**Rapid charging provision, multiplicity and Battery Electric Vehicle (BEV) mobility in the UK**

**Abstract:** This paper provides significant new insights into the spatial heterogeneity of public rapid charging provision for Battery Electric Vehicles (BEVs) in the UK. In particular, the paper makes three new and original contributions to our understanding of BEV mobility and the importance of rapid chargers and the multiplicity of rapid charging provision therein. First, the paper sets out a new conceptual framework which captures the different dimensions of BEV mobility. Second, the paper highlights the importance of multiplicity, recognising the important distinction between i) 'on-site' multiplicity; and ii) spatial multiplicity in rapid charging provision. Both have received relatively little attention to date yet are highlighted as being fundamental in shaping an individual’s ability to undertake extended journeys by a BEV. Third, the paper highlights how the development of charge point multiplicity is currently largely restricted to large urban areas and strategic road networks with current policies focusing on enhancing BEV infrastructure along the TEN-T Trans-European Comprehensive Transport Network. In considering spatial multiplicity in relation to the “reserve range” of BEVs, the paper identifies spatial variations in road network connectivity. Limited interconnectivity in rural areas - and which is particularly apparent for lower range BEVs - reflects an emerging market failure with the potential to undermine efforts to secure a “just transition” to BEVs.

**1. Introduction**

Ongoing initiatives to deliver a low-carbon future are increasingly focusing on the role of transportation as a sector that has thus far remained “stubbornly immune” (Kuby, 2019, p.46) to attempts to reduce greenhouse gas (GHG) emissions in most western economies. For example, in 2018, transport accounted for 28% of domestic GHG emissions in the UK, of which 90% was related to road transport (Department for Transport, 2020). A rapid and mass transition to electric vehicles (EVs) is therefore central to plans to reach net zero emissions with bans on the sale of exclusively petrol and diesel vehicles within the next decade having already been announced by several nations (Pereirinha et al., 2018).

As an alternative-fuel vehicle (AFV), the “refuelling” method for battery electric vehicles (BEVs) differs markedly from those used for conventional ICE (internal combustion engine) vehicles (Sun et al., 2016; Kuby, 2019). The charge points used to charge plug-in electric vehicles can be subdivided into two main categories - “Destination Chargers” and “Rapid Chargers”. Destination chargers (also known as slow chargers) typically use type 2 connectors and conventional single phase (3-7 kW) AC power supplies that are converted to the DC current required to charge the traction battery by a vehicle’s on-board charger. With the time required to charge the battery from a low state of charge typically requiring several hours, they are primarily used in situations where the car is likely to be stationary for a significant time period when the user is involved in another activity (for example, staying at home, working, shopping or eating out; Sun et al., 2015; Kuby, 2019). Whilst tri-phase AC power supplies provide possible charge rates of up to 22 kW, their limited availability coupled with the restrictions of on-board chargers means rates are currently limited largely to 3-11kW.

Rapid chargers (also known as fast chargers or quick chargers) use a DC current to bypass the vehicle’s on-board charger, directly charging the traction battery at rates of ≥50kW or more via a CCS (Combined Charging System) or CHAdeMO (“Charge de Move”) connector. In typically charging a battery from a low to a high state of charge in less than an hour, they provide a refuelling experience more equivalent to conventional petrol or diesel pumps (Motoaki and Shirk, 2017). The recent development of ultra-rapid or ultra-fast chargers (also known as high-powered chargers or “HPCs”) with charge rates of ≥100kW enable recharging rates increasingly comparable with liquid fuels, with Tesla V3 chargers already providing peak charge rates of 250kW equating to the addition of over 160 miles of range (260 km) in 10 minutes. Conversely, whilst low power destination chargers can in theory be used for longer journeys, their use is restricted to unplanned emergency charging required to avoid a driver becoming stranded (Kuby, 2019).

This paper focuses specifically on the accessibility of the public rapid charging networks essential for regional connectivity and a mass transition to full BEVs (Nicholas and Hall, 2018). Such networks enable the rapid refuelling required for longer journeys that exceed half of the vehicle’s range (Motoaki and Shirk, 2017; Neaimeh et al., 2017) and unexpected emergencies when charging time is limited (Sun et al., 2016). With a sparsity of provision and associated “range anxiety” being cited as key barriers to purchase (Franke et al., 2012; Bonges and Lusk, 2016; Liao et al., 2017; McKinsey & Company, 2018), network expansion is considered central to extending the user base beyond early adopters who have tended to use BEVs largely for urban commuting and to retain conventional vehicles for longer journeys (Christensen et al., 2010; Lorentzen et al., 2017; Nicholas and Hall, 2018). Public funding has therefore been largely targeted towards the establishment and enhancement of provision on the strategic road networks required for rapid and long distance intranational and even international travel (RCN, 2013; Department for Transport, 2020). Conversely, private finance has played a key role in the development of the rapid charging infrastructure in urban areas where they are used by private owners who lack destination charging at home or work, taxi drivers, commercial vans and as a general safety net for everyday use (Lorentzen et al., 2017).

Nevertheless, relatively little attention to date has explored the spatial distribution of public rapid chargers at a national level and the network’s influence and associated restrictions on the mobility patterns of BEV owners (see Neaimeh et al. 2017 for a notable exception). Furthermore, whilst a number of studies have highlighted both the functional and psychological importance of the rapid charging infrastructure in encouraging BEV drivers to make longer journeys and to optimise the use of their cars (e.g. Liao et al., 2017; Bakker, 2011; Franke et al., 2012; Rauh et al., 2015), there has been little focus in general on the differing dimensions of BEV mobility, including the significance of the multiplicity of rapid charging provision. In this paper we therefore develop a new conceptual framework which seeks to capture the different influences shaping BEV mobility. A second key contribution of the paper relates to the influence of multiplicity on long distance mobility that can be differentiated between i) ‘on-site’ multiplicity and ii) spatial multiplicity in which multiple chargers are accessible within the reserve range of the BEV. This is a crucial in that ‘range anxiety’ may be fuelled by a perceived risk of an isolated charger already been occupied by another vehicle, being out of order or being blocked by an ICE vehicle (ibid., p.65), thereby restricting patterns of mobility and BEV adoption.

A third contribution of the paper involves the identification of spatial inequities relating to the multiplicity of rapid charging provision, especially in rural areas. For example, in the UK, whilst the focus for public investment to date has been on the strategic road network, there is growing awareness of an emerging “market failure” and associated need for targeted public investment in more remote rural areas (e.g. The Energyst, 2020, p32; Ofgem, 2021). In addition, a recent draft EU report has explicitly made reference to the potential social inequalities arising from an uneven distribution of public rapid chargers and the need for a “just transition” as “(transition) will only be successful if it is a just and fair one to ensure that everyone, including disadvantaged communities, benefit from zero emission" (Transport and Environment, 2020). In considering spatial multiplicity and the “reserve range” of BEVs, the paper evaluates spatial variations in access to suitable charge point provision and their impacts on the current interconnectivity of the road network required to ensure a “just transition”.

**2. Public rapid charging and BEV mobility dimensions**

Previous research on BEV mobility has generally focused on the importance of i) developments in battery technology and cost and improvements in the range and affordability of BEVs (e.g. Nykvist et al., 2019); ii) the personality and experience of the user (e.g. Rauh et al., 2015), iii) the optimal siting of charging stations (Morrisey et al., 2016; Neaimeh et al., 2017; Anderson et al., 2018; Philipsen et al., 2018; Kuby, 2019); iv) the capacity of energy grids and their ability to respond to charging demands in specific locations (Yen-Chung et al., 2015); and v) the quality and reliability of the charging infrastructure (for example, charging speed and access issues; Davidov and Pantos, 2017). Limitations in any of these elements can limit the perceived mobility resources afforded by BEVs (Franke et al., 2012) and thereby act as a barrier to their widespread adoption (Philipsen et al., 2016).

Further consideration of the existing literature relating to BEV mobility and charging infrastructure, reveals several other dimensions which shape BEV mobility and which we have drawn together within a new conceptual framework. This framework gives particular emphasis to the influence of multiplicity that has received limited attention previously and which we discuss further in the results and analysis section.

The first dimension relates to the importance of ‘*fixity*’. It is apparent from the UK that the uneven spatial distribution of ‘fixed’ rapid charging infrastructure serves to differentially shape the ability of individuals to be mobile and to facilitate longer distance BEV mobility journeys into, within and beyond different types of areas. This is - at least in part - a consequence of an ongoing policy focus on provision across strategic networks. The key metric employed within a draft European Transport and Environment report assessing the current state of the charging infrastructure within EU member states pays particular attention to the number of rapid (fast) CCS chargers per 100 km along the Trans-European Comprehensive Transport (TEN-T) network (Transport and Environment, 2020). In the UK, the TEN-T network covers motorways and some trunk roads – i.e. the Strategic Road Network (SRN). It has been calculated that as of 2020 there were about 19 ‘rapid’ chargers per 100km of the TEN-T network in the UK, a figure currently higher than any other EU member state (ibid.). Meanwhile, a new £500 million “Rapid Charging Fund” announced in March 2020 in the UK will initially concentrate the provision of high-powered chargers (>150kW) at motorway service areas with the initial aim of having at least six High Powered Chargers (HPCs) per motorway service station on the TEN-T network by 2023 (Department for Transport, 2020). Consequently, in considering the current limitations to BEV mobility, there is a clear need to assess the level and distribution of fixed rapid charging infrastructure across the entire transport network, which encompasses both urban and rural areas (for a similar discussion on the importance of fixity in shaping rural mobility see the work of Milbourne and Kitchen, 2014; Carson and Carson, 2013; and Shergold et al., 2012).

A second dimension of BEV mobility involves ‘*complexity*’. Given the spatial heterogeneity in rapid charging provision, this means that the task of charging a BEV can be highly complex. For example, complexity arises in terms of both the type of charging connector available (Chademo vs CCS vs Type 2) and the diversity of charge point providers and the apps / registrations / RFID cards required to utilise their chargers. This problem has been recognised within a draft Automated and Electric Vehicles Act in the UK designed both to standardise payment methods (and facilitate the use of credit and debit cards to initiate charging sessions) and to require providers to co-operate and share data in order to develop a roaming facility that will allow BEV drivers to use any public charge point through a single payment method (Department for Transport, 2020).

A third dimension associated with BEV mobility relates to ‘*time*’. A common theme emerging from existing research is the length and variability in the time required to recharge a BEV that highlights one of the fundamental differences with the refuelling of ICE vehicles. Undertaking a long journey in a BEV commonly takes significantly longer as a result of the time required to charge en route. Botsford and Edwards (2015) estimated, for example, that a Nissan Leaf requiring a 30-minute charging stop every 60 miles would require four hours longer than an ICE car to make a 550-mile trip from Washington to Oregon in USA. An additional complexity is the non-linear rate at which BEVs rapid charge with charging power tapering as the state of charge (SoC) increases. In studying the use of fast chargers as part of a US trial, Motoaki and Shirk (2017) consequently noted that drivers spent more time at the charger than was necessary, incurring a greater time penalty particularly when charging provision was free. BEV users may experience significant time delays if charging points are occupied, blocked, inoperative or unusable. In addition, they may need to make a detour from their intended route simply to access the charging infrastructure or to access familiar or preferred rapid chargers (Sun et al., 2015; Kuby, 2019).

A fourth dimension relates to the importance of ‘*planning*’. Route planning longer journeys in a BEV can be a complex task in view of the variations in the vehicle’s range (which can be significantly affected by season, weather and topography), variations in the personality and experience of the user and their “range safety buffer” (Franke et al., 2012) and the need to “map match” the expected mobility resource (perceived range) to a limited charging infrastructure (Sun et al., 2016; Kuby, 2019). The need to assess the availability and reliability of charging infrastructure en route (both prior to the trip and potentially during the trip) in turn involves the selection and utilisation of one or more apps that provides crucial information on the status, reliability and availability of the charging infrastructure and another area of complexity (e.g. Liao et al., 2017; Lorentzen et al., 2017). Given the current scarcity of rapid charging provision in many rural areas of the UK and beyond, BEV users making longer trips transiting areas of limited provision need to take particular care in planning their journeys with a lack of alternative charging options increasing the risk of becoming stranded or incurring a time delay of several hours if a destination charger is the only option available. The absence of rapid charging provision in large parts of the British countryside is consequently shaping patterns of mobility with anecdotal evidence that BEV users are already actively avoiding these areas (BBC, 2020).

The preceding dimensions lead to a key point that underpins the central arguments in this paper – namely the crucial role played by ‘*multiplicity*’. Multiplicity in the context of BEVs has previously been discussed in several ways: i) in relation to charging a multiplicity of batteries (Amiri et al., 2018); ii) in terms of using different sources of electricity to charge BEVs (see Pereirinha and Trovão, 2012); and iii) multiplicity in respect of chargers on a particular supply network (for example, see Bentley et al., 2010). Yet there has been a virtual absence to date of an explicit focus on the importance of multiplicity of charging provision at particular locations (‘on-site’ multiplicity) in influencing route planning choices and shaping long distance BEV mobility. This is a crucial point given we have already identified the challenges of time, complexity and planning in shaping BEV mobility.

Previous studies on the use of rapid chargers commonly make an implicit assumption that such chargers will always be operational. In reality, the inclusion of reliability standards within recent national legislation (e.g. Gov.uk, 2019) recognises ongoing concerns in this area and the need for on-site multiplicity as a result. In assessing the development of charging infrastructure in Norway, the world’s most advanced EV market, Lorentzen et al. (2017) noted how the allocation of state funding for the initial roll out of charging infrastructure required a minimum provision of two least two multi-standard DC rapid chargers (with both CCS and CHAdeMO connectors) as well as two 22kW AC chargers to accommodate potential equipment failure and reduce charging queues. The importance of on-site multiplicity has been recognised within the development of Tesla’s bespoke “supercharger” network whose speed and ease of use is considered central to the company’s commercial success (see businessinsider.com, 2020). More recently, the appearance and development of dedicated charging hubs such as Gridserve’s first “electric forecourt” in the UK with 36 rapid chargers highlights the increasingly influential role on-site multiplicity is expected to play in encouraging a modal shift to BEVs (Gridserve, 2021).

The development of an interconnected geographical network of chargers enabling region-to-region travel is considered a key initial priority for rapid charging provision (Nicholas and Hall, 2018). Within this field of research there has been a considerable focus on the importance of charging networks and subnetworks for EVs given current power distribution grid constraints (e.g. Sundstrom and Binding, 2017; Vassileva and Campillo, 2017). Additional research has explored the use of network design in optimising the charging infrastructure required to accommodate increasing levels of BEV usage given their range limitations. Zheng et al. (2017) identify the optimal location of charging nodes as a discrete network design problem in which BEV users will seek to minimise their generalised cost in relation to both travel time and energy consumption that in turn depends on the resultant traffic flows. Yang et al. (2016) have identified the initial state of charge as well as charger location and charging time as additional complexities that will dictate route choice and therefore network provision. Within this context, the presence of spatially proximate rapid chargers can provide multiplicity at the network level in which the presence of ‘back up’ rapid charging options that can be reached within the reserve range of the BEV can be considered an alternative to ‘on site’ multiplicity (see Scott et al. (2020) and Anderson et al. (2017) for a discussion of ‘back up’ charging more generally).

Increasing the multiplicity of provision in either of these forms is therefore key to enhancing redundancy in charging infrastructure and to enhancing the reliability of charging. It is also important in reducing queuing times to charge and to maximise charge rates in situations where the power would otherwise be split between two vehicles sharing the same stall. Hence in summary, increasing i) the density of provision of rapid chargers at charging locations; and ii) the density of provision along different types of road networks which traverse both urban and rural areas (in order to enhance options for multiplicity for charging in a particular area) is a key concern that requires further attention. In so doing, this will be fundamental to reducing range anxiety and creating the interconnected charging infrastructure required to promote the more widespread transition to BEVs. Such issues are now considered in more depth.

**3. Methods**

To examine the spatial distribution and heterogeneity of current rapid charging provision within the UK and the multiplicity of infrastructure requires relevant charging point data. This should be a simple and relatively straightforward task. However, in the context of the UK, the most comprehensive, up to date and detailed charging point databases are currently privately owned. This means that while a cartographic visualisation of the data is usually freely available, obtaining the raw data for further analysis is problematic as it is under copyright law (Lane, 2018). Such companies obtain their data from a variety of sources including directly from those who manage the chargers, from BEV car dealerships, or from individual users who help keep such maps up to date by contributing through crowd sourcing (Shufflebotham, 2019).

Nevertheless, there are two publicly available EV charging datasets that can be accessed freely, the National Charge Point Registry (NCPR, 2018) and the Open Charge Map (OCM, 2020) initiative. In the context of this paper, OCM data was used as it combines official datasets such as the NCPR with additions from BEV users. With over 1000 locations added or updated each month it is a robust data source that provides a comprehensive list of charging points. More importantly for the purpose of this article, the information provided for each charging location includes the output power *and* the number of charging points - albeit with some limitations as 16% of the rapid charging locations do not include information about the number of charging points. The whole dataset for the UK was downloaded on 15/12/2020 from OCM. A focus was placed on charging locations with a charging capacity of at least 42kW to identify rapid chargers.

In terms of on-site multiplicity, data was subsequently analysed and visualised through GIS approaches and a combination of relevant data sources. Charging locations were transformed from tabular form into a geographical representation through converting X and Y pairs of coordinates (provided by the original datasets) into point shape files and filtered depending on the output power and the number of charging points. Road network information was obtained from official sources (McGarva, 2017 and OSNI, 2021), with Strategic Road Network (SRN) data derived by selecting only motorways and trunk roads. In addition, a road network-based buffer was used to calculate distances between the actual location of rapid chargers (see Figure 1) and each type of road. In turn, the respective rural / urban classification systems of relevance to each area of the UK (Office for National Statistics, 2019; Scottish Government, 2018; UK Data Service, 2011) were used to derive a picture of multiplicity in relation to rural / urban areas split into 20km x 20km grid squares, and with the number of rapid charging outlets then calculated within each grid square (Figure 2).

To explore spatial multiplicity, network analysis was used in order to identify areas of the UK road network where multiplicity existed dependent on how many rapid charging locations could be found in proximity to each other. The road network considered included all motorways and A roads - the two road types most likely to be used when travelling longer distances. For each rapid charging location, a network-based buffer zone was created up to a certain distance depending on the scenario to be modelled (Author, 2020), in this case 20km and 35km. If two buffers had some level of overlap they were joined, thus creating a network where spatial multiplicity of rapid charging provision was available at the given distance. By repeating the process with all rapid charging locations across the UK - while keeping those located on off-shore islands isolated (for example, the Isle of Wight) - several levels of multiplicity were evident. First, at both distances a core multiplicity area with over 1,000 charging locations could be identified within which an alternative or back up rapid charging location is available to BEV users within either 20 or 35km if the chosen one was unavailable. Second, when modelling at 20km (Figure 3a), two further areas with significant but less expansive levels of multiplicity were apparent around the Bristol Channel and Scotland’s Central Belt with 150 and 233 charging locations respectively. Finally, in both models (Figure 3a and Figure 3b) a series of isolated networks with some multiplicity - between 2 and 33 chargers - but disconnected from the main multiplicity networks were also identified.

**4. Results and analysis**

Variations in the counting of public charging points that can result in the double counting of connectors that cannot be used independently has led to the recognition of a need for greater methodological clarity and harmonisation when assessing current provision. Within the results that follow, a charging “location” is referred to as a facility offering rapid charging infrastructure. The number of charging “stalls” available at each location is used as the basis for assessing the on-site multiplicity provided as they can be used simultaneously for rapid charging. Conversely, whilst a single stall may offer multiple connectors (e.g. type 2, CHAdeMO and CCS), currently these rarely allow for the simultaneous rapid charging of multiple vehicles and therefore do not necessarily indicate multiplicity in rapid charging provision.

*4.1 On-site multiplicity*

Figures 1a-1f initially consider on-site multiplicity in absolute terms. For example, whilst Figure 1a highlights all public rapid charging locations in the UK (n = 2314), Figures 1b and 1c illustrate how on-site multiplicity becomes progressively more limited in terms of the number and distribution of locations offering at least two or at least four independent rapid charging stalls respectively at a single location. Indeed, if we take public rapid charger locations where there are at least two separate charging stalls (Figure 1b: n = 962), these sites are generally limited to some of the major cities in the UK (for example, London, Birmingham, Bristol, Manchester, Newcastle, Glasgow and Edinburgh) as well as along some of the major trunk road networks (such as the M40, M1, M6 etc; also see below). In contrast, other parts of the UK, including most of north and central Wales, the South West of England, Northern Ireland and parts of the east of England and northern Scotland display more limited provision.

If the analysis is extended to focus solely on locations where on-site multiplicity extends to four or more charging stalls (Figure 1c: n=248), this reveals a much more restricted pattern of provision: such sites are wholly absent in Northern Ireland, severely restricted in Wales and Scotland (except for Dundee, Edinburgh and Glasgow) and limited in England to small clusters in the major cities (e.g. London, Bristol, Leeds and Manchester) and linear arrays principally along the main motorway networks. Given the necessity for BEV drivers to have contingency options in case their ‘chosen’ rapid charger is inoperative, occupied or blocked, this may act as a barrier to BEV drivers seeking to traverse large parts of the UK through a single long-distance trip that is not directed along these strategic road connections. Alternatively, it is likely to add additional complexity to the associated route planning.

With reference to the SRN of the UK, in absolute terms, Figure 1d highlights how the total number of chargers currently located within 1 mile or 1.6km of the SRN, which includes just over half of the total number of rapid chargers currently available in the UK (50.6%; 1171). However, Figures 1e and 1f identify how on-site multiplicity along the SRN in the UK remains more limited, with sites with two or four or more stalls numbering 570 (24.6%) and 173 (7.5%) of the total number of rapid charging locations respectively. In contrast, if the focus is turned to A-roads, Figure 1g reveals how in absolute terms most of the rapid chargers in the UK at present lie within 1 mile of an A-road (2223 or 96.1% of all rapid charging locations) but with on-site multiplicity again diminishing, with locations with two or four or more stalls numbering 900 (38.9%) and 224 (9.7%) of total charging locations respectively.

**Insert Figure 1 here**

Breaking the analysis down further, a consideration of rapid charging provision along the SRN and A-roads can also be made for the different devolved administrations of the UK in more relative terms. In section 2 of the paper, we highlighted how a key metric employed to assess the current state of the charging infrastructure within EU member states involves a focus on the number of rapid (fast) CCS chargers *per 100 km* along the Trans-European Comprehensive Transport (TEN-T) network (Transport & Environment, 2020). Hence consistent with the methods adopted in the European Transport and Environment Report (Transport and Environment, 2020), Table 1 uses this measure to assess the current provision of on-site multiplicity by considering the total number of charging locations with 1, 2+ or 4+ along the SRN or A roads for different devolved areas of the UK. This indicates that the total number of rapid charging locations per 100km varies across the UK, with the highest figures being recorded in England (n=11.33) and Scotland (n=7.33) and the lowest in Wales (n=2.80) and Northern Ireland (n=1.13; row 1). More interestingly, the gap between England and Scotland narrows when considering the total number of locations with two or more charging stalls (5.20 per 100km of SRN in England compared to 4.51 per 100km of SRN in Scotland). In contrast, Wales and Northern Ireland record much lower figures with the numbers of locations with two or more charging stalls totalling 1.07 per 100km of SRN in Wales and 0.53 per 100km of SRN in Northern Ireland (row 2). For locations with four or more charging stalls (row 3), the figures drop to 1.57 per 100km of SRN in England whilst this figure is 1.49 per 100km of SRN in Scotland, For Wales and Northern Ireland, the figures are 0.18 and zero respectively in terms of locations with this level of on-site multiplicity.

**Insert Table 1 here**

In contrast to absolute levels of provision, Table 1 additionally indicates how multiplicity in relative terms (pro-rata) is even less evident on A roads compared to (already low) figures for the SRN. For example, if we only count the availability of two or more charging stalls per 100km of A road, the total number of charging locations with 1, 2+ or 4+ charging stalls per 100km of A road (2.04) is over 50 per cent less than the equivalent figure for the SRN (5.20; row 2). Such patterns are replicated across other parts of the UK.

Thus, in overall terms there is some way to go before large amounts of on-site rapid charging multiplicity and redundancy are available in the context of the UK’s SRN and A roads, with current provision along A roads being concentrated in and around Greater London and with only small pockets occurring elsewhere. This highlights the influence of current BEV ownership and demand whilst raising issues of social equity with respect to existing charging provision.

Another way of visualising the challenges of on-site multiplicity in terms of its spatial variability is represented in Figure 2. This map sub-divides the country into 20km x 20km (400km2) grid squares and with the squares shaded in grey highlighting areas that lack of on-site multiplicity: there are either no public rapid charging stalls or only one rapid charger in a particular charging location. In contrast, those areas not greyed out have at least two rapid charging stalls at a charging location within a 20km x 20km area. In utilising the respective rural-urban classifications for different parts of the UK - and with urban areas being highlighted in purple - this figure highlights the urban-centric nature in the current provision of on-site multiplicity and the high levels of demand associated with locations with high population densities and vehicle kilometres travelled (Nicholas, 2010). In contrast, the distribution of grey boxes highlights an absence of on-site multiplicity in many rural localities including North and Mid-Wales, north England, the Scottish Borders and northern Scotland where the demand for rapid charging is much more limited.

**Insert Figure 2 here**

*4.2 Spatial multiplicity*

Figures 3a and 3b explore the national provision of spatial multiplicity as an alternative type of charge point redundancy and back-up charging discussed in section 3. In generating these figures, we draw on literature relating to the “reserve range” of BEVs to consider the implications of uneven spatial multiplicity for BEV mobility. First, the literature on “reserve range” highlights the ways in which BEV users seek to maintain a "safety range buffer" (Franke et al., 2012). For example, Bonges and Lusk (2016) note how 50% of the range of the BEV is a significant threshold for range anxiety to commence, although this varies from person to person. Furthermore, Sun et al. (2016) noted that users never allowed the SoC of the battery to drop somewhere between 10% and 20% before initiating a rapid charging session. Therefore, in using a figure of c.10% as the lowest threshold value, this equates in range terms to an average “safety buffer” of around 20km for an early BEV (such as a 30kWh Nissan Leaf) or a modern low range BEV (such as a Mini Electric) with a maximum range of 200km. A 35km safety buffer meanwhile equates to a modern longer-range BEV such as a Volkswagen ID3 (with medium-sized battery) with a maximum range of 350km (EV database, 2021).

Figure 3a thus uses the road infrastructure of the UK to consider the extent to which BEV users can employ their reserve range or safety buffer to travel to an alternative rapid charger if the rapid charger they plan to use is out of order, blocked or already in use and on-site multiplicity is not available. The assumption in such a scenario - reflective of the need to make BEV mobility as efficient and smooth as possible to facilitate mass adoption - is that individuals would not wish to utilise a public destination charger due to the significant time penalty incurred. Consequently, Figure 3a illustrates the connected road networks that currently have rapid charging redundancy in the form of spatial multiplicity where one rapid charger is within 20km of another.

The distinction between the road network is undertaken to illustrate the levels of connectivity and to identify discrete sub-networks that provide different degrees of network multiplicity. The roads coloured in blue constitute the UK’s largest interconnected network where spatial multiplicity in rapid charging is very much in evidence. For example, it illustrates that an individual would be able to make a journey from the South East coast of the UK to the North West or to the North East of England with charging redundancy / spatial multiplicity being available throughout. Put another way, individual BEV users may have different levels of ‘range’ in respect of their BEV but would have back up options for recharging along a range of interconnected road infrastructures in this part of the country.

Those roads in Figure 3a coloured in green constitute areas of moderate network multiplicity (focused on Scotland’s central belt and South Wales and the South West of England) where it is also possible to benefit from spatial multiplicity and to undertake extended trips with redundancy of rapid charging provision on offer but with more limited region-to-region interconnectivity. On the other hand, those roads coloured in red constitute areas where there are relatively low levels of network multiplicity that provide more limited and localised access to spatial multiplicity within which individuals would have access to backup rapid charging options. Finally, roads depicted in grey offer no spatial multiplicity.

Thus, it is evident that higher levels of spatial multiplicity and interconnectivity are present within and between the major urban areas of the UK whilst in many rural areas spatial multiplicity of public rapid charging provision is currently limited in its extent and these areas are geographically isolated in the context of EV mobility. Hence if ‘on-site’ multiplicity is limited, such areas become ‘higher risk’ zones for BEV drivers where range anxiety is heightened by a reliance upon individual rapid chargers, requiring more careful planning (e.g. to assess charger reliability) and entailing a higher likelihood of unplanned (and much longer) emergency charging at a “destination charging” point if the rapid charging provision is inoperable (Sun et al., 2016).

**Insert Figure 3a and 3b here**

Finally, Figure 3b extends the analysis to consider those roads in the UK where rapid chargers are within 35km of each other. This indicates that most of the UK’s roads have this level of spatial multiplicity and with only those roads highlighted in grey (predominantly in West Wales, Northern Ireland and small areas of Western Scotland) lacking rapid charging redundancy. This highlights an important connection between battery size, BEV range, spatial multiplicity and ultimately regional interconnectivity. Users of BEVs with larger batteries and longer ranges are more able to overcome complexities of charging, to access a wider multiplicity of provision and to retain reserve rapid charging options across larger areas of the UK. Conversely, the owners of BEVs with lower ranges are far more restricted in their ability to access this spatial multiplicity.

**5. Conclusion**

A key contribution of this paper lies in the new conceptual framework set out in order to capture the importance of *fixity* (of rapid charging infrastructure), *complexity* (of charging), *time* (to charge), *planning* (to negotiate charging infrastructure when making longer trips) and *multiplicity* in shaping BEV mobility. In view of current concerns about the reliability of existing rapid charging infrastructure and the increasing demand on existing infrastructure, the latter is considered crucially important in shaping long distance trips using a BEV that has hitherto been given limited attention. The paper has also illustrated how fixity, time, complexity and planning come together more specifically in relation to spatial multiplicity. As such, engaging with spatial multiplicity may be dependent on the fixity of charging networks and the ability to plan routes to reach alternative charging infrastructure, as well as overcoming complexity in respect of understanding what charging options may be available. Furthermore, utilising spatial multiplicity can be considered inefficient in terms of both time and energy in requiring a diversion to another location if the preferred rapid charger is out of order, blocked or already in use and / or available on-site multiplicity is limited.

Subsequently, the empirical contribution of the paper involved an analysis of both ‘on-site’ and spatial multiplicity in shaping mobility and the subsequent identification of the spatial unevenness of current multiplicity in the UK. In respect of on-site multiplicity, Figures 1a-1c indicate that less than half of the current number of public rapid charging locations in the UK offer any sort of on-site multiplicity (41.6%; n=962) whilst just over 10% (n= 248) of locations offer greater levels of on-site multiplicity and 4+ charging stalls.

Further consideration of charging provision in relation to key metrics used to assess provision across the EU revealed considerable differences in the number of public rapid charging locations per 100km of the SRN across the UK with England offering 11.33 locations per 100km of SRN, Scotland 7.33, Wales 2.8 and Northern Ireland 1.13 (Table 1). These values are considerably lower when on-site multiplicity is considered. It is also evident that public rapid charging locations per 100km are also much less prevalent for A-roads than they are for the SRN, highlighting the ongoing policy focus on the primary road network in the UK.

Finally, the use of network analysis to examine the accessibility of spatial multiplicity in which BEV users can use their reserve range to use a backup public rapid charger reveals different levels of current road network connectivity across the UK. The current provision of interconnectivity offering spatial multiplicity was observed to be urban-centric with rural areas being poorly served. Modern BEVs with longer reserve ranges allow access to greater levels of interconnectivity although the associated increased costs raise concerns about social equity.

Moving forward, such findings are important for a number of reasons. In terms of academic research, more work is required to explore the importance of a number of the challenges to BEV mobility set out in the conceptual framework. This is particularly the case in relation to evaluating the importance of contingency and multiplicity from a user perspective in a range of different spatial contexts, including more remote rural areas. Further consideration is also required to statistically analyse the relationship between the provision of on-site and spatial multiplicity and BEV adoption rates as a key demand-side driver. From a policy perspective - and in a European context - the emphasis of enhancing rapid charging infrastructure along the TEN-T / SRN may undermine efforts to secure a “just transition” to BEVs. Greater attention will therefore need to be placed on how the multiplicity of BEV charging can be supported in towns, villages and more remote (rural) areas across Europe (Transport and Environment, 2020) and beyond. At the very least this will require national and local governments across the world to work alongside private sector partners to address the significant challenges associated with the development of a charging infrastructure suitable for mass adoption. This will require considerable public investment being directed towards the development of charging infrastructure in rural areas in particular where the customer base may be small and where costs of electricity grid connections can be very high, the importance of which is finally being recognised in the UK at the time of writing (Ofgem, 2021).

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