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Going further with smaller EVs: System-level battery range, emissions and charging infrastructure analysis

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ABSTRACT

Electric vehicles are a necessary part of a zero-carbon future. However, one in five motorists worldwide depend on small petrol motorcycles for their transport needs — vehicles for which no satisfactory low-carbon substitute exists. Meanwhile, the rise in electric car ownership is not reducing GHG emissions as much as often thought, due to the significant emissions from producing ever-larger batteries. Both problems can be solved by uncovering the mechanisms of long distance EV travel, beyond battery range, where the interaction with recharging infrastructure governs vehicle performance.

This study develops a new model for journeys involving multiple run-recharge cycles and introduces a novel metric for EV performance — Day Range. Not only does this allow a direct comparison between a wide variety of vehicle and infrastructure options but, by further manipulating the formulae, high level trends can be observed and specific quantitative guidelines extracted.

In vehicle design, a strong emphasis on efficiency and recharge rates can drastically reduce both in-use and embodied energy while matching the touring performance of a conventional, resource intensive, heavy battery car. Meanwhile, the recharging network can be developed to better support this lower energy use. Taking the example of the UK motorway network, charge rates up to only 100 kW should be installed with the focus instead falling on reliably reducing chargepoint intervals at least as far as the existing target of 28 miles, and ideally much further. In doing so, required battery capacity can be reduced from the 60 kWh+ currently seen as necessary to as little as 25 kWh.

The resulting vehicles not only consume less energy in motion but emit far less greenhouse gases during manufacture and will cost less to produce, allowing a much wider uptake of electric vehicles than possible under the existing, energy intensive battery vehicle touring paradigm.

1. Introduction

The urgency and scale of work needed to avoid climate breakdown can no longer be ignored and a rapid elimination of greenhouse gas (GHG) emissions cannot be delayed (Stern, 2015; Lynas, 2020; IPCC, 2022). While some industries – notably electricity production – have substantially decarbonised in recent years (BEIS, 2020), harmful emissions from the automotive sector continue to increase (Sims et al., 2014; Hung et al., 2021). This is an unacceptable situation.

Switching from personal to public transit networks will undoubtedly yield the greatest reductions in GHG emissions (Berners-Lee, 2020) but some road traffic will be inevitable and the associated emissions must be minimised. Battery Electric Vehicles (BEVs) are already being adopted for local and urban transport (Period, 2021), however they continue to be at a disadvantage to Internal Combustion Engine (ICE) vehicles when covering long distances (Guerra, 2019). At particular disadvantage are motorcycles and similar light vehicles whose low gross mass and purchase price prevent the use of large batteries but it is these vehicles, with both lower embodied as well as in-use emissions, that should be utilised where possible.

1.1. The importance and opportunities of light vehicles

Light vehicles can no longer be ignored in the efforts to electrify road transport; motorcycles alone constitute 20% of the global vehicle fleet and completely dominate in large areas of the global south (Motorcycling - Wikipedia, 2022), where public transport alternatives are often irregular or entirely lacking. For example, over 60% of India's petrol is consumed by two-wheelers (Jeyapandiarajan et al., 2018) with motorcycles representing 75% of Indian vehicle sales (Rajper and Albrecht, 2020). In China, motorised two-wheeler sales beat passenger

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cars by seven to one in 2006 (Rajper and Albrecht, 2020) and, at the extreme, cities like Solo in central Java barely see any other form of transport with almost one motorcycle per person and over 80% of all journeys made by powered two-wheeler (Guerra, 2019).

Light battery vehicles such as scooters are already supplanting equivalent ICE vehicles in urban areas (Cheng et al., 2013) due to lower running cost, local pollution and the relatively low range and power requirements of this environment (Rechkemmer et al., 2019). Many studies therefore focus exclusively on local journeys (Bishop et al., 2011) and there is a tangible absence of literature tackling light BEV long-distance touring. However, these vehicles will remain confined to niche applications and unable to replace even the smallest ICE vehicles if they are unable to meet a user's occasional long-distance needs, however infrequent (Guerra, 2019).

Alongside the already motorcycle-dominated roads of Asia and Africa, smaller vehicles offer an opportunity reduce transport emissions on the resource hungry roads of the global North. Electrification of road vehicles typically reduces per-mile emissions at the cost of substantially higher embodied or up-front emissions due to battery manufacture (Degen and Schütte, 2022). This can lead to much smaller gains than often assumed; one study found a maximum reduction in GHG emissions of only 46% under optimised conditions, assuming no change in driver habits or vehicle type (Meinrenken et al., 2020) and there is a distinct possibility that emissions can be increased by a poorly judged switch away from ICE vehicles (Hung et al., 2021; Barkenbus, 2017). In light of this, a much greater emphasis must be placed on battery size reduction, made possible by both conventional methods such as smaller vehicle types, changes in transport habits and increased vehicle efficiencies as well as new measures specific to battery vehicles such as optimised infrastructure as we show in Section 5.

The objective of this study, therefore, is to investigate the touring abilities of lightweight, low-cost electric vehicles in order to provide an insight into universal trends governing travel beyond battery range. Through a better understanding of how minimal resources can best be used, we show how long distance BEV travel is possible without recourse to oversized batteries thus reducing both cost of, and emissions from, battery electric vehicles.

1.2. Literature review

In the rapidly evolving environment of the emerging BEV market, early papers, such as by Dong et al. (2014), were forced into the twin assumptions that (i) driver habits will not change in the transition to BEVs and (ii) that longer journeys must still be made by fossil fuel power. In light of the rapid electrification of road transport in some areas, the legislative elimination of private ICE vehicles in some jurisdictions and (not least) the impending climate catastrophe worldwide, these assumptions look somewhat outdated in more recent papers that adopt an essentially identical approach, e.g. Zhang et al. (2020). These studies examine variance of battery State-of-Charge (SOC) over a large set of journeys taken from multiday transport studies of large, developed metropolitan areas (Seattle, USA and Karlsruhe and Halle, Germany, respectively), in order to ascertain the optimum combinations of charge point location and vehicle specification to maximise BEV uptake. In both papers the difference between regular short trips and occasional long journeys in excess of vehicle range are identified and the shorter journeys, encompassing the majority of miles driven, naturally present the easiest opportunity for a BEV to outcompete an ICE vehicle.

The ambition of this early approach is taken a step further by Meinrenken et al. (2020), who specifically aim to design cars with an optimum range that would minimise overall GHG emissions. Based on a realistic set of assumptions and data, this work thoroughly investigates the trade-offs between electric vehicles, with high embodied and low in-use emissions, and ICE vehicles, with low embodied and high in-use emissions. Meinrenken et al. find that electric vehicles with a range of only 40 to 98 miles offer the maximal GHG reduction, with the relatively few journeys that exceed the electric range still being undertaken by ICE vehicle. Although necessary in the early stages of EV adoption and still prevalent today, this approach cannot entirely meet the paper's stated objective to shift personal transportation from gasoline fuel to a long term, sustainable alternative as it is dependent on retaining some ICE vehicle travel. At first sight, it seems these findings must provide the optimum solution to minimise GHG emissions but the paper acknowledges how sensitive the conclusion is to the emissions of electricity production, assumed to be $291 g_{eq}$/kWh; a figure greater than the grid mix available in many countries already (Nationalgrideso.com, 2021) and substantially higher than that required to avoid climate breakdown.

As stated most explicitly by Zhang et al. (2020), this method aims to estimate the upper bound of the BEV market, implicitly assuming that the remaining vehicles must remain ICE propelled. In light of the developing climate emergency, we must consider a future where all necessary road journeys are made by BEV utilising low emissions electricity and not perpetuate the 'low hanging fruit' approach that was necessary ten years ago?

Instead of assuming drivers cannot be inconvenienced and asking how to maximise electrified journeys, we should assume all journeys must be electrified and only then ask how to minimise any inconvenience. Under this pragmatic assumption long distance travel becomes the limiting case, and in recent years great advances have been made in both battery and charging technologies (Tu et al., 2019; Dixon and Bell, 2020) with longer journeys, consisting of multiple run-and-recharge cycles, now an everyday reality for heavier BEVs such as the Tesla Model 3 discussed in this paper.

Given this need for long-distance BEV travel, the optimum location of recharging points must be found, as explored by He et al. (2019) who formulates the problem as a mixed integer program and a modified flow-refuelling location model (FRLM) which is solved via a branch-and-bound algorithm to find the best locations for a limited number (between 50 and 250) rapid chargers across the US interstate network. The work is specifically premised on enabling "cars and trucks" with ranges of 60–250 miles (reflecting current BEV trends) to follow existing journey profiles. It will be immediately clear that these battery ranges largely exceed the 40–98 mile ideal found by Meinrenken et al. and so must deviate substantially from an optimum solution. Therefore, although this approach represents a valid method to enable the transition to long-distance EV travel under the existing energy-intensive heavy-car paradigm, no provision is made for a global minimisation of emissions by optimising vehicle characteristics alongside charging infrastructure, merely minimising the cost of infrastructure in isolation. Indeed, even the relative merits of different charge rates are ignored under the requirement to cater for the emerging high-energy vehicle fleet.

Entirely avoiding this high-energy assumption, a refreshingly novel approach to battery sizing is followed by Gong et al. (2020) who accept that not all EV users can adopt the American-style electrification model of a large car charging in a private garage. Instead they study the requirements of an urban population living in high-rise buildings and analyse the feasibility of a vehicle with a removable battery operating in Beijing — a large city representative of many densely populated metropolitan cities in developing countries. While focussed heavily on shorter, more regular journeys this paper is refreshing in its divergence from the dominant 'bigger is better' approach to battery sizing, preferring the uptake of smaller and therefore less costly cars, which is likely to lead to easier and faster EV diffusion, especially in populous developing countries. Assuming a near-future increase in battery energy density, the conclusion is that portable battery sizes of only 5.5 kWh would be optimal based on two packs per vehicle and the innovative possibility of borrowing or swapping-out batteries for occasional longer journeys. Contrasting this with examples such as the American Recovery and Reinvestment Act of 2009 which provides tax credits for BEVs on a per-kWh basis, the authors question the wisdom of current government incentive policies that are tilted towards the development of larger and heavier EVs with larger and heavier batteries.

While not typically included in papers discussing EV design and optimisation, the climate argument against oversized batteries is strong due to their high 'up-front' or 'embodied' emissions from manufacture. In their study on the climate mitigation effects of vehicle electrification in Europe, Hung et al. (2021) complain that the larger batteries being used in BEVs to alleviate range anxiety counteract to some extent the potential climate benefits of these vehicles and, especially in areas with high carbon electricity production, lead to high uncertainties as to the magnitude of the climate mitigation benefits, if any, from BEV adoptions. In light of increasing EV battery sizes, their findings suggests that curbing this trend as much as possible (for example encouraging the uptake of smaller vehicles) will maximise the potential climate mitigation effects of electrification.

However, it is clear from a variety of sources, ranging from the analysis of European transport data by Stark et al. (2015) to user surveys conducted in the motorcycle-dependant city of Solo, Indonesia (Guerra, 2019), that BEV uptake is ultimately dependent on meeting the user's occasional touring needs and not merely their typical daily requirement, particularly when users only have access to a single low-cost vehicle. Therefore, EVs must meet the conflicting requirements of a minimising battery size while maximising long-distance touring capabilities.

It is critical, however, that we do not confuse battery range (a vehicle characteristic) with touring ability (a vehicle-infrastructure interaction) when discussing long journeys, as ultimately every BEV must stop to recharge. The overall journey time, including both running and recharging, must be considered once battery range is exceeded. The only paper found to describe this interaction between vehicle and infrastructure focusses primarily on grid demand, only proceeding to mention vehicle average speeds in the final section as something of an afterword to the main investigation. Nonetheless, Tsirinomeny et al. (2014) does describe the run-recharge cycles of a 24 h journey by electric car, albeit in a particularly controlled environment and utilising as yet unrealistic charge rates. He uses this analysis to compare two different vehicles and assess their suitability for this mode of travel.

1.3. Research gap

There is a clear need to reduce resource consumption from road transport and yet the current trend remains towards larger, heavier electric vehicles results in serious uncertainties about any GHG reductions from their uptake (Hung et al., 2021). At the same time, a large minority of global road transport is by motorcycle or other light vehicle whose fundamental design, usage and purchase price will not support large batteries (Rajper and Albrecht, 2020). Clearly these two problems, of separate origins, are interlinked and in both cases the ability to traverse long distances is required for any meaningful market penetration (Stark et al., 2015). A technical solution enabling long-distance travel by smaller EV would go some way to solving both but, in order to do so, further investigation is required in the following areas:

- Mechanisms of long distance travel by battery vehicle
- Extra-urban or high-speed light BEV operation
- Vehicle design with regard to the above two points
- Interaction between road conditions (particularly charging infrastructure) and the above three points

1.4. Methodology

Starting with the analysis of Tsirinomeny et al. (2014) and expanding it into more realistic road conditions, this investigation aims to produce a simple but robust model from which general trends can be extracted and interpreted to aid both vehicle and infrastructure design. A set of assumptions about vehicle and rider/driver behaviour over a long journey will be outlined and formed into a qualitative model of the mechanisms involved. Relevant engineering parameters can then be introduced to transform the qualitative model into a quantitative, algebraic description.

By maintaining a simple analysis, these models can be easily manipulated to examine the high level trade-offs and limits in real-world applications. Individual parameters may be varied (as in Section 3.1) or further constraints introduced (such as Section 3.6) to demonstrate trends or outcomes that may not yet be apparent from real-world experience.

While this work will also be pertinent to areas already dependant on light vehicles, we will base this study on a highly developed road network, the UK motorways, to show the potential opportunities to reduce cost and environmental impact through a more considered, low energy approach.

1.5. Study outline

Section 1 seeks to illustrate the importance of light vehicles in the world at present, and show that opportunities exist to reduce GHG emissions from transport by a wider adoption of light vehicles, provided suitable supporting infrastructure exists.

Section 2 lays out a set of assumptions about long distance EV travel, over a distance exceeding battery range, and constructs a qualitative model of how battery SOC will vary over the multiple run-recharge cycles of such a journey. Sections 2.1 and 2.2 transform this into two quantitative models to describe EV touring ability over infinite and time-limited journeys, respectively, culminating in a novel metric for EV touring ability: Day Range. Section 2.3 provides a real journey as a case study to test the assumptions of the models.

With these two models established, Section 3 applies them to real optimisation problems, working up from vehicle design in Section 3.1 through the various infrastructure considerations in sequence (charge-point separation, optimum road speed etc.) to develop a unified picture of how a road network can be developed to ensure access to lower energy vehicles, reduce per-mile energy consumption and allow vehicles to traverse large distances while avoiding inefficient redundant battery capacity. By doing so, not only can total fleet battery size be directly reduced, but also smaller, cheaper EVs will become viable replacements for ICEVs, encouraging uptake and so further reducing transport emissions.

The uncertainty analysis of Section 4 discusses the potential problems arising from the data selected to represent road conditions in this study. Section 5 discusses the theoretical and practical implications of this study, as well as the drawbacks of this model before Section 6 concludes by summarising the investigation and its outcomes.

2. Proposed BEV touring model

In order to explore the interactions between a battery vehicle and its environment over a long journey (greater than its battery range and so involving one or more en-route recharges), a model must be established based on simple and robust assumptions both about the vehicle's behaviour and that of the driver (or rider, in the case of a motorcycle). We assume that the vehicle will:

- Discharge at a nominally constant rate and road speed, and
- Recharge at a constant rate that is the same at every recharge stop.

We can also assume that a sensible rider/driver undertaking a long battery vehicle journey will:

- Start the journey with a fully charged battery,

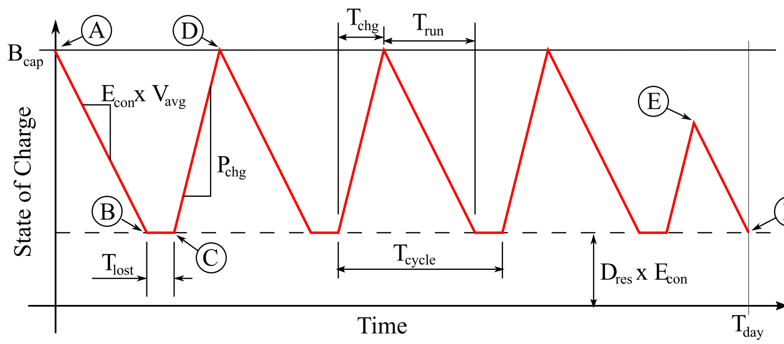

Fig. 1. Explanation of BEV Touring Model. The qualitative model of Section 2 can be approximated by seven nominal parameters allowing variations in design to be explored. The vehicle is assumed to depart with a full charge (A) and run at constant power until an externally imposed reserve range is all that remains (B). Some time is then lost before the vehicle begins charging (C) at constant power and departs again when fully charged (D). For simplicity all lost time is aggregated prior to the recharge. The final charge event is cut short (E) to maximise total distance covered by avoiding unnecessary recharging time and so ending the journey with only the reserve range remaining (F). As outlined in the text, it is assumed that one full charge event can take place outside of the journey time.

- Stop to recharge before the battery is fully depleted, to ensure some "Contingency Range" remains,
- Unavoidably lose some time at each recharge point in finding, operating and paying for the chargepoint, and
- Not waste journey time by fully recharging the battery if they know there is sufficient charge to reach their destination.

Additionally we will assume the rider/driver is travelling alone and so, if touring for multiple days, will break their journey with overnight stops during which the EV can be fully recharged. In this case, each day of a longer tour can be treated simply as an isolated journey as described above.

To model this behaviour, we can consider how battery State of Charge (SOC) will vary over the multiple run-recharge cycles involved in a long journey, as shown in Fig. 1. The journey begins with a full charge (point A, Fig. 1) and then discharges at a constant rate until only the 'reserve' range remains (B). Some time will be lost before and after charging at a nominally constant rate, although for simplicity we can consider all of this 'lost time' as aggregated prior to the recharge (C). Travel can then resume when the battery is fully recharged (D) and this full run-recharge cycle continues for the majority of the journey. The exception is the final recharge which is terminated early (E), the rider or driver knowing that there is sufficient range to complete the final run (F) and wishing to save time by avoiding unnecessary charging. It will be noted that one entire charge event is actually absent, being completed overnight or otherwise outside the journey time.

To numerically model this touring BEV behaviour, we have identified these six relevant engineering parameters:

B_{cap} is the maximum capacity of the battery (kWh)
E_{con} is the average vehicle per-mile energy consumption (kWh/mile)
P_{chg} is the recharge power (kW)
D_{res} is the reserve range (miles)
T_{lost} is the time lost in use of the recharging facility (hours)
V_{avg} is the vehicle average speed when underway (mph)

Fig. 1 also demonstrates visually how these engineering parameters will be utilised to link the vehicle-to-infrastructure interaction with real-world touring performance in Sections 2.1 and 2.2. This qualitative model can now be transformed into a quantitative model in two different ways, describing average speed over multiple run-recharge cycles or the sum total distance the vehicle could cover in a specified time.

2.1. An infinite journey: Run-recharge cycle speed

The simplest way to derive a metric of touring performance from the qualitative description of Section 2 is to arrange the six parameters into a conventional speed equation to give the average speed over a run-recharge cycle: V_{cycle}.

$$V_{cycle} = \frac{(B_{cap}/E_{con}) - D_{res}}{\left[B_{cap}.(\frac{1}{E.V_{avg}} + \frac{1}{P_{chg}})\right] - \left[D_{res}.(\frac{1}{V_{avg}} + \frac{E_{con}}{P_{chg}})\right] + T_{lost}} \quad (1)$$

The numerator is the vehicle's maximum range minus the reserve range, while the denominator is the time taken for a whole run-recharge cycle. The first term of the divisor describes the time it would take to deplete and recharge the entire battery, dividing the battery capacity by running and charging power respectively. The second term subtracts the time reduction due to the reserve capacity, reserve distance divided by speed, and reserve battery capacity ($D_{res}.E_{con}$) divided by charge power. The final term is the lost time due to extraneous delays such as finding, using and paying at the chargepoint.

This first proposed model of BEV touring will prove to be extremely useful in the Analysis of Section 3 due to its algebraic flexibility and the ease with which it assimilates further assumptions. However, while the results of this equation (Table 1) are strongly indicative of a vehicle's touring performance, the implicit assumption of infinite journey length neglects potentially significant end effects.

2.2. The absent charge: Introducing day range

To improve upon this basic analysis we examine the more realistic case of journey time excluding one of the required charge events, as shown in Fig. Fig. 1. To achieve this, we have introduced new variable T_{day} to describe the length of time in which the journey takes place. This may seem odd at first, as journeys are typically completed when a set distance, rather than time, has elapsed but a time limit allows a more universal comparison across a wide range of vehicle abilities, and is indeed applicable to a single day of a longer tour. Instead of stating how long a vehicle will take to traverse a set distance, we are instead stating what distance it is capable of achieving in a set time. This metric can then be taken as a measure of a particular vehicle's suitability for long distance touring.

Day range can be found from the same set of parameters used to find V_{cycle} in (1). With reference to Fig. 1, we begin with the duration of the three individual components of a full run-recharge cycle:

$$T_{run} = \frac{B_{cap} - (D_{res}.E_{con})}{V_{avg}.E_{con}} \quad (2)$$

$$T_{chg} = \frac{B_{cap} - (D_{res}.E_{con})}{P_{chg}} \quad (3)$$

And T_{lost} is predefined as a variable. Summing, these give the length of one complete cycle:

$$T_{cycle} = T_{run} + T_{chg} + T_{lost} \quad (4)$$

Table 1
Vehicle model parameters — Data from various sources.

Vehicle	B_{cap} (kWh)	E_{con} (Wh/mi)	P_{chg} (kW)	v_{avg} (mph)	Range (miles)	V_{cycle} (mph)	Day range (miles)
Petrol M'cycle	144	746	22,000	60	194	55	673
Petrol Car	315	746	22,000	50	423	48	587
Charging Bullet[a]	4.8	90	2.38	40	53	14	178
Zero SR/S	12.6	127	6	55	99	23	318
Ideal BEM[b]	15	95	24	60	158	44	558
Tesla Model 3	75	236	250	48.3	318	44	541
Nissan Leaf E+	62	259	50	45	239	35	460

[a]Used in case study.
[b]Battery Electric Motorcycle.

Allowing us to compute the number of full cycles (N_{cycles}) within T_{day} excluding the first run (which has no associated recharge) and the final shortened run-recharge cycle by dividing and rounding the fraction down to an integer:

$$N_{fract} = \frac{T_{day} - T_{run} - T_{lost}}{T_{cycle}} \tag{5}$$

$$N_{cycles} = \lfloor N_{fract} \rfloor \tag{6}$$

Two cases exist depending on whether the remainder ($r = N_{fract} - N_{cycle}$) contains enough time for a complete recharge and run ($t = T_{run}+T_{chg}$). If so, Day Range (DR) is simply a whole number of runs but, more commonly, DR is found by multiplying V_{avg} by the proportion of T_{day} spent running:

$$DR = \begin{cases} V_{avg}.T_{run}.(N_{cycles}+2), & r \geq t \\ V_{avg}.\left[T_{day} + T_{chg} - T_{lost}.(N_{cycles}+1)\right].\left[\frac{T_{run}}{T_{chg}+T_{run}}\right], & otherwise \end{cases} \tag{7}$$

Having established a set of equations to calculate day range all that remains is to set the length of time available for travel. For this study T_{day} = 12 hours has been selected as a reasonable, but not excessive, duration for a solo traveller undertaking a long journey or one day of a multi-day tour.

While this investigation will certainly be of interest in regions where light vehicles are already the norm, in order to investigate the energy-reduction possibilities for more developed road networks the infrastructure parameters have been selected to model UK motorway travel: 28 miles reserve range, based on the Department for Transport target for motorway service station spacing (DfT, 2013) and fifteen minutes of lost time (Transport Focus, 2017).

Table 1 shows the relevant parameters of several vehicles and their resulting calculated day range and V_{cycle}. All the vehicles described utilise modern Lithium batteries and either AC (< 43 kW) or DC chargers. This data has been selected to represent high speed travel as closely as possible but due to a wide variety in available information, different road speeds have been quoted preventing a truly direct comparison. This is explored further in Section 3.2.

2.3. Case study: A big trip by small EV

To provide a concrete example of the type of journey described by the above models, a suitable long-distance challenge was selected for an example of a small BEV, with time, speed and SOC data recording to ensure the assumptions held up to reality.

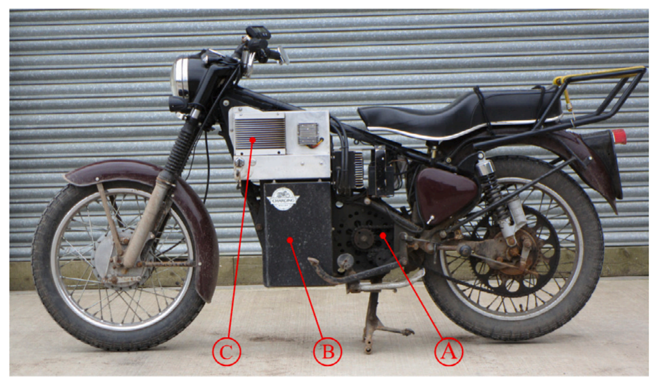

Fig. 2. The "Charging Bullet" electric motorcycle was tested over a 170 mile journey. It is converted from a 1961 Royal Enfield Bullet using a Saietta 95R motor (A) powered by second life Nissan Leaf cells (B) via a Kelly KDZ controller (C). Approx 170 kg with 6 kW continuous power giving 50 mph and 60 mile range. Datalogging by Grin Technologies Cycle Analyst.

The vehicle under test is a one-off battery electric motorcycle converted from a petrol 350cc Royal Enfield Bullet motorcycle (the "Charging Bullet", Fig. 2) (Varney, 2020). The drivetrain consists of twelve repurposed first generation Nissan Leaf battery modules providing a nominal 45 V via a 12S4P cell arrangement giving a real storage capacity of 4.8 kWh protected by an "Orion Jr." battery management system. A Kelly KDZ PWM controller feeds power to a brushed, axial-flux Saietta 95R motor producing up to 6 kW of continuous power. Maximum speed is approximately 50 mph and a 60 mile range is obtainable. Charging is via a 3 $kW_{nominal}$, 230 V single-phase AC charger which can be plugged into either a Type 2 chargepoint or domestic 3-pin socket.

Instrumentation is by Grin Technologies Cycle Analyst V3 (Grin, 2021), a proprietary cycle computer for electric bicycles easily adapted for small BEVs, Fig. 3. This records distance by spoke-mounted magnet on the front wheel and calculates battery State-Of-Charge (SOC) by 'coulomb counting' power output taken via voltage measurements across the battery terminals and a shunt resistor passing full battery current. Datalogging is by proprietary Grin Technologies datalogger which also records GPS location, useful for post-processing; all readings were taken at 1 Hz.

To ensure the vehicle would be tested against a route laid down to provide a moderate challenge for ICE vehicles of similar size and power,

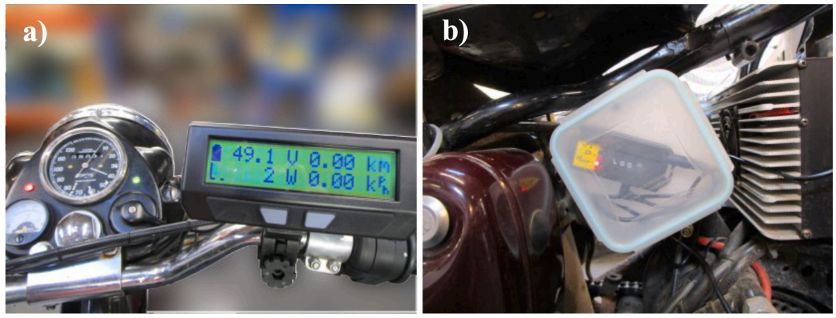

Fig. 3. (a) A Grin Technologies Cycle Analyst mounted to the handlebar is used to calculate distance and battery SOC. (b) This data is stored at 1 Hz on a GPS enabled Grin Technologies datalogger mounted in a waterproof box beneath the motorcycle seat.

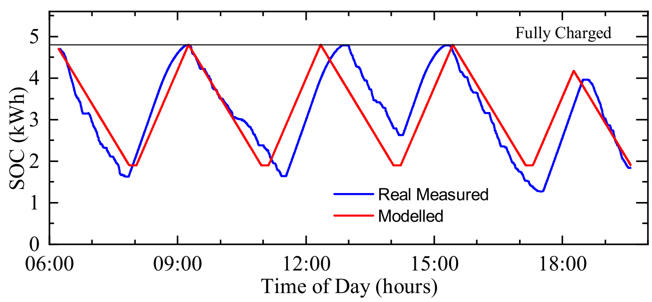

Fig. 4. Variation of State Of Charge (SOC) measured over a real journey compared with the model of Section 2.2, showing reasonable agreement in spite of the necessary simplifications. Small variations converge to consistent nominal figures over the long timescale under inspection.

Table 2
Values assumed where necessary in analysis (approximating Zero SR/S).

Parameter	Value	Units	Reference
V_{cycle}	40	mph	i.e day range approx. 500 mi
V_{avg}	55	mph	Zero (2021)
E_{con}	127	Wh/mi	Zero (2021)
B_{cap}	12.6	kWh	Zero (2021)
P_{chg}	6	kW	Zero (2021)
D_{res}	28	miles	DfT (2013)
T_{lost}	.25	hours	Transport Focus (2017)
Electricity emissions[a]	0.181	$kgCO_{2eq.}$/kWh	Nationalgrideso.com (2021)
Battery emissions[a]	104	$kgCO_{2eq.}$/kWh	Hao et al. (2017)
Annual mileage	5000	miles	Assumed
Battery lifespan	10	years	Assumed

[a]Varies by geographical area (Hung et al., 2021; Degen and Schütte, 2022).

the Vintage Motor Cycle Club's 2020 "Herefordshire Compass Ride" event was selected as a suitable long-distance challenge. This road event requires competitors to visit a number of geographical points sited roughly along the border of Herefordshire, a rural county in the West Midlands of England. It is a navigation, not speed, event but must be completed within one 24 h period. Four suitable chargepoints were selected to recharge en-route with minimal detours. These were chosen for reliability; at each selected point enough charge would remain in the battery to reach another nearby chargepoint, should the primary choice be unavailable or out of order. This dictated the 'reserve range' in this example, although was not called upon during this particular journey.

A 3 kW_{nom} AC charger was used and the charge rate can be seen to reduce at around 80% SOC in line with standard constant-current to constant-voltage Li-ion charging practice. Based on prior experience of touring by small BEV the battery was fully recharged at each opportunity to maximise flexibility, and minimise range anxiety, except the final charge which was stopped at 4 kWh to save approximately twenty minutes of unnecessary recharging. This provided adequate charge for the final leg, including a reasonable reserve capacity of 1.8 kWh or 22 miles.

Fig. 4 shows the recorded SOC alongside an example of the Day Range model (Section 2.2) using the parameters: T_{day} = 13.4 h; B_{cap} = 4.8 kWh; E_{con} = 79.5 Wh/mile; D_{res} = 23.8 miles; T_{lost} = 10 min; V_{avg} = 21.4 mph; P_{chg} = 2.38 kW.

Despite small fluctuations due to changes in weather, speed and gradient impacting discharge rate, and real-world chargepoint location affecting the exact SOC when recharging began, the overall trends are a strong match with the qualitative model.

3. Analysis

The models presented in Sections 2.1 and 2.2 allow direct comparison of touring abilities across a wide range of vehicles and infrastructures. The following sections take this further, utilising both of these models to find general trends and even specific quantitative guidelines for vehicle and infrastructure design. In order to draw these conclusions, the robust premisses of the models must be supplemented with the following assumptions and caveats.

Charge Rate (P_{chg}) may be limited by more than one factor, for example either the power a specific grid connection can provide, or the maximum rate a battery can receive energy. While many other considerations may play a role in practice, where relevant this analysis considers only these two limits, with charge proceeding at the lower of the two.

Reserve Range (D_{res}) is defined in the model as the average range remaining when recharging commences. This will depend heavily on driver preference alongside the vagaries of infrastructure along the route they traverse. This study treats D_{res} as equal to maximum chargepoint spacing, as it can be reasonably assumed that they are related and of similar magnitude. With the recent rise of BEV use, data gathered from real journeys may now reveal a more complex relationship but this lies beyond the scope of the present study.

Many of the analyses of this section require certain fixed figures to be assumed in order to construct plots and explore the interaction of the parameters under inspection. Where this is the case, values approximating long distance travel by Zero SR/S battery motorcycle, a contemporary light BEV, have been used and are listed in Table 2.

3.1. Vehicle design

Much attention has recently been focused on improving the battery capacity (Loganathan et al., 2019) and charge rate (Tu et al., 2019) of electric cars in order to improve their long distance abilities, resulting in vehicles such as the Tesla Model 3 and Nissan Leaf E+ described in Table 1. While it is certainly possible to obtain day ranges comparable with ICE vehicles in this way, care should be taken not to cover up poor economy with rapid charging and large batteries. This risks replicating the inefficient approach of ICE vehicles and electrification can even

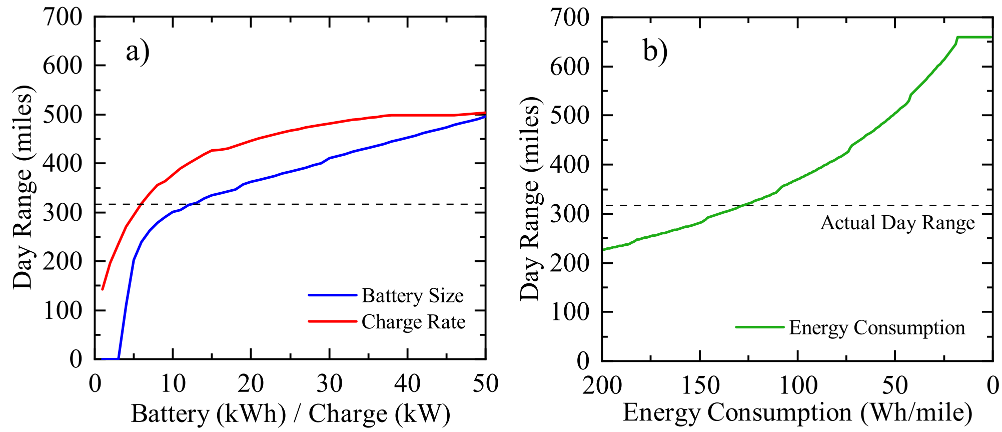

Fig. 5. Variations of modelled Day Range with (a) Battery size and Charge Rate and (b) Energy Consumption for the 2020 Zero DS-R electric motorcycle. The day range of the existing design is marked by a horizontal dashed line. The biggest gains can be made by improving the energy consumption, especially as increasing the battery size or charge rate will directly increase the mass and/or price of the motorcycle.

increase CO_2 emissions in areas with high carbon intensity electricity, including parts of Europe, China, Australia and the USA (Hung et al., 2021; Barkenbus, 2017).

Fig. 5 shows the fundamentally different effects of changing battery size, charge rate and energy use of the Zero DS-R electric motorcycle. Simply increasing the battery size or charge rate will indeed increase the day range but with diminishing returns in both cases, Fig. 5(a). Motorcycles face an additional problem here as vehicle size and weight are both constrained by the physical abilities of the rider. This places a practical upper limit on battery mass that is not present in four-wheeled design, apart from cost and legislative concerns. Charge power may also be limited by this effect, being constrained by available technology and battery capacity, see Section 3.6.

By contrast, Fig. 5(b) shows increasing returns on day range from improvements in energy consumption. Comparing both graphs of Fig. 5, it can be seen that a doubling of either battery capacity or charge rate individually would be required to increase day range to 400 miles, whereas this could be achieved by a reduction in energy consumption of only 20%. Reducing energy use is certainly an engineering challenge but with an unladen weight already at 230 kg, doubling the battery mass is equally unlikely. In practice a combination of methods are required to increase the day range of light vehicles, however the blunt approach of ever increasing battery size or charge rate is not only expensive and impractical, it may well be the least effective option in this case.

By considering optimistic, though feasible, figures for a hypothetical optimised touring Battery Electric Motorcycle ('Ideal BEM' in Table 1), a day range of 558 miles can be achieved, comparable to the Tesla Model 3 in this example. In doing so it consumes 12% of the energy of the petrol motorcycle and less than half of the energy of the heavy Tesla, as well as having a battery only one fifth of the size; reducing vehicle cost as well as embodied carbon, see Section 3.3.

3.2. Road speeds

The results quoted in Table 1 have been selected for descriptive purposes from reliable, publicly available information and it has been noted that the energy consumption has been recorded at a variety of speeds. In fact, day range will vary with cruising speed as two effects compete (Dixon and Bell, 2020; Schoenberg and Dressler, 2019). A higher speed will allow the vehicle to traverse a greater distance when underway but will use more energy, shortening runs and increasing the fraction of time spent charging.

To assess the impact of road speed on day range we must simplify reality. By assuming the vehicle overcomes only rolling resistance and

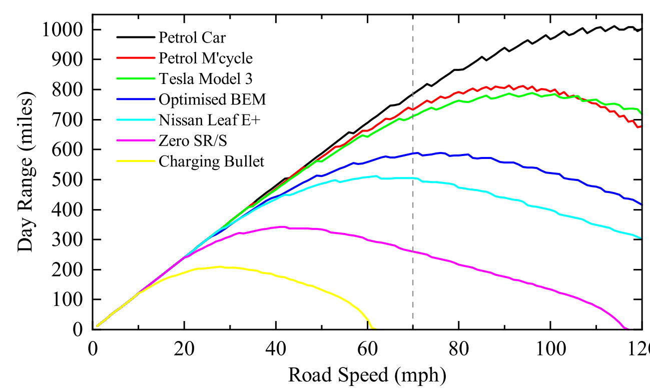

Fig. 6. Variations of Day Range with Road Speed for different vehicles. Fast roads tend to constrain speeds close to the speed limit (dashed vertical line) (DfT, 2019) so many smaller BEVs would benefit from a reduction in this limit. High road speeds preferentially benefit more expensive and energy intensive BEVs.

aerodynamic drag via a fixed drivetrain efficiency (Ehsani et al., 2010) we can relate energy consumption to speed with Eq. (8).

$$E_{con} = \frac{mgC_{rr} + \frac{1}{2}\rho C_d A v^2}{\eta} \quad (8)$$

Where m is the vehicle gross mass (kg), g is the gravitational acceleration (m/s^2), C_{rr} is the coefficient of rolling resistance, ρ is air density (kg/m^3), $C_d A$ is the vehicle drag factor (m^2), v is speed (m/s) and η is the drivetrain efficiency.

This assumption allows us to compare day ranges at various road speeds as shown in Fig. 6 using the parameters shown in Tables 1 and 3. As the data quoted are from real road testing, any effects from changes in speed or elevation are included in the calculated value of $C_d A$ which cannot therefore be taken as the true drag of the vehicle. Consequently these results do not accurately represent these particular vehicles, only demonstrate more general trends.

Different vehicles achieve their optimum day range at different speeds, often somewhat different to the speeds quoted in Table 1. It can also be seen that, for most of the BEVs in Fig. 6, the optimum speed lies below the UK national speed limit of 70 mph but in practice road speed is constrained to a narrow range (DfT, 2019) and these vehicles will be unable to achieve their full potential. Once again it should be noted that although it may increase day range in some cases, higher speed will always increase energy consumption and associated emissions.

Table 3
Calculated speed coefficients – Used to produce Fig. 6.

Vehicle	B_{cap} (kWh)	E_{con} (Wh/mi)	v_{avg} (mph)	Drivetrain η	Mass (kg)	C_{rr}	$C_d A$ (m^2)
Petrol M'cycle[a]	144	746	60	0.2	238	0.02	0.65
Petrol Car[b]	315	746	50	0.2	1000	0.01	0.77
Charging Bullet	4.8	90	40	0.8	258	0.02	0.56
Zero SR/S	12.6	127	55	0.8	309	0.02	0.45
Ideal BEM	15	95	60	0.8	300	0.02	0.25
Tesla Model 3	75	236	48.3	0.8	1806	0.01	0.86
Nissan Leaf E+	62	259	45	0.8	2006	0.01	1.08

[a]350cc Enfield Bullet.
[b]VW Up!.

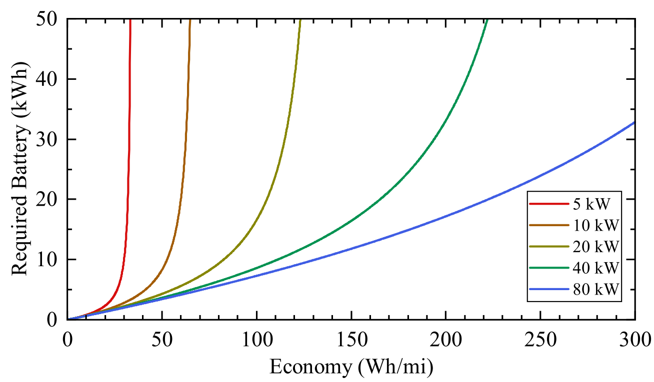

Fig. 7. Battery sizes required to achieve a predefined Cycle Speed (V_{cycle} = 40 mph) at a variety of charge rates. Larger batteries are required to support higher energy consumption up to a 'knee point', beyond which the specified charge rate cannot support the Cycle Speed. This suggests a poorly specified infrastructure could require unnecessarily large vehicle batteries and that a minimum charge rate is required for touring, see Section 3.5.

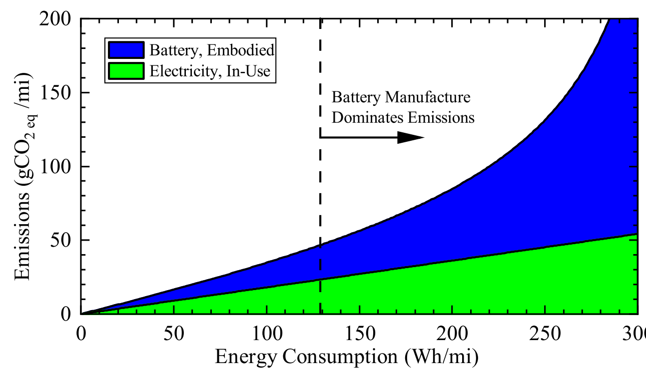

Fig. 8. Quantities of GHG emissions resulting from recharging and battery production, with varying energy consumption (E_{con}). Per-mile embodied emissions are greatly increased as the 'knee point' of Fig. 7 is approached and dominate, in this example, over 129 Wh/mi (dashed line) requiring a battery of 11 kWh: figures very similar to the Zero SR-S motorcycle. A battery life of 10 years, 5,000 miles annual use and a charge rate (P_{chg}) of 50 kW have been assumed here, as well as $Vavg$ = 55 mph and $Vcycle$ = 40 mph, equivalent to a day range of around 500 miles. For simplicity, other components of vehicle emissions have not been considered.

3.3. The cost of inefficiency

Higher in-use energy consumption not only increases emissions from electricity use directly, it is clear from Table 1 that it is also associated with larger batteries and therefore embodied emissions. Minimum viable battery size can be found by rearranging (1) to give (9) and the results are shown in Fig. 7. The relevant values shown in Table 2 have been used, being selected to approximate the Zero SR/S for this and subsequent analyses.

$$B_{cap} = \frac{Dres.\left[\frac{E_{con}}{P_{chg}} + \left(\frac{1}{V_{avg}} - \frac{1}{V_{cycle}}\right)\right] - T_{lost}}{\frac{1}{P_{chg}} + \frac{1}{E_{con}}.\left(\frac{1}{V_{avg}} - \frac{1}{V_{cycle}}\right)} \tag{9}$$

The curves of Fig. 7 effectively expand on the "Battery Size" plot of Fig. 5.a and demonstrate that required battery size increases steadily with energy use (E_{con}) up to a 'knee point' where which it increases rapidly and beyond which the predefined cycle speed is unobtainable, at this charge rate.

By making a number of assumptions about vehicle usage, lifespan and associated emissions (Table 2), per-mile GHG emissions can be approximated for battery manufacture as well as electricity used for recharging. In this example other emissions have been neglected but are typically smaller than the emissions presented and approximately proportional to one or both of them. The results are presented in Fig. 8 and show that both in-use and embodied energy increase with worsening E_{con}. Moreover, due to the non-linearities demonstrated in Fig. 7, battery embodied emissions can easily equal and exceed in-use emissions. Here, this occurs at 129 Wh/mile where a battery of 11 kWh is required, similar to the Zero SR-S motorcycle albeit utilising an unrealistic 50 kW charge rate. This type of analysis is notoriously sensitive to assumptions about vehicle lifetime and embodied emissions (Hung et al., 2021), so further detail has not been attempted here but this example demonstrates the potential dangers of high energy consumption requiring oversized batteries, not least when extra battery mass will itself invariably increase energy consumption (E_{con}).

3.4. The battery barrier

Fig. 9 shows the impact of increasing reserve range on the day range of the vehicles in Table 1. Here the consequences are more significant for shorter range vehicles. As required reserve range increases, day range reduces and rapidly drops to zero as the reserve range dominates and then exceeds battery range; this is particularly obvious when contrasting the petrol car and motorcycle, having similar fuel economy (55 mpg_{imp}) but tank sizes of 16 and 35 litres, respectively.

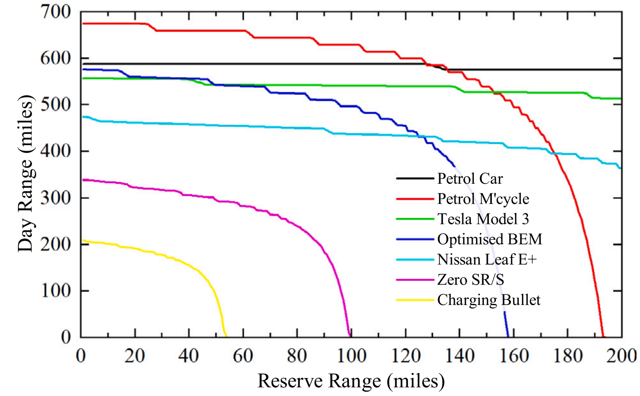

Fig. 9. Impact of Reserve Range on Day Range. The distance between charge points very quickly becomes limiting for shorter-range BEVs and gaps of over 60 miles exist in practice (MSO, 2021). The installation of infrequent, high rate charge points risks locking out lower cost, lower energy BEVs from a long-distance road network.

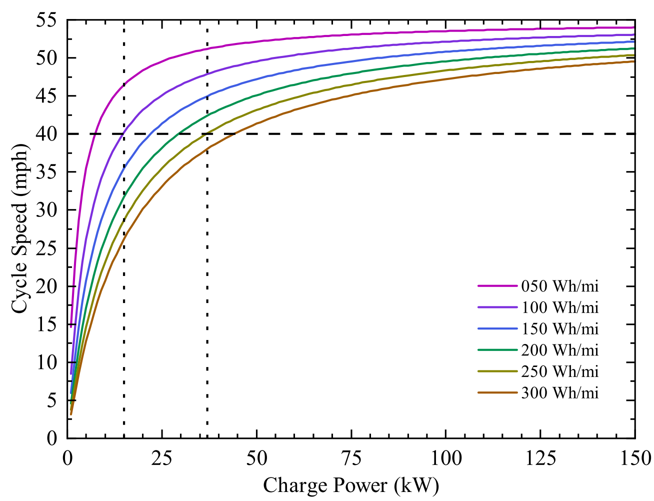

Fig. 10. Cycle Speed vs. Charge Power for a variety of E_{con}. For effective touring a minimum power must be available for recharge. Considering a Cycle Speed V_{cycle} = 40 mph to be acceptable, equivalent to a day range of about 500 miles, a realistic minimum charge point power of between 15 kW and 40 kW is required, for vehicles consuming 100 Wh/mi and 250 Wh/mi, respectively. The curves are derived from (11) based on the figures of Table 2.

While the UK Department for Transport target of 28 miles between service stations has been selected for reserve range in this paper's calculations, in reality this can be much greater with gaps of over 60 miles reported in the UK motorway network (MSO, 2021). Uncertainty surrounding these larger gaps significantly impacts the ability of light electric vehicles to undertake long journeys, limiting their uptake and potentially locking in high energy vehicle use in this sector.

3.5. Minimum charging requirements for touring

The discussion so far has suggested that available chargepoint power should be sacrificed in favour of much shorter chargepoint intervals in order to reduce necessary reserve range (D_{res}). However, Section 3.3 and inspection of Figs. 7 and 11 suggests that individual charge point power places an ultimate limit on vehicle touring ability.

A lower bound for necessary charge power can be obtained from (1) by assuming that, as battery size increases, run-recharge cycles become very long and the effects of lost time and reserve range become negligible:

$$T_{lost} \rightarrow 0 \quad \text{and} \quad D_{res} \rightarrow 0 \tag{10}$$

Under these assumptions (1) simplifies to:

$$V_{cycle} = \frac{1}{\frac{1}{V_{avg}} + \frac{E_{con}}{P_{chg}}} \tag{11}$$

The results of (11) are presented in Fig. 10, showing Cycle Speed vs. Charge Power for various values of E_{con} at V_{avg} = 55 mph. If we continue our assumption that successful touring begins at V_{cycle} = 40 mph (dashed line) we find a range of lower bounds for chargepoint power capability from approximately 15 kW to 40 kW (dotted lines) for realistic values of E_{con} between 100 Wh/mi and 250 Wh/mi, respectively.

3.6. Infrastructure to minimise battery size

It has been established, in Section 3.3, that minimising vehicle battery size should be a priority but Section 3.4 demonstrates that there is a danger of locking-out the resulting low energy BEVs from an unsuitable road network. Section 3.5 further complicates matters by finding a minimum viable charge rate. Taken together, this raises the question of how to prioritise available resources when designing a long-distance road network charging infrastructure to cater for all road users and simultaneously minimise resource consumption.

To examine the trade-off between available chargepoint power (which limits P_{chg}) and the interval between chargepoints (represented here by D_{res}) a new factor must be introduced. Linear Available Power (LAP) can be defined as the average recharge power available to a vehicle per unit distance; kW/mile in this study. This is not simply the total power installed along a route, divided by the distance, as it represents only what is available to a single vehicle. For example a 100 kW charger located every 10 miles has a LAP of 10 kW/mile, provided the chargepoint is not oversubscribed and so unavailable, similarly a 50 kW charger located every 5 miles has a LAP of 10 kW/mile. However, a bank of two 50 kW chargers every 10 miles has a LAP of only 5 kW/mile as the vehicle in question will only be able to make use of one 50 kW charger in 10 miles of travel. This analysis relies on LAP as a proxy for infrastructure investment, implying that cost rises monotonically with LAP. While perhaps generally true, there exist many real cases to contradict this, not least the relatively high cost-per-kW of low power (< 10 kW) chargepoints. Nonetheless, (12) defines the LAP coefficient, k_{LAP}, for this study:

$$k_{LAP} = \frac{P_{chg}}{D_{res}} \tag{12}$$

It is important to stress that the following analysis does not depend on the vehicle stopping to recharge every five or ten miles, in the above examples, only that the reserve range is approximated to five or ten miles: the distance a driver or rider must allow for contingencies when selecting a charge point. Using this definition of k_{LAP}, (9) can be re-written as (13):

$$B_{cap} = \frac{E_{con}.D_{res}.\left[\frac{E_{con}}{k_{LAP}} + D_{res}.\left(\frac{1}{V_{avg}} - \frac{1}{V_{cycle}}\right) - T_{lost}\right]}{\frac{E_{con}}{k_{LAP}} + D_{res}.\left(\frac{1}{V_{avg}} - \frac{1}{V_{cycle}}\right)} \tag{13}$$

Fig. 11 (a) and (b) show curves of constant k_{LAP} relating Battery Size to Reserve Range and Charge Power, respectively. The black curves show the minimum battery sizes required to obtain a cycle speed of 40 mph at various LAP, chargepoint intervals (equated here with reserve range) and chargepoint power. It can be seen that, for any particular LAP, a minimum battery requirement exists at an optimum chargepoint spacing and power, with any deviation from these optima requiring extra battery capacity to obtain equal performance, at potentially high cost in both financial and environmental terms.

As found for charge power in Section 3.5, certain asymptotes are visible but the minimum battery sizes are the most interesting feature. Perhaps the first impression is the very small battery sizes apparently required for touring, only 5 kWh to 12 kWh in this example, rather

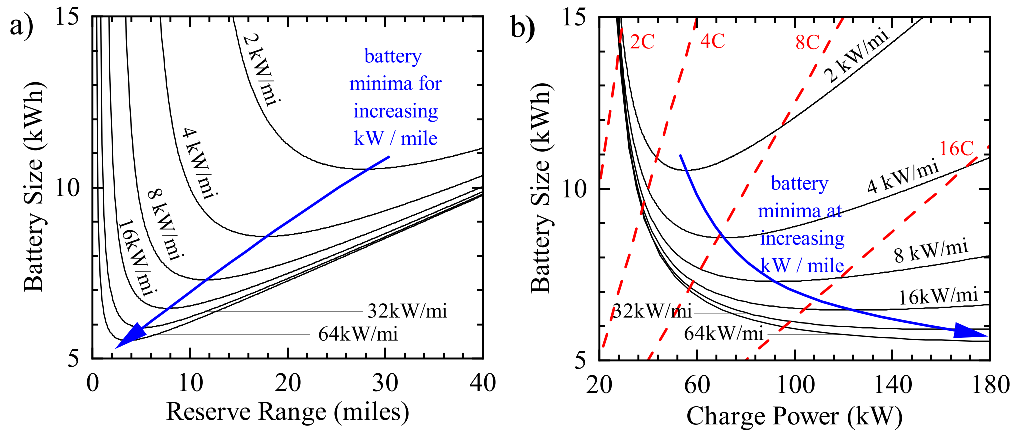

Fig. 11. Battery sizes required to obtain V_{cycle} = 40 mph at different K_{LAP} values. By assuming infrastructure cost is consistent with Linear Available Power (LAP, see text and (12)), the question of how to compromise between frequent charge points (low D_{res}) and high charge rates (P_{chg}) can be tackled. As available LAP increases, both D_{res} and P_{chg} must improve but at different rates (blue arrows).

than the 60 + kWh currently accepted as necessary (Table 1). This is partly due to the low energy consumption of the Zero SR/S under consideration, compared with a large car, but substituting a higher value of E_{con} = 250 Wh/mi still yields viable batteries below 25 kWh. The black curves represent realistic LAP values increasing exponentially from 2 kW/mi to 64 kW/mi; for visualisation, this varies from a sparse 50 kW charger every 25 miles, somewhat approximating the existing UK network, to an unrealistic plethora of 350 kW chargers at 5 mile intervals.

The reader will also observe from Fig. 11.b the coexistence of high charge rates and small battery capacities. The rate at which a battery can safely charge or discharge can be described by its C-rate (units [h^{-1}]), which is a cell-level limit so linking maximum Charge Power to Battery Capacity:

$$\frac{P_{chg}}{B_{cap}} \leq C_{rate} \tag{14}$$

For smaller batteries the C-rate, rather than infrastructure, may limit P_{chg} and so touring ability. Its value is related to available cell and battery technologies and is at present approaching $1.5C$–$3C$, representing an 80% recharge in approximately 15 to 30 min. A range of C-rates are shown in Fig. 11.b by red dashed lines and will limit battery size reductions in order to maintain the required charge power. For example a touring motorcycle battery capable of receiving a $3C$ charge would need at least 11 kWh of battery, double its potential minimum size, regardless of available LAP. This reveals the importance of cell- and battery-pack technologies to the touring abilities of small vehicles.

The loci of Battery minima presented in Fig. 11 (blue arrows) are not actually independant, being linked by the definition of LAP in Eq. (12). By combining the curves of battery minima (blue arrows in Fig. 11) on axes of Charge Power vs. Reserve Range as in Fig. 12 the actual battery sizes and LAP become hidden but curves describing quantitative infrastructure guidance for battery minimisation emerge. Plots covering the range of realistic private vehicle energy consumption (E_{con}) have been presented, each being the loci of minimum required battery size as LAP increases from right to left, shown by the grey arrow. Also included are the C-rate limits as in Fig. 11.b which have been found to relate simply to reserve range as shown in (15):

$$D_{res} = \frac{1}{C_{rate} \cdot \left(\frac{1}{V_{avg}} - \frac{1}{V_{cycle}} \right)} \tag{15}$$

A method for sizing ideal chargepoint power and spacing, for increasing investment or LAP, to minimise battery size is suggested with reference to the curves of Fig. 12:

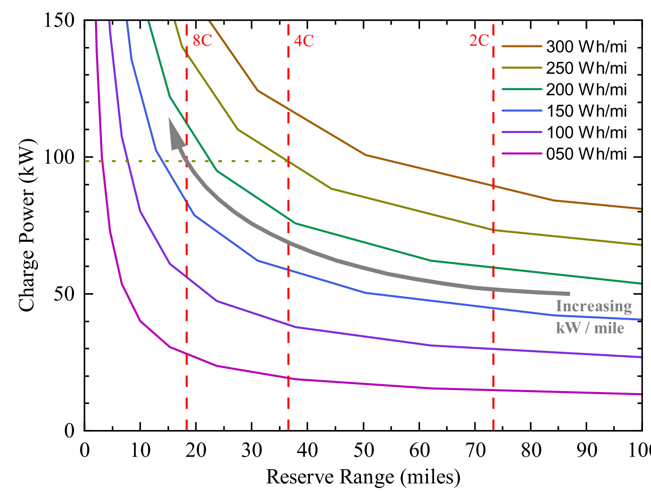

Fig. 12. Loci of optimum Charge Power vs. Reserve Range to minimise required vehicle battery as LAP varies, for different E_{con}. Obtained by combining the minima of Fig. 11 (a) and (b), this shows that, as available LAP increases (kW/mi, grey arrow), D_{res} should be reduced before P_{chg} is increased. Also shown are battery C-rates demonstrating limits on charge rate, see text and (14).

1. Construct a plot such as Fig. 12 based on appropriate assumptions and targets, V_{avg} = 55 mph and V_{cycle} = 40 mph in this example (see also Section 4).
2. Select the curve for the value of E_{con} of interest, perhaps an upper bound such as 250 Wh/mi (yellow curve).
3. For increasing available LAP (kW/mi), as shown by the grey arrow, increase available chargepoint power and reduce maximum chargepoint spacing as described by the curve (follow the yellow curve ‘uphill’ from right to left).
4. If the maximum likely C-rate is exceeded, around $4C$ at present, there is no benefit to increasing chargepoint power and attention should be focussed entirely on reducing the maximum spacing of chargepoints to minimise required reserve range (i.e. transferring to the dotted yellow horizontal line).

Following this method for E_{con} = 250 Wh/mi and a (high) C-rate of 4, a maximum available charge power of approximately 100 kW is arrived at in order to minimise required battery size and so help reduce overall road vehicle emissions. Beyond this, resources should be directed at minimising chargepoint intervals. A much lower value of approximately 40 kW is obtained if E_{con} could be kept as low

Table 4
Uncertainties associated with Section 3.5.

P_{chg}(kW) required with V_{avg} = 55 mph and various V_{cyc}:			
V_{cyc} (mph)	100 Wh/mi	250 Wh/mi	% change
30	6.6	16.5	−55.0%
35	9.6	24.1	−34.4%
40	**14.7**	**36.7**	**0%**
45	24.8	61.9	+68.7%
50	55.0	137.5	+275.0%
P_{chg}(kW) required with V_{cyc} = 40 mph and various V_{avg}:			
V_{avg}(mph)	100 Wh/mi	250 Wh/mi	% change
45	36.0	90.0	+145.5%
50	20.0	50.0	+36.4%
55	**14.7**	**36.7**	**0.0%**
60	12.0	30.0	−18.2%
65	10.4	26.0	−29.1%

Table 5
Uncertainties associated with Section 3.6.

Optimum chargepoint strategy for various V_{cyc}:				
V_{cyc} mph	D_{min} miles	P_{chg} kW	B_{cap} kWh	change %
30	17.0	42.6	11.0	−55.0%
35	24.8	62.1	16.0	−34.4%
40	**37.9**	**94.6**	**24.4**	**0.0%**
45	63.9	159.7	41.2	+68.8%
50	142.0	354.9	91.6	+275.0%
V_{avg} = 55 mph, k_{LAP} = 2.5 kW/mi				
Optimum chargepoint strategy for various V_{avg}:				
V_{avg} mph	D_{min} miles	P_{chg} kW	B_{cap} kWh	change %
45	92.9	232.3	60.0	+145.5%
50	51.6	129.1	33.3	+36.4%
55	**37.9**	**94.6**	**24.4**	**0.0%**
60	31.0	77.4	20.0	−18.2%
65	26.8	67.1	17.3	−29.1%
V_{cyc} = 40 mph, k_{LAP} = 2.5 kW/mi				

as 100 Wh/mi by good vehicle design and/or low road speeds (see Sections 3.1 and 3.2). Higher available charge rates may be of benefit to vehicles with larger batteries but this represents a diversion of resources away from obtaining a road network with the minimum possible energy use, battery size and associated emissions; it instead supports higher energy consumption at the risk of blocking low energy vehicles entirely.

3.7. Guidelines for a low energy charging infrastructure

The analyses outlined throughout Section 5 each conclude with key findings to enable the development of a road transport system, consisting of complementary vehicles and infrastructure, with minimal energy use and emissions.

Based on the assumptions made throughout this section, several points can be made about the UK transport system specifically. Firstly, charge point regularity is critical due to the link between reserve range and perceived chargepoint intervals. Therefore the largest chargepoint intervals on a network must be minimised to ensure consistency and reliability. Secondly, chargepoints between 40 kW and 100 kW are suitable for low energy touring. Higher charge rates may provide greater convenience to drivers of high energy BEVs but this is not compatible with minimising emissions, particularly if it diverts resources away from chargepoint regularity. Specifically, the installation of chargepoints exceeding 100 kW at the expense of meeting or exceeding the 28 mile service station interval target represents poor resource allocation. Finally a small reduction in national speed limit may help the uptake of light, low energy BEVs in particular while reducing energy consumption and required battery size across all vehicles.

In areas with lower road speeds and smaller, lower energy vehicles, charge rates between 15 kW and 40 kW with much reduced charge point intervals may provide a better solution.

An infrastructure constructed along these lines should encourage the use of low energy vehicles and enable battery minimisation while limiting the benefit of vehicles adopting an inherently high-energy design approach.

4. Uncertainty analysis

The numerical conclusions obtained in Sections 3.5 and 3.6 are subject to variations in all of the parameters first described in Section 2.1. While the changes in some parameters (eg. Charge Power and Energy Consumption) are explicitly explored in the analysis, and shown in the curves of Figs. 10 and 12, variations in Cycle Speed (V_{cyc}) and Average Speed (V_{avg}) must also be considered.

Table 4 shows how minimum required Charge Power alters as V_{cyc} and V_{avg} are varied around the design point discussed in Section 3.5 and Fig. 10 (bold row in tables). Similarly, Table 5 shows how the optimum chargepoint strategy (Chargepoint Spacing and Power) varies with these two parameters for a certain value of investment: $k_{(LAP)}$ = 2.5 kW/mi, approximately the design point where the yellow 250 Wh/mi curve meets the dashed yellow line in Fig. 12 and discussed in the surrounding text. It will be noted that the percentage variations are identical due to similar curves, as both analyses are based on the same equations.

In all the cases shown, the results can vary strongly with changes in either V_{avg} or V_{cyc}, producing results as much as 275% larger than discussed in the analysis for a 10 mph change (a relatively large variation for these values). However, the potential increases are much greater than potential decreases in all cases due to the non-linear nature of the functions involved, which take shapes similar to those already explored in Figs. 10 and 12. The reasons for this are intuitively clear: as we attempt to increase Cycle Speed (V_{cyc}) closer to Average Road Speed (V_{avg}), the available time for recharging rapidly diminishes and the fraction of time to recharge decreases exponentially. In essence, by rearranging (11) to give:

$$\frac{V_{cycle}.E_{con}}{P_{chg}} = 1 - \frac{V_{cyc}}{V_{avg}} \tag{16}$$

we can see that as:

$$V_{cyc}/V_{cru} \rightarrow unity, P_{chg} \rightarrow \infty \tag{17}$$

The effect of this is rapidly increasing minimum recharge rates (Table 4) at the expense of longer chargepoint intervals and oversized batteries (Table 5). On one hand, this highlights the necessity of ensuring accurate and reliable numbers for this study (which here have been taken from the available literature eg. vehicle specifications) but, on the other hand, shows the importance of careful consideration of V_{cyc} and V_{avg} in reality. Much as when historical speed limits were chosen as a trade off between safety and time taken (The Times, 1935), society will now have to decide where to set that compromise to minimise GHG emissions.

5. Discussion

In this study, BEV use over long journeys has been recorded, modelled and developed into a convenient metric for assessing vehicle touring performance — Day Range. This new theoretical tool has both reiterated the value of minimising vehicle energy use through good design as well as uncovering the critical role that recharging infrastructure plays in a vehicle's long-distance performance. BEVs and their infrastructure can no longer be considered in isolation and must, instead, be viewed as a coherent system to maximise the benefits of road vehicle electrification.

5.1. Comparison with prior studies

While exploring an entirely new approach to battery sizing, it is interesting to note the similarities with previous studies. The conclusion here is that a suitable infrastructure could require batteries of only 25 kWh even for larger cars with E_{CON} = 250 Wh/mi, or put another way a range of around 100 miles. While not by any means a direct comparison, this is not far beyond the optimum ranges of 40–98 miles found by Meinrenken et al. (2020), based on a reversion to ICE propulsion for many of the longer journeys. Could this suggest a potential roadmap to lower carbon motoring, whereby shorter-range EVs are supplemented by internal combustion engines (either separate vehicles or hybrid powertrains) just until their suitably designed supporting infrastructure is constructed?

Similarly, the lower estimate of 12 kWh found in this study is only a little greater than the two 5.5 kWh removable batteries advocated by Gong et al. (2020), with both assessments relying on somewhat smaller and more energy-efficient vehicles. Perhaps with suitable infrastructure, Gong et al.'s vehicles could undertake long journeys without the extra "modular batteries borrowed or shared from the family's second EV" or, similarly, the 'recharge power' of this study could be vastly increased by swapping leased batteries en-route, achieving touring abilities on a par with ICE vehicles. The small battery sizes resulting from reduced energy consumption open up many options that would be simply unworkable with the weight of the 60 kWh+ batteries currently employed.

5.2. Practical implications

Today, one in five motorists worldwide depend on cheap, lightweight petrol vehicles with no low-carbon substitute available. If we are to tackle this electrification challenge we must focus on minimising energy consumption and, while the design of high efficiency motors, controllers, batteries and chargers is expensive, the unit production costs can be brought down by a reduced dependency on resource-intensive batteries. Similarly, by focussing on chargepoint regularity these small machines can be called upon to traverse great distances on a recharging network installed at a lower cost than occasional, exotic fast chargers that are wholly inappropriate to this type of vehicle.

This is not the only area where this study carries an important message; in regions with an already burgeoning long-distance BEV culture, such as the UK, the potential reductions in GHG emissions from electrification are becoming lost under the sheer weight of batteries. For too long, the electric motorist has been left to operate in isolation and forced to rely on larger and larger batteries to cover the required distance. Instead, infrastructure planners must focus on chargepoint regularity to relieve range anxiety, perhaps combined with reduced road speeds to curb energy consumption across the system. Not only will this avoid locking-out the truly low-energy small EVs, as is the risk in developing nations where they are more widespread, but will also allow the larger electric cars to shed much of their oversized battery. Emissions from battery manufacture are thus reduced both by enabling smaller battery capacities and by limiting the relative advantage of vehicles attempting to adopt the high-consumption fast-recharge model.

5.3. Limitations of this study

This study is not the first to suggest that there is a preferable alternative to the high-energy heavy car paradigm to road transport electrification but it proposes a simple model to demonstrate how this may be achieved without sacrificing occasional touring capacity. There are, however, two potential drawbacks to a parametric model of this kind: the parameters and the model itself.

As discussed in the uncertainty analysis of Section 4, and visible in many figures within the analysis of Section 3, most of the parameters discussed are subject to 'tipping points' and nonlinearities that require a good degree of confidence in the numbers used. While we have attempted to select reliable and representative data to put forward a realistic viewpoint, it is possible that further research could modify our conclusions and we hope that this assessment stands up to validation by other authors.

The model itself has been founded on a robust set of assumptions and verified to some extent by experience, research and the case study of Section 2.3. However, the drawback of such a simple parametric model is its reliance on average figures to represent variable and uncertain conditions. For example, the definition of a constant reserve range can be seen to vary even in the limited example of the case study presented, further research could prove that the model requires modification to accommodate this. In any case, this type of mechanistic tool will tend to make way for more sophisticated data-based models, such as those described in the literature review, as more time is spent exploring this critical area.

5.4. Future directions for research

This investigation aims to begin, rather than end, a conversation and several avenues of further research would be invaluable to build on its conclusions:

- Much of this study hinges on the relationship between reserve range and chargepoint interval. Clearly this is a very subjective relationship, depending on many factors such as: real geographic chargepoint intervals, perceived risk of stranding or range anxiety, information availability or familiarity with the local infrastructure etc. It would be invaluable to investigate more thoroughly the relationship between these multifarious factors.
- As shown in the uncertainty analysis of Section 4, greater confidence in the parameters chosen for the model would be invaluable to accurately represent different conditions and requirements. In particular there is little available information on acceptable journey times in different areas, which will impact required V_{cyc} or Day Range.
- This study implies a benefit from transferring investment from the individual vehicle (reducing battery size) to the infrastructure (reduced chargepoint intervals etc.). This will undoubtedly be beneficial to some extent but there will ultimately be an optimum ratio of infrastructure to vehicular investment, from both a cost and emissions perspective.
- The focus here has been on the potential improvements for a developed road network such as UK motorway system but much of the analysis would be of direct benefit to areas already dependant on light vehicles. A similar study should be applied to the prevalent road conditions in these areas.

6. Conclusion

We have shown that the existing heavy car paradigm for BEV touring risks repeating the mistakes of the past by masking high energy use with rapid charging and large batteries. It is also possible that a supporting infrastructure based on expensive (and so infrequent) high speed charge points could lock out low energy vehicles from a long distance road network altogether. In any case, many countries lack the infrastructure or personal wealth to depend on these complex and expensive solutions to long distance travel, often also lacking other low-carbon, low-cost alternatives such as rail and bus services.

Along with efficient vehicle design, appropriate infrastructure considerations have been found critical in minimising overall vehicle emissions through battery size reduction. Wide chargepoint intervals, or even high road speeds, can prevent low energy vehicles from using a long-distance road network altogether. As well as impacting long journeys, this has the potential to further increase overall energy use as high-energy vehicles (either ICE or heavy BEV) are used for short trips in order to retain an occasional touring capacity, particularly where households depend on a single vehicle.

Guidelines have been presented to ascertain upper and lower bounds of sensible chargepoint power, with numerical examples from UK motorways finding chargers in excess of 100 kW to represent poor resource allocation. Planning policy should instead focus on minimising and regularising chargepoint intervals, at least to achieve the 28 mile target in place since 2013. The current roll-out of high power charging stations (now up to 350 kW) at infrequent locations biases the network in favour of high-energy, heavy vehicles such as the Tesla Model 3. This has the potential to lock-out low energy vehicles altogether and miss any opportunity to minimise overall emissions.

Promisingly, careful allocation of resources can lead to surprisingly low energy touring. Not only can in-use energy be minimised through good vehicle and road design but, by examining the trade-off between chargepoint spacing and power, battery sizes can be minimised and embodied energy drastically reduced. Rather than the 60 kWh+ batteries currently in production, capacities as small as 12 kWh to 25 kWh could allow successful touring depending on vehicle type, with further reductions possible if battery C-rate can be improved. Not only does this represent huge savings of embodied emissions across the vehicle fleet but reduced vehicle mass will itself help reduce electricity consumption.

In practice, the results of this paper could mean significantly reduced road transport emissions if correctly applied and backed up with continued efforts to reduce electricity and battery related emissions. Although a modal shift away from inherently energy intensive personal transport is critical to achieving a zero-carbon future, some road traffic will always be necessary and so the challenge of low-cost, long-distance electric vehicles must be solved.

CRediT authorship contribution statement

Frederick Spaven: Conceptualization, Methodology, Writing – review & editing. **Yuanchang Liu:** Writing – review & editing. **Mehdi Baghdadi:** Methodology, Writing – review & editing, Supervision.

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.

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