The private and social cost of the electric car: a comparison between models of different car market segments

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1. Introduction to the economical sustainability of electric cars

After the Kyoto Protocol, the subscribing countries have taken actions in order to reduce the greenhouse gases (GHG) emissions, the principal cause of the global warming phenomenon. The European Union has issued regulations affecting the main production sectors as transportation, that in 2012 has resulted as the second largest contributor of GHG emissions at EU-28 level with the 21.9% (European Commission, 2015). Regulation (EC) n. 443/2009 states that all the new registered passenger vehicles have to respect the emission cap fixed at 130 g/km for the period 2012-2015, reaching the goal of 95 g/km in 2020 (European Commission, 2009).

Car manufacturers have consequently started to produce passenger vehicles respecting the mentioned CO_2 emissions targets, introducing in the European car market new powertrains/fuel options like hybrid, bi-fuel, electric cars. The decision makers (DMs) such as consumers, mobility managers, Public Authorities have consequently an extended possibility to choice the optimal powertrain in respect to their preferences, their mobility patterns, private and social costs.

This paper aims to asses the economical sustainability of electrified powertrains in the Italian car market. Section 2 presents a Decision Support Model (DSM) approach to support decision-makers in estimating private and social costs of passenger cars with different fuel options. Section 3 reports a DSM case study application to estimate the electrified cars competitiveness in respect to the "conventional" gasoline and diesel ones in terms of private and social costs. Section 4 summarises the main results.

2. The DSM approach

Regulation (CE) n. 443/2009 has affected the Italian car market speeding up the supply of an increased variety of car powertrains: considering the whole sales in the first 10 months of 2015 the market shares

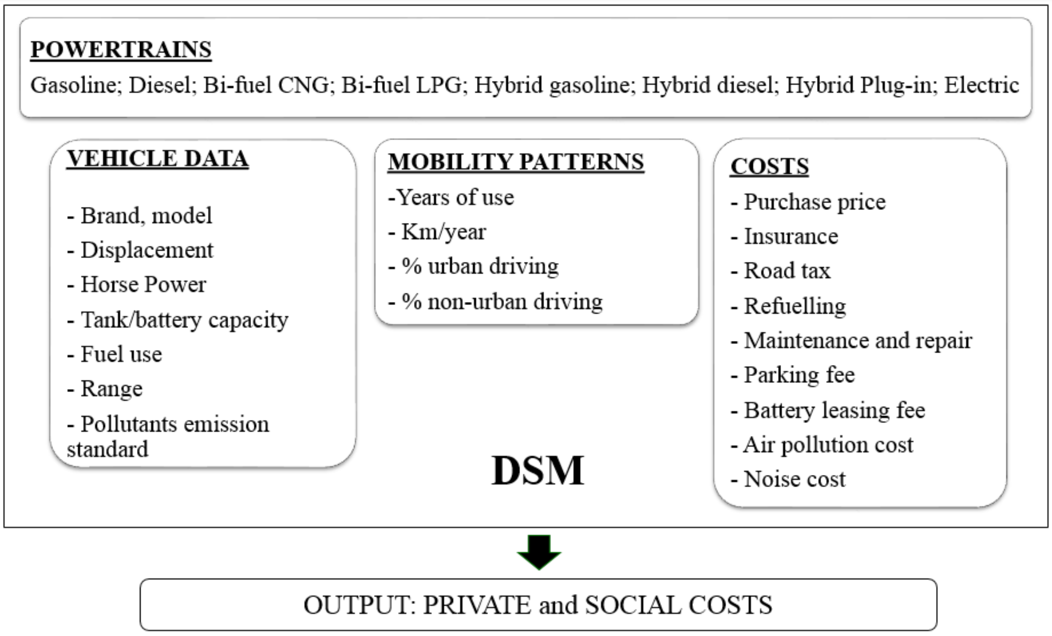

Figure 1 – The DSM theoretical framework

where, respectively, 55,3% diesel, 31,1% gasoline, 7,9% Liquefied Petroleum Gas (LPG), 4,1% Compressed Natural Gas (CNG), 1,6% Hybrid, 0,1% Electric (UNRAE, 2015).

The DMs' purchaising behaviours take into account monetary parameters (e.g. initial price, operating costs, etc.), non-monetary parameters (e.g. car models availability, range, refuelling stations distribution, etc.) and, finally, the mobility patterns (e.g. km/year, urban or non-urban driving, years of usage, etc.). At the powertrain selection moment all these information are difficult to be gathered, managed, used, evidencing the requirement of Decision Support Models (DSM). These decision-making support tools should suggest to private DMs the optimal car powertrain to buy while to public entities the fuel options to subsidize.

A DSM is an intelligent human- computer system which supports decision-making activities aiming at semi-structured decision-making problem.

Figure 1 shows the DSM application to the optimal car powertrain choice. First, the DM identifies the powertrains to compare among the ones available in the Italian car market in 2015. Secondly, the DM selects the car models to compare by a list of 76 options[1] and, finally, inserts the mobility patterns information. The vehicle and mobility pattern data are inputs for the DSM estimation of specific costs like insurance, road tax, etc. Then, specific costs with the same nature are aggregated in the following outputs[2]:

- Total Cost of Ownership: the cost that the DM has to sustain in order to buy and use a car with a specific powertrain at current fuel prices;
- Social Lifecycle Costs: the costs imposed to the society by the DM's use of a car model with a specific powertrain (i.e. road transport negative externalities).

[1] The related vehicle data are already stored in the DSM database. The reference is http://www.quattroruote.it/

[2] For a detailed description of the DSM theoretical framework, see Rusich, Danielis 2015.

3. Conventional v/s alternative powertrains: a case study

In recent years, car manufacturers have started to produce vehicles with different levels of electrification in order to optimize the performances of gasoline and diesel engines or to provide less pollutant fuel options. A brief description of the electrified powertrains available in the Italian car market is reported in the following lines, listed since the less electrified to the most one.

- Gasoline and diesel Hybrid Vehicles (HEVs): equipped with two engines, one combustion (gasoline or diesel) and one electric. A battery stores the energy produced by the combustion engine or by regenerative braking systems. The interaction between the combustion and the electric powertrains depends on the level of hybridisation:
  - Mild hybrid: the electric engine is not able to move alone the vehicle in a normalized driving cycle;
  - Full hybrid: the electric engine is able to move alone the vehicle in a normalized driving cycle;
- Gasoline and diesel Plug-in Hybrid Vehicles (PHEVs): HEVs in which the battery can be recharged also without the combustion engine, by plugging the vehicle in the electricity grid;
- Extended Range Electric Vehicles (EREVs): equipped with an auxiliary power unit built-in or externally attached to a PHEV to increase the electric range;
- Electric Vehicles (EVs): equipped with the only electric powertrain (battery + electric engine).

The higher the level of electrification is, the better energy efficiency and lower pollutants emissions are achieved. This means that, apparently electrified vehicles should ensure fuel savings and reduced environmental impacts: these "alternative" powertrains are expected to be more economical sustainable (in terms of private and social costs) than the "conventional" gasoline and diesel ones. The following paragraph aims to verify if, in concrete, vehicles with "alternative" powertrains on sale in the Italian car market are more economical sustainable than the "conventional" ones.

3.1 Case study design

The DSM is used as assessment tool for a sample of 39 car models belonging to the Italian car market segments in the first 10 months of 2015. Considering that the supply of "alternative" powertrain car models is not homogeneous among market segments, the following assumptions have been adopted in the case study design:

- A-B market segment = mini cars (A) + small cars (B);
- C-D market segment = medium cars (C) + large cars (D);
- E-F market segment = executive cars (E) + luxury cars (F).

Figure 2 reports the sample composition in terms of number of vehicles considered per powertrain. In order to stress the comparison between car models with "conventional" and "alternative" powertrains, only a gasoline and diesel car model per market segment is present while the whole supply of "alternative" car models per market segment is taken into account.

Figure 2 evidences that the supply of "alternative" car powertrain is not homogeneous in the Italian market: EVs and Gasoline HEVs are currently the ones with the broadest range. Figure 3 reports the distribution of the powertains considered in the sample per market segment. It evidences that also within market segments, the supply of "alternative" powertains is not harmonized.

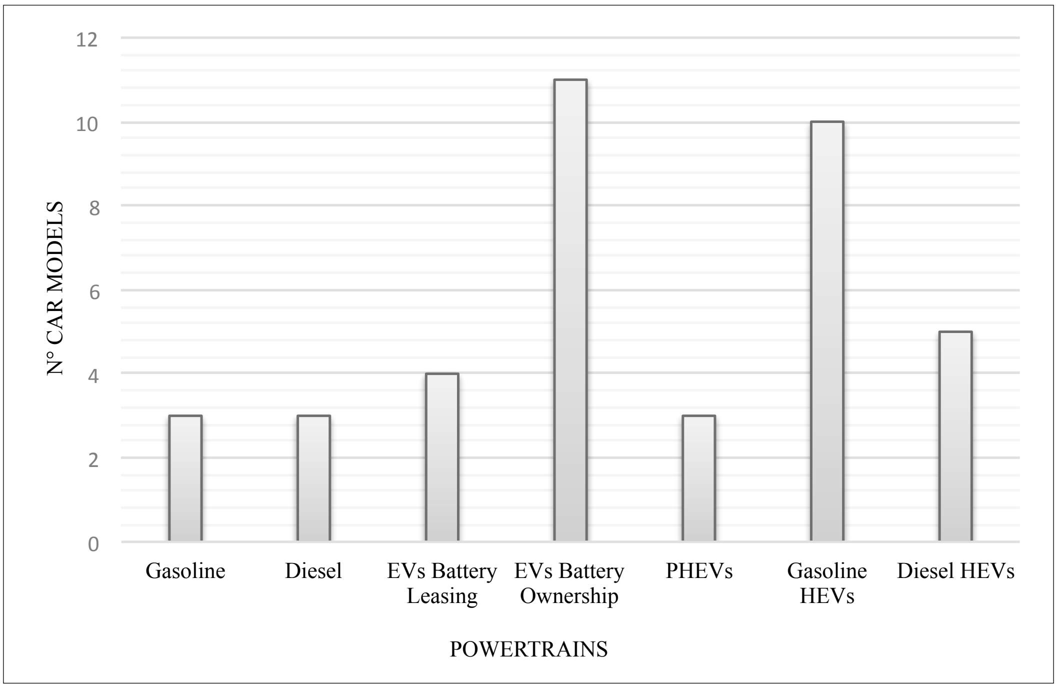

Figure 2 – Car models considered per powertrain

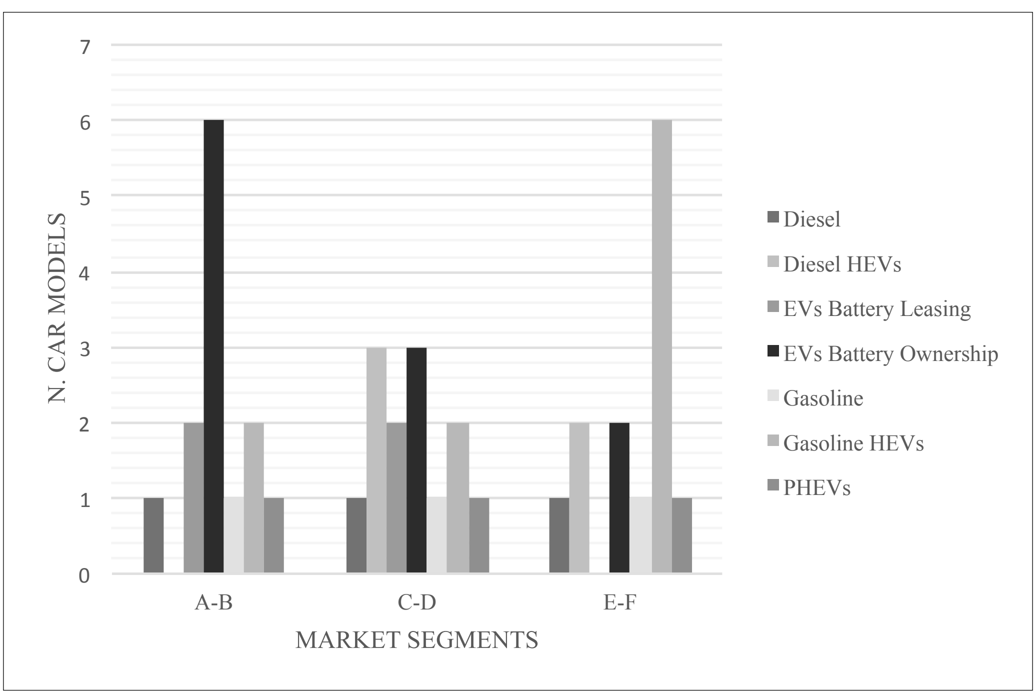

Figure 3 – Sample composition per market segment

Figure 3 evidences tha the current supply of EVs (own battery + leased battery)[3] is mainly focused on the A-B market segments due to limited battery ranges, high battery costs and a scarce widespread of the electric refuelling stations in the road transportation network. The battery leasing business model is applied to medium and small sized EVs mainly because the leasing convenience is reduced when increasing kilometres driven and battery sizes increase.

Considering HEVs, the gasoline ones are currently more widespread while the diesel ones are absent in the A-B car market segment. PHEVs are in a starting market phase.

3.2 The Total Cost of Ownership

The Total Cost of Ownership (TCO) is an estimation of the costs that the DM has to sustain in order to buy and drive a car model for a specific mobility pattern at current fuels prices. The TCO is computed as follows:

TCO = Vehicle Capital Costs + Present Value of Annual Operating Costs

The Vehicle Capital Costs is the car purchase price while the Present Value of Annual Operating Costs includes the costs incurred during the vehicle lifetime. More in detail, in the Annual Operating Costs are accounted:

- Fuel Costs;
- Battery leasing fees (for EVs with battery leasing);
- Insurance costs;
- Ordinary and extraordinary maintenance and repair costs;
- Parking costs;
- Vehicle excise duties.

These costs are estimated starting by the vehicle data stored in the DSM database and assuming a specific mobility pattern: 10 years of usage, 80% urban trips and a varying number of km/year (5,000; 10,000; 15,000; 20,000; 25,000). The variability of this last parameter is justified by the requirement to evaluate if, as the number of km/year increases, the more electrified powertrains become the optimal choice in terms of TCO. An actualization formula is applied in order to take into account the present value of money during time and report it to the decision moment (Rusich, Danielis 2015). The comparison process among the selected car models is in two steps: firstly, the identification of the car model with the lowest TCO (optimal choice); secondly, the TCO difference estimation among the optimal choice and the other ones.

Table 1 shows TCO comparison's results among the car models with "alternative" and "conventional" powertrains belonging to the Italian market segment A-B.

[3] Two business models to sell electric vehicles: the owned battery one implies that the customer becomes owner of the battery, pays a higher purchase price and is in charge of all the risks related to the battery. The battery leasing business models allows a reduced purchase price but on a monthly basis the customer has to pay a leasing fee whose amount depends of the number of kilometres driven per year and the years of contract. With the battery leasing business model, the car manufacturer remains in charge of the risks of battery failure.

Table 1 – TCO difference among the optimal car model option and the other ones belonging to market segment A-B

Powertrain	Car Model	TCO Difference (€) for 10 years of use and varying km/year driven				
		5000	10,000	15,000	20,000	25,000
Gasoline	Fiat Panda Easy	0	0	0	984	4,036
Diesel	Ford Fiesta TdCi	2,921	1,907	892	862	2,899
EV Battery Own.	VW E-Up	8,172	5,120	2,068	0	0
Gasoline HEV	Toyota Yaris	7,593	6,663	5,733	5,787	7,909
EV Battery Own.	Smart ForTwo E. D.	9,708	7,843	5,978	5,098	6,285
EV Battery Leas.	Smart ForTwo E. D.	10,067	8,202	6,337	5,457	6,644
EV Battery Own.	Citroen C-Zero	12,102	9,799	7,497	6,178	6,928
EV Battery Own.	Peugeot iOn	12,334	10,031	7,729	6,410	7,160
EV Battery Own.	Mitsubishi iMiev	13,908	11,606	9,303	7,985	8,734
EV Battery Leas.	Renault Zoe	13,210	10,884	9,240	9,455	12,127
Gasoline HEV	Honda Jazz Hybrid	9,845	10,094	10,344	11,578	14,879
EV Battery Own.	BMW i3	20,233	17,121	14,009	11,881	11,820
PHEV	BMW i3	27,400	25,234	23,067	21,885	22,771

Up to 15,000 km/year driven, the gasoline Fiat Panda Easy is the optimal car model and the diesel Ford Fiesta TdCi represent the suboptimal choice. If 20,000 km/year are driven, the electric VW E-Up with battery ownership has the lowest TCO.

The comparison states that in market segment A-B car models with "conventional" powertrains have a lower TCO than car models with "alternative" powertrains if a less intensive car usage is considered (less than 20,000 km/year). A first reason concerns the fact that PHEVs, EREVs, HEVs and EVs are in general more expensive than "conventional" car models in A-B market segment[4]. A second aspect concerns the relation between operating costs and mobility patterns: the more electrified vehicles generate TCO savings under intensive car usage conditions thanks to reduced operating costs in respect to the "conventional" powertrains (e.g. 0.28 €/km the Peugeot iOn electric with battery ownership; 0.46 €/km for the gasoline Fiat Panda Easy). As an example, the VW E-Up electric with battery ownership fills the initial extra-money expenditure of 15,550€ under the conditions of 20,000 km/year driven and 10 years of usage thanks to the lowest operating costs in the car model sample considered (0.26 €/km).

The diesel HEVs are absent in the market segment A-B, nonetheless the technology is available in the Italian car market. The reason is that this "alternative" powertrain is applied on mid-size and large size car models. Focusing on the PHEVs supply in the market segment A-B, only BMW i3 is sold in Italy evidencing a starting market phase.

[4] 11,600€ the gasoline Fiat Panda Easy; 14,750€ the diesel Ford Fiesta TdCi; 19,200€ the gasoline Hybrid Toyota Yaris; 30,698€ the electric with battery ownership Peugeot iOn; 41,150€ the BMWi3 Range Extender.

Table 2– TCO difference among the optimal car model option and the other ones belonging to market segment C-D

Powertrain	Car Model	TCO Difference (€) for 10 years of use and varying km/year driven				
		5000	10,000	15,000	20,000	25,000
Gasoline	Fiat Punto Twinair	0	0	0	0	0
EV Batt. Own.	Nissan Leaf	11,127	8,751	6,375	3,998	1,622
Diesel	VW Golf Trendline	7,606	7,841	8,077	8,313	8,549
EV Battery Leas.	Nissan Leaf	12,914	10,537	8,842	8,022	7,592
EV Battery Leas.	Renault Fluence	15,735	12,988	10,144	8,371	5,235
EV Batt. Own.	VW E-Golf	17,708	14,681	11,655	8,628	5,602
Gasoline HEV	Toyota Auris	14,111	14,001	13,892	13,783	13,673
EV Batt. Own.	Ford Focus Electric	21,434	19,074	16,715	14,356	11,997
Gasoline HEV	Toyota Prius	16,800	16,993	17,186	17,379	17,572
PHEV	VW Golf GTE Phev	24,650	23,283	21,916	20,550	19,183
Diesel HEV	Peugeot 3008	26,853	27,142	27,432	27,722	28,011
Diesel HEV	Citroen DS5	29,966	30,592	31,218	31,844	32,471
Diesel HEV	Peugeot 508	37,539	39,005	40,471	41,936	43,402

In the sample of car models belonging to market segment C-D, the gasoline Fiat Punto Twinair is always the optimal choice in terms of TCO. The suboptimal choice is the diesel VW Golf Trendline up to 15,000 km/year while the electric with battery ownership Nissan Leaf is more competitive in terms of TCO if 20,000km/year or an increased distance is covered.

The comparison states that in market segment C-D the TCO differences between the optimal choice and other car models are more significant than in the case of market segment A-B. In particular in the case of diesel HEVs with the Peugeot 508 car model reaching a 43,402€ TCO difference in correspondence of 25,000 km/year driven and 10 years of usage. In general, car models with "conventional" powertrains (gasoline in particular) have a lower TCO than the "alternative" ones. The difference with car market segment A-B is that the mentioned trend has some exceptions. More in detail, up to 15,000 km/year driven the suboptimal choice is the diesel VW Golf Trendline but the electric with battery ownership Nissan Leaf has the best TCO performance if more than 20,000 km/year are driven. When 25,000 km/year are covered, also the electric with leased battery Renault Fluence and the electric with battery ownership VW E-Golf have a lower TCO than the diesel car model. Two main explanations:

- The EVs purchase prices are higher in respect to the car models with "conventional" powertrains[5];

[5] The gasoline Fiat Punto Twinair 13,900€; the diesel VW Golf Trendline 21,650€; the electric with battery leased Renault Fluence 28,500€, the electric with battery ownership Nissan Leaf 30,690€ and the VW E-Golf electric with battery ownership 37,600€.

- The reduced operating costs of the EVs make them as much competitive as the distance covered per year increases, as shown in Table 3.

Table 3: Operating Cost in €/km

km/year	Fiat Punto Twinair	VW Golf Trendline	Nissan Leaf	Renault Fluence	VW E-Golf
5,000	0.45	0.46	0.31	0.47	0.30
10,000	0.31	0.31	0.20	0.28	0.18
15,000	0.26	0.26	0.16	0.21	0.15
20,000	0.23	0.23	0.14	0.18	0.13
25,000	0.22	0.22	0.13	0.16	0.12

The gasoline HEVs and PHEVs are not optimal choices: the TCO is higher on average than the optimal choice of 13,892€ for the gasoline HEV Toyota Auris, of 17,186€ for the gasoline HEV Toyota Prius and, finally, of 21,916€ for the PHEV VW Golf GTE.

Table 4 – TCO difference among the optimal car model option and the other ones belonging to market segment E-F

Powertrain	Car Model	TCO Difference (€) for 10 years of use and varying km/year driven				
		5000	10,000	15,000	20,000	25,000
Gasoline HEV	Lexus CT	0	0	0	773	3,348
EV Batt. Own.	Mercedes B Class El.	6,952	4,377	1,802	0	0
Diesel	V60 D3 kinetic	10,060	10,439	10,818	11,969	14,923
PHEV	Mitsubishi Outlander	17,523	16,793	16,063	16,105	17,950
Gasoline HEV	Lexus IS	16,793	18,592	20,391	22,963	27,336
EV Batt. Own.	Tesla Model S	37,553	37,250	36,946	37,416	39,687
Diesel HEV	Mercedes E Class	33,436	36,205	38,975	42,518	47,863
Gasoline HEV	BMW 3 Series Hyb.	39,803	43,225	46,648	50,843	56,840
Gasoline HEV	Infiniti Q50 Hybrid	41,021	45,633	50,245	55,630	62,817
Gasoline HEV	Lexus RX405h	42,487	46,705	50,923	55,914	62,707
Gasoline	Audi A8	65,815	70,458	75,101	80,516	87,734
Gasoline HEV	Mercedes S400 Class	80,291	83,972	87,653	92,107	98,363
Diesel HEV	Mercedes C Class	110,993	112,105	113,217	115,102	118,788

Considering the Italian car market segment E-F, Table 4 shows an increased supply of gasoline HEVs in respect to the other market segments. Up to 15,000 km/year driven, the optimal choice in terms of TCO is the gasoline HEV Lexus CT thanks to the cheapest purchase price (27,700€). The suboptimal choice is the EVs with battery ownership Mercedes Benz Class B with a TCO difference that ranges from 6,952€ when 5,000 km/year are driven to 1,802€ if the annual distance is 15,000 kilometres. The Mercedes Benz Class B becomes the optimal choice thanks to operating cost savings of 0.08€/km in correspondence of 20,000 km/year driven and 0.10€/km when the annual distance covered is 25,000 kilometres.

In general, Table 4 shows that in market segment E-F the difference between private costs reaches values very high if compared with the market segment A-B and C-D due to the presence of luxury cars. About "conventional" powertrains, the diesel car models have a reduced TCO in respect to the gasoline ones because the gasoline engines use much more fuel than the correspondent diesel version in vehicles with a lot of power horses and displacement.

Finally, the PHEV Mitsubishi Outlander's TCO difference to the optimal choice ranges between 17,523€ if 5,000 km/year are driven and 17,950€ if the annual distance covered is 25,000 km/year.

3.2.1 TCO Sensitivity Analysis: the case of increased conventional fuels prices

The TCO assessment highlights that several electric car models are competitive with the "conventional" ones under certain conditions: an intensive car usage (more than 20,000 km/year), 10 years of ownership, mainly urban trips and current fuels prices. More in detail, the TCO results are influenced by favourable oil market conditions, reflected in gasoline and diesel Italian prices of 1.47€/l and 1.35€/l respectively in October 2015 (ACI, 2015). A sensitivity analysis is provided in order to assess the impact of increased gasoline and diesel prices on the TCO comparison between "conventional" and "alternative" car powertrains. The reference period is June 2014, the month in which the oil market price has reached the peak in the last two years. The correspondent gasoline price is 1.75€/l while the diesel one is 1.64€/l. The electricity price in the compared periods is equal to 0.018€/kWh (ACI, 2015).

Table 5 reports the TCO difference for car models belonging to market segment A-B at June 2014 conventional fuels prices. The comparison results remain unvaried in respect to ones reported in Table 1: the optimal solution is still the gasoline Fiat Panda Easy up to 15,000 km/year driven while for more than 20,000 km/year the electric with battery ownership VW E-Up has the best TCO performance.

Table 5 – TCO difference among the optimal car model option and the other ones belonging to market segment A-B with June 2014 conventional fuel prices

Powertrain	Car Model	TCO Difference (€) for 10 years of use and varying km/year driven				
		5000	10,000	15,000	20,000	25,000
Gasoline	Fiat Panda Easy	-	-	-	3,147	6,740
EV Battery Own.	Volkswagen E-UP	7,632	4,039	446	-	-
Diesel	Ford Fiesta TdCi	2,787	1,639	490	2,489	4,933
EV Battery Own.	Smart ForTwo E. D.	9,167	6,762	4,356	5,098	6,285
EV Battery Leas.	Smart ForTwo E. D.	9,526	7,121	4,715	5,457	6,644
Gasoline HEV	Toyota Yaris	7,403	6,283	5,163	7,189	9,662
EV Battery Own.	Citroen C-Zero	11,561	8,718	5,875	6,178	6,928
EV Battery Own.	Peugeot iOn	11,793	8,950	6,107	6,410	7,160
EV Battery Own.	Mitsubishi iMiev	13,368	10,524	7,681	7,985	8,734
EV Battery Leas.	Renault Zoe	12,670	9,803	7,618	9,455	12,127
Gasoline HEV	Honda Jazz Hybrid	9,806	10,017	10,229	13,587	17,390
EV Battery Own.	BMW i3	19,693	16,040	12,387	11,881	11,820
PHEV	BMW i3	19,693	16,040	12,387	11,881	11,820

Table 6 shows that if the omparison takes place among car models of market segment C-D, an increase in gasoline and diesel prices can modify the TCO results reported in Table 2. More in detail, the Nissan Leaf electric with battery ownership becomes the optimal solution if at least 25,000 km/year are driven.

Table 6 – TCO difference among the optimal car model option and the other ones belonging to market segment C-D with June 2014 conventional fuel prices

Powertrain	Car Model	TCO Difference (€) for 10 years of use and varying km/year driven				
		5000	10,000	15,000	20,000	25,000
Gasoline	Fiat Punto Twinair	-	-	-	-	1,127
EV Batt. Own.	Nissan Leaf	10,578	7,652	4,726	1,800	-
Diesel	VW Golf Trendline	7,467	7,565	7,662	7,759	8,983
EV Battery Leas.	Nissan Leaf	12,364	9,438	7,193	5,823	5,970
EV Battery Leas.	Renault Fluence	15,186	11,889	8,495	6,172	3,613
EV Batt. Own.	VW E-Golf	17,158	13,582	10,006	6,430	3,980
Gasoline HEV	Toyota Auris	13,957	13,694	13,431	13,167	14,031
EV Batt. Own.	Ford Focus Electric	20,884	17,975	15,066	12,158	10,375
Gasoline HEV	Toyota Prius	16,685	16,763	16,840	16,917	18,121
PHEV	VW Golf GTE Phev	24,198	22,378	20,558	18,739	18,046
Diesel HEV	Peugeot 3008	26,707	26,852	26,996	27,140	28,411
Diesel HEV	Citroen DS5	29,823	30,306	30,789	31,272	32,882
Diesel HEV	Peugeot 508	37,456	38,839	40,222	41,605	44,114

In the case of car models belonging to market segment E-F, the increase in conventional fuel prices at June 2014 levels does not change the optimal car model choice. Up to 15,000 km/year driven the gasoline HEV Lexus CT has the lowest TCO but is overtaken by the electric with battery ownership Mercedes Class B if 20,000 km/year or more are considered.

Table 7 – TCO difference among the optimal car model option and the other ones belonging to market segment E-F with June 2014 gasoline and diesel prices

Powertrain	Car Model	TCO Difference (€) for 10 years of use and varying km/year driven				
		5000	10,000	15,000	20,000	25,000
Gasoline HEV	Lexus CT	-	-	-	2,447	5,440
EV Batt. Own.	Mercedes Class B El.	6,534	3,540	547	-	-
Diesel	V60 D3 kinetic	10,141	10,600	11,060	13,966	17,418
PHEV	Mitsubishi Outlander	17,232	16,211	15,189	16,614	18,586
Gasoline HEV	Lexus IS	16,881	18,768	20,656	24,989	29,870

EV Batt. Own.	Tesla Model S	37,134	36,413	35,691	37,416	39,687
Diesel HEV	Mercedes E Class	33,447	36,228	39,009	44,237	50,012
Gasoline HEV	BMW 3 Series Hyb.	40,083	43,786	47,489	53,639	60,335
Gasoline HEV	Infiniti Q50 Hybrid	41,249	46,090	50,931	58,218	66,052
Gasoline HEV	Lexus RX405h	42,759	47,248	51,738	58,674	66,157
Gasoline	Audi A8	66,304	71,435	76,567	84,145	92,269
Gasoline HEV	Mercedes S400 Class	80,573	84,537	88,501	94,912	101,869
Diesel HEV	Mercedes C Class	110,979	112,077	113,175	116,719	120,810

Generally, the increase in conventional fuel prices implies higher annual operating costs for gasoline, diesel, gasoline and diesel HEVs, PHEVs car models while the EVs ones remain unvaried. Therefore, the TCO gap between "conventional" and "alternative" car models expands as much as the level of electrification increase. Anyway, the higher EVs fuel savings are not sufficient to change the optimal car model choice in the case study.

3.3 Social Lifecycle Costs

The Social Lifecycle Costs (SLC) is the costs that the DM imposes to the society for the use of a car model with a specific powertrain. More in detail, when a driver has to decide how to make a trip, the action effects on the other citizens' life are not taken into account, because no compensation payment for the caused damage will be required. The cost will be paid by the society (concept of negative transportation externality), generating a sub-optimal resource allocation (Danielis, 2001).

In the scientific literature, the SLC assessment is performed on a lifecycle inventory of fuels and electricity basis (Well-to-Wheels assessment, WtW[6]). The Global Warming Potential (GWP) is the most reported result followed by acidification (SO_2, NO_X), smog (CH_4, NMVOC) and toxicity impacts (Hawkins et al., 2012). A lack of consensus in the SLC results is due, firstly, to the fact that HEVs, PHEVs, EREVs, EVs are relatively new powertrains and, secondly, to the complexity of the electricity supply chain that makes results dependent on the energy mix considered and on the period of the day of recharging operations (Massiani and Weinmann, 2012). Rusich, Danielis (2015) reports that nonetheless the EVs are expected to have a GWP lower than gasoline and diesel vehicles their impacts should become comparable or worse than "conventional" powertrains if a carbon intensive energy mix is considered. Distinguishing by SLC production stages, gasoline and diesel vehicles are estimated to have a higher GWP and local air pollution emissions in the car use stage (Tank-to-Wheels, TtW) while EVs mainly in the energy production stage (Well-to-Tank, WtT).

The DSM algorithm estimates three types of social costs related to the car models considered in the case study:

- The WtW Global Air Pollution Cost: that is the Carbon Dioxide (CO_2) emissions cost related to the lifecycle inventory of fuels and electricity;

[6] Well-to-Wheel is the specific Life Cycle Assessment used for transport fuels and vehicles. The analysis is broken in two stages: the "Well-to-Tank" stage that incorporates the fuel production and processing and fuel delivery or energy transmission and the "Tank-to-Wheel" stage that deals with vehicle operation itself.

- The WtW Local Air Pollution Cost: that is the sum of the Nitrogen Oxides (NO_X) emissions cost, the Sulphur Oxides (SO_X) emissions cost and the Particulate Matter (PM) emissions cost all related to the lifecycle inventory of fuels and electricity;
- The TtW Noise Cost: that is the Annoyance cost and Human Damages cost related to the car usage stage.

The following SLC computational formula is applied:

SLC = WtW Global Air Pollution Cost + WtW Local Air Pollution Cost + TtW Noise Cost

About the estimation of the WtW Global Air Pollution Cost, the DG MOVE[7] data concerning CO_2 emissions per kilometre and the external cost per ton of CO_2 for "conventional" and almost all the "alternative" powertrains are used as DSM input data. The EU28 electricity production mix in 2010 represents the basis to estimate PHEVs and EVs CO_2 emissions values per kilometre. The HEVs data concerning CO_2 emissions per kilometre and the external cost per ton of CO_2 are gathered by the JRC study "Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context".

The WtW Local Air Pollution Cost estimation is performed taking as a reference the DG MOVE study for the values concerning the external costs of the local air pollutants emissions and considering the local pollutants emissions per kilometre reported by Rusich, Danielis (2015). More in detail, the values related to NO_X and SO_X external costs are are estimated to be equal inside and outside urban centers while the PM external costs increase in urban and metropolitan areas. Therefore, the WtW Local Air Pollution Cost estimation varies depending on the mobility pattern applied: the more kilometres in urban or metropolitan environments are driven, the higher SLC is achieved. Table 8 summarises the DSM external costs per air pollutant.

The monetary value of each pollutant emissions consist of health costs, building/material damages and damages for the ecosystem (e.g. crop losses).

The Noise Cost is estimated distinguishing urban and interurban trips, using the following formula:

Noise Cost (€) = Urban Noise Cost + Interurban Noise Cost

The DG MOVE study presents external values depending on the period of the journey (night/day) and the type of traffic (dense/thin) for urban, suburban and rural areas. As in the case of the external cost of local air pollution, also the Noise external cost is higher in dense populated areas.

Table 8 – External cost per air pollutant (€/g)

Air Pollutant	WtT	TtW
NOX	0.01	0.01
SOX	0.01	0.01
PM rural	0.12	0.12
PM urban	0.21	0.21
PM metropolitan	0.65	0.65
CO2	0.000093	0.000093

Source: DG MOVE (2015) and Rusich, Danielis (2015)

7 DG MOVE (2015), "State of the Art on Alternative Fuels Transport Systems in the European Union – Final Report".

Finally, the report of the assumptions adopted in the car models' SLC estimation: a mobility pattern of 10 years of usage, 80% urban trips and a varying number of km/year driven (5,000; 10,000; 15,000; 20,000; 25,000).

Table 9 reports the result of the SLC comparison between the "conventional" powertrains and the "alternative" ones. EVs result the optimal choice thanks to, firstly, no tailpipe emissions in the TtW phase and, secondly, to the absence of combustion in the electric engine that eliminates the production of noise during the use phase. The social impact of EVs varies between 297€ when 5,000 km/year are driven and 1,487€ when 25,000 km/year are covered.

Table 9 – Social Lifecycle Cost of car models with "conventional" and "alternative" powertrains considered in the case study

Powertrain	Social Lifecycle Cost (€) for 10 years of use and varying km/year driven				
	5000	10,000	15,000	20,000	25,000
Gasoline	993	1,986	2,979	3,973	4,966
Diesel	881	1.763	2,644	3,526	4,407
Gasoline HEV	719	1,438	2,156	2,875	3,594
Diesel HEV	705	1,410	2,115	2,820	3,525
EV	398	796	1,194	1,592	1,990
PHEV	517	1,034	1,551	2,068	2,585

The SLC performance of PHEVs is very close to the EVs ones, because PHEVs driving cycles use mainly the electric powertrain, leaving to the combustion engine only the function to extend the total range without the requirement of a refuelling operation. The SLC difference between PHEVs and EVs is estimated to vary between 86€ when 5,000 km/year are driven and 429€ when 25,000 km/year are covered.

The hybridisation of gasoline and diesel engines (gasoline and diesel HEVs) allows a reduction of the "conventional" powertrains inefficiencies, producing benefits in terms of fuel consumption and the related pollutant emissions, not in a way comparable to PHEVs and EVs. The reason is that in mild hybrid and full hybrid configurations the electric engine is used to support the conventional one in start and stop operations, in acceleration operations and, in the case of full hybrid car models, in full electric short trips.

In respect to the optimal choice, the SLC of HEVs is estimated higher of about 223€ when 5,000 km/year are driven and increases reaching the 1,113€ when 25,000 km/year are covered. Diesel HEVs have a similar trend: the SLC is estimated to be higher than the one of EVs of about 235€ when 5,000 km/year are driven and increases reaching the 1,176€ when 25,000 km/year are covered.

Considering "conventional" powertrains, the SLC of diesel cars is better than the gasoline ones. Diesel car models are estimated to be cheaper of about 51€ when 5,000 km/year and 203€ when 25,000 km/year are covered. If the SLC difference with EVs is considered, the gasoline car models are estimated to have an increased environmental impact of about 429€ when 5,000 km/year are driven and 2,145€ when 25,000 km/year are covered. About diesel car models, they are estimated to range from a value of 378€ when 5,000 km/year are driven to a value of 1,891€ when 25,000 km/year are covered. The explanation is that EVs have a simplified technical structure that avoids energy losses in the car use stage (TtW), that means reduced fuel consumption and related local and global pollutants emissions. In addition, as described in the previous lines, EVs produce less noise in the TtW stage than "conventional" powertrains thanks to the absence of combustion in the engine. Table 10 reports the difference in terms of SLC between the optimal choice and the other powertrains considered in the case study.

Table 10 – SLC difference (€) for 10 years of use and varying km/year driven

Powertrain	Social Lifecycle Cost (€) for 10 years of use and varying km/year driven				
	5000	**10,000**	**15,000**	**20,000**	**25,000**
Gasoline	595	1,190	1,785	2,380	2,976
Diesel	483	967	1,450	1,933	2,417
Gasoline HEV	321	642	962	1,283	1,604
Diesel HEV	307	614	921	1,228	1,535
EV	0	0	0	0	0
PHEV	119	238	357	476	595

4 Conclusions

After the emission of the Directive EC n. 443/2009 car manufacturers have started to supply car models with "alternative" powertrains in respect to the "conventional" gasoline and diesel. These new technologies are supposed to guarantee an increased powertrain lifecycle energy efficiency (WtW) with a related reduction of global air pollution, local air pollution and noise external costs. In particular, vehicles with a different level of electrification seem to be the most promising to target these goals, thanks to a technical structure able to optimise and reduce the inefficiencies of the "conventional" powertrains. Nonetheless, the car market shares of the first ten months of 2015 show that electrified vehicles represent a contained percentage of the new registered cars: 1.5% HEVs, 0.1% EVs (UNRAE, 2015).

Firstly, this data can be explained by the absence of public subsidies for HEVs, PHEVs and EVs able to reduce their purchase prices and consequently to increase customers demand.

Secondly, gasoline HEVs, diesel HEVs, PHEVs and EVs are estimated to have, in general, a TCO higher than the one related to conventional car models. The purchase price gap is so significant that the reduced operating costs (deriving by the hybridisation or electrification of the powertrain) are not sufficient to recover it if less intensive mobility patterns are considered. In market segment A-B, the electric with battery ownership VW E-Up represents a suboptimal solution in respect to the gasoline Fiat Panda Easy in case of 10 years of use and more than 20,000 kilometres per year are driven. In market segment C-D, the electric with battery ownership Nissan Leaf represents a suboptimal solution in respect to the gasoline Fiat Punto Twinair if 10 years of use and more than 20,000 kilometres per year are driven. In market segment E-F, characterized by a high purchase prices variability of all the powertrains, the gasoline HEV Lexus CT represents the optimal choice up to 15,000 km/year driven while the electric with battery ownership Mercedes Benz Class B has the lowest TCO if 20,000 km/year or more distances are covered. The TCO assessment results remain almost unvaried also if increased conventional fuels prices are taken as a reference in the case study. More in detail, in correspondence of the gasoline and diesel fuel prices of June 2014, the month in which the oil market price has reached the highest level in the last two years, the gap between the annual operating costs of "conventional" and "alternative" car models expands as much as the level of electrification increase. Anyway, the higher EVs fuel savings are not sufficient to change the optimal car model choice in the market segments considered in the case study.

By a SLC perspective, an subsidy provided by Public Authorities directed to HEVs, PHEVs and EVs should be justified because all these powertrains allow a social cost reduction in respect to the gasoline and diesel ones. In particular, if 80% of urban trips, 10 years of usage and the EU28 energy mix 2010 are assumed, the EVs perform as the best: they are estimated to have a SLC lower than the gasoline car models of about 429€ when 5,000 km/year are driven and 2,145€ when 25,000 km/year are covered. If diesel car models are considered, EVs models are estimated to pass from a value of 378€ when 5,000 km/year are driven to a value of 1,891€ when 25,000 km/year are covered. The SLC assessment should evidence higher EVs benefits if a more carbon intensive energy mix or a mobility pattern with a higher percentage of metropolitan or urban trips are assumed.

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