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Economic and Environmental Assessment of Technologies Optimizing the Execution of Long Trips for Electric Vehicles

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Abstract: Further advances in hardware and software features are needed to optimize battery and thermal management systems to allow for the execution of longer trips in electric vehicles. This paper assesses the economic and environmental impacts of the following features: eco-charging, eco-driving, smart fast charging, predictive thermal powertrain and cabin conditioning, and an advanced heat pump system. A Total Cost of Ownership (TCO) and externalities calculation is carried out on two passenger cars and one light commercial vehicle (LCV). The energy consumption data from the vehicles are based on experiments. The analysis shows more benefits for the LCV, while the smart fast-charging feature on the car shows a slight increase in TCO. However, negative results did not contribute significantly compared to the ability to install a smaller battery capacity for similar use.

Keywords: battery electric vehicle (BEV); driver experience; environment; extended range electric vehicle; energy consumption

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1. Introduction

One of the challenges for battery electric vehicle (BEV) acceptance is autonomy for long trips, also known as "range anxiety". To tackle this issue, new hardware and software features providing strategies to enable the execution of long trips by BEVs were developed within the Connected Electric Vehicle Optimized for Life, Value, Efficiency and Range (CEVOLVER) project. More specifically, the project tackled the challenge of executing long trips in a reasonable time with a small battery capacity. This was achieved by using the features under study to try to increase battery autonomy and therefore optimize the execution of long trips without changing the battery itself. Such features are user oriented, such as eco-routing, eco-charging, and eco-driving. The project considered an approach based on users' experiences in different use cases to improve the comfort and usability of BEVs for long day trips. While it can be beneficial for reducing range anxiety, adding such features might have an impact on the overall cost of ownership and on the environmental performance of the vehicle. If not beneficial, especially in terms of cost, it could hinder the acceptance of BEVs with such solutions. This paper therefore focuses on the economic and environmental impacts of the features during the vehicle's ownership. The assessment includes the total cost of ownership (TCO) and external costs analysis regarding greenhouse gas emissions. The technological developments are compared to the baseline vehicles.

1.1. Range Anxiety and Technological Developments to Increase Battery Autonomy

While BEVs could help improve the environmental performances of the transport sector, their growth is facing some challenges. The main reasons hindering BEV acceptance from consumers' perspectives are range anxiety and the potential lack of charging infrastructure [1–7].

Range anxiety is a challenge that starts with its own definition, which can vary from one study to another, leading to different interpretations of how to tackle it. While

Liu et al. (2023) state that range anxiety refers more to "energy replenishment" anxiety and estimate that it is the main problem to solve [1], Rainieri et al. (2023) mention that one of the main sources of range anxiety is individual characteristics [5]. Regarding Franke et al. (2016) [2], the study defines range anxiety as "range stress", which is related to the fact that the resources to overcome the range are insufficient. However, these studies tend to agree on the fact that most BEVs available on the market can meet most consumers' travel needs [1,2,4,5,8]. Liu et al. (2023) go even a bit further by stating that ultra-long-range BEVs are actually not needed as they does not solve the problem of energy replenishment anxiety [1]. Furthermore, such cars raise the cost of BEVs due to high purchase and insurance costs, which can also hinder their acceptance. Using TCO and considering range anxiety, the study establishes that the optimal range would be 400 km. The study therefore states that the current BEV market could be sufficient for more than 98% of consumers' needs. Needell et al. (2016) also found that most existing and affordable vehicles can be sufficient to meet the energy needs of 87% of vehicle days in the United States [8]. Such findings are contradictory to the trend from the transport sector to produce BEVs with longer ranges [1]. Indeed, to face range anxiety issues, automotive companies are increasing the range of BEVs by increasing battery capacity and developing charging infrastructure, including fast charging. Those solutions come with some burden. Increasing battery capacity comes with different issues such as the rising cost of BEVs and also an increasing demand for critical materials such as cobalt, nickel, graphite, and lithium [1]. Regarding improving charging infrastructure, He et al. (2023) also pinpoints the fact that its growth depends on the adoption of EVs, as stakeholders are more reluctant to develop charging facilities without growing demand [3].

Several other solutions exist to tackle range anxiety challenges that do not necessarily involve changing the cars on the market. When range anxiety is defined by range stress or individual characteristics, the consensus is that learning experiences and range tolerance help to overcome the stress of not being able to reach a destination [2,3,6]. Other solutions are more technical and practical and are the focus of this paper. One main reason for range anxiety is the unreliability of autonomy and the variation of driving range throughout the usage of the vehicle [4,6]. Predictive models that can provide a more accurate range prediction for vehicles will help in that context. The accuracy is enhanced by collecting more parameters such as on-route data on traffic conditions and battery conditions [7,9,10]. In CEVOLVER, the feature that tackles a part of this issue is eco-charging, which uses real traffic conditions and is explained in more detail in Section 1.2. Another solution is to reduce the energy consumption of the vehicle. It can be achieved through thermal management systems that also help to enhance the life span of the battery. As assessed by Biswas (2020) [11], such systems generally include Heating, Ventilation and Air Conditioning (HVAC); Battery Management System (BMS); and Traction Cooling System (TCS). They ensure the optimal operating condition of the components based on their thermal efficiencies. Finally, eco-driving also helps reduce energy consumption for a certain trip [12]. It can be achieved through learning experiences and/or with advice while driving, such as suggested speed [13–15]. As for the driving range estimations, such add-on's accuracy benefit from on-route information and battery parameters [14,15]. Another possibility for enhancing eco-driving is vehicle platooning [16,17], but such technological advancement is still at an experimental stage.

When analyzed in the literature, the solutions' effectiveness in the studies is assessed through energy consumption gains, tested or simulated. It is not evaluated in terms of cost or environmental performances, which could be helpful to assess the effects on overall usage and to quantify possible burdens. When considering TCO and externalities analysis, the method is often used to compare costs of BEVs or alternative vehicles with equivalent Internal Combustion Engine Vehicles (ICEVs) [18–24]. However, some studies [1,25] quantified the economic performances to qualify the necessity of longer-range BEVs. As mentioned, Liu et al. (2023) calculated the TCO of BEVs with different ranges [1]. The study considers the battery replacement needs for a certain usage, which will differentiate between smaller and bigger EVs. The study shows that despite the battery replacement, the TCO is higher for higher electric range BEVs. Pfriem et al. (2013) found similar results for commercial fleet usage [25]. The TCO for the fleet is beneficial compared to commercial ICEVs when using small-range BEVs. Such studies used the TCO to promote the cost benefit of short-range BEVs and to question the actual need of long-range BEVs.

In this paper, the features under study are assessed in terms of economic and environmental aspects, also including the use of energy consumption data from testing under real driving conditions on open roads or test benches. This is because while the features might be successful in terms of executing longer trips without additional time, some burden in terms of costs or environmental performances might appear and hinder the application of such features. The quantification of the effect on costs will allow assessment of the significance of the potential burdens or benefits compared to the objectives of executing the longer trips on time. Furthermore, the emphasis on the cost and environmental potential benefit might help with the overall acceptance of BEVs with smaller battery sizes.

The next section will present the features and the system evaluated during the project.

1.2. System Description

The system includes three different parameters: the vehicle, the features tested and the use case. During the CEVOLVER project, six features were tested on three different vehicles in different use cases:

- One light commercial vehicle (LCV) with a 68 kWh battery;
- One passenger car with a 24 kWh battery (car 1);
- One passenger car with a 42 kWh battery (car 2).

The two passenger cars are identical except for the battery capacity. The baseline vehicle is defined as the vehicle without the CEVOLVER features switched on. Table 1 summarizes the systems considered for the experiments with the baseline vehicles, the corresponding use case, and the specific features switched on during testing. Each line of the table refers to one test that has been performed, once with the features not used and once with the features switched on. Thermal-related features have been tested on test benches and the others on open roads.

Table 1. Summary of baseline vehicles, the use cases and features. Legend: LCV—light commercial vehicle, NEDC—New European Driving Cycle.

Vehicle	Use Case	Feature
LCV	Parcel service daily job	Eco-charging
LCV	Parcel service daily job	Eco-driving
Car 1	Regular commute from home to work	Predictive thermal powertrain conditioning and predictive thermal cabin conditioning
Car 1	NEDC	Hardware changes in the heat pump
Car 2	Private visit of 350 km	Eco-charging
Car 2	Private visit of 350 km	Eco-charging and eco-driving
Car 2	Private visit of 350 km	Eco-charging and eco-driving and smart-fast charging

The use case describes the type of usage the vehicle faces and sets the boundaries of the experiments (i.e., the type of trips completed). The “parcel service daily job” means the vehicle is used for parcel delivery, mainly in urban areas. The charging of the vehicle is performed after returning to the distribution center. The “Regular travel to and from work” refers to a short-range trip from work to home, with a distance of 30 km. The charging is executed after arriving home at a charging station. The “private visit of 350 km” refers to occasional visits to relatives during the weekend or holiday trips. Since the trip is long, this use case assumes that one fast charging is required at a public charging station and one home charging during the visit.

As for the features, eco-charging determines the most energy- and time-efficient charging and routing strategy for the trip based on traffic conditions. Different parameters are considered, including traffic and weather conditions, which enhance the accuracy of such development. Still, the real value-add comes with the intelligent recommendation for fast charging that is optimized based on the assessment of the overall trip and not just the need to find the next charging station when the state of charge drops below a set value. The functionality of the feature is detailed in De Nunzio et al. (2020) [7]. Eco-driving ensures the speed recommendation to optimize energy consumption according to an analysis of the route and traffic conditions. The specificities are detailed in Ngo et al. (2021) [26]. In addition, smart fast charging conditions the battery before a fast charge to ensure the full charging power is available. It prevents the battery from overheating, which would lead to a longer charging time. The driving and charging conditions are based on the data gathered from the eco-charging features. The predictive thermal powertrain optimizes the use of the powertrain components based on their thermal efficiency, and the predictive thermal cabin conditioning ensures a comfortable cabin temperature while reducing the energy consumption from the climatization system. The software development is detailed in Wahl et al. (2022) [27] and in Chen et al. (2020) [28]. Finally, the advanced heat pump system developed in the project OPTEMUS allows the use of heat from electric components and batteries to warm up the cabin as described in the project website and in Ferraris et al. (2020) [29,30].

2. Materials and Methods

The assessment is based on the TCO and the assessment of external costs, focusing on greenhouse gas (GHG) emissions. TCO is a widely applied and accepted methodology to assess the economic impacts of a product. For all the vehicles, the TCO and external costs of the baseline vehicle will be compared to the TCO and external costs with the added developments. The geographic scope of the study is Belgium. However, Italy and Sweden conditions are also considered to cover different climate conditions for assessing the predictive thermal powertrain, cabin conditioning, and heat pump hardware changes since these goals are related to extreme weather conditions.

2.1. Total Cost of Ownership

The TCO methodology [31] compares the affordability of the vehicles by summing all costs that occur during the ownership of a vehicle. It can be defined as a tool to support understanding the actual cost of buying and using a particular good or service.

When calculating the TCO of a vehicle, there are two aspects to consider: Capital Expenditure (CAPEX), which are the one-time costs occurring to acquire fixed assets (e.g., the vehicle), and operating expenses (OPEX), which are the expenditures occurring during the operation of the vehicle at the present value (e.g., operational costs and non-operational costs). For vehicles, the TCO accounts for purchase costs, fuel, operating costs, and non-fuel operating costs. The TCO is based on the net present value of the vehicle's lifetime [32]. Therefore, Equation (1) is used for the one-time cost, and Equation (2) is used for recurring costs.

$$PV = A_t \frac{1}{(1+r)^t}, \quad (1)$$

$$PV = A_0 \times \frac{(1+r)^t - 1}{r \times (1+r)^t} \quad (2)$$

where:

PV is the present value given in EUR.
A_t is the one-time cost at time t.
A_0 is the annual recurring cost.
r is the real discount rate.
t is the time expressed as the number of years.

The real discount rate can be retrieved from the European Central Bank, considering the years 2011 to 2021. The critical assumptions for the TCO calculation are related to the vehicle's lifetime of ownership and are shown in Section 3.

2.2. Externalities

Externalities can be defined as uncompensated social or environmental effects due to social or economic activities [33]. In this study, the focus is on the climate change impact category. Therefore, externalities are based on the environmental impacts of the electricity consumed by the vehicles, which depends on the country-specific electricity production mix. The average carbon price for 2021, equivalent to 53.45 EUR/ton CO_2 [32,34], is considered. The carbon footprint is calculated with the Intergovernmental Panel on Climate Change (IPCC) characterization factors [35] with electricity mix data from the Ecoinvent 3.8 database [36]. Table 2 summarizes the carbon footprint and external costs for each country considered.

Table 2. Carbon footprint and external costs of electricity production per country.

Country	Carbon Footprint (kgCO_2 Eq/kWh)	External Cost (EUR/kWh)
Belgium	0.220	0.018
Sweden	0.022	0.001
Italy	0.395	0.021

2.3. Data Collection

The critical assumptions for the TCO calculation are related to the vehicle's lifetime of ownership (Table 3). The ownership of the vehicle is set to 10 years [37]. The discount rate is set to −3% [38]. The distance driven for the use cases does not necessarily cover the entire annual distance traveled with the vehicle. Therefore, additional kilometers are added to reach the average annual distance traveled in Belgium [39]. The impacts of the features are applied only to the distance the use case covers. This method allows an economic and environmental analysis of the developments per use case assessed during the experiments.

Table 3. Key assumptions for the vehicle life cycle. LCV—light commercial vehicle, NEDC—New European Driving Cycle.

Parameters	Value	Unit	Reference
Duration of ownership	10	Years	[37,39]
LCV annual distance	21,000	km	Aligned with the corresponding use case and the annual distance driven by a LCV in Belgium in 2019 [40]
Car 1 annual distance for the use case: regular travel to and from work	7500 (out of 15,000)	km	Aligned with the use case
Car 1 annual distance for the NEDC	15,000	km	Aligned with the distance driven per year in Belgium
Car 2 annual distance for the use case: private visit of 350 km	4200 (out of 15,000)	km	Aligned with the use case considering a once-a-month visit to relatives
Real discount rate	−3	%	[38]

2.3.1. Experimental Data

The energy consumption data presented (Figure 1) and duration of the trip are primary data obtained during the CEVOLVER experiments. Each feature was tested for the corresponding use case. First, the baseline vehicles were driven on a specific trip corresponding to the use case. Then, the same vehicles were driven using the additional project features.

Eco-charging, eco-driving, and smart fast charging were tested on open roads while the others were tested on test benches.

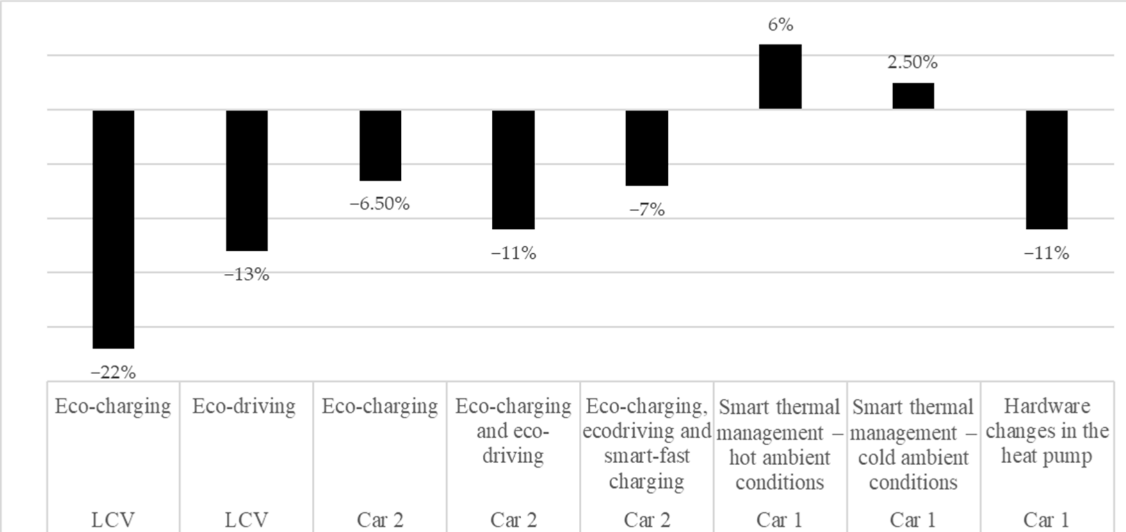

Figure 1. Summary of the changes in electricity consumption per vehicle from the baseline use case.

Regarding the LCV, eco-charging and eco-driving were tested separately, which means that the open road trips were slightly different for the two tests. For eco-charging, the trip with the baseline vehicle was the recommended one by the GPS to go from point A to point B. Then, eco-charging was used to define the most optimized road to take. Therefore, the two trips were not similar. For eco-driving testing, both trips were the same and corresponded to the optimized one provided by the eco-charging feature.

Specific Case of the Predictive Thermal Powertrain and Cabin Conditioning Features and the Hardware Changes in the Heat Pump

The experiments to reach the objectives set for thermal-related features are based on extreme weather scenarios. The features are indeed expected to help with energy consumption and the time to reach a certain temperature within the car during extreme temperature conditions. The provided data show the energy consumption for different trips for a certain ambient temperature (either −10 °C or +35 °C). Therefore, the extrapolation of these data and scenarios is slightly different than for the rest of the experiments.

As mentioned earlier, three countries with different temperature distributions are assessed for the boundaries: Belgium, Italy, and Sweden. Belgium is supposed to represent a middle-temperature condition, whereas Italy represents a hotter country and Sweden a colder one. The data were then adapted to each country. For Sweden, when necessary, the conversion rate taken is based on the one used by the European Alternative Fuels Observatory (EAFO), which is SEK 1 = EUR 0.097 [41].

The Open Power System Data provided an hourly temperature distribution for 2019 [42]. It helped to determine a percentage of time (Table 4) when the temperature is either above 28 °C or below 0 °C in a year. For the hardware changes, only the percentage related to cold temperatures is considered as only cold temperature conditions have been tested. This percentage is applied to the distance driven for the use case, and the changes in electricity consumption (Figure 1) are then applied to the corresponding kilometers. While it is difficult to predict the behavior of the developments and the savings potential under different temperature levels, the differences between the different predictions are expected to be marginal. Therefore, for simplification reasons, it is assumed that the potential saving from the experiment is the same for all ambient temperatures considered within "extreme weather conditions".

Table 4. Distribution of the temperature in a year for Belgium, Italy, and Sweden.

Country	Temperature below 0 °C (%)	Temperature over 28 °C (%)
Belgium (BE)	4.23	1.28
Italy (IT)	0.27	6.95
Sweden (SE)	18.46	0.01

2.3.2. Cost at Purchase Time

This section provides all purchase costs. It must be highlighted that the purchase price of a car in Table 5 can vary from region to region because of the choice of additional equipment consumers choose. These costs would affect the TCO by increasing or reducing the overall cost for both the use case with and without features. However, despite these price differences, the percentage changes between the two scenarios will stay the same.

Table 5. Summary of the costs at purchase time.

Costs		Value	Unit	Reference
LCV purchase cost		39,210	EUR	[43]
Car 1 purchase cost		29,424	EUR	[44]
Car 2 purchase cost		24,900	EUR	[45]
Registration costs	Belgium	0	EUR	Flanders, Belgium [46]
	Italy	150	EUR	Italy [47]
	Sweden	0	EUR	Sweden [46,47]
Features' cost	Eco-driving	0	EUR	Assumed to be included in the car purchase price.
	Eco-routing	0	EUR	
	Smart-fast charging	0	EUR	

2.3.3. Operational Costs

All operational costs, including electricity, are summarized in Tables 5–8. The cost of home charging is based on the average European price of electricity in the year 2019 [35], before the actual context of the energy crisis and geopolitical conflicts. This cost is considered constant for all ten years in this study. Given the actual context, the future and even actual electricity costs are very unstable and thus very difficult to predict. It will also impact the TCO. However, this TCO assessment focuses more on developing saving potential. Therefore, the results will still allow a first understanding of the economic impact of the features even without considering the situation at the time of writing.

Table 6. Operational costs for Belgium.

Operational Costs	Specificity	Value	Unit	Reference
Electricity cost at public charging	Chargers	0.32	EUR/kWh	[41]
	Fast chargers	0.60		
Electricity cost at home charging	all	0.22	EUR/kWh	[48]

Table 7. Operational costs for Italy.

Operational Costs	Specificity	Value	Unit	Reference
Electricity cost at public charging	Chargers	0.45	EUR/kWh	[41]
Electricity cost at home charging	all	0.22	EUR/kWh	[48]

Table 8. Operational costs for Sweden.

Operational Costs	Specificity	Value	Unit	Reference
Electricity cost at public charging	Chargers	0.29	EUR/kWh	[41]
Electricity cost at home charging	all	0.22	EUR/kWh	[48]

2.3.4. Non-Operational Costs

All non-operational costs, including road tax, insurance, maintenance, tire replacement, and technical control are summarized in Table 9. Maintenance, tire replacement, and technical control are vehicle specific. In addition, to estimate the real insurance cost in Belgium, a simulation was made for insurance costs with a specific person profile for both baseline vehicles. It is assumed that the person subscribed to the two types of insurance: the civil liability with basic protection rights and full omnium, which is a type of insurance in Belgium covering most car issues.

Table 9. Non-operational costs per vehicle.

Non-Operational Costs		Vehicle	Value	Unit	Reference
Small maintenance		Car 1 and 2	63	EUR/year	[49]
Large maintenance		Car 1 and 2	157.00	EUR/2 years	[49]
Maintenance before 5 years		LCV	185	EUR/year	[50]
Maintenance after 5 years		LCV	199	EUR/year	[50]
Tire replacements		LCV	591	EUR/40,000 km	[51–53]
		Car 1 and 2	234.44	EUR/40,000 km	[51–53]
Road tax	Belgium	All	0	EUR	[54]
	Italy	All	39.99	EUR/year after 4 years	[54]
	Sweden	All	35.55		[54]
Technical control	Belgium	LCV	59.80	EUR/year	[55]
		Car 1 and 2	45.10	EUR/year, after 4 years	[55]
	Italy	Car 1 and 2	79.02	EUR/every 2 years after 4 years	[56]
	Sweden	Car 1 and 2	58.20	EUR/year after 4 years	[57]
Insurance costs: civil liability	Belgium	LCV	655.96	EUR/year	[54]
		Car 1 and 2	248.19	EUR/year	[55]
	Italy	Car 1 and 2	344	EUR/year	[56]
	Sweden	Car 1 and 2	248.19	EUR/Once in year 3 Once in year 5 And once a year after	[57,58]

3. Results and Discussion

Figure 2 depicts the overall results from the TCO and externalities assessment comparing the use cases with or without the features. All developments considered resulted in rather small changes in the cost assessment. The changes ranged from −4% to +0.11%. The most significant and beneficial changes appeared for eco-charging and eco-driving with the LCV. These results are explained by the reduction in energy consumption. However, it is difficult to compare all vehicles and their respective results and confirm that the biggest changes would always be for vehicles like LCVs. Indeed, these differences may be due to one vehicle itself and the usage scenario differences that affect the direct extrapolation and boundaries of the TCO.

For the LCV, in both scenarios, the use of the developments reduces the TCO. A greater benefit is observed for the eco-charging features than for eco-driving; however, it is expected that the combination of the two would lead to an even bigger reduction of the energy consumption and therefore the overall TCO.

Cost savings were observed for cars but to a lesser extent. Regarding car 2, adding smart fast charging shows a slight reduction of benefit compared to the two other scenarios. It means that conditioning the battery to gain charging time also increases energy consumption for long-distance trips and, subsequently, the car TCO. Still, this negative environmental and cost effect is small and therefore remained less important than the fact that the driver can reach the destination on time for a long trip. The burden is also overcome using the other features. As expected, and shown by the results on car 1, the hardware changes are even more beneficial for countries with colder weather conditions. Small increases in energy consumption were observed for the thermal predictive conditioning features. Energy savings were actually shown regarding the powertrain energy efficiency, but it overlapped with other effects specific to the experiment. While the increase itself is also small, these additional costs are also neglectable as they depend on the experiment type and the drivers.

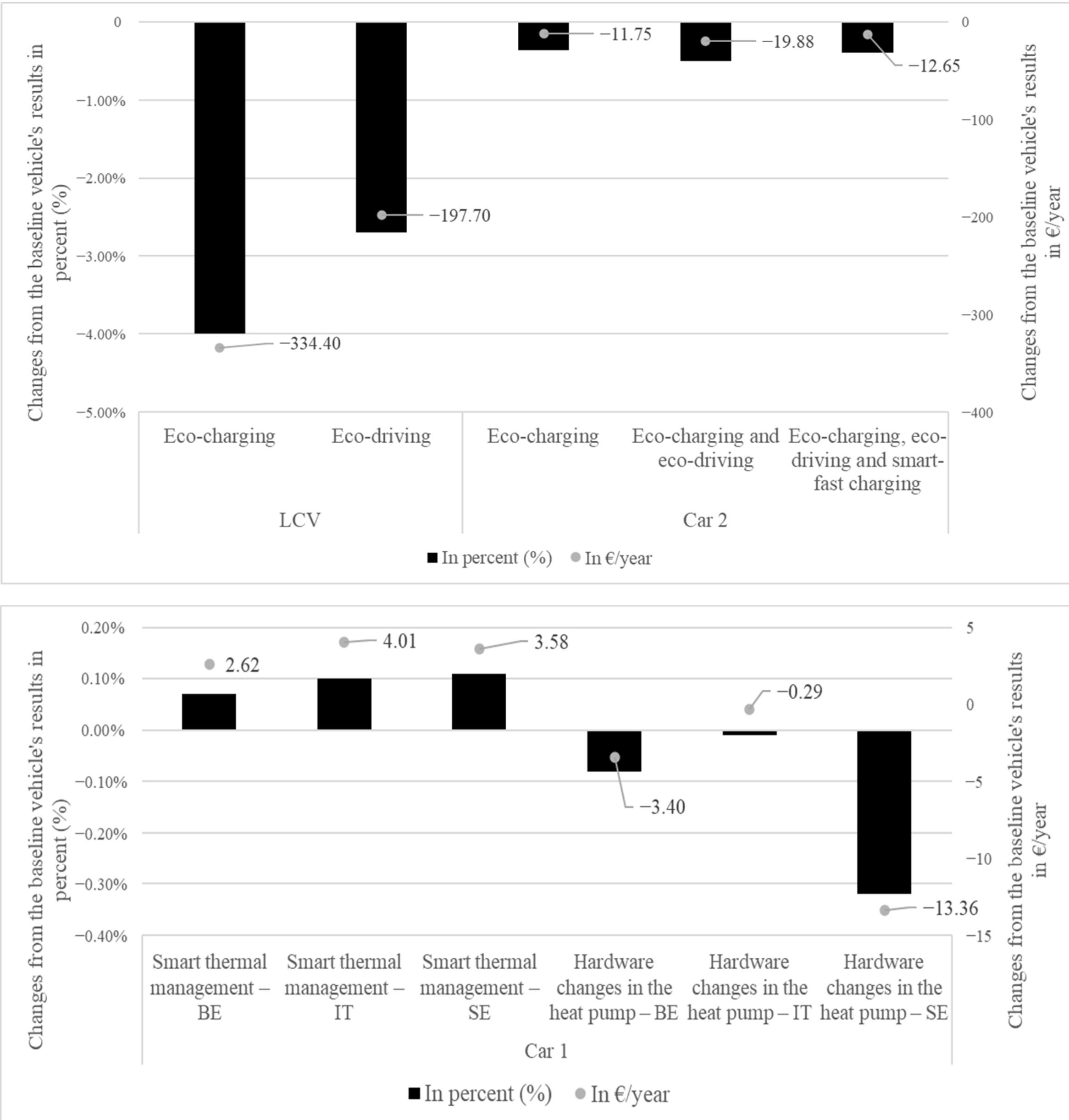

Figure 2. Overview of the changes in the TCO with the addition of the externalities' impacts. The bar graph is for the results in percent, and the point is for the results in EUR/year.

Overall, the results show that TCO and externalities reductions obtained by gains in energy efficiency are very small. This is because all demonstrator vehicles have the same battery capacity for the baseline tests and tests with enabled features. However, many features developed in CEVOLVER contribute to installing batteries with smaller capacities by ensuring outlier behavior (long trips, under severe ambient climate conditions), which typically determines the battery size and can be covered by smaller batteries with intelligent strategies, and as shown by the TCO and external costs, with no additional economic or environmental burden and even some small benefits. Therefore, greater differences are expected when comparing the TCO of the vehicle with CEVOLVER features to the TCO of a vehicle with the actual battery size required for similar usage.

4. Conclusions

This study examined the environmental and economic impacts of using features developed in the CEVOLVER project to reduce range anxiety in BEV drivers by improving the execution of long trips. While their effects are usually assessed in terms of energy consumption, this study took the approach to quantify the impacts in terms of costs for the overall usage. The features were of two kinds: hardware and software. They are related either to the driving and charging behavior or the thermal management system. A TCO and externalities approach has been carried out to understand their effects by comparing vehicles with and without the developed features. Several parameters including the duration of the trip or the energy consumption of the vehicles were retrieved from experiments performed during the project.

The use of the hardware and software features tested in CEVOLVER led to small environmental and economic impacts compared to the baseline vehicle. However, it proved that longer trips with the same vehicle are doable, with only a neglectable effect on TCO and no unexpected burden that could hinder their usage. The main advantage lies in the potential to reduce the vehicle's battery capacity for similar use. This would benefit the energy consumption in the use phase, costs, and also materials demand. Therefore, greater benefits are expected when considering the production phase in the externalities assessment. However, such benefits are not shown by the TCO and would require further research.

A limitation of the assessment was that extrapolating the experiments' results for the overall usage of the vehicle was in some cases not possible. As mentioned above, some use cases do not necessarily cover the entire usage of the vehicle. Further research to understand the effects on the additional distances could help show the full potential of the features on energy consumption reduction.

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