Decarbonising our transport system:
Vehicle use behaviour analysis to assess the potential of transitioning to electric mobility

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ABSTRACT: The transport sector is responsible for over 20% of the global carbon emissions. One of the strategies to reduce its impact includes transitioning to electric vehicles (EV). However, this represents several challenges to existing cities, such as the lack of a charging network compatible with different vehicles archetypes, the increase in energy demand, and the aged infrastructure that can result in power shortages. In this paper is presented a behaviour analysis covering a 49-vehicle fleet of a university in the UK. One year data was analysed, including 150,656 journeys undertaken by various taskforces. The results indicate that 96.3% to 99.8% of the time, the pattern of use fit within the current range of capacity of EVs. Stationary time analysis showed that most of the vehicles remained parked overnight (+10 hours) and during daytime the vehicles were not used simultaneously. This is a convenient scenario to implement vehicle-to-grid, which would allow the users to monetise their vehicles by using their batteries as assets. A vehicle-parking location analysis identified potential locations for charging infrastructure. Finally, reductions of 79.6% in carbon emissions were estimated if the fossil-fuelled vehicles were to be replaced by EVs. This reduction may increase as grid energy is decarbonised.
KEYWORDS: Electric Vehicles, Vehicle to Grid, Renewable Energy, Energy Storage, Decarbonising the Grid

1. INTRODUCTION

The World Health Organisation estimates that 92% of the world's population lives in places where the pollution exceeds the recommended air quality levels [1]. Recently, as a result of the pandemic-related restrictions on movement, average air pollution levels have fallen to unprecedented levels all over the world [2], [3] and by up to 60% in the UK [4], [5], where experts predict a consequent dramatic reduction in incidences of asthma and hospital admissions related to non Covid-19 respiratory conditions [6]. The pandemic effect on air pollution provides us with a glimpse of how a low-carbon future could look like.

The transport sector alone is currently responsible for 20.5% of the global carbon emissions [7]. The Intergovernmental Panel on Climate Change has warned that rapid changes are required in all aspects of society in order to limit global warming to 1.5°C [8]. Even though the pandemic demonstrated that the reduction in economic activity and traffic restrictions effectively reduced carbon emissions, it is estimated that emissions levels could exceed the pre-pandemic levels as soon as the economy and transport are reactivated, if no measures are taken to avoid this [9].

In order to reduce carbon emissions generated by the transport system, many governments have set targets to phase out fossil fuel vehicles and replace them with electric vehicles (EV). Some of the most ambitious plans have been established by Norway to suspend the sale of internal combustion engine (ICE) vehicles by 2025, followed by Germany, Netherlands, India and Israel by 2030, UK by 2035, and France, Taiwan and China by 2040.

In order for this transition to electric mobility to be successful, much has to be changed in our cities. In particular, we will need to install charging networks compatible with different vehicles archetypes, increase the generation of renewable energy to compensate for the added demand, and prevent energy shortages by appropriately using the vehicles' batteries to balance the grid [10].

According to Noel et al [11], it has been reported that 'range anxiety' is a prominent concern of users considering adopting electric vehicles, as well as, price, charging infrastructure and consumer perception. Over the last decade, new technologies, such as vehicle-to-grid (V2G), have been trialled to integrate the transport system with the energy system in order to overcome some of the barriers for the uptake of electric vehicles [10].

V2G refers to using the bi-directional capacity of EVs to store energy and sell it to the grid on demand [12]. It aims to use "EV battery packs as aggregated distributed grid-based energy storage" [13 p.1]. Some of the benefits include: a) the support it can provide to the energy grid by help regulating the peak demand; b) economic incentives to the end user from selling the energy back to the grid; c) the optimisation of the energy cost; and, more importantly, d) renewable energy storage (particularly wind and solar sources), which is essential to decarbonise the energy grid [10].

In this paper, the authors present a user behaviour analysis of a university fleet of 49 vehicles looking at the patterns of stationary time, parking location and simultaneous use. The fleet was chosen because it provides various services for the university's large estate, reflecting, albeit in a smaller scale, the situation found in a city. The authors then assess the compatibility of the fleet with available EV and V2G technology, undertake a feasibility assessment of the charging infrastructure, and produce an estimate of the potential carbon emissions reduction if EV was to be adopted where possible.

2. METHODOLOGY

The sample evaluated was a fleet of 49 vehicles from the University of Nottingham (40 diesel and 9 electric vans). These vehicles were tracked using Trakm8 telematics system [14]. The vehicles were split into six clusters according to the service provided, named Fleet 1 to 6, in order to anonymise the data (Table 1). One year of historical data was extracted for five of the fleets and six months data for the remaining fleet (as this was the only data available for Fleet 6 at the time of this research). In total, 150,656 journeys were analysed. The telematics retrieved consisted of start and end date of the journey, duration, initial and final location and distance travelled, among others. A journey was defined as the event when the vehicle travelled from one location to other; journeys with distance equal to zero were excluded.

Table 1 – Dataset Summary

Cluster	# vehicles	Dataset	# Journeys
Fleet 1	5	12 months	22,111
Fleet 2	22	12 months	54,976
Fleet 3	8	12 months	17,576
Fleet 4	4	12 months	18,494
Fleet 5	3	12 months	12,379
Fleet 6	7	6 months	25,120
Total	49	-	150,656

The data analysis included descriptive statistics, stationary time analysis, vehicle parking location likelihood and simultaneous use analysis. Sensitive information, such as individual characteristics of the vehicles or tasks details were anonymised. This study was approved by the Ethics committee from the Faculty of Engineering of the University of Nottingham and the University Estates team.

3. RESULTS

The dataset was filtered to identify the patterns of behaviour of the fleets. The frequency use of the vehicles according to the day of the week was extracted by looking at the percentage distribution from Monday to Sunday. It was found that five of the fleets have more than 93% of their active time from Monday to Friday, and Fleet 6 registered a relatively uniform distribution of the journeys across the seven days of the week (variation of 2.5% between days). Therefore, the analyses for Fleets 1 - 5 were conducted only for weekdays.

Table 2 presents a summary of the descriptive statistics of the distances travelled per journey and per day. The *Journey Distance* refers to the miles registered per trip. Fleet 5 registered the highest mean distance (2.5 miles, SD = 3.6), which means that these vehicles are used for longer journeys in comparison to the other fleets. The maximum distance travelled in a single journey was 162.8 miles, registered by a vehicle from Fleet 3.

Table 2 – Descriptive Statistics: Journey Distance and Day Distance registered per fleet.

	Fleet	Mean	Std. Deviation	Maximum
Journey Distance (miles)	1	0.8	1.5	58.4
	2	1.4	2.1	40.1
	3	1.7	3.5	162.8
	4	1.5	2.9	47.5
	5	2.4	3.6	23.8
	6	1.9	2.5	59.1
Day Distance (miles)	1	13.9	9.5	121.1
	2	15.4	10.3	92.6
	3	16.4	14.1	326.3
	4	27.9	17.7	100.9
	5	42.3	23.9	99.5
	6	43.3	23.7	126.3

The *Day Distance* is the cumulative distance travelled in a day per vehicle. This was analysed per fleet. Fleet 6 recorded the highest mean (43.3 miles, SD = 23.7), followed by Fleet 5 (42.3 miles, SD = 23.9). The maximum distance travelled in a day was 326.3 miles, registered by a vehicle from Fleet 3. However, it was noted that the very long journeys that populate the maximum column were rare, which is why the mean day distances are low.

3.1. Stationary Time Analysis

The average percentage of *Stationary Time* provides a view on the probability of a vehicle to be stationary at a specific moment. In Figure 1, each line represents the calculated average per fleet during weekdays. In this graph, 100% means that all the vehicles of the fleet remained stationary during the time evaluated, while a case of 0% of stationary time would mean that all the vehicles were in use.

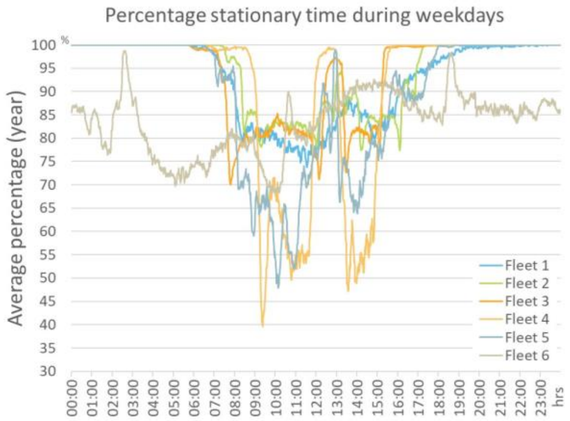

Figure 1 - Stationary Time during weekdays, 100% means that all the vehicles are stationary. As the percentage is lower, the probability of the vehicles to be used is higher.

Fleet 6 was the only group of vehicles that remained active 24 hours across the year; the rest of the fleets remained stationary overnight. Peak usage occurred between 8:00 to 12:00hrs, and 13:00 to 16:00 hrs.

3.2. Vehicle Parking Location

During the operation of the vehicles, they use different parking locations in order to deliver their services. The dwell time at these sites can significantly vary according to the services provided. If the fleet was to be electric, the location of the parking and charging stations would become a crucial factor to be considered, because of the feasibility of the installation and the amount of infrastructure investment required. Therefore, this work included a *Vehicle Parking Location* analysis that aimed to identify the main parking site of the vehicles in a 24 hours period. To achieve this, the postcode registered at the end of each journey and the dwell time of the vehicles in these locations were overlapped. For example, Figure 2 presents the *Average Likelihood* of Fleet 2 of being at specific locations in a 24 hours period during a year.

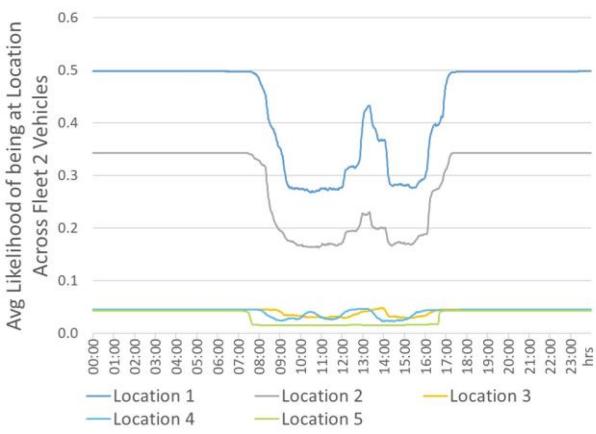

Figure 2 - Average likelihood of being at Locations (1-5) across all the vehicles of Fleet 2

Location 1 and 2 were the sites where Fleet 2 vehicles presented a highest likelihood to be parked overnight (Figure 2), indicating also that the vehicles returned to this location between 12:30 - 14:00 hrs.

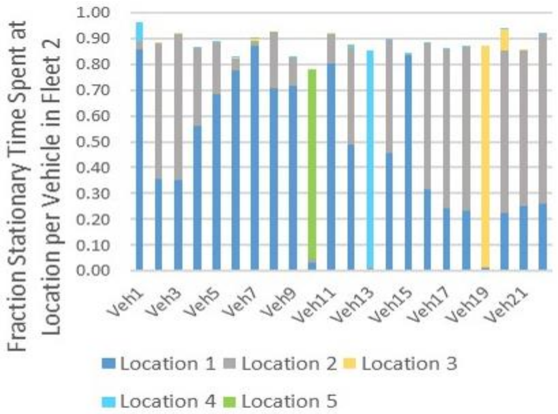

Figure 3 - Fraction of Stationary Time at Locations (1-5) for each vehicle of Fleet 2

Figure 2 would suggest that Locations 1 and 2 would be good candidates for charging points to serve the whole of Fleet 2. However, a breakdown of time spent per location for each vehicle in the fleet, shown in Figure 3, indicated that three vehicles in this fleet stay overnight at locations other than 1 and 2, suggesting the need for additional chargers. This highlights some of the challenges in transitioning a diverse fleet of vehicles to EV.

This analysis was repeated with the other fleets using other locations in order to identify the main parking sites and best possible location of charging stations for each of them.

3.3. Simultaneous Use

The *Simultaneous Use* analysis aimed at identifying the behaviour patterns of the vehicles and the most active hours of the fleets. In Figure 4, the colour scale represents the number of vehicles used simultaneously per minute, white means zero vehicles and red all vehicles (the total number of vehicles varies according to the fleet size). The vertical axis corresponds to the months evaluated (January to December 2018 for Fleets 1 to 5, and December 2018 to May 2019 for Fleet 6), and the horizontal axis refers to a 24 hours period.

In Figure 4 is observed that each fleet presents a different pattern of behaviour. For instance, Fleet 1 does not have a specific start and end of the operation, while Fleet 2 has a sharp starting time around 7:30 am and is finishing activities at 5:00 pm. As previously reported in the *Stationery Time* analysis, Fleet 6 operates 24/7. It is also noticed that during the active periods, there are different gaps occurring across the year for all fleets, usually around midday for Fleets 1-5. These gaps are different for Fleet 6 happening at 3:00 am, 11:00 am and 7:00pm.

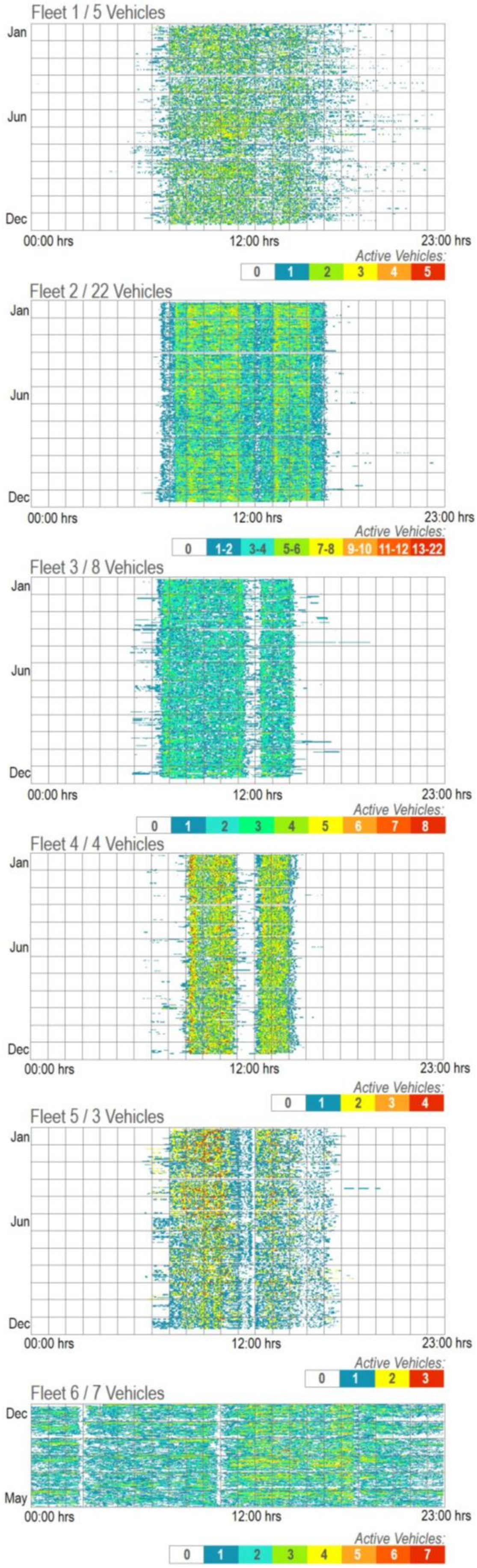

Figure 4 - Simultaneous Use Analysis Fleet 1 to 6

4. DISCUSSION

As seen in Table 2, the mean *Journey Distance* of the fleets varied between 0.8 and 2.4 miles, and the mean *Day Distance* were between 13.9 to 43.3 miles. If only these values were considered to decide whether the fleets function is compatible with an electric version of the vehicles, then it could be determined that the transition to EVs would be possible as a 40 kWh battery van has a range of 115 miles [15]. This range could cover almost three times the average range required for the busiest fleet in a day (e.g. Fleet 6: 43.3 miles). However, 'range anxiety' has been reported as a combination of feeling stressed by the possibility of the battery running low, and the situation when the "…driver needs to drive a longer distance than the EV is usually capable of going in a single charge" [11 p.97] .

In order to analyse the situations that may cause 'range anxiety', the maximum distance values from Table 2 were reviewed. According to Pearre et al [16] and Gonder et al [17], an EV could fit 95% of the required daily mileage, assuming a *Day Distance* of 100 miles. Therefore, this assumption was considered for each fleet. For most of the fleets, exceeding 100 miles in a day was rare; for instance: Fleet 1 exceeded 100 miles two times in a year, Fleet 3 six times and Fleet 4 once. This means that 99.8% of the time the operation of these vehicles would fit with the range capacity of an EV. On the other hand, Fleet 6 exceeded 100 miles 46 times in a year; however, this represented 3.7% of the time, meaning that 96.3% of the time this fleet would fit current EV range capacity. In addition, the *Stationary Time* analysis provided evidence of several opportunities to charge the vehicles during the daytime, which could also support to alleviate the 'range anxiety'. It must also be noted that EV technology is progressing quickly, and range capacity is increasing significantly with every new vehicle model.

4.1. Charging Infrastructure

The *Stationary Time* analysis showed that, with the exception of Fleet 6, the vehicles remained stationary for at least 10 hours during the nights over the year. This time would allow for a full charge of the vehicles to take place assuming a wall box charger (6.6 kWh). In addition, according to the results presented in Figure 1 and 2, during the day, many of the vehicles were stationary between 12:30 and 14:00 hrs. This period could be used to connect the vehicles to the grid. Figure 3 indicates that the vehicles returned to the same main location during midday. Therefore, the charging infrastructure could be centralised in the main building where the fleets operate.

The *Simultaneous Use* analysis provides a view of the peak time during the operation of the fleets, as well as an insight on the number of vehicles available to connect to the chargers. As an example of this, Fleet 2 rarely operates 22 vehicles at the same time, and during peak time around 7-8 vehicles are in use. This means a potential to have the remaining 14 vehicles connected to the grid during the daytime if they are located at the main parking site.

Considering the bi-directional power flow between the vehicles and the energy grid provided by V2G technology, the *Simultaneous Use* analysis, allowed the identification of compatible fleets. For instance, Fleet 1 to 5 are good candidates for bi-directional charging, as they presented a very predictable stationary time throughout the year. V2G can help facilitate the integration of renewable energy sources; therefore, fleets that remained stationary during midday, such as Fleets 1 to 5 could be used as storage of energy produced by, for example, photovoltaic panels.

Conversely, Fleet 6 would not be compatible with a V2G system, as it presents high usage 24/7. Moreover, as this fleet has a frequent use, the drivers would require to connect and disconnect the vehicles often. This action could interfere with the operation and efficiency of the fleet. Therefore, a wireless charging system would be a better fit for this fleet.

The main parking location is a key factor for V2G aggregation services [18], as the efficiency of the system relies on the availability of vehicles for the connection to the grid, as "it must be parked close enough to an available charging station to be plugged in" [19 p.2]. This work's exploration of the vehicle main locations determined preliminary optimal location charging points to be installed at the university campus (Figures 2 and 3). The outcomes of the *Vehicle Parking Location* analysis were discussed with the electrical services manager from the university to assess the feasibility to install charging stations at different locations. Three types of scenarios were identified:

1. High feasibility sites: locations that would require minor investments (e.g. parking site located close to a power station, enough power capacity, minor ground works).
2. Medium feasibility: sites that would require some investment to adequate installations (e.g. soft ground works required to reach power station).
3. Low feasibility: installations that would require high investments (e.g. power station located far requiring high investments in groundworks, limitation on power supply).

The infrastructure costs are a key factor of V2G systems, as this will define the success of the business models. Therefore, it is estimated that only locations with high or medium feasibility are apt for installation.

4.2. Reduction of Carbon Emissions

It has been reported that uncontrolled charging of EVs can overload the demand on the grid and increase carbon emissions [10]. According to Jochem et al [20] at an early stage, the uncontrolled unidirectional charging of EVs will be adequate to penetrate the market. However, it is expected that system will evolve to a controlled stage where the unidirectional charging allows reducing pollutants by postponing the charging process to an optimal time (e.g., when the grid has a low energy demand and/or high renewable energy production). Nevertheless, bi-directional controlled charging (V2G) will be required to achieve a scenario where the vehicle batteries can support the national energy grid by storing intermittent sources of energy (e.g. wind and solar) [20]. This will allow reducing carbon emissions not only by stopping burning fossil fuels to power vehicles, but also to decarbonise the grid system by better integrating renewable sources.

In order to assess the carbon savings from replacing a fossil-fuelled vehicle to EVs, the carbon emissions of one of the vehicles from Fleet 1 were extracted from Trakm8. The vehicle evaluated was a Peugeot Boxer HDI 335. This vehicle travelled 7,200 km in a year generating 1,505 kg of carbon (CO2) emissions. The results were compared with an equivalent EV in the market, a Nissan e-NV200 [15]. With a battery capacity of 40 kWh, this vehicle has a range of 115 miles and a consumption of 330 Wh/miles. This vehicle would require 1,476 kWh of energy to travel 7,200 km in a year. Assuming an overall grid factor of 0.208 kg of CO2/kWh [21] multiplied by 1,476 kWh, results in 307 kg of CO2 emissions in a year. This means a reduction of 79.6% of the carbon emissions, if the diesel vehicle is replaced by an EV. These calculations are estimated values as carbon emissions from the energy grid fluctuate depending on the annual average mix, time-dependent sources and balancing strategies from political measures [20].

In order to reduce carbon emissions, cities will need to optimise the generation, storage, sharing and distribution of energy. The integration of the transport and energy systems was firstly envisaged by Letendre and Kempton [22] twenty years ago; however, the combination of EV technology development, feasible energy storage and renewable energy infrastructure was required to realise this future [10].

5. CONCLUSIONS

In this work, the authors developed a methodology using behaviour analysis to identify key aspects of vehicle use in order to assess the potential for a transition to electric mobility. Stationary Time, Vehicle Parking Location and Simultaneous Use were explored to identify the compatibility of EV technology with the studied fleet, the feasibility of a charging infrastructure and the environmental benefits that could be obtained.

This study demonstrated that between 96.3% and 99.8% of the time the current diesel vehicles use were compatible with the range of capacity of EVs. This means that 'range anxiety', a common challenge for the uptake of EV technology, was usually caused by a very small amount of events in a year. Dwelling times of 10 hours during the night, low simultaneous use and frequency of parking locations demonstrated the suitability of V2G technology. In addition, it was estimated that a change from diesel to EVs would result in a reduction in carbon emissions of around 79.6%. This could be reduced further by a decarbonised energy grid, which could be helped by a better integration of renewable energy through the use of the storage available within the vehicle batteries.

Although this study was undertaken using a relatively small fleet, the lessons learnt are application to city-scale challenges.

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