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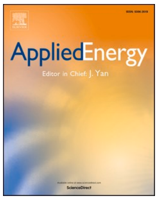

Levelized cost of driving for medium and heavy-duty battery electric trucks

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HIGHLIGHTS

- Methodology for total cost of ownership and levelized cost of driving of battery electric trucks.
- Different levels of battery and charging technology improvement.
- Different operational trip profiles (urban, short-haul or regional, long-haul).
- Designing optimum driving range or battery sizing and cost competitiveness of battery electric trucks.
- Opportunity costs for charging activities and operational time calculations.

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ABSTRACT

The total cost of ownership (TCO) of trucks is known as one of the main decision-making factors by logistics operators for adopting alternative powertrains such as battery electric trucks (BETs). In this study, we develop a very detailed levelized cost of driving (LCOD) model to analyse the TCO of BETs and conventional trucks (CTs) in

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Abbreviations: Adjustment factor for average battery capacity lost during the battery lifetime, ACL; Average driving speed, ADS; Adjustment factor for the purchase price difference between a BET and a CT (battery pack excluded), $AF_{BET/CT}$; Default ambient temperature, AT_{Def}; Annual average ambient temperature in a region, AT_{Reg}; Annual working days, AWDs; Battery electric trucks, BETs; Battery pack price, BPP; Battery pack purchase price per kWh, bpp; Battery replacement cost, BRC; Battery pack replacement numbers, BRN; Battery pack replacement time intervals, BRT; Usable state of charge (SOC) for the battery pack, BU_{SOC}; Lifetime charging cycle of the battery pack, CC; Charger equipment cost, CEC; Charger cost per hour for fast/ultra-fast chargers, chcphF; Charger cost per hour for slow chargers, chcphS; Deviation drive ratio for on-road charging activities, Chd; Charging power for "mid-shift" fast charging activities, ChPF; Charging power for "off-shift" slow charging activities, ChPS; Conventional trucks, CTs; Discount rate, d; Driver cost, DC; Driving cost per working hour, DC_h; Density of mixed conventional diesel fuel, D_{Diesel}; Down payment, DP; Loan's down payment ratio, DP_r; Daily vehicle kilometres travelled, DVKMT; Electricity/energy consumption ratio due to 1 °C change of ambient temperature, $E_{ATA(1d)}$; Energy (fuel/electricity) cost, EC; Relative powertrain energy consumption ratio of BET over CT, $E_{CT/BET}$; Electric road systems, ERS; BET's tank-to-wheel (TTW) energy consumption per km, $E_{TTW\_BET\_km}$; European Union, EU; Euro standard emission ratio, $Euro_{\alpha}$; Fuel cell electric trucks, FCETs; Fraction of time driving with free flow speed, Ff; Gross profit margin of a trucking company, GPM; Gross vehicle weight, GVW; Base vehicle insurance cost with 40 t GVW, $icbv_{km}$; Kilometre, km; Refurbishment cost factor of the battery pack, K_r; Used product discount factor for the battery pack, K_u; Load capacity of a CT, lc_{CT}; Loading and unloading activities (number of stops per daily trips), $L\&UN_{km}$; Levelized cost of driving, LCOD; Lower heating value of diesel fuel, LHV; Loan interest paid, LIP; Loan principal repayment, LPR; Total number of years for loan payments, M; Maintenance cost, MC; Maintenance cost ratio of a BET over a CT, $mcr_{BET/CT}$; Maintenance cost ratio, mcr_{km}; Medium and heavy-duty trucks, MHDTs; Time frame in year for the TCO, N; Net present value, NPV; On-road charging accessibility distance ratio based on the proportion of R, OChD; Opportunity charging potential during loading/unloading and rest time, OPC; Optimum driving ranges, ORs; Parameter value for the effect of age on RV_{CT}, PA; Price of fuel (diesel), P_D; Price of electricity, P_E; Profit lost during the charging time in a BET, PL; Parameter value for the effect of mileage on RV_{CT}, PM; Annual interest rate for the loan, r; Deviation in driving distance to access an on-road charging station, RChd; Loading/unloading time, RL&U; End of life residual value, RV; State of charge, SOC; Tonne, t; Driver's working hours of a BET, t_{BET}; Driver's working hours of a BET per km, t_{BET_km}; Time spent on deviation in the driving distance because of on-road charging, t_{Chd}; Total cost of ownership, TCO; Driver's working hours of a CT, t_{CT}; Driver's working hours of a CT per km, t_{CT_km}; Time spent driving on routes, t_{CTd}; Tonne-kilometre, tkm; Time spent on loading and unloading activities at each stop in origin(s) or destination(s), $t_{L\&U}$; Time spent on "mid-shift" fast charging activities, t_{OCh}; United Kingdom, UK; Payload capacity utilization ratio of a CT, UR; United State, US; US dollar, USD; Diesel consumption volume per km, V_{d_km}; Free flow driving speed in highways, vFf; Lifetime vehicle kilometres travelled, VKMT; Vehicle purchase price, VPP; CT purchase price with 40 t GVW, $VPP_{40T\ CT}$; Saturated driving speed in urban streets, vU; Zero-emission trucks, ZETs; Energy efficiency for the charging equipment, η_{Ch}.

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Levelized cost of driving (LCOD)
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Charging technology

medium and heavy-duty truck weight classes. The model has methodological advancements such as developing opportunity costs for charging activities, using a detailed operational time calculation, and analysing the optimum driving ranges or battery sizing. By implementing an extensive sensitivity analysis of LCOD for CTs and BETs over 43 variables, it is revealed that the key parameters such as operational driving range, battery pack price, state of charge of battery, driver cost, "mid-shift" charging power, ambient temperature, opportunity charging, and driving speed have major impacts on the cost competitiveness of BETs vs. CTs. In addition, the impact of battery and charging technology improvements as well as designing optimum driving ranges are examined in three different operational trip profiles (urban, short-haul or regional, long-haul). The result shows that: 1) BETs in urban trip profiles with the current and/or short-term battery technology might be economically viable alternatives for CTs without the help of the policy measures, 2) BETs with below 40 t gross vehicle weight and the long-term improvements in battery technology in all the operational trip profiles might be economically viable alternatives for CTs without the help of the policy measures, and 3) the implementation of policy measures affecting the relative costs of CTs and BETs and development of fast-charging facilities would be needed to support the above 40 t BETs in short-haul and long-haul trips for the current and/or short-term as well as mid-term battery technologies.

1. Introduction

Governments, businesses, and other organizations have committed to working together to enable new zero-emission medium- and heavy-duty trucks [1]. Zero-emission trucks (ZETs) mainly refer to battery electric trucks (BETs) and fuel cell electric trucks (FCETs) to replace conventional trucks (CTs) which use diesel fuel in internal combustion engines. [2].

Truck manufacturing and road freight transport are very cost-sensitive industries. The total cost of ownership (TCO) of a truck is known to be a key decision-making factor by logistics operators [2–4]. Research suggests that ZETs may already have or will in the near-term have lower TCO than CTs [5–12], especially in the best use cases. Many studies have claimed that BETs are more economically viable than FCETs [2,13,14]. Under certain circumstances (e.g., different driving cycles, trip profiles, weight classes, and accessibility to clean electricity), BETs can be the best alternative for CTs in terms of lower carbon abatement cost and TCO [8,15]. However, a few studies concluded that FCETs might be a more competitive alternative than BETs for long-haul freight transport [12,16].

Three different approaches have been used for the TCO calculations of different powertrains and fuel alternatives: 1) TCO without the net present value (NPV) [5,17,18], 2) TCO based on NPV [6,7,11,19–21], and 3) TCO and levelized cost of driving (LCOD) based on NPV [10,16]. The last approach for TCO calculation a valid option for medium and heavy-duty trucks (MHDTs) to evaluate and present the levelized and discounted cost elements per kilometre (km) and tonne-kilometre (tkm) [10,16] and was also used in this work.

Different charging facilities have been considered for BETs such as charging stations, battery swapping stations, and electric road systems. Among all the possible charging solutions to date, plug-in charging stations with a manual connector might be seen as the main option for BETs because of lower investment cost and flexibility in route planning. However, the cost of the time spent on charging stations might become economically and operationally unviable for some trip profiles with high daily mileages and large battery sizes. The current trend in charging technology development is towards elevated powers up to 1 MW and beyond to enable fast (20–45 min) charging and taking into account increased battery sizes of HD electric vehicles. A new standard for Megawatt Charging System is being developed to match the foreseen needs of BETs [22,23]. Moreover, optimum cost-efficient battery sizing should be considered to match the operational use case requirements, based on key parameters such as the different levels of battery technology and charger specifications for different weight classes of MHDTs in different trip profiles.

Developing a parametrized model for TCO calculation of BETs that is more detailed than those used in previous studies might be beneficial in different ways: 1) It improves the results of decision choice models used in the strategic assessment models with techno-economic approaches [24–26], 2) It provides a clearer picture of the key cost elements of the BET fleets operation for the logistics operators, and 3) It helps the logistics professional and researchers to better understand the opportunities and limitations in BETs in different categories (e.g., trip profiles, battery technologies). Such a detailed parametrized model should include parameters such as costs for charging activities, volume lost, energy efficiency, energy consumption, and battery size or driving range. In this study, we aim to develop a TCO model for BETs and CTs with an LCOD approach to cover all the key parameters. Therefore, we seek answers to the following research questions:

1. What are the key parameters in levelized cost of driving calculations for battery electric trucks and conventional trucks?
2. How do different battery and charger specifications affect cost efficient or optimum driving ranges (ORs) of battery electric trucks in different trip profiles?

In this study, we define the OR as the operational driving range (mostly linked with battery capacity) that results in the lowest LCOD for a BET for a given infrastructure implementation and charging strategy. The study focuses on medium-duty trucks and heavy-duty trucks referring to the weight classification of the gross vehicle weight (GVW) ranges within 4.5 t – 11.7 t and above 11.7 t, respectively. This study analyses the impact of potential techno-economic developments on the competitiveness of BETs at a global level. However, many different techno-economic parameters and assumptions are assumed based on the research studies conducted in Europe and United States. The study does not assess the impact of policy measures (e.g., road tolls, and carbon pricing) in detail because of the following reasons: First, the focus of this study is on the analysis of the TCO of BETs as it depends on battery and charging technology improvement. Second, the policy measures and implementations vary widely in different regions and countries [6,7]. Finally, strategic assessment [24,26–28] is a more appropriate tool to evaluate the policy measures from perspectives such as economic, environmental, and energy.

2. Literature review

There is a growing body of literature on BET application on road freight transport focusing on the technical aspect in previous years. Also, the TCO analysis of BETs has gained attention in recent years. Our focus is on the research published during the 2020s because of the rapid technological development of BETs. We identified 21 research studies including research papers and technical reports in the years 2020–2022. Around half of these research studies were published only in 2022. Table A1 in Appendix A presents a summary of the literature and highlights some important items of TCO for BETs, specifically: the opportunity cost of time spent on refuelling/recharging, battery technology developments, driving cycles and operational trip profiles, driving range or battery size optimization, and the models that include detailed delivery parameters based on origin-destination flow and travel routing. In the following paragraphs, first, we highlight the scope, methodology, and result of these studies, in the light of our research questions. Then, we identify and discuss the research gaps in the literature at the end of this section.

2.1. Literature review for the first research question

Searching for the responses to the first research question, we found the following recent studies discussing key parameters of LCOD. Different levels of detail in the calculation of LCOD and/or TCO in the research resulted in some similarities and differences in their methodologies, analyses, and conclusions. Papers we found classified different cost elements as capital and operating expenses [7,12,21,29], overhead cost [12], time-dependent cost [12], and distance-dependent cost [7,21].

A few papers [7,9,29,30] discussed the impact of different policy measures (e.g., different forms of taxation such as the tax on fuel or electricity, road tolls, and carbon pricing). Basma et al. [7] discussed the impact of different policy measures and financial incentives on the TCO of the tractor-trailer in 7 different European countries. They were optimistic that a combination of all policy measures including purchase incentives, emission trading system, and road tolls may lead to a lower TCO for a new BET compared to a CT. Noll et al. [29] also provided a more detailed analysis of the policy measures. They proposed that policymakers have to deal with operating cost parameters (e.g., tolls and fuel costs) before capital cost parameters (e.g., subsidies on BET purchase) to improve the competitiveness of BETs. However, Hovi et al. [9] highlighted that the policy measure impact for TCO parity of BETs over CTs could be very low (around 14% of CT TCO) compared to the investment cost including BET and battery purchase price and charging infrastructure cost (around 48% of CT TCO).

Multiple papers investigated the impact of more detailed TCO analysis regarding BET technology (e.g., energy efficiency, charging power, battery characteristics):

Burke and Sinha [8] emphasized the role of initial purchase cost (i.e., battery cost) and operating cost (i.e., electricity cost) on the cost competitiveness of BET technologies and different weight classes based on a simplified TCO calculation. They concluded that BETs will be competitive if the battery cost is 70–100 $/kWh and the electricity price is 0.10 $/kWh. Ghandriz et al. [19] discussed cost reduction potential by using driving automation systems. They highlighted the role of driver cost, battery cost, and charging infrastructure costs as the most important cost elements in the TCO analysis of heavy-duty BETs.

Nykvist and Olsson [17] stated that even by using an ultra-fast charger (1 MW charger) the most significant cost parameters per km in BETs, especially in the current battery technology scenarios, are the battery cost and the insurance. They considered the impact of charging time on the insurance cost and labour cost as well as the opportunity cost of capital during charging for BETs. However, these extra costs were estimated to be very low because of the short charging time of using the 1 MW charger. Burnham et al. [16] and Hunter et al. [10] highlighted the role of driver's cost for charging BETs in different weight classes and trip profiles. They also considered the impacts of different working shifts (single and multi-shift) as well as weight and volume-limited scenarios on the TCO analysis.

Phadke et al. [18] analysed different battery price specifications for regional-haul and long-haul road freight transport in the US. They showed that the largest cost parameters for BETs are battery and energy costs. Hao et al. [21] added intangible cost in their TCO analysis for different powertrain alternatives over a wide range of vehicle weight classes in China. The intangible cost in this research is a sum-up of the range anxiety cost, alternative vehicle cost (applicable when the BET cannot meet daily travel needs), and repower annoyance cost (e.g., including driver's working time for waiting in a charger station and searching for a free charger station) components.

ITF [11] published a report of TCO analysis for different powertrains (including BET and FCET) within 12 groups of trucks (classified based on combinations of trip profiles and weight classes) in Europe. This study concluded that purchase price reduction as well as further improvements in energy efficiency and battery energy density may make BETs cost competitive with CTs. Gunawan and Monaghan [15] evaluated the total cost of carbon abatement (TCA) for different powertrains alternatives (including BET and FCET) of a truck fleet with a 32 t GVW for mining application in a case study in Ireland. They concluded that the energy cost, vehicle, and charging infrastructure are the most significant cost parameters in the TCO analysis. Noll et al. [29] focused on improving charger infrastructure costs in the cost parity of BETs over CTs. They highlighted that energy cost and energy storage cost had the largest impacts on the cost competitiveness of BETs in different countries in Europe. However, the change in energy costs and financial incentives (tolls and subsidies) resulted in different levels of competitiveness for BETs in different European countries.

Tol et al. [2] evaluated the techno-economic uptake potential of BETs and FCETs for different vehicle segments in the European Union and the United Kingdom. Battery cost and purchase cost (excluding battery) reduction in future are the main drivers of BET cost competitiveness in this study. Zhang et al. [14] evaluated the emission and TCO of different powertrain alternatives including BET for a heavy-duty truck with 29.5 t GVW in China. They illustrated that fast charging takes a small proportion of the TCO; but in general, using fast chargers increases TCO because of lower battery lifetime, less charging cycles and/or higher electricity prices.

Regarding the above paragraphs, the answers to the first research question vary widely in the existing literature. Such variations are because of different background assumptions and calculations methods in the existing literature: 1) the papers used various methodologies for TCO or LCOD calculation with different levels of detail, 2) the geographical scopes and fiscal policies vary in the papers, 3) the papers implemented various levels of techno-economic development (e.g., for battery specifications and charger power), and 4) the operational trip profile specifications vary in the papers.

2.2. Literature review for the second research question

Regarding the second research question, we found the following recent studies analysing the battery and charger specification impact on the optimum driving ranges (ORs) of BETs in different trip profiles. Only three research were found analysing and discussing ORs and battery sizing based on the battery and charger specifications as well as trip profiles:

Baek et al. [31] evaluated the impact of optimum battery sizing on the profit changes by battery electric trucks in the urban area. They built their framework based on parameters such as vehicle powertrain efficiency, battery efficiency and degradation, and delivery requests. Mauler et al. [12] analysed TCO for different powertrain alternatives (including BET and FCET) of a 40 t GVW truck for current and future scenarios of battery technology improvements in the United States. They concluded that the most important parameter in the analysis was energy price. They also recommended R&D topics to improve the cost competitiveness of BETs by focusing on the potential improvement of overall energy efficiency as well as capital cost reduction.

Zhu et al. [32] evaluated the TCO of a 49 t BET for different charging powers (slow and fast) and battery-swapping solutions in China. They implemented sensitivity analysis of the OR based on different parameters such as payload capacity utilization rate and average speed of trucks for different charging specifications. They presented the investment cost of "supercharging" (with a charging rate of 4C) would be around 60% higher than the fast charging (with a charging rate of 1C). However, they illustrated that the difference in levelized cost would take a very small proportion (less than 3%) of the TCO of a BET.

In addition to the above references, there are many papers [2,6,8,10,11,16,19,20,31] that did not analyse the ORs or optimum battery sizing but examined the TCO of different driving ranges over different battery specifications, charger specifications, and/or trip profiles.

2.3. *The identified research gaps in the literature*

The following research gaps are identified in the literature:

- Although the opportunity cost for charging activities is calculated in a few recent studies [10,11,16,17,19,21], only one study [12] analysed the profit lost as the value of time spent on terminal and "mid-shift" fast charging [23] with different charging powers and battery specifications.
- In a few studies [11,12], the mandatory break-time is one of the main assumptions to estimate driving range by a BET. These studies assumed that recharging activities happen during break-time, and either the driver would get paid [12] or would not get paid [11] for recharging activities. However, no study was found to analyse the impact of uncertainty in opportunity charging during loading/unloading and rest time on TCO or LCOD of BETs.
- Only one study [19] was found to analyse the sensitivity of TCO over detailed operational parameters (e.g., time spent on loading/unloading, "mid-shift" charging time). However, no research was found to evaluate the TCO of BETs based on such detailed operational time calculation over different levels of battery and charger technology improvement.
- Most studies consider a set of predefined BET's driving ranges for different driving cycles, vehicle weight class, and operational trip profiles (e.g., urban vs. short haul and long haul) [5,7,16–18,20]. However, no research was found using a dynamic approach for analysing the ORs or optimum battery sizing over different driving cycles, GVWs, and operational trip profiles based on different battery and charger specifications.

To fill the identified gaps in the literature and answer the research questions presented in Section 1, Section 3 presents the methodology and data analysis process. Section 4 presents the results and Section 5 discusses the results. Finally, Section 6 presents the general conclusions of this study.

3. Data and methods

The TCO of a CT and BET include recurring cost elements and one-time cost elements. The LCOD of each powertrain technology might reflect a better picture of the TCO of different cost elements per km and tkm. The general parameters used in TCO and LCOD calculations are the time frame in year for the TCO (N), discount rate (d), payload capacity utilization ratio (UR), and gross vehicle weight. The cost unit in this study is the US dollar (USD) which can be converted to Euro by applying the average exchange rate in 2022 (1.054 USD) [33]. We developed programming codes in R to cover all the following calculation steps and the codes are available at GitHub [34].

In this study, we assumed that the same payload capacity in a CT would be delivered by a BET with a different curb weight and GVW (because of powertrain difference and battery weight). We calculate the impact of curb weight change of BETs vs. CTs on energy consumption of BETs. To simplify the visualizations in the analysis, we only represent GVW of CT in the results.

The main equations for TCO and LCOD (Eq. (1–8)) are represented in Section 3.1 and Section 3.2. The cost equations for all the identified elements are represented by captions starting with "A1" in Section 2.1 in Appendix A. More detailed cost equations are represented by captions starting with "A2" in Section 2.2 in Appendix A. All the variables used in the equations are defined in Section 2.3 in Appendix A. We also provided a graphical representation of the model structure for BETs (see Fig. A1-A8 in Section 2.4 in Appendix A). The following sections summarize the methodology used in this study.

3.1. *LCOD for conventional trucks (CTs)*

The main equations for LCOD of a CT are represented by Eq. (1–4). The TCO, cash flow for different years, and LCOD (per km and tkm) are specified based on 8 different cost elements in the equations. The cost elements are the down payment (DP), loan principal repayment (LPR) and loan interest paid (LIP) for purchasing a CT, insurance cost (IC), energy (fuel) cost (EC), maintenance cost (MC), driver cost (DC) and the CT's end of life residual value (RV).

$$TCO_{CT(j)} = \sum\nolimits_{i=0}^{N} \frac{C_{CT(j,i)}}{(1+d)^{i}}, \tag{1}$$

$$C_{CT(i)} = \begin{cases} DP_{CT}, & i = 0 \\ LPR_{CT(i)} + LIP_{CT(i)} + IC_{CT} + EC_{CT} + MC_{CT} + DC_{CT}, 1 \leq & i \leq M \\ IC_{CT} + FC_{CT} + MC_{CT} + DC_{CT}, M < & i < N \\ \quad -RV_{CT}, i = N & \end{cases} \tag{2}$$

$$LCOD_{CT\_km(j)} = \sum\nolimits_{j} \left(TCO_{CT(j)} \Big/ \sum\nolimits_{i=1}^{N} \frac{VKMT_{i}}{(1+d)^{i}} \right) \tag{3}$$

$$LCOD_{CT\_tkm(j)} = \sum\nolimits_{j} \left(TCO_{CT(j)} \Big/ \sum\nolimits_{i=1}^{N} \frac{VKMT_{i} \times lc_{CT} \times UR}{(1+d)^{i}} \right) \tag{4}$$

Where j index is the cost elements, list of individual cost elements of a CT are j(1:8) = {DP, LPR, LIP, IC, EC, MC, DC, RV}, i index is the year of operation, M index is the total number of years for loan payments, N is the time frame for TCO analysis, $TCO_{CT(j)}$ is the TCO of the cost element j, $C_{CT(i)}$ is the cash flow of the cost elements in year i, $LCOD_{CT\_km(j)}$ is the LCOD of the cost element j per kilometre, $LCOD_{CT\_tkm(j)}$ is the LCOD of the cost element j per tonne-kilometre, $VKMT_i$ is the vehicle kilometres travelled in year i, d is the discount rate, lc_{CT} is the load capacity, UR is the payload capacity utilization ratio. Following sections provide more details of the cost elements including all the variables and equations for LCOD of a CT.

3.1.1. *Vehicle*

The cost related to buying a CT is formulated via the first three cost elements (DP_{CT}, LPR_{CT}, and LIP_{CT}) by using an amortized loan Eq. [35]. DP_{CT} is paid in advance in the year 0 and loan costs (LPR_{CT} and LIP_{CT}) are paid according to the loan repayment plan (see Eq. (A1.1c-A1.3c)). Variables in these cost elements are the vehicle purchase price (VPP_{CT}), loan's down payment ratio (DP_r), annual interest rate for the loan (r), and total number of years for the loan payments (M). VPP_{CT} is estimated for different GVWs regardless of the lorry type (e.g., rigid, tractor-trailer, etc.). The equation Eq. (A2.48) used for VPP_{CT} is a regression model fitted by Nykvist and Olsson on available data for the vehicle price at a global level [17].

3.1.2. *Insurance*

The insurance cost (IC_{CT}) is a recurring cost and is paid annually for the life span of a truck. The equations relevant to IC_{CT} are Eq. (A1.4c, A2.22). These equations are developed by referencing a 40 t GVW CT and calculating the other weight class based on relative purchase price assumptions from [36]. Variables in IC_{CT} are VPP_{CT}, CT purchase price with 40 t GVW ($VPP_{40T\ CT}$) and base vehicle insurance cost with 40 t GVW ($icbv_{km}$).

3.1.3. *Fuel*

The energy cost (EC_{CT}) is a recurring cost based on driving mileage. The equations for estimating EC_{CT} are Eq. (A1.5c, A2.3, A2.18, A2.25, A2.42-A2.44). The fuel consumption equations in this study are based on regression models from a real-world dataset for highway and urban freight transport by a wide range of GVWs and lorry types (e.g., rigid, tractor-trailer, etc.) [37,38]. Variables in EC_{CT} are the price of fuel (diesel) (P_D), GVW, free flow driving speed in highways (vFf), fraction of time driving with free flow speed (Ff), Euro standard emission ratio ($Euro_\alpha$), and UR.

3.1.4. Maintenance

The maintenance cost (MC_{CT}) is a recurring cost based on driving mileage. The equations for estimating MC_{CT} are Eq. (A1.6c, A2.29). The main variable in this cost parameter is the maintenance cost ratio (mcr_{km}) formulated based on a CT purchase price according to [39].

3.1.5. Driver

The driver cost (DC_{CT}) is a recurring cost based on the driver's working hours. The driver's working hours (t_{CT}) include time spent on loading and unloading activities at each stop in origin(s) or destination (s) ($t_{L\&U}$) and time spent driving on routes (t_{CTd}). Since the refuelling of a diesel tank for a long-haul CT may take up to a few minutes, we skip the unnecessary complex calculations for time spent on refuelling activities in a CT. The equations for estimating the DC_{CT} are Eq. (A1.7c, A2.2, A2.34-A2.35, A2.38). The variables in DC_{CT} are the driving cost per working hour (DC_h), daily vehicle kilometres travelled (DVKMT), loading/unloading time (RL&U), loading and unloading activities (number of stops per daily trips) ($L\&UN_{km}$), vFf, saturated driving speed in urban streets (vU), and Ff.

3.1.6. End of life residual value of vehicle

The residual value (RV_{CT}) in year N is considered as an income (negative cost) in cash flow. The equations for estimating RV_{CT} are Eq. (A1.8c, A2.48). Eq. (A1.8c) is developed by [16,40] based on the CT's purchase price. Variables in RV_{CT} are parameter value for the effect of age on RV_{CT} (PA), parameter value for the effect of mileage on RV_{CT} (PM), N, and lifetime vehicle kilometres travelled (VKMT).

3.2. LCOD for battery electric trucks (BETs)

The main equations for LCOD of a BET are represented in equations Eq. (5–8). The TCO, cash flow for different years, and LCOD (per km and tkm) are specified based on 11 different cost elements in the equations. The cost elements are the DP for purchasing, charger equipment cost (CEC), LPR and LIP for purchasing, IC, energy (electricity) cost (EC), MC, DC, battery replacement cost (BRC), RV, and profit lost during the charging time (PL).

$$TCO_{BET(j)} = \sum\nolimits_{i=0}^{N} \frac{C_{BET(j,i)}}{(1+d)^i} \tag{5}$$

$$C_{BET\ (i)} = \begin{cases} DP_{BET} + CEC, & i = 0 \\ LPR_{BET(i)} + LIP_{BET(i)} + IC_{BET} + EC_{BET} + MC_{BET} + DC_{BET} + PL_{BET},\ 1 \leq & i \leq M \\ IC_{BET} + FC_{BET} + MC_{BET} + DC_{BET} + PL_{BET}, M < & i < N \\ \qquad -RV_{BET} + PL_{BET}, i = N & \end{cases} \text{, BRC will be added to the arguments BRN times in time intervals of BRT in N years} \tag{6}$$

$$LCOD_{BET_{km}(j)} = \sum\nolimits_{j} \left(TCO_{BET(j)} \middle/ \sum\nolimits_{i=1}^{N} \frac{VKMT_i \times (1 + Chd)}{(1+d)^i} \right) \tag{7}$$

$$LCOD_{BET_{tkm}(j)} = \sum\nolimits_{j} \left(TCO_{BET(j)} \middle/ \sum\nolimits_{i=1}^{N} \frac{VKMT_i \times (1 + Chd) \times lc_{CT} \times UR}{(1+d)^i} \right) \tag{8}$$

Where j index is the cost elements, list of individual cost elements of a BET are j(1:11) = {DP, CEC, LPR, LIP, IC, EC, MC, DC, BRC, RV, PL}, i index is the year of operation, M index is the total number of years for loan payments, N is the time frame for TCO analysis, $TCO_{BET(j)}$ is the TCO of the cost element j, $C_{BET(i)}$ is the cash flow of the cost elements in year i, $LCOD_{BET\_km(j)}$ is the LCOD of the cost element j per kilometre, $LCOD_{BET\_tkm(j)}$ is the LCOD of the cost element j per tonne-kilometre, $VKMT_i$ is the vehicle kilometres travelled in year i, d is the discount rate, lc_{CT} is the load capacity for a CT, UR is the payload capacity utilization ratio of a CT, BRN is times in time intervals of BRT in N years. BRN is the battery pack replacement numbers, and BRT is the battery pack replacement time intervals in year. Following sections provide more details of the cost elements including all the variables and equations for LCOD of a BET.

3.2.1. Vehicle

The cost related to buying a BET is formulated via the first three cost elements (DP_{BET}, LPR_{BET}, and LIP_{BET}) by using an amortized loan equation [35]. DP_{BET} is paid in advance in the year 0 and two other costs (LPR_{BET} and LIP_{BET}) are paid according to the loan repayment plan (see Eq. (A1.1b, A1.3b-A1.4b)). Variables in these cost elements are the VPP of a BET (VPP_{BET}), DP_r, r, and M. The estimation of VPP_{BET} is associated with a high uncertainty level because of variations in the battery pack price (BPP) and battery specifications. Therefore, Eq. (A2.47) is developed to reflect different battery pack settings (see Eq. (A2.3-A2.4)) for different operational driving ranges. The extended equations also include the same equations used for vehicle price Eq. (A2.48), and tank-to-wheel (TTW) energy consumption per km ($E_{TTW\_BET\_km}$) Eq. (A2.1-A2.3, A2.10-A2.16, A2.25, A2.42-A2.44, A2.49).

Since the battery pack capacity is an unknown variable based on an operational driving range and involved with both BPP and energy consumption equations, an iterative loop is specified in the programming codes [34] with a convergence satisfaction constraint ($\Delta BPC < 1kWh$) to estimate the battery pack capacity required for the given operational driving range. The variables involved in the estimation of $E_{TTW\_BET\_km}$ are GVW of CT, operational driving range, relative powertrain energy consumption ratio of BET over CT ($E_{CT/BET}$), usable state of charge (SOC) for the battery pack (BU_{SOC}), adjustment factor for average battery capacity lost during the battery lifetime (ACL), electricity/energy consumption ratio due to 1 °C change of ambient temperature ($E_{ATA(1d)}$), default ambient temperature (AT_{Def}), annual average ambient temperature in a region (AT_{Reg}), energy efficiency for the charging equipment (η_{Ch}), density of mixed conventional diesel fuel (D_{Diesel}), lower heating value of diesel fuel (LHV), gravimetric density or specific energy of battery pack (GDBP), vFf, vU, Ff, UR, and $Euro_\alpha$. In addition to the above variables involved in $E_{TTW\_BET\_km}$, variables such as adjustment factor for the purchase price difference between a BET and a CT (battery pack excluded) ($AF_{BET/CT}$) and battery pack purchase price per kWh (bpp) are needed to estimate the costs related to the purchase of a BET.

3.2.2. *Charger infrastructure*

The CEC is calculated based on the levelized cost of using a charger. Since the major part of the CEC is considered as an investment to buy and install the charger infrastructure by the fleet or truck owner [2,17,41], we assumed CEC as a one-time paid cost in year 0 by the fleet owner. This means that each BET is assumed to have a dedicated slow charger or charging point at the depot hub for "off-shift" charging activities [23]. The main equation for estimating CEC, Eq. (A1.2b), is developed to consider one full charge by slow chargers during "off-shift" (e.g., for resting at night or at long stops) Eq. (A2.8) and the rest of the requirements for driving a BET by "mid-shift" fast charging activities [23] Eq. (A2.7, A2.36). In addition to the variables mentioned in the previous paragraph for estimating $E_{TTW\_BET\_km}$, variables such as charging power for "mid-shift" fast charging activities (ChPF), charging power for "off-shift" slow charging activities (ChPS), charger cost per hour for fast/ultra-fast chargers (chcphF), and charger cost per hour for slow chargers (chcphS) are needed for estimating the CEC.

3.2.3. *Insurance*

The insurance cost (IC_{BET}) is a recurring cost and is paid annually for the life span of a truck. The main equations relevant to IC_{BET} are Eq. (A1.5b, A2.21) and the main variables are the $VPP_{40T\ CT}$ and $icbv_{km}$. Extended equations are also needed for estimating IC_{BET} based on other cost elements such as the VPP_{BET}, $E_{TTW\_BET\_km}$, and t_{CT}. Eq. (A2.33, A2.35, A2.37-A2.39) are needed to calculate the driver's working hours (t_{BET}) for estimating IC_{BET}. The variables such as the deviation in driving distance to access an on-road charging station (RChd), opportunity charging potential during loading/unloading and rest time (OPC), on-road charging accessibility distance ratio based on the proportion of operational driving range (OChD), and ChPF are required for estimating t_{BET}.

3.2.4. *Electricity*

The energy cost (EC_{BET}) is a recurring cost based on driving mileage. The main equations for EC_{BET} are Eq. (A1.6b, A2.17). The extended equations include all the equations for the $E_{TTW\_BET\_km}$ estimation based on the previous paragraphs. In addition to the variables used in the calculation of $E_{TTW\_BET\_km}$, the main variable for EC_{BET} is the price of electricity (P_E).

3.2.5. *Maintenance*

The maintenance cost (MC_{BET}) is a recurring cost based on driving mileage. The equations for estimating the MC_{BET} are Eq. (A1.7b, A2.28-A2.29). The main variables in this cost parameter are the mcr_{km} and maintenance cost ratio of a BET over a CT ($mcr_{BET/CT}$).

3.2.6. *Driver*

The driver cost (DC_{BET}) is a recurring cost based on the driver's working hours. The t_{BET} includes $t_{L\&U}$, t_{CTd}, time spent on deviation in the driving distance because of on-road charging (t_{Chd}), and time spent on "mid-shift" fast charging activities (t_{OCh}). The main equation for the calculation of DC_{BET} is Eq. (A1.8b) and the main cost parameter is DC_h. As it is described in the previous paragraphs, in addition to the equations used for estimating the DC_{CT}, the extended equations for estimating the t_{BET} are Eq. (A2.33, A2.35, A2.37-A2.39). The relevant variables are the OPC, RChd, OChD, ChPF, DC_h, DVKMT, RL&U, $L\&UN_{km}$, vFf, vU, and Ff.

3.2.7. *Battery replacement*

Battery replacement cost is a recurring cost that might happen multiple times during N years. Variables such as battery pack replacement numbers (BRN) and battery pack replacement time intervals (BRT) in N year time frame need to be calculated for the cash flow. The main equations for estimating the BRC are Eq. (A1.9b, A2.5-A2.6, A2.9, A2.23, A2.32, A2.45). In addition to these equations, extended equations such as Eq. (A2.3-A2.4) are required for estimating $E_{TTW\_BET\_km}$ and BPP. The given equations for the BRC also include the residual value income (negative cost) of reselling the old battery pack. In addition to the variables used in equations for estimating the $E_{TTW\_BET\_km}$, other variables such as the refurbishment cost factor of the battery pack (K_r), used product discount factor for the battery pack (K_u), lifetime charging cycle of the battery pack (CC), ACL, bpp, BU_{SOC}, RChd, and OChD are needed to estimate BRC. The cyclic lifetime assessment of the battery system used a simplified approach in this paper, assuming a cycle life as given in Appendix Table A6.

The battery energy storage system and the cyclic lifetime assessment of the battery system used a simplified approach in this paper, very similar to the previous research [10,16,17]. The most important parameters in the approach are the usable state of charge (SOC) for the battery pack (BU_{SOC}), the adjustment factor for average battery capacity lost during the battery lifetime (ACL), Lifetime charging cycles of the battery pack (CC). BU_{SOC} and ACL aggregate the long-term and average impacts of depth of charge/discharge and state of charge in the battery system. However, the CC is specified based on strategic scenarios [17,42] in battery technology developments which do not consider the detailed stress factors like depth of charge/discharge and state of charge, chemistry, temperature/C-rate, or the amount of fast charging.

3.2.8. *End of life residual value of vehicle*

The residual value (RV_{BET}) in year N is considered as an income (negative cost) in cash flow. The main equations for estimating the RV_{BET} are Eq. (A1.10b, A2.5-A2.6, A2.9, A2.24, A2.30-A2.31, A2.45). In addition to the variables used for $E_{TTW\_BET\_km}$ and BPP, other variables such as PA, PM, N, operational driving range, K_r, K_u, CC, RChd, OChD, and VKMT are needed to estimate RV_{BET}.

3.2.9. *Profit lost during the charging time (PL)*

The last cost parameter for a BET is the PL which is calculated as a recurring annual cost. The main equations for estimating PL are Eq. (A1.11b, A2.19-A2.20, A2.40). Extended equations from previous paragraphs are needed to calculate TCO_{CT}, t_{BET}, and t_{CT}. In addition to the variables used in the calculation of TCO_{CT}, t_{BET}, and t_{CT}, other variables such as the gross profit margin of a trucking company (GPM), annual working days (AWDs), N, and DVKMT are needed to calculate PL.

3.3. *Methodological advancements*

3.3.1. *Opportunity costs for charging activities in BETs*

According to Mauler et al. [12], the opportunity cost in BET has two components: forgone lost capacity and lost profit for charging time. In this study, we assumed that the same payload transported by a CT can be delivered by a BET without any restriction for extra volume and weight. Lost payload capacity is a minor issue as most commodities are not weight restricted [37]. Also, according to EU directive 2015/719 (2015), the extra weight because of alternative powertrains (including BET technology) should not be penalised [43]. Therefore, there is no need to calculate the profit lost for the freight capacity lost. However, different countries might have their own restriction for maximum authorized weights and dimensions of vehicles related to road safety and infrastructure characteristics.

We assumed that the lost profit for charging time in BET has three components: 1) insurance cost for extended working hours for doing the recharging activities, 2) driver cost for extended working hours for doing recharging activities, and 3) PL or the value of time for the time spent on recharging activities. The first two items are hidden in IC_{BET} and DC_{BET} cost elements for BETs. The third item is explicitly calculated as PL during the charging time for BETs. We defined a variable (OPC) for analysing the impact of different levels of opportunity charging potential during loading/unloading and rest time on LCOD of BETs. We assumed no opportunity charging potentials during loading/unloading and rest time (OPC = 0%) as default, but also analysed the impact of full opportunity charging potential during loading/unloading and rest time (OPC = 100%).

3.3.2. Designed driving range vs. driver's mandatory rest time

A few studies [11,12] used mandatory break-time as the main criterion to design the operational driving range in BET. The choice of driving range should not be limited based on the mandatory break-time. The mandatory rest stop, for example, a 45-min rest in a 4.5 driving hour based on the EU regulation (Amendment of Regulation (EC) No 561/2006) [44] does not necessarily lead to an optimum driving range because there is a high level of uncertainty [45] to implement above schedule for different routes with different levels of charger infrastructures availability during loading/unloading and rest time.

Regarding the identified problem in the previous paragraph, the OR should be designed based on a comprehensive BET LCOD to cover all the costs (e.g., opportunity costs). In this study, we analyse the impact of OR on the BET LCOD reduction based on identified key parameters and extensive sensitivity analysis. Section 3.4 and Section 3.5 provide detailed information and assumptions for battery and charger specifications, and operational trip profiles.

3.3.3. Operational time calculations

Two series of equations are provided to estimate the driver's working time estimate per km for a BET (t_{BET_km}) and CT (t_{CT_km}). The first series of equations, represented by option 1 in Eq. (A2.9, A2.33-A2.39), provide an operational time calculation procedure based on aggregated or average values for some important parameters such as the deviation drive ratio for on-road charging activities (Chd), $L\&UN_{km}$, RL&U, DVKMT, OPC, and average driving speed (ADS). The second series of equations, represented by option 2 in Eq. (A2.9, A2.33-A2.39), is suggested as an operational time calculation procedure in a detailed model using disaggregated data based on the available road freight survey and a simulation approach for on-road charging activities in different routes. We only use the first option for the operational time calculation procedure in this study to facilitate the impact analysis of different battery and charger specifications on the TCO of BETs. By using aggregated values for Chd, $L\&UN_{km}$, RL&U, DVKMT, and ADS, we can simply conduct a sensitivity analysis of these variables on LCOD and TCO in different classifications. Section 3.5 provides more details of default values, lower and upper ranges for these variables.

3.3.4. Other assumptions

To avoid the complexity in the calculation of the TCO and LCOD for different levels of battery and charger technology improvements, we did not consider the variation of annual VKMT and different cost variables (e.g., bpp, P_E, P_D) in different ages of a BET and CT because of the following reasons: 1) Their impact on the TCO are associated with more complex time-dependent uncertainties, and 2) Calculations for the OR in this study require the assumptions of equal DVKMT in all working days. Instead, we provided an extensive sensitivity analysis for evaluating the impact of uncertainties in all the variables (including VKMT and cost variables) on TCO.

Table 1
Battery specification scenarios (BSSs).

Parameters	Battery specification scenarios (BSSs)		
	Short-term battery specification scenario (ST-BSS)	*Mid-term battery specification scenario (MT-BSS)*	*Long-term battery specification scenario (LT-BSS)*
Battery pack purchase price (bpp) (USD/kWh)	*300*	*200*	*100*
Usable state of charge for the battery pack (BU_{SOC}) (%)	*75*	*78*	*95*
Lifetime charging cycle of battery pack (CC)(cycles)	*3000*	*4500*	*6000*
Gravimetric density or specific energy of battery pack (GDBP)(Wh/kg)	*125*	*250*	*400*

3.4. Battery and charger specifications and operational trip profiles

Battery specifications in this study are customized for three different scenarios. Short-term battery specification scenario (ST-BSS) represents the technology constraints for the current and/or short-term horizon. Mid-term battery specification scenario (MT-BSS) represents the constraints for the mid-term horizon. Long-term battery specification scenario (LT-BSS) represents the constraints for the long-term horizon. The battery characteristics for ST-BSS, MT-BSS, and LT-BSS scenarios are specified based on the following variables: bpp, BU_{SOC}, CC, and GDBP (see Table 1 and also check the references in Table A6 in Section 3.1 Appendix A). It should be mentioned that the future development of batteries will not necessarily combine the performance values given in MT-BSS and LT-BSS all at the same time. In this study, the assumptions for the battery specification scenarios (BSSs) are aligned with the Strategic Research Agenda targets for MHD-BETs in Europe [42].

Table 2 presents the characteristics of four different trip profiles. Variables such as the DVKMT, vFf, vU, Ff, $L\&UN_{km}$, M, time frame for TCO analysis (N), and RL&U are specified for each operational trip profile. The aggregated trip profile aimed to provide a generic TCO / LCOD analysis and implementing sensitivity analysis over a wide range of variables in Section 4.1, Section 4.2, and Section 4.3. The next operational trip profiles (urban, short-haul or regional, and long-haul) aimed to narrow down the TCO / LCOD analysis in Section 4.4.

In this study, addition to using the slow chargers for "off-shift" slow charging, three levels of ChPF specification (200 kW, 450 kW, 1 MW) are considered to be examined associated with the different BSSs (ST-BSS, MT-BSS, and LT-BSS). Fast and ultrafast charging powers up to 500 kW are commercially available currently [46]. The megawatt ultra-fast chargers might be commercially available very soon in 2024–2025 [47,48]. Fig. 1 shows the timeline visualization and potential coverage of BSSs over the ChPF specifications and operational trip profiles.

3.5. Default values and sensitivity analysis for an aggregated trip profile

In addition to the specified values for battery and charger

Table 2
Assumptions for the operational trip profiles.

Parameters	Operational trip profile classifications			
	Aggregated [1]	*Urban* [2]	*Short-haul or Regional* [2]	*Long-haul* [2]
Daily vehicle kilometres travelled (DVKMT) (km)	*500*	*200*	*400*	*800*
Time frame for TCO analysis (N) (year)	*10*	*10*	*8*	*4*
Free flow driving speed in highways (vFf) (km/h)	*80*	*60*	*80*	*80*
Saturated driving speed in urban streets (vU) (km/h)	*20*	*20*	*20*	*20*
Fraction of time driving with free flow speed (Ff)	*0.75*	*0.5*	*0.8*	*0.95*
Loading and unloading activities per km ($L\&UN_{km}$) (1/km)	*0.06*	*0.1*	*0.01*	*0.002*
Total number of years for loan payments (M) (year)	*5*	*5*	*5*	*4*
Loading/unloading time (RL&U) (min)	*30*	*10*	*30*	*30*

[1] For more details on the variable assumptions, please check the references in Table A8 in Section 3.3 in Appendix A.

[2] For more details on the variable assumptions, please check the references in Table A7 in Section 3.2 in Appendix A.

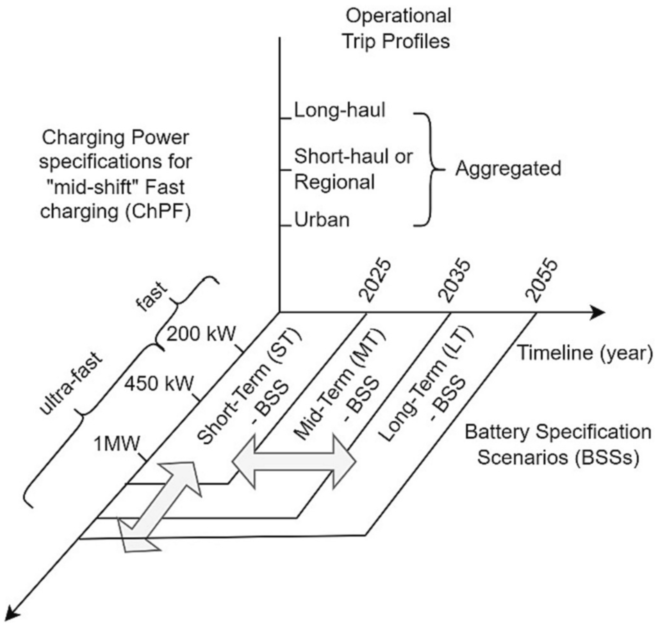

Fig. 1. The operational trip profiles, battery specification scenarios (BSSs), and charging power specifications for "mid-shift" fast charging (ChPF).

characteristics and operational trip profiles in the previous section, we set default values for the other variables based on Table A8 in Section 3.3 in Appendix A. Table A8 in Section 3.3 in Appendix A also provides 43 important variables with detailed information of their uncertainty ranges. Then, we implemented a Monte Carlo method in the programming codes [34] to reflect the impact of different variables' uncertainty on the comparative cost analysis of CT and BET. Finally, a sensitivity analysis for all the 43 variables implements uncertainties based on the lower and upper ranges defined for them.

4. Results

The following sections present the results of data analysis in this study. Section 4.1 provides a comparative LCOD of BETs and CTs for the aggregated trip profile with different battery technology and charger specifications over different GVWs. Section 4.2 presents a comparative cost structure for the aggregated trip profile with different battery technology and charger specifications over different GVWs. Section 4.3 presents sensitivity analysis and Monte Carlo simulation for a CT and BET. Finally, Section 4.4 presents the OR for the battery technology and charger specifications over different GVWs, operational trip profiles (urban, short-haul or regional, and long-haul), and other key parameters such as the average ambient temperature and opportunity charging potential.

4.1. BET to CT LCOD differences of the aggregated trip profile for various battery technology and charger specifications

Fig. 2 shows the BET to CT LCOD difference of the aggregated trip profile for three battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and "mid-shift" fast charging (ChPF) specifications (200 kW, 450 kW, and 1 MW) over different GVWs of CT. In Fig. 2, diagram A illustrates the BET to CT LCOD difference in USD per km and diagram B presents the BET to CT LCOD difference in USD per tkm. Fig. 2 illustrates that the following combinations of the battery specifications and fast-charging powers result in the lower LCOD for BETs in all GVWs: the mid-term horizon scenario (MT-BSS) for battery technology combined with 1 MW ChPF specification, the long-term scenario (LT-BSS) for battery technology characteristics combined with 450 kW and 1 MW ChPF specifications.

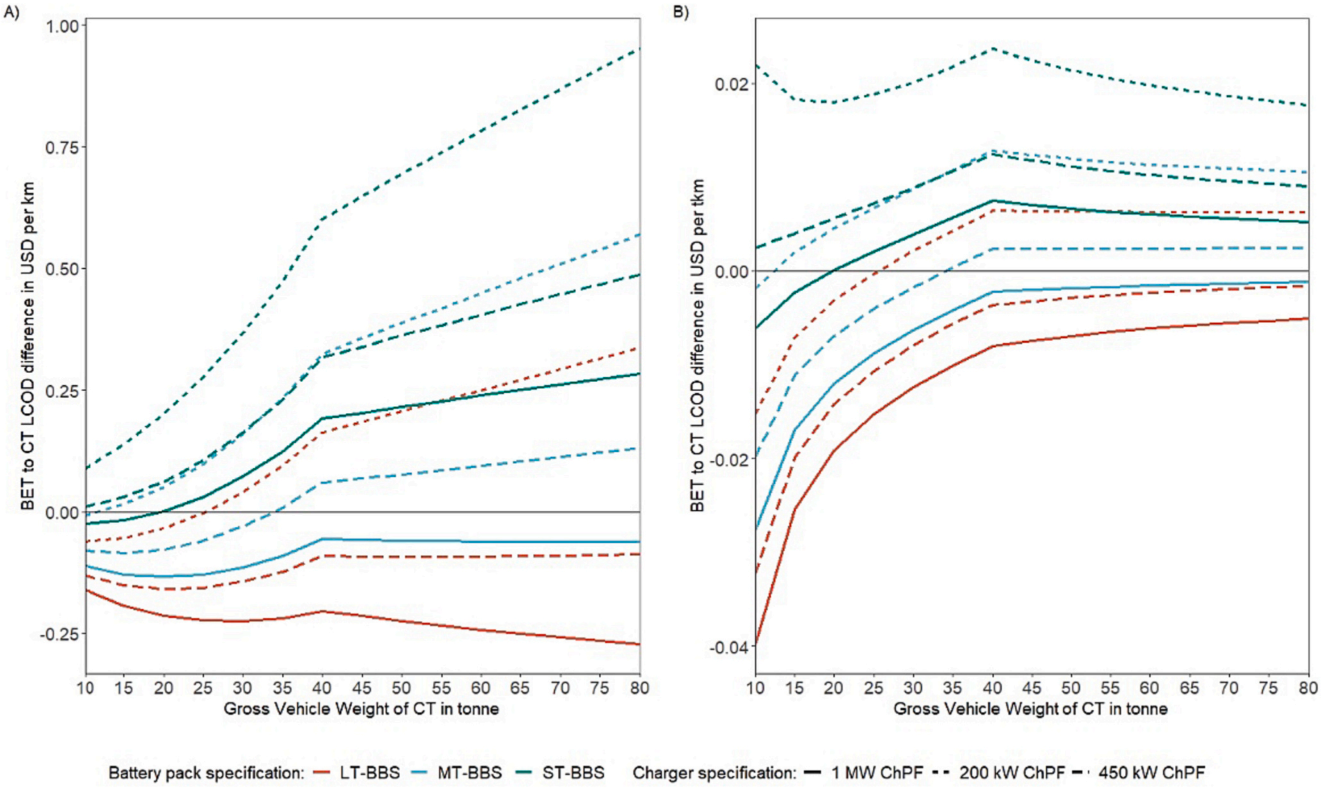

Fig. 2. BET to CT LCOD differences of the aggregated trip profile A) in USD per km and B) in USD per tkm for battery technology specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and "mid-shift" fast charging (ChPF) specifications (200 kW, 450 kW, and 1 MW) over different GVWs.

Combinations of ST-BSS with 1 MW ChPF specification, MT-BSS with 450 kW ChPF specification, and LT-BSS with 200 kW ChPF specification result in a lower LCOD in BETs with GVWs lower than 20 t. It can be seen that BETs in ST-BSS with 200 kW and 450 kW ChPF specifications are not a cost-competitive alternative for CTs for all the GVWs over 10 t. The variation of BET to CT LCOD difference per tkm for ST-BSS combined with 200 kW ChPF specification in GVW below 40 t can be explained by the variation of the $E_{CT/BET}$ for these weight classes. Regarding the discussion provided for default values for $E_{CT/BET}$ in Table A8 in Appendix A, the $E_{CT/BET}$ are assumed to decrease gradually from 3.5 in a 8 t BET to 2.5 in a 40 t BET. It is worth noticing that this is a simplified approach on $E_{CT/BET}$ as both the powertrain and vehicle configurations will change and there are multiple configuration options across the GVW scale. This is evident in the graph as inflection points are visible at 40 t GVW.

4.2. Comparative cost structure analysis of BETs and CTs for the aggregated trip profile with different battery and charger specifications

Fig. 3 shows the cost structure of CTs and BETs for the aggregated trip profile with different battery technology specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and ChPF specifications (200 kW, 450 kW, and 1 MW) over different GVWs. At first glance, all cost elements seem to increase by GVW. From a closer look, it can be seen that the LCOD for the driver cost in CTs is the only constant value (1.25 USD per km) over different GVWs. The driver cost has the largest share in CTs and BETs. However, since the growth rates of other cost elements are higher, the share of driver cost in the cost structure is reduced by the increase of GVW (see Fig. A9 in Appendix A). The second most important cost element in CTs is fuel cost.

The cost structure changes dramatically from CTs to BETs as the vehicle purchase cost increases and the energy cost decreases significantly. Battery replacement cost also has a significant effect in ST-BSS, but not in MT-BSS and LT-BSS as the battery life cycle is longer. Charger equipment cost has only a minor significance in all BET

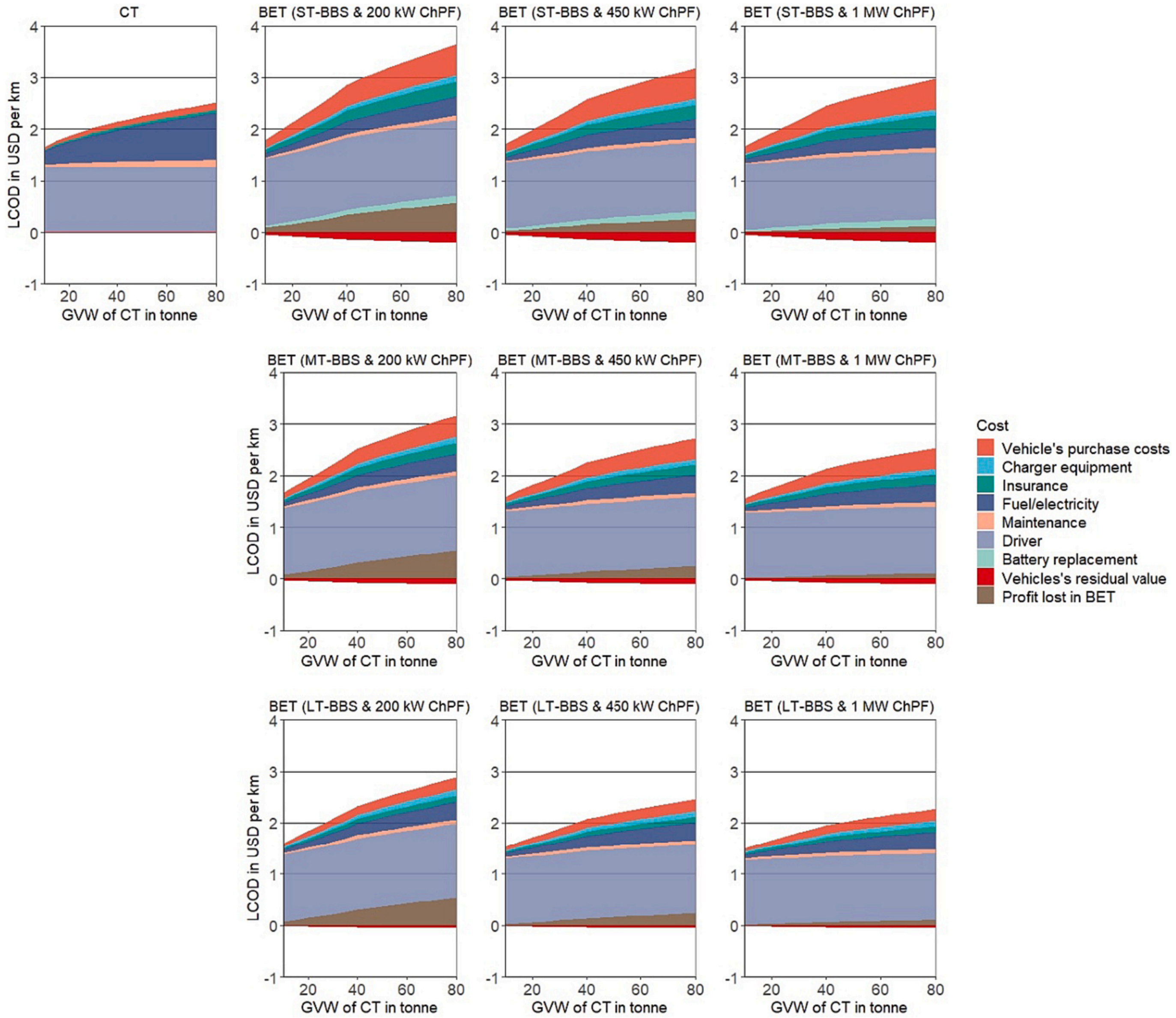

Fig. 3. Cost structure (LCOD in USD per km) of CTs and BETs for the aggregated trip profile with different battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and "mid-shift" fast charging (ChPF) specifications (200 kW, 450 kW, and 1 MW) over different GVWs.

scenarios, even with a megawatt “mid-shift” fast charging. This result is aligned with the previous research by Zhu et al. [32], who also illustrated that the utilization rates of charger stations (fast or ultra-fast chargers) have a larger impact on the LCOD of BET compared to the charging power. Hence, it seems highly profitable to invest in megawatt charging to reduce the opportunity costs. The PL for the time spent on charging activities is identified as the second major cost in all battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) combined with a 200 kW ChPF specification. The differences in the PL for the time spent on charging activities can be explained by the delivery time difference of CTs and BETs for the aggregated trip profile in different battery and charger specifications (see Fig. A10 in Appendix A).

In this study, similar to Zhu et al. [29], we assumed an equal electricity price (PE) for different levels of ChPF specification (200 kW, 450 kW, and 1 MW). However, it is likely that the price is higher with higher charging power, but from hauliers’ perspective, it is likely acceptable to pay more for higher charging power. The “mid-shift” charging time also affects the insurance cost and driver cost, as explained in Section 3.3.1. The results are subject to different levels of uncertainty. The TCO and LCOD calculations in this study include large numbers of variables. The next section discusses the impact of uncertainty in different variables on a comparative LCOD over different GVWs.

4.3. Sensitivity analysis of LCOD for CTs and BETs for the aggregated trip profile

Fig. 4 presents the sensitivity analysis of BET to CT LCOD difference per tkm over 43 variables for the aggregated trip profile of a 40 t CT. The BET to CT LCOD difference per tkm is presented as the relative change to the default CT LCOD for the aggregated trip profile. The default values as well as the lower and upper ranges illustrated in Fig. 4 are based on Table A8 in Appendix A. The largest variation (from −23% to +37% of CT LCOD per tkm) in the sensitivity analysis is due to the change of $E_{CT/BET}$, followed by the sensitivities due to variations in opportunity charging potential during loading/unloading during and rest time, driving speed, diesel consumption, and daily vehicle kilometres travelled. All of these highlight the benefits of the energy efficiency of battery electric powertrains, particularly in conditions where the energy efficiency of diesel powertrains is poor. It also highlights the need for more real operational data and validated simulations on BET energy consumption across the GVW under various conditions, to improve the accuracy of the TCO estimates.

The variables with BET to CT LCOD difference per tkm changes lower −5% and above +5% of the default CT LCOD are the OPC, AT_{Reg}, operational driving range, BPP, DVKMT, DC_h, vFf, diesel consumption volume per km (V_{d_km}), $E_{ATA(1d)}$, ChPF, P_D, GPM, BU_{SOC}, and the $E_{CT/BET}$. Many of these variables relate to the opportunity costs, highlighting the importance of high “mid-shift” fast charging powers. The V_{d_km} in Fig. 4 presents almost the same changes as the vFf does. This justifies the descriptions for the calculation of the V_{d_km} in Eq. (A2.42).

Fig. A11 and Fig. A12 in Appendix A present Monte Carlo simulation results for the impact analysis of uncertainties in the variables on BET to CT difference per tkm and km for the GVWs of CT from 10 to 80 t with a 5-t interval. The diagrams in Fig. A11 and Fig. A12 present Monte Carlo simulation results by randomly changing the variables to the lower and upper ranges based on Table A8 in Appendix A, which are also represented in Fig. 4. The box plots in Fig. A11 and Fig. A12 in Appendix A are generated based on 1000 iterations of Monte Carlo simulation and present the 25th, median and 75th percentiles. Regarding the results of Monte Carlo simulation, less than 25% of the 1000 iterations result in a lower LCOD for BETs compared to CTs in GVWs over 40 t. However, the relevant figure for GVWs lower than 40 t varies between 25% to 50%. A practical solution to dealing with high levels of uncertainty in LCOD can be to use the operational classifications and scenarios that reduce the uncertainty levels of the key variables (with lower −5% and above +5% uncertainty impact) in the cost analysis. In the next section, we use more detailed classifications in the comparative cost analysis to cover more specific values for these variables.

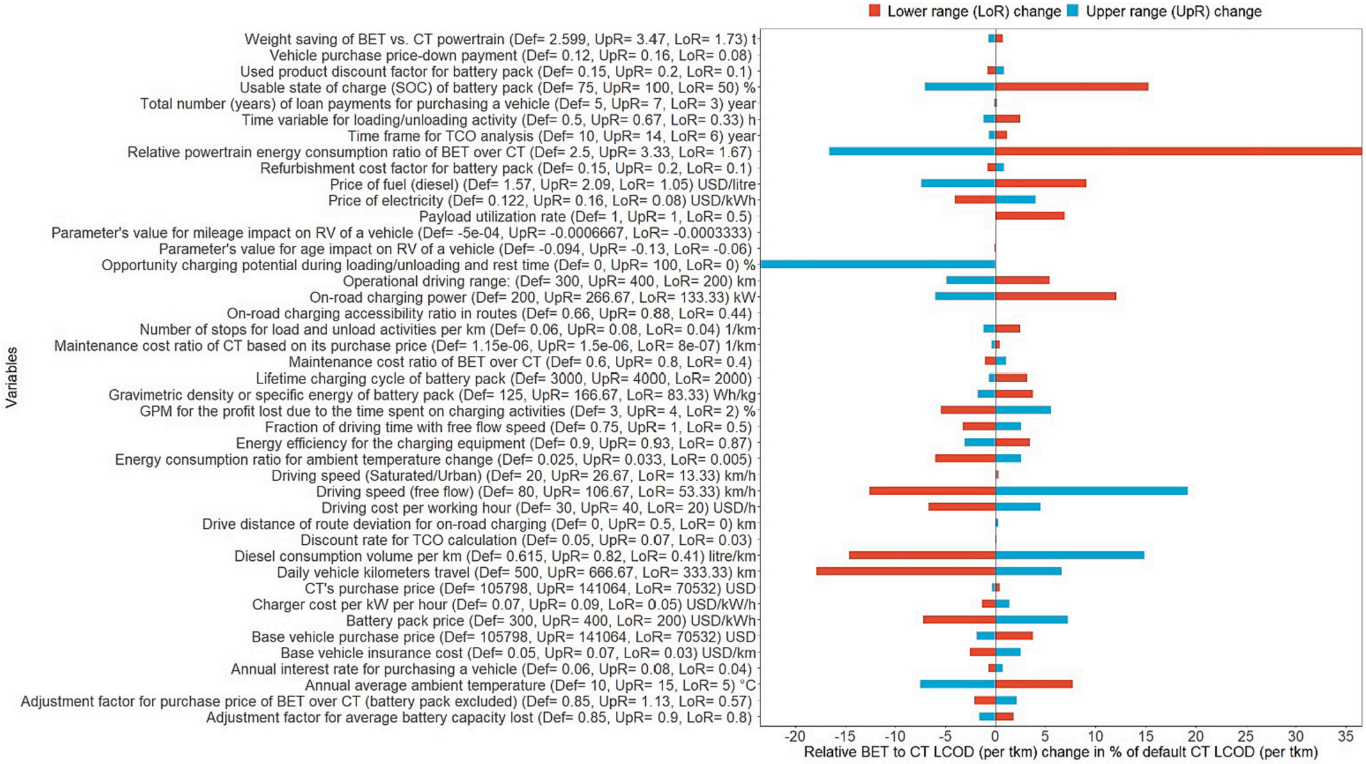

Fig. 4. Sensitivity analysis of BET to CT LCOD difference (per tkm) based on lower and upper range of 43 variables for the aggregated trip profile of a 40 t CT.

4.4. Optimum BET driving range (OR) for operational trip profiles (urban, short-haul or regional, and long-haul) with different battery technology and charger specifications

As is concluded in the previous section, to reduce the uncertainty levels in the results we need to use more detailed operational classifications (e.g., operational trip profiles), validated models and scenarios to cover more specific values for the variables with high levels of uncertainty impacts on the BET to CT LCOD. The majority of the highlighted variables with lower −5% and above +5% uncertainty impact for the BET to CT LCOD difference in Fig. 4 would be covered in the battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and ChPF specifications (200 kW, 450 kW, and 1 MW) (see Table 1 and Table A6 in Appendix A) combined with the operational trip profiles (urban, short-haul, and long-haul) (see Table 2 and Table A7 in Appendix A). These variables are DVKMT, the $E_{CT/BET}$, vFf, ChPF, BPP, and BU_{SOC}. We specify three other variables such as OPC, AT_{Reg} and operational driving range for the LCOD analysis in this section. In our model, we can identify an OR value with the lowest BET LCOD for the above-specified classification scenarios including battery technology and sizing, charger specifications, operational trip profiles, opportunity charging potential during loading/unloading and rest time, and the ambient temperatures over different GVWs.

We decided to not evaluate the other highlighted variables, with the lower −5% and above +5% uncertainty impact for the BET to CT LCOD difference in Fig. 4, for the following reasons: 1) The variable (e.g., E_{ATA}

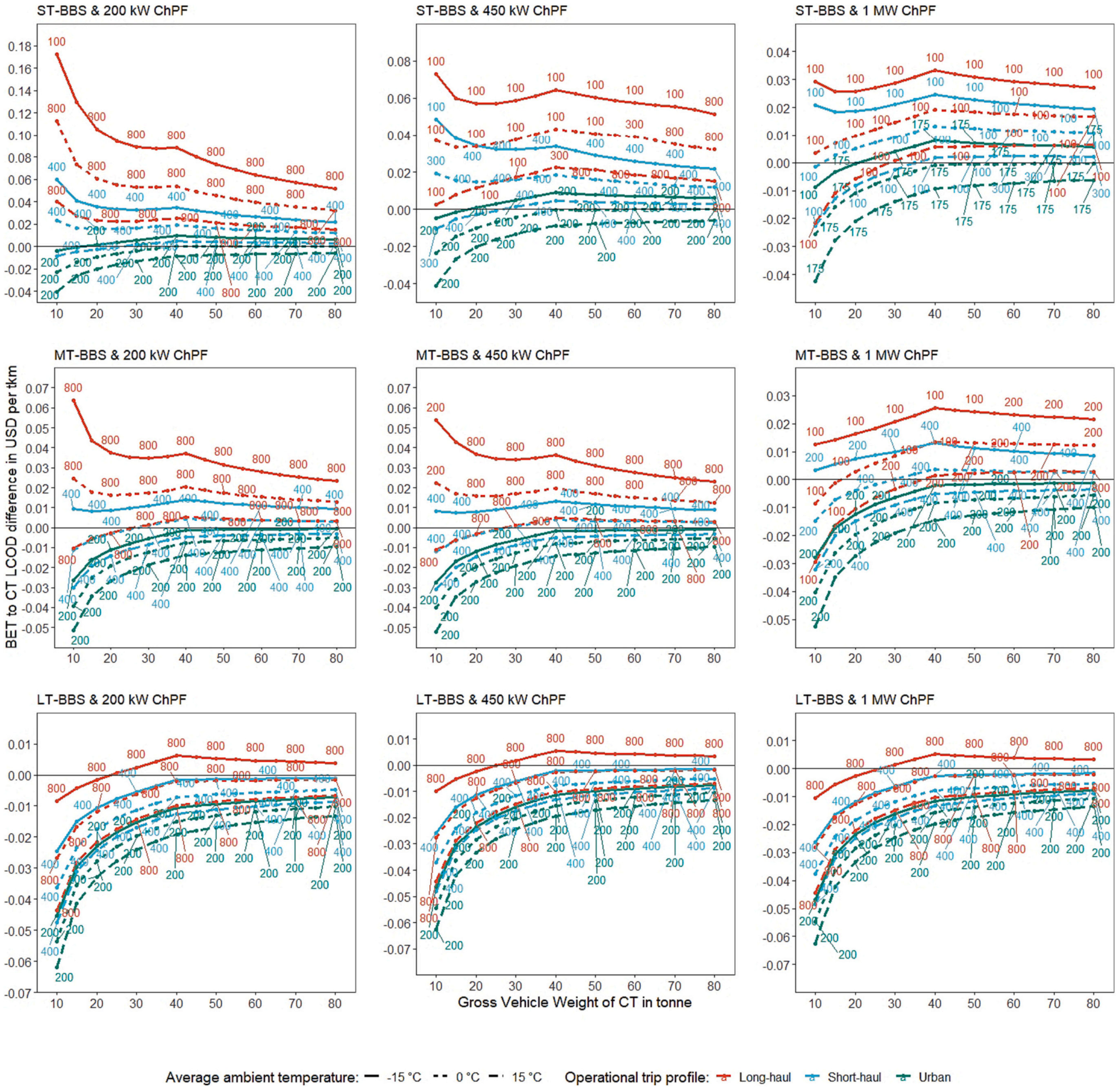

Fig. 5. The ORs and BET to CT LCOD differences per tkm in different battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and "mid-shift" fast charging (ChPF) specifications (200 kW, 450 kW, and 1 MW) over different GVWs of CT, operational trip profiles (urban, short-haul, and long-haul) and average ambient temperatures (−15, 0, and + 15 °C). The texts over the line graphs present ORs.

$_{(1d)}$) cannot be specified further by using any classifications because the uncertainty root in the lack of knowledge in the literature review; and 2) The variable is a critical cost element that might need to be specified for a region based on a strategic or integrated assessment model [24–26,49] (e.g., DC_h, P_D, GPM of a trucking company for the profit lost for the time spent on charging activities).

Fig. 5 shows the ORs and BET to CT LCOD differences per tkm in different battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and ChPF specifications (200 kW, 450 kW, and 1 MW) over different GVWs, operational trip profiles (urban, short-haul, and long-haul) and average ambient temperatures (−15, 0, and + 15 °C). The line graphs in Fig. 5 are generated based on the OR (represented by the labels above the line graphs with the same colour) for the BET to CT LCOD difference per tkm of GVWs from 10 to 80 t with a 5 t interval. In our analysis, the OR is selected as the most competitive BET vs. CT LCOD within the search ranges from 100 to 900 km by a 25 km interval, to cover and examine almost all the driving ranges mentioned in the literature.

The graphs in Fig. 5 shows that even in the current and/or short-term battery technology scenario (ST-BSS) combined with the 200 kW ChPF, we can expect a lower or equal LCOD for BETs compared to CTs in urban trips with a positive ambient temperature in all GVWs. Moreover, the graph shows that even with the help of battery technology improvement (LT-BSS) and 1 MW ChPF, we cannot achieve a lower LCOD for BETs heavier than 30 t GVWs compared to CTs in long-haul trips with −15 °C ambient temperature. We refer to graphs in Fig. A13-A15 in Appendix A for analysing more details of the ORs, battery pack capacities, and the

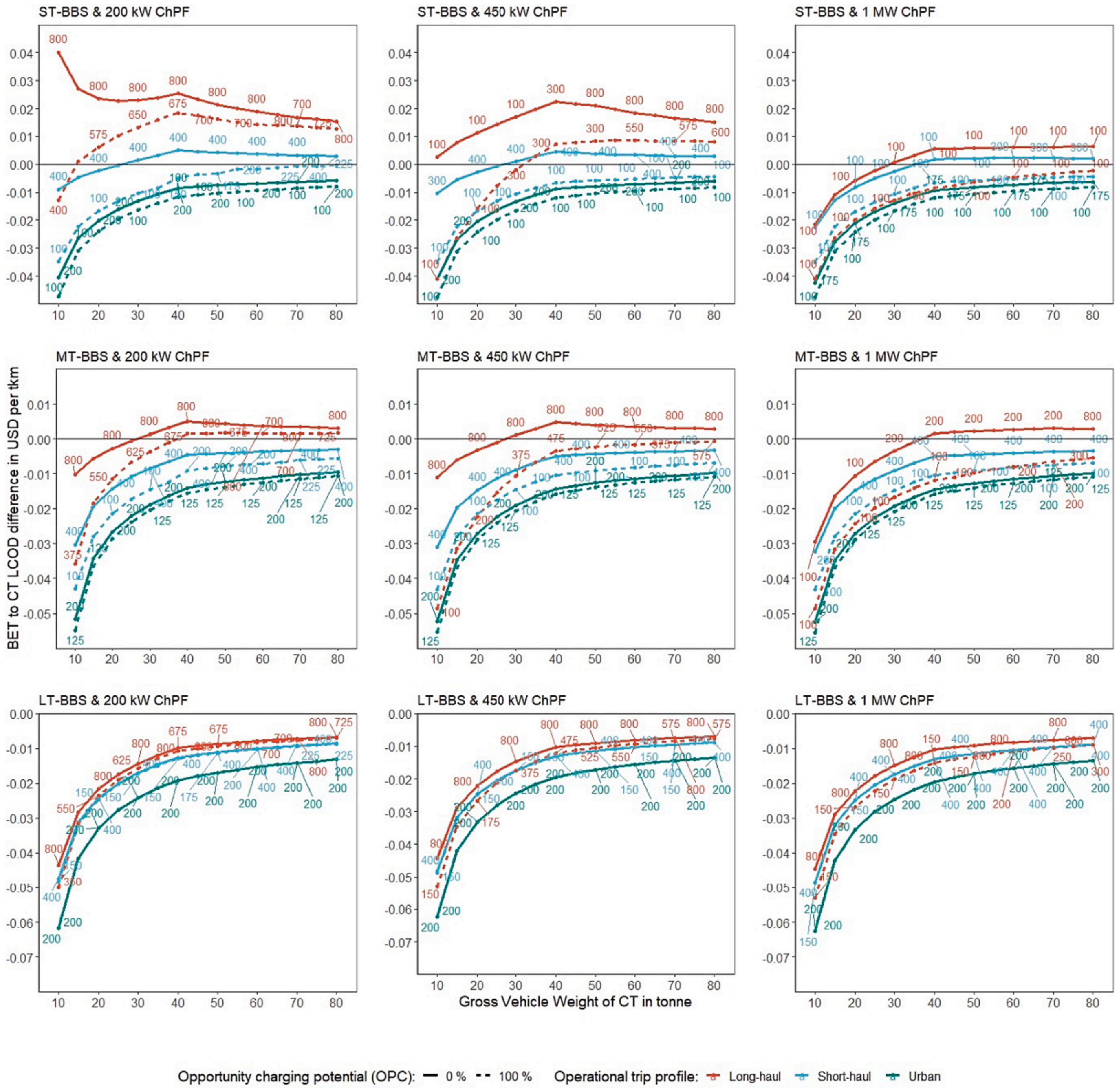

Fig. 6. Optimum driving ranges (ORs) and BET to CT LCOD differences per tkm in different battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and “mid-shift” fast charging (ChPF) specifications (200 kW, 450 kW, and 1 MW) over different GVWs, operational trip profiles (urban, short-haul, and long-haul), and opportunity charging potential scenarios during loading/unloading and rest time (OPC = 0% and 100%). The texts over the line graphs represent the ORs.

curb weight change of BETs in Fig. 5.

The results of the ORs in Fig. 5 can be summarised in the following notes: 1) The ORs mainly vary between the graphs and not over GVWs; 2) The ORs in urban trip profiles are not sensitive to the ChPF; 3) The ORs in the current and/or short-term battery specification scenario (ST-BSS) combined with 1 MW ChPF specification are the lowest compared to the relevant figures in other battery specification scenarios, ChPF specifications, and operational trip profiles scenario combinations; 4) In the long-term battery specification scenario (LT-BSS) combined with all ChPF specifications, the mid-term battery specification scenario (MT-BSS) combined with 200 kW and 450 kW ChPF specifications, and the current and/or short-term battery specification scenario (ST-BSS) combined with 200 kW ChPF specification, the ORs are equal to the DVKMT specified for each trip profile (200 km for urban trip, 400 km for short-haul trip, and 800 km for long-haul trip); and 5) Even with the help of the OR design, the battery size and capacity would be a major challenge in the short- and mid-term battery specification scenarios (ST-BSS and MT-BSS) combined with lower ChPF specifications (200 kW and 450 kW) especially for the long-haul operational trip profile.

To understand the impact of the ORs on the BET LCOD changes represented in Fig. 5, Fig. A16 in Appendix A is provided with more details of the potential LCOD reduction in BETs based on the relative BET to CT LCOD per tkm change in percentage of CT LCOD (with a default 300 km operational driving range). Fig. A16 in Appendix A shows that the maximum reductions of BET LCOD with the OR specifications are estimated around 225%, 95%, and 35% of CT LCOD with a default 300 km range assumption, for long-term battery specification scenario (LT-BSS) combined with 200 kW, 450 kW, 1 MW ChPF specifications, respectively. The major reduction potentials of BET LCOD due to the OR setting are expected to occur in the heaviest trucks and long-haul trips. As a trend, the short-haul and urban trip profiles follow the long-haul trips but with lower levels of LCOD reduction due to OR setting.

To assess the impact of OPC variation on LCOD of BETs and ORs, Fig. 6 in Appendix A provides graphs to present ORs and BET to CT LCOD differences per tkm in different battery technology improvement scenarios (ST-BSS, MT-BSS, and LT-BSS) and ChPF specifications (200 kW, 450 kW, and 1 MW) over different GVWs, operational trip profiles (urban, short-haul, and long-haul), and opportunity charging potential scenarios during loading/unloading and rest time. Graphs in Fig. 6 in Appendix A are specified for two extreme scenarios of opportunity charging potentials during loading/unloading and rest time (OPC = 0% and 100%) in a moderate temperature (+15 °C).

Taking a close look at the graphs in Fig. 6 in Appendix A, the results are summarised in the following notes: 1) The opportunity charging has a very low impact on the LCOD reduction of BET in urban trip profiles; 2) The opportunity charging plays a major role in the cost competitiveness of BET vs. CTs in the current and/or short-term and mid-term battery specification scenarios (ST-BSS and MT-BSS) if the high ChPF specifications (450 kW and 1 MW) will be used for the short-haul and long-haul trip profiles; and 3) The opportunity charging might have the least impact on the LCOD reduction of BET in the long-term battery specification scenario (LT-BSS) for all the trip profiles.

In this study, the delivery time delay and curb weight change are calculated in the TCO and LCOD of BETs based on the ORs. However, the operational challenges might be associated with the implementation of BETs because of these two items. The operational driving range above the DVKMT does not cause any delivery time delay. Therefore, it might be interesting to analyse the variation of the above items based on the lower DVKMT than the operational driving range.

Fig. A17 in Appendix A shows the delivery time differences for different battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and ChPF specifications (200 kW, 450 kW, and 1 MW) over different GVWs, operational trip profiles (urban, short-haul, and long-haul) with 25%, 50%, and 75% of the average daily mileage for the operational driving ranges by BETs. The graphs show that the main factor for the delivery time delay analysis in BETs is the ChPF and the battery technology improvements have very small impacts on it. Fig. A18 in Appendix A shows the curb weight change for different battery specification scenarios (ST-BSS, MT-BSS, and LT-BSS) and ChPF specifications (200 kW, 450 kW, and 1 MW) over different GVWs of CT, and operational trip profiles (urban, short-haul, and long-haul) with 25%, 50%, and 75% of the average daily mileage for the operational driving range by BETs. The graphs show how the improvement of the GDBP in the battery technology scenarios leads to a lower curb weight in BETs compared to the CTs.

5. Discussion

In this section, first, we highlight the key findings and contributions in the methodology for TCO and LCOD analysis in Section 5.1. Then we discuss the results in Section 5.2.

5.1. Methodology

We modelled LCOD per km and tkm for BETs and CTs with 10–80 t GVWs. The LCOD per km and tkm are formulated based on a detailed parametrized TCO analysis [34]. Some of the available models in the literature [5–7,10–12,16–21,32] included detailed parametrizations that can be comparable to our model. However, our model has some improvements compared to these models.

Using the OR for the comparative analysis of BET to CT LCOD in our model presents a more realistic evaluation over different driving cycles and operational trip profiles, GVWs, battery, and charger specifications. Previous studies [5–7,10,11,16–21] assumed predefined driving ranges or battery sizes in their BET TCO analysis, except for two studies [12,32], which used ORs for BET TCO analysis of a specific size of the truck.

Opportunity costs during the “mid-shift” fast charging activities in this study include the driver working time cost, insurance cost, and the truck company profit lost. Some previous studies partially cover the above cost items in their opportunity costs during the “mid-shift” fast charging activities based on the driver working cost [10–12,16,17,19], insurance cost [17], and the truck company profit lost [12]. No research was found in the literature that covers all the above items.

Thanks to the comprehensive TCO and LOCD parametrization in this study, the sensitivity analysis could reveal key parameters with high levels of impact on BET and CT LCOD. We used the result of sensitivity analysis to justify the categorizations (e.g., operational trip profiles) required for further analysis in Section 4.3 and Section 4.4. Moreover, coupling the sensitivity analysis with a stochastic modelling approach (Monte Carlo simulation) provides a deeper understanding of the uncertainty impacts of different parameters on LCOD by using box plots for different GVWs. A few studies [11,17,19,29] have used a stochastic approach to visualize the impact of uncertainties of identified key variables on their TCO analysis. However, we believe that the sensitivity analysis in our model covers a larger number of variables (43 variables) compared to these studies.

In this study, we used a detailed operational parametrization based on aggregated or average values which also can be applied for the detailed models using disaggregated data, based on the available road freight survey, and a simulation approach for on-road charging activities in different routes. However, in this study, we only used aggregated/average values for the key parameters in the operational time calculation procedure to facilitate the impact analysis of different battery technology and charging specifications on LCOD.

5.2. Results

We highlight and discuss some key aspects and general trends in the results:

1) BETs in the urban trip profiles can be a cost-competitive alternative with the current and/or short-term battery technology even without the implementation of additional policy incentives;
2) Even with an advanced battery technology improvement scenario (LT-BSS) combined with a megawatt ChPF specification, road freight transport electrification remains challenging in the long-haul trip profiles when combined with cold temperatures (around −15 °C). This raises the need for further development on vehicular and powertrain technologies and analyses on alternative or complementing system solutions such as battery swapping, electric road systems (ERS) and utilization of hydrogen;
3) The mid-term scenario for the battery technology improvement (MT-BSS) might be supportive of the cost competitiveness of less than 40 t BETs and moderate temperature (15 °C) in short-haul and long-haul trip profiles. However, the implementation of the policy measures (e.g., fuel and electricity taxation, road tolls, and carbon pricing) is needed for heavier trucks in long-haul and short-haul trip profiles;
4) The optimum driving ranges in urban trip profiles are not sensitive to the implementation of different levels of fast-charging powers mainly because the analysed daily vehicle kilometres travelled (DVKMT) in the urban trip profiles are low and therefore the BETs in the urban trip profiles are not dependent on the opportunity charging by fast/ultra-fast chargers. The majority of required electricity for the BETs in the urban trip profiles would be provided by "off-shift" slow charging (e.g., during the rest time at night or at long stops), which implies that subsidies for slow-charging may accelerate the uptake of urban delivery BETs better than subsidies for fast/ultra-fast chargers. However, if the vehicle utilization rate and DVKMT of urban missions increase, the need for "mid-shift" fast charging may emerge;
5) The ORs in the current and/or short-term as well as mid-term battery technology scenarios (MT-BSS and ST-BSS) combined with very high ChPF specifications (1 MW) are lower than the ORs in the long-term future battery technology scenario (LT-BSS) combined with very high ChPF specifications (1 MW) in all GVWs. This is mainly because of battery price variations in different battery specification scenarios. Revealing that the full benefits of a megawatt "mid-shift" fast charging are associated with lower battery capacities in the current and/or short-term as well as mid-term battery technology scenarios;
6) The ORs in the mid- and long-term developments for the battery specifications (MT-BSS and LT-SPP) combined with various charging powers are close to the DVKMT in each trip profile (200 km for urban trips, 400 km for short-haul trips, and 800 km for long-haul trips). This suggests that the DVKMT will be the main parameter for designing ORs and battery sizing in the mid- and long-term future; and.
7) The opportunity charging associated with using high ChPF specifications (450 kW and 1 MW) might help to achieve cost competitiveness of BETs vs. CTs in the short-haul and long-haul trip profiles for the current and/or short-term as well as mid-term battery technology scenarios (ST-BSS and MT-BSS). This reveals the essential need for planning and investments to improve the accessibility of public fast-chargers in the road networks and fast-charging facilities at the most demanding destination(s) for BETs.

We also noticed that it is very hard to make a comparison between the results in this study and others based on the BET and CT LCOD per km or tkm because of the following reasons:

1) Different studies use different specifications for the key parameters such as battery and charger characteristics, driving cycles, vehicle sizes, and operational trip profiles.
2) Different methodologies were developed to calculate TCO analysis. Even with the same assumptions for battery and charger characteristics, driving cycles, vehicle sizes, and operational trip profiles, the research results from the previous studies are hardly comparable to this study because of the following reasons:
   1. Some references [6, 7, 11, 17, 19–21] only calculate TCO based on the NPV without discussing the LCOD per tkm or km;
   2. Some references [5, 17, 18] provide very simplified calculations based on different cost elements for TCO without using the NPV approach; and
   3. Some references [6, 7, 10, 11, 16, 20] modelled the annual variation of key parameters such as annual VKMT and different costs (e.g., battery pack price per kWh, fuel and electricity costs) over the truck's ages.

6. Conclusions

The key results of this study show:

1. BETs in urban trip profiles with the current and/or short-term battery technology assumption can be economically viable alternatives for CTs without the help of policy measures.
2. The cost competitiveness of BETs over CTs with below 40 t GVW and long-term improvements in battery technology are very promising in all "mid-shift" fast charging power. However, in long-haul trip profiles and harsh weather conditions with an ambient temperature around −15 °C, the BETs application remains challenging and might be economically unfeasible even with the help of a megawatt "mid-shift" fast charging power, raising maybe the need for further analyses on policy measures and additional solutions such as opportunity charging and electric road systems.
3. The implementation of policy measures (i.e., taxation on diesel fuel, subsidies for the electricity price and battery price) as well as increasing the potential of opportunity charging during loading/unloading and rest time (e.g., by investing in fast-charging facilities) would be needed to support the BETs in short-haul and long-haul trip profiles with above 40 t GVW for the current and/or short-term as well as projected mid-term scenarios of battery technology characteristics.

In this study, we developed a total cost of ownership (TCO) and levelized cost of driving (LCOD) model for battery electric (BET) and conventional trucks (CT) to answer the research questions and fill the identified gaps in the literature. We provided a very detailed discussion based on the sensitivity analysis of the key parameters in LCOD in Section 4.3 to answer the first research question "What are the key parameters in levelized cost of driving calculations for battery electric trucks and conventional trucks?". We found that the improvement of battery technology characteristics (e.g., usable state of charge and lifetime charging cycles), utilization of higher power chargers, and reduction in battery price, all reduce the TCO gaps between the BETs and CTs. We also highlighted the role of the ambient temperature, opportunity charging, and the optimum driving ranges.

We discussed and provided detailed answers in Section 4.4 and Section 5.2 for the second research question "How do different battery and charger specifications affect cost-efficient or optimum driving ranges (ORs) of battery electric trucks in different trip profiles?". The results show that, first, the ORs in urban trip profiles are not sensitive to the implementation of different levels of "mid-shift" fast charging power. Second, the ORs in the current and/or short-term battery technology characteristics would be lower than the mid- and long-term development characteristics mainly because of the high battery price. Third, the daily vehicle kilometres travelled will be the main parameter for designing ORs and battery sizing in the mid- and long-term future in all trip profiles.

The TCO and LCOD models developed in this study aimed to improve the estimate of large-scale adoptions of BETs based on the different improvement levels of battery and charger characteristics in the future. The model might need improvements in the following aspects:

1. The energy/fuel consumption equations for both BET and CT can be improved and calibrated based on more details of the truck applications (e.g., refuse truck, trucks with a cooling system),
2. The stochastic approach can be applied for estimating the OR based on the statistics data of key variables (e.g., daily mileage),
3. If the TCO model is going to be used for specific regions, the policy measures should be considered in the TCO and LCOD model via the cashflow,
4. Different electricity prices could be used for different levels of fast charging power based on a detailed charger infrastructure analysis, and
5. Battery lifetime variations could be considered in scenario assumption for battery design based on detailed stress factors and parameters such as levels of fast charging powers, battery operative window and temperatures.

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CRediT authorship contribution statement

Mehdi Jahangir Samet: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Heikki Liimatainen:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Mikko Pihlatie:** Writing – review & editing, Validation, Investigation, Conceptualization. **Oscar Patrick René van Vliet:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The calculation steps and procedures for the levelized cost of driving are represented by flowcharts and list of equations in the Appendix A. Further information about the programming codes (in R) are available online: https://github.com/MehdiJahangirSamet/LCOD-of-BET

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.122976.

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