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Simulation model for long-distance mobility with battery electric vehicles: a multi-perspective analysis

Julien Baltazar^{a,*}, Flore Vallet^{a,b}, Julien Garcia^c

^aUniversité Paris-Saclay, CentraleSupélec, Laboratoire Génie Industriel, 3 rue Joliot-Curie, 91190 Gif-sur-Yvette, France

^bIRT SystemX, Paris-Saclay, Avenue de la Vauve, 91127 Palaiseau, France

^cStellantis, Centre technique Vélizy, route de Gisy, 78140 Vélizy-Villacoublay, France

* Corresponding author: julien.baltazar@centralesupelec.fr

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Abstract

Battery electric vehicles (BEVs) are considered a potential solution to tackle the main environmental issues of road transport. However, their deployment is limited, notably for long-distance trips where BEVs suffer from short ranges, slow charges, and lack of infrastructure. Considering these technological, sociological, and environmental stakes of BEV deployment, this paper aims to highlight the interests of multi-perspective analysis for electromobility. It introduces a methodology to analyse and compare performances of both conventional vehicles and BEVs, considering diverse possible usages. Fleet simulations on the highway linking Paris to Lyon (France) were conducted to provide recommendations for designers and insights for electromobility stakeholders such as drivers, carmakers, or infrastructure planners. Performance criteria such as average travel time, the number of charging points to install, and environmental impacts have been used to compare vehicles and evaluate the influence of users' behaviours and electricity mix. This study quantifies the travel time differences between conventional vehicles, average BEVs, and high-end BEVs and the effect of the driving speed choice and battery management on the performance criteria. Finally, electricity consumption is identified as a significant source of the BEV highway traffic environmental impacts, although they depend on the regional electricity mix; the battery life cycle is also an important source of impacts.

Keywords

Multi-perspective analysis, battery electric vehicles, simulation, long-distance mobility, user behaviour, environmental impacts

1 Introduction

Individual mobility and passenger cars mainly rely on internal combustion engines and petrol. Thus, they are a significant cause of environmental impacts. In France, the road transport activity implied the emission of 127 Mt CO₂ eq in 2019, representing 29 % of the internal greenhouse gas emissions of the country [1]. Therefore, transport highly contributes to climate change [2]. Other problems are caused by internal combustion engine vehicles (ICEVs). For example, several health damages are caused by toxic gases and particles, including nitrogen oxides (NO_x), whereas 52 % of NO_x comes from road transport in France [1].

Therefore, many countries are willing to change mobility usages and technologies to reduce these impacts. One option is the deployment of battery electric vehicles (BEVs) which receive much support and investments from governments [3]. However, several barriers have been identified for BEV deployment. First, their relevance depends on the electricity mix of the region where BEVs are used and the battery management because its production requires much energy and critical materials [3, 4]. Moreover, the range and the charging management are technical barriers limiting BEV adoption because users expect performances to be close to ICEVs' for their long-distance trips [5]. Lastly, a significant part of BEV costs is linked to batteries and power electronics [6], so BEVs with high-capacity batteries and high-performances for long-distance trips are expensive.

In the context of a collaborative research project between industrial and academic designers, the objective was to define a joint approach for multi-perspective analyses of electromobility deployment. The paper aims to give insights into long-distance BEV deployment and recommendations to designers for future work considering mobility. For this, it proposes a large scope study dealing with the following question: *What insights can the consideration of BEV usage diversity and an environmental assessment provide to designing of an electric mobility system?*

In section 2, some references are presented to define the framework for charging network dimensioning, territorial environmental assessment, and user behaviour modelling. In section 3, a simulation method is proposed to compare the system performances in various use cases. Finally, some results (section 4), observations, and recommendations about BEV deployment are detailed (section 5).

2 Dimensioning and assessing electric mobility systems

A review was conducted to feed a method to design an electric mobility system in the territorial context of long-distance mobility usage.

2.1 Methods to dimension charging infrastructures

The charging infrastructures are essential for the deployment of BEVs. The literature presents different approaches to design infrastructure networks [7].

Among the works studied, Mourad et al. (2020) proposed a model to determine an optimal deployment of fast-charging stations distributed among predefined locations [8]. This method is applied to the road network of an urban community using traffic flow measures to model charging demand.

With another approach, Micari et al. (2017) defined an *ad hoc* method to design the charging station network of the Italian highways [9]. It relies on traffic flow measures, a consideration of the highest charging demand during peak hours, and the national distribution of BEV sales.

2.2 Methods for territorial environmental assessment of mobility

A territorial assessment can be developed to calculate the potential environmental impacts of a mobility system. Several studies using life cycle assessment (LCA) at urban or regional scale have been reviewed.

Le Féon (2012) proposed a method to assess the global warming impact of urban mobility in an agglomeration [10]. It includes the indirect emissions of transports and considers the user trip purposes to analyse the greenhouse gas emissions caused by passenger transportation finely.

François et al. (2017) applied LCA to the results of mobility simulations of an urban area [11]. Urban mobility has been evaluated through assessments of the transport system and travel habits.

Finally, Bortoli and Christoforou (2020) proposed to use a consequential LCA approach to evaluate the environmental consequences of the breakthrough of free-floating e-scooters in Paris [12]. All transportation modes have been assessed and modal shifts have been estimated using a user survey.

2.3 Methods including BEV usage and adoption behaviour modelling

The need to consider users in the design of future electric mobility systems has been underlined in the literature.

Some papers include users' behaviour considering the charging infrastructure usage. Davidov and Pantoš (2017) introduced a quality of service indicator in an optimisation model for charging station planning [13]. This indicator describes the total charging time acceptable for the user depending on the trip length. For their road charging infrastructures planning, Micari et al. (2017) applied a safety margin parameter to consider that some BEV users charge their vehicles more often than others because of range anxiety [9].

Moreover, adoption tendencies can be considered for mobility analysis. Jahn et al. (2020) defined their fleet using four BEV models that match the vehicle class distribution of Berlin. They also used real-world charging behaviour data to simulate the fleet in a city [14]. The results have been used to determine urban charging strategies.

2.4 Gap analysis

This literature overview has identified a lack of studies proposing global multi-perspective analysis for BEV and infrastructure deployment.

First, no study about infrastructure planning seems to integrate an environmental analysis. However, a significant stake in electric mobility is reducing the environmental impacts of transport and justifying trade-offs. So, it seems relevant to evaluate electric mobility impacts at a territorial scale while including those of the fast-charging infrastructures and considering the influence of the BEV users' behaviour, such as their driving speed.

Then, among the studies assessing environmental impacts at a territorial scale, none seems to deal with long-distance mobility or framework propositions to evaluate impacts of highway traffic.

Moreover, the effect of user behaviour is sometimes considered in studies. However, none of them evaluate its influence on the global performances of a mobility system or include a diversity of behaviours about charge management.

Finally, the performance differences between BEV models are often underlined, but this variety is rarely integrated into studies. Also, there are regular technological enhancements of BEVs, so stakeholders should consider them for long-term infrastructure planning or car user recommendations. However, there is a lack of studies analysing the effects of the future evolutions of BEVs.

3 Proposition of a simulation model for long-distance electric mobility

To study BEV long-distance mobility while addressing the gap analysis, the proposition of this paper is about developing a simulation model of a highway including multicriteria evaluations, the diversity of usage, and perspectives for BEV developments. Using simulations has been motivated by its convenience to model different user behaviours. It also avoids conflicts between agents and convergence issues. The simulation model was programmed in Python. The input data and simulation parameters are imported from Excel files, and the simulation results are exported in another Excel file. Developing a simulation model in this way has been motivated by the context of the research project: the authors created a tool that could be understandable and usable by anyone, even without prior knowledge about modelling, simulation, or optimisation. This section and the Figure 1 present the research methodology to design the simulation model. The case study is the A6 French highway between Paris and Lyon.

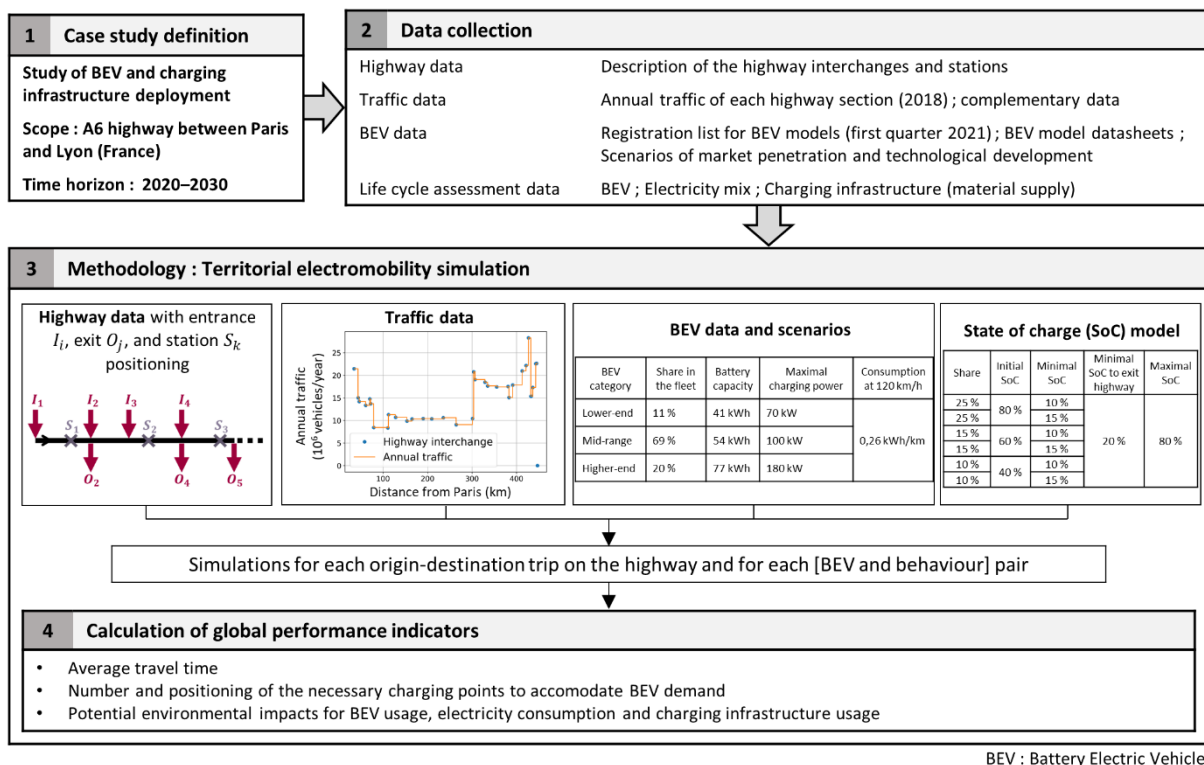


Figure 1 : General framework of the model

3.1 Identification of traffic and vehicle data

Traffic data were collected from road network administrators to make the model representative of the real-world situation. They include the 2018 annual averages of the light vehicle traffic measured between each road interchange [15]. The infrastructure network dimensioning needs to accommodate the charging peak demand, so a complementary study was conducted. According to the measures provided by a French highway administrator (APRR/AREA), the hourly traffic during summer weekends in the most used direction can be three times superior to the yearly average value, and the average trip distance during these periods is about 1.6 times longer than the average.

BEV data were collected to characterise the fleet circulating on the road network. The fleet definition is based on the BEV sales in France during the first quarter of 2021 [16]. The carmaker datasheet of

each model has been used to get the battery capacity, the maximal charging power, the consumption, and the mass of each BEV. Then, four representative categories have been defined to aggregate BEVs of similar dimensioning. A part of the BEVs with the lowest battery capacities are excluded from the fleet driving on the highway because they are less expected to perform long-distance trips. The data of a charging operator (Fastened) were used to determine the typical charging performances according to the BEV model, its maximal charging power, and its current state of charge [17]. Finally, BEV penetration and technological perspectives for the 2020-2030 horizon were estimated according to carmaker expert interviews and the expectations in the literature [3, 18].

3.2 Determination of the demand from multiple data sources

The previous traffic data are the vehicle flows measured at different punctual locations. They are not sufficient to describe the trips because the charging needs directly depend on their lengths. For example, all trips shorter than 100 km usually do not require any charge. Therefore, a specific method to reconstitute the trips is proposed: it estimates the vehicle flow between each road entrance and exit pair.

This method relies on traffic hypotheses. First, the traffic is divided into two halves for each direction of circulation: this hypothesis is acceptable for daily, monthly, or yearly traffic averages. Then, the input and output flows at each interchange are evaluated by an *ad hoc* flow balance method. Its main parameter is fitted using a measure of the average travel distance on the A6 highway provided by APRR/AREA. Finally, the origin-destination matrix is computed with a method inspired by the iterative proportional fitting procedure.

3.3 User behaviour model definition

A variety of driver behaviours is introduced in the model by defining the driving speed and the battery state of charge management. Their influence on the mobility system performances is evaluated by various indicators, including the average travel time for the trips done on the highway, which is calculated by the equation (1).

$$ATT^k = \frac{\sum_{i,j} m_{ij}^k |d_{ij}| t_{trip,ij}^k}{\sum_{i,j} m_{ij}^k |d_{ij}|} \quad (1)$$

with ATT^k , average travel time for the trips done on the highway by the BEVs from the fleet k (h),
 m_{ij} , traffic flow between the entrance i and the exit j (vehicles/year),
 d_{ij} , distance between the entrance i and the exit j (km),
 $t_{trip,ij}^k$, total travel time for a BEV from the fleet k performing a trip between the entrance i and the exit j (h).

The diversity of charging management is based on several assumptions. First, car drivers enter the road with diverse initial states of charge according to the distance they travelled since their last charge. Also, users ensure they exit the highway with enough range to continue their trips, so a minimal state of charge is required. Then, some users feel more range anxiety than others: it implies that they usually charge their vehicles sooner than others. Finally, battery charge duration depends on the time BEV drivers wish to spend at the station because they do not necessarily wait until the battery is full.

3.4 Method for the environmental assessment of the highway electric mobility system

The simulator includes an electromobility environmental assessment whose functional unit is to “Enable the mobility of all-electric passenger cars on the highway during a year”. The evaluation is performed for the indicators i listed in Fig. 2. Impacts are calculated from carmaker internal data that consider the whole life cycle of electricity consumption and BEV usage. The batteries are supposed to be made in China. There is a lack of data in grey and scientific literature about charging infrastructures, so only the material supply impacts are assessed. They were calculated from the material inventory of a 50 kW charging point done by Lucas et al. (2012) [19], considering a lifespan of 10 years. The impacts for a 175 kW charging point have been extrapolated using a mass-power relation established from various constructors’ datasheets. The impacts of each BEV fleet are calculated by equation (2).

$$EI_{i,k} = \frac{d_k}{d_{FU}} \left(\frac{m_k}{m_{vehicle}} ei_{i,vehicle} + \frac{C_k}{C_{battery}} ei_{i,battery} \right) + E_k \cdot ei_{i,elec} + N_{CP} \frac{ei_{i,CP}}{T_{CP}} \quad (2)$$

with $EI_{i,k}$, annual environmental impact i of the fleet k (impact unit/year or IU/year),

d_k , cumulative annual distance travelled in the highway by the fleet k (km/year),

d_{FU} , lifespan of the BEV reference (km),

m_k , mass of a BEV from the fleet k excluding its battery (kg),

$m_{vehicle}$, mass of the BEV reference excluding its battery (kg),

$ei_{i,vehicle}$, life cycle environmental impact i of the BEV reference excluding electricity consumption and battery impacts (IU),

C_k , battery capacity of a BEV from the fleet k (kWh),

$C_{battery}$, battery capacity of the BEV reference (kWh),

$ei_{i,battery}$, life cycle environmental impact i of the battery of the BEV reference (IU),

E_k , cumulative annual electricity consumption due to traffic of the fleet k in the highway (kWh/year),

$ei_{i,elec}$, life cycle environmental impact i of electricity usage (IU/kWh),

N_{CP} , number of charging points in the highway,

$ei_{i,CP}$, life cycle environmental impact i of the material supply for a charging point (IU),

T_{CP} , estimate of the lifespan of a charging point (years).

3.5 Case study

The case study is the A6 highway that links Paris to Lyon (France). It is a 450 km road that is highly busy, especially during summer weekends, so this choice seems relevant for long-distance mobility analysis.

During each simulation, charging needs are computed in every service station for each trip, BEV category, and user behaviour. Every charging point is supposed to have a power of 175 kW: it corresponds to the typical infrastructures currently installed in France. There is never any queue in charging stations, but four minutes are supposed to be necessary to access and egress the charging station. Furthermore, the traffic between 2020 and 2030 is supposed to remain equal to 2018. Finally, the electricity mix of the 2017 European Union (EU-28) is considered.

4 Multi-perspective simulation results

This section presents a sample of simulation results to highlight some observations about long-distance mobility. We propose a comparison of performances (1) for different fleets and (2) for

different user behaviour, as well as (3) some recommendations to limit environmental impacts. Recommendations considering charging station dimensioning are not detailed here for the sake of brevity.

4.1 Comparison of performances between ICEVs and BEVs from different ranges

Long-distance mobility is a barrier to BEV adoption. Indeed, BEVs perform high-speed, long-distance trips significantly slower than ICEVs because of charging needs. Current BEVs have an average battery capacity of 50 kWh and an average maximal charging power of 95 kW. So, if a driver keeps its battery state of charge between 10 and 80%, the average BEV can drive for 55 min at 130 km/h and be recharged in about 27 min.

There are also travel time inequalities among BEVs. For all trips simulated, the average travel time is 1h58 with average BEVs, whereas it is 1h43 with high-end BEVs. In the future, travel times should decrease considering technological evolutions; the average travel time should go from 1h58 to 1h48 at best. However, this prospective value is still way higher than the one obtained for ICEVs, estimated at 1h33 if their users do 20 min breaks every 2h drive. The 2030 high-end BEV using 350 kW infrastructures could reach a 1h32 average.

4.2 Users' behaviour analysis

The influence of user behaviour can be assessed for different input parameters. The following analyses are based on the driving speed choice and the charging management.

The driving speed has a variable influence over the average travel time depending on the BEV model. Average travel times are 1h58 or 2h03 for the average BEV driven at 130 km/h or 110 km/h respectively, whereas they are 1h43 or 1h52 for the high-end BEV driven at 130 km/h or 110 km/h, respectively. So, for the average BEV user, driving slower does not significantly affect its overall travel time. However, it reduces electricity consumption by 22 % and thus charging cost. Nevertheless, this strategy has the disadvantage of reducing the resting time at charging stations by a third, whereas the driving time increases.

BEV users may consider performing partial charges during long-distance trips to save time overall and reduce infrastructure occupancy. Indeed, for most BEVs performing a 175 kW charge, charging power decreases slowly after reaching 30 % of the state of charge and considerably after 80 %. So, stopping charges at 80 % instead of 100 % reduces the average travel time from 2h07 to 1h58 and the required number of charging points on the highway by 24 %.

4.3 Environment assessment of the BEV mobility on the highway

Potential environmental impacts were assessed for the BEV traffic on the highway, and the results are presented in Figure 2. Consistently with the literature, batteries are a significant source of environmental impacts. The will to develop high-capacity batteries comes from long-distance trips, so the mastery of battery life cycle impacts is a priority, especially if the strategy is to provide even larger batteries.

Then, electricity consumption is a significant cause of environmental impacts if an average European electricity mix is considered. This tendency is lower if a French mix is used for assessing impacts. BEV usage is globally more relevant when the electricity mix has low fossil fuel sources. So, the rise of BEVs should be paired with strong electricity plans to reduce carbon intensity and enhance BEV's positive effects.

Moreover, reducing driving speed on highways influences electricity consumption and the related impacts, even though this effect depends on the electricity mix. If all users drive at 110 instead of 130 km/h, global warming potential is reduced by 13 % with the EU-28 mix, or 7 % with the French mix.

Finally, the results suggest that infrastructures are a minor impact source. However, only the material supply impacts have been assessed, so those related to manufacturing, distribution, installation, maintenance, and end-of-life are not computed.

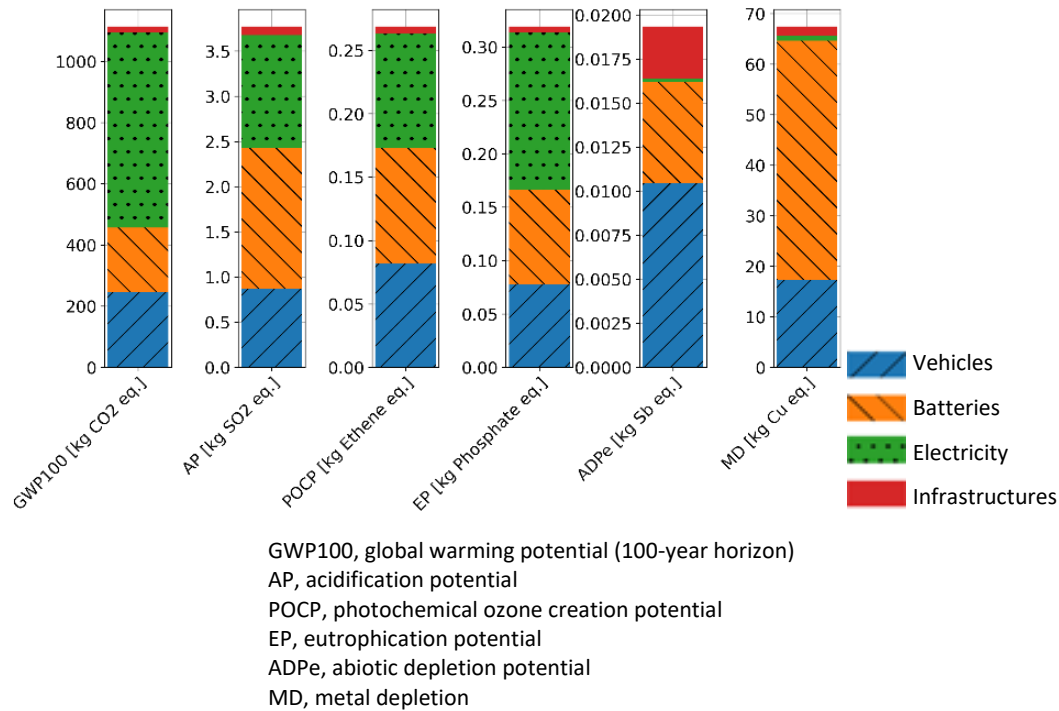


Figure 2 : Hourly average of the environmental impacts caused by BEVs circulating on the highway in 2024, including car usage, electricity consumption (EU-28 mix), and material supply for charging infrastructures (driving speed: 130 km/h, maximal state of charge: 80 %).

5 Discussion and final conclusion

This paper aims to provide multi-perspective recommendations to enhance the potential of BEV deployment. It deals with design for electromobility and sustainability: it promotes the assessment of environmental impacts and the consideration of user behaviour and BEV diversity. Indeed, we identified significant effects that only appear when these aspects are addressed. The case study focuses on long-distance trips on a highway because they are a barrier to BEV adoption. The analysis of simulation results enabled the drawing of some general recommendations for electromobility designers.

First, real-world traffic data are necessary to make recommendations for a mobility system, but they often need to be completed or adapted. The method to calculate origin-destination flows from traffic measures is helpful to determine trip lengths and deduce charging needs. An additional traffic analysis highlighted that the reduction of peak traffic is a solution to lower infrastructure needs because traffic during summer weekends is about five times higher than the yearly average. Moreover, the diversity of the initial states of charge of the vehicles entering the highway should be considered to get realistic distributions of charging. But, the data does not provide information about the parts of the trips done outside the road. So, considering the anterior battery usage to determine

the initial state of charge diversity has been difficult. More broadly, there is also a lack of data about the state of charge management, including range anxiety.

Moreover, the methodological contributions of the article have provided insights about BEV deployment. Comparing ICEVs and BEVs from different ranges highlighted significant travel time differences. So, the rise of BEVs may create a mobility inequality between those that can afford brand new expensive BEV models and those that use old lower-end models. To some extent, reducing the effective driving speed can mitigate this effect. Also, an innovative method to compute charging power according to the BEV model and its current state of charge has been helpful to analyse the influence of charging frequency over the mobility system performances.

However, this paper lacks a complete sensitivity analysis to strengthen its results because the study only targets some specific input parameters. It also does not include an uncertainty analysis. The highest sources of uncertainties are the traffic analysis results (e.g. the peak traffic value), the vehicle consumption and the prospective of technological evolutions, the battery management by users, and the life cycle environmental data, notably for charging stations.

Furthermore, although electromobility is generally presented as a promising solution to tackle environmental issues, mobility studies usually do not characterize the environmental performances of electric vehicles or services. Life cycle assessment can be performed to grasp the magnitude of impacts, identify the most significant ones, and determine actions to reduce them. This paper identified that electric consumption and battery usage were important sources of impacts for long-distance mobility. The reduction of fossil sources in electric mixes and the good management of the battery life cycle could enhance BEV environmental benefits. A limit of the study is about fast chargers that might be a source of significant impacts; however the authors found insufficient information to characterise their life cycle inventory.

Finally, a dichotomy was identified between the will to reduce BEV environmental impacts and the objective to make BEVs credible passenger cars for long trips. The potential to reduce transport impacts through electrification is clear. However, developing powerful batteries and fast charging stations decreases this potential while they only are necessary for long trips that represent a minor usage for a common driver. In the short term, the bigger the size of affordable batteries, the better the acceptance of BEVs. So, increasing battery size seems to be the current objective to enhance greenhouse gas reduction, among others. However, in the long term, dimensioning BEVs according to the maximal need through powerful batteries may not be sustainable. It appears that the current usages of long-distance mobility might have to be reconsidered depending on future technological potentials.

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