Total cost of ownership, social lifecycle cost and energy consumption of various automotive technologies in Italy

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JEL classification:
R40
Q40
Q50

Keywords:
Total cost of ownership
Social cost
Energy consumption
Car
Electric vehicle

A B S T R A C T

This paper estimates the total cost of ownership, social lifecycle cost and energy consumption of 66 cars with different fuel/powertrains available in Italy in 2013. The aim is to provide the various private and public decision makers with information that could allow them to better understand the current market penetration of the various automotive technologies and to predict the future one. It is found that the car operated by conventional fuels (gasoline, diesel) is currently the least expensive as far as the total costs of ownership are concerned. The bi-fuel liquefied petroleum gas (LPG) and the bi-fuel compressed natural gas (CNG) internal combustion engine vehicles are in the same price range. Both the battery electric vehicles (BEVs) and, especially, the hybrid ICEVs are more expensive. On the contrary, the social lifecycle costs of the BEVs are the lowest, thanks not only to their zero air pollutants' emissions in the use phase but also to their reduced noise emissions. The amount of the social costs relative to the total cost of ownership, estimated using recent European parameters, represents at the most 6% of the total cost. Consequently, even if the external costs were internalized, the alternative fuel vehicles would not become convenient for the final consumer from a monetary point of view. Considering the energy consumption, with the 2011 Italian energy production mix, the BEVs and the diesel hybrid are the most energy efficient cars. Focusing on 7 specific models, and simulating realistic scenarios, it is found that the relative ranking of the BEVs in terms of total costs improves moderately when the traveled distance increases, subsidies are introduced and battery price drops. However, the BEVs become convenient only when the annual distance traveled is at least 20,000 km, a value much higher than the current Italian average and posing serious issues in terms of vehicles' range. Only a joint reduction of the battery price to €240/kWh from initial estimated cost of €412/kWh and the introduction of a subsidy would make the BEVs competitive with the current average Italian annual distance traveled.

1. Introduction

The movement of people and goods is crucial for economic and social development. Yet, it consumes considerable amounts of energy and generates various environmental impacts including global and local polluting emissions. As vehicle ownership is forecasted to increase dramatically worldwide, in order to achieve a better balance between the pros and cons of transportation, governments enact incentives and regulations to develop new vehicles and foster the use of cleaner fuels. The automotive industry reacts developing many vehicles' engine/fuel options (compressed natural gas; liquefied petroleum gas; hybrid; range extender; full electric; hydrogen, fuel cell, etc.). Within a given infrastructural and regulatory framework, the consumer ultimately decides which vehicle to buy and use on the basis of his/her preferences for a number of attributes, including purchase and operating costs, energy consumption and environmental impact.

Both governments and consumers are influenced in their decision-making process also by the existing scientific evidence. However, the scientists who estimate the costs of different vehicles and their energy and environmental efficiency are faced with a difficult task since there are many uncertainties due to lack of data, uncertain data sources and high variability in measurements in the areas of the energy, environmental and economic evaluation.

A further difficulty is the lack of a unique and easy-to-communicate indicator because of the existence of many

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http://dx.doi.org/10.1016/j.retrec.2015.06.002

Acronyms

BEVs	battery electric vehicles
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
E85	ethanol
EVs	electric vehicles
FC	fuel-cell vehicles
FC-HEV	fuel-cell hybrid electric vehicles
FC-PHEV	fuel-cell plug-in hybrid electric vehicles
GHG	greenhouse gas emissions
GWP	global warming potential
HEVs	hybrid electric vehicles
ICEVs	internal combustion engine vehicles
Leased BEV	BEV with battery leasing
Li-ion	lithium-ion batteries
LPG	liquefied petroleum gas
Ni-MH	nickel–metal hydride batteries
NMVOC	non-methane volatile organic compounds
NO_x	nitrogen oxide
PHEVs	plug-in hybrid electric vehicles
$PM_{2.5}$	particulate matter (2.5 μm diameter)
PM_{10}	particulate matter (10 μm diameter)
PV	present value
SO_x	sulfur oxide
SO_2	sulfur dioxide
TtW	tank-to-wheels
WtT	well-to-tank
WtW	well-to-wheels
VOCs	volatile organic compounds

heterogenous components: economic costs expressed in monetary terms; energy consumption expressed in energy units; environmental impacts expressed in g/km for the various air pollutants; and noise expressed in decibel. This paper chooses to compare the alternative cars in terms of total cost of ownership (TCO), social lifecycle cost (SLC) and energy consumption.

The costs of a car are inevitably time- and location-specific. The cost of buying, running and maintaining a car continuously changes over time and varies by location. The vehicles' purchasing costs, insurance costs, fuel costs, taxes and subsidies are country-specific due to different market structures, firms' strategies or purchasing power. The energy content and the energy impact depend on the energy mix of the country. The impact of air pollutants depends on the characteristics of the locations where they are released. Furthermore, technological innovation develops very rapidly so that an indicator estimated with today's parameters, based on historical data, might not be valid tomorrow.

Notwithstanding this variability and uncertainty, decisions need to be taken by policy makers, car manufacturers and consumers on the basis of existing knowledge.

Focusing on Italy, this paper contributes to the current knowledge by providing an estimate with up-to-date parameters of the TCOs, social costs and energy consumption of 66 car models. In order to obtain this result, the lifecycle energy consumption and environmental emissions are calculated and a monetary assessment of the external costs is provided making use the monetary values more appropriate to the Italian situation. The estimates are made taking into account urban and intercity trips. Finally, a sensitivity analysis is performed in order to evaluate how the results depend on the model's parameters.

The estimates on TCO, SLC and energy consumption provided in the paper could be useful to the public and private (firms and consumers) decision makers to make more informed decisions and to the analyst to understand the present and future market penetration of the various automotive technologies in Italy. To the best of our knowledge, no estimates for Italy have been so far provided.

The paper reviews the literature in Section 2. Section 3 presents the model used to estimate the private and social costs of alternative technologies is. In Section 4, the results obtained for 66 models available in Italy are discussed. In Section 5, 7 specific, more homogenous car models are compared and in Section 6 a sensitivity analysis for the 7 models is performed, focusing focus on the impact of varying the annual kilometers driven, introducing a subsidy for less polluting cars, and reducing the battery price. In Section 7 conclusions are drowned.

2. Literature review

Although there is an abundant literature on the comparison among different vehicles technologies in terms of private and social costs, energy use and environmental impacts. For a variety of reasons, few consensus results have emerged.

2.1. Environmental and energy assessments

A survey by Hawkins, Gausen, and Strømman (2012) and Hawkins, Singh, Majeau-Bettez, and Strømman (2012) reviewed 55 studies from peer-reviewed and gray literature containing environmental and energy assessments. Their focus is on the comparison between internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs). Their conclusion is that very few full lifecycle inventory studies exist. They find that more studies include the lifecycle inventory of fuels and electricity than the lifecycle inventory of the vehicle itself. The Global Warming Potential (GWP) is the most frequently reported result followed by acidification (SO_2, NO_x), smog (CH_4, NMVOC, NO_x), and toxicity impacts.

Various factors can explain this lack of knowledge and consensus.

A crucial factor is that HEVs, PHEVS and EVs are still a relatively new technology with a scarce penetration compared to ICEVs. As a consequence, some features are yet not well-documented. For instance, with regards to batteries: a) the battery chemistry and size are not fully-established yet; the Li-ion and a Ni-MH batteries are most widely used, with different materials availability for battery production; b) the battery lifetime is still unknown,[1] the end of life impact of the battery (down-cycling, reuse, and recycling) is not yet sufficiently researched; c) battery management systems, electronic controls, and temperature control systems are still under research and improvement.

Moreover, the battery and electricity supply chain is very complex. Many, and very diverse, electricity production possibilities and mixes are available, the interaction with the infrastructure is yet to be understood with regards to both the infrastructure used to transmit and distribute electric energy and the infrastructure for

[1] It varies in the range of 150,000–300,000 km and the expected lifetime for Li-ion batteries appears to have more than doubled in the last 10 years (Zackrisson, Avellán, & Orlenius, 2010).

charging the EVs such as grid-to-battery and battery-to-grid systems. The effect of the time of the day used for charging on the overall energy efficiency is an example of an issue not yet fully researched. Interesting contributions have been recently made by Massiani and Weinmann (2012) and Graff Zivin, Matthew, Kotchen, and Mansurc (2014).

All these aspect make the environmental, energy and cost impact assessment on the HEVs, PHEVs and EVs quite difficult.

With reference to the environmental impact, Rusich and Danielis (2013, Table 1, p. 4) report the results presented in 35 recent papers of different vehicle technologies. They find that EVs are often estimated to have a GWP lower than the conventional ICEVs. The result is, however, strongly dependent on how electricity is produced and distributed. If carbon intensive sources are used, the GWP of the EVs is comparable or, in some cases, even worse than some advanced ICEVs. A recent study for the US carried out by Graff Zivin et al. (2014) was able to estimate marginal CO_2 emissions of electricity demand accounting for location and time of day. They find that the CO_2 emissions per mile from driving EVs are less than those from driving a hybrid car in the western United States and Texas. In the upper Midwest, however, charging during the recommended hours at night implies that PEVs generate more emissions per mile than the average car currently on the road.

Distinguishing between fuel and car production and car use, it is evident that ICEVs generate global warming pollution mostly in the car use phase while EVs in the energy and car production phase.

Focusing on local air pollutants, when the US energy mix is taken into account, in global terms the NO_x emissions are similar for ICEVs and EVs, the VOC and CO emissions are higher for the ICEVs while the PM_{10} e $PM_{2.5}$ and the SO_2 emissions are higher for BEVs. ICEVs emit mostly local pollutants in the car use phase while BEVs in the energy and car production phase. ICEVs' local pollution emissions are spatially widespread and occur in urban areas, whereas EVs local pollution emissions are spatially concentrated and do not occur in dense urban areas: this is the characteristic that makes them highly appealing to the general public.

Notwithstanding the importance of conducting a spatial analysis, there are only few studies that attempt to differentiate between the effects of harmful pollutants considering the location of emission. Huo, Wu, and Wang (2009) propose an interesting Well-to-Wheels (WtW) assessment of some pollutants (NO_x, PM_{10}, $PM_{2.5}$, CO, VOCs), focused on North America. They find that WTW emissions of the vehicle/fuel systems differ significantly, in terms not only of the amounts but also with respect to locations and sources. Another recent study by the National Petroleum Council (2012) confirms that the BEVs are a very promising instrument to reduce urban air pollution: while urban VOC and urban NO_x contribute most to ground-level ozone in populated areas, all alternative fuel-vehicle systems are comparable to or lower than the 2005 gasoline vehicle baseline emissions. Unfortunately, to the best of our knowledge no such study exists for the European Union.

With reference to the energy efficiency of the different fuel/powertrain options, energy use is traditionally evaluated via a Well-to-Wheels (WtW) assessment, which is composed of two stages: the fuel cycle stage (Well-to-Tank, WtT) and the vehicle use stage (Tank-to-Wheels, TtW). These two stages make up a sort of lifecycle analysis of a fuel/powertrain option.

Rusich and Danielis (2013, Table 2, p. 11) report the results presented in 19 recent papers concerning the relative WtW energy efficiency of various fuel/powertrain models. No consensus emerges in this literature: in some studies, the BEVs is more efficient than the ICEVs (Baptista, Silva, Gonçalves, & Farias, 2009; Lucas, Silva, & Neto, 2012; Shen, Han, Chock, Chai, & Zhang, 2012; Svensson, Møller-Holst, Glöckner, & Maurstad, 2007); in other studies the opposite is true (Geringer & Tober, 2012; Torchio & Santarelli, 2010). Apart from the obvious data uncertainties, this lack of consensus shows that the energy efficiency ranking of different fuel, crucially depend on the energy mix.

2.2. Total cost of ownership

The literature also contains a set of studies dealing with the user's TCO of a vehicle. A thorough review of these studies is presented in Michalek et al. (2011). In their own study, Michalek et al. (2011) assess the TCO incurred to own and operate various types of vehicles plus the cost of the oil and damages caused by lifetime emissions charged to the owner at the time of purchase, assuming no change in driving patterns. They find that the HEVs have an advantage over the conventional ICE vehicles, whereas the PHEV20[2] is slightly more costly. On the contrary, the PHEV60 and the BEV have a substantially higher net cost. No subsidy or tax break is considered.

Recently, Faria, Moura, Delgado, and de Almeida (2012) compared 5 types of cars: a diesel and gasoline ICEV, an HEV, a PHEV and a BEV. The Volkswagen Golf is used as an example of this gasoline and diesel type of cars, the Toyota Prius, Chevrolet Volt and Nissan Leaf, respectively are used to represent the HEV, range extender and BEV cars. The authors evaluate the ownership cost for each vehicle type to determine the economic value of the investment, accounting for purchase and operational costs as well as depreciation. The operational cost, per year, is calculated based on a total distance driven of 15,000 km and the average 2011 EU energy prices for fuel and electricity. Two estimates are reported: after 5 years and after 10 years. After 10 years, the diesel ICEV is still the cheapest, followed by the HEV, the BEV, the gasoline ICEV, and the PHEV. Hence, the BEV becomes cheaper than the gasoline ICEV but is €2142 more expensive than the diesel ICEV. The price difference declines because the lower operational costs are allowed more time to compensate the depreciation costs. Note that the BEV enjoys a €5000 subsidy.

2.3. The battery electric vehicles

With specific reference to the BEV, Hacker, Harthan, Matthes, and Zimmer (2009) critically review the impact on the environment and on the electricity market of a large scale introduction of electric cars in Europe. They stress the need to consider four spheres, in an integrated way, in order to evaluate the environmental effects of large-scale introduction of electric vehicles: 1) the technical sphere (i.e., the reliability of battery systems, the energy demand per vehicle, the degradation of batteries, and the bi-directional connection to the grid); 2) the mobility sphere, that is the actual mileage substitution from conventional cars; 3) the energy sphere, that is what type of electricity (fossil, renewable, nuclear) is used for charging and what consequences charging has on the operation of existing power plants and construction of new power plants; and 4) the legal sphere, that is the overall legislation regarding all aspects of energy production and consumption as well as greenhouse gas reduction is designed in a way that emission reduction in the transport sector are not offset by increases of emission in other sectors.

de Wilde and Kroon (2013) analyze the current EU legislation to reduce passenger car emissions after 2020 and propose some improvements, based mainly on CO_2-limits on conventional vehicles. They stress the need to foster the market introduction of electric

[2] The number represents the distance traveled with battery pack, 20 km (PHEV20) or 60 km (PHEV60), whereas the BEV is equipped with a 240-km battery pack (and no gasoline engine).

and hydrogen vehicles, given their potential to reach eventually a higher overall CO_2-reductions.

Tessum, Hill, and Marshall (2014) present the most recent and, probably, most comprehensive analysis of the lifecycle air quality impacts of conventional and alternative light-duty vehicles in the United States. They evaluate the air quality related human health impacts of 10 such technologies, including liquid biofuels, diesel, and compressed natural gas (CNG) Internal Combustion Engines; EV (with various powering sources); and hybrid EV. They implement spatially, temporally, and chemically detailed lifecycle emission inventories; comprehensive, fine-scale chemical transport modeling; and exposure, concentration—response, and economic health impact modeling for ozone (O_3) and fine particulate matter ($PM_{2.5}$). They find that powering vehicles with corn ethanol or with coal-based or "grid average" electricity increases monetized environmental health impacts by 80% or more relative to using conventional gasoline. Conversely, EVs powered by low emitting electricity from natural gas, wind, water, or solar power reduce environmental health impacts by 50% or more. Consideration of potential climate change impacts alongside the human health outcomes further reinforces the environmental preferability of EVs powered by low-emitting electricity relative to gasoline vehicles.

3. A model to estimate the private and social costs of alternative automotive-technology cars

This section presents the model used to estimate the private and social costs of different alternative automotive-technology cars in Italy. Three values are estimated: the total costs of ownership (TCO), social lifecycle costs (SLC) and energy consumption. For an easier understanding, only some parameters are presented in this section while others are presented in the Appendix.

3.1. The total costs of ownership

The TCO of a car is the cost of holding a car for 10 years, driving a given annual distance at the prevailing fuels cost. Some assumptions about these variables are relaxed in the sensitivity analysis presented in Section 4. The TCO is calculated as follows:

$$TCO = Vehicle\ Capital\ Cost + present\ value\ of\ the\ annual\ operating\ costs$$

The *Vehicle Capital Cost* is the manufacturer's suggested retail price of the car minus the possible subsidy. The *present value (PV) of the annual operating costs* includes all costs incurred during the lifetime of the vehicle. The following annual operating costs have been considered:

Annual fuel cost: it depends on the urban and interurban fuel consumption of the car, on urban and interurban mileages and on the fuels' prices. For conventional ICEVs and HEVs, fuel cost has been calculated as follows:

$$Annual\ fuel\ cost = average\ annual\ km\ driven *Fuel\ efficiency*Fuel\ Price$$

The fuel efficiency is the quantity of fuel consumed to drive 100 km. It depends on the share of urban/interurban distances. In the case of bi-fuel vehicles, one can distinguish between a primary and a secondary fuel. For instance, CNG and LPG cars can run with both these fuels (called primary) or with a secondary fuel (gasoline or diesel). Depending on prices, availability and preferences, each driver chooses which fuel or fuels mix to use. In our model, the simplified assumption is made that the driver makes 75% of the distance with the more convenient alternative fuel. The annual fuel cost is, hence, estimated as follows. First, the total car range is estimated.

$$Primary\ fuel\ range\ (km) = \frac{Primary\ fuel's\ tank\ capacity}{Fuel\ efficiency\ of\ the\ primary\ fuel}*100$$

$$Secondary\ fuel\ range\ (km) = \frac{Secondary\ fuel's\ tank\ capacity}{Fuel\ efficiency\ of\ the\ secondary\ fuel}*100$$

$$Total\ Car\ Range\ (km) = Primary\ fuel\ range\ (km) + Secondary\ fuel\ range\ (km)$$

The total number of primary and secondary fuel tank refillings necessary to drive the assumed annual distance is obtained by dividing the average annual kilometers driven by the total car range. The annual fuel cost is estimated multiplying the number of refillings by their cost. For EVs, the following formula has been used:

$$\text{Annual electricity costs} = \text{Average annual km driven} * \text{energy requirements/km} * \text{Electricity average retail price per kWh}$$

Annual battery leasing fees: only for EVs with leased battery. The amount depends both on the average annual kilometers driven and on the contract length in years.

Average annual insurance cost: it varies among individuals according to the person's age, accident record, city of residence, engine type, etc. In order to take into account all these aspects, a price quotation for insurance has been searched for all the car models considered.

Annual ordinary maintenance and repair cost: it is usually incurred after some years or after a given number of kilometers (e.g., 15,000 km). The model assumes as a reference the values provided by the website of ACI (Automobile Club per l'Italia). Similar data are used by companies for computing their employees' travel costs.

Annual extraordinary maintenance and repair cost: it is related to brakes, shock absorbers, tires and clutch. The average Italian value referring to 2011 has been provided by the ACI website.

Average annual parking cost: it includes garage costs and parking fees. The average Italian value referred to 2011 has been used, assumed equal across vehicle types except for electric vehicles which are assumed to bear no parking cost as they are often exempted from the parking charge in city centers.

Annual vehicle excise duty: In Italy, this amount depends on the horsepower and the European air pollution standards. Furthermore, the Italian government provides discounts for alternative fueled vehicles. CNG and LPG vehicles pay a road tax 25% lower than that applied to gasoline vehicles, while EVs have a total exemption for the first five years. No deductions are currently available for HEVs.

Compared to the literature our model makes some simplifying assumptions due to lack of sufficient and reliable data. Differently from Gilmore and Lave (2013), it assumes that the car is held 10 years (close to the Italian average age of a car) and that the residual value of the car is zero.[3] Such assumption penalizes the cars that

[3] Assuming implicitly (as pointed out by an anonymous reviewer) that the net present value of its future services minus use and maintenance cost is smaller than the net present value of a new car services plus purchase costs minus use and maintenance costs.

Table 1
WtW energy use (MJ/km).

Fuel/powertrain	WtT	TtW	WtW
ICEV (gasoline)	0.432	1.872	2.304
ICEV (diesel)	0.360	1.620	1.980
ICEV (bi-fuel CNG)	0.324	1.980	2.304
ICEV (bi-fuel LPG)	0.216	2.016	2.232
ICEV hybrid (gasoline)	0.288	1.584	1.872
ICEV hybrid (diesel)	0.252	1.296	1.548
BEV	1.296[a]	0.540[a]	1.836[a]

[a] Our estimate.
Source: Torchio and Santarelli (2010), Edwards et al. (2013) and Huss et al. (2013).

Table 2
Well-to-Wheels emission per km driven (g/km).

Fuel/powertrain	WtW_{NOx}	WtW_{PM}	WtW_{SOx}	WtW_{GHG}
ICEV (gasoline)	0.139	0.009	0.127	179.10
ICEV (diesel)	0.238	0.007	0.097	145.18
ICEV (bi-fuel CNG)	0.082	0.007	0.035	152.59
ICEV (bi-fuel LPG)	0.055	0.005	0.136	153.96
ICEV hybrid (gasoline)	0.195	0.007	0.107	122.50
ICEV hybrid (diesel)	0.119	0.005	0.078	115.62
BEV	0.133	0.004	0.145	63.59

Source: Van Essen et al. (2011), Edwards et al. (2013), Huss et al. (2013), and Rusich and Danielis (2013).

better retain a value. Differently from Al-Alawi and Bradley (2013), the maintenance and repair costs are assumed to be constant over the years and are not a function of the total distance traveled as in Al-Alawi and Bradley (2013). These limitations could be taken care of when the data become available or a sensitivity analysis could be performed to evaluate their impact on the cars' ranking.

3.2. Lifecycle energy consumption

Following Torchio and Santarelli (2010), Edwards, Larivé, Rickeard, and Weindorf (2013) and Huss, Maas, and Hass (2013), the estimate of the Well-to-Wheels (WtW) energy consumption is performed distinguishing between the Well-to-Tank (WtT) and the Tank-to-Wheels (TtW) components.[4] An average of the above quoted studies is used. For the BEVs only, the values are computed taking into account the 2011 Italian energy mix. The data used are summarized in Table 10 in the Appendix. The average values have been used. More properly, as quoted in the literature review, Graff Zivin et al. (2014) estimate spatially and time-of-day differentiated marginal energy consumption of electricity demand to evaluate the BEVs energy consumption. Our parameters are reported in Table 1.[5]

The ICEV hybrid (diesel) is the less energy intensive car, followed by the BEV, characterized by the highest WtT, but the lowest TtW energy consumption.

By multiplying these parameters by the total distance driven, one gets a complete lifecycle energy consumption assessment.

3.3. Social lifecycle costs

Using a car generates also social lifecycle costs (SLC), mostly associated with air pollution, either greenhouse gases (CO_2, NO_2, CH_4) or local air pollutants (NO_X, SO_X, PM), and noise. The estimate of the social lifecycle costs is fraught with difficulties and uncertainties, both related to the estimate of the lifecycle physical emission and with their economic valuation. Following Michalek et al. (2011), in this paper, the air pollution assessment considers the entire lifecycle (WtW), while the noise assessment refers only to the car use phase. Hence:

$$\begin{aligned} \textit{Social Costs} &= \textit{WtW Global Air Pollution Cost} \\ &\quad + \textit{WtW Local Air Pollution Cost} + \textit{Noise Cost} \end{aligned}$$

The WtT and the TtW emission per km driven (g/km) (see Tables 11 and 12 in the Appendix) are derived from the Van Essen et al. (2011), Edwards et al. (2013), Huss et al. (2013), except for the BEVs, whose values are computed based on the 2011 Italian average energy mix (Table 2).

The bi-fuel CNG and LPG ICEVs have the lowest values in all pollutants. The ICEVs (gasoline and diesel) have high values for NOx and GHG. The BEV performs well in terms of GHG and PM but performs currently badly in terms of NO_X and SO_X.[6]

Finally, we compute the social costs. The monetary value of each pollutant emissions consist of health costs, building/material damages, crop losses and costs for further damages for the ecosystem (biosphere, soil, water). We used the values reported in Table 3.

For each pollutant the environmental cost per km driven are estimated as follows:

$$\begin{aligned} \textit{WtW}\ (€/km) &= \textit{WtT}^{*}(g/km)*\textit{WtT External Cost}\ (€/g) \\ &\quad + \textit{TtW}\ (g/km)*\textit{TtW External Cost}\ (€/g) \end{aligned}$$

These values are multiplied by the average kilometer driven per year and discounted to obtain the total value.

Noise costs have been calculated considering vehicle-per kilometer costs (€/km) of this externality, obtained by Maibach et al. (2008), distinguishing between urban and interurban trips. The costs are estimated as follows:

$$\textit{Noise Cost} = \textit{Noise Urban Cost} + \textit{Noise Interurban Cost}$$

where:

[4] Well-to-Wheel is the specific Life Cycle Assessment used for transport fuels and vehicles. The analysis is broken into stages called "Well-to-Tank" ("well-to-station"), and or "Tank-to-Wheel" ("station-to-wheel" or "plug-to-wheel"). The first stage incorporates the feedstock or fuel production and processing and fuel delivery or energy transmission. It is also called the "upstream" stage. The second stage, the "downstream" stage, deals with vehicle operation itself.

[5] An anonymous referee signals that the calculation of the actual consequences of Alternative Fuel Vehicles' diffusion may involve further difficulties considering the regulatory context in which it takes place. This complication is twofold. On the one side, it relates to the cap on CO_2 emissions involved by European Trading System: this system implies that emissions by the energy sector are unresponsive to the introduction of additional EVs (these rather substitute other, socially desirable, uses of energy). This would imply that non-tailpipe emissions of EVs are zero. On the other side, considering tailpipe emissions, regulation EU 443 implies that car manufacturers have to respect some maximum average fleet emissions. This system allows converting the low emissions of Alternative Fuel Vehicle's in increased emissions for Conventional Vehicles. In this setting, the diffusion of AFV would not reduce tailpipe emission. Confrontation between the authors and the referees did not allow reaching agreement on these possible effects. While they may deserve further consideration, we choose in this paper not to consider them in order to avoid extra complications.

[6] In order to correctly appreciate this data, it is worth mentioning that a recent report from the European Environment Agency (2013) states that important gains could be made in many European countries if better technology is used by the electricity-generating large combustion plants. If the Industrial Emission Directive (2010/75/EU) and its more stringent emission limit values are implemented, as prescribed, by 2016, at European level (EU-27) NO_x emissions have the potential to be 36% lower than in 2009, SO_2 and dust 66% and 64% lower, respectively. In Italy, the potential gains are estimated to be equal to 21% for NO_x (from 67.2 to 53 kt), to 50% for SO_2 (from 55.1 to 27.8 kt) and to 23% for dust (from 2.2 to 1.7 kt).

Table 3
External costs per pollutant (€/g).

Air pollutant	WtT cost	TtW cost
NO_x	0.01	0.01
SO_x	0.01	0.01
PM rural	0.12	0.12
PM urban	0.21	0.21
PM metropolitan	0	0.65
GHG	0.000093	0.000093

Source: adapted from Van Essen et al. (2011).

$$Noise\ Urban\ Cost\ (€/year) = Yearly\ Kilometers * \%\ Urban\ Kilometers * Average\ Urban\ Noise\ Cost\ Noise\ Interurban\ Cost\ (€/year) = Yearly\ Kilometers * \%\ Interurban\ Kilometers * Average\ Interurban\ Noise\ Cost$$

All costs are discounted. Furthermore, it is assumed that EVs have a 90% reduction in noise emissions, while for HEVs it is 20%.[7]

4. Estimates for various automotive technologies in Italy

Recently, new fuel/powertrain options have been introduced in the Italian car market. In 2013, however, the market (with a size of 1.3 million cars) was still dominated by the diesel ICEVs with a share of 54.10%, followed by the gasoline ICEVs with 30.6%. Third is the bi-fuel LPG ICEV with 8.9%; bi-fuel CNG with ICEV is at 5.2%. The new entrants, hybrids and BEVs, are at 1.14% and 0.07%, respectively (UNRAE, 2014).

In this section, the model presented in the previous section is applied to 66 car models (Table 9 in Appendix). The car models have been chosen among the ones which were most popular in Italy in 2013 for each fuel/powertrain available (UNRAE, 2014). The estimates are made under these assumptions:

a) driven distance is 10,000 km per year;
b) car ownership duration is 10 years;
c) WtT emissions take place in a rural area and the TtW emission in an urban area, and
d) car trips are made 80% in intercity roads and the remaining in urban roads. Some of these assumptions will be relaxed later in the sensitivity analysis.

Table 4 reports the results obtained by fuel/powertrain.[8] Column (a) reports the number of car models considered for each fuel/powertrain. It can be noted that the categories are of different size since the number of models is quite different among fuel/powertrain categories. For instance, the supply of BEVs with the leased battery and of diesel hybrid is still very limited. Due to this fact and to the inherent heterogeneity among car models, the values presented in Table 4 (as pointed out by an anonymous referee) cannot be generalized, since they reflect car's type and size differences. Nevertheless, they do represent the average values of a sample of models available to the Italian consumers in 2013 in each fuel/powertrain categories.

Column (b) reports the average lifelong TCO of the models considered. The Gasoline ICEVs are the less expensive, followed by the bi-fuel LPG ICEVs and by the bi-fuel CNG ICEVs. The hybrids are the most expensive, followed by the BEVs. Obviously, this ranking should be interpreted with caution since it reflects the car models chosen. Although they belong mostly to the segment B of the market, they are rather differentiated in terms of size, power, and performance.[9]

Column (c) reports the average estimated social cost of each category. The BEVs generate the lowest social costs (at least 50% less than the other cars). Contrary to a common view, this results depends more from the noise benefits than to the air pollution benefits, The detailed estimates are reported in Rusich and Danielis (2013). Note also that the SLC represents between 1.6% and 6.1% of the total cost. Consequently, they ranking in terms of TCO coincide with that in terms of total costs presented in column (d).

Column (e) reports the energy consumption of each grouping. Our estimate indicate that hybrid (diesel) ICEV uses less energy than the others, thanks to the lowest WtT energy consumption and good performances also in the TtW phase. The BEVs are the best in the TtW stage, thanks to compared to ICEVs, but they are the worst in the WtT stage.

The last column (f) reports the average ranking, with the lowest and highest ranking in brackets, of the cars included in a category on the basis of the total cost indicator. It is also illustrated in Fig. 1. For instance, the gasoline ICEVs range from the 7th to the 33rd position in terms of total cost; the average ranking is 18.6. Overall, they are least expensive cars. On the contrary, the hybrid (diesel) ICEVs are the most expensive. They rank at best 60th and at worse 64th, hence, on average they rank 62.

5. Estimates for 7 cars with different fuel/powertrain on sale in Italy

The developed model is now applied to compare 7 specific, more homogenous car models, six of which belonging to the market segment B 'small cars': the gasoline VW Polo, the diesel Ford Fiesta, the bi-fuel CNG Fiat Punto Evo Natural Power, the bi-fuel LPG Alfa Romeo MiTo, the hybrid Toyota Yaris, the BEV with leased-battery Renault Zoe and one belonging to car market segment A "mini cars" the BEV Peugeot iOn. The market segment B has been chosen because most of these fuel/powertrain options are available in this car category while other segments do not offer these fuel/powertrain (e.g. bi-fuel CNG and hybrid diesel powertrains are not installed in "large" cars and the hybrid powertrains is not installed in "mini" cars).

Two base case scenario are estimated to take into account of different use conditions:

[7] Identifying the sources of noise, distinguishing between noise generated by the engine exhaust system and transmission and that generated from the interaction of tires with the road surface is a difficult subject. Even more difficult is to estimate the marginal contribution that could be made by an EV in real traffic conditions. Our assumption is tentative and supported by Mahajan and Rajopadhye (2013), who estimate a 9–15% contribution of the tires, the remaining coming from the engine (22–30), exhaust system (25–35), intake system (5–15), fan and cooling system (7–15), transmission (12–15).

[8] Note that for BEVs, car models supplied in the market with the battery ownership business model are separated from those supplied with the battery leasing business model.

[9] For instance, the ICEVs (Gasoline) results the best because most of the selected models are "mini cars".

Table 4
TCO, social cost and energy consumption by fuel/powertrain.

Fuel/powertrain	Car models considered (a)	TCO (€) (b)	SLC (€) (c)	Total cost (€) (d)	Energy consumption (kWh) (e)	Average ranking (highest-lowest) (f)
ICEV (gasoline)	10	29,665	1935	31,600	64.3	18.6 (7–33)
ICEV (diesel)	11	34,657	1721	36,378	54.8	33.0 (11–52)
ICEV (bi-fuel CNG)	10	32,894	1594	34,488	64.3	25.7 (2–54)
ICEV (bi-fuel LPG)	11	31,312	1586	32,899	61.6	20.4 (1–46)
ICEV hybrid (gasoline)	6	53,984	1402	55,387	52.5	53.8 (35–65)
ICEV hybrid (diesel)	4	65,210	1377	66,587	43.2	62.0 (60–64)
BEVs with owned battery	10	47,279	777	48,057	51.3	43.2 (15–66)
BEVs with leased battery	4	40,717	777	41,495	51.3	44.5 (30–55)
Total or average	66	38,964	1462	40,426	57.2	18.6 (7–33)

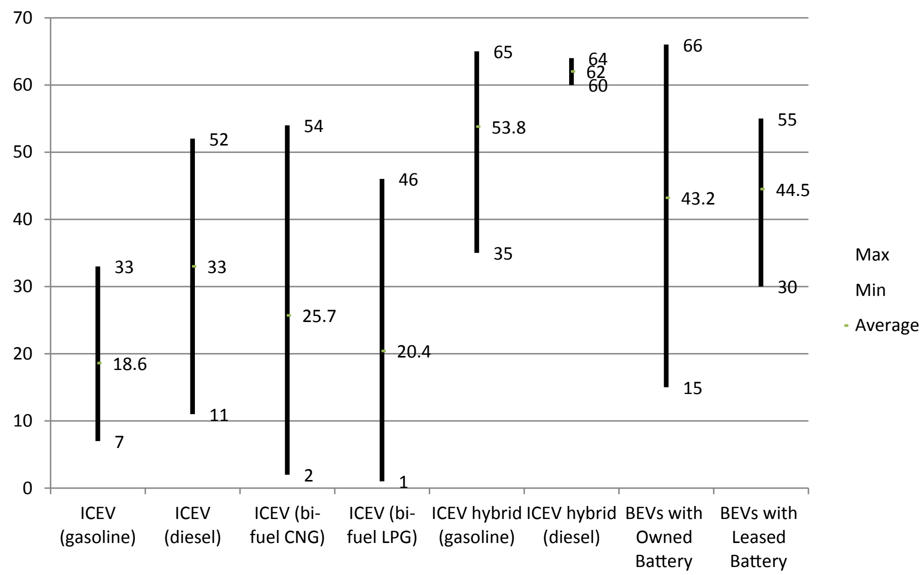

Fig. 1. Ranking of the 8 car groupings by fuel/powertrain (maximum, minimum and average values).

An *urban* base case scenario (the car is held 10 years, driven 10,000 km per year, 80% of the trips take place in urban roads; emission are WtT rural/TtW metropolitan).

A *intercity* base case scenario (the car is held 10 years, driven 20,000 km per year, 80% of the trips take place in intercity roads; emission are WtT rural/TtW rural).

The results are reported in Tables 5 and 6.

Under the urban scenario assumptions, Table 5 shows that from a private point of view Fiat Punto (bi-fuel CNG) is the cheapest car, followed at close distance by Ford Fiesta (diesel) and VW Polo (gasoline). The Toyota Yaris (hybrid) and Alfa R. MiTo (bi-fuel LPG) are slightly more expensive. The BEVs are the most expensive. These results are mainly due to the differences in the purchasing costs. In fact, the very low operating cost of Peugeot iOn (BEV) does not offset, in 10 years with 10,000 km per year, the purchasing cost difference. The cheapest BEV costs about €7000 more than the cheapest car.

The SLC varies between €778 and €2113, which is much lower than the TCOs. The largest part of this cost is represented by global pollutants emissions, with values ranging between €482 of the BEVs and €1357 of the VW Polo (gasoline). The residual part of the social cost is primarily due to local air pollution costs. For this parameter, values range from €184 of the Alfa R. MiTo (bi-fuel LPG) to €385 of the Ford Fiesta (diesel). Finally, the BEVs present the lowest noise cost values.

As far as energy consumption is concerned, the most efficient cars are the BEVs Renault Zoe and Peugeot iOn, thanks to the lowest energy use in the TtW stage.

Similar estimates are made in the intercity base case scenario (Table 6) to test whether different driving conditions (length and location) produce different results. The changes are not dramatic: the cheapest car is now the Ford Fiesta (diesel), while the Fiat Punto (bi-fuel CNG) ranks second. The Alfa Romeo MiTo (bi-fuel LPG) becomes the most expensive, ant the BEVs gain the 5th and 6th position. The cheapest BEV costs now about €5000 more than the cheapest car, due to higher capital costs. The previous results are confirmed for the social costs and energy consumption.

6. Sensitivity analysis

In order to evaluate the impact of different parameters on the relative performance of the alternative fuel/powertrain cars a sensitivity analysis should be estimated. In this paper we focus on: a) variations in annual kilometers driven; b) the introduction of a subsidy for less polluting cars; c) a battery price reduction. Further analysis is reported in Rusich and Danielis (2013).

6.1. Scenario 1 — varying the annual distance driven

We start by comparing the total costs of the 7 fuel/powertrain cars when the average annual kilometers driven increase from 5000 to 15,000 km per year in the urban scenario and from 15,000 to a hypothetical 25,000 km per year in the intercity scenario, holding all other variables of the base case scenario constant.

Table 5
TCO, social cost and energy consumption in the urban base case scenario.

Car model	TCO (€)			SLC (€)			Total cost (€)	Energy consumption (kWh)		
	Purchase price	Annual operating cost	Total	WtT	TtW	Total		WtT	TtW	Total
VW Polo (gasoline)	11,900	2570	32,738	401	1712	2113	34,852	11.8	52.4	64.3
Ford Fiesta (diesel)	14,000	2160	31,515	330	1569	1900	33,414	9.8	45.1	54.8
Fiat Punto (bi-fuel CNG)	15,425	1947	31,209	260	1513	1773	32,982	9.2	55.1	64.3
Alfa Romeo MiTo (bi-fuel LPG)	20,600	2133	37,895	152	1613	1764	39,659	5.8	55.8	61.6
Toyota Yaris (hybrid)	18,650	1995	34,822	337	1208	1545	36,367	8.4	44.1	52.5
Peugeot iOn (owned battery)	30,369	1217	40,236	754	24	778	41,014	35.8	15.5	51.3
Renault Zoe (leased battery)	21,850	2148	39,273	754	24	778	40,051	35.8	15.5	51.3

Assumptions: car held 10 years, annual traveled distance of 10,000 km, 80% trips are urban, and emissions are WtT rural/TtW metropolitan.

Table 6
TCO, social cost and energy consumption in the intercity base case scenario.

Car model	Private cost (€)			Social cost (€)			Total cost (€)	Energy consumption (kWh)		
	Purchase price	Annual operating cost	Total	WtT	TtW	Total		WtT	TtW	Total
VW Polo (gasoline)	11,900	3211	37,937	802	2953	3756	41,693	23.6	104.8	128.5
Ford Fiesta (diesel)	14,000	2663	35,595	661	2668	3328	38,923	19.6	90.1	109.7
Fiat Punto (bi-fuel CNG)	15,425	2676	37,118	520	2555	3075	40,193	18.4	110.2	128.6
Alfa Romeo MiTo (bi-fuel LPG)	20,600	3112	45,829	304	2754	3058	48,887	11.7	111.6	123.3
Toyota Yaris (hybrid)	18,650	2531	39,175	675	2039	2714	41,889	16.8	88.2	105.0
Peugeot iOn (owned battery)	30,369	1497	42,509	1509	47	1556	44,065	71.6	30.9	102.6
Renault Zoe (leased battery)	21,850	2702	43,759	1509	47	1556	45,315	71.6	30.9	102.6

Assumptions: car held 10 years, annual traveled distance of 20,000 km, 80% trips are intercity, emissions are WtT rural/TtW rural.

The results are illustrated in Fig. 2 with reference to the total cost. Since the proportion between fixed (purchase) and variable (operating) costs is very different among cars, the increased distance travel improves the relative ranking of the cars with low annual operating costs. This is the reason why the Fiat Punto (bi-fuel CNG) becomes the cheapest choice in the urban scenario if more than approximately 8000 km per year are driven. Also the hybrid Toyota Yaris and the BEVs improve their relative ranking. In the intercity scenario, the Ford Fiesta (diesel) remains the cheapest choice. The Peugeot iOn (owned battery) becomes the fourth best choice.

6.2. *Scenario 2 — introduction of Italian subsidies for less polluting cars in 2014*

The Italian Parliament in 2012 passed a law to support sustainable mobility in Italy (Italian Government, 2012). More specifically, subsidies are granted for less polluting cars in the period 2013—2015 as reported in Table 7. The impact on the relative total cost is reported in Fig. 4.

Thanks to the subsidy, the Ford Fiesta (diesel) is the cheapest option regardless of the kilometers driven per year. The subsidy has a considerable impact on the Peugeot iOn (BEV) performance which becomes the cheapest car when more than 20,000 km per year are driven. Such scenario is at the moment not realistic in the case of Italy, since the annual average distance traveled per car is about 12,000 km per year. Furthermore, given the current BEV range it would require a charging infrastructure both at home and at work which is currently not available yet.

6.3. *Scenario 3 — a battery price reduction*

Nowadays, battery cost accounts approximately 40% of the BEVs purchase price. Many reports estimate that, thanks to an increase in battery manufacturing and the BEVs market penetration, the battery manufacturing costs will drop in next years. The price of the battery is subject to great uncertainty. On the basis of the various gray literature reports, we have assumed that the Lithium-ion battery from a starting estimated cost of €412 per kWh (Geringer & Tober, 2012; National Petroleum Council, 2012) would drop to €354 per kWh and then to €240 per kWh. The impact on the relative total cost of the cars is illustrated in Fig. 5.

A battery price reduction influences Toyota Yaris (hybrid) and BEVs performances, in proportion of the battery capacity of the model considered. Fig. 3 shows that a battery manufacturing cost reduction only is not sufficient to make BEVs competitive with other options considered.

6.4. *Scenario 4 — joint scenario: subsidy and battery price reduction*

When the subsidy applies, a battery price reduction to €240 per kWh would make the BEVs quite competitive relative to most cars but the Ford Fiesta (diesel), even with an annual distance of 10,000 km per year (Fig. 6).

7. Conclusions and policy implications

This paper presents the results of an estimation of the TCO, SLC and the lifecycle energy consumption of different vehicle technologies available in Italy in 2013. In a first step, a sample of 66 models is considered in order to capture the average characteristics of the different technologies. It is found that the car operated by conventional fuels (gasoline, diesel) have the lowest Total Cost of Ownership. This explains why they are currently dominating the Italian car market. The bi-fuel LPG and the bi-fuel CNG ICEVs are in the same price range (and, in fact in Italy they have a relatively significant market share, about 5—7%), but suffer from issues connected with the much less dense charging network. Both the BEVs and, especially, the hybrid ICEVs are more expensive. The BEVs suffer also from the well known range problem.

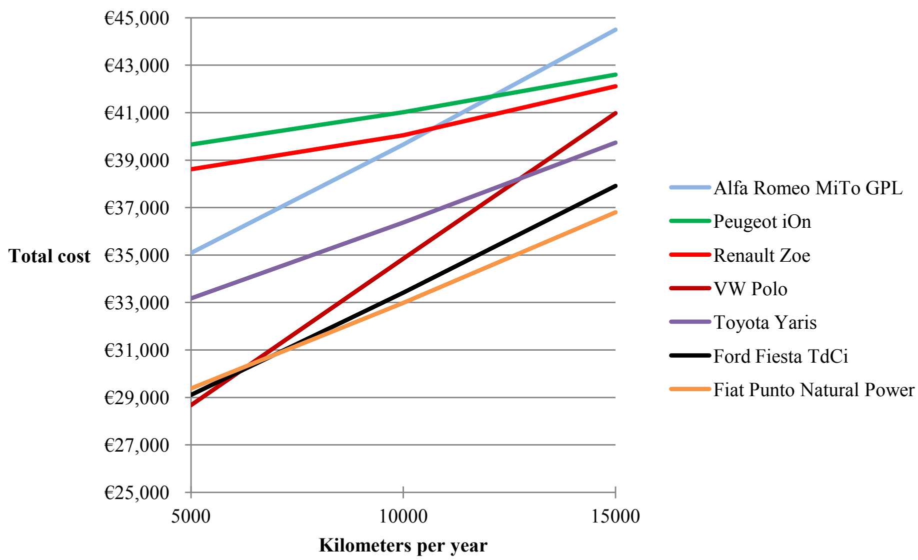

Fig. 2. Total cost varying the annual kilometers driven (urban scenario).

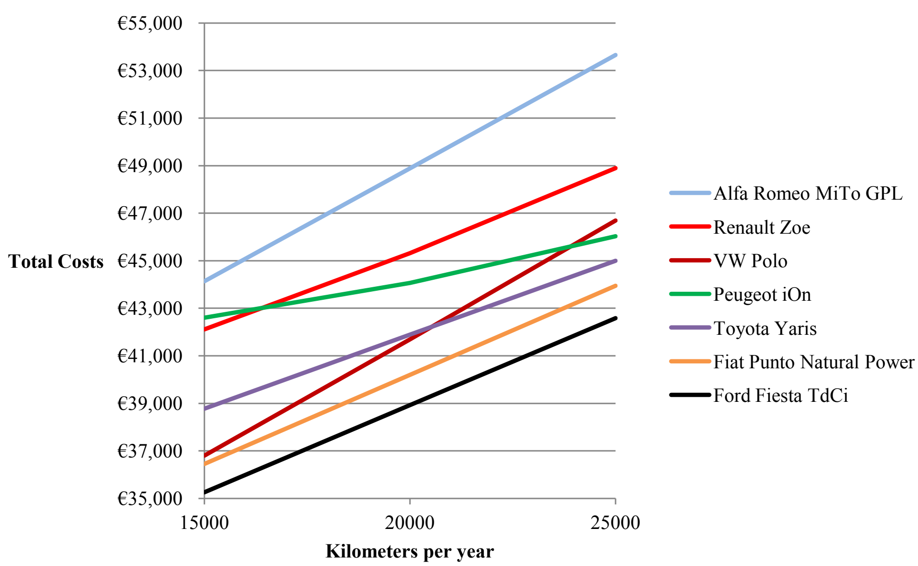

Fig. 3. Total cost varying the annual km driven (intercity scenario).

Table 7
Subsidies for low polluting cars in Italy.

VW Polo (gasoline)	Ford Fiesta (diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
–	€2000	–	–	€3730	€5000	€4370

On the contrary, the SLC of the BEVs are the lowest, thanks not only to their zero air pollutants' emissions in the use phase but also to their reduced noise emissions. The amount of the SLC relative to the TCOs, estimated using recent European parameters, represents at the most 6% of the total cost. Consequently, even if the external costs were internalized, BEVs would not become convenient from a purely monetary point of view for the final consumer.[10]

Considering the energy consumption, with the current average Italian energy production mix, the BEVs and the diesel hybrid are the most energy efficient cars.

Focusing on 7 specific models, and simulating sufficiently realistic future scenarios, it is found that the relative ranking of the BEVs improves moderately when the distance traveled increases, the subsidies are introduced and the battery price drops. The subsidy is comparatively the most effective strategy. However, the BEVs become convenient only when the annual distance traveled is at least 20,000 km, a value much higher than the current Italian average and conflicting with the current BEVs' range properties.

[10] Liu and Santos (2015) arrive at a similar conclusion considering only the internalization of the social costs of carbon.

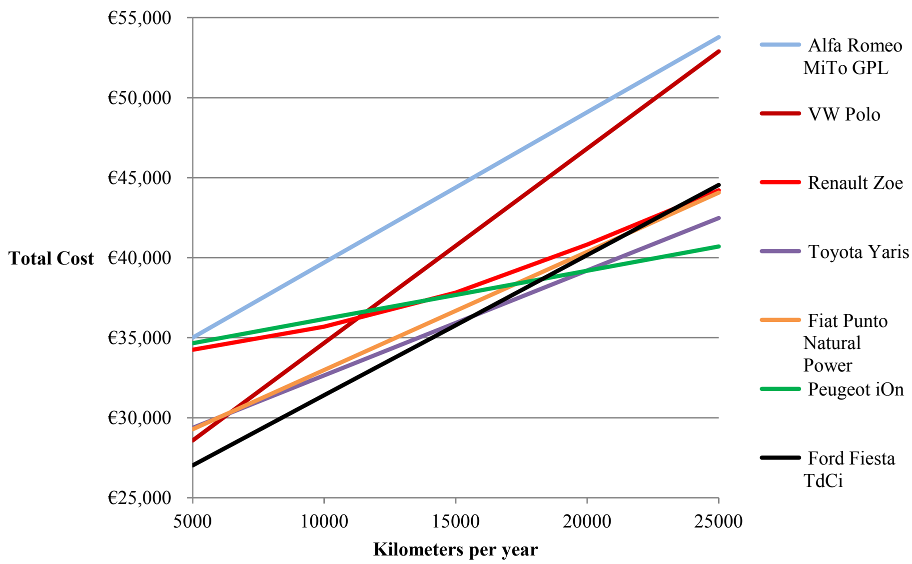

Fig. 4. Total cost after the Italian subsidies for less polluting cars varying the annual kilometers driven.

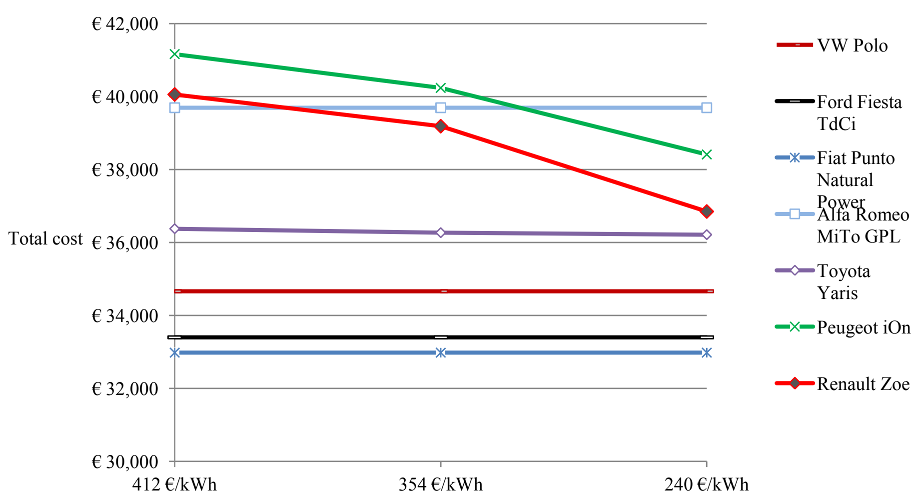

Fig. 5. Total cost with declining battery prices varying the annual kilometers driven.

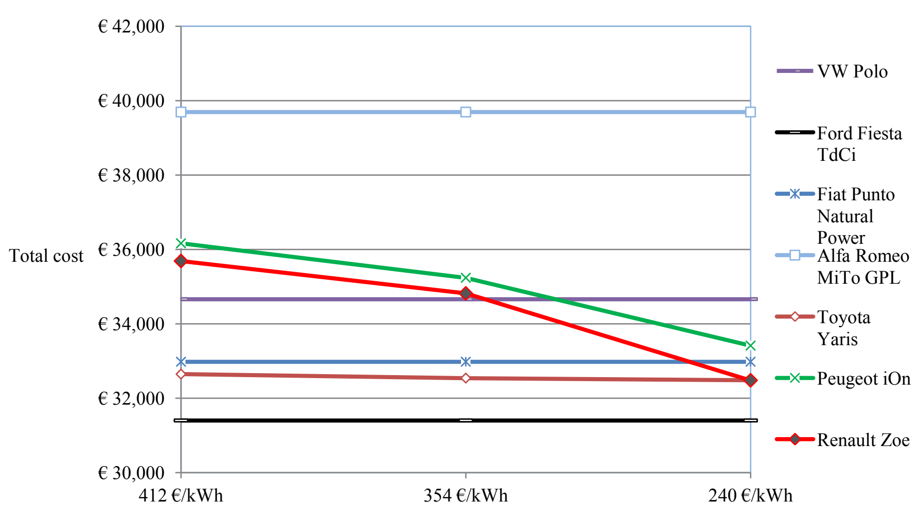

Fig. 6. Total cost including the subsidy with declining battery prices varying the annual kilometers driven.

Only a joint reduction of the battery price to €240 per kWh (starting an estimated cost of €412 per kWh) and the introduction of the subsidy would make the BEVs competitive at the current average Italian annual distance traveled. These results are similar to other studies. For instance, Kammen, Arons, Lemoine, and Hummel (2008) concludes that for the PHEV to be economical under current market conditions, battery cost must decline to below $500/kWh or U.S. gasoline must remain at $5/gallon (the December 2014 value is $2.6/gallon). Al-Alawi and Bradley (2013) find that the payback period of the PHEVs relative to the ICEVs is positive, varying between 2 and 6 years depending on the car models. A study by Massiani (2015) finds that in Germany even aggressive policies would fail to generate a significant market share for the BEVs in the long run.

The paper focused on the financial aspects of car technology choice, but of course, they are by no means the only variables that determine the selection of a car; cultural factors, car appearance and driving style are other important determinants. The usual caveats on the data uncertainties about the emission factors, the energy content factors and, especially, the environmental cost factors do apply.

Appendix

Table 8
Parameters, assumptions, sources used in the model.

Model inputs	Value	Source
Car parameters:		
VW Polo 1.4 Comfortline gasoline:		
Purchase price (€)	15,060	www.quattroruote.it
Horsepower	85	Equivalent to 62 kW. www.quattroruote.it
European Standard	5	www.quattroruote.it
Urban gasoline use (l/100 km)	8	www.quattroruote.it
Interurban gasoline use (l/100 km)	4.7	www.quattroruote.it
Mixed gasoline use (l/100 km)	7.34	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO_2 emissions (gCO_2/km)	139	Value referred to the Tank-To-Wheels stage. www.quattroruote.it
Ford Fiesta Ikon 1.4 TDCi diesel:		
Purchase price (€)	14,750	www.quattroruote.it
Horsepower	70	Equivalent to 51 kW. www.quattroruote.it
European Standard	5	www.quattroruote.it
Urban diesel use (l/100 km)	5.3	www.quattroruote.it
Interurban diesel use (l/100 km)	3.5	www.quattroruote.it
Mixed diesel use (l/100 km)	4.94	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO_2 emissions (gCO_2/km)	110	Value referred to the Tank-To-Wheels stage. www.quattroruote.it
Fiat Punto Natural Power 1.4 Easy bifuel (gasoline–CNG):		
Purchase price (€)	17,250	www.quattroruote.it
Horsepower	77	Equivalent to 57 kW. www.quattroruote.it
European Standard	5	www.quattroruote.it
Urban gasoline use (l/100 km)	7.9	www.quattroruote.it
Interurban gasoline use (l/100 km)	5.4	www.quattroruote.it
Mixed gasoline use (l/100 km)	7.4	Value calculated considering fuel use and urban/interurban percentages of km driven.
Urban CNG use (kg/100 km)	5.4	www.metanoauto.com
Interurban CNG use (kg/100 km)	3.5	www.metanoauto.com
Mixed CNG use (kg/100 km)	5	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO_2 emissions (gCO_2/km)	149	Value referred to the Tank-To-Wheels stage. www.quattroruote.it
Alfa Romeo MiTo 1.4T Upload bifuel (gasoline–LPG):		
Purchase price (€)	20,600	www.quattroruote.it
Horsepower	120	Equivalent to 88 kW. www.quattroruote.it
European Standard	5	www.quattroruote.it
Urban gasoline use (l/100 km)	8.5	www.quattroruote.it
Interurban gasoline use (l/100 km)	5.2	www.quattroruote.it
Mixed gasoline use (l/100 km)	7.84	Value calculated considering fuel use and urban/interurban percentages of km driven.
Urban LPG use (l/100 km)	10.9	www.alfaromeopress.com
Interurban LPG use (l/100 km)	6.8	www.alfaromeopress.com
Mixed LPG use (l/100 km)	10.1	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO_2 emissions (gCO_2/km)	145	Value referred to the Tank-To-Wheels stage. *www.quattroruote.it*
Toyota Yaris 1.5 hybrid Lounge:		
Purchase price (€)	17,800	www.quattroruote.it
Horsepower	100	Equivalent to 74 kW. www.quattroruote.it
European Standard	5	www.quattroruote.it
Battery capacity (kWh)	0.936	www.hybrid-sinergy.eu
Urban gasoline use (l/100 km)	3.5	www.quattroruote.it
Interurban gasoline use (l/100 km)	3	www.quattroruote.it
Mixed gasoline use (l/100 km)	3.4	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO_2 emissions (gCO_2/km)	79	Value referred to the Tank-To-Wheels stage. www.quattroruote.it
Peugeot iOn full electric:		
Purchase price (€)	28,318	www.quattroruote.it
Horsepower	67	Equivalent to 49 kW. www.quattroruote.it
European Standard	Zero E.	www.quattroruote.it
Battery capacity (kWh)	16	www.quattroruote.it
Range (km)	150	www.quattroruote.it
Energy use (kWh/100 km)	10.7	Value obtained dividing the battery capacity for the range and multiplying the result for 100. This value has been used for urban and interurban drives.
CO_2 emissions (gCO_2/km)	0	Value referred to the Tank-To-Wheels stage. www.quattroruote.it
Renault Zoe full electric with battery leasing:		
Purchase price (€)	21,650	www.renault.it
Horsepower	89	Equivalent to 65 kW. www.renault.it
European Standard	Zero E.	www.renault.it
Battery capacity (kWh)	22	www.renault.it
Range (km)	210	www.renault.it
Energy use (kWh/100 km)	10.5	Value obtained dividing the battery capacity for the range and multiplying the result for 100. This value has been used for urban and interurban drives.
CO_2 emissions (gCO_2/km)	0	Value referred to the Tank-To-Wheels stage. www.quattroruote.it
Subsidies for less polluting cars:		
2012 (€)	–	Subsidies were not available in Italy in 2012,
2013 (€)	20% of the	purchase price
However the subsidies have a cap: Max 5000€ if CO_2		emissions ≤ 50 g/km; Max 4000€ if CO_2 emissions ≤ 95 g/km; Max 2000€ if CO_2 emissions ≤ 120 g/km. D. Lg n.83 22/06/2012, Art. 17-decies

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Table 8 (*continued*)

Model inputs	Value	Source
PV(AOC) – present value of annual operating costs:		
Social rate of discount *r* (%)	5	
Average insurance cost (€/year)	715	Value referred to the Italian context in 2011. Aci-Census Servizi (2011)
Average ordinary maintenance costs (€/year)	140	Value referred to the Italian context in 2011. For EVs a 50% reduction has been assumed. Aci-Census Servizi (2011)
Average extraordinary maintenance cost (€/year)	128	Value referred to the Italian context in 2011. For EVs a 50% reduction has been assumed. Aci-Census Servizi (2011)
Average yearly parking cost (€/year)	218	Value referred to the Italian context in 2011. It includes garage costs and parking fees). Aci-Census Servizi (2011)
CNGs road tax reduction (%)	75	Road tax is only the 25% of that required for a corresponding gasoline car.
LPGs road tax reduction (%)	75	Road tax is only the 25% of that required for a corresponding gasoline car.
EVs road tax reduction (%)	100	Total exemption for the first 5 years, after the same scheme for the above types has been applied.
HEVs road tax reduction (%)	0	No deductions.
Gasoline price (€/l)	1843	Average value for the first semester of 2012.
Diesel price (€/l)	1697	Average value for the first semester of 2012.
Compressed natural gas (CNG) price (€/kg)	0.919	Average value for the first semester of 2012.
Liquefied petroleum gas (LPG) price (€/l)	0.824	Average value for the first semester of 2012.
Electricity price (€/kWh)	0.182	Average value for the first semester of 2012. http://www.autorita.energia.it
Battery leasing fee (€/month)	79	Monthly fee referred to the Renault Zoe, assuming a 36 months leasing and 12,500 km driven per year. www.renault.it
TtW_NC – noise costs:		
Full electric cars noise reduction (%)	20	Thanks to a limited full electric range, a small noise reduction has been assumed.
Hybrid cars noise reduction (%)	90	Because the electric motor operates quietly, we have considered only noise produced by wheels during the car use.
(NUC) Urban noise external cost (€/km)	0.0082	Average daily value, obtained assuming that 90% of trips are made during the day and 10% are made at night. "Handbook on estimation of external costs in the transport sector" (Maibach et al., 2008, p.73)
(NIC) Interurban noise external cost (€/km)	0.0007	Average daily value considering suburban and rural travels, obtained assuming that 90% of trips are made during the day and 10% are made at night. "Handbook on estimation of external costs in the transport sector" (Maibach et al., 2008, p.73)
Energy efficiency:		
Gasoline cars:		
WtT_ (kWh/km)	0.11	Value obtained transforming the Concawe, Eucar, European Commission (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
TtW_ (kWh/km)	0.49	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
Diesel cars:		
WtT_ (kWh/km)	0.08	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
TtW_ (kWh/km)	0.47	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.

Table 8 (*continued*)

Model inputs	Value	Source
CNG cars:		
WtT_ (kWh/km)	0.103	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
TtW_ (kWh/km)	0.537	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
LPG cars:		
WtT_ (kWh/km)	0.06	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
TtW_ (kWh/km)	0.53	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
Hybrid cars:		
WtT_ (kWh/km)	0.07	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
TtW_ (kWh/km)	0.32	Value obtained transforming the Concawe et al. (2008) results expressed in MJ/100 km in kWh/km. Value refers to 2010.
Full electric cars:		
Battery manufacturing costs forecasts:		
2012 (€/kWh)	450	Value referred to lithium-ion batteries, Hensley, Newman, Rogers, and Shainian (2012)
2020 (€/kWh)	160	Value referred to lithium-ion batteries, Hensley et al. (2012)
2025 (€/kWh)	130	Value referred to lithium-ion batteries, Hensley et al. (2012)

Table 9
List of the 66 models considered.

GASOLINE: Fiat-Panda Easy; Fiat-Punto Twinair; Lancia-Ypsilon Twinair; Fiat-500 Twinair; Toyota-Yaris; Citroen-C3 Attraction; Renault-Clio Energy; VW-Polo; Peugeot-208 Access; Smart-ForTwo MHD Coupé;
DIESEL: Fiat-500L MTJ Pop; VW-Golf Trendline; Nissan-Qashqai DPF Acenta; Fiat-Panda MTJ Pop; Renault-Clio Sporter; Fiat-Punto MTJ Street; Alfa Romeo-Giulietta Progression; VW-Polo TDI; Citroen-C3 Hdi; Ford-Fiesta TdCi; Peugeot-308 Hdi;
CNG: Fiat-Panda Turbo Natural Power; Fiat-Punto Natural Power; Lancia-Ypsilon Metano; VW-Eco UP; Fiat-Qubo Natural Power; Opel-Zafira EcoM.; Fiat-500L Twinair Turbo Nat.; Fiat-Doblò Natural Power; Seat-Mii Ecofuel; VW-Touran TSI Ecofuel;
GPL: Lancia-Ypsilon GPL Ecochic; Alfa Romeo-MiTo GPL; Opel-Corsa GPL Ecotech; Fiat-Panda EasyPower Pop; Fiat-Punto EasyPower; Fiat-500 EasyPower; Ford-Fiesta Ikon; Nissan-Qashqai GPL; Dacia-Sandero GPL; Alfa Romeo-Giulietta Prog.; Opel-Meriva GPL;
HYBRID: Lexus-IS; Toyota-Auris; Toyota-Prius; Lexus-CT; Peugeot-508; Peugeot-3008; Lexus-RX 450h; Citroën -DS5; Mercedes-Classe E Hybrid Executive; Toyota-Yaris;
ELECTRIC leased battery: Nissan-Leaf; Smart-ForTwo Electric Drive; Renault-Fluence; Renault-Zoe;
ELECTRIC owned battery: Nissan-Leaf; Citroën -C-Zero; Smart-ForTwo Electric Drive; Mia Electric-L 12 kWh; Mia Electric-L 8 kWh; Peugeot-iOn; Mitsubishi-iMiev; Tesla-Roadster; Ford-Focus Electric; BMW-i3;

Table 10
The European and Italian energy mix and energy efficiency.

	Energy efficiency factors (MJ_x/MJ_f)	Italian 2011 energy mix (%)	WtT_e (MJ_x/MJ_f) based on the Italy 2010 energy mix
Nuclear	2.70	0	
Coal	1.60	12.1	19.36
Oil	1.60	7.3	11.68
Gas	1.30	0.6	0.78
Hydro	0.10	42	54.6
Wind	0.10	13.5	1.35
Waste	0.30	2.9	0.29
Other renew	0.10	3.1	0.93
Imports		4.8	0.48
Average	1.35	13.7	14.9

Table 11
Well-to-Tank emission per km driven (g/km).

Fuel/powertrain	WtT^*_{NOx}	WtT^*_{PM}	WtT^*_{SOx}	WtT^*_{GHG}
ICEV (gasoline)	0.079	0.004	0.126	26.05
ICEV (diesel)	0.058	0.002	0.096	24.98
ICEV (bi-fuel CNG)	0.022	0.002	0.034	25.79
ICEV (bi-fuel LPG)	0.030	0.002	0.135	14.06
ICEV hybrid (gasoline)	0.067	0.003	0.106	21.90
ICEV hybrid (diesel)	0.047	0.001	0.077	20.02
BEV	0.133	0.004	0.145	63.59

Table 12
Tank-to-Wheels emission per km driven (g/km).

Fuel/powertrain	TtW_{NOx}	TtW_{PM}	TtW_{SOx}	TtW_{GHG}
ICEV (gasoline)	0.06	0.005	0.001	153.05
ICEV (diesel)	0.18	0.005	0.001	120.2
ICEV (bi-fuel CNG)	0.06	0.005	0.001	126.8
ICEV (bi-fuel LPG)	0.025	0.005	0.001	139.9
ICEV hybrid (gasoline)	0.052	0.004	0.001	100.6
ICEV hybrid (diesel)	0.148	0.004	0.001	95.6
BEV	0	0	0	0

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