the monetary value of the difference of the CO_2 emissions between non-BEVs and BEVs ranges from −€1133 (tax) to +€3192 (subsidy), depending on the car segment and on the country considered.

The model allows internalising some of the great uncertainties that we have found in CO_2 quantification and evaluation during our previous analyses (Nocera et al., 2015a). However, at least two caveats apply. First, regarding the single parameters analysed in the model, unitary emissions and fuel economy are probably the most relevant aspects to be further investigated. We have based our evaluations on the values provided by EPA (2016), which are known to be closer to real values than the European methodology (see Section 2 for further details). However, real-world fuel consumption and CO_2 emissions are found to be 20–40% higher than these estimations (Wolfram and Lutsey, 2016). Our estimate could be improved by increasing the number of models included in the non-G_ICEVs category. Moreover, a specific analysis of the environmental cost of producing and discharging the batteries could be added and could be taken into account to estimate the value of an economically justifiable subsidy or tax.

Second, the legislation regarding alternative vehicles considers only the TTW phase and not the whole WTW approach. Accordingly, the tailpipe emissions of BEVs are 0, while those of vehicles powered by other fuels are higher. By considering this restricted limitation, BEVs are the least polluting vehicles. However, TTW seems a rather limited approach to deal with the carbon issue, because the production and distribution of fuels and energy are a fundamental component of the process (Svennson et al., 2007). The passage from a WTW analysis to a LCA could include some additional information, as it takes into account also the phases of components manufacturing, vehicle assembly and recycling. However, these phases have been found to be small contributors to life-cycle energy use and CO_2 emissions (Dunn et al., 2015), so WTW boundaries seem adequate for this type of analysis.

Some final considerations can be also drawn, regarding the policy implications in terms of energy and transport. By comparing the economic valuation of CO_2 emissions with the incentives given to alternative vehicles in each EU country (Table 7), we have shown in which instances subsidies to BEVs can be justified in terms of carbon reduction. Here, the energy mix again plays a major role. In those countries where the energy mix is based on renewable or alternative primary sources (e.g. Sweden and Latvia), the incentives to BEVs are fully justified in terms of carbon savings. In other cases, where the energy production is still based on traditional sources (e.g. Estonia and Greece), the adoption of subsidies to BEVs is not an actual contribution to the reduction of CO_2 emissions. Indeed, it can be confirmed as a stimulus to incentivize a market penetration of BEVs, to be carried out together with a contextual modification of the energy policy. Regarding this point, in 2014 about 53% of the EU-28′s gross inland energy consumption came from imported sources (Eurostat, 2017). A further growth of BEVs could increase this dependency. These aspects pose relevant issues about the real sustainability of electric mobility with reference to the European energy policies. Capros et al. (2016) have recently discussed these aspects referred to a more general context. They developed specific future scenarios that vary, among the others, according to the variation in final energy demand in transport by fuel type.

Second, even if one of the most important aspects, CO_2 emissions are only one of the elements that contribute to the definition of the national policies concerning incentives and taxations. There are other transport externalities to be considered in the definition of the most adequate policies, and they should include at least accidents, air pollution, climate change and noise (Jochem et al., 2016). Hirte and Tscharaktschiew (2013), for instance, determined the optimal subsidy rate through a more comprehensive analysis, which includes also tax interaction effects, changes in travel costs (or differences in travel costs between conventional fuel-powered cars and EVs) and redistribution effects. They found that EVs should not be subsidized but taxed.

Third, a robust policy to improve the efficiency of alternative vehicles should include not only the aspects related to the subsidies to the drivers, but also other measures, such as the development of adequate recharging infrastructures and other integrative measures (preferential access to lanes, management of parking areas or low-emission zones).

Decisions taken today, particularly those related to the redesign of the vehicular fleet, and the location and design of the transport infrastructures necessary for BEVs, affect how well the transport system adapts to climate change far into the future. Focusing on the problem effectively should help avoid costly future investments and disruptions to operations, on the way to providing guidance for transport decision makers on how best to proceed along this path.

Appendix A. Average WTW CO_2 emissions per mile by country (grams)

	A	B	BG	HR	CY	CZ	DK	EST	SF	F	D	GR	HU	IRL
Small cars														
D_ICEV	354	311	347	364	361	341	346	352	369	350	332	354	362	357
G_ICEV	491	417	479	509	504	468	478	488	517	484	453	492	506	496
HEV	261	265	262	261	261	263	262	262	260	262	263	261	261	261
BEV	106	159	245	177	251	227	119	267	111	208	212	352	174	209
PHEV	150	145	149	151	151	149	149	150	152	150	148	150	151	150
Medium sized cars														
D_ICEV	425	351	413	442	438	402	411	422	450	418	387	426	440	430
G_ICEV	427	370	418	441	437	410	417	425	447	422	398	428	439	431
HEV	260	259	260	260	260	260	260	260	261	260	260	260	260	260
BEV	114	176	270	192	274	250	129	292	119	228	235	386	189	228
PHEV	192	190	191	192	192	191	191	191	192	191	191	192	192	192
Large cars														
D_ICEV	469	386	456	489	484	444	454	466	498	461	426	470	486	475
G_ICEV	517	431	503	537	532	491	501	514	546	508	473	518	534	522
HEV	156	154	155	156	156	155	155	155	156	155	155	156	156	156
BEV	116	196	280	192	276	263	134	300	118	235	251	395	190	232
PHEV	171	159	169	174	173	167	169	170	175	170	165	171	173	171
Small SUV														
D_ICEV	446	398	439	458	455	432	438	445	463	442	422	447	456	449
G_ICEV	470	412	460	483	480	452	459	468	490	464	440	470	481	473
HEV	331	343	333	328	329	335	333	331	326	332	337	331	328	330
Standard SUV														
D_ICEV	528	458	517	545	540	507	515	526	552	521	492	529	542	533
G_ICEV	624	548	612	642	638	601	610	622	650	617	585	625	639	629
HEV	367	373	368	366	366	369	368	367	365	368	370	367	366	367
BEV	130	219	321	220	317	300	151	345	134	269	286	456	217	265
PHEV	175	175	175	175	175	175	175	175	175	175	175	175	175	175
Station wagon														
D_ICEV	374	326	366	385	382	359	365	372	390	369	349	374	383	377
G_ICEV	434	377	425	448	444	417	424	432	454	429	405	435	446	438
HEV	250	261	252	247	248	253	252	250	246	251	255	250	248	249
BEV	112	168	264	192	272	243	127	288	119	224	227	381	188	225
PHEV	168	168	168	168	168	168	168	168	168	168	168	168	168	168

	I	LV	LT	L	M	NL	PL	P	R	LK	SLO	ES	S	UK
Small cars														
D_ICEV	343	362	344	336	304	316	350	349	349	353	356	362	357	326
G_ICEV	472	506	474	461	405	425	484	482	482	489	495	506	496	443
HEV	262	261	262	263	266	265	262	262	262	262	261	261	261	264
BEV	137	86	83	125	235	165	246	272	179	139	248	241	69	205
PHEV	149	151	149	148	144	146	150	149	150	150	150	151	150	147
Medium sized cars														
D_ICEV	406	439	407	395	340	359	418	416	416	423	428	439	430	377
G_ICEV	413	438	414	404	360	376	422	420	420	426	430	438	431	390
HEV	260	260	260	260	259	259	260	260	260	260	260	260	260	260
BEV	149	92	89	136	264	183	270	299	196	151	271	262	73	227
PHEV	191	192	191	191	190	190	191	191	191	191	192	192	192	191
Large cars														
D_ICEV	448	486	450	435	372	395	462	459	460	467	473	486	475	415
G_ICEV	495	533	497	482	418	441	509	506	507	514	521	533	522	461
HEV	155	156	155	155	153	154	155	155	155	155	156	156	156	154
BEV	155	92	92	143	299	202	279	310	202	155	276	264	74	246
PHEV	168	173	168	166	157	160	170	169	169	170	171	173	171	163
Small SUV														
D_ICEV	434	456	435	427	390	403	442	440	441	445	449	456	450	415
G_ICEV	455	481	456	446	402	418	464	462	463	468	472	481	474	432
HEV	334	328	334	336	346	342	332	332	332	331	330	328	330	339
Standard SUV														
D_ICEV	510	542	512	499	447	466	522	519	520	526	532	542	533	483
G_ICEV	605	639	606	593	536	557	617	615	615	622	628	639	629	575
HEV	369	366	369	370	374	372	368	368	368	367	367	366	367	371
BEV	175	103	102	161	337	227	319	355	230	175	317	304	82	279
PHEV	175	175	175	175	175	175	175	175	175	175	175	175	175	175
Station wagon														
D_ICEV	362	383	363	354	318	331	369	368	368	372	376	383	377	343
G_ICEV	420	445	421	411	368	383	429	427	428	433	437	445	438	397
HEV	253	248	252	254	262	260	251	251	251	250	249	248	249	257
BEV	146	91	88	132	249	175	265	293	192	149	268	261	73	219
PHEV	168	168	168	168	168	168	168	168	168	168	168	168	168	168

Appendix B. Percentage of runs that a non-BEV of a specific segment emits less CO_2 than the BEV of that segment

	A	B	BG	HR	CY	CZ	DK	EST	SF	F	D	GR	HU	IRL
Small cars														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.99	0.00	0.00	0.00	1.00	0.00	0.00
PHEV	0.00	0.96	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00
Medium sized cars														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	1.00	0.00	1.00	0.03	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00
PHEV	0.00	0.14	1.00	0.38	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	0.18	1.00
Large cars														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00
PHEV	0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00

Standard SUV														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
PHEV	0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00
Station wagon														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	1.00	0.00	0.99	0.38	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00
PHEV	0.00	0.69	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00

	I	LV	LT	L	M	NL	PL	P	R	LK	SLO	ES	S	UK
Small cars														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00
PHEV	0.00	0.00	0.00	0.00	1.00	0.98	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00
Medium sized cars														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	0.00	0.00	0.97	0.00	1.00	1.00	0.00	0.00	1.00	0.36	0.00	0.00
PHEV	0.00	0.00	0.00	0.00	1.00	0.24	1.00	1.00	0.82	0.00	1.00	1.00	0.00	1.00
Large cars														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.73	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.16	1.00	1.00	0.00	1.00
PHEV	0.01	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00
Standard SUV														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PHEV	0.97	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00
Station wagon														
D_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G_ICEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEV	0.00	0.00	0.00	0.00	0.08	0.00	0.98	1.00	0.00	0.00	0.98	0.79	0.00	0.00
PHEV	0.00	0.00	0.00	0.00	1.00	0.94	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00

Appendix C. Monetary costs of CO_2 emissions through the life of a non-BEV (distinguished by segment) and compared to a BEV of that segment at the national level

	A	B	BG	HR	CY	CZ	DK	EST	SF	F	D	GR	HU	IRL
Small cars														
D_ICEV	1206	816	346	1007	345	434	1115	321	1433	924	636	11	595	686
G_ICEV	1872	1390	804	1779	787	925	1766	839	2254	1806	1285	571	1041	1336
HEV	758	545	28	473	47	111	689	−47	841	334	254	−371	297	230
PHEV	218	−72	−330	−133	−310	−298	146	−440	231	−384	−344	−817	−66	−273
Medium sized cars														
D_ICEV	1510	958	513	1331	499	601	1396	512	1835	1253	825	166	775	946
G_ICEV	1522	1043	515	1334	506	616	1415	508	1823	1270	872	172	784	946
HEV	712	427	−49	385	−31	24	632	−136	797	200	122	−512	243	143
PHEV	382	77	−270	12	−250	−224	303	−381	414	−238	−231	−787	22	−169
Large cars														
D_ICEV	1716	1052	651	1568	622	731	1589	676	2103	1503	960	317	905	1148
G_ICEV	1945	1292	805	1828	774	904	1818	847	2371	1807	1203	508	1059	1366
HEV	192	−216	−401	−204	−389	−390	105	−516	212	−513	−504	−965	−114	−346

PHEV	267	−178	−347	−113	−339	−336	175	−453	314	−414	−444	−901	−64	−269
Standard SUV														
D_ICEV	1932	1293	700	1733	680	812	1799	712	2327	1665	1115	306	1012	1252
G_ICEV	2399	1770	1015	2265	989	1162	2264	1062	2876	2285	1606	695	1325	1696
HEV	1152	798	148	806	161	249	1055	75	1303	636	439	−359	492	463
PHEV	218	−232	−474	−248	−457	−457	118	−612	233	−605	−579	−1133	−137	−414
Station wagon														
D_ICEV	1269	848	345	1045	346	439	1170	313	1509	947	650	−27	619	703
G_ICEV	1563	1121	545	1383	541	658	1460	538	1864	1337	946	219	815	986
HEV	668	466	−80	331	−53	6	597	−178	721	155	130	−538	219	95
PHEV	271	−9	−341	−112	−316	−297	195	−463	280	−373	−321	−865	−49	−272

	I	LV	LT	L	M	NL	PL	P	R	LK	SLO	ES	S	UK
Small cars														
D_ICEV	1083	999	1121	1277	173	606	373	281	315	550	589	421	1674	606
G_ICEV	1755	1520	1703	2028	426	1038	857	774	567	902	1343	912	2500	1195
HEV	676	627	710	831	68	423	55	−46	143	315	82	89	1081	276
PHEV	71	235	266	144	−222	−71	−346	−449	−57	28	−529	−308	463	−290
Medium sized cars														
D_ICEV	1338	1260	1410	1563	199	693	533	437	418	700	850	596	2099	766
G_ICEV	1380	1255	1407	1615	246	771	547	448	420	708	863	604	2089	820
HEV	595	606	685	745	−16	323	−36	−147	112	281	−53	6	1058	151
PHEV	236	362	409	338	−178	46	−280	−392	−11	106	−426	−237	672	−180
Large cars														
D_ICEV	1518	1429	1597	1764	202	747	659	566	493	806	1059	734	2368	875
G_ICEV	1766	1601	1790	2044	313	936	829	737	579	927	1319	903	2638	1103
HEV	−2	230	260	69	−352	−200	−444	−559	−84	2	−665	−390	466	−447
PHEV	63	294	330	139	−338	−177	−391	−504	−55	41	−580	−335	568	−396
Standard SUV														
D_ICEV	1749	1591	1783	2042	285	946	728	614	546	905	1158	805	2638	1036
G_ICEV	2250	1942	2177	2607	504	1320	1072	962	721	1152	1687	1149	3192	1493
HEV	1031	947	1070	1253	88	607	173	44	247	495	275	228	1613	449
PHEV	−1	261	294	84	−393	−213	−520	−655	−101	−1	−782	−460	531	−509
Station wagon														
D_ICEV	1133	1056	1184	1338	174	628	374	274	326	576	590	425	1772	621
G_ICEV	1437	1281	1437	1679	296	838	589	491	437	731	923	642	2129	893
HEV	580	560	636	731	22	367	−53	−166	96	260	−89	−19	983	169
PHEV	127	276	313	214	−204	−17	−350	−464	−51	49	−538	−311	535	−260

Appendix D. Differences between minimum, average and maximum values of CO_2 emissions in different countries in reference to a diesel vehicle

	A	B	BG	HR	CY	CZ	DK	EST	SF	F	D	GR	HU	IRL
Small cars														
min	−43	−29	−12	−36	−12	−16	−41	−11	−54	−34	−24	−9	−22	−25
mean	1206	816	346	1007	345	434	1115	321	1433	924	636	11	595	686
max	31,631	20,841	9487	27,245	9060	11,424	29,605	8404	36,811	24,015	16,370	350	15,555	18,540
Medium cars														
min	−56	−34	−18	−48	−17	−23	−52	−17	−71	−46	−31	−7	−29	−34
mean	1510	958	513	1331	499	601	1396	512	1835	1253	825	166	775	946
max	39,529	23,860	14,681	36,708	13,045	15,838	37,240	13,248	46,474	32,149	20,791	4474	20,122	26,163
Large cars														
min	−64	−38	−22	−57	−21	−28	−59	−22	−82	−56	−36	−14	−34	−42
mean	1716	1052	651	1568	622	731	1589	676	2103	1503	960	317	905	1148
max	44,874	26,558	19,125	43,711	16,227	19,246	42,486	17,393	52,985	38,248	23,802	8695	23,417	32,160

Standard SUV														
min	−70	−47	−24	−62	−23	−30	−66	−24	−89	−62	−42	−13	−37	−46
mean	1932	1293	700	1733	680	812	1799	712	2327	1665	1115	306	1012	1252
max	50,633	32,506	20,018	47,596	17,773	21,380	47,896	18,425	59,303	42,789	28,192	8115	26,303	34,517
Station wagon														
min	−46	−31	−12	−37	−12	−16	−43	−11	−57	−35	−24	−715	−23	−26
mean	1269	848	345	1045	346	439	1170	313	1509	947	650	−27	619	703
max	33,293	21,638	9406	28,253	9093	11,586	31,087	8212	38,742	24,648	16,760	1	16,170	18,961
	I	LV	LT	L	M	NL	PL	P	R	LK	SLO	ES	S	UK
Small cars														
min	−39	−36	−41	−46	−6	−22	−14	−10	−12	−20	−22	−15	−63	−22
mean	1083	999	1121	1277	173	606	373	281	315	550	589	421	1674	606
max	28,558	27,091	29,525	32,486	4668	15,419	9970	7929	8477	14,394	15,872	10,804	42,845	15,695
Medium cars														
min	−48	−46	−52	−57	−7	−26	−20	−15	−16	−25	−32	−21	−80	−30
mean	1338	1260	1410	1563	199	693	533	437	418	700	850	596	2099	766
max	35,326	34,641	37,117	38,910	5498	17,135	14,435	13,334	11,412	18,249	23,439	14,912	53,005	19,534
Large cars														
min	−54	−52	−58	−65	−7	−28	−25	−19	−19	−28	−42	−26	−90	−35
mean	1518	1429	1597	1764	202	747	659	566	493	806	1059	734	2368	875
max	40,067	39,451	42,053	44,262	5714	18,105	18,017	18,170	13,600	20,947	29,651	18,279	59,594	22,068
Standard SUV														
min	−62	−58	−65	−74	−10	−35	−27	−21	−20	−32	−44	−28	−99	−40
mean	1749	1591	1783	2042	285	946	728	614	546	905	1158	805	2638	1036
max	46,136	43,395	46,935	51,328	7828	23,647	19,696	18,752	14,876	23,608	31,894	20,188	67,197	26,503
Station wagon														
min	−41	−38	−43	−48	−6	−23	−14	−10	−12	−21	−22	−15	−66	−23
mean	1133	1056	1184	1338	174	628	374	274	326	576	590	425	1772	621
max	29,882	28,638	31,186	34,019	4680	15,978	9989	7598	8773	15,066	15,879	10,947	45,316	16,109

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