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REPORT

Total cost of ownership of electric cars compared to diesel and gasoline cars in Belgium

December 2019

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Abstract - We compare the TCO of fully electric cars (BEV) with those of diesel and gasoline cars. The comparisons are performed both between "class averages" and between individual models. In the size class "small", BEV only have a lower TCO for an expected lifetime that exceeds most estimates of the planning horizon people use when purchasing cars. In the size class "medium", BEVs have a lower TCO than conventional cars if their expected lifetime mileage is high enough (160 000 km over 8 years or 120 000 km over 12 years). "Big" electric cars have higher TCO than their conventional counterparts for any reasonable assumption regarding their use profiles, at least for private users. Our analysis confirms that, in the current market context, the main factor affecting the adoption of electric cars is not their total cost of ownership.

Abstract – We vergelijken de levenscycluskost van elektrische wagens met deze van diesel- en benzinewagens. De vergelijkingen worden zowel uitgevoerd voor "klassegemiddeldes" als voor individuele modellen. "Kleine" elektrische wagens hebben alleen een lagere levenscycluskost voor een levensduur die hoger ligt dan meeste schattingen van de planningshorizon die mensen gebruiken wanneer ze auto's kopen. "Middelgrote" elektrische wagens hebben een lagere levenscycluskost dan conventionele wagens in dezelfde grootte-klasse indien de afstand afgelegd over hun totale levensduur lang genoeg is (160 000 km over 8 jaar of 120 000 m over 12 jaar). Voor "grote" elektrische wagens is deze kost zelfs groter voor elke redelijke waarde van de gebruiksprofielen, tenminste voor particulieren. Onze analyse bevestigt dat in de huidige markcontext, andere elementen dan de levenscycluskost een sleutelrol spelen in het verklaren van de marktaandelen van elektrische wagens.

Abstract - Nous comparons le coût total de possession (Total Cost of Ownership ou TCO) des voitures entièrement électriques à celui des voitures diesel et essence. Les comparaisons sont effectuées tant entre des « moyennes par classe » qu'entre modèles individuels. Pour les voitures de petite taille, les voitures entièrement électriques ont un TCO inférieur uniquement pour des durées de vie dépassant la plupart des estimations d'horizon de planification qu'utilisent les individus lors de l'achat d'une voiture. Pour les voitures de taille moyenne, les voitures entièrement électriques ont un TCO inférieur à celui des voitures conventionnelles si leur kilométrage escompté est suffisamment élevé (160 000 km sur 8 ans ou 120 000 km sur 12 ans). Les «grosses» voitures électriques ont un TCO plus élevé que leurs homologues conventionnelles pour toute hypothèse raisonnable concernant leurs profils d'utilisation, du moins pour les utilisateurs privés. Notre analyse confirme que, dans le contexte du marché actuel, le principal facteur ayant une incidence sur l'adoption des voitures électriques n'est pas leur coût total de possession.

Jel Classification - R41, Q52, Q55
Keywords - total cost of ownership, alternative fuels, battery technology, electric cars, technology adoption

Foreword

The work presented in this report is based on a collaboration agreement between the FPS Mobility and Transport and the Federal Planning Bureau. The collaboration focusses on the development and exploitation of statistical information, the development of long-term transport projections and the analysis of transport policies.

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1. Introduction

Understanding how economic agents take their decisions is key to well-informed policy decisions. For instance, in order to assess the impact of policies aiming at influencing the composition of the car stock, policy makers need to understand what features of a car drive the purchase decisions of households and firms.

In order to represent this decision making process, economists typically work with discrete choice models. In those models, decision makers are confronted with a discrete number of alternatives (for instance, different car models) and are assumed to choose the alternative that maximizes their utility. This utility function can include a wide range of car-related parameters (besides the financial ones) such as their power, their autonomy, their size and their luggage space. The key point in this approach is that the economic analyst does not *impose* on the choice model how people trade off those features (for instance, a higher purchase price for more luggage space). Instead, the trade-offs are *estimated* empirically. These estimates can be based on observed choices made in real markets (revealed preference data) or on stated-preference data, which are "*collected in experimental or survey situations where respondents are presented with hypothetical choice situations*" (Train 2002, p. 174). Discrete choice models also leave room for the representation of unobserved consumer heterogeneity (see also Train (2002) for more details).

Besides the above-mentioned comprehensive approach, a simpler approach consists in comparing the Total Cost of Ownership (TCO) of different cars[1], and assigning the demand to the minimal costs technology. An important advantage of this approach is that it relies mostly on data that are available. However, it omits non-monetary attributes such as the car's performance, which are known to be important in car choices. In the case of alternative powertrains, non-monetary attributes such as the range and the availability of a charging infrastructure can even be the key barriers to adoption.

Moreover, calculating the TCO requires discounting of future costs such as the operating costs. There is long standing controversy in economics whether people discount "rationally" when purchasing cars. Greene (2010) concludes from an extensive literature review that people use irrationally high discount rates. However, Grigolon et al. (2018) provide empirical evidence that this conclusion does not hold if one takes into account that the annual mileage varies across users (and thus that users who drive a lot will attach a higher weight to fuel costs when choosing a car).

Finally, using the TCO as sole decision criterion does not take into account consumers' heterogeneity (Massiani 2013). Clearly, if only monetary attributes would matter or if decision makers would be homogeneous, everybody would end up with the same car.

It is therefore not surprising that discrete choice models remain the preferred instruments or that existing TCO models in the literature are complemented with parameters that represent model/brand supply and technology suitability (charging access, driving range compatibility) (see for instance Brand, Cluzel and Anable (2017)).

1 Informally, the total cost of ownership of a car is the discounted sum of all the costs over its lifecycle, minus its residual value (when applicable). We will provide a more explicit definition further in the text.

Nevertheless, assessments of TCOs can be a useful complement to discrete choice models. Suppose for instance that the discrete choice model assigns a high market share to a car type with a high TCO compared to the alternatives. There are several (not mutually exclusive) possible explanations for this. It could be that the discrete choice model has identified variables (for instance, the autonomy of the vehicles) that are more decisive than cost considerations alone. It could also be that the (implicit) discount rate, expected lifetime and resale values used in the TCO calculations differ from the ones that were used (implicitly) in the observations used for the estimation of the discrete choice model. In other words, comparing the outcomes of TCO and discrete choice models leads to a deeper understanding of the results of both types of models, and enriches the analysis.

In this paper, we will compare the TCO of fully electric cars (BEV) with those of diesel and gasoline cars. For the calculation of the TCO, we will rely on the cost data used in the discrete car choice submodel of the Belgian CAr Stock MOdel (CASMO) - we refer to Franckx (2019) for more details on this model. The output of the CASMO model feeds the Belgian national transport demand model PLANET, which is used for the elaboration of long-term transport demand projections (BFP 2019).

This paper is structured as follows. First, we summarize the most important input data for the model: (a) the classification of car types (b) the key data sources (c) the composition and the distribution of the purchase costs on the one hand, and the variable costs on the other hand (d) the annual mileage of cars, per vehicle class (e) the expected lifetime of cars (f) the expected lifetime of batteries. Second, we present the TCO in 2017 for three different values of the expected lifetime of car. We compare the average values per car class, but also look at the distribution of TCOs within each car class. Third, given that our results had shown that the ranking of the TCO depends on the expected lifetime of cars and their annual mileage, we determine the car class with the lowest TCO (on average) for a range of values for those parameters. Finally, we discuss our results and identify ideas for further work.

The key contributions of this paper are: (a) it looks at a broader range of car models than most existing TCO calculations; the comparisons are performed both between "class averages" and individual models (b) it shows how the lifetime of cars is a crucial variable in TCO comparisons and discusses the key uncertainties regarding this parameter.

2. Description of the input data

2.1. The COPERT classification

For the purposes of emission modelling, cars are often grouped according to their COPERT emission class, which is determined by fuel and size. COPERT is a computer simulation programme used for the calculation of air pollutant emissions from road transport, which is used as an input in official annual national inventories (see Emissia 2018).

In the current paper, we distinguish following fuel classes: gasoline, diesel and battery electric cars.[2]

In order to apply the COPERT methodology, we have split gasoline and diesel cars according to the following criteria:

– Cylinder capacity less than 1 400 cc: “small”;

– Cylinder capacity between 1 400 and 2 000 cc: “medium”;

– Cylinder capacity larger than 2 000 cc: “big”.

We have ignored the COPERT class “mini” for gasoline cars, as the number of cars in this size class is negligibly small compared to the existing car stock.

For electric cars, there is only one COPERT class. We have however also split electric cars in categories “small”, “medium” and “big” according to the capacity of their batteries. For given dimensions of the car, the battery capacity is a proxy for the autonomy of the car, or, for a given autonomy, for the dimensions of the car. We have taken 20 kWh and 80 kWh as respective thresholds for the “electric car size classes” - while this is arbitrary, it corresponds pretty well to the classification we would obtain based on the car’s physical dimensions. We have also verified that these “size classes”" are relatively homogeneous in terms of driving range.

In what follows, we shall use “BEV” as short-hand for “battery electric vehicle”, and “conventional fuels” to refer to “diesel and gasoline”.

2.2. Datasets

In short, the sources for the car related data (such as their cost and autonomy) are the following:

– All assumptions on tax rates are based on an annual publication by the Federal Public Service Finance, the “Tax survey”.

– For each COPERT class, the purchase cost has been calculated as the average purchase cost of the 20 best sold models[3] in the class (weighted according to the share of each model in the sales). The cost information was obtained from the “Moniteur Automobile” for gasoline, diesel and electric cars.

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2 In CASMO, we had also considered CNG, LPG, hybrid and plug-in hybrid cars. In the current paper, we have chosen to focus on the car types for which we have the most reliable estimates for all cost components.

3 To the extent that data were available on those models.

– For electric vehicles, the range in 2017 was estimated per size class as the weighted average range of the ranges per size class (weighted according to the share of each model in the sales). These data were obtained mostly from Wikipedia, where we have used the lower bounds to the estimated ranges.[4]

– The annual maintenance costs are based on Letmathe and Suares (2017). Insurance costs have been obtained from the National Bank of Belgium.[5] Annual control costs have been estimated using the annual report of GOCA, the professional association of car inspection centres.

– Projections of fuel prices and electricity prices come from the long-term energy outlook for Belgium to 2050 (Devogelaer and Gusbin 2017).

– The annual report "Kilometers afgelegd door Belgische voertuigen" published by the Federal Ministry of Mobility and Transport (FOD Mobiliteit en Vervoer, 2017) contains estimates of the mileage and the car stock for 5 fuel types (gasoline, diesel, LPG, CNG and electric) and for 20 age classes.

For the classification of the cars according to size class, we have used the cylinder capacity reported by the DIV for cars with internal combustion engine. For electric cars, we have used data on the battery capacity, which were available on Wikipedia.

We present here the results with the data that were collected for the most recent long-term projections for transport demand in Belgium (BFP 2019) – the figures will be updated in 2020.

2.3. Purchase and monthly variable costs per COPERT class

This section digs a bit deeper in the contribution of the different cost components to the total variable (or fixed) costs for different car types. This will help us putting our values for the TCOs in perspective.

An important element to keep in mind here is that *all* tax rates used here are the tax rates that apply to cars owned by private households. They do not reflect the tax rates that apply to company cars, while a significant part of the Belgian car stock consists of company cars that are provided to employees as "benefit in kind" (the so called "salary cars"). We will come back to this issue when appropriate.

2.3.1. Variable costs

Table 1 gives the variable costs for all relevant COPERT classes. The costs are reported for 2017, expressed in EUR per month, and split in their respective components:

– the annual traffic tax;

– fuel cost per month, including excise taxes and VAT;

– the non-fuel variable taxes per month: these are the taxes on the periodic technical control, maintenance and insurance;

– the "other" variable costs (periodic control, maintenance and insurance).

[4] This is usually the EPA Federal Test Procedure, which is more conservative (and arguably realistic) than the New European Driving Cycle, which is also often reported.

[5] Statistics published as part of the supervisory review process of insurance and reinsurance undertakings.

Table 2 gives the shares of those cost components, expressed in percentages of total variable costs.

For the sake of the comparability between the different car types, we have assumed that all cars drive 10 000 kilometres per year in order to calculate the cost per month.

Note that "fuel cost" refers both to electricity and to diesel or gasoline.

For the ease of comparability, we have grouped the cars per size class.

Table 1 Values of the components of variable costs in 2017
EUR per month

Car Type	Size	Traffic tax	Fuel Costs	Variable Taxes	Other variable costs	Total
diesel	big	47	80	28	117	273
BEV	big	2	41	34	150	227
gasoline	big	76	125	27	113	341
diesel	medium	27	62	23	96	209
BEV	medium	2	34	20	83	140
gasoline	medium	25	101	22	91	240
diesel	small	17	44	22	91	175
BEV	small	3	23	19	75	121
gasoline	small	15	86	19	79	199

Table 2 Shares of the components of variable costs in 2017
In %

Car Type	Size	Traffic tax	Fuel Costs	Variable Taxes	Other variable costs
diesel	big	17	30	10	43
BEV	big	1	18	15	66
gasoline	big	22	37	8	33
diesel	medium	13	30	11	46
BEV	medium	2	24	15	60
gasoline	medium	10	42	9	38
diesel	small	10	25	13	52
BEV	small	3	19	15	62
gasoline	small	7	43	10	40

The most important observations can be summarized as follows.

First, in all size classes, BEVs have lower variable costs than gasoline and diesel cars. Note that, while the fuel cost for BEVs is always lower than for gasoline and diesel cars in the equivalent size class, this is not always the case for the maintenance costs. For "big" BEVs, they are higher than for "big" gasoline and diesel cars.[6]

We should note here that the values reported by Letmathe and Suarez (2017) and used in our calculations are substantially higher than some other estimates in the recent literature, such as Palmer et al. (2018). The difference is especially pronounced for the larger models. While Letmathe and Suarez (2017) report an annual maintenance cost for Teslas ranging from 1 152 to 3 062 EUR (depending on the annual mileage), sources in the grey literature[7] estimate annual maintenance costs ranging from around 200 USD to 360 USD.

6 The estimates in Letmathe and Suarez (2017) are based on the data base from the German automobile club ADAC. https://www.adac.de/infotestrat/autodatenbank/autokosten/autokosten-rechner/default.aspx.

7 See for instance https://cleantechnica.com/2019/06/12/tesla-model-3-maintenance-guide-costs-even-lower-than-i-thought/

This is clearly one of the more contentious assumptions used in the analysis, and we shall come back to this in the remainder of the paper.

Second, diesel cars have lower variable costs than gasoline cars in the same size class: the lower fuel costs of diesel cars compensate their higher maintenance costs.

Third, the fuel costs and the "other" variable costs are the largest components of total variable costs. The share of fuel costs in total variable costs varies between 18% and 43%.

In the case of conventional fuels, there is a clear "jump" in the traffic tax between the size segments "medium" and "big".

2.3.2. Purchasing cost

Table 3 presents the total costs of purchasing a car, which is the sum of its purchase price and the license tax (BIV). In the case of BEVs, the purchase price also includes the cost of a home charging point (1 250 EUR).

Table 3 Values of the components of the purchase cost in 2017
EUR

Car Type	Size	Purchase Price	Licence tax	Purchase Cost
diesel	big	45896	983	46879
BEV	big	81682	20	81702
gasoline	big	64166	2412	66578
diesel	medium	28122	446	28568
BEV	medium	37361	13	37374
gasoline	medium	24056	376	24432
diesel	small	18704	189	18893
BEV	small	28399	25	28424
gasoline	small	17363	141	17505

The license tax is the average tax rate per COPERT class - the tax levied on individual cars depends on the technical characteristics of those cars. The value for big gasoline cars clearly stands out - this reflects that most of the cars in this segment are luxury cars.

We can make the following observations.

First, in all size classes, the total purchase cost of BEVs is higher than that of diesel and gasoline cars. In the size segment "big", their purchase costs are about twice as high as for diesel cars. The differences are slightly less pronounced for the "medium" and "small" cars, but remain non-negligible.

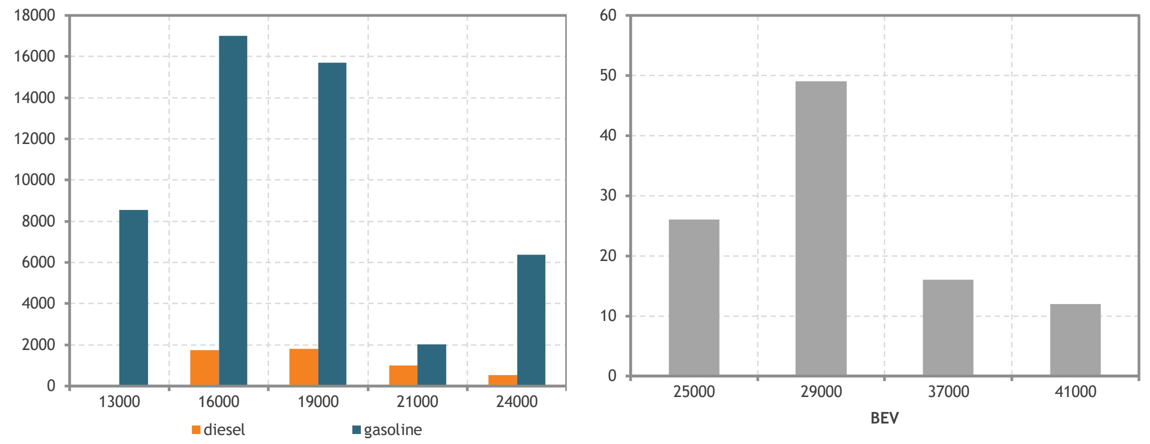
Second, the figures confirm that gasoline cars in the size segment "big" are atypical, as they have a higher average purchase cost than diesel cars - in the other size segments, the average purchase cost is higher for diesel cars.

Of course, one has to be careful with comparisons based on average values. We therefore also have a look at the *distribution* of the purchase costs. Clearly, if there are BEVs with lower purchase costs than conventional cars, then they will have lower TCOs for any lifetime and annual mileage.

Graph 1 represents the distribution of the purchase price of the 20 best sold small diesel and gasoline cars on the one hand, and the distribution of the purchase price of *all* the small BEV models available on the Belgian market on the other hand.

We see that, in the size segment "small", there is no overlap in the purchase costs of conventional cars and BEVs: the purchase cost is higher for all BEVs.

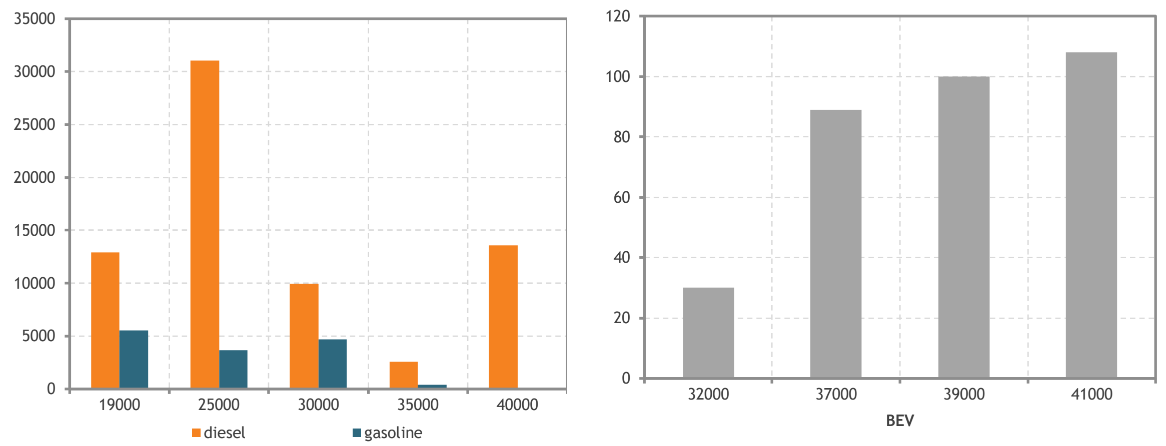
Graph 1 Distribution of the purchase price of the 20 best sold "small" models
X axis: price in EUR, Y-axis: sales in number of cars



Graph 2 gives the distribution of the purchase price of the 20 best sold medium diesel and gasoline cars on the one hand, and the distribution of the purchase price of all the medium BEV models available on the Belgian market on the other hand. For this size segment, the situation is different.

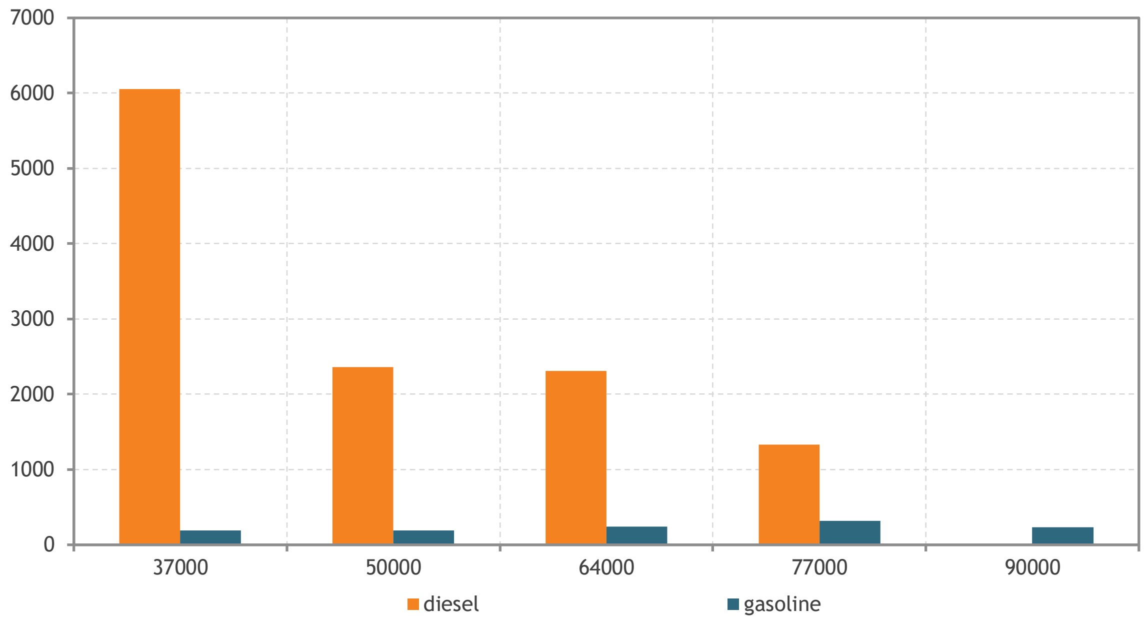
On the one hand, the cheapest BEVs have a purchase price that lies around the intermediate value for gasoline and diesel cars. On the other hand, the most expensive medium diesel cars have purchase costs that are comparable to those of the most expensive medium BEVs.

Graph 2 Distribution of the purchase price of the 20 best sold "medium" models
X axis: price in EUR, Y-axis: sales in number of cars



In the size segment "big", the only BEV included in the analysis is the Tesla Model S. If we compare Graph 3 with the figure reported in Table 3 (81 682 EUR), we see that the purchase cost of the big BEV lies well above the most expensive diesel cars - but lies in the same range as the most expensive gasoline cars.

Graph 3 Distribution of the purchase price of the 20 best sold "big" diesel and gasoline models
X axis: price in EUR, Y-axis: sales in number of cars



2.4. Annual mileage of cars

It is reasonable to assume that a household takes into account its expected driving needs (based on factors such as household composition, commuting distance, accessibility to public transport etc) when it decides what car to purchase. A household with a high expected annual mileage will tend to prefer a car with low variable costs, while a household with a low expected annual mileage will tend to prefer a car with low purchase costs. Thus, taken from this perspective, what we need to compare is the TCO for different car types for a given annual mileage.

In order to choose "typical" values, we first have a look at the behaviour that has been observed historically.

Table 4 gives the annual mileage of gasoline and diesel cars in 2016[8]. We see that the annual mileage of diesel cars is systematically higher than that of gasoline cars, especially for the "medium" and "big" categories.

8 This is the most recent year for which data were available.

Table 4 Annual mileage diesel and gasoline cars in 2016

Car type	Size	Annual Mileage
gasoline	small	10222
gasoline	medium	9543
gasoline	big	8944
diesel	small	16350
diesel	medium	20075
diesel	big	19738

For electric cars, the reported data on the annual mileages are not differentiated according to size class. However, with 18 621 km per year in 2016, the average mileage of electric cars is comparable to that of medium and large diesel cars.

2.5. The expected lifetime of cars

One of the key parameters in any TCO calculation is the expected lifetime of the car.

How to measure this parameter is less trivial than appears at first sight, and it is worthwhile elaborating on this issue.

A first possible approach is to use the expected time during which the *first* owner will hold a car - this requires knowledge of the second-hand value of the car at the end of this period of first ownership. A second possibility is to use the total expected lifetime of the car until it is scrapped. If we use the latter approach, we make the implicit assumption that the initial purchasing cost reflects the net present value of the expected second-hand price that the car can capture.

In this section, we will discuss how this has been tackled in the recent literature, and then summarize the key statistics for Belgium.

2.5.1. Short survey of the recent literature

In the literature, there is not really a consensus on the appropriate value to use for the expected lifetime of cars.

For instance, based on 2014 FEBIAC data[9], De Clerck et al. (2016) reckon that a Belgian owns a car for 8 years and 45 days, on average. Their TCO analysis does not include a resale value (not even as scrap) of the car at the end of its lifetime.

Rather than representing the Total Cost of Ownership of cars as the net present value of all expected costs, Björnsson and Karlsson (2017) use an annuity factor of 15% instead to express the fixed cost as an annual cost - this annuity factor is compatible with a huge number of reasonable values of the “discount rate and expected lifetime” pair, but Björnsson and Karlsson do not report the underlying assumptions. They do not mention the issue of the resale value of the cars either.

[9] FEBIAC is the federation representing the Belgian manufacturers and importers of passenger cars, commercial vehicles, motorcycles and bikes and their suppliers.

Vanhaverbeke et al. (2017) expand the analysis of De Clerck et al. to take into account vehicle-to-grid services of electric vehicles. They assume a lifetime of 8 years and 267 days, using slightly more up to date figures for Belgium (2016 FEBIAC data).

Letmathe and Suares (2017) explicitly consider the "option to reuse BEV batteries as second-life storage devices for renewable energies and to recycle the batteries after their useful lifetime". Given that the "typical vehicle holding period of the first owner was 64 months in Germany in 2005", they assume a vehicle holding period for the first owner of 5 years. We will come back to the issue of the resale and recycling values of batteries in section 2.6.

Lévay et al. (2017) assume that the vehicles are owned for 4 years by their first users. In order to estimate the resale values, they used "online automotive information sources, such as Edmunds.com, NADA, KBB, Whatcar.com, and Autoscout24". Analysis of the data showed that "(d)epreciation data are well-grounded for ICE vehicles. The second-hand market for EVs, however, is not well established yet in the EU. New EV sales became considerable only in 2011 when registrations reached almost 10,000 units in the EU.(…) It is evident that EVs lose a larger share of their initial value. In fact, some of the small electric cars, such as the Nissan Leaf, are among the vehicles that depreciate the most during the first years of ownership (…). A partial reason is that the purchase price of some EV models decreased during their life-cycle as a result of technological advances, e.g., battery cost reduction, leading to a decrease of the resale value of earlier variants."

Based on German data, Danielis et al. (2018) assume 6 years as the length of *first* ownership. They emphasize that it is difficult to predict the residual value of a car: "*Age and the total distance driven are certainly leading parameters. However, other factors play a role such as driving habits, colour, brand, size, specific market demand and so on.*" Moreover, they point out that the uncertainty of the depreciation rate for electric vehicles is higher than for conventional cars. Therefore, in their baseline, they[10] "*assume that ICEVs and HEVs retain 20% of their initial value, whereas BEVs hold only 10%, because, being a new technology, is subject to rapid technological depreciation. However, such assumption is reversed in the year 2025, as in the year 2025, ICEVs will probably be an old technology subject to many limitations (e.g., inner-city access restriction), leading to faster depreciation rates than those of BEVs*." Given the high level of uncertainty, they treat the resale value as a stochastic variable that follows a normal distribution with mean equal to the estimated resale value and a 1 000 EUR variance.

Mitropoulos et al. (2017) assume a lifetime of 10.6 years. As they do not discuss resale values, we infer that they assume that the car is fully depreciated over its lifetime.

Using data from the UK, Dun et. al. (2015) estimate the "average retirement age of petrol cars in 2012-2013 (…) to be 14.4 years while for diesel cars it was 14.0 years (…) Looking at how retirement age has evolved over time, the historic datasets show that average retirement ages for petrol and diesel cars have been increasing year on year since 2006-2007. From 2006 to 2013, the average age of retirement increased by almost 7% for petrol cars and by almost 12% for diesel cars."

[10] In their terminology, ICEV stands for "internal combustion engine" and HEV for "hybrid engine vehicle".

Weldon et al. (2018) consider the costs over a period of 10 years using four electric vehicles (EV) and four comparable internal combustion engine vehicles. Batteries for EV are assumed to be replaced after 8 years. They do not consider any resale value for the car, essentially because "*depreciation of EVs is still a relatively new concept due to their comparatively recent introduction to the vehicle market. One primary factor contributing to this ambiguity is the resale value of EV batteries due to aspects such as deterioration and the problem of recycling potentially harmful chemicals*". Given this uncertainty, they consider three different scenarios for the future prices of batteries.

The lifetime of ten years used by Weldon et al. is slightly longer than the actual average age at retirement of cars in Ireland (the country where Weldon et al. performed the TCO) but the general tendency is for the average age of vehicles in Ireland to increase: "*in 2000 the average age of a vehicle was 5.6 years; however in 2013 the average vehicle age was 8.6 years, and the average age of vehicles has increased every year since 2000*". They also consider different types of usage profiles.

Summarizing, most studies assume that the first owner of a car owns the car for 4 to 6 years, while estimates for the total lifetime vary from 8 to 14 - this is a very wide range of estimates. There is also some international evidence that the lifetime of cars is increasing through time.

Let us now turn to the most recent evidence for Belgium.

2.5.2. Descriptive statistics for Belgium

Above examples show that the approach that can be used is constrained by data availability. The key data source for our analysis is the Belgian national vehicle registry, the DIV, which contains data on all vehicle registrations. Note that, while the DIV identifies a car with its chassis number, the DIV only records the time during which a car was associated to a Belgian license plate. Thus, even though we can identify the succession of license plates to which a car was linked, we cannot trace back what happened with the car before it got its first Belgian license plate, or after its last license plate was handed in. As a result, we cannot distinguish between a second hand car that was imported and a new car that is brought into circulation. Similarly, we cannot see whether a car was scrapped or exported. Some cars also vanish temporarily from the database, because they have been sold on the second hand market, and there is a transition period between the former owner handing in his license plate, and the new owner requesting a new one. With these caveats in mind, we have made the following assumptions to estimate the average lifetime of cars in Belgium: we have taken 2016 as last year for our data set, and assumed that all cars that had been taken out of the database and not registered again before the end of 2017, have effectively been taken out of circulation in Belgium (exported or scrapped).

Given the absence of data on the second hand market, we consider the cost of ownership over a car's *entire* lifetime, not just for its first owner. Table 5 gives the median and average age at which diesel and gasoline cars were retired from the DIV database between 2002 and 2016 - this time series is too recent to give any meaningful estimates for electric cars. We also represent the standard deviation.

We see that median and average are close, both for diesel and gasoline cars. We see that diesel cars are retired much earlier than gasoline. This probably reflects the high share of company cars among diesel cars. van Gijlswijk et al. (2018) show that most company cars in The Netherlands are exported after their first use, because they belong to a market segment that is not attractive for domestic car users. One should of course be careful in extrapolating from the Dutch to the Belgian situation, but this explanation seems plausible.

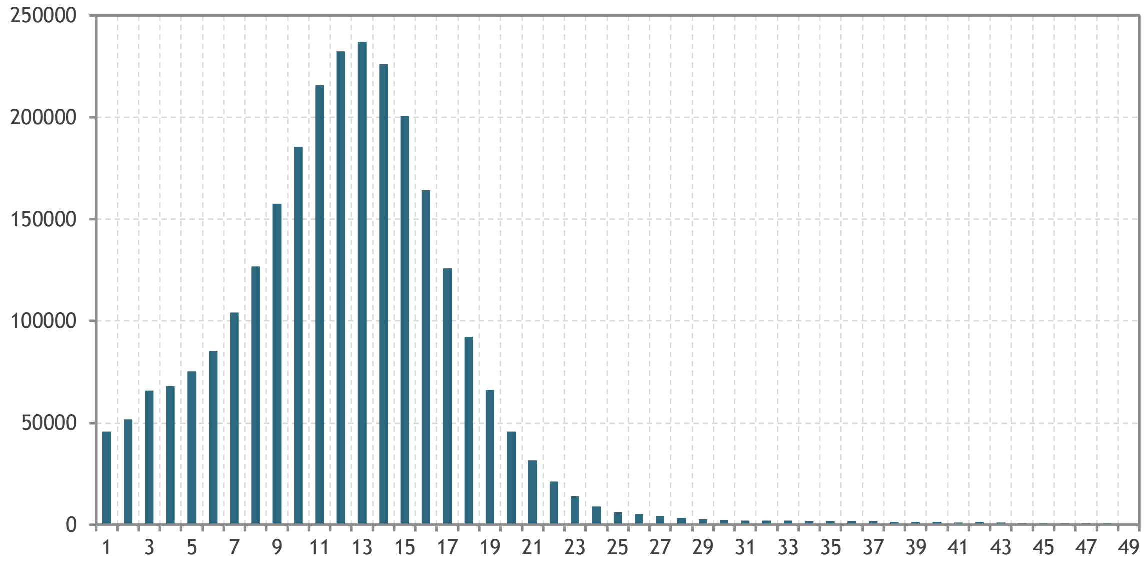
However, the most striking observations is the very high value of the standard deviation for both conventional fuels, indicating a high diversity in use profiles.

Table 5 Median and average lifetime of gasoline and diesel cars
Number of years

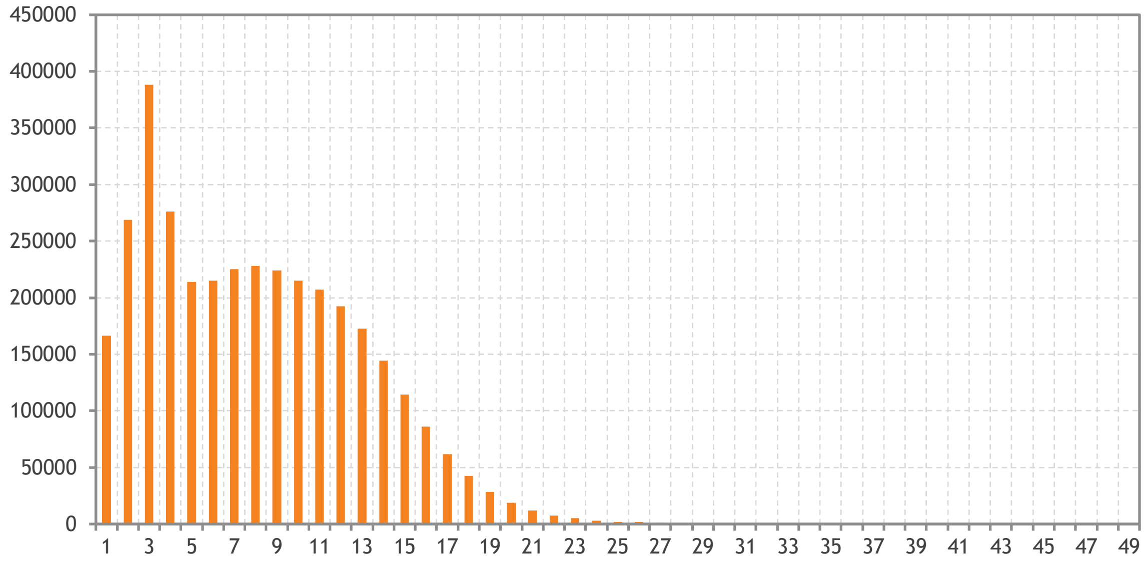
Car Type	Median Lifetime	Mean Lifetime	Standard Deviation Lifetime
gasoline	11.4	12	6.7
diesel	6.8	6	5.7

This is confirmed by Graph 4 and Graph 5, which represent the histograms of the age distribution of gasoline and diesel cars.

Graph 4 Number of gasoline cars retired from circulation in Belgium
X-axis: age; Y-axis: number of cars



Graph 5 **Number of diesel cars retired from circulation in Belgium**
X-axis: age; Y-axis: number of cars



In both cases, the distribution is skewed - for gasoline cars slightly less than for diesel cars. Especially in the case of gasoline cars, we also observe a "long tail" of very old cars that probably have very atypical user profiles (old-timers, for instance). In the case of diesel cars, there is a clear peak for the number of cars that are retired from the Belgian car stock around the age of four - again, this probably reflects former company cars that are exported.

Given the level of uncertainty reflected in the data, it is appropriate to calculate the TCO for different values of the expected lifetime of cars.

2.6. The expected lifetime of batteries

A complication in the calculation of the TCO of BEVs is that a key cost components of a BEV, its battery, may well have a shorter economic life than the car itself. Moreover, there is a lot of uncertainty regarding what will happen to those batteries when they reach the end of their useful life in a BEV.

As discussed above, Letmathe and Suares (2017) explicitly consider the "*option to reuse BEV batteries as second-life storage devices for renewable energies and to recycle the batteries after their useful lifetime*". Indeed, they point out that if the battery falls below 80% of its capacity (and thus is no longer ready for use in the EV), it can be sold independently of the vehicle for second-life purposes (such as stationary energy storage solutions), or be sold for recycling activities.

They therefore explicitly consider the battery-related costs and revenues, and develop a consumer-oriented TCO model "*for the purchasing years 2016 and 2021 including the battery resale value for its second use and second life*". Further, they "*apply a Monte Carlo simulation to determine the overall distribution and overlap of ownership costs between EVs and ICEVs*" and use three different user profiles (occasional drivers, normal drivers and frequent drivers).

In an even more recent study, Drabik and Rizos (2018) assume that a battery has an average lifespan of eight years in a *vehicle*. However, they point out that *"(i)nstead of recycling batteries that have been removed from vehicles, the battery can be remanufactured and the cells can be provided with a second-life in a storage application. (…) Second-life EV batteries available for storage applications could still provide a useful life in a future electricity system due to further increases in intermittent renewables connected to the European electricity grid*." In other words, the uncertainty goes beyond the expected lifespan of a battery, and also applies to what happens to it after it is no longer useful for automotive applications - and thus also to its value at the end of its automotive application: "*Various sources show very different views and predictions regarding the share of batteries that will sustain a second-life, emphasizing that the market is currently very uncertain*." Drabik and Rizos (2018) assume that 30% of batteries will enter a second life. If those batteries do enter a second life, it is assumed that they "*will have a further 10 years added to their lifetime before fully reaching their end-of-life*."

Desai et al. (2019) estimate the life of batteries for BEVs "*as a function of number of charging-discharging cycles and depth of discharge*". For instance, they show that "*the battery of 27 kWh with efficiency 3.71 miles per kWh, depth of discharge 80%, and 3,500 charging-discharging cycles can provide 280,476 miles in its lifetime, and with 18,000 annual miles, the battery life would be 15.6 years*." Different battery characteristics or use profiles would of course lead to different conclusions.

Finally, according to Hoekstra (2019), "*current batteries are estimated to last at least 1,500 to 3,000 cycles before they lose 20% of capacity, giving an electric car with 450 km of range a battery lifetime of 450k to 1,350k km*." Given that cars with a range of 450 km tend also to have high purchase costs, they are unlikely to be bought by people who don't drive a lot - but it is clear that even for very high annual mileages, lifetimes far above 15 years don't appear unrealistic.

In what follows, we will not consider this issue explicitly, but keep it in mind as a factor that might affect the economic lifetime of a BEV.

3. Total cost of ownership

In this section, we calculate the average TCO of the different car classes in 2017. In other words, this analysis is performed using historical data.

In the absence of reliable data regarding the expected value of cars on the second-hand market and on the possible replacement of the battery of electric vehicles during their lifetime, we ignore those issues for the time being. We also ignore any revenues from vehicle-to-grid services in the case of electric cars (see Vanhaverbeke et al. 2017) - this leads to an upward bias in our estimates of the TCO for BEVs.

We assume that the private discount rate is 1.5 %. While this is lower than the rates that are commonly used in the literature, it is consistent with the interest rates we have found on www.beste-autolening.be, a website dedicated to the comparison of car loans on the Belgian market.

We calculate the TCO for three different assumptions as to the expected lifetime of cars.

3.1. TCO with expected lifetime of 15 years

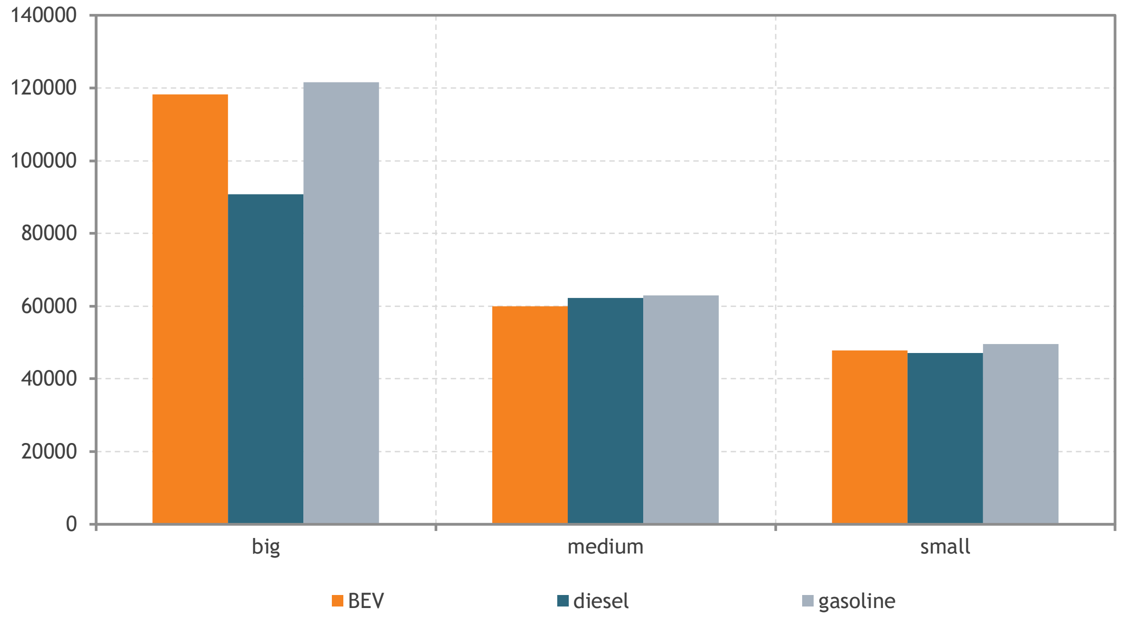
In this section, we calculate the TCO under the assumption that the expected lifetime is 15 years for all car types. 15 years is slightly above the median value for gasoline cars, but much higher than the median value for diesel cars. We also assume that the annual mileage is 10 000 km, which is approximately the value for gasoline cars, but lower than the value for diesel cars.

In other words, the analysis assumes a rather "long" economic life and a rather "low" annual mileage. These assumptions should be kept in mind when interpreting the results.

Graph 6 summarizes the average values of the TCO per size class. We complement this graphical analysis with Table 6, which gives, for each car type, the difference in percentage compared to the minimum TCO in their respective size class.

We see that medium electric cars have, a slightly lower TCO than gasoline and diesel cars. In the category "small", electric and diesel cars are almost on par, and have a slightly lower TCO than their gasoline counterparts. In the size segment "big", both gasoline and BEV cars have a much higher TCO than diesel cars - this reflects that these cars are mostly in the premium market.

Graph 6 TCO of cars in 2017 (annual mileage of 10 000 km and lifetime of 15 years)
Y-axis: EUR



Except for "big" cars, the differences in TCO within each size class are much less pronounced than the differences in purchasing costs discussed in section 2.3.2.

Table 6 Relative difference compared to minimum TCO in size class (annual mileage of 10000 km and lifetime of 15 years)
%

cartype	small	medium	big
BEV	1.7	0.0	30.2
diesel	0.0	3.8	0.0
gasoline	5.2	5.2	33.8

Under the assumptions of a "long" economic life and a "low" annual mileage, BEVs thus perform really well, *on average*, in terms of their TCO in the size classes "small" and "medium".

However, such averages can hide important variations at the level of individual cars, and there is scope for overlap between the different car types, especially when the differences in average costs are really small (as is the case here).

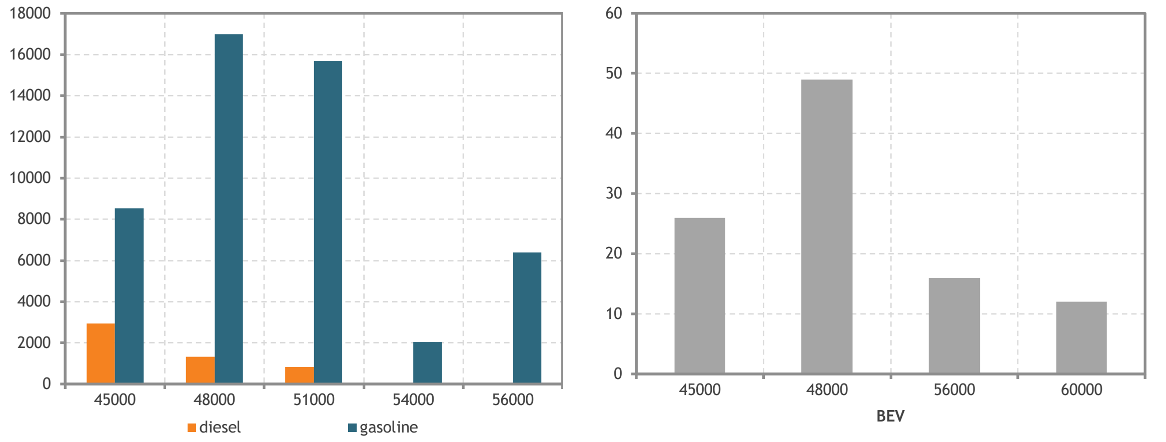
We therefore have a look at the distribution of the TCOs, with the caveat that this only reflects differences in the individual purchase prices. Indeed, our current data set does not allow a calculation of all variable costs components for individual car models. Therefore, for the variable costs, we work with the average values for each car type/size class combination.

Graph 7 gives the distribution of the TCO of the 20 best sold small diesel and gasoline cars, and of all small BEVs on the market in Belgium.

We had seen in Section 2.3.2 that, in the size segment "small", there is no overlap in the purchase costs of conventional cars and BEVs. The situation is completely different when we look at the TCO: the ranges completely overlap. Actually, we see that the relatively low average TCO for small diesel cars is to a large extent due to a skewed distribution, where most sales are in the lowest car cost quantiles. For gasoline cars and BEVs, sales are much more evenly spread over the different car cost quantiles.

Graph 7 Distribution of the TCO of the 20 best sold "small" models (annual mileage of 10 000 km and lifetime of 15 years)

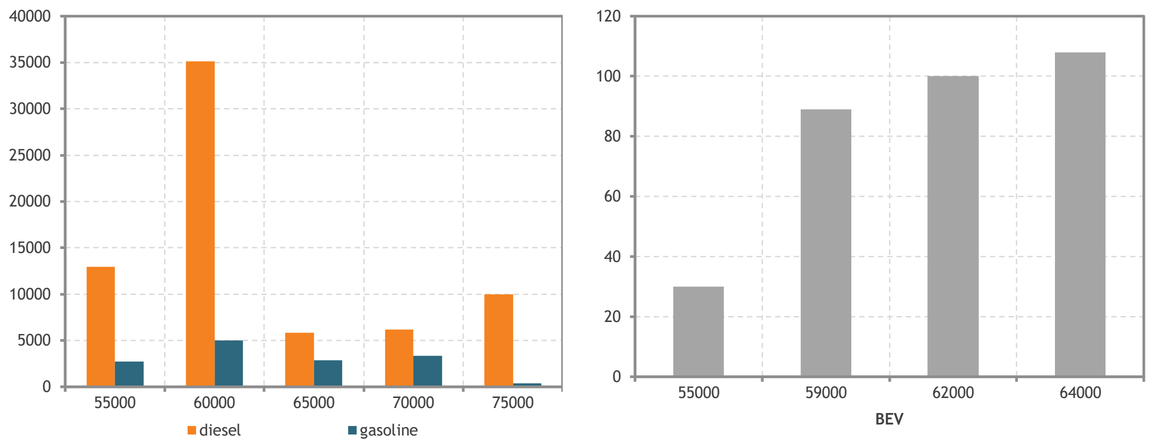
X axis: TCO in EUR, Y-axis: sales in number of cars



Graph 8 gives the distribution of the TCO for medium-size cars. Here, a new pattern emerges. The range of TCO for BEV is largely contained within the range for conventionally fueled cars, but is narrower. The TCO for gasoline cars are evenly spread, while the TCO for diesel cars has a very high modus around 60 000 EUR, but also has some clear outliers to the right.

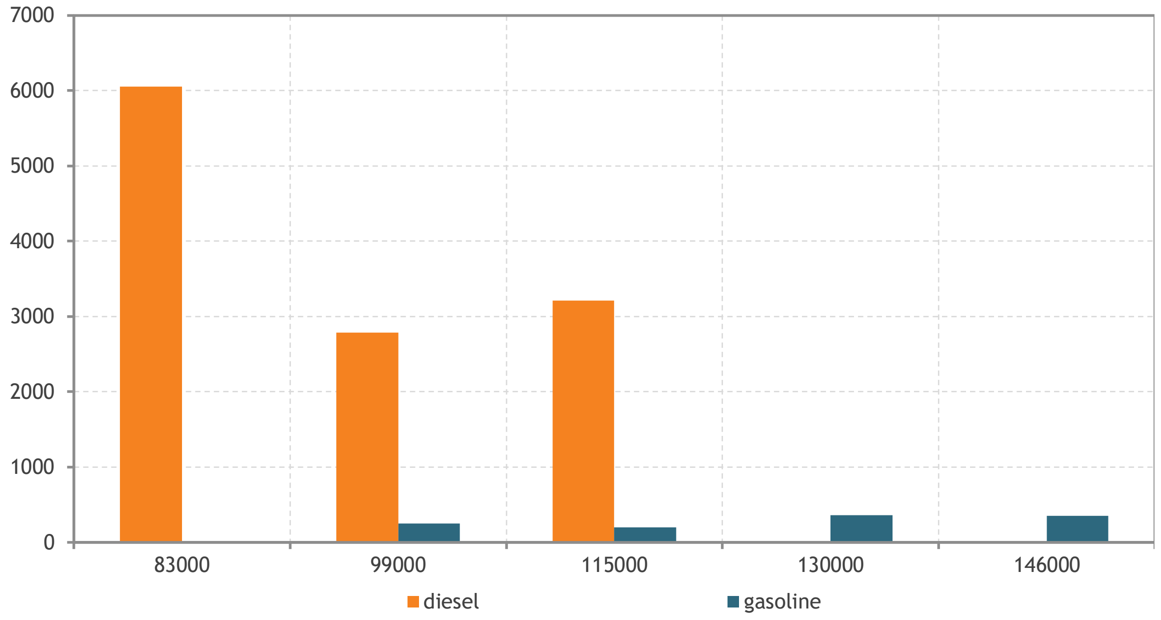
Graph 8 Distribution of the TCO of the 20 best sold "medium" models (annual mileage of 10 000 km and lifetime of 15 years)

X axis: TCO in EUR, Y-axis: sales in number of cars



In the size segment "big", the only BEV is the Tesla Model S, which has a TCO of around 123 000 EUR. If we compare this with Graph 9, we see that the TCO of this model lies well above the most expensive diesel cars - but lies in the same range as the most expensive gasoline cars.

Graph 9 Distribution of the TCO of the 20 best sold "big" diesel and gasoline models (annual mileage of 10 000 km and lifetime of 15 years)
X axis: TCO in EUR, Y-axis: sales in number of cars



In summary, when we look at the distribution of the TCO, it is clear that, except in the size class "big", there are BEV models available with a TCO that is lower than the TCO of some conventionally fueled cars in the same size segment.

We should also keep in mind that the size class "big" probably has a higher share of company cars than the other size classes. Given that company cars are subject to a different fiscal regime than cars owned by private households, it may well be that, even in this size class, BEV models have lower TCO for some use categories. This could be a topic for further research, depending on the availability of data.

Given above results, the very low penetration rate of BEVs in the size segments "small" and "medium" is especially puzzling.

One possible explanation is that the economic lifespan and the annual mileage we have assumed here are not relevant for all use profiles. Actually, we had already shown in Sections 2.4 and 2.5.2 that both the annual mileage and the expected life of diesel and gasoline cars differ substantially.

In the case of BEVs, we know that their annual mileage is on average close to that of diesel cars, but little is known about their expected lifespan. On the one hand, because of their high fixed and low variable costs and limited autonomy, most existing electric cars are essentially suited for use profiles which drive a lot on an annual basis but whose individual trips are typically relatively short and which have readily access to charging - think of service cars. This should lead to a shorter lifetime in years. On the other hand, electric cars are less subject to maintenance and wear and tear, and this should lead to a longer lifetime. The net effect on their expected lifetime is not yet clear: electric cars have not yet been long enough on the market to yield useful data.

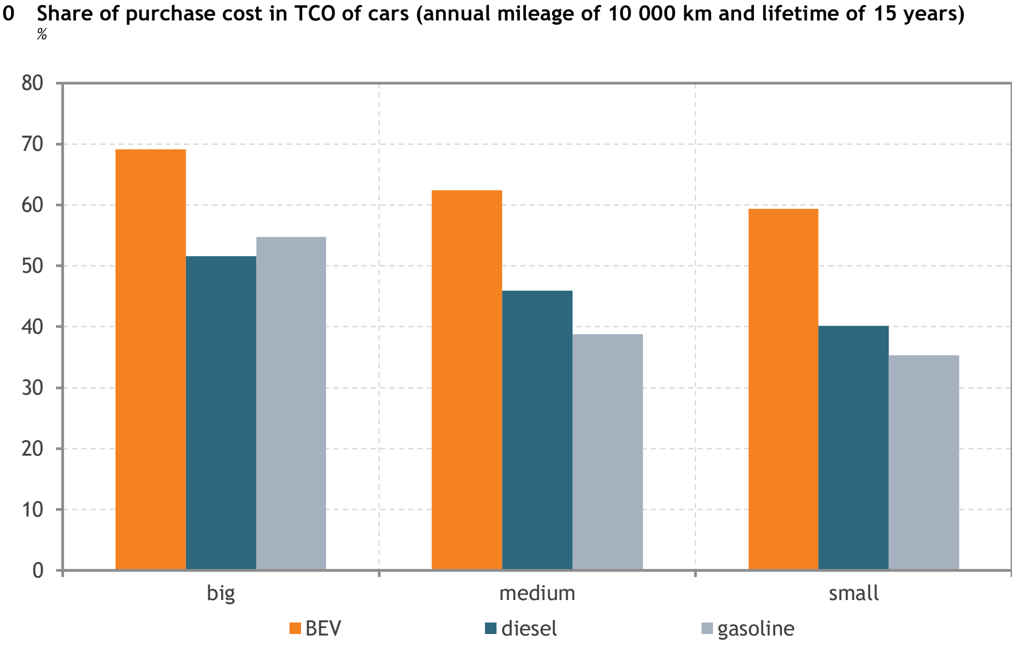
Before considering alternative assumptions with respect to economic lifespan and annual mileage, we first explore another issue: Greene (2010) has argued that most consumers overvalue the purchase cost of cars compared to variable costs when buying a car (or, equivalently, the discount rate they have in mind are higher than the relevant market rates).

It could therefore be useful to have a look at the share of purchase costs in the TCO.

Graph 10 shows the shares of the purchase cost in a car's TCO. These shares vary from around 34% for small gasoline cars, to way above 60% for "big" electric cars. We see that this share tends to be higher for larger cars. Moreover, for each size segment, we see the same pattern emerge. The share of the purchase costs in the TCO is higher for BEVs than for gasoline and diesel cars. Except in the size segment "big", the share of the purchase costs is clearly higher for diesel than for gasoline cars.

If consumers do indeed overvalue the purchase cost of cars, consumers will attribute a higher "subjective" value to the TCO of BEVs than implied by the analysis above. This could already be a first step to understanding the low market shares of these car types.

Graph 10 Share of purchase cost in TCO of cars (annual mileage of 10 000 km and lifetime of 15 years)



Fortunately, this user myopia can easily be represented analytically: either we recalculate the TCO for a higher discount rate, or we use a shorter lifespan, reflecting the user's "subjective" planning horizon.

3.2. TCO with expected life time of 8 years

As discussed above, the actual economic life time of private cars is an uncertain variable, with a high standard deviation. Moreover, we have strong prior reasons to expect these lifetimes to differ according to the fuel used and the user profiles.

Also, it is controversial whether the discount rates people use when evaluating future costs and benefits corresponds to the market rates.

We therefore explore how sensitive our previous outcomes are to different assumptions regarding the economic lifetime.

The question is then what could be a meaningful alternative assumption.

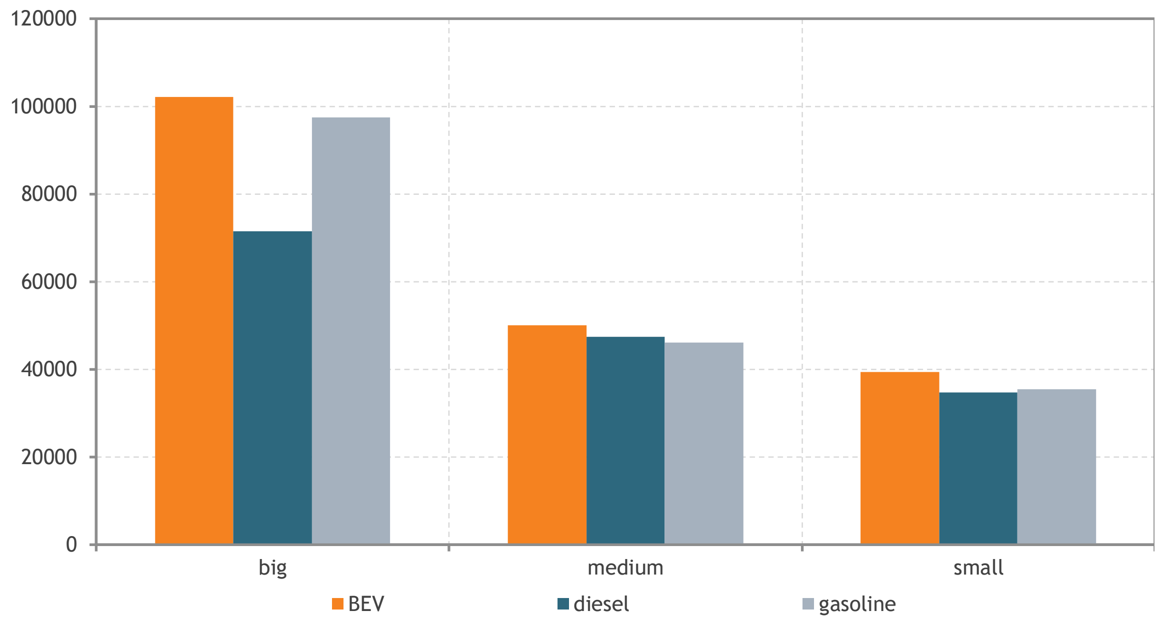
One possible criterion has already been suggested in Section 2.6. There is also considerable uncertainty regarding the values of batteries on the second-hand market and their longevity, and these are areas that are constantly evolving. While some authors suggest that lifetimes of 15 years or more are realistic, others (such as Drabik and Rizos 2018) assume that a battery has an average lifespan of eight years in a *vehicle*.

If the more conservative estimates are correct, then assuming an economic lifetime of 15 years without considering the costs of buying a second battery (and adding the expected value of selling the first battery on the second-hand market) could lead to a gross underestimation of the TCO of electric vehicles.

In the absence of consensus estimates, we instead recalculate the TCO under the assumption of a shorter lifetime for the cars - considering a higher discount rate would have comparable effects.

Graph 11 represents the TCO under the assumptions of an economic life of 8 years, while maintaining the assumption of an annual mileage of 10 000 km.

Graph 11 TCO of cars in 2017 (annual mileage of 10 000 km and lifetime of 8 years)
Y-axis: EUR



A visual comparison with Graph 6 shows that, although the TCO have decreased, the ranking in the "small" and "medium" segments remains roughly the same except that BEVs now perform slightly worse and that gasoline cars move up in the ranks of lowest TCO. Also, with this shorter life time, the gap between diesel cars and all other car types becomes even larger.

Table 7 gives, for each size class, the difference in percentage compared to the minimum TCO in each size class. They are generally higher than those reported in Table 6.

Table 7 Relative difference compared to minimum TCO in size class (annual mileage of 10000 km and lifetime of 8 years)
In %

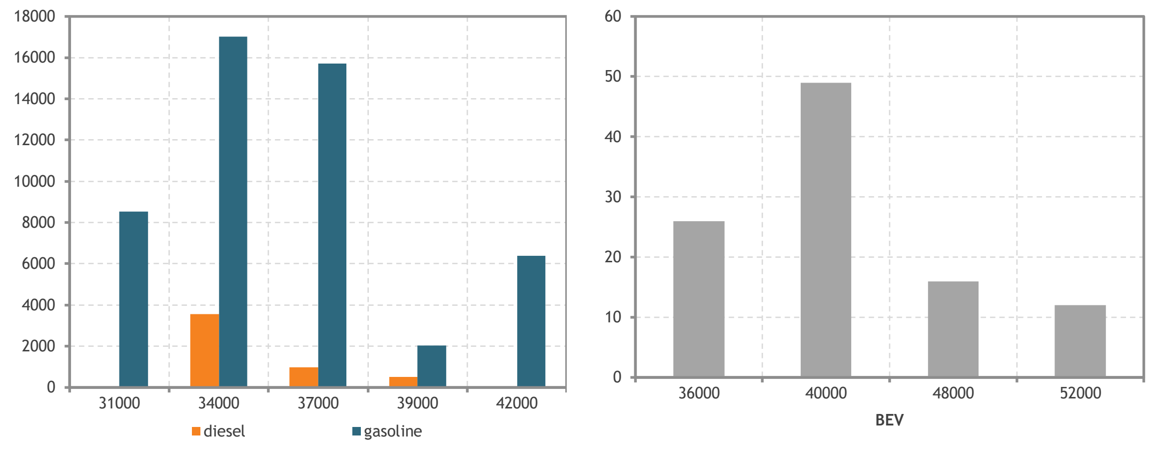
cartype	small	medium	big
BEV	13.3	8.6	42.9
diesel	0.0	2.9	0.0
gasoline	2.2	0.0	36.2

We can thus conclude that the ranking of the technologies according to their TCO remains largely the same for an economic life of 8 years, except that BEVs now perform worse in terms of TCO.

Following the same approach as in Section 3.1, we also look at the distribution of TCOs for individual cars.

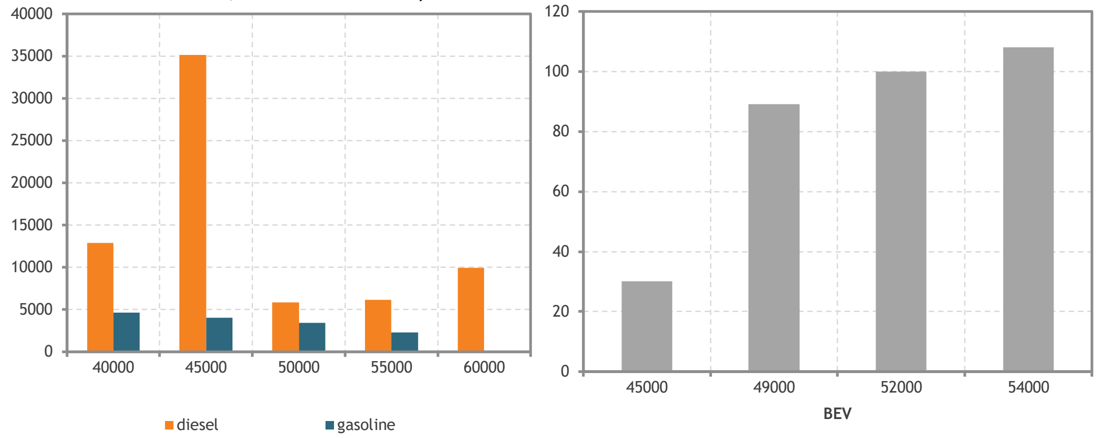
Graph 12 shows an interesting change compared to the calculation for an economic life of 15 years: the distribution of TCOs for small BEVs shifts to the right compared to the distribution for small conventionally fueled cars..

Graph 12 Distribution of the TCO of the 20 best sold “small” models (annual mileage of 10 000 km and lifetime of 8 years)
X axis: TCO in EUR, Y-axis: sales in number of cars



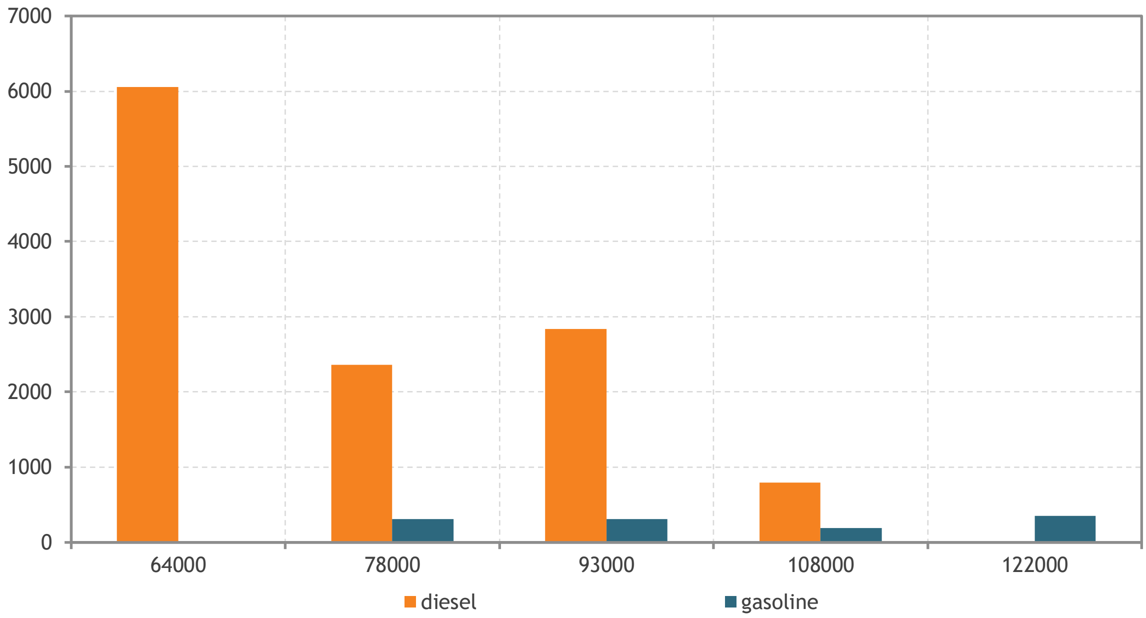
For medium cars, the situation is different. Graph 13 shows that the range of TCO for BEV is still contained in the range for conventionally fueled cars. Even though the center of gravity of the distribution of BEVs shifts to the right, we see that there are BEV models for which the TCO is lower than for some medium conventionally fueled cars.

Graph 13 Distribution of the TCO of the 20 best sold "medium" models (annual mileage of 10 000 km and lifetime of 8 years)
X axis: TCO in EUR, Y-axis: sales in number of cars



In the size segment "big", the TCO of the Tesla Model S (around 107 000 EUR) lies well above the most expensive diesel cars but still lies in the same range as the most expensive gasoline cars.

Graph 14 Distribution of the TCO of the 20 best sold "big" diesel and gasoline models (annual mileage of 10 000 km and lifetime of 8 years)
X axis: TCO in EUR, Y-axis: sales in number of cars



In summary, even though a lower lifespan implies a less advantageous TCO for BEV cars compared to conventionally fueled cars, we see that there are still individual BEV models that have a lower TCO than some individual conventional models, especially in the size class "medium".

3.3. TCO with expected lifetime of 4 years

In this section, we consider a third possible assumption for the lifetime of car. Indeed, according to Greene (2010) and Element Energy Ltd (2013), consumers typically consider pay-back periods of four years, which is much smaller than any empirical estimate of the mean value of a car's economic lifetime.

If these are indeed the pay-back periods that respondents in the Hoen-Koetse study used when comparing the purchase costs and the monthly costs, then even a lifetime of 8 years misrepresent their preferences. A comprehensive analysis should thus also explore the implications of very short time horizons, even if more recent work by Grigolon et al. (2018) casts some doubts on those estimates.

In Graph 15, we compare the "perceived" TCO if consumers have a time horizon of 4 years. In the size segments "small" and "medium", diesel and gasoline cars now perform best, and have broadly comparable TCOs. However, the TCO of BEVs is now clearly higher, on average.

In the size segment "big", the cost advantage of diesel cars compared to BEVs and gasoline cars increases further when the expected lifetime is short.

Graph 15 TCO of cars in 2017 (annual mileage of 10 000 km and lifetime of 4 years)
Y-axis: EUR

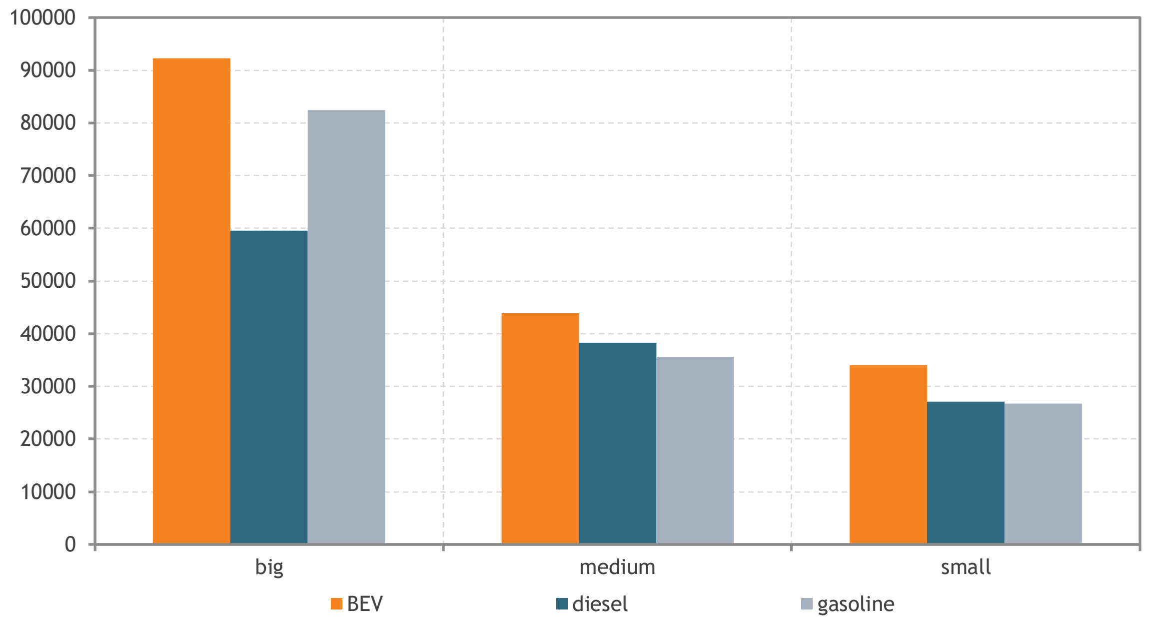


Table 8 gives, for each size class, the difference in percentage compared to the minimum TCO in each size class.

Table 8 Relative difference (in %) compared to minimum TCO in size class (annual mileage of 10 000 km and lifetime of 4 years)
In %

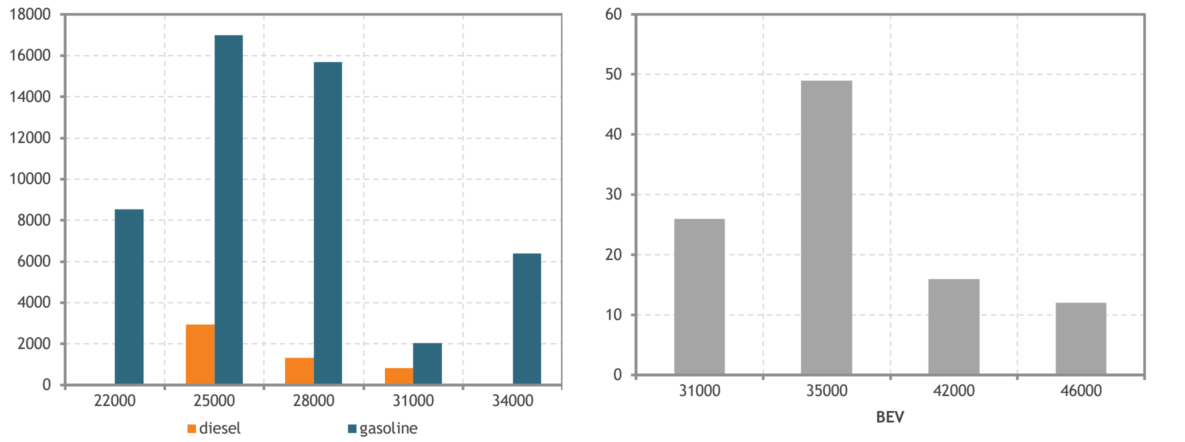
cartype	small	medium	big
BEV	27.2	23.4	54.9
diesel	1.0	7.6	0.0
gasoline	0.0	0.0	38.4

Thus, with very short mental time horizons, the TCO of electric cars is clearly higher *on average*.

When we look at the complete distribution of TCOs for this size class, Graph 16 shows that, compared to an economic life of 8 years, the distribution of TCOs for small BEVs shifts even further to the right compared to the distribution for small conventionally fueled cars. There is only one BEV model that has a lower TCO than the gasoline car with the highest TCO, and all small diesel cars have a lower TCO than small BEVs.

Graph 16 Distribution of the TCO of the 20 best sold "small" models (annual mileage of 10 000 km and lifetime of 4 years)

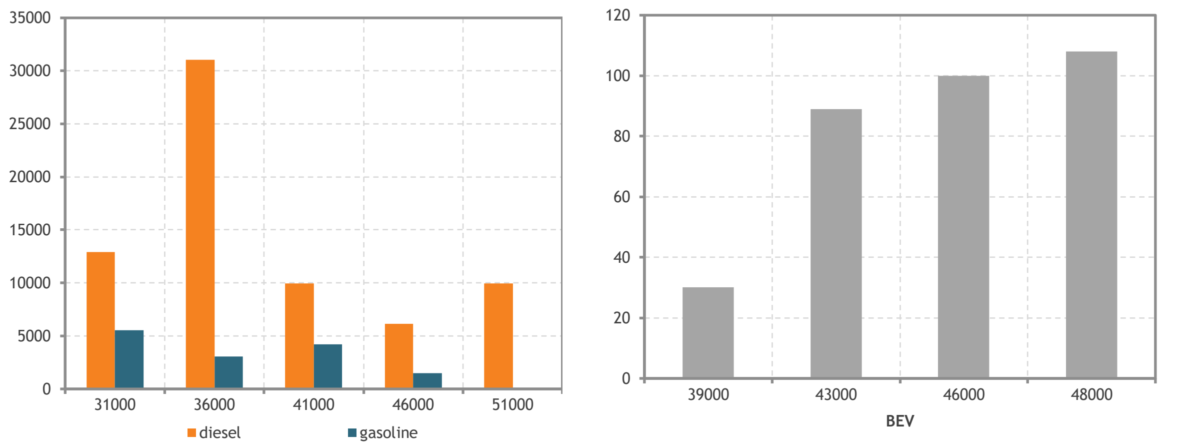
X axis: TCO in EUR, Y-axis: sales in number of cars



Graph 17 shows that, in the case of medium cars, the range of TCO for BEV is still contained in the range for conventionally fueled cars. Even though the centre of gravity of the distribution of BEVs has shifted even further to the right, we see that there are BEV models for which the TCO is lower than for some medium conventionally fueled cars.

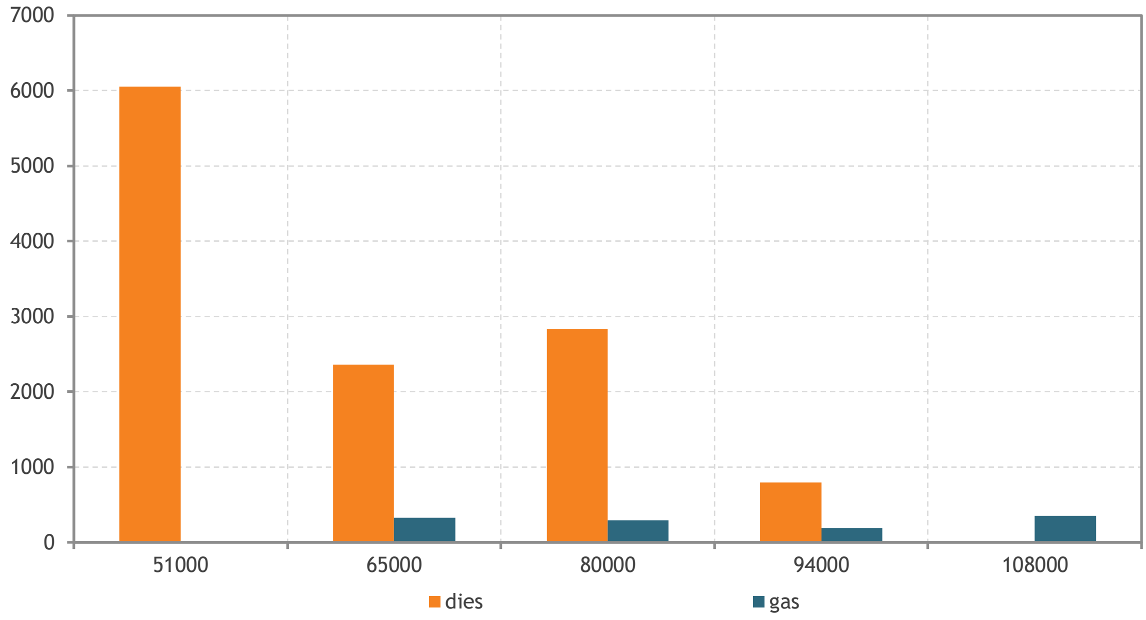
Graph 17 Distribution of the TCO of the 20 best sold "medium" models (annual mileage of 10 000 km and lifetime of 4 years)

X axis: TCO in EUR, Y-axis: sales in number of cars



In the size segment "big", the relative values of the TCO for different powertrains do not really change compared to an economic life of 8 years.

Graph 18 Distribution of the TCO of the 20 best sold "big" diesel and gasoline models (annual mileage of 10 000 km and lifetime of 4 years)
X axis: TCO in EUR, Y-axis: sales in number of cars



In summary, even though a lower lifespan implies a less advantageous TCO for BEV cars compared to conventionally fueled cars, we see that there are still individual models that have a lower TCO than some individual conventional models, especially in the size class "medium".

3.4. TCO with higher mileage

As pointed out above, the annual mileage of car varies a lot between car types. Increasing the annual mileage for a given lifespan should have qualitatively similar effects as increasing the lifespan for a given annual mileage: it leads to an increased share of the variable costs in the TCO. However, due to discounting, the effects are not proportional: doubling the annual mileage leads to a larger increase in the variable costs than doubling the lifespan.

As a sensitivity analysis, we have recalculated the TCO for a life span of 8 years and 20 000 km for the annual mileage; this is more or less the observed mileage for electric cars and medium and big diesel cars. With the lifetimes we use in this analysis, the impact of discounting is so small that we see the same patterns emerge as for a lifespan of 15 years and an annual mileage of 10 000 km. We therefore do not report the detailed results here.

4. Leased batteries

As noted in Section 2.6, a key element of uncertainty in the evaluation of the TCO is the lifetime of a car, and, in the case of BEV, whether the battery will be replaced over this lifetime.

One possibility to circumvent this problem could be to assume that the batteries are leased rather than purchased.

However, data on leasing prices are rare.

Using estimates for the leasing costs provided by Letmathe and Suares (2017), we have shown that leasing batteries is only the more economic option for cars with annual driving distances under the 10 000 km and relatively short expected lifetimes (8 years or less). Given that, historically, the annual mileage of electric cars is far above this threshold, leasing does not appear to be a relevant substitute for purchasing the battery pack.

5. The smallest TCO option for lifetime-mileage combinations

Our analysis so far has shown that a longer expected lifetime or a higher annual mileage tend to improve the position of car types and sizes with high purchase costs and low variable costs. We therefore calculate a "frontier" of lifetime-mileage combinations for which an "average" car would have the lowest TCO in its size class.

We perform this exercise for annual mileages of 10 000, 15 000 and 20 000 km and for lifetimes of 4, 8, 12 and 16 years.

Table 9 gives the result for the size segment "small". We see that, in 2017, "average" electric cars have the lowest TCO if the annual mileage and the expected lifetime are high enough - note that this corresponds to a total mileage over the lifetime of a car of at least 240 000 km.

Table 9 Cartype with smallest TCO in size segment "small"

Annual Mileage	4 years	8 years	12 years	16 years
10000	gasoline	diesel	diesel	diesel
15000	diesel	diesel	diesel	BEV
20000	diesel	diesel	BEV	BEV

"Average" small gasoline cars appear to be the cheapest option only for the lowest possible annual mileage-lifetime combination. As this corresponds to a total mileage over the lifetime of a car of just 40 000 km, this case does not seem very relevant in practice.

This result may seem surprising, given that this is the size segment where gasoline cars clearly dominate diesel cars in terms of market shares (see Franckx 2019). However, we need to keep in mind that this refers to the "average" cars. Graph 1 shows that, in the size segment "small", the purchase price for the 20 best sold gasoline cars has a much broader range than for the best sold diesel cars. Moreover, we see that, for comparable purchase prices, the sales for gasoline cars are always much higher than for diesel cars. Exactly the same pattern can be observed for the distribution of the TCO (see Graph 7, Graph 12 and Graph 16), which suggests that other elements than the TCO alone play a role here.

For all the other combinations, the lowest TCO are obtained for diesel cars.

Table 10 Cartype with smallest TCO in size segment "medium"

Annual Mileage	4 years	8 years	12 years	16 years
10000	gasoline	gasoline	BEV	BEV
15000	gasoline	diesel	BEV	BEV
20000	gasoline	BEV	BEV	BEV

Table 10 gives the result for the size segment "medium". Average electric cars have the lowest TCO for lifetimes of at least 12 years, even for a relatively low annual mileage of 10 000 km per year. For a lifetime of 4 years, average gasoline cars have the lowest TCO. It is only for a lifetime of 8 years that no vehicle type has the lowest TCO for all size classes.

In the size segment "big", diesel cars have the lowest TCO for all the lifetime-mileage combinations.

6. Discussion

We can summarize our main findings as follows.

Whether or not BEVs have a lower TCO than ICE cars depends crucially on the expected economic lifetime, the annual mileage and the size class. For the "small" segment, we see that "average" BEVs have approximately the same TCO as "average" conventional cars for an expected mileage of at least 240 000 km over the car's entire life-cycle - except for cars with a very high annual mileage, this is obviously incompatible with the time horizon of 4 years people typically used when considering the purchase of a new car. In the "medium" segment, the relative position of BEVs is slightly better - they already have the lowest TCO for a an expected mileage of at least 160 000 km over 8 years or 120 000 km over 12 years.

In the size segment "big", the TCO for BEVs is always higher than for diesel cars, and higher than for gasoline cars for lifetimes of 8 years or less. This is a bit paradoxical: it is precisely the size class where BEVs have the most obvious cost disadvantage compared to conventional cars that has been growing the fastest over the last few years. This is also the size class where, in terms of TCO, diesel cars perform better than all other car types.

One possible explanation is that a lot of cars in this size class are company cars, to which a different fiscal regime applies, which could make BEVs more attractive than diesel or gasoline cars.

On the other hand, in the size class "medium", we found individual BEV models that have a lower TCO than some individual conventional models, even for an "irrationally short" lifespan - this shows the importance of complementing comparisons between average values with a look at the complete distribution of TCOs.

In general, our analysis confirms the hypothesis that, in the current market context, the main barrier to the adoption of electric cars is not their total cost of ownership. Other elements appear to be crucial, some of which are easily quantifiable (such as the expected autonomy of an electric car, the availability of a charging infrastructure, long delays in the delivery of orders or the diversity of models on offer), others less (such as consumers' conservatism and range anxiety).

7. Further work

In this paper, we have compared the TCO for several COPERT classes used in CASMO.

Whilst this analyses is an important first step, there is also a clear agenda for further work.

First, we have recognized the substantial large range surrounding the relevant time-frame for the calculation of the TCO. However, this is far from the only variable that is subject to uncertainty.

For instance, at this moment, we can only speculate how the market for end-of-life batteries will develop. Also, the market for second hand electric cars is not well developed either, and there is a lack of reliable estimates of resale prices. However, the future resale values affect the TCO of cars that are being purchased right now. Actually, it could be argued that the high uncertainty regarding the effective lifetime and the resale value of BEVs is one of the barriers for their further uptake.

As discussed above, estimates of maintenance costs also vary widely.

It would therefore be useful to use Monte Carlo simulations with respect to the key uncertainties to verify how they affect the robustness of our key conclusions (as for instance in Danielis et al. 2018, Liu & Lin 2017 and Letmathe and Suares 2017).

Second, as discussed in Vanhaverbeke et al. (2017) the possibility to deliver vehicle-to-grid services should be included in the TCO of electric cars - doing so will further improve the TCO of BEVs compared to conventional fuels.

Third, where possible, we need to differentiate the variable costs according to the individual car models, rather than work with averages per COPERT class.

Fourth, our analysis is based on the observed purchase prices of currently existing model. Following the methodology developed by Desai et al. (2019), we could use a bottom up approach starting from the vehicle components to estimate the additional cost of a BEV compared to an equivalent ICE car.

Finally, here we have considered different usage profiles, without looking at the actual *distribution* of usage profiles in Belgium. As Desai et al. (2019) have done for the US, we could use the results of Belgian travel surveys to estimate the share of the Belgian population for which electric vehicles would have a lower TCO than their conventional counterparts. Given the important share of company cars in the Belgian car stock, it could also be worthwhile to explicitly calculate the TCO for some profiles of company car users. One could even go one step further and differentiate the use profile to take into account that fuel consumption depends on *where* and *when* the cars are driven (as in CGDD 2017).

If we know the distribution of the different usage profiles, we could even estimate the global budgetary impact of subsidies that would lead to cost parity between BEVs and their conventional counterparts.

Whether this will actually be possible is of course highly dependent on the availability of data.

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