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Investigating the technical, economic and environmental performance of electric vehicles in the real-world: A case study using electric scooters

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ABSTRACT

This work presents the findings of a small-scale electric scooter trial in Oxford, United Kingdom. The trial scooters were instrumented with global positioning satellite data loggers and energy meters to record their time of day usage and charging regimes. The scooters were most likely driving at 09:00, 12:45 and 17:15 and charging at 10:15–10:40. The electric scooter normalized mains-to-wheel energy use was 0.10 kWh km^{-1}. The electric scooter total operating costs (electricity and battery replacement) of £0.045 km^{-1} is 24% greater than the best selling equivalent petrol motorcycle and 1.7 times lower than the best selling car. The electric scooter uses 0.45 MJ km^{-1}, or 2.9 times and 6.1 times less than the petrol motorcycle and car, respectively. Further, the electric scooter can achieve zero carbon dioxide equivalent (greenhouse gas, GHG) emissions when electricity from renewable energy sources is used. In 2008, there were 247 000 motorcycles in the UK vehicle fleet of equivalent size to the trial scooter. Scaling up the electric vehicle fleet size accordingly would avoid 0.60 billion car or motorcycle kilometres and 54–110 kt associated GHG. The fleet would require 59 GWh, or 0.015% of total annual generation with a time-shifted, peak demand of 250 MW, or 0.44% of the 58 GW maximum national demand.

1. Introduction

This paper investigates the technical, economic and environmental performance of electric vehicles in the real-world. A recently completed trial of eleven electric scooters in Oxford, United Kingdom is used as the case study. As at December 2010, a trial of more than 340 electric vehicles utilizing 200 charging stations was underway in the UK [1]. With these trials ongoing and the last published electric vehicle trial data from 1998 [2], researchers must continue to assume: time of day and day of the week vehicle trip characteristics; real-world performance; when and for how long electric vehicles are charged; the impacts that electric vehicles may have on the power grid under large-scale deployment; and their well-to-wheel life cycle emissions. The novel contributions of this work are the empirically derived answers to the vehicle performance and charging behaviour-related questions.

The energy use by many electric vehicles is assessed using either the energy balance or driving cycle approach. In the former, the total capacity of the battery pack and normalized energy use per unit distance are used to determine the vehicle range. Using driving cycles assesses the ability of the vehicle to meet both the energy and power requirements of real-world driving and yields more accurate electric vehicle energy use figures [3]. This work uses measured driving behaviour data to determine the actual normalized energy use.

Much of the literature assumes all users employ the same charging regime with simultaneously connecting and disconnecting from the mains. Moreover, there is an assumption that the first trip of the day begins with a full battery pack. In the absence of empirical data, a more defensible approach is to assume either unrestricted charging [4,5] or utility control of charging [4]. This work uses measured charging behaviour to determine when and for how long the electric scooters are charged.

Passenger vehicle (road) transport can be analyzed on a number of bases, such as energy use, the carbon dioxide equivalent greenhouse gas (GHG) emissions therefrom, vehicle fleet size, distance travelled and road congestion. Road congestion arises chiefly from the imbalance between vehicle fleet size, kilometres travelled and road capacity [6,7]. In the UK from 1995[1] to 2007, total (four-

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[1] 1995 is used as the base year as the UK Department for Transport (DfT) changed its recording methodology in that year.

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wheeled) vehicle fleet size increased by 2.7% per annum, however the rate of increase of their kilometres travelled lagged at 1.4% [8]. It has been suggested that the UK (and other countries) may be approaching "peak travel," where annual vehicle kilometres travelled per unit gross domestic product decreases [9]. Nevertheless, congestion is expected to persist until the imbalance between the number of road users and the infrastructure capacity is reversed.

Road congestion may be reduced by downshifting to smaller capacity vehicles. Two-passenger vehicles, such as motorcycles, scooters, motor-assisted cycles (e-bikes) and ultimately (pedal) bicycles are options which maintain driver autonomy, while bringing average passenger occupancy in line with vehicle seating capacity. In Asian cities, population density, lack of extensive infrastructure to support cars, road congestion and affordability make powered two- and three-wheelers attractive options [10]. However, the large numbers of these vehicles on the roads are responsible in part for the congestion experienced [11].

A consequence of modal downshifting from four- to two-wheeled vehicles has been an increase in urban air pollution from the latters' two- and four-stroke internal combustion engines [10–14]. These impacts have been observed in Asian urban centres, where the two- and three-wheeler vehicle fleet represents both the majority of total vehicles in service [11,13] and the vehicle segment with highest growth [14–16]. Asian governments have encouraged the technology shift from petrol to electric two-wheelers in an effort to halt declining air quality due to pollution. The large-scale shift to e-bikes (demand), combined with inefficient battery manufacture and poor disposal practices has led to the problem shifting from urban air quality to lead pollution [16]. Since 2000, Taiwan has developed a policy to promote the use of electric scooters (to escape the air pollution caused by internal combustion engine-driven models) that incorporate more advanced technology to reduce the lead pollution from current electric versions [17]. The existing battery disposal regulations in the UK are expected to mitigate pollution concerns.

The extent of congestion in Asian cities is not mirrored in British ones. However, use of a vehicle which allows travel at efficient speeds while maintaining independence of movement is considered a common desire of motorists. Other incentives peculiar to UK cities include congestion charging, environment levies and restricted car parking. An electric scooter may be one option for preserving autonomous travel within the British urban environment.

The findings of this work are based on the trial of a small fleet of 11 electric scooters (Fig. 1 and Table 1) which were deployed in Oxford, United Kingdom in April to June, 2010 under an employer-led ownership scheme. The triallists were selected from the employee base at the two city universities and the city council. 69 men and 43 women responded to the initial trial advertisement. Most of the respondents were aged 30–39 years. The bus, car and bicycle were the most common modes of transport. The commuting distance for most respondents was 5–9.5 km. The 11 trial participants were all over age 25 years and had never owned a scooter or motorcycle. Siting recharging infrastructure at the workplace is appropriate as the commute to and from work constitutes the majority of weekly driving. Moreover, employer ownership of the charging infrastructure shifts the burden of investment from the consumer. Two charging points were funded by each of the three employers and installed at convenient workplace locations (Fig. 2). The scale – number of months, number of scooters and single location – of the trial precludes the drawing of far-reaching conclusions on both the performance of electric scooters in real-world driving and the type of consumer most suited to them. However, the findings of this study offer a timely marker in an otherwise sparse set of real-world electric vehicle usage and consumer data.

Table 1
Technical specifications of trial scooter.

Specification	Value
Motor power (kW)	3
Range (km)	48
Top speed (km h)$^{-1}$	72
Battery cell technology	Valve-regulated lead acid [a]
Cell capacity (Ah)	38 @ 12 (V)
Number of cells	5
Battery voltage (V)	60
Number of cycles	400
Battery cost (£)	300
Recharge time (h)	5–8
Retail price (£)	1895
Calculated tank-to-wheel energy use (kWh km^{-1})	0.048

[a] http://www.greensaver.cn/en/product/manage/upload/picupload/sp36-12.pdf for details on the Greensaver SP36-12 valve-regulated lead acid battery. The SP36-12 uses a silicon gel electrolyte which offers reliable, maintenance-free service life in many applications, including in vehicles [27].

Fig. 1. Trial scooter at a charging station.

The requirements of the instruments and their integration are described in Section 2. There is a discussion on the limitations to the data collection and its effect on the analysis in Section 2.2. The driving and charging data are presented using trip-based summary statistics and probability distributions in Sections 3.1 and 3.2, respectively. The latter reflects the variation in observed user behaviour at the fleet scale. The scooter technological, economic and environmental performance are normalized per kilometre travelled and compared with that of both the best selling 125 cc petrol motorcycle (to which the trial electric scooter is equivalent) and the best selling car in the UK in 2008 in Section 3.4. The impacts of replacing the trial electric scooter batteries on the total running cost are discussed as part of a sensitivity analysis in Section 3.5. The trial findings are scaled up to assess the total avoided car/petrol motorcycle kilometres travelled, associated avoided GHG emis-

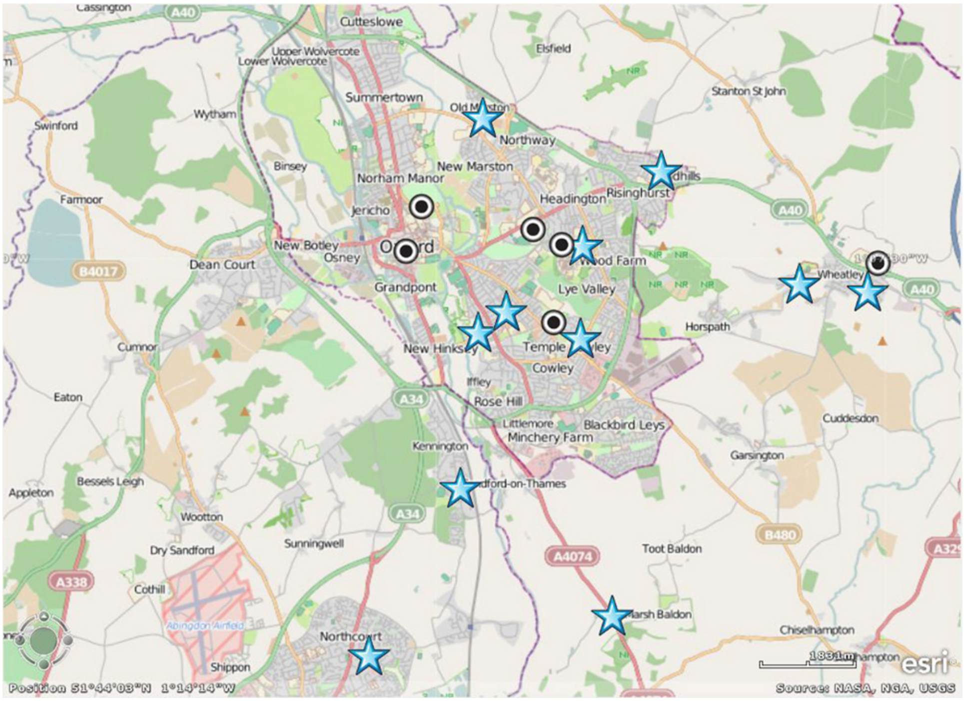

Fig. 2. Map of City of Oxford and surrounding area with indicating charging locations (black and white roundrel) relative to where participants' live (blue star). Map created in ArcGIS Explorer. Map images are the copyright of OpenStreetMap contributors, CC-BY-SA. OpenStreetMap can be viewed online at www.openstreetmap.org and license details at www.creativecommons.org. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

sions and the impacts that charging regimes may have on electricity generation and its transmission across the network in Section 3.6.

Table 2
Scooter energy use based on GPS trip information and Electrocorder charging energy for the EDF scooter, compared with odometer and charging station readings for DZS. The median energy use of 0.099 kWh km^{-1} is used in the calculations. The MAD values are given.

Scooter	Energy (kWh)	Distance (km)	Energy use (kWh km^{-1})
EDF	2.9	27	0.10
	1.3	25	0.11
	1.2	11	0.26
	0.85	24	0.12
	2.3	14	0.16
	1.6	6	0.27
	2.4	35	0.069
	0.77	15	0.051
	3.1	37	0.082
	2.4	31	0.079
DZS	13	220	0.057
	8.5	150	0.057
	2.5	41	0.060
	3.7	60	0.061
Median	2.4	25	0.099
MAD	0.41	10	0.041

Table 3
Normalized operating costs, WTW energy use and GHG emissions per kilometre travelled between the trial electric scooter, best selling equivalent motorcycle and best selling car in the UK in 2008.

Vehicle	Operating (fuel) costs (£km^{-1})	Energy use (MJ km^{-1})	GHG emissions (g km^{-1})
Trial electric scooter	0.013	0.45	49
Best-selling equivalent motorcycle	0.035	1.3	90
Best-selling car	0.076	2.7	190

2. Method

2.1. Trip and charging data collection

The design of the measurement system to capture real-world driving and charging behaviour was based on the assumption that users would charge their scooters daily. This would ensure that there was always energy in the onboard battery supplying the instruments. Scooters are identified in this work by the last three letters of their registration plate – EDJ, EDF, EDC, DZY, DZX, DZV, DZT, DZO, DZW and DZS.

The driving behaviour was captured using a global positioning satellite (GPS) data logger and represented by a high resolution, 1 Hz velocity-time profile. The data loggers[2] had a horizontal position and velocity accuracy to 1–5 m and 0.1 m s^{-1}, respectively. They were installed at the beginning of the trial and set to record date, time, latitude, longitude, velocity and altitude if the scooter was travelling greater than 2 km h^{-1}. Else, the device was set not to log, as the scooter was assumed to be stationary. The final scooter odometer readings were used to verify the total distance recorded by the GPS data logger. The GPS data will be used in the development of a driving cycle, the specifics of which are outside the scope of this paper. The 1 Hz recording frequency was chosen in line with that used in driving cycle development literature. Further, altitude was included in this study as a factor in the total road load which the scooter motor must overcome [18].

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[2] See http://www.globalsat.co.uk for details.

Charging current and voltage (average, maximum and minimum) data was recorded at 0.0033 Hz using a single phase energy data logger[3] which was installed between the scooter charger and the mains plug. Charging events bound periods when the scooter is in motion. The energy data logger sampled the mains signal at 800 Hz. Average, minimum and maximum current and voltage were recorded at 0.0033 Hz, or once every 5 min, with an accuracy of ±2%. Energy logging capacity was at least 25 days.

The energy data logger was deployed on four scooters for one week each during the trial to gather the typical, seven day charging frequency and duration. It is acknowledged that assigning the energy meter to a trial participant for one week was insufficient to capture all variations in charging habits over the long term. However, rotating the scooters under measurements was the compromise between capturing four weeks of data from one user or data for one week from four participants. This compromise is justified on account of the "commuter" model upon which the study was based, where the majority of scooter trips were to and from work. The final charging station meters were used to verify the energy data logger records.

Aggregate mains-to-wheel (or tank-to-wheel, TTW) scooter energy use was calculated by identifying the energy drawn by the battery pack between two consecutive charging events bounding a period of driving. The normalized scooter energy use was the quotient of the energy drawn and the distance travelled. The use of charging data necessarily includes the battery charging mains-to-wheel efficiency. Excluding the battery charging–discharging losses yields the electric scooter powertrain-only energy use.

The profile employed by the scooter charger was measured using the energy meter. In the first 4 h, the current increased from 2.8 A at 0.34 A h^{-1} to a 4.1 A peak, corresponding to power draws of 0.63 kW increasing to the maximum of 0.95 kW. Following the peak power, the current reduced at 1.1 A h^{-1} to 0.48 A, then to 0.12 A over the next 7 h at 0.055 A h^{-1} (Fig. 3).

2.2. Design limitations

The GPS data logger used its integrated battery to avoid being a parasitic load on the scooter battery. It was assumed that users would connect their scooter to the charging point daily to ensure there was always energy in the 20-h capacity GPS logger battery. However, only two of the 11 participants charged that often. Therefore, many of the GPS loggers switched off when their batteries were low and required a manual restart. The result was an incomplete GPS dataset across the 11 scooters. In particular, few weekend trips were recorded. The data collection endeavours were further complicated by participants having varied timetables, making it difficult to know when a scooter would be at a particular location to ensure that the equipment could be checked and restarted, if necessary. Finally, the frequency of equipment checks necessary precluded the monitoring of the DZW, DZP and DZO scooters on account of their charging stations' distant location from the city centre.

The charging station meters provided an incomplete, sometimes aggregated and a likely underestimated quantity of total energy used to supply the scooters. The incompleteness derives from only two of the charging stations having meters placed at the scooter connection point. Therefore, the total energy demand periodically and over the trial duration from the other charging stations could not be included. The meters which were visible indicated the total energy draw of the charging point. In the locations where these charging stations serviced more than one scooter, their individual demands could not be disaggregated. Ultimately, the convenience of the standard 13 A IEC cable (as opposed to a proprietary interface) to connect the scooter charger to mains allowed participants to charge wherever was convenient. Therefore, the charging point meter readings were likely underestimates of the true, total energy used throughout the trial.

Table 4
Final odometer reading and distance measured by GPS per scooter.

Scooter identification	Final odometer reading (km)	Distance measured by GPS (km)	%
EDJ	539.40	108.47	20.11
EDF	961.35	803.01	83.53
EDC	316.80	97.22	30.69
DZY	830.00	597.82	72.03
DZX	900.00	37.59	4.18
DZV	349.00	24.22	6.94
DZT	385.00	76.93	19.98
DZO	147.30	14.91	10.12
DZW	303.80	15.79	5.20
DZS	600.00	259.57	43.26
Total	5 332.65	2 055.94	38.55

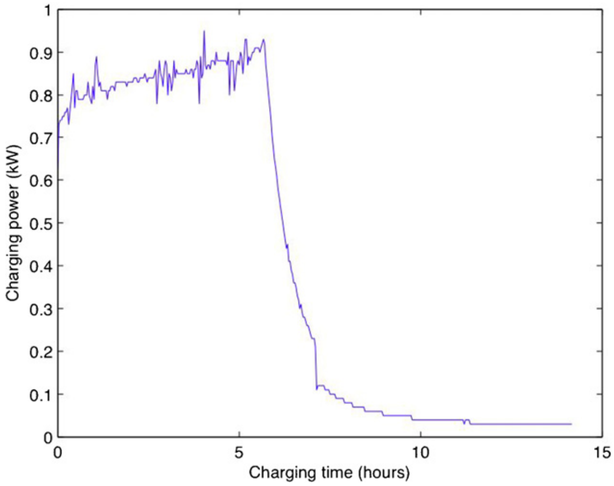

Fig. 3. Charging power profile for scooter measured using the energy meter. In the first 4 h, current increases from 2.8 A at 0.34 A h^{-1} to a 4.1 A peak. It reduces at 1.1 A h^{-1} from the peak to 0.48 A and to 0.12 A at 0.055 A h^{-1} over the remaining charging time.

3. Results and discussion

3.1. Driving behaviour

Trip information provided insights to the individual scooter user behaviour. A trip was bounded by zero velocity periods greater than 10 min to ensure that short stops, such as when in congested areas, did not distort the trip statistics. The trip information included trip start and end time, duration and distance travelled for weekdays.

The GPS data loggers captured 39% of the 5300 km driven by the 11 scooters during the trial, based on the odometer readings (Table 4). Median morning trip duration was 15 min, beginning at 09:08 and ending 09:23, with users travelling a median 7.8 km at 12 km h^{-1}. Median evening trip start time was 17:12, ending 17:39 with the 8 km distance travelled at 7 km h^{-1}. The median absolute deviation (MAD) of morning and evening trip times was 6 min and 11 min, respectively (Table 5). Most of the data, as a percentage of odometer distance travelled, was recorded from the EDF scooter.

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[3] See http://www.electrocorder.com/AL-2VA.asp for details on the Electrocorder AL-2VA.

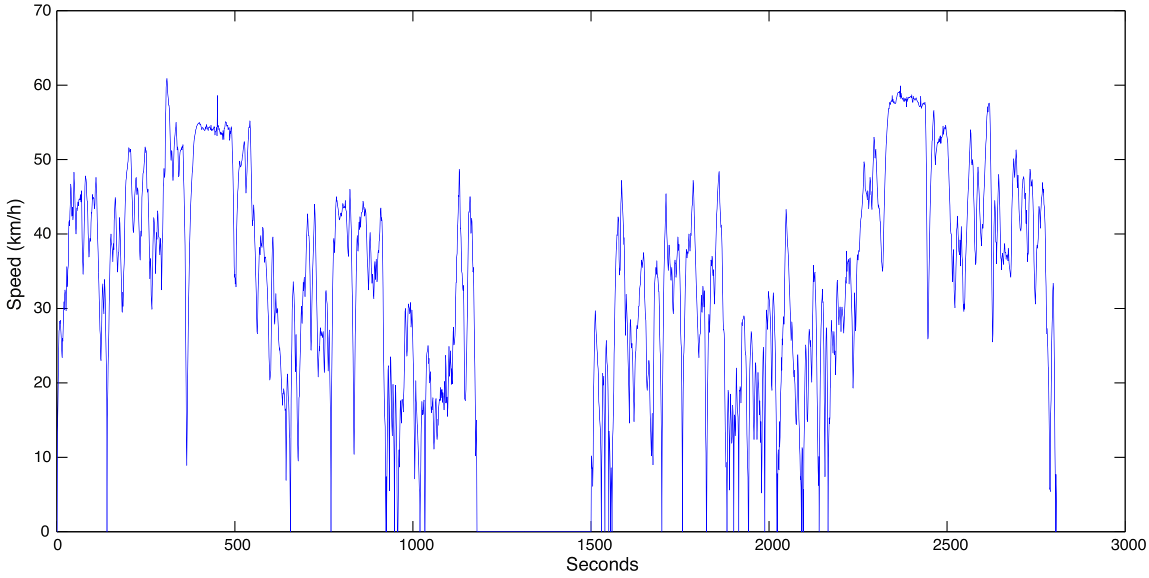

Fig. 4. Velocity–time profile recorded for scooter EDF on an afternoon and morning commute to work on 18 May, 2010, respectively.

An example of the variability in the driver's behaviour is given by observing the EDF morning and evening commute on 18 May, 2010 (Fig. 4).

The trip start and end times across all scooters were combined to create a driving probability distribution, representing the fleet behaviour. Each trip was divided into 5-min intervals against which a binary 1 = driving/0 = no driving variable was applied. A distribution of probabilities across 24-h was derived from the chance that a scooter was driving in any 5-min time interval. The highest probability that one of the four – DZX, EDC, EDF and EDJ – scooters which were instrumented with the energy meter was driving was 0.18 and occurred at 17:15 (Fig. 5). This was consistent with departure from the work place at the end of the day. The afternoon driving probability peak was higher than that of the morning (as opposed to the same). This is likely because the GPS data loggers were often restarted when the scooters were already at the workplace/charging point, therefore after the morning commute. Consequently, fewer morning commutes were logged. The morning peak occurred at 09:05, with probability 0.11.

Considering the entire fleet, the highest probability that a scooter would be driving was 0.10, representing the evening departure from the work place at 17:15 (Fig. 6). The morning peak occurred at 09:00, with probability 0.08. Over the entire fleet (and notably absent from Fig. 5), a number of midday trips were recorded. Scooters were most likely to be on the road at 12:45 with a probability of 0.05. The probability of being on the road was zero after 14:10, suggesting the end of lunch time excursions.

The driving behaviour exhibited in the trial is insufficient to draw broad conclusions on either the overall energy use by the electric scooters under all conditions or their ability to satisfy real-world driving requirements compared to others available on the market. However, the trip behaviour exhibited in the trial should reflect that of a wider user set since the daily workplace commute occurs between two fixed points.

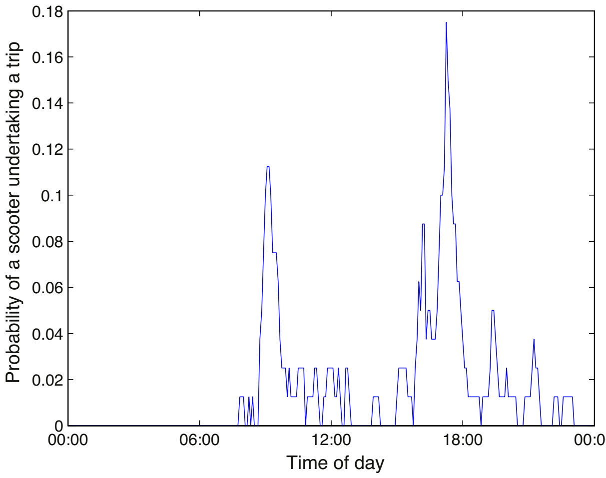

Fig. 5. Probability of a scooter driving in any 2-min period over 24-h. The morning peak occurs at 09:05 with probability of 0.11. The evening peak coincides with departure from the work place at 17:15 with a probability of 0.18. Data is based on scooters DZX, EDC, EDF and EDJ.

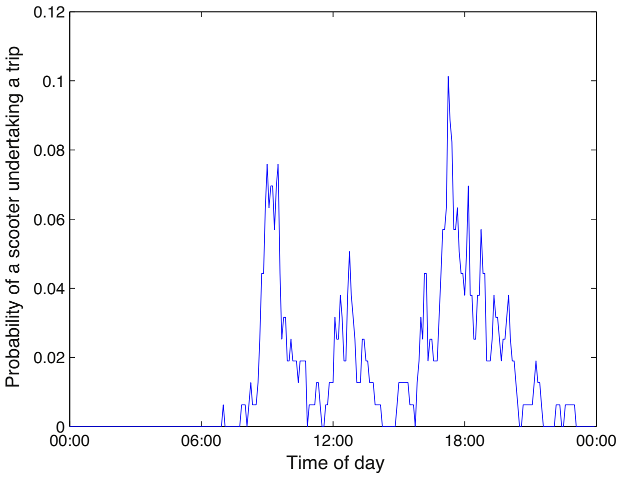

Fig. 6. Probability of a scooter driving in any 5-min period over 24-h. The morning peak occurs at 09:00 with probability of 0.08. The midday (lunch time) trip excursion peaks at 12:45 with probability 0.05 and the evening peak coincides with departure from the work place at 17:15 with a probability of 0.10.

Table 5
Median morning and afternoon trip events recorded using DG-100 GPS for Monday to Friday work week. The median and median absolute deviation (MAD) across all scooters is included.

Scooter	Morning		Duration (min)	Distance (km)	Median speed (km h^{-1})
	Start	End			
DZT	09:10	09:20	00:10	3.05	7.32
EDF	08:57	09:14	00:17	11.74	16.57
EDJ	09:05	09:27	00:22	7.25	7.91
EDC	09:07	09:14	00:07	2.76	9.46
DZY	08:33	08:56	00:23	11.00	11.48
DZO	09:52	10:23	00:31	12.63	9.78
DZS	09:27	09:41	00:14	3.16	5.43
DZX	10:50	10:59	00:09	8.25	22.00
Median	09:08	09:23	00:15	7.75	12.40
MAD	00:24	00:23	00:06	4.08	14.73

Scooter	Afternoon		Duration (min)	Distance (km)	Median (kmh^{-1})
	Start	End			
DZT	17:19	17:39	00:20	3.24	3.89
EDF	17:08	17:30	00:22	9.85	10.74
EDJ	17:02	17:43	00:41	7.96	4.66
EDC	17:12	17:29	00:17	3.89	5.49
DZY	18:38	18:57	00:19	12.28	15.51
DZV	18:05	18:23	00:18	4.70	6.27
DZS	17:53	18:07	00:14	3.80	6.51
DZX	12:41	13:01	00:10	5.74	13.11
DZW	12:10	12:48	00:38	14.47	9.14
Median	17:12	17:39	00:27	7.96	7.08
MAD	01:18	01:19	00:11	4.28	8.83

Table 6
Median morning-only, afternoon-only and all-day charge events in Monday to Friday work week for 4 scooters using the Electrocorder. The median across all scooters is included.

Scooter	Morning		Duration (h)	Energy (kWh)
Morning-only	Start	End		
DZX	05:38	08:26	02:48	2.43
EDF	09:14	11.56	02:42	2.42
EDJ	09:14	09.28	00:14	0.17
Median	09:14	09:28	00:14	0.17
MAD	00:32	01:59	01:27	0.38

Scooter	Afternoon		Duration (h)	Energy (kWh)
Afternoon-only	Start	End		
DZX	12:10	12:36	00:26	0.04
EDC	15:37	23:43	08:06	1.74
EDF	15:37	18:07	02:30	1.21
EDJ	12:42	17:06	02:44	1.61
Median	14:09	17:36	03:26	1.41
MAD	01:27	07:52	06:24	0.65

Scooter	Afternoon		Duration (min)	Energy (kWh)
All-day	Start	End		
DZX	09:01	16:35	07:34	2.35
EDC	08:59	14:39	05:40	1.23
EDF	09:06	16:28	07:22	2.85
EDJ	09:52	14:16	04:24	1.64
Median	09:03	15:33	06:29	1.99
MAD	00:07	01:07	01:00	1.94

3.2. Charging regimes

Charging event information was used to highlight individual driver behaviour. Charging events were bounded by periods of zero current draw, consistent with the scooter being either disconnected from the mains or the battery being full. Charging information included event start and end time, duration and energy drawn.

The charging regime summary data for the four bikes which were instrumented with the energy meter – DZX, EDC, EDF and EDJ – suggested charging events most often began in the morning, consistent with arrival at work. Ten of the 26 charging events measured were afternoon-only sessions, while nine began in the morning and ended in the afternoon. The remaining seven were morning-only sessions. The MAD of morning-only and all-day charging events is 32 min and 7 min, respectively. However, afternoon-only events have a higher MAD of 90 min (Table 6). Similarly, the MAD of end times are 120 min and 60 min for morning-only and all-day sessions, respectively. The afternoon-only sessions show the greatest variability at 8 h. The final charging point meter readings at the two charging stations with visible meters were 56 kWh, servicing up to four scooters, and 28 kWh for a single scooter, respectively.

A charging probability distribution over 24-h was created, using 5-min intervals, in a manner similar to that of the driving probability distribution. The highest probability that a scooter would be charging was 0.54 and occurred in the period 10:15–10:40 (Fig. 7). A charging probability to 0.43 was observed in the period 13:55–14:20, coinciding with the end of the lunch time trips at 14:10. The probability of charging falls from the post-midday excursion charging peak to the overnight value of 0.034.

A probability distribution of the state of the scooter at any instant – charging or driving – was obtained by combining the probability of the scooter charging with that of it driving (Fig. 8).

The aggregate power profile of the four – DZX, EDC, EDF and EDJ – scooters charging, from the grid perspective, was derived from the superposition of individual scooter power demand for each 5-min interval (Fig. 9). However, the implications have no immediate spatial significance. That is, the ability for the electric power network to meet any additional load posed by charging electric scooters (and electric vehicles, in general) will be a function of both the time of day and the location in the grid that the vehicles are being connected.

Individual motorists are expected to charge their electric vehicles at convenient times and locations. During the work week, the charging distribution found in this work is expected to dominate, infrastructure permitting, if users wish to ensure a fully charged

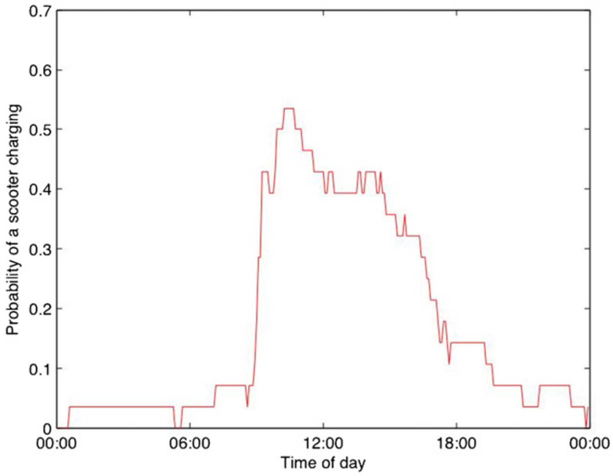

Fig. 7. Probability of a scooter charging in any 5-min period over 24-h. The morning peak occurs in 10:15–10:40 with probability 0.54. The post-midday trip charging occurs in 13:55–14:20 with probability 0.43 and the probability of charging falls steadily to 0.034 overnight. Data is based on scooters DZX, EDC, EDF and EDJ.

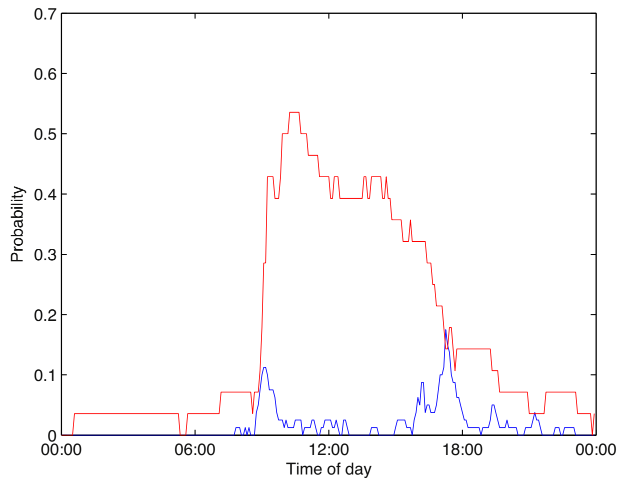

Fig. 8. Composite probability of a scooter charging (red) or driving (blue) over a 24-h period. Data is based on scooters DZX, EDC, EDF and EDJ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

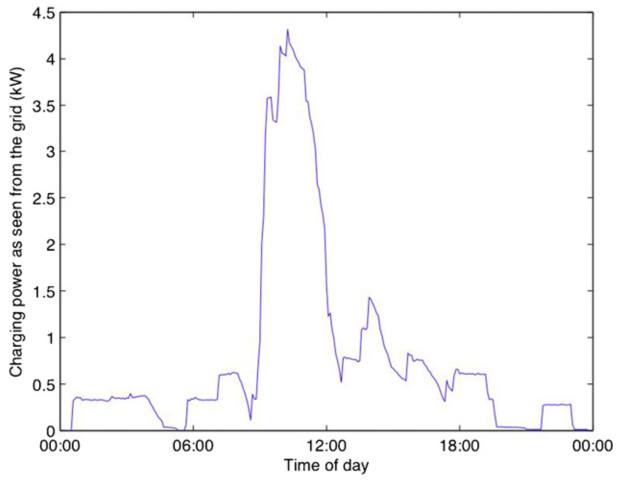

Fig. 9. Demand profile as seen from the grid when Electrocorder data is combined. The peak demand of 4.3 kW occurs at 10:15 and 18.9 kWh is drawn from the grid over the 24-h. Data is based on scooters DZX, EDC, EDF and EDJ.

battery pack for both a midday excursion and the evening return journey home.

3.3. Energy use by the scooters

The average TTW energy use by the scooter was derived by using complete charging and driving trip event data from the energy meter and GPS loggers, respectively, as the most defensible approach. A complete pair of records was only available from EDF (Table 2).

The (EDF) scooter's median TTW energy use was 0.10 kW h^{-1} km. The charging efficiency of the 2.3 kWh pack is 69%, which is at the low end of the published 72–78% range of valve-regulated lead acid battery efficiency [19]. The median powertrain energy use was 0.068 kW h^{-1} km. It was assumed that charging and discharging efficiencies are equal and that each scooter battery had the same battery efficiency characteristics. At 0.10 kW h^{-1} km, the real-world energy use by the scooter is 30% lower than that calculated from its stated range, battery capacity and assumed roundtrip efficiency (Table 1).

3.4. Scooter operating costs and emissions

The operating costs of the trial electric scooter were compared to those of the best selling car and the best selling 125 cc petrol motorcycle in the UK in 2008 and normalized to distance travelled. The use of a scooter may be considered a modal downshift from using a car. The switch from internal combustion engine in the best-selling petrol motorcycle to the electric motor of the trial scooter indicates a technology shift, without any loss in drivability. Ownership of motorcycles is highest at 3.4% in households which own one or more cars [20]. Therefore, a supposition was made that the total annual distance travelled per person may be split across a two- and four-wheeler, justifying the inclusion of car performance results for comparison.

The best selling car in the UK in 2008 was the Ford Focus [21], available with petrol and diesel engines. The proportion of diesel to petrol Ford Focus vehicles sold was assumed to be 47%, matching that of the lower medium vehicle class to which it belongs [21]. The sales-weighted Ford Focus fuel use was 6.8 l petrol equivalent (100 km)$^{-1}$ at £1.10 (l petrol equivalent)$^{-1}$ [22]. Therefore, normalized operating costs, TTW energy use and emissions were £0.076 km^{-1}, 2.4 MJ km^{-1} and 150 g CO_2 km^{-1}, respectively. Including the energy used and GHG emitted when supplying 1 MJ petrol equivalent to the tank (WTT) [23,24], the normalized, well-to-wheel (WTW) energy use and emissions increase to 2.7 MJ km^{-1} and 186 g GHG km^{-1}, respectively.

The best selling 125 cc motorcycle[4] in the UK in 2008 was the Honda PS 125 [20]. The scooter was only available in petrol, using 3.2 l petrol to complete 100 km.[5] The normalized operating costs, TTW energy use and emissions were £0.035 km^{-1}, corresponding to a petrol price of £1.10 l^{-1} in 2008 [22], 1.1 MJ km^{-1} and 76 g CO_2 km^{-1}, respectively. Incorporating the WTT impacts of the petrol production pathway [23,24] increases the normalized WTW energy and GHG emissions to 1.3 MJ km^{-1} and 90 g GHG km^{-1}, respectively.

The use of electricity by the trial electric scooter incurs a "fuel" cost. The normalized operating costs were £0.013 km^{-1}, corresponding to the national average electricity mix price of £0.13 kW h^{-1}.[6] TTW energy use and emissions were 0.36 MJ km^{-1} and 0 g GHG km^{-1}. The energy intensity of the national electricity mix was 0.25 MJ (MJ)$^{-1}$ in 2008[7], with GHG emissions factor of 500 g GHG kW h^{-1} (138 g GHG (MJ)$^{-1}$) [25]. Normalized WTW energy use and emissions per kilometre using the trial electric scooter increase to 0.45 MJ km^{-1} and 49 g GHG km^{-1}, respectively.

Charging the electric scooters from electricity generated from renewable energy sources results in zero normalized WTW emissions, notwithstanding the emissions and other externalities incurred in their construction, commissioning and decommissioning [26]. A survey of suppliers of electricity using renewable energy sources and their respective products yielded a median cost of £0.14 kW h^{-1}.[8] Consequently, normalized operating costs rise by 5.4% to £0.014 km^{-1} (Table 3). Despite the higher fuel cost, the

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[4] The trial electric scooter is considered a motorcycle because its equivalent motor capacity exceeds 50 cc and its top speed is greater than 48 km h^{-1}. Scooter-style motorcycles have an engine integrated with the rear suspension or a step-through chassis, independent of engine and wheel size and transmission type [28].

[5] See the Honda PS 125 at http://www.scootermoped.net/scooter-fuel-consumption.html.

[6] Based on the 2008 structural indicator for the UK. Value used represents the median between the prices of £0.131 kW h^{-1} and £0.125 kW h^{-1} in the first and second half of 2009 for a domestic consumer of between 2500 and 5000 kWh yr^{-1}. Data is available from the Statistics Office of the European Union, EUROSTAT in Table nrg_pc_204.

[7] Use 8–363 kt oil equivalent used to generate 380 GWh gross [25].

[8] Companies included were Ecotricity, Good Energy, Green Energy UK, Lo CO_2 Energy and OVO New Energy, surveyed at www.greenelectricity.org/tariffs.php.

electric scooter remains 5.6 times and 2.6 times less expensive to operate than the best selling car and petrol motorcycle, respectively.

The battery is an expensive component in the electric vehicle powertrain, from €50–150 $\mathrm{kW\,h^{-1}}$ for valve regulated lead-acid batteries to €1000 $\mathrm{kW\,h^{-1}}$ for lithium ion technologies [19]. Batteries have a finite lifetime (number of charge–discharge cycles) and an imperfect roundtrip charge–discharge efficiency. The frequent battery cycling which may be expected with electric vehicle use and a relatively low maximum number of cycles results in multiple battery pack replacements over the vehicle lifetime. The average lifetime of motorcycles in the UK was 10 years in 2008 [20]. Therefore, battery expenditure switches from a single, initial capital outlay to an ongoing operational expense, or consumable.

The economic analysis was extended to include an annual battery replacement cost, based on the £ 300 battery pack, originally provided with the trial scooter (Table 1). The annual battery replacement cost was calculated as the quotient of total battery cost and its projected lifetime in years, disregarding the time value of money. The battery lifetime of 105 charges per year is derived from the electric scooter TTW energy use of 0.10 $\mathrm{kWh\,km^{-1}}$ and a 2.3 kWh capacity battery pack. The average distance travelled per scooter over the trial dates (13 April 2010–25 June 2010) was scaled to an annual 2400 km. Driving for one year utilized 26% of the total number of battery cycles, with a £ 79 annual replacement cost. New total operating (electricity and battery replacement) costs are £0.045 $\mathrm{km^{-1}}$ (£0.046 $\mathrm{km^{-1}}$ with low GHG-electricity), of which battery replacement constitutes £0.033 $\mathrm{km^{-1}}$ or 72%. Electric scooter operating costs are now 1.7 times lower than that of the car, but 24% more expensive than the best selling motorcycle.

3.5. Sensitivity analysis

A sensitivity analysis was conducted about the battery cost, cycles lifetime, battery charge–discharge efficiency and scooter energy use to assess the effects on annual replacement cost from the electric scooter perspective. The trial electric scooter normalized operating cost is given in (Eq. (1)). P_{total} may be converted from a total operating cost matrix to a binary matrix, B, by comparing each (i, j, k) entry with the operating cost of the car and petrol motorcycle. The electric scooter is more cost effective than the car for all battery prices up to £1000 $\mathrm{kW\,h^{-1}}$, a charge–discharge efficiency greater than 95% if the number of cycles is at least 600. These conditions account for 83% of the entries in P_{total} (Fig. 10). Outside of these conditions, there is a blend of factors which define thresholds (blue line in Fig. 10) where the electric scooter total operating cost equals that of the car (Eqs. (1)–(3)). 54% of entries in P_{total} represent combinations of electric scooter battery characteristics which yield an operating cost greater than that of the petrol motorcycle (Fig. 11). The electric scooter total operating cost equals that of the petrol motorcycle (blue line in Fig. 11, Eqs. (4)–(6)).

Changes in petrol and diesel prices influence the operating costs for the car and petrol motorcycle. The electric trial scooter is more cost-effective to operate than the car and petrol motorcycle at fuel costs of £1.10 l petrol equivalent^{-1} and £0.52 l petrol^{-1}, respectively. Similarly, the emissions threshold at which use of the electric trial scooter avoids WTW GHG emissions is 910 $\mathrm{g\,GHG\,kW\,h^{-1}}$ and 1900 $\mathrm{g\,GHG\,kW\,h^{-1}}$ for the car and petrol motorcycle, respectively. With the UK national average electricity mix at 500 $\mathrm{g\,GHG\,kW\,h^{-1}}$ and decreasing [25], use of the trial electric scooter is expected to yield positive avoided GHG emissions.

3.6. Scaling up scooter penetration in the UK

The avoided vehicle kilometres, GHG emissions and impacts of large-scale charging on the national power grid were simulated using the 247 000 125 cc petrol motorcycles that the trial scooter is equivalent in size to. The scaled electric scooter fleet requires 59 GWh or 0.015% of the 380 TWh electricity generated in 2008 [25] to complete the 0.60 billion avoided car or petrol motorcycle kilometres. When charging from the average electricity mix, 82 kt GHG from the car or 24 kt GHG from the petrol motorcycle are avoided. Using low-GHG electricity suppliers increases the avoided emissions to 110 kt GHG for the car and 54 kt GHG for the petrol motorcycle.

The load profile developed in Section 3.2 (Fig. 9) was scaled to that of 247 000 scooters and compared to the regular, no-scooter demand profile in the UK[9] on 3 January and 20 July. These were the days when the maximum (58 GW) and minimum (21 GW) power demands were recorded in 2008, respectively. The scooters' peak demand of 250 MW occurred in 10:15–10:40. For 3 January, the scooter charging was approaching its minimum at the end of the work day (Fig. 12b) when the national demand began to rise to its overall maximum of 58 GW at 17:30. For 20 July, the scooter charging regime precedes the 34 GW peak of the day, which occurred at 12:30 (Fig. 12a).

Charging the scaled fleet of electric scooters required median additional power of 0.059% on 3 January and 0.094% on 20 July of the total national demand throughout the respective days. Satisfying the demand of the large-scale scooter fleet exceeds 0.10% of the hourly national demand for 3 h from 09:00 to 12:00 on 3 January and for 7.5 h from 09:00 to 16:30 on 20 July. The maximum charging power required by the large-scale scooter fleet occurred at 10:30, requiring an additional 0.49% on 3 January and 0.81% on 20 July of national demand. Moreover, charging the large-scale scooter fleet requires an additional 0.44% at 17:30 on 3 January and 0.75% at 12:30 on 20 July, corresponding to the times at which national demand peaked. This relatively small additional baseline load which occurs in advance of the day and evening peaks is not expected to have significant impact on the power system (Fig. 12).

3.7. Overnight charging of scaled up electric scooter fleet

Much of the literature on charging regimes assumes the use of overnight electricity generation capacity to satisfy electric vehicle charging needs. In this work, overnight charging was simulated by shifting the charge start time of the scaled charging distribution (Fig. 9) to 2300, taking the overnight period as 2300–0600. For 3 January, the median additional demand was 0.042%, exceeding 0.10% for seven of the eight overnight charging hours and for 7.5 of the 24 h in total. For 20 July, the median additional demand was 0.07%, exceeding 0.10% for all eight overnight charging hours and for 12.5 of the 24 h in total. Therefore, although the electric scooter load exceeds 0.1% of national demand for more hours when charging overnight than during the day, it remains small in comparison to the national demand.

It is expected that the retail price of electricity will be lower during overnight charging than during the day. However, 72% of the electric trial scooter full operating cost is associated with battery replacement. Therefore, holding battery replacement fixed, the electric scooter only becomes cost-competitive with the best selling petrol motorcycle when electricity costs are £0.002 $\mathrm{kW\,h^{-1}}$, or 60 times lower than the average cost of £0.13 $\mathrm{kW\,h^{-1}}$. Thus, the full operating costs of the electric trial scooter are not expected to be as low as the petrol motorcycle during overnight charging.

Users of 125 cc petrol motorcycles travelled an average 5600 km in 2008, or 2.3 times further than the electric scooter annual

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[9] Data obtained from the National Grid metered half-hourly electricity demand, available online at http://www.nationalgrid.com/uk/Electricity/Data/Demand+Data/.

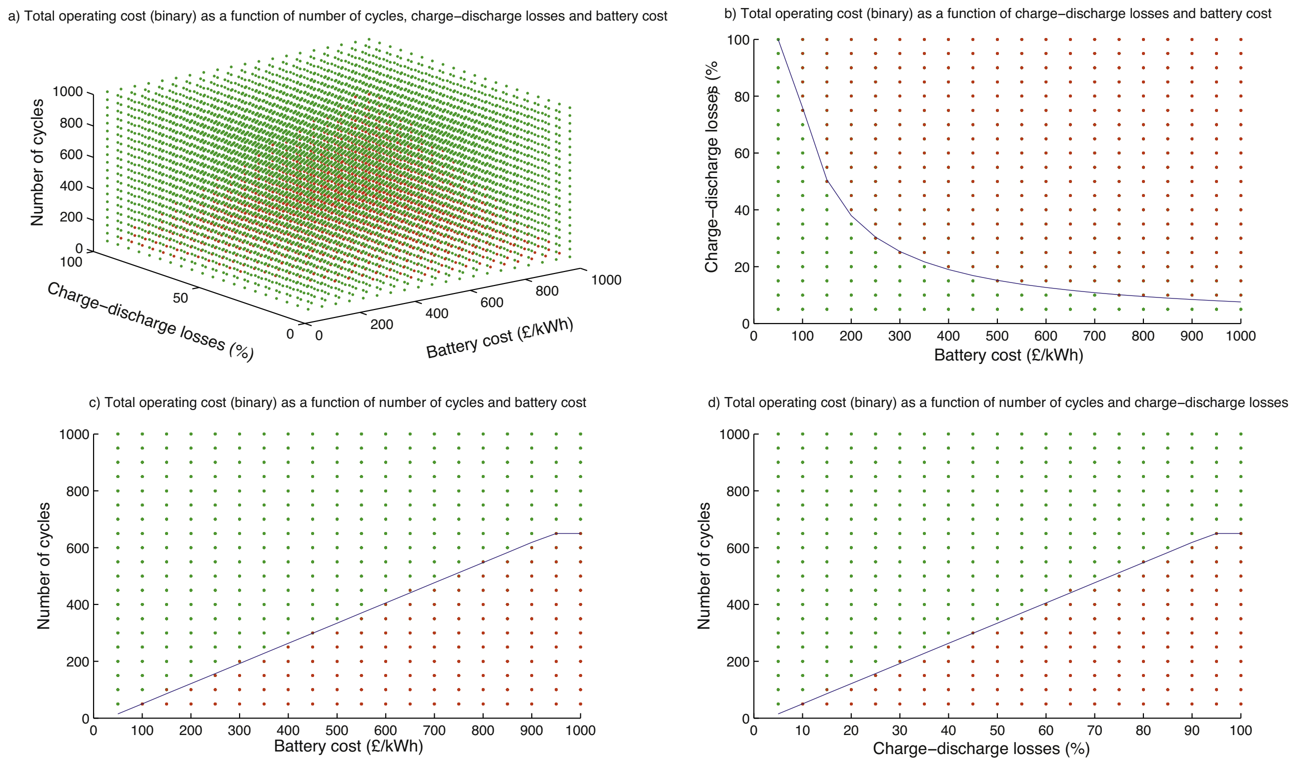

Fig. 10. Plot of total electric scooter running cost in binary form as a function of: (a) lifetime number of cycles, battery cost and charge–discharge losses; (b) charge–discharge losses and battery cost; (c) number of cycles and battery cost; and (d) number of cycles and charge–discharge losses. Green dots indicate that the total operating cost of the electric scooter at least equal to that of the car. Red dots indicate that the operating costs of the car exceed that of the electric scooter. The blue line represents the normalized cost threshold where the costs are equal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

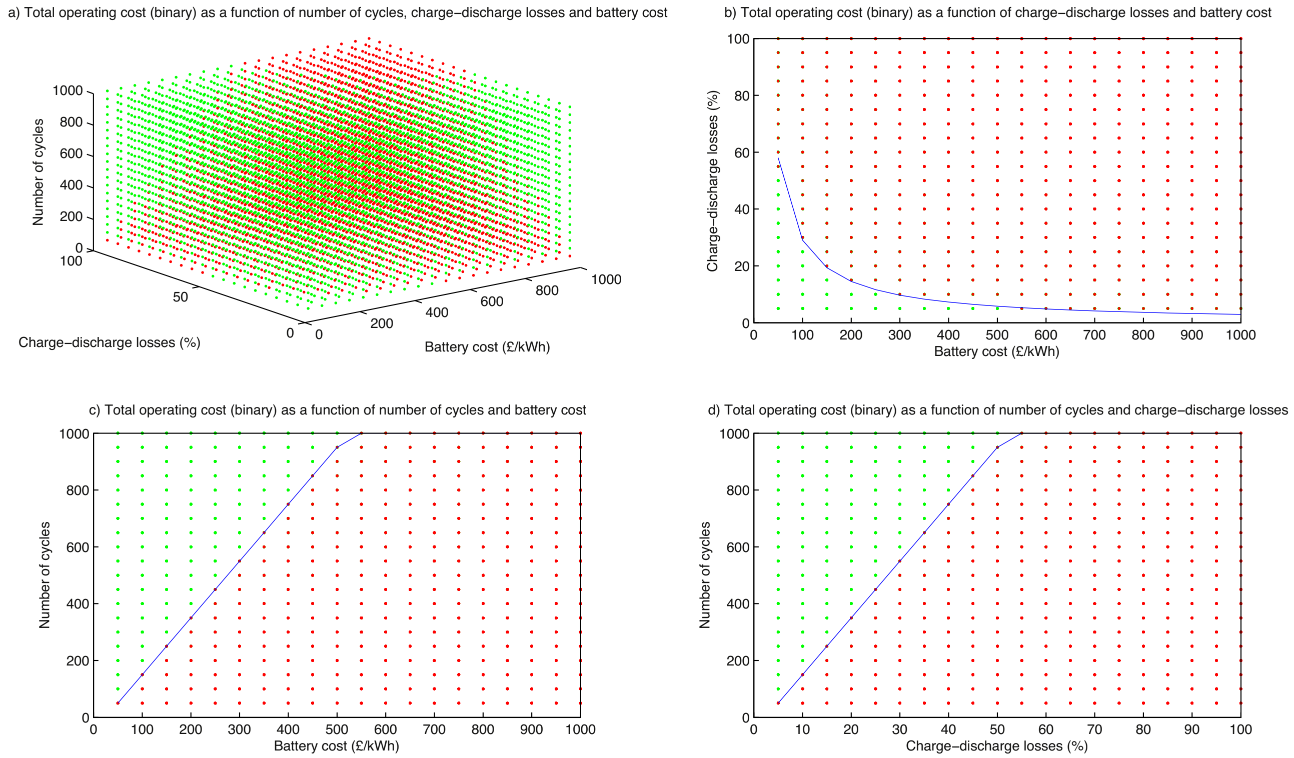

Fig. 11. Plot of total electric scooter running cost in binary form as a function of: (a) lifetime number of cycles, battery cost and charge–discharge losses; (b) charge–discharge losses and battery cost; (c) number of cycles and battery cost; and (d) number of cycles and charge–discharge losses. Green dots indicate that the total operating cost of the electric scooter at least equal to that of the car. Red dots indicate that the operating costs of the car exceed that of the electric scooter. The blue line represents the normalized cost threshold where the costs are equal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

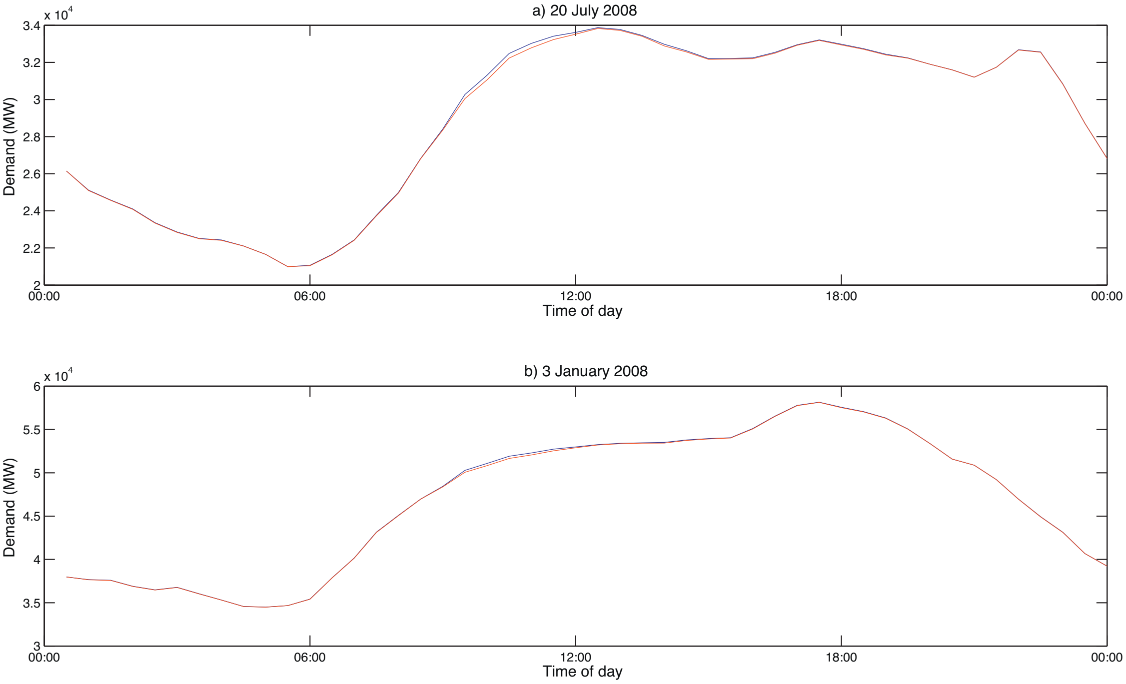

Fig. 12. Composite of scaled scooter demand (blue) with non-scooter national demand (red) in MW for (a) 20 July when the minimum national demand of 21 GW was recorded; and (b) 3 January when the maximum national demand of 58 GW was recorded in 2008. The peak in scooter demand of 250 MW occurs in 10:15–10:40. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

distance of 2400 km measured in the trial. The discrepancy is attributed to the different ranges of the trial electric scooter and petrol motorcycle. The range of the scooter on one charge is published as 48 km, but is 23 km in practice using the TTW 0.10 kWh km^{-1}. In contrast, the range of the petrol motorcycle is 11 times greater at 250 km. The relatively low range of the trial electric scooter makes long trips infeasible. Therefore, the 5600 km undertaken by petrol motorcycles constitutes a generous upper bound to the expected annual electric scooters distance travelled.

4. Conclusions

The use of two-wheeled vehicles is growing in the UK, outpacing passenger car vehicle fleet size and kilometres travelled. The UK is in a position to leap frog the air quality and lead pollution burdens borne in Asian urban centres by introducing electric scooters with managed battery manufacturing and disposal facilities. There are few published results data from electric vehicle trials and those ongoing in the UK are yet to report. This work presents the findings from a recently concluded three-month trial of 11 electric scooters in Oxford.

The scooters were instrumented with GPS data loggers and energy meters to provide insights into on the road performance, charging behaviours and ultimately, overall scooter energy use. Median trip length was 7.8 km, travelled at 15 km h^{-1}. For the work week commute, the scooters were most likely to be driving at 09:05 and at 17:15, with midday trips occurring at 12:45. They were most likely to be charging at 10:15–10:40. The electric scooter has TTW energy use of 0.10 kWh km^{-1}, which yields operating costs and WTW energy and GHG per kilometre of £0.013 km^{-1}, 0.45 MJ km^{-1} and 49 g GHG km^{-1}, respectively. The electric scooter uses 6.1 times less energy, emits 3.8 times less GHG and costs 5.9 times less to operate per kilometre than the best selling car in the UK in 2008. Similarly, the electric scooter uses 2.9 times less energy, emits 1.8 times less GHG and costs 2.7 less to operate per kilometre than the best selling petrol motorcycle.

The trial electric scooter battery pack is considered a consumable on account of its frequent replacement throughout the vehicle lifetime. Annual pack replacement cost of £ 79 accounts for 72% of the final total operating (electricity and battery replacement) cost. The total operating costs increase to £0.045 km^{-1}, becoming 24% more expensive than that of the petrol scooter. Cost-effectiveness of the electric scooter is related to the changes in operating costs of the car and petrol motorcycle on account of liquid fuel prices. Identifying these thresholds informs the choice of the battery pack to maintain the cost competitiveness of the electric scooter. Analogously, emissions from electric scooter use exceeds those of the car and petrol motorcycle for electricity supply GHG intensities of 910 g GHG kW h^{-1} and 1900 g GHG kW h^{-1}, respectively.

Scaling the 11 trial scooters to the fleet of 247 000 equivalent motorcycles driving an annual distance of 2400 km leads to 54 kt GHG and 111 kt GHG avoided from petrol motorcycle and car use, respectively, when low GHG-emitting electricity suppliers are used. At scale, the scooters require 59 GWh, or 0.015% of the total electricity generated in 2008. The peak charging power demand is 250 MW, or up to 0.75% of the daily national maximum load. The scooter fleet peak occurs at 10:15–10:40 which is 2 h earlier than the maximum daily demand in the worst case. Therefore, notwithstanding network constraints, the effect of large-scale electric scooter fleet charging is manageable on account of its marginal load which is time-shifted from the existing national demand peak.

Acknowledgements

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Appendix A. Math formulae

1.

$$P_{total} = \left(\sum_{j}^{E_{\max}} \sum_{k}^{Y_{\max}} \sum_{i}^{C_{\max}} \frac{batt\_cost(i)}{batt\_cyc(k)} * e_{scooter} * \frac{batt\_eff(j)}{100} * \frac{1}{V} \right) + P_{electricity}; \quad \forall\, batt\_cost = [50:50:C_{\max} = \pounds 1000\,\text{kW<CE:HSP SP="0.25"/>h}^{-1}]; \quad \forall\, batt\_eff = [5:5:E_{\max} = 100\%]; \quad \text{and}\,\forall\, batt\_cyc = [50:50:Y_{\max} = 1\,000\, cycles] \tag{1}$$

where P_{total} is three dimensional matrix of the total, normalized operating (battery replacement and electricity) cost per kilometre; $batt\_cost$ is the battery cost vector (£ kW h^{-1}); $batt\_eff$ is the battery charge–discharge losses vector (%); $batt\_cyc$ is the vector of battery charge–discharge cycles in its lifetime; $e_{scooter}$ is the trial electric scooter normalized TTW energy use = 0.10 kWh km^{-1}; V is the battery pack capacity = 2.3 kWh; and $P_{electricity}$ is the normalized cost per kilometre of electricity only = £0.013 km^{-1}.

2. For all number of lifetime cycles $k < 650$ cycles (Fig. 10b):

$$j = \begin{cases} 7600/i & \text{if } i < 100; \text{ and} \\ 100, & \text{otherwise.} \end{cases} \tag{2}$$

3. For all charge–discharge efficiencies $j > 5\%$ (Fig. 10c):

$$k = \begin{cases} 0.71i - 21 & \text{if } i < 650; \text{ and} \\ 650, & \text{otherwise.} \end{cases} \tag{3}$$

4. For all battery costs $i >$ £50 kW h^{-1} (Fig. 10d):

$$k = \begin{cases} 7.1j - 21 & \text{if } j < 650; \text{ and} \\ 650, & \text{otherwise.} \end{cases} \tag{4}$$

5. For all number of lifetime cycles $50 \leq k \leq 1\,000$ cycles (Fig. 11b):

$$j = \begin{cases} 2900/i & \text{if } i < 1000; \text{ and} \\ 1\,000, & \text{otherwise.} \end{cases} \tag{5}$$

6. For all charge–discharge losses $5 \leq j \leq 100\%$ (Fig. 11c):

$$k = \begin{cases} 2i - 50 & \text{if } i < 55; \text{ and} \\ 55, & \text{otherwise.} \end{cases} \tag{6}$$

7. For all battery costs up to $50 \leq i \leq$ £ 1000 kW h^{-1} (Fig. 11d):

$$k = \begin{cases} 20j - 50 & \text{if } j < 1000; \text{ and} \\ 1\,000, & \text{otherwise.} \end{cases} \tag{7}$$

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