Analysis of Fast Charging Arrangements for Electric Heavy Goods Vehicles

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Abstract— **Electric heavy goods vehicles (HGVs) are a key step towards reducing road freight emissions. However, they require large batteries and fast chargers. There is interest in exploring high-capacity chargers at warehouse docks that can charge at a rate of 1 MW. These chargers are expensive and complex but are needed to run big-battery electric HGVs without a change in logistics operations. Hence, this paper aims at evaluating scenarios in which high-capacity chargers are useful by estimating battery sizes required for various logistics operations. The paper also aims to evaluate the circumstances under which high-capacity chargers are economically feasible using a 15-year cost break-even model. It is seen that high-capacity chargers are useful and economically feasible for journeys with smaller stop durations and longer distances, but not for journeys with longer stops. It is also observed that they need to be supplemented by different charging strategies and dynamic charging techniques.**

I. INTRODUCTION

Heavy goods vehicles (HGVs) constitute 18% of all road transport emissions in the UK [1], 29% in India [2], and 27% in South Africa [3]. Decarbonisation of road freight is critical to reaching global net zero goals, but the optimal pathways for each country will differ. It is important to study how solutions under consideration in nations in the UK and Europe can be adapted to work in countries with higher road freight demands and distinct geographical characteristics, such as India, China and South Africa [4].

There are several short-term methodologies for decarbonising road freight that can be implemented immediately [5] and carried forward to a net-zero future. Some examples include aerodynamic and lightweight trailers [6], driver training for eco-driving [7], higher capacity vehicles [8] and proper fleet maintenance [9]. However, being a long-term problem, it draws more focus on long-term solutions. Some of the long-term decarbonisation pathways being explored currently include green hydrogen fuel cell electric HGVs, biofuel HGVs and battery electric HGVs. Green hydrogen fuel cell HGVs are not as efficient as battery electric HGVs in terms of 'well-to-wheel' energy and emissions [10], and biofuel HGVs are restricted by insufficiency in the biofuel supply chain [11]. Hence, battery electric HGVs remain the best option for decarbonising HGVs.

Electrification of HGVs can be aided by installing 'fast' or 'high-capacity' chargers at locations such as warehouse docks, where HGVs usually stop for a short amount of time for loading or unloading. Such infrastructure can be procured through a provider that installs the chargers and then generates an income by selling electricity from the chargers. It is possible to use existing HGV rest stops and fuelling station locations for this, and also add more locations based on demand.

At the same time, it needs to be evaluated whether long-distance road freight trips can be electrified using high-capacity chargers. The economics of these high-capacity static chargers also needs to be studied in terms of their usage. Hence, this study aims at studying the feasibility of executing long-distance road freight journeys with the support of high-capacity static chargers and the costs of installing these chargers. The study aims to answer questions such as in what scenarios are high-capacity chargers more useful than slower chargers, and under what circumstances are they economically viable. To answer these questions, the objectives of this study are as follows:

1) Estimate battery size requirements with high-capacity chargers for different types of logistics journeys in diverse geographies.
2) Evaluate the cost break-even duration for high-capacity chargers in terms of their usage per day.

The following section presents a methodology for estimating the energy consumption of electric HGVs, followed by a cost break-even formulation for static chargers. This is followed by results in terms of battery sizes required for various journeys, the sensitivity of the profit margin in electricity selling in the usage required for chargers, and use cases where high-capacity chargers are useful.

II. BATTERY SIZE ANALYSIS

A. Methodology

The first part of the analysis involves modelling the effect of placing different sizes of static chargers along existing freight routes and calculating the battery sizes required. This is done using a drive cycle generator and a vehicle model [12].

The drive cycle synthesiser used here, developed in [12], uses the origin, destination and rest stops to generate a route for the vehicle using 'HERE Maps'. It then overlays the specified charger locations and charger capacities on the route to generate the desired drive cycle and a 'charging signal' containing charging powers and times. The information about

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The authors acknowledge the support of members of the Centre for Sustainable Road Freight, which is funded by industry partners and UKRI under EPSRC Grant EP/R035199/1.

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the speed and elevation of the route along with the charging signal is then passed on to the vehicle model.

The vehicle model, detailed in [12], is based on a battery electric bus model developed in [13] and validated in [6]. The model was scaled to fit a 44-tonne electric HGV with electric road systems (ERS) and static charging in [12] and validated using data from Siemens and Scania. The vehicle model includes auxiliary loads such as refrigeration [14]. The model generates a 'followed' drive cycle along with the battery charge based on the HGV's energy consumption over the drive cycle and the charging opportunities.

B. Data Processing

The battery size analysis is performed for two charger sizes – 600 kW and 1 MW and for two use cases – a logistics company with long-haul freight and a supermarket with a multi-drop scenario. The charger sizes are based on the fact that heavy vehicles with large batteries (larger than 600 kW) will need higher capacity chargers and the expectation that megawatt standard chargers will be available soon.

The selected journeys are given as inputs to the vehicle model, which then gives the battery size required based on the lowest battery dip. The battery size needs to be chosen such that it only dips to around 80% of its maximum capacity based on manufacturer warranty conditions. Hence, the required battery size is obtained by dividing the largest dip by 0.8. The data for these journeys is collected as follows.

1) Logistics Company Long-Haul (South Africa): The journey data for the logistics company, based in South Africa, was collected by analysing their two most frequent trips on their telematics portal. One of the selected trips was from Durban to Johannesburg and Pretoria, which is a single-day trip, and the other was a 'tramping' journey originating in Durban as well. The routes for these trips are shown on maps in Fig. 1 and discussed further in the Results section.

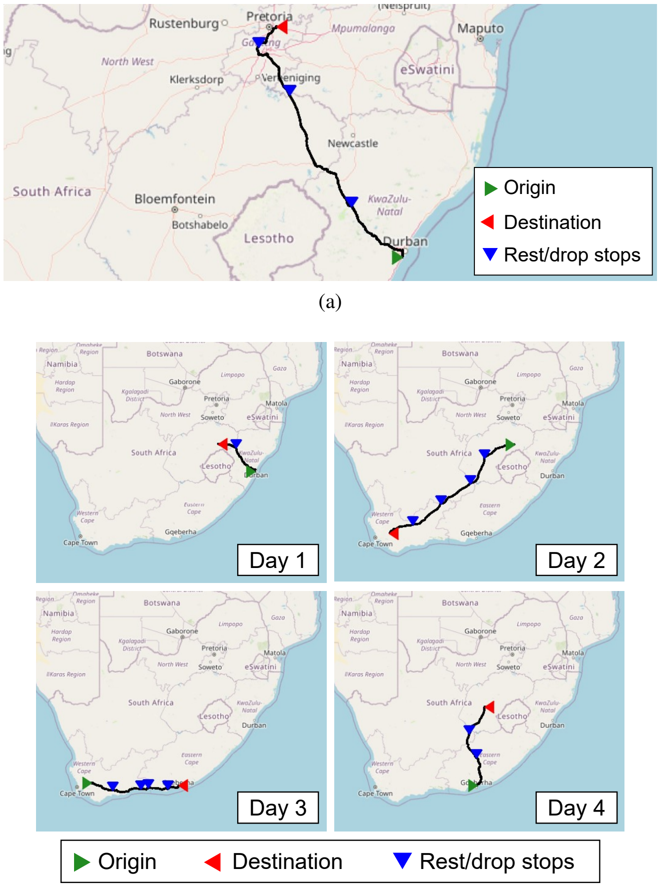
2) Supermarket Multi-Drop (UK): The data for the supermarket, based in the UK, was obtained from the analysis done in [12]. Three of their most popular multi-drop trips, originating and ending in Aylesford, were chosen for this analysis. Since one of them has a trip longer than 4.5 hours, a rest stop was added as per the regulations for HGV driving in the UK. The maps for these trips are shown in Fig. 2.

III. STATIC CHARGER PRICING

The second part of the analysis focuses on obtaining an expression for the number of hours per day for which a charger must be used for it to be profitable, i.e., to achieve cost break-even within a certain duration. This is done by evaluating the costs involved in setting up and maintaining a charger, and the income from selling electricity. This formulation is derived from a similar method used in [15] for analysing ERS. The parameters used in this analysis are explained in Table I.

A. Income

The income from the static charger is modelled based on the number of hours per day for which the charger is in use (n_h). The annual income also depends on the number of days for which the charger is in use (n_d), the power supplied by the charger (P_max) and the electricity profit margin (Δr_e).



(a)

(b)

Fig. 1. Journeys analysed in South Africa: (a) single-day long-haul from Durban to Pretoria and (b) multi-day tramping.

Thus, the annual income from a charger is given as:

$$C_{+,\mathrm{annual}} = n_\mathrm{h}\, n_\mathrm{d}\, P_\mathrm{max}\, \Delta r_\mathrm{e}. \tag{1}$$

It is assumed that the income increases every year based on an annual inflation rate of r_z. Hence, the total income until the year n_y is:

$$C_+ = C_{+,\mathrm{annual}} \Big(1 + (1+r_\mathrm{z}) + (1+r_\mathrm{z})^2 + \ldots + (1+r_\mathrm{z})^{n_\mathrm{y}} \Big). \tag{2}$$

By adding the terms of the geometric progression, the final income until the break-even point is:

$$C_+ = n_\mathrm{h}\, n_\mathrm{d}\, P_\mathrm{max}\, \Delta r_\mathrm{e} \frac{(1+r_\mathrm{z})^{n_\mathrm{y}} - 1}{r_\mathrm{z}}. \tag{3}$$

B. Expenditure

For this analysis, the expenditure is modelled as a sum of the charger installation costs and the maintenance costs. The total installation cost, C_cap, is a sum of the unit cost of the charger, the charger installation cost and the grid connection cost and the values are presented in Table I [16], [17].

TABLE I

PARAMETERS IN THE COST ANALYSIS

Parameter	Description	Value (600 kW charger)	Value (1 MW charger)
–	Unit cost of the charger + installation cost	£250,000 + £25,000	£500,000 + £25,000
C_{cap}	Total capital cost per charger (total grid conn. size):		
	For a single charger	£795,000 (0.6 MW)	£1,295,000 (1.0 MW)
	In a set of 3 chargers	£745,000 (1.8 MW)	£1,545,000 (3.0 MW)
	In a set of 5 chargers	£895,000 (3.0 MW)	£1,445,000 (5.0 MW)
	In a set of 10 chargers	£770,000 (6.0 MW)	£1,107,500 (10.0 MW)
f	Annual maintenance cost as a fraction of capital cost	5% pa	5% pa
n_{d}	Number of days the charger is in use, per year	365	365
n_{i}	Duration of the loan	15 years	15 years
n_{y}	Cost break-even duration for the charger	15 years	15 years
$P_{\max}$	Charger capacity	600 kW	1000 kW
Δr_{e}	Electricity profit margin	variable	variable
r_{i}	Loan interest rate for installing the charger	6%	6%
r_{z}	Average rate of inflation, year-on-year	3%	3%

It is assumed that the installation cost is in the form of a commercial loan with a duration of n_{i} years and an annual compounded interest rate of r_{i}. Hence, the sum of annual instalments paid until the year n_{y} is:

$$C_{-,\text{charger}} = C_{\text{cap}}\, n_{\text{y}} \left(\frac{r_{\text{i}}\,(1+r_{\text{i}})^{n_{\text{i}}}}{(1+r_{\text{i}})^{n_{\text{i}}}-1} \right). \tag{4}$$

It is further assumed that the maintenance cost per year would be a fraction, f of the initial capital cost, considered to be 5% in this case [18]. Hence, the total maintenance until the year n_{y}, accounting for inflation similar to (2), is:

$$C_{-,\text{maint}} = f\, C_{\text{cap}}\, \frac{(1+r_{\text{z}})^{n_{\text{y}}}-1}{r_{\text{z}}}. \tag{5}$$

The net expenditure is a sum of the installation and maintenance costs, thus given by:

$$C_{-} = C_{-,\text{charger}} + C_{-,\text{maint}}. \tag{6}$$

$$\therefore\, C_{-} = C_{\text{cap}} \left[n_{\text{y}}\, \frac{r_{\text{i}}\,(1+r_{\text{i}})^{n_{\text{i}}}}{(1+r_{\text{i}})^{n_{\text{i}}}-1} + f\, \frac{(1+r_{\text{z}})^{n_{\text{y}}}-1}{r_{\text{z}}} \right]. \tag{7}$$

C. Cost break-even

Considering n_{y} to be the break-even duration, the income and expenditure at this point would be equal. Hence, at n_{y} years:

$$C_{+} = C_{-}. \tag{8}$$

Substituting the expressions for the income and expenditure from (3) and (7), respectively:

$$\begin{aligned} n_{\text{h}}\, n_{\text{d}}\, P_{\max}\, \Delta r_{\text{e}}\, \frac{(1+r_{\text{z}})^{n_{\text{y}}}-1}{r_{\text{z}}} \\ = C_{\text{cap}} \left[n_{\text{y}}\, \frac{r_{\text{i}}\,(1+r_{\text{i}})^{n_{\text{i}}}}{(1+r_{\text{i}})^{n_{\text{i}}}-1} + f\, \frac{(1+r_{\text{z}})^{n_{\text{y}}}-1}{r_{\text{z}}} \right]. \end{aligned} \tag{9}$$

$$\therefore\, n_{\text{h}} = \frac{C_{\text{cap}} \left[n_{\text{y}}\, \frac{r_{\text{i}}(1+r_{\text{i}})^{n_{\text{i}}}}{(1+r_{\text{i}})^{n_{\text{i}}}-1} + f\, \frac{(1+r_{z})^{n_{\text{y}}}-1}{r_{z}} \right]}{n_{\text{d}}\, P_{\max}\, \Delta r_{\text{e}}\, \frac{(1+r_{z})^{n_{\text{y}}}-1}{r_{z}}}. \tag{10}$$

This equation for n_{h} gives the number of hours that the charger must be used per day for it to achieve cost break-even within n_{y} years, given the parameters shown in Table I. While the expression is sensitive to all the considered parameters, it is found to be most sensitive to the electricity profit margin (Δr_{e}) and the capacity of the charger. Hence, the usage required is analysed with respect to these quantities in the Results section.

IV. RESULTS

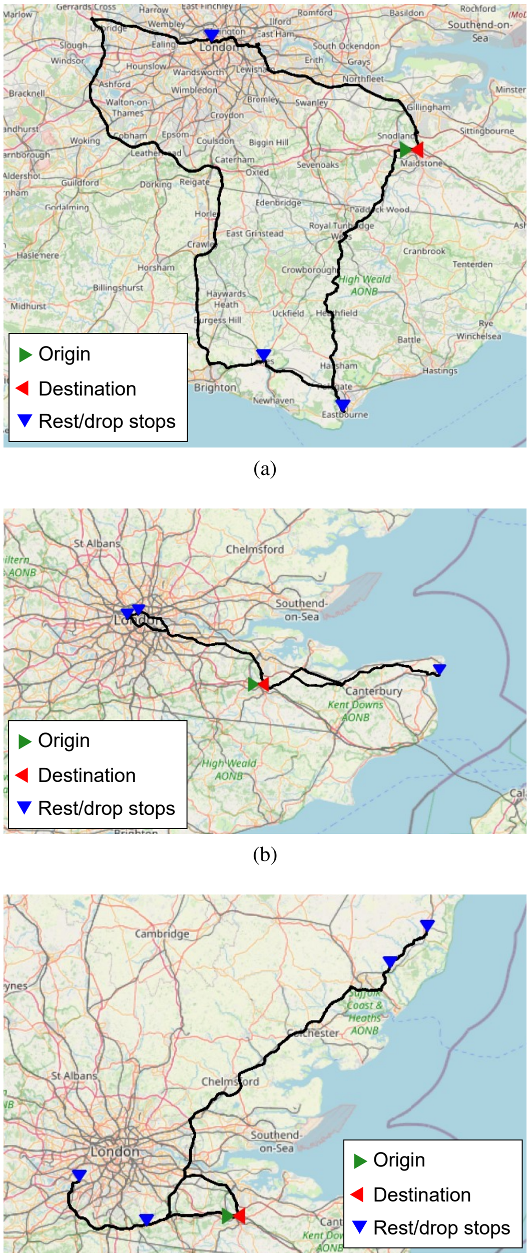
A. Battery Size Analysis

The battery size analysis was performed for a logistics company in South Africa and a supermarket in the UK, and the results are presented in this section. The journeys chosen are a single-day long-haul journey and a multi-day tramping journey for the logistics company in South Africa, and three single-day multi-drop journeys for the supermarket in the UK. It is assumed that chargers are available at the rest stops, possibly booked in advance through a booking app.

1) Logistics Company Long-Haul (South Africa): The single-day journey for the logistics company, shown in Fig. 1a, originates in Durban and ends at Pretoria. It has two rest stops of 30 minutes and 15 minutes, respectively, and a drop-off stop in Johannesburg for 2 hours. The multi-day tramping journey, shown in Fig. 1b, has one 15 minutes rest stop on day 1 and four rest stops of 15 minutes each on day 2. On day 3, the first three rest stops are 15 minutes each and the final one is for 1 hour, and on day 4, both rest stops are for 15 minutes each.

The results with the required battery sizing with different charging cases for the logistics operator are shown in Table II. For the first journey, the drop location is the last stop in Johannesburg, which is very close to the end of the journey. Hence, introducing drop location charging does not reduce the required battery size much, due to the larger battery dip.

Introducing rest stop charging, however, reduces the battery size significantly, particularly when there is a 1 MW fast charger. The necessary battery sizes are reduced by faster charging here because of longer distances and smaller durations of rest stops. In this case, the maximum battery size required for the single-day journey with 1 MW rest



(a)

(b)

(c)

Fig. 2. Journeys analysed in the UK: (a) journey #1 via Eastbourne, (b) journey #2 via Bloomsbury and (c) journey #3 via Saxmundham.

stop charging is 790 kWh, while for the multi-day journey is around 960 kWh. These numbers show that faster charging can support single-day journeys with batteries smaller than 800 kWh using high-capacity chargers without a change in operations. However, longer multi-day journeys need batteries larger than that, which is not feasible due to the additional weight, loss of payload and therefore, increased costs. Such journeys would require either additional stops, a change in logistics operations, or dynamic charging on the move using ERS.

2) Supermarket Multi-Drop (UK): The battery size analysis for a supermarket in the UK is done for three ‘multi-drop’ journeys originating and ending at their depot in Aylesford. Journeys #1 and #2, shown in Figs. 2a and 2b, respectively, only have drop-off stops. Journey #3, shown in Fig. 2c, also has a rest stop on the last trip, as regulations require drivers to rest for 45 minutes after 4.5 hours of driving.

The battery sizes required for each of these journeys for the supermarket in the UK with the different charging strategies are shown in Table III. As seen in the table, the maximum battery size required for these three journeys is similar when using 600 kWh and 1 MW chargers for the drop stop charging scenario. This is because multi-drop journeys have more frequent stops and shorter distances between the stops. Therefore, faster charging is not required.

B. Split Rest Stop Strategy (UK)

While the current regulations on driver rest stops in the UK do not affect diesel HGVs, there is a need to evaluate the regulations for electric HGVs. There is a possibility to further reduce battery sizes required for a journey by having more frequent but shorter duration rest stops rather than less frequent and longer rest stops. Charging at such rest stops would increase the minimum battery dip and thus, decrease the battery size required.

In the rest stop charging scenarios, split rest stops have a significantly lower battery size requirement which is around 45% lower than standard rest stops for all cases, as seen in Table III. There is a slight advantage when using faster chargers due to the reduced stop duration and also because these are not as frequent as drop stops.

C. Break-Even Analysis

The cost break-even formulation shown in (10) can be used to obtain the duration for which a charger must be in use per day for it to be economically viable. One of the key sensitivity parameters in this formulation is the electricity profit margin, which significantly affects the break-even period. Fig. 3 shows the effect of the electricity profit margin on the usage required per day for each charger, to achieve cost break-even within 15 years. The various curves correspond to different charger setups, which could be just one charger or a charger in a set of 3, 5 or 10 chargers. These curves do not occur in order of the number of chargers, because UK grid connection costs are non-linear with respect to the grid connection size required. It is seen in the figure that the best range of values for the electricity profit margin is between £0.04/kWh and £0.1/kWh, as any lower means that the usage per day increases rapidly, and any more is not required.

It is also seen from Fig. 3 that there is not much difference in the plots for the 600 kW and 1 MW chargers. This can be attributed to the fact that while a 1 MW charger is more expensive, it can sell more electricity in the same amount of time. While the 1 MW charger will therefore need to be used for a smaller amount of time than the 600 kW charger for long-duration stops, it would not make a difference if the stop duration of an individual HGV is small.

It is also seen in Fig. 3 that the usage required per charger for different sizes of charger sets is within 30% of that of one charger on its own. Therefore, the cost analysis is not

TABLE II

BATTERY SIZE REQUIREMENTS FOR JOURNEYS IN SOUTH AFRICA

Journey	Battery size (kWh)				
	No Charging	**DC 600 kW**	**DC 1 MW**	**SC 600 kW**	**SC 1 MW**
Journey #1: Durban - Johannesburg - Pretoria	1708	1534	1534	1138	790

Journey	Battery size (kWh)		
	No Charging	**SC 600 kW**	**SC 1 MW**
Journey #2: Multi-day 'tramping'			
Day 1: Durban - Bethlehem	1139	949	824
Day 2: Bethlehem - Worcester	2116	1355	854
Day 3: Worcester - Port Elizabeth	1472	726	553
Day 4: Port Elizabeth - Bloemfontein	1589	1208	958
Max. required battery size	2116	1355	958

SC: static charging at rest stops, DC: static charging at drop locations.

TABLE III

BATTERY SIZE REQUIREMENTS FOR MULTI-DROP SUPERMARKET JOURNEYS IN THE UK

Journey	Battery size (kWh)						
	NC	**DC 600 kW**	**DC 1 MW**	**SC 600 kW**	**SC 1 MW**	**SCS 600 kW**	**SCS 1 MW**
Journey #1: Aylesford - Eastbourne - Lewes - Marylebone - Aylesford	818	287	287	818 (No stops)	818 (No stops)	454	454
Journey #2: Aylesford - Bloomsbury - Kensington Gardens - Ramsgate - Aylesford	700	316	316	700 (No stops)	700 (No stops)	396	396
Journey #3: Aylesford - Saxmundham - Woodbridge - Kingston - Aylesford	1152	466	466	847	847	471	424
Max. required battery size	1152	466	466	847	847	471	454

NC: no charging, DC: static charging at drop locations, SC: static charging at rest stops (45 min stop every 4h 30m), SCS: static charging at split rest stops (30 min stop every 2h 15m).

very sensitive to how many chargers are installed at a stop. The number of chargers can be decided based on the peak demand at that location, and such that each charger is able to meet its minimum usage required for cost break-even. This will ensure that there are enough chargers available and that they are all profitable.

D. *Charge Events Required*

Based on this formulation, the number of daily charge events required at a stop location or a warehouse can be estimated using the number of hours of usage needed and the stop duration. This analysis considers a charging stop at a warehouse, where a high-capacity charger is installed at each loading bay. The charger is used for a short amount of time by the HGV during loading or unloading at the bay.

The number of such charge events required daily considering a stop time of 20 min for each HGV is shown in Table IV for different electricity profit margins and for a 15-year cost break-even period. These are obtained using the daily usage required in hours corresponding to different values of the electricity profit margin. As seen in the table, increasing the profit margin from £0.04/kWh to £0.06/kWh significantly changes the number of daily charge events required. A profit margin of £0.08/kWh requires that a warehouse charging bay should be used around 20 times throughout the day for 20 min stops, i.e., for around 6.5 hours for it to be profitable.

This does not change much between the two charger sizes as the stop time is small and it can be assumed that an HGV will need charging for the full duration of the stop. Based on this analysis, it can be recommended that for smaller stop durations, high-capacity chargers are as economically feasible as low-capacity chargers.

V. CONCLUSIONS

This paper analysed the arrangement of high-capacity static chargers for different journey types in different geographies. The first part of the paper used an electric HGV energy consumption model to estimate the battery sizes required for various types of logistics operations. This helped in understanding the usefulness of high-capacity chargers for such journeys. The second part formulated a cost break-even model for static chargers and used it to analyse the economic feasibility of high-capacity chargers.

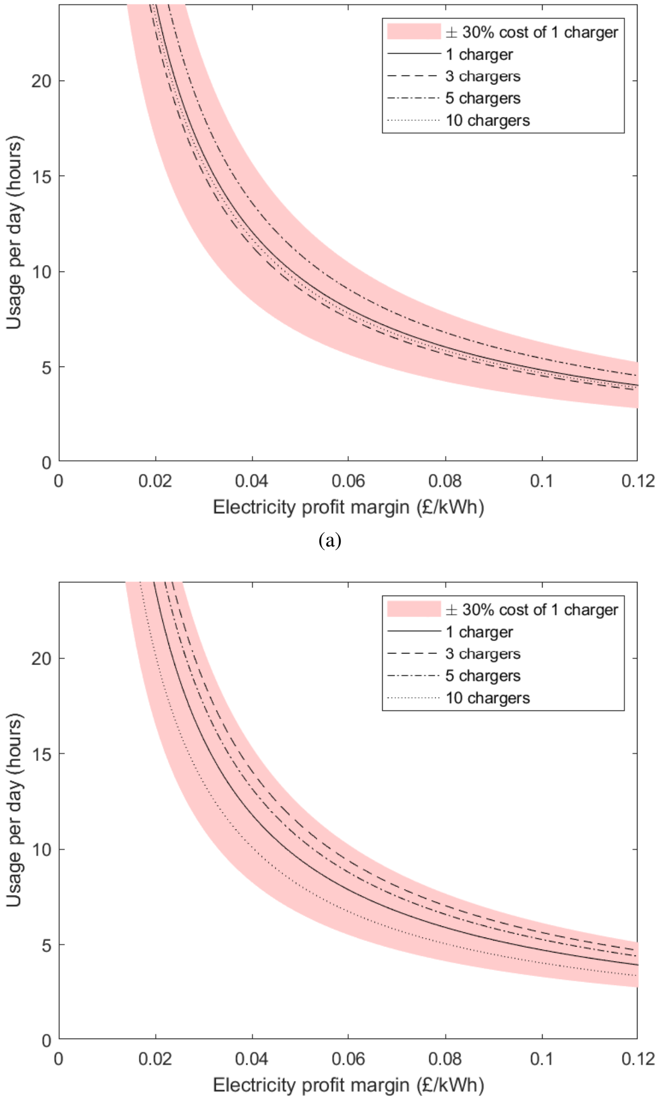
Based on these analyses, the following conclusions can be drawn:

1) Splitting fewer longer charging stops (45 min every 4h 30m) into multiple smaller duration stops (30 min every 2h 15m) results in a reduced battery size requirement by around 45%.
2) High capacity chargers result in a significant reduction in battery size requirements for long-distance electric HGV journeys, but not for short-distance journeys with frequent or longer stops.
3) High-capacity chargers are as economically feasible as low-capacity ones for small stop durations of around 20 min because they have similar break-even periods given the same usage.

TABLE IV

NUMBER OF DAILY CHARGE EVENTS REQUIRED FOR A 15-YEAR COST BREAK-EVEN

Location Stop Time: 20 min	**Required minimum number of daily charge events**			
	$\Delta r_e = £0.04/\text{kWh}$	$\Delta r_e = £0.06/\text{kWh}$	$\Delta r_e = £0.08/\text{kWh}$	$\Delta r_e = £0.1/\text{kWh}$
600 kW charger	41	27	20	16
1 MW charger	42	28	21	17



(a)

(b)

Fig. 3. Usage per day required to achieve cost break-even in 15 years for (a) 600 kW charger and (b) 1 MW charger.

4) For long-distance journeys in sparse geographies, static charging needs to be supplemented by dynamic on-road charging.

From these conclusions, it is seen that fast chargers work well in most cases but are not very useful in a few cases. Hence, the type of charging infrastructure required will vary across different types of logistics operations and diverse geographies. It may be noted that this analysis can be performed for any route in any country given proper placement of chargers and rest stops. In future, a network of such journeys can be used to analyse the exact placement of high-capacity static chargers based on their utilisation, along with the incorporation of a charging speed profile.

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