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Regional Electric Vehicle Energy Consumption and Carbon Emissions in Great Britain

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Abstract

This work presents the regional differences in electric vehicle (EV) real-world energy consumption and associated carbon emissions during charging in Great Britain (GB). A model was developed considering the variability in road traffic, ambient temperature, and electricity grid profile between the GB regions on EV carbon emissions under uncontrolled and smart scenarios. The results show the variations in EV energy consumption and carbon emissions impacted by where, when, and how an EV is driven and charged. Carbon emission reduction varies from 5% to 33% between the regions when switching to delayed smart charging, shifting the charging process outside peak hours. An optimised smart charging that moves the charging events to periods of low grid carbon intensity reduces carbon emissions from 6% to 55%, affected by region grid carbon intensity and energy consumption.

Keywords: electric vehicles; energy consumption; carbon emissions; regional differences; charging time

1. Introduction

The deployment of electric vehicles (EVs) depends on the optimisation of charging infrastructure to attend local charging demand (Mourad and Hennebel, 2020). Analysis of EV driving behaviour and charging patterns provides valuable information to reduce carbon dioxide (CO_2) emissions and develop charging infrastructure. EV energy consumption is influenced by ambient temperature and road traffic (Al-Wreikat et al., 2022). The electricity grid

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carbon intensity changes depending on the hour of the day and season. For example, CO_2 emissions from electricity generation in Finland are doubled during winter due to increased fossil fuel use compared to summer (Lajunen, 2018).

McLaren et al. (2016) covered the analysis of EV emissions under four different charging infrastructures and scenarios, home, time-restricted and workplace charging, with five different electricity grid profiles, from a high to a low carbon-intense electricity generation mix. The results show that workplace charging has the lowest emissions in all scenarios, except in the case of a high carbon electricity mix, while the time-restricted had the higher emissions value in most cases. The authors highlight that the price of electricity at off-peak hours and policies that do not encourage daytime could lead to an increase in emissions.

Li et al. (2019) investigated the regional difference in CO_2 emissions reduction from adopting EVs in China using well to wheel analysis, showing that the reduction varies considerably between the regions and suggesting that policies need to be adjusted to consider the impact of EVs in each region. Onat et al. (2015) performed a similar study in the United States with similar results about the difference between each region. There is a substantial gap in the knowledge of EV benefits will have on the environment from a global standpoint, as the majority of previous regional studies were performed in the United States or China (Requia et al., 2018). Furthermore, as pointed out by the author, there is a need for studies in other regions, as EV emissions are affected by many factors besides the source of energy generation, such as driving patterns, charging infrastructure, policies, and climate.

A review of the United Kingdom (UK) Net Zero strategy emphasises the importance of local regions role in meeting the national net zero ambitions, as 30% of greenhouse gas (GHG) emissions reductions rely on local authority involvement, and 82% of all UK emissions are under the influence of local authorities (Skidmore, 2023). Taking a regional approach will allow identifying the best path to meet net zero targets considering regional variations in transport and electricity grid (Grid, 2022). Therefore, to identify further opportunities for decarbonising passenger vehicles, analysis is needed considering the UK region variability in road traffic and electricity grid profile.

This work aims to evaluate EV energy consumption and CO_2 emissions under different charging scenarios on a sub-national basis. The main novelty of this work is that the effects of regional differences in electricity grid mix, driving patterns, and ambient temperature on an EV energy consumption and CO_2 emissions while charging under uncontrolled and smart charging is reported for the first time. The impact of a delayed charging strategy on CO_2 emissions was investigated on a sub-national basis, based on the new smart charge points regulations. An optimised charging schedule for minimising related CO_2 emissions from EV charging was presented in each region.

2. Methodology

This section describes the model created to investigate the differences in CO_2 emissions from EV using uncontrolled, delayed or optimised charging under two schedules – routine and minimal – in each region of Great Britain (GB). The model considers regional differences in road traffic, ambient temperature and electricity grid profile.

2.1. Charging Schedules Description

The majority of EV charging is expected to occur at home (Crozier et al., 2020) due to the convenience of home charging since it is the most common location for vehicles, and the preferred scenario by EV users to charge at home in the evening (Crozier et al., 2018). According to a UK dataset of residential charging, the most popular time for plugging in EV is between 5 pm and 7 pm, with an average total plug-in duration of 12 hours and 41 minutes (DfT, 2018). Two charging schedules were considered – routine and minimal – based on the work by Dixon et al. (2020). A routine charging schedule describes a case in which drivers view charging to carry negligible inconvenience and turn into a routine, where users plug in their EVs every time they arrive home regardless of the battery state of charge (SOC) (Dixon et al., 2020). The minimal charging schedule represents a case where drivers see charging as inconvenient and aim to have fewer times to plug in their EVs.

Charging frequency is a factor to be considered in the minimal schedule that depends on the battery capacity and SOC for which the EV should be charged. The model assumes the driver to plug in the EV once the battery SOC drops to 15%, as the minimum allowed SOC for emergencies (Hecht et al., 2021), and charge the battery until 90% SOC, a suggested value by vehicle manufacturers to maintain the best battery performance (Tikka et al., 2021).

2.2. Uncontrolled and Smart Charging

2.2.1. Uncontrolled Charging

The initial model analysis measures the impact of uncontrolled charging on CO_2 emissions under the two schedules – routine and minimal – considering the plug-in time starts at 6 pm and ends at 7 am to reflect the home charging situation. Home charging power of 7 kW was used, as most chargers are likely to be rated at that power due to no difference in price compared to slower 3.5 kW chargers (Dixon and Bell, 2020).

2.2.2. Delayed Smart Charging

In May 2022, the UK government announced that the Electric Vehicle (Smart Charge Points) Regulation which state that new private charge points must be pre-set to not charge during peak hours between 8 am to 11 am and 4 pm to 10 pm (OPSS and BEIS, 2022). The model was extended to evaluate the impact of delayed smart charging on CO_2 emissions by delaying the charging to start after 10 pm to reflect the new regulations requirements.

2.2.3. Optimised Smart Charging

An optimisation charging model was created to provide an optimal schedule for charging an EV to minimise the CO_2 emissions while considering the constraints on the charging window between 6 pm and 7 am. The model measures the total charging duration to determine the number of charging events for both routine and minimal schedules and then identifies the times when the electricity grid has the lowest carbon intensity.

Figure 1 shows the general behaviour of uncontrolled, delayed, and optimised charging for routine and delayed schedules. The park time refers to the total duration when the EV is plugged in from 6 pm until 7 am, charging times are the periods when the EV is charging and idle times are the hours when the EV is plugged in but not charging.

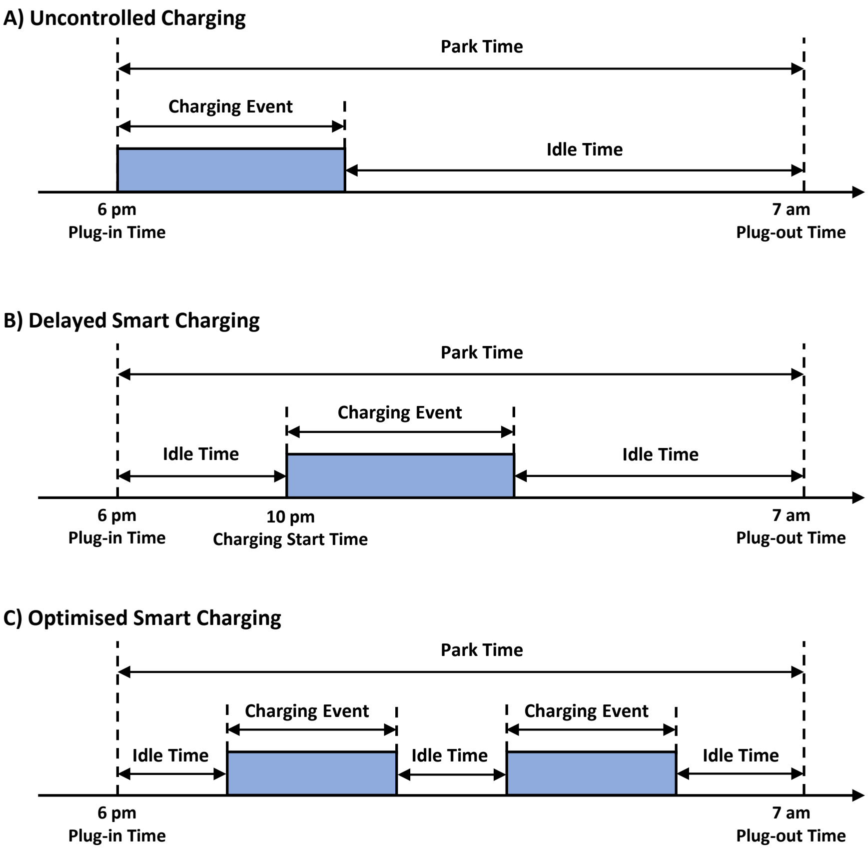

Fig. 1. General presentation for uncontrolled, delayed and optimised charging for routine and minimal schedules.

2.3. Road Traffic

The department for transport (DfT) does not provide separate data for car traffic in each region divided by road class; therefore, it had to be determined using the currently available data. In the first step, the model takes the 2019 data of road traffic by vehicle type and road class in GB (DfT, 2021), extracts the car traffic for each road class and measures the percentage of road traffic covered by cars to the total road traffic by road class. Then, the obtained percentages combined with the data for road traffic by road class and region provided by the DfT (2021) were used to calculate the car traffic in each region divided by road class.

The mileage in each region was determined using car traffic by region data (DfT, 2021) and the total number of cars in each region. Then, the distance covered for each road class was determined using the mileage in every region and multiplied by the percentage of car traffic by road class calculated from the previous step in each region.

Monthly traffic flow varies between road classes. For example, August has the highest traffic flow for motorway roads, while for urban and rural roads, June has the highest traffic flow. In comparison, January has the lowest traffic flow for all road classes. The monthly traffic flow by vehicle type and road class data was applied to all regions, obtained from DfT (2021) to calculate the monthly distance covered by road class per car for each region.

2.4. Temperature and SEC Data

The monthly ambient temperature for every region was obtained from Met Office data to account for temperature impact on energy consumption (Met Office). The model uses the specifications for the average new registered EV, which are 64 kWh battery capacity and 415 km driving range based on the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) driving cycle, determined from DfT (2022), Vehicle Certification Agency (https://carfueldata.vehicle-certification-agency.gov.uk/downloads/default.aspx) and EV-database (https://ev-database.org). The relation between temperature and EV specific energy consumption (SEC) under different road classes was based on real driving cycle (RDC) (Al-Wreikat et al., 2022). A usable battery capacity of 90%, 90% charging efficiency and 95% battery efficiency were applied to calculate the annual CO_2 emissions.

2.5. Regional Grid Carbon Intensity

Data for the electricity grid carbon intensity was obtained from the 2019 National Grid Carbon Intensity API website (National Grid). The Carbon Intensity API provides a historical regional breakdown of carbon intensity with 30 min resolution. The model in this work extracts the half-hourly data from the Carbon Intensity API for each day and produces monthly carbon intensity profiles for each region.

3. Results and Discussion

3.1. EV Energy Consumption

Figure 2 shows the variation of EV annual energy consumption when driving in each region divided by road class, considering the difference in mileage, road class and ambient temperature between the regions. The low temperatures in northern regions cause an increase in energy consumption. While North East and North West regions have similar mileage, driving in North East presents lower energy consumption due to the higher portion of rural driving, which is less affected by temperature. London has the lowest energy consumption because of the low mileage. Both East of England and West Midlands have nearly equal energy consumption to the national average, but West Midlands has much closer value for urban driving. The EV real-world driving range has the highest drop from the advertised WLTP range in Scotland, followed by North West with 18% and 17%, respectively. London has the lowest impact, dropping the EV range from WLTP to RDC by 8%, compared to the national average of 15%.

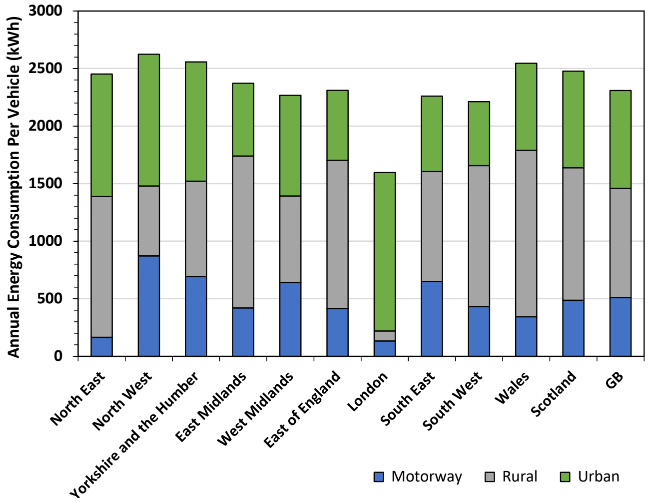

Fig. 2. Annual EV energy consumption by road class in each region of Great Britain.

3.2. Charging Scenarios CO_2 Emissions

3.2.1. Uncontrolled charging

The impact of routine and minimal schedules on annual CO_2 emissions using uncontrolled charging for each region is shown in Figure 3. In general, the minimal schedule has lower CO_2 emissions than the routine case, in GB leads to yearlong saving of around 84 $kgCO_2$, 12.7% reduction. The percentage of reducing CO_2 emissions increases in the West Midlands to 19.9% but drops to 3% in Wales. In the routine schedule, the charging events are around 1 to 1.5 hours, since a small amount of energy is needed, leading to higher CO_2 emissions because when routinely plugging in the vehicle at 6 pm and charging starts immediately, nearly the entire charging event will happen during high carbon intensity period. For the minimal schedule, while the first part of the charging event will occur during peak hours, the charging will continue beyond the period of high electricity grid carbon intensity, as a typical EV takes around 7 hours to charge the battery from 15% to 90% SOC using a 7kW charger.

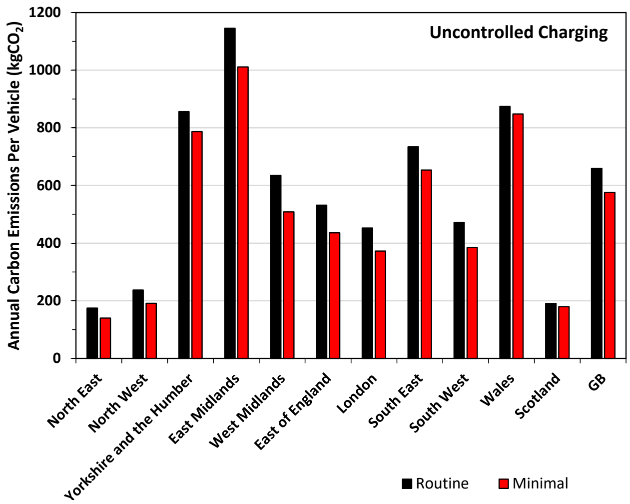

Fig. 3. Annual CO_2 emissions per vehicle using uncontrolled charging under routine and minimal schedules for each GB region

3.2.2. Delayed smart charging

Figure 4 shows the annual CO_2 emissions when using delayed smart charging, shifting the start of charging events from 6 pm to 10 pm. Comparing to Fig 3, switching from uncontrolled charging to delayed smart charging reduces CO_2 emissions on a national level by around 21% and 12% for routine and minimal charging schedules, respectively. Regions that benefit the least from delayed smart charging, such as Wales, have relatively flat electricity grid carbon intensity. East Midlands, with the highest annual CO_2 emissions, can save 229 kCO_2 by switching from an uncontrolled routine schedule to a delayed charging or 110 $kgCO_2$ for the minimal case. Regions with low annual CO_2 emissions will still benefit from the delayed charging, as the North East region reaches around 32% for both charging schedules.

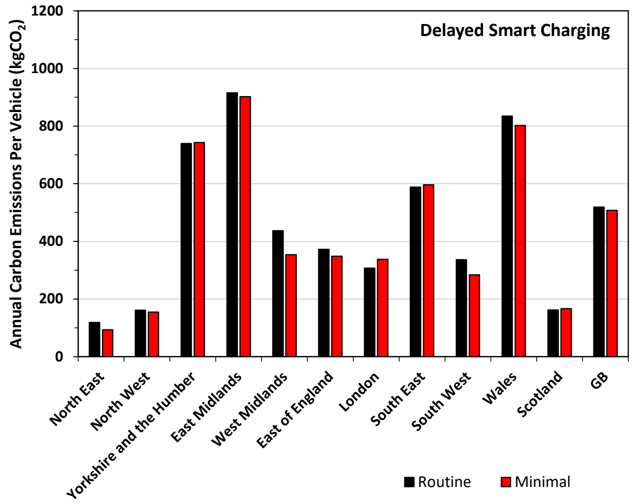

Fig. 4. Annual CO_2 per vehicle using delayed charging in routine and minimal charging schedules for each GB region.

3.2.3. Optimised smart charging

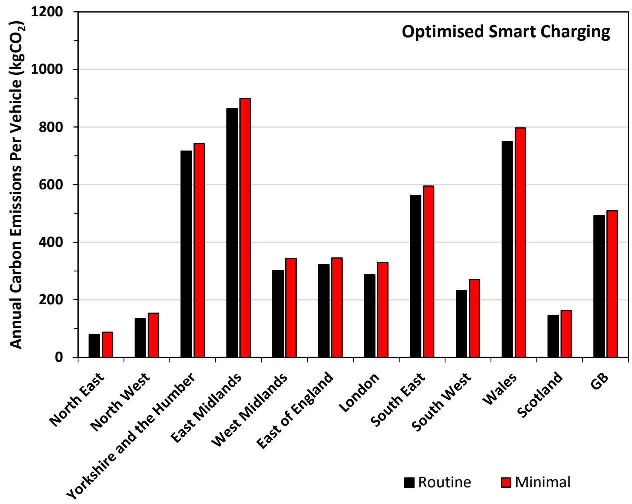

Fig. 5. Annual CO_2 emission per vehicle using optimised charging in routine and minimal charging schedules for each GB region.

Figure 5 shows the impact of optimised smart charging to minimise CO_2 emissions for each region under routine and minimal schedules. Opposite to uncontrolled charging (Figure 3), using optimised smart charging when plugging in an EV every day has lower CO_2 emissions than charging once the SOC drop to a minimum value. When switching from uncontrolled charging to an optimised smart charging that minimises CO_2 emissions, the maximum reduction of 54% occurs in the North East region, followed by West Midlands with 53%. While the North East already has a small annual CO_2 emission, switching from uncontrolled to optimised can save 95 $kgCO_2$ for routine schedule. In GB, optimised charging reduces CO_2 emissions by 25% in routine schedule and 12% for minimal schedule.

3.2.4. EV Carbon Emissions per Travel Distance

Carbon emissions per km when charging an EV using uncontrolled, delayed or optimised charging under routine or minimal schedules are summarised for each region in Figure 6. The results show the variations in carbon emissions per km impacted by where, when, and how an EV is charged as a direct result of the differences in electricity grid carbon intensity. Higher energy consumption in winter due to lower ambient temperature also cause increased CO_2 emissions from EVs. CO_2 emissions reduction varies between regions when switching from uncontrolled to smart charging. For example, delayed charging reduces CO_2 emissions by 4% to 33%, while optimised charging cuts CO_2 emissions between 6% and 55%. When comparing the regions, the carbon emissions per km trend follows a similar pattern to the overall CO_2 emissions, except for London. While the overall CO_2 emissions for London are lower compared to East of England, carbon emissions per km for London are between 43 gCO_2/km to 39 gCO_2/km compared to East of England, 36 gCO_2/km to 22 gCO_2/km. Therefore, if the distance travelled per year was the same for both regions, charging an EV in London would lead to 23% to 18% higher CO_2 emissions than in East of England.

In the minimal schedule, optimised charging has little benefit in reducing CO_2 emissions for most regions compared to delayed charging. This behaviour is due to the less flexibility in moving the charging events in the minimal schedules as a result of the longer charging time compared to the routine schedule, which has a short charging window, making it more flexible to move. Also, delaying the charging to 10 pm already shifts the charging from the period of high carbon intensity, thus there is less opportunity to reduce CO_2 emissions further. In routine schedules for some regions, the benefits of optimised charging are far higher than delayed charging in reducing CO_2 emissions, such as West Midlands, South West and Wales. The variation in smart charging benefits under different charging scenarios in each region suggests that to maximise the opportunity for EVs to further reduce transport sector CO_2 emissions, charging strategies for EVs should be planned based on regional basis.

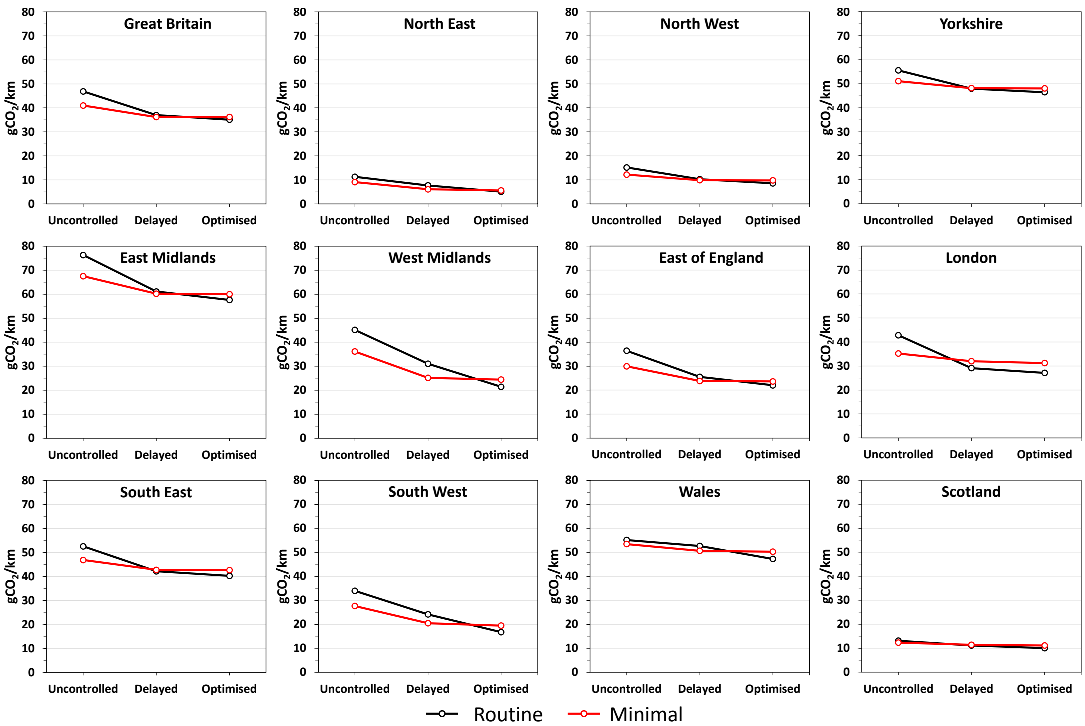

Fig. 6. Carbon emissions per km under different charging scenarios for each GB region

4. Conclusion

A model was created to investigate the regional differences in EV energy consumption and the associated CO_2 emissions while charging in each region of Great Britain. The developed model considers the difference in road class, mileage, ambient temperature and electricity grid profile in each region. The impact of two charging schedules – routine and minimal – on CO_2 emissions was evaluated using uncontrolled and smart charging. From this investigation, the following conclusions can be drawn.

- Charging an EV daily at peak hours regardless of the battery SOC under uncontrolled charging results in 15% higher CO_2 emissions than charging the vehicle once the battery drops to a specific SOC.
- A variation in reducing CO_2 emissions between the regions was observed using smart charging. Delayed charging reduces CO_2 emissions by 4% to 33%, while optimised charging to minimise CO_2 emissions led to a reduction between 6% and 55%, depending on the region.
- Delaying the charging reduces CO_2 emissions for routine and minimal schedules by 21% and 12%, respectively, as charging events are shifted away from peak hours of high electricity carbon intensity.
- Optimised charging reduces CO_2 emissions by 25% in routine schedule and 12% for minimal schedule compared to uncontrolled charging, but it has little benefit in reducing CO_2 emissions compared to delayed charging to 10 pm as it already shifts charging events away from the period of high carbon intensity.

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