

An electric road system or big batteries: Implications for UK road freight

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ABSTRACT

An Electric Road System (ERS)—comprising a network of overhead cables to charge Heavy Goods Vehicles (HGVs) via a pantograph pick-up—is a cost-competitive solution to rapidly decarbonise the UK road freight sector. A major benefit over conventional battery electric HGVs is the reduction in battery capacities needed to fulfil logistics needs. In this study, we develop a detailed vehicle simulation model and use it to calculate the battery capacity requirements of real UK logistics journeys against a range of ERS network sizes and on-route static charging options. The results show that, averaged over all static charging scenarios, ERS reduces battery sizes by 41 %, 62 %, and 75 % for the ‘Light’ (2,750 km), ‘Medium’ (5,500 km) and ‘Heavy’ (8,500 km) ERS scenarios. Of the static charging scenarios, drop-off charging is shown to be more effective than rest stop charging at reducing battery sizes.

Introduction

Background

The climate crisis is arguably the defining challenge of our age. The Intergovernmental Panel on Climate Change (IPCC) predicts the earth’s average temperature will likely exceed the critical threshold of 1.5 °Celsius within the early 2030s relative to pre-industrial levels [32]. This can only be averted through urgent and drastic interventions in the most carbon-intensive sectors of society. In the UK, while the energy sector has been steadily decarbonising over the last 20 years, emissions from the transport sector have remained relatively stable, such that transport now represents the largest contributor to greenhouse gas (GHG) emissions in the UK at 27 % of the total in 2019 [17]. Road transport carries the biggest share of transport emissions at 91 %. Heavy Goods Vehicles (HGVs) account for 16 % of road transport emissions despite accounting for only 5 % of vehicle kilometres travelled [17].

The UK government has committed in law to a reduction of GHG emissions of 78 % by 2035 relative to 1990 levels [11], with a target of net zero emissions by 2050 [27]. As part of this plan, it has pledged to end the sale of non-zero emission HGVs by 2040, with those 26 t or less being phased out by 2035 [18]. The HGV sector is one of the most

‘difficult-to-decarbonise’ sectors [10], given the vehicles’ significant power and energy requirements. (The total energy footprint of HGVs in the UK is estimated to be 8.2 gigawatts [12], around two and a half times the planned capacity of the UK’s Hinkley Point C nuclear power station.) These targets present a significant challenge for the sector, and drastic solutions will be required at scale in a relatively short timeframe.

Recent trends and research have highlighted three likely solutions for zero-emission HGVs:

- **‘Big-battery’ electric vehicles (B-BEVs)**, with battery capacities of the order of 500–1000 kWh, and a supporting network of high-powered static chargers potentially including those which meet the ‘Megawatt Charging System’ (MCS) standard (1000+ kW). Examples of first-generation ‘big-battery’ BEVs include the 44-tonne-rated Volvo FMX electric (up to 540 kWh, with charging at up to 250 kW) [57], the 65-tonne rated Scania (up to 624 kWh, with charging at up to 375 kWh) [47], and the 37-tonne-rated Nikola Tre (733 kWh, with charging up to 350 kW) [39].
- **Hydrogen fuel cell electric vehicles (FCEVs)**, with large fuel cell stacks, hydrogen tanks (storing either liquid or gaseous hydrogen), and relatively small battery packs. A near-production example is the 37-tonne rated Nikola Tre FCEV, which is reported to have 70 kg of

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onboard hydrogen storage, a 200-kW fuel cell stack, and a 164-kWh battery pack [38].

- **BEVs with an Electric Road System (ERS) (ERS-BEVs)**, whereby battery electric HGVs can draw traction power and charge their batteries dynamically when travelling on the most highly trafficked parts of the road network. While there are no confirmed plans for commercial production, Scania has previously produced pantograph-equipped hybrid electric HGVs for use in ERS trials in Sweden and Germany [46], equipped with 18-kWh battery packs.

An ERS can comprise either overhead conductive, in-road conductive, or in-road inductive power transfer. An overhead conductive system where HGVs connect to catenaries via a deployable pantograph offers the most technology-ready and economically attractive solution and forms the basis of most ongoing trials. In-road inductive systems suffer from lower power transfer efficiencies and cannot offer the power required by HGVs, while in-road conductive systems present concerns for safety and road maintenance [5].

Studies have shown that an ERS-BEV solution is the lowest total carbon-emitting option in certain regions [2,5,37,53]. A clear benefit of an ERS, however, is the reduction in the necessary battery sizes in comparison to a comparable B-BEV solution [55], due to the ability to charge dynamically along major trunk roads. This leads to associated reductions in vehicle costs, embodied carbon emissions, and vehicle weight. The reduction in battery sizes over a national fleet of HGVs will likely far outweigh any additional embodied carbon in the ERS infrastructure, though a detailed study on this is still required.

In comparison, larger battery packs impose additional cost and additional weight which reduces vehicle energy efficiency and which, in mass-limited payload scenarios, can result in additional vehicles required to perform the same transport task. Other benefits include a better distribution of charging loads on the electricity grid over the day compared to MCS-standard static charging, and the efficient utilisation of green electricity directly from the grid into the vehicle instead of via the battery (when operating on the ERS). In comparison, the use of green hydrogen as an energy vector for FCEVs requires around three times the amount of green electricity at the source [8] with significant implications for the costs of the fuel and power generation.

While this study is concerned with road freight vehicle technologies, it is worth mentioning the role of modal shift, especially to rail, in the transition to a net zero freight system in the UK and elsewhere. Rail freight is more energy efficient than road freight: diesel traction freight rail has a carbon intensity of around a third of that of an equivalent diesel-powered 40-tonne articulated HGV, while electric traction freight rail has an intensity of around an eighth of the diesel HGV equivalent [22]. Modal shift to rail is hence an important part of the freight decarbonisation effort. However, diesel-powered rail is of course not a zero-emission solution, and only around 7 % of UK freight rail is electrically-powered [13]; the global figure is around 9 % [30]. Furthermore, loads which are suited to modal shift are limited to longer journeys and journeys within reasonable distance of a suitable railhead. Hence, modal shift is not expected to play as large a role in the transition to net zero by 2050 as the shift to electrification in road freight.

Literature review

Research has demonstrated the feasibility and benefits of ERS in several European countries including Germany [6], Scandinavia [52, 53], Belgium [3], and the UK [2]. The ‘ELISA’ ERS trial has been in operation on the A5 between Darmstadt and Frankfurt in Germany since 2019, with ongoing data collection and analysis activities [48]. The demonstrator is based on the Siemens eHighway system and is illustrated in Fig. 1. A study by PIARC (World Road Association) with a broader geographical view concluded that ERS is feasible in high-income countries, while highlighting several challenges associated with implementation in low- and middle-income countries (LMICs).

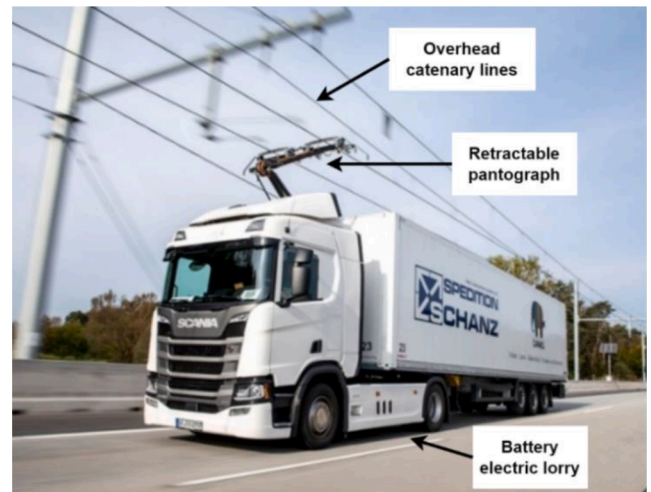


Fig. 1. An HGV travelling on the Siemens eHighway system [51].

Nonetheless, the Indian government recently announced plans for an ERS on the Delhi–Mumbai Expressway within the next three years [36].

The UK study [2] suggested that an ERS—based on the Siemens eHighway catenary system—would be the most economical solution for achieving net zero HGVs in the UK by 2050. The research identified three phases of ERS construction as shown in Fig. 2. These represent different lengths of the UK major road network which could potentially be electrified, starting with the routes most trafficked by HGVs, and extending later to less trafficked routes. The three phases represent approximately 1650, 4010 and 7560 two-way km of roads, respectively. The total infrastructure cost was estimated to be £19.4 billion over 8 years, which was then assessed against business models for fleet operators, infrastructure providers and government. The results suggest that a business model in which fleet operators and infrastructure providers enjoy attractive payback periods of 1.5 and 15–20 years respectively is possible, while government recoups 100 % of lost diesel tax revenues. The study did not, however, account for the challenges of running and charging vehicles off the ERS network, nor did it account for realistic logistics journeys. In many ways, these are the more difficult aspects of the system design.

In a subsequent study [1], the authors carried out a technoeconomic comparison of ERS-enabled electric HGVs and green hydrogen fuel cell electric HGVs. The hydrogen refuelling infrastructure was estimated to be around half the cost of the equivalent ERS infrastructure (£10 billion vs. £19.4 billion). However, the high purchase and fuel costs of the FCEVs resulted in the government having to heavily subsidise fleet operators to maintain favourable payback periods. In order to meet the same target 1.5-year payback period, the government would have to provide fuel subsidies ranging from 131 % to 265 % of the total 2020 diesel tax revenue in 2030 to 16 % to 110 % by 2040. Under all scenarios considered, they showed that the ERS pathway was a more energy-efficient and cost-effective solution for long haul freight in the UK than green hydrogen. In the analysis, ERS was assumed to reduce the necessary battery sizes of the BEV fleets, but the actual battery pack capacities were assumed. This leaves open the important question of precisely what battery size needs result from a given ERS network size. This would enable a more detailed economic analysis on the cost trade-off between ERS and large battery HGVs.

In 2021, the UK Department for Transport (DfT) funded several feasibility studies into B-BEVs, ERS-BEVs and FCEVs in the UK, as part of the preparation process for planned demonstrators [16]. As part of this, a preliminary study evaluated the vehicle and charging requirements for a UK ERS demonstrator consisting of 50 lane-km of ERS on the M180 (the site initially identified by Ainalis et al. [2]) [45]). Several possible vehicle variants were identified for different journey types utilising the

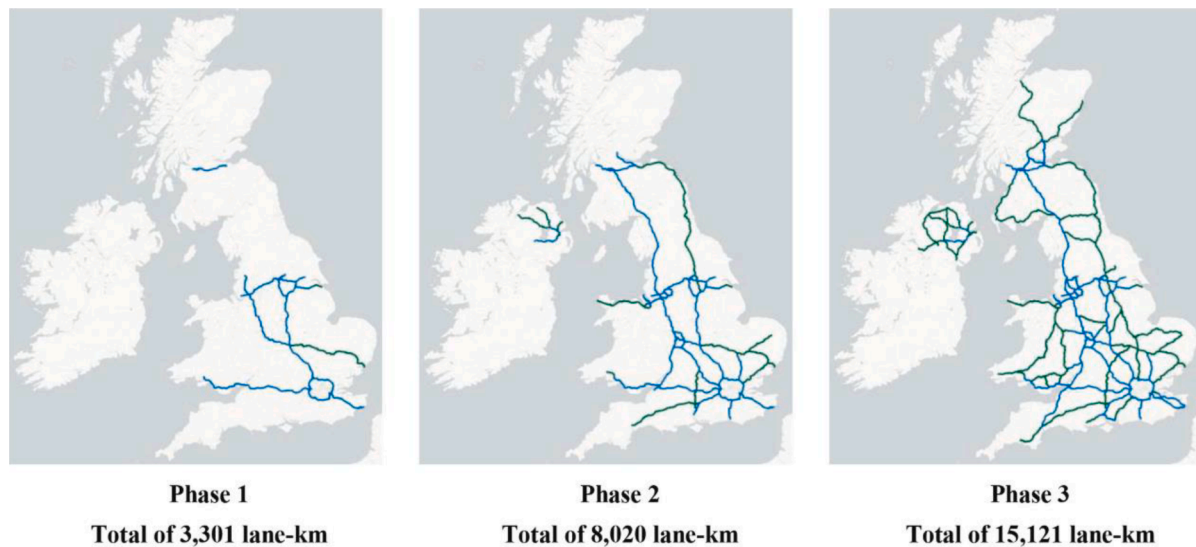


Fig. 2. Proposed 3-phase roll-out of ERS in the UK, from Ainalis, Thorne and Cebon [2].

short ERS demonstrator section, including 150 kWh and 500 kWh ERS-BEVs, and hybrid ERS-BEVs for journeys with significant travel off the demonstrator section.

We can now turn to a review of studies in which the impact of ERS on battery sizing has been considered. While the electric road system concept has existed for over a century (i.e., trams with overhead catenary charging), only in the last decade has the concept been studied in some detail as an economically viable system to support electric trucks and/or cars at scale. Early work focussed on small-scale use cases in Sweden and the USA was presented in 2012 and 2013 [21,56], though the assessment of the impact of ERS on battery sizes has been more recent still. While many studies assert that ERS would reduce battery sizes [5], few have sought to quantify this with many studies resorting to assumed battery sizes.

In a 2013 study of the economics of an in-road conductive ERS between Stockholm and Gothenburg in Sweden [56], researchers assumed battery sizes of 250 kWh for trucks and 11.2 kWh for cars using the system. The authors note that ERS will likely reduce necessary battery sizes, but that limited data on ERS prevents knowing this to any degree of certainty. One of the first studies seeking to quantify this came in 2016, again in Sweden, in which a simulation framework was developed to find the optimal ERS network length and battery size for three ERS scenarios: in-road conductive, overhead conductive, and in-road inductive [52]. The study focussed on general vehicle traffic, and found optimal battery sizes ranging from 4 to 17 kWh for ERS lengths ranging from 480,000 km to 4,300,000 km. In studying the trade-off, a highly theoretical framework was used wherein the ERS was modelled as a square grid, and the linear distance between the grid squares was used to calculate battery size (i.e. not using routed distance along the road network). Schulte and Ny [49] reaffirm the assertion that ERS should reduce battery sizes, but focus more on the life cycle performance of ERS infrastructure and do not assess battery sizing in any detail.

A 2021 study assessing the socio-economic benefits of ERS in Sweden assumed a battery size of 175 kWh for an ERS electric truck based on a desired of-highway range of 100 km, while battery sizes of 1200 and 1560 kWh were assumed for the competing 40 and 60-tonne 'big-battery' trucks [7]. A 2022 study on the techno-economic merits of ERS (again for the case of Sweden), was one of the first to study the ERS and battery size trade-off in detail [44]. A range of possible battery sizes (from 75 to 1000 kWh) was assessed against a range of charging scenarios (including ERS, depot charging, drop-off charging, and public charging) for the case of medium and heavy goods vehicles (from 16 to 60 tonnes). Modelled freight flow data was used. The results show that

for the case of a 40-tonne HGV with a 250-kWh battery pack 60 % of routes can be operated with a combination of ERS and drop-off charging, while 53 % of routes can be operated with ERS and depot charging. The figure drops to 17 % and 13 % without the ERS; comparable coverage would require battery sizes of 450 kWh and 1000 kWh respectively. Public static charging was shown to yield only 1–17 % operational coverage in all battery size scenarios. Charging power capacities of 100, 500, 750 and 300 kW were assumed for depot, destination, public and ERS charging respectively. A similar trade-off study was conducted for the case of passenger vehicles in 2022, showing that the addition of ERS on 25 % of E and N roads in Sweden reduced median battery sizes from 220 to 278 kWh to 85–110 kWh, a reduction of approximately 60 % [50].

More recent studies have not assessed the trade-off in as much detail but provide additional insights. A study on the case of Flanders (Belgium) presents the trade-off between ERS length and battery size only in terms of total economic cost and emissions [4]. The study considers assumed battery sizes of 100–400 kWh for ERS trucks and 800–1200 kWh for 'big-battery' trucks. However, it does conclude that a battery of 100 kWh can serve most industrial sites in the region based on proximity of the sites to the motorway network (and assuming the vehicle leaves the network with a fully-charged battery). In a German case study, battery sizes of 125 kWh and 1000 kWh were assumed for ERS and big-battery electric trucks respectively [41]. Finally, a North American case study considered different ERS and battery size scenarios for 36-tonne trucks between Toronto and Montreal [14]. Battery sizes of 267, 401, and 534 kWh for ERS trucks, and 1068 kWh big-battery trucks were considered, with the big-battery case based on the expected battery sizing of the Tesla Semi. The authors showed that ERS allowed a 50 % reduction in battery size versus the no-ERS case with comparable performance, provided the ERS could provide at least 250 kW of power.

Contributions

The importance of the trade-off between the extent of ERS infrastructure and battery sizing has been made clear in various economic studies, but the availability of a framework to directly quantify this interaction for heavy goods vehicles is lacking. Several studies have relied on pre-assumed battery sizes, simplified models of the road network or specific routes (as opposed to a national scale scenario), and none consider actual realistic truck journeys on a driving cycle level. The work of Rogstadius [44] is the closest comparable study for the case of Sweden, but this relies on pre-selected battery size scenarios and uses

generalised commodity freight flow data as a proxy for actual truck journeys. Furthermore, there have been no studies in this regard for the case of ERS in the UK. In this work, we develop a novel framework for assessing the trade-off between ERS and battery sizes for heavy goods vehicles on a national scale, which provides a direct quantification of the balance between ERS length and location and battery size. The framework incorporates a detailed vehicle and routing model from which real-life truck journeys can be simulated (with known origin, destination, and stop locations), realistic rest stop behaviour based on driver hour requirements, and a realistic ERS network model based on known truck traffic and feasible build-out scenarios. The framework is applicable to any country.

We then apply the framework to a UK case study, considering a range of future charging infrastructure scenarios on a national scale and analysing how these would impact the required battery sizes of future 44 t HGVs. The scenarios include four ERS scenarios (no ERS, ‘Light’, ‘Medium’, ‘Heavy’), and three static charging scenarios (depot charging only, depot charging plus drop-off charging, and depot charging plus rest stop charging). (Note that the ERS scenarios considered are distinct from the three roll-out phases in Fig. 2.) Eight real UK truck journeys were analysed across a range of logistics scenarios. The results offer some of the first detailed insights into vehicle battery sizes for a UK ERS in the literature. These will help academics and policymakers understand the trade-offs between B-BEVs and ERS-BEVs, drop-off charging versus rest stop charging (for both B-BEVs and ERS-BEVs), and the benefits of a more extensive ERS network on reducing battery sizes.

Simulation model

Details of the simulation model and its validation, the representative journeys considered, and the ERS and static charging scenarios considered are detailed below.

Model overview

The simulation model comprises two sub-models: the driving cycle generator and the vehicle model, which will be discussed respectively in the following sections.

Driving cycle generator

The driving cycle generator creates a route map and a fully characterised driving cycle (e.g., speed and charging profiles), and is summarised in Fig. 3. It was implemented in Python and makes use of the HERE Maps routing API and elevation data [25].

First, a pair of origin and destination coordinates is provided, along with the coordinates of any known drop-off stops (i.e., waypoints) along the route. (The precise journey origins and destinations used in this study are detailed in Table 1.) These inputs are processed via the HERE Maps routing algorithm to generate a GPS-defined route (using the ‘fastest time’ route generation option), speed profile, and elevation profile. The speed profile uses posted speed limits to set the maximum speed on each road section as appropriate for HGVs. The vehicle was assumed to stop at any intersections and roundabouts, and any traffic effects were neglected.

Second, three possible ERS topographies are provided to the model in

Table 1

The locations of origins, drop-offs and destinations for the edge-case journeys evaluated.

Journey type	Origin	Drop-off stops	Destination
Warehouse-to-warehouse	Swindon (industrial estate)	N/A	Newton Aycliffe (warehouse)
	Royal London Hospital	N/A	Wath-upon-Dearne (warehouse)
Multi-drop	Andover (logistics depot)	Lymington, Romsey, Andover, Yeovil, Ongar	Andover (logistics depot)
	Aylesford (distribution centre)	Eastbourne, Lewes, Marylebone	Aylesford (distribution centre)
	Aylesford (distribution centre)	Bloomsbury, Kensington Gardens, Ramsgate	Aylesford (distribution centre)
Tramping	Aylesford (distribution centre)	Saxmundham, Woodbridge, Kingston-upon-Thames	Aylesford (distribution centre)
	Tirril	Shap, Bolton, Buxton, St Ives (Cams)	Wetherby (overnight)
	Wetherby	Newton Stewart, Girvan, Irvine	Tirril

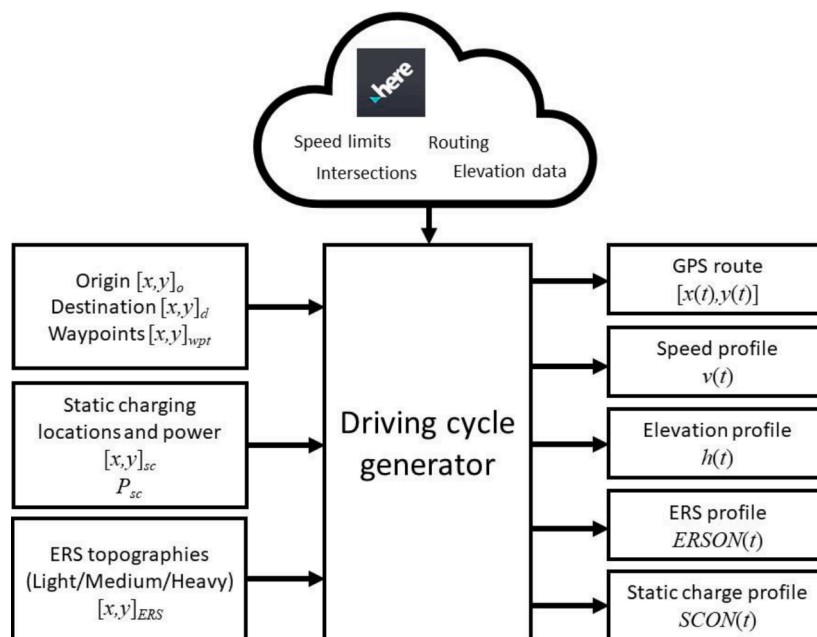


Fig. 3. Schematic of the inputs and outputs of the driving cycle generator.

the form of polygons which envelope the electrified sections of road. These polygons were generated beforehand using QGIS, an open source geographic information system [40]. (More detail on the specification of the ERS polygons is given later.) The overlap between the planned route GPS coordinates and these polygons is calculated which defines a binary ERS profile signal, indicating the availability of ERS as a function of time throughout the driving cycle.

Finally, static charging information is provided for each stop, i.e., whether there is a charger present, the charging capacity in kW, and the duration of the stop. The driving cycle generator converts this into a static charge profile in the time domain.

Vehicle model

The vehicle model was developed in MATLAB and Simulink [35] and is summarised in Fig. 4. The model takes as input the outputs from the driving cycle generator, along with a set of vehicle specifications and drive control parameters and outputs a time history of vehicle power and energy consumption, speed and acceleration, and battery state-of-charge. It was assumed that the ERS is able to supply the required traction power plus an additional 150 kW to charge the battery pack. This results in a typical total power draw from the ERS of approximately 300 kW during motorway cruising, in line with design specifications indicated by manufacturers and similar assumptions in recent studies [14,44]. A vehicle mass of 44 t was assumed throughout the journey. An auxiliary load was included to represent cabin heating and trailer refrigeration. Battery ‘dip’ (the total energy drawn from an unlimited battery in kWh) was calculated for each journey as this allows the battery requirements for a journey to be calculated without assuming a given battery capacity. A usable state of charge of 10–90 % was assumed (giving $SOC_{usable} = 80\%$). Further details of the model and parameters used in the simulation model are provided in Appendix A.

Vehicle model validation

The model was validated against test data provided by TU Darmstadt which was collected in the course of the ELISA field trial (‘Elektrifizierter, Innovativer Schwerverkehr auf Autobahnen’ - Electrified, innovative road freight transport on motorways), which was funded by the Federal Ministry for Economic Affairs and Climate Action [48]. Measured vehicle data (including power demands from the diesel engine, electric motor, battery pack, and pantograph, and vehicle mass) were provided for a 40-tonne hybrid HGV operating around Darmstadt

and Frankfurt, including use of the eHighway test site. The vehicle utilises a parallel hybrid electric powertrain with a 450 hp (335 kW) internal combustion engine, a 130 kW electric motor and an 18 kWh battery. After data cleaning, a 35 km section of the 230 km journey which included some travel on the eHighway was isolated and found to be suitable for the validation. An ERS battery charging rate of 10 kW was chosen in the model to match the average rate observed in the measured data when the vehicle was connected to the eHighway. This is at the lower end of known overhead catenary power transfer capabilities of 15–85 kW [5].

The result of the validation is shown in Fig. 5. In the scenario shown here, the recorded speed of the vehicle was used as the reference speed for the model. The vehicle mass was 40.2 t. Because the simulation model is a full electric and not hybrid, some processing was required to appropriately compare the model with the experimental measurements. The traction power was calculated from the measured data (calculated from measurements of both ICE and EM power, by assuming a transmission efficiency of 95 %), and this was compared with the traction power calculated from the model. Then, an ‘effective battery dip’ was calculated by adding the measured ICE power demand as if it were being supplied from the battery in addition to the battery’s measured demand. This could then be compared with the calculated battery dip from the full electric model. The results show an excellent agreement between model and experiment in both the power demand and the battery dip, with a final difference in battery dip of 0.93 kWh over 35 km out of a total modelled battery dip of 46 kWh (i.e., a 2 % difference). A second scenario in which the modelled theoretical speed profile was used yielded a final difference of 0.61 kWh (i.e., a 1.3 % difference).

Charging scenarios

Three possible ERS topologies were considered [55]. These are based partly on the original proposed phases [2], but now represent distinct UK network options, as opposed to three phases of a single proposed network. Each topography represents a different electrified length assuming that both directions of travel would be electrified in all cases. These are illustrated in the diagrams of Fig. 6 and are referred to as the ‘Light’ (c.2750 km), ‘Medium’ (c.5500 km) and ‘Heavy’ (c.8500 km) options (i.e., 5500, 11,000 and 17,000 single-track km respectively). ERS ‘Light’ represents a consolidation of the roads with the highest HGV traffic counts according to the UK Department for Transport [15]. Additional roads with the next highest HGV traffic counts were added

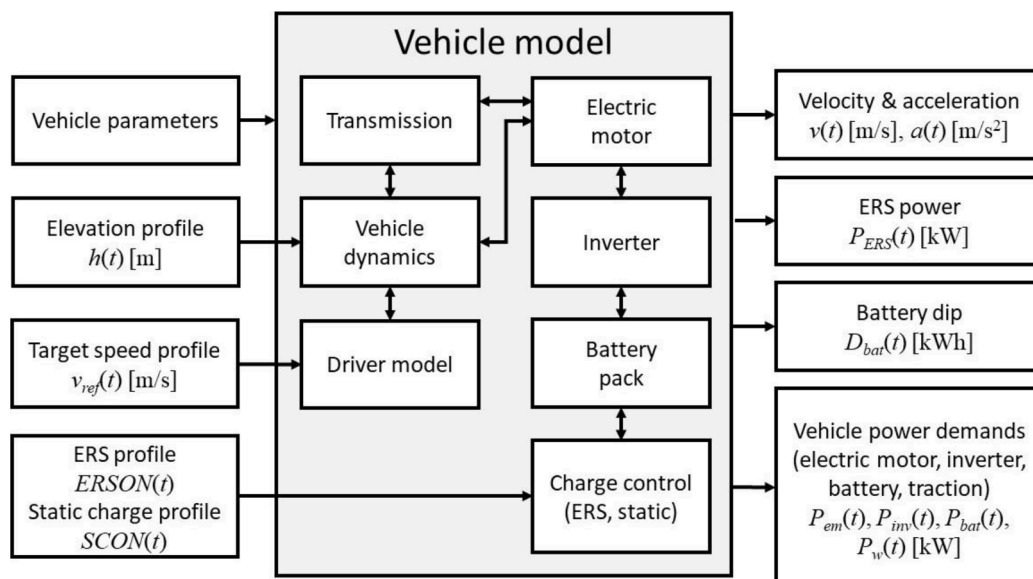


Fig. 4. Schematic of the components, inputs and outputs of the vehicle model.

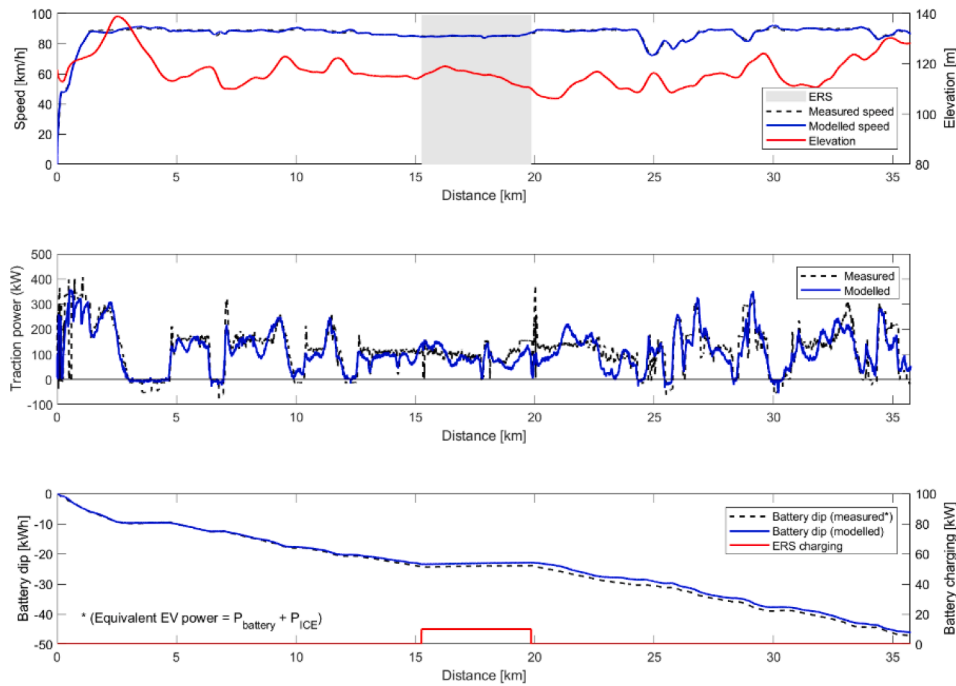


Fig. 5. Comparison of model predictions with vehicle test data collected by the ELISA project for vehicle speed (top), traction power (centre) and battery dip (bottom).

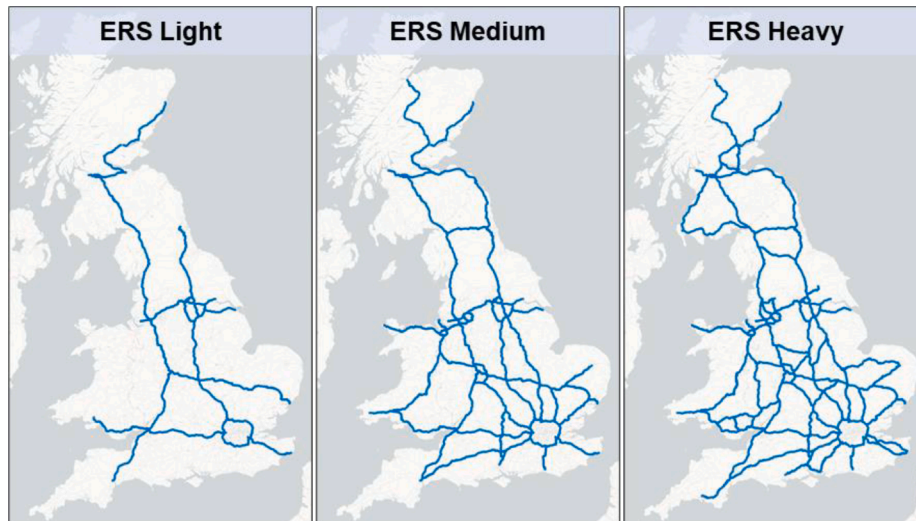


Fig. 6. Proposed alternative ERS topographies used in this study. From left to right: ‘Light’ (c.2,750 km), ‘Medium’ (c.5,500 km) and ‘Heavy’ (c.8,500 km).

for the ‘Medium’ and ‘Heavy’ topographies respectively. A fourth scenario of ‘No ERS’ was also considered representing the ‘big battery’ scenario.

In addition, three static charging systems were considered, providing up to twelve unique charging scenarios for each journey. All scenarios assumed that low-powered depot charging is available, and that vehicles would begin a journey from the depot fully charged. However, the availability of on-route static charging is different in each scenario, the options being: (i) no static charging, (ii) drop-off charging (i.e., charging at warehouses or retail outlets during each drop-off stop), and (iii) rest stop charging (i.e., charging at truck stop facilities during each rest stop). High-powered static chargers were assumed for the drop-off and rest stop charging. It was assumed that rest stops take place in line with UK drivers’ hours regulations [19], and with drop-off stops not contributing to driver rest time. Charging power of 100 kW was assumed

for depot charging and 600 kW for drop-off and rest stop charging, in line with industry expectations and recent work [44].

UK drivers are required to stop for 45 min for every 4h30m of driving, which can be taken in multiple breaks; for the current study we assumed that a single 45-minute break was taken after each 4h30m of driving. A suitable rest stop was assumed to be available near the vehicle’s location at the required stop time. This assumption was subsequently reviewed (see later). Charging times at drop-off stops were assumed to be 20 min each.

Journey data

A set of data for logistics journeys was obtained from three freight operators in the UK. These were a supermarket, a small single-truck company, and a third-party logistics operator (3PL). In each case,

journey data consisting of origin, destination, and drop-off locations were provided. It was found that all the journeys could be characterised as either: (i) ‘warehouse to warehouse’ (repeatable journeys typically between two points such as a port and a warehouse or a distribution centre and a warehouse), (ii) ‘multi-drop’ (journeys making several stops on and off the trunk road network, such as supermarket deliveries), and (iii) ‘tramping’ (long multi-drop journeys typically undertaken by small operators where the truck and driver don’t return to depot for several days). From this dataset, a subset of ‘edge cases’ was identified to study which represented some of the more challenging truck journeys within each of the three journey categories. The selected journeys are summarised in Table 1. The tramping operation covered two days, each of which was assessed separately assuming that the vehicle would be able to fully recharge at an overnight stop between the two legs.

Model output

The final output from the models includes a route map and fully characterised driving cycle time-history, examples of which are given in Fig. 7 and Fig. 8 for an all-day ‘tramping’ scenario with ERS ‘Light’ and

drop-off static charging. The top plot in Fig. 8 shows the target vehicle speed in the dashed black line (as output by the driving cycle simulator), the actual speed as achieved by the vehicle/driver model in the solid black line, with the elevation profile in red. Sections of the journey on an ERS section of road are shaded grey. Four 20-minute drop-off stops are evident in the example, as well as a 45-minute rest stop at around 5h30m (after 4h30m of driving). The bottom plot shows the resultant battery state of charge (SOC) profile in black as measured in ‘battery dip’ (total energy consumed). Also shown are any charging opportunities via ERS (blue) or static charging (red). The availability of the charging is shown as a dashed line; the line is solid when the battery actually draws charge. A battery capacity of 357 kWh would be required for this journey scenario.

Results

The results from the validated vehicle simulations are presented in this section, including analyses of the general journey characteristics, calculated battery sizes, and the locations of rest stops.

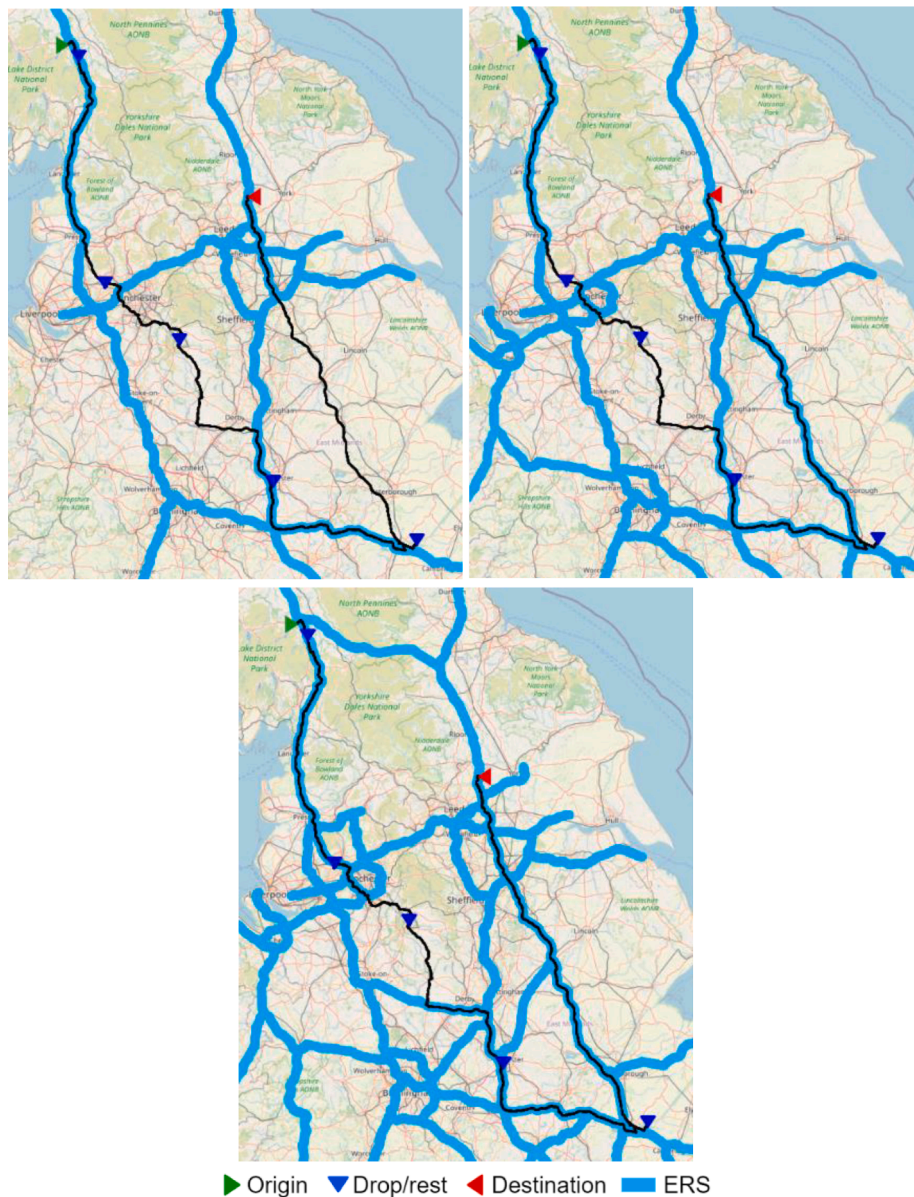


Fig. 7. Tramping Day 1 route with ERS ‘Light’ (left), ‘Medium’ (centre), and ‘Heavy’ (right).

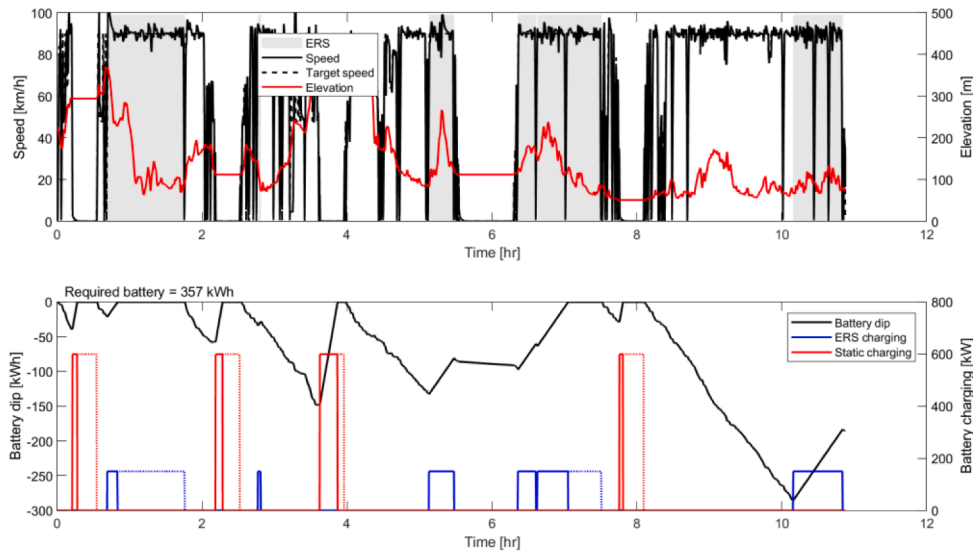


Fig. 8. Tramping Day 1 driving cycle (top) and battery dip (bottom) with ERS ‘Light’ and drop-off charging.

Journeys

Table 2 gives a summary of each of the journey distances, duration, and average vehicle energy consumption. Average energy consumption ranges from 1.73 kWh/km to 2.09 kWh/km, depending on the route, elevation profile and the number of stop-start events. Recall that this assumes a fully laden 44-tonne vehicle with auxiliary loads for the entirety of the journey, and so this represents the upper end of what might be expected. The applicability of the static charging scenarios to each journey is also shown.

Battery sizes

Summarised battery capacity results are given in Table 3, Table 4, and Table 5, for the warehouse-to-warehouse, multi-drop, and tramping journeys respectively. Each table shows the calculated battery capacity requirements for each of the four ERS scenarios (‘L’ = ‘Light’, ‘M’ = ‘Medium’, ‘H’ = ‘Heavy’) and three static charging scenarios. Some cells are empty as the case is not applicable (e.g., journeys of less than 4h30m did not include a simulated rest stop). In some scenarios, the same battery sizes result from both ‘Light’ and ‘Medium’, or ‘Medium’ and ‘Heavy’ ERS topographies. In these cases, either the added ERS segments do not overlap with the route, or they affect a segment of the route not associated with the maximum battery dip. (For example, if additional ERS were added to the scenario in Fig. 8 such that the battery could now charge between the 4- and 5-hour locations, it would not impact the required battery size for the journey which is in fact dictated by the long section of the journey off the ERS between the 8- and 1-hour locations.) Recall that these results represent the highest expected values with an

HGV fully laden to 44 t for the duration of the journey.

The impact of adding an ERS network on reducing the necessary battery pack sizes is clear. In most cases, the addition of ERS ‘Light’ makes the biggest impact, reducing the battery size from 1479 to 573 kWh in one case (‘Tramping day 1’, no static charging), a reduction of 906 kWh. Extending the ERS further from ‘Light’ to ‘Medium’ has a varied impact depending on the journey, but in one case reduces the battery size from 1503 to 880 kWh (‘Andover logistics depot’, no static charging), a reduction of 590 kWh. In most cases, increasing further to the ‘Heavy’ ERS network presents additional reductions though with diminishing returns and increased capital costs. (The ‘Light’ and ‘Medium’ ERS topographies already target the routes with the highest HGV traffic volumes, and so as more ERS is added to less-trafficked routes the strength of the economic case will reduce.)

The addition of drop-off charging significantly reduces the required battery sizes across all scenarios, from 1503 to 479 kWh in one instance (‘Andover logistics depot’), a reduction of 1020 kWh. This assumes that retailers and warehouses are willing to install expensive charging capacity, which will in many cases be servicing third-party vehicles. While there is some evidence of the roll-out of chargers for smaller urban distribution vehicles [31], there is no guarantee that this would be available at all drop-off locations as modelled here. The availability of charging facilities at rest stops is perhaps a more likely scenario, although the observed reduction in battery sizes is not quite as pronounced as that in drop-off charging due to the typically shorter total time spent at rest stops than drop-off stops. However, significant reductions in battery size are still observed, with a reduction from 1436 to 866 kWh in the ‘Tramping day 2’ journey.

Table 6 summarises the average battery size reductions in kWh and

Table 2
Journey distances, durations, and average power requirements.

Journey	Distance (km)	Duration (hr)	Energy cons. (kWh/km)	Energy cons. (kWh)	Static charging scenarios	
					Drop-off	Rest stops
Swindon to Newton Aycliffe	420	5.9	1.73	727	n	y
Royal London to Wath Dearn	289	3.6	1.65	477	n	n
Andover (logistics depot)*	686	15.2	1.94	1331	y	y
Aylesford Eastbourne	317	6.2	2.06	653	y	n
Aylesford Bloomsbury	279	5.8	2.03	566	y	n
Aylesford Saxmundham	480	8.3	1.91	917	y	y
Tramping Day 1	674	10.9	1.76	1186	y	y
Tramping Day 2	607	9.7	1.89	1147	y	y

* Actual rest stop times known and used in simulation.

Table 3
Required battery capacities (in kWh), warehouse-to-warehouse journeys.

<u>Swindon to Newton Aycliffe</u>					<u>Royal London Hospital to Wath Dearne</u>						
		ERS topography						ERS topography			
		None	L	M	H			None	L	M	H
Static charging	None	908	181	129	129	Static charging	None	599	502	71	71
	Drop-off	–	–	–	–		Drop-off	–	–	–	–
	Rest stops	755	181	129	129		Rest stops	–	–	–	–

Table 4
Required battery capacities (in kWh), multi-drop journeys.

<u>Andover logistics depot</u>					<u>Aylesford Eastbourne</u>						
		ERS topography						ERS topography			
		None	L	M	H			None	L	M	H
Static charging	None	1503	880	290	224	Static charging	None	818	588	366	342
	Drop-off	479	337	103	88		Drop-off	336	226	223	223
	Rest stops	794	794	290	224		Rest stops	–	–	–	–
<u>Aylesford Bloomsbury</u>					<u>Aylesford Saxmundham</u>						
		ERS topography						ERS topography			
		None	L	M	H			None	L	M	H
Static charging	None	709	700	684	268	Static charging	None	1148	492	181	181
	Drop-off	314	314	310	97		Drop-off	465	233	87	87
	Rest stops	–	–	–	–		Rest stops	847	492	181	181

Table 5
Required battery capacities (in kWh), tramping journeys.

<u>Tramping day 1</u>					<u>Tramping day 2</u>						
		ERS topography						ERS topography			
		None	L	M	H			None	L	M	H
Static charging	None	1479	573	367	224	Static charging	None	1436	1011	1011	384
	Drop-off	718	357	167	122		Drop-off	675	377	377	252
	Rest stops	910	429	367	224		Rest stops	866	544	544	290

Table 6
Potential battery capacity reductions relative to ‘no ERS’ (in kWh and%), averaged over all journeys.

<u>Ave. battery size reduction (kWh)</u>		ERS topography			<u>Ave. battery size reduction (%)</u>		ERS topography		
		L	M	H			L	M	H
Static charging	None	459	688	847	Static charging	None	43 %	64 %	79 %
	Drop-off	191	287	353		Drop-off	38 %	58 %	71 %
	Rest stops	346	532	618		Rest stops	42 %	64 %	74 %
Ave. reduction:					Ave. reduction:		41 %	62 %	75 %

percentage over all journeys which result from the addition of ERS relative to a ‘no ERS’ benchmark. The battery size reductions in kWh vary between static charging scenarios with the largest savings expected in the scenarios with the highest benchmark battery sizes. However, the percentage reductions are relatively consistent across all static charging scenarios, with average reductions of 41 %, 62 % and 75 % with the introduction of ERS ‘Light’, ‘Medium’ and ‘Heavy’ respectively.

The battery pack of a 44-tonne battery electric HGV represents upwards of 50 % of the cost of the vehicle [29] and so these reductions represent significant savings to operators either purchasing or leasing such vehicles. Such a battery reduction also translates into an important reduction in embodied GHG emissions. In a life cycle analysis carried out by Scania based on a 28-tonne 300-kWh 3-Axle rigid truck, the battery cells were found to account for 41 % of embodied emissions in the production of the vehicle [9]. Considering that there are now commercially available 40-tonne tractor units with battery capacities of over 600 kWh, we can conclude that battery packs for 44-tonne HGVs will account for well over 50 % of the vehicle’s embodied emissions. Assuming a representative battery cost and carbon footprint of US \$132/kWh and 150 kgCO₂/kWh respectively [20,23], these results represent savings of approximately US\$25,000–112,000 and 29–127 tCO₂ per vehicle relative to a ‘no ERS’ scenario.

It is useful to compare the purely ‘big-battery’ (‘BB’) scenarios (with either drop-off or rest stop charging, but no ERS) with purely ERS scenarios (with no static charging other than depot charging). These cases correspond to the top row and left column of Tables 3–5. This provides insights into the outcomes of not investing heavily into either big batteries and static charging or investing in ERS infrastructure (with associated reductions in battery sizes and hence vehicle costs). A comparison of the required battery sizes is presented in Fig. 9. Note that the battery sizes for the ‘BB-rest’ scenario (no ERS, rest stop charging) are closely matched at the time between stops is prescribed in all cases and variations are mostly due to differences in speed profiles and elevation along each route. In comparison there is more spread in the ERS results up to the ‘Heavy’ scenario in which most of the truck roads used in each journey are electrified. It is also clear that the tramping and multi-drop journeys yield the largest battery size requirements due to having large portions of the journey off the ERS.

From Fig. 9 we can conclude that drop-off charging is the most effective big-battery static charging strategy to minimise battery sizes. For the ERS scenarios, battery size parity with this seems to exist somewhere between the ‘Light’ and ‘Medium’ ERS scenarios. Of course, drop-off charging requires all warehouses and major retailers to simultaneously invest in fast-charging infrastructure, whereas ERS charging

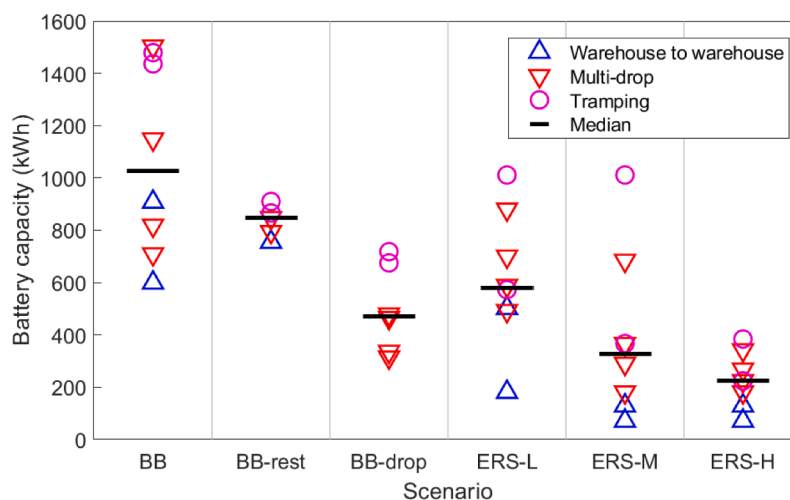


Fig. 9. A comparison of the required battery capacities in the B-BEV and ERS-BEV scenarios.

can be installed across the country by a single entity. Realistically, a ‘Light’ or ‘Medium’ ERS scenario would be supported by a moderate distribution of rest stop charging facilities, but these facilities would require substantially less charging power and power supply capacity than the equivalent for the big-battery scenario. The ‘Tramping day 2’ scenario is a relative outlier due to its significant off-motorway driving requirements, and operators with such journeys would need to adjust their routes for ERS in future in this scenario.

We can compare the results with those from the limited comparable studies in the literature. An average 1000 kWh battery pack for the big-battery scenario with no ERS (Fig. 9) compares well with the finding of Rogstadius [44], as too does the finding that ERS plus drop-off charging can achieve an approximately 50 % reduction in battery sizes (Table 6). (In this case the ERS ‘Light’ topography is probably most comparable with the coverage used in the study.) However, the two studies differ significantly in the observed impact of rest stop/public charging. The present study assumes availability of rest stops where needed based on a driving time while the 2022 study appears to use only known large, designated rest area sites in Sweden. A 50 % reduction relative to no static charging case also compares well with the findings of Darcovich et al. [14]. Finally, where previous studies have assumed battery sizes for ERS trucks and big-battery trucks of around 125–400 and 800–1500 kWh respectively, this seems to be reasonably well-justified. However, the present study has shown how this is sensitive to different combinations of ERS and static charging, as well as large variations between individual journeys. In particular, we have shown that battery sizes for the ‘big-battery’ scenario can be bought down to around 500 kWh if charging is available at all drop-off locations. The assumed ERS HGV battery sizes of 150 and 500 kWh in a precursor UK study [45] are shown to align very well with the calculated range of 129–544 kWh for ERS ‘Medium’ and rest stop charging (Table 4 and Table 5).

Rest stop locations

The rest stop locations in the simulations were solely determined by driving time, as the actual location of future public truck stops with static charging are not known. Here, we evaluate the locations of these rest stops against the current known locations of truck stop sites in the UK. Existing truck stop location data were sourced from three publicly available datasets, as summarised in Table 7. Many of the recorded sites may be duplicates and out-of-date; nevertheless, they provide an indication of the distribution of existing truck stop sites across the UK, each of which may, in future, provide static charging facilities for HGVs. In a few cases, an obvious known truck stop was not included in any of the datasets, and so these additional sites were added manually.

Table 7

Publicly available truck stop location datasets used.

Source	Number of stops	Coverage	Notes
HGV Alliance UK Ltd [26]	348	England, Scotland, Wales	Includes truck stops categorised as either ‘fuel’ or ‘HGV parking’. Data is continually sourced via public submission subject to review and can be edited by request.
truckingjobs.co.uk [34]	199	England, Scotland, Wales	Includes ‘truck stops’ and ‘safe parking spots’. Data is continually sourced via public submission subject to review and can be edited by request.
Transport Scotland [54]	33	Scotland	Data provided by the Scottish Enterprise GIS Team. Data is valid as of 12 April 2010.

The locations of the simulated journey rest stops are shown in Fig. 10 alongside the existing truck stop locations. The ERS ‘Medium’ topography is shown for illustration. Three of the simulated rest stops occur at an existing truck stop site, while another three are within 16 km of the nearest truck stop facility. In terms of the calculated battery capacities (Tables 3–5), this suggests that an additional ~30 kWh may be required for these journeys at most, but, depending on the nature of the journey and where the precise minimum battery dip occurs, this value may be lower or even zero. The remaining rest stop location at Barrhill (day 2 of the tramping journey) is a clear outlier, occurring a significant 111 km from the nearest known truck stop site. Tramping journeys were expected to present some of the most challenging scenarios given their often-extensive travel off of the major road network, and this example has demonstrated this.

We can further observe from Fig. 10 that existing truck stops tend to be concentrated around the major trunk road network and hence around the likely path of the proposed ERS. ERS-enabled HGVs travelling along the network will likely rely less on static charging at existing truck stop locations along the ERS network, and more on static charging sites located off the ERS as illustrated in the example of Barrhill above. However, the number of such sites and their operational capacity will likely be small compared to existing major truck stops. An extensive analysis of representative UK journeys would be required to gain more insights into the possible number and location of such additional sites for a given ERS configuration.

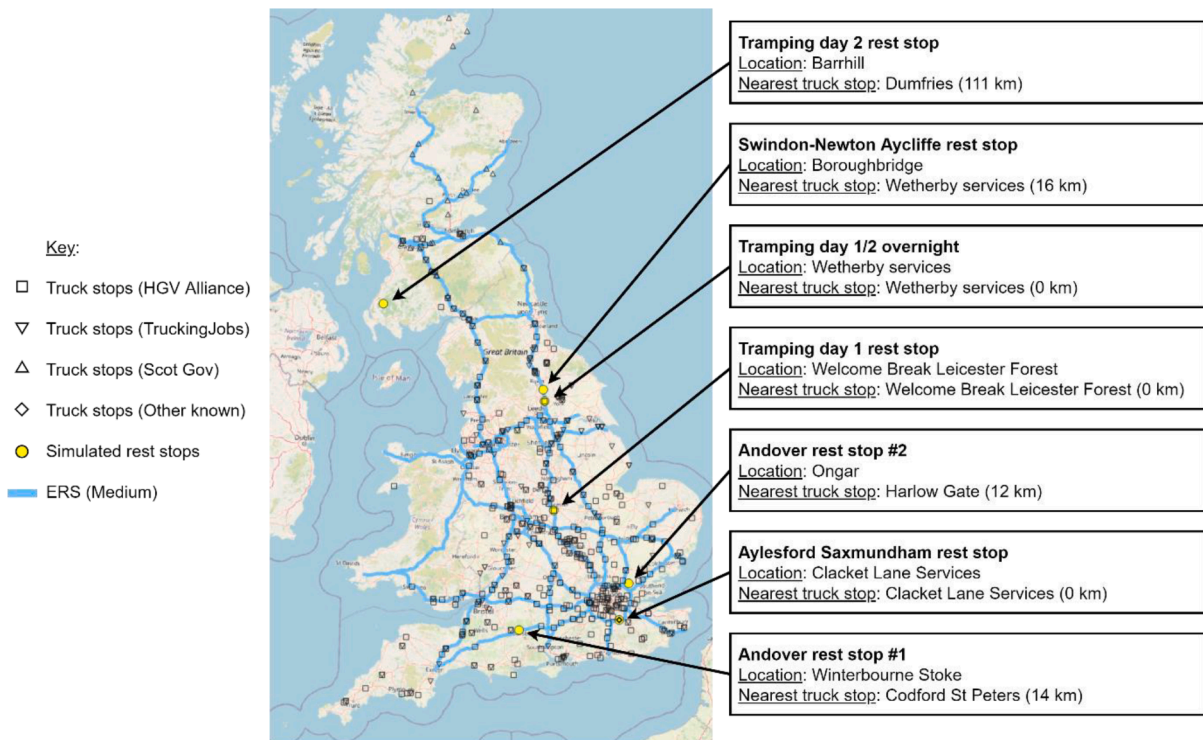


Fig. 10. A comparison of the simulated rest stop locations with existing truck stop sites.

Conclusions and future work

A simulation-based study of a proposed Electric Road System (ERS) for UK road freight has been carried out, using a detailed route and vehicle simulation model. Four scenarios of ERS (none, 'Light', 'Medium', and 'Heavy') and three scenarios of on-route static charging (none, drop-off charging, and rest stop charging) were evaluated. A selection of eight real-world journeys were simulated which included 'warehouse-to-warehouse', 'multi-drop', and 'tramping' operations, and the required battery size in each scenario was calculated. From this study, we can conclude the following:

- 1 Without ERS or on-route static charging, battery sizes of between 599 and 1503 kWh would be required to fulfil the journeys considered, assuming an HGV loaded to 44 t throughout the journey. Average energy consumption rates were calculated to be between 1.65 and 2.06 kWh/km.
- 2 The addition of an ERS was shown to reduce the required battery capacity in all static charging scenarios relative to a scenario with no ERS. Battery capacity reductions of 41 %, 62 %, and 75 % were calculated for ERS topographies of length 2750, 5500, and 8500 two-way km respectively ('Light', 'Medium' and 'Heavy' ERS), averaged over all journeys. Reductions ranged from 191 to 847 kWh, depending on the static charging scenario, which implies approximate cost and embodied carbon emission savings of US \$25,000–112,000 and 29–127 tCO₂ per vehicle relative to a 'no ERS' scenario.
- 3 Both drop-off and rest stop charging were shown to reduce battery sizes across all ERS scenarios. Drop-off charging was shown to be the more effective of the two resulting in smaller battery sizes for the journeys considered, while rest stop charging provided a more consistent battery capacity requirement between journeys.
- 4 An ERS between the 'Light' and 'Medium' topographies in length with no on-route static charging was shown to yield comparable average battery sizes to large-scale drop-off charging for the considered journeys (approximately 450 kWh).

These results provide valuable insights into how policy decisions pertaining to charging infrastructure will have a direct impact on the cost and embodied carbon emissions of future electric HGVs in the UK and elsewhere. There is a trade-off between a centralised ERS with a smaller network of static chargers at rest stops and HGVs with smaller batteries, and a large, decentralised network of 'megawatt' charging facilities at warehouses and retail outlets along with large-battery HGVs. In the former case, a large ERS construction project could be coordinated and funded centrally, while the investment burden on transport operators is reduced due to smaller batteries. In the latter case, a disparate group of warehouses and retailers would need to be encouraged to invest in the required large-scale static charging infrastructure in a coordinated manner, while a significant cost burden will lie with the operators to purchase HGVs with large batteries.

If the vehicle purchase costs are prohibitive, the uptake of zero emissions HGVs will not be sufficiently rapid and will likely require additional investment from government in the form of subsidies to ensure that decarbonisation goals are met. Furthermore, the decision to pursue either an ERS- or 'big battery'-led policy will impact energy planning and energy policy as the two solutions would result in different loading patterns on the electricity grid, with ERS likely resulting in lower peak loads and hence minimal grid expansion. However, a full assessment of the costs, risks and logistical implications will be required to support such an important policy decision.

Future work will investigate in more detail the cost and carbon implications of the various ERS and static charging scenarios, taking particular account of the trade-off between big batteries with high-capacity static charging and smaller batteries supported by an ERS. A broader study of a larger dataset of UK truck journeys will also be carried out to get a more detailed statistical distribution of battery capacity requirements for the different charging scenarios beyond the edge-cases considered here. Additional factors to be considered will be the impact of battery size on payload capacity and energy consumption, and variations on current rest stop practises. Finally, the current study has only considered individual journeys, while current logistics operations require an individual truck to perform a range of journey types. Further

analysis will assess the implications of this for future logistics operations and vehicle allocation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A – Simulation model and parameters

The vehicle simulation model was implemented in MATLAB and Simulink [35]. The model builds on a previous battery electric vehicle model which was validated for a city bus in London [33]. The bus model was adapted for application to a 44 t articulated HGV with functionality for ERS and static charging added in consultation with industry collaborators Scania and Siemens. An overview of the high-level model framework is given in Fig. 4.

The standard vehicle longitudinal equations of motion are contained in the vehicle dynamics block, and are formulated on a power basis as follows [24,28]:

$$m \cdot a(t) \cdot v(t) = P_w(t) - P_a(t) - P_{rr}(t) - P_g(t) - P_{aux}(t)$$

where m is the mass of the vehicle, a is the longitudinal acceleration, v is the longitudinal speed, P_w is the power applied at the drive wheels, P_a is the required power to compensate for aerodynamic drag, P_{rr} is the required power to compensate for rolling resistance, P_g is the required power to compensate for road gradient, and P_{aux} is the power drawn for auxiliary services (cab heating and refrigeration). These are in turn calculated as follows:

$$P_a(t) = \frac{1}{2} \rho_{air} C_D A v(t)^3$$

$$P_{rr}(t) = C_{rr} m g v(t)$$

$$P_g(t) = m g \sin(\theta(t)) v(t)$$

$$v(t) = \int a(t) dt$$

where ρ is the density of air, g is the gravitational acceleration, C_D is the aerodynamic drag coefficient, C_{rr} is the rolling resistance coefficient, A is the vehicle’s frontal area, and θ is the road gradient. The road gradient is a function of the elevation profile $h(t)$ and distance travelled $d(t)$ as follows:

$$\theta(t) = \int \frac{h(t)}{d(t)} dt$$

$$d(t) = \int v(t) dt$$

The power at the wheels is supplied by electrical energy from either the ERS directly (if the vehicle is on a section of ERS), or the on-board battery (if the vehicle is off of the ERS network). In both cases, a driveline efficiency accounts for losses in the transmission, inverter, and battery. The power draw from the ERS and battery are then measured as follows:

$$P_{ERS-traction} = \frac{P_w}{\eta}, P_{bat-traction} = \frac{P_w}{\eta}$$

Where $P_{ERS-traction}$ is the power drawn from the ERS to provide traction power, $P_{bat-traction}$ is the power drawn from the battery, and η is the driveline efficiency. The traction power P_w is controlled via the driver model block which uses a proportional-integral-derivative (PID) controller to track the reference vehicle speed provided by the driving cycle generator.

When the vehicle is connected to a section of ERS, and the battery state-of-charge (SOC) is below 100 %, the ERS will simultaneously charge the battery while providing traction power. A fixed charging rate of $P_{ERS-charge} = 150$ kW is assumed, such that the total power draw from the ERS is approximately 300 kW during motorway cruising, in line with design specifications indicated by manufacturers and similar assumptions in recent studies [14,44]. The availability of the ERS along the driving cycle is indicated by a binary signal, $ERSON$, generated from the driving cycle generator. The total power drawn from the ERS can hence be summarised as follows:

$$P_{ERS} = (P_{ERS-traction} + P_{ERS-charge}) \cdot ERSON, SOC < 100\%$$

$$P_{ERS} = (P_{ERS-traction}) \cdot ERSON, SOC = 100\%$$

The battery can be charged via three pathways: regenerative braking, dynamic charging via the ERS or from static charging. Regenerative braking occurs whenever P_w is negative and $SOC < 100\%$, charging the battery at a rate of:

$$P_{bat-regen} = \eta \cdot P_w, P_w < 0 \cap SOC < 100\%$$

Dynamic charging via ERS occurs whenever $SOC < 100\%$ and $ERSON = 1$:

$$P_{bat-ERS} = P_{ERS-charge} \cdot ERSON, SOC < 100\%$$

Static charging occurs whenever $SOC < 100\%$ and $SCON = 1$, where $SCON$ is the binary signal indicating the existence of a static charger (an output of the driving cycle generator):

$$P_{bat-SC} = P_{SC} \cdot SCON, SOC < 100\%$$

The static charging power, P_{SC} , can be any of $P_{SC-depot}$, $P_{SC-drop}$, or $P_{SC-rest}$, the specified power capacity of chargers at depots, drop-off stops, and rest stops respectively. The net power into the battery (P_{bat}) and net energy stored in the battery (E_{bat}) at any time can hence be calculated as follows:

$$P_{bat} = P_{bat-traction} + P_{bat-regen} + P_{bat-ERS} + P_{bat-SC}$$

$$E_{bat} = \int P_{bat} dt$$

In practice, the simulation adopts a ‘big-battery’ approach instead of using SOC. Battery dip ($D_{bat} = \Delta E_{bat}$) is the net energy drawn from the battery (measured in –kWh) provided a hard limit of $D_{bat} \leq 0$ has been maintained throughout the driving cycle (i.e., $SOC \leq 100\%$). Using SOC would require the battery size to be known *a priori*, whereas with battery dip we can determine the battery size *a posteriori*. Once a full driving cycle has been simulated, the required battery capacity for a journey, C_{bat} , can be determined as follows:

$$C_{bat} = -\frac{\min(D_{bat})}{SOC_{usable}}$$

where SOC_{usable} is the usable state-of-charge range of the battery. For these simulations a usable state of charge of 10–90 % was assumed, giving $SOC_{usable} = 80\%$.

The assumed model parameters are summarised in Table 8. We assume the maximum vehicle mass permissible in the UK of 44 tonnes. Vehicle parameters such as rolling resistance and frontal area were obtained from representative values supplied by manufacturers. Vehicle speed was limited to 90 km/h. An auxiliary load of 4 kW for trailer refrigeration was assumed, based on published semi-trailer refrigeration cycle performance [42,43]. An additional 1 kW was assumed for cabin heating/cooling, giving a total of $P_{aux} = P_{refrig} + P_{heat} = 5$ kW. An estimated overall drivetrain efficiency of 90 % was obtained from manufacturers, as was the useable battery state-of-charge range of 80 %. Charging rates were selected to be representative of a future charging network system, based on current technology trajectories and insights from vehicle and ERS manufacturers.

Table 8
Simulation parameters.

Parameter	Description	Value
m	Vehicle mass	44,000 kg
C_{rr}	Rolling resistance coefficient	0.006
C_D	Aerodynamic drag coefficient	0.7
A	Frontal area	7 m ²
d	Rolling diameter of driven wheel	1.0125 m
ρ	Density of air	1.225 kg/m ³
g	Gravitational acceleration	9.81 m/s ²
P_{refrig}	Trailer refrigeration power (average continuous)	4 kW
P_{heat}	Cabin heating power (average continuous)	1 kW
η	Overall driveline efficiency	90 %
v_{max}	Maximum vehicle speed	90 km/h
SOC_{usable}	Usable battery state of charge	80 %
$P_{ERS-charge}$	ERS battery charging power capacity	150 kW
$P_{SC-depot}$	Depot charger power capacity	100 kW
$P_{SC-rest}$	Rest stop charger power capacity	600 kW
$P_{SC-drop}$	Drop-off (warehouse/retailer) charger power capacity	600 kW

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