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Impact of driving characteristics on electric vehicle energy consumption and range

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Abstract: This study investigates the impact of driver behaviour/driving-style on the energy consumption, state-of-charge (SOC) usage and range, of all-electric vehicles (EVs). Results from many driving cycles using a sole driver, along with those from a pre-defined ~40 km route encompassing both urban and rural roads in Sheffield (UK) with various drivers, are given and analysed. The platform for the study is an all electric-drive Smart Fortwo ED, supplied using Zebra battery technology. Measurements of real-time quantities such as wheel speed and SOC over a number of driving trials show that energy consumption is significantly affected by driving style, and that through basic statistical analysis of acceleration profiles, for instance, a metric for assessing 'good driving practice' can be obtained. It is ultimately shown that the difference between driving in a moderate manner, and more aggressively, can make ~30% difference in energy consumption – amounting to 30 g/km of CO_2 (equivalent) over the driving duty considered in this case. The results also highlight the substantial savings that can be accrued by appropriate traffic management in congested areas, by allowing the driver to minimise periods of repeated acceleration/deceleration and allow longer periods of steady-speed motion. Although a pure EV platform is used to focus the study, ultimately the results are more widely applicable to plug-in hybrid counterparts.

1 Introduction

Substantial environmental, economic and legislative drivers exist in the UK to promote lower carbon cars. Policy initiatives such as graduated 'Vehicle Excise Duty' and company car taxation, plus exemptions on the London congestion charge and free parking in some areas, have promoted a shift in consumer purchasing behaviour. More than 11% of new vehicles now sold in the UK have CO_2 emissions below 120 g/km. However, the vast majority of these vehicles are petrol and diesel powered and the use of electric drive in the UK has, to-date, played only a small part in this shift. Nevertheless, recent UK policy analysis has highlighted electric drive as a potential technology capable of decarbonising road transport [1]. Building on the Stern [2] report, commissioned by the UK government in 2005, which examined the economics of climate change, the 2007 King [3] review looked specifically at low carbon cars. In examining the role of road transport in the UK, which currently accounts for approximately 22% of the UK CO_2 emissions, the King report commented that a 60–80% reduction in CO_2 per km is required if the UK is to meet its commitments to tackling climate change. Reviewing this target, King developed a trajectory for attainment, which is focused on the long-term electrification of road transport, supported by an increasingly 'decarbonised' electricity generating sector. With this background, this paper considers the impact of driving-style on the efficiency and range of electric vehicles (EVs), with an ultimate goal of providing real-time driver feedback to facilitate maximum sustainability and improved power network utilisation – identified as a key impediment to rapid widespread deployment [4]. Unlike previously reported methods for determining EV dynamic characteristics and the relationship to power consumption using analytical [5] and model-based algorithms [6], here, real-time statistical techniques are shown to provide an effective basis for determining the efficacy of driving style on energy availability. Moreover, the underlying principles can also be applied to (plug-in) hybrid vehicles, which attracts a similar degree of investigation but has yet to be adequately solved – the reader is directed to [7, 8], for instance.

2 Smart ED platform

Developed by Daimler and Zytek, the 2008 Smart ED is a pure electric driven two-seater passenger car, based on the 450 chassis, Fig. 1 and has been used for UK wide trials over the proceeding period. Although now being superseded by the updated 451 chassis that supports Li-based battery technology, significant amounts of real-time data have been collected for the 450 variant that provide insight into the impact of driver behaviour on EV performance – it is the results of a portion of these studies that are reported here. The electric drive train is fitted with Zytek into a 'glider' vehicle from Daimler where the internal combustion engine would have been, and accommodation is

Fig. 1 *Smart ED electric vehicle*

made for the high-voltage battery in the area previously housing the gasoline tank.

The Smart ED uses a 12 kWh (usable power) sodium-nickel-chloride 'Zebra' battery coupled to a brushless DC permanent magnet electric machine, which is currently limited to ~20 kW to preserve battery capacity. Delivering approximately 300 V, with a high gravimetric energy density (~120 Wh/kg) the Zebra battery is well suited to electric-drive applications that incur high utilisation duties [9]. However, the Zebra battery operates at high temperatures (270–350°C) with cell chains being interconnected and packaged within a sealed, vacuum insulated, air-cooled modular casing and requires a portion of the operational energy to maintain temperature, if not it draws a continual current when plugged in. The Zebra pulse power capability is appropriate for typical EVs acceleration profiles, at around 1.5× the rated power (170 W/kg) and offers significantly increased cycle life, ≃3500 nameplate cycles, when compared with lead-acid batteries, for instance. The electric machine is sized to provide sufficient acceleration through a standard Smart gearbox (fixed in second gear), and acts as a generator when the vehicle is on coast down or under braking, to give a 'regenerative' functionality.

3 Driving characteristics

Operational deployment analysis is based on data collected from the Smart ED over a period of 11 months (October 2008 – September 2009). The following sections present salient points from the study pertaining to the impact of differing driver behaviour characteristics.

3.1 Range analysis (single driver, various driving cycles)

Examining individual driving cycles provides a 'snap-shot' of vehicle behaviour. To examine the underpinning characteristics, analysis has been undertaken across multiple trips and differing duty cycles. Fig. 2*a* shows (state-of-charge (SOC) against distance travelled) results from 12 different driving cycles, starting at various initial battery %SOC, and over a variety of journey distances. Notably, no additional 'hotel loads' (i.e. power consuming, user-convenience features such as air-conditioning and heating, for instance) were used throughout the trials.

The results show that the gradient of SOC decline appears consistent across trips and distance. This mirrors typical laboratory range test performance on rolling roads. Specifically, the mean gradient over all trials is – 1.275%SOC (consumed)/km, indicating a mean vehicle range of 78.4 km over all trials. By extrapolating the gradient of each trial to provide an indication of 'expected range for each trial', the minimum and maximum range will lie between 71 km and 88 km (from the minimum and maximum gradients) over non-trivial journey distances. It is also notable that the rate of %SOC usage is not significantly affected by the initial %SOC of the battery. Nevertheless, a caveat is now introduced – although trial measurements have been taken over differing cycles, they are all essentially considered as either urban or suburban. Evidence from driving cycles that include motorway trials (for instance, from trial studies in the north-east, UK [10]) show that range predictions can vary much more significantly. Evidence for this is also available from the 12 trials presented here by considering the energy usage at a more 'micro' level, that is, reducing the distance base to consider behaviour on a km-by-km basis. Fig. 2*b* shows a scatter diagram of the incremental distance travelled (km) per 1% reduction in SOC, plotted against the absolute battery %SOC that the reading was taken at, for the same 12 trips presented in Fig. 2*a*. From the results it is evident that over short distances significant differences in %SOC usage can occur. Specifically, from Fig. 2*b*, the standard deviation (S.D.) of the data is ~0.1 about a mean of 0.77, which highlights an issue for current EVs in general. Namely, by comparison with traditional internal combustion engine vehicles that have relatively long absolute ranges (typically between 500 and1500 km), the relatively low average range of current EVs means that, to promote user

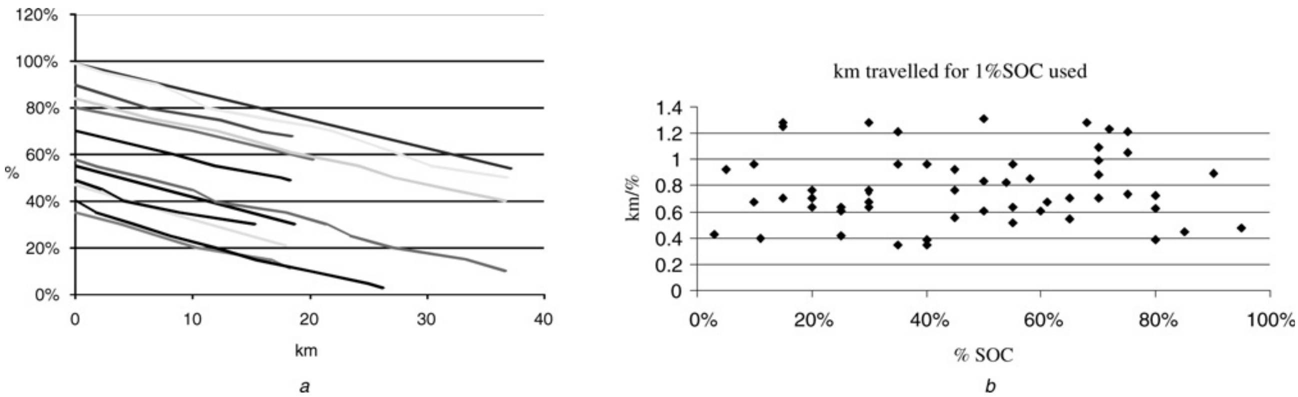

Fig. 2 *Results from 12 trials*

a SOC against distance travelled (no auxiliary/hotel loads)
b Incremental km travelled for 1% incremental SOC consumed against absolute %SOC for the 12 driving trials shown in *a*

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confidence, greater precision is required for estimating the remaining vehicle range. For example, while it is acceptable to estimate the range of a typical vehicle to perhaps ± 10 km on long journeys from an expected mean of 500 km, when the mean vehicle range is 78 km similar error bars are 'less comfortable'. Moreover, it will now be shown that the impact of different driving behaviour/styles also has a substantial impact on energy usage, and hence, vehicle range.

3.2 Range analysis (various drivers)

To provide a degree of consistency for the investigation, a driving cycle comprising of a combination of urban and country roads in and around the Sheffield and Peaks regions (UK) is used throughout. The total distance travelled for each trial is ~40 km – brief details of the route are provided in the Appendix. Wheel velocity profiles for five example trials are shown in Fig. 3, undertaken during similar parts of the day when traffic congestion was minimal so as to reduce this as a contributory factor in the results (the presented order of the results is not chronological – discussed later). Notably, in each case, the trial takes ~57 min (± 2 min). The urban part of the cycle takes place during approximately the first and last one-fifth of each trial.

As a benchmark for comparing and contrasting results, the New European Driving Cycle (NEDC) cycle is also considered, Fig. 4.

From Fig. 3 it is evident that although the underlying trends, for each cycle, are qualitatively similar (as expected) there progressively exists higher short-term transient activity on each result from (i) to (v). The driving cycles will now be referred to as (i)–(v) throughout to ensure consistency. A comparison with the results of Fig. 4 shows that the (often used) benchmark NEDC cycle possesses far lower dynamic content.

From real-time measurements, it can be shown that the additional 'activity' presented by more 'aggressive' driving

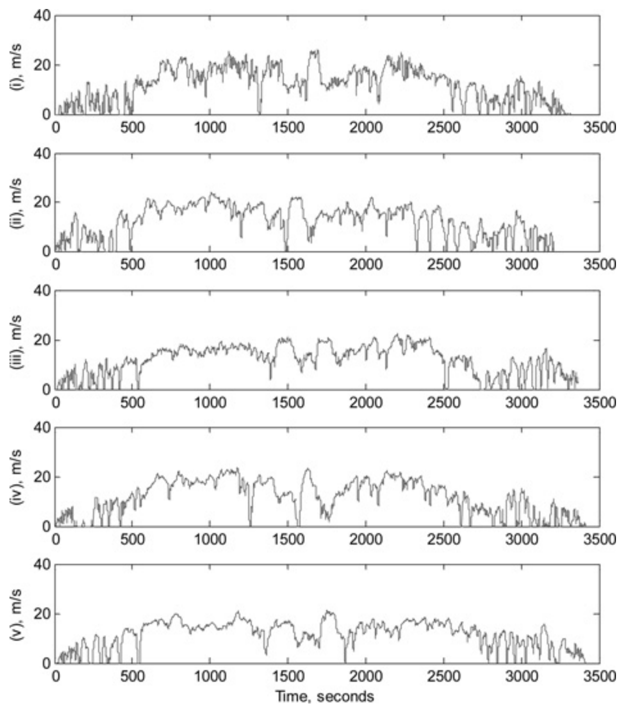

Fig. 3 *Velocity profiles of five driving trials (i)–(v)*

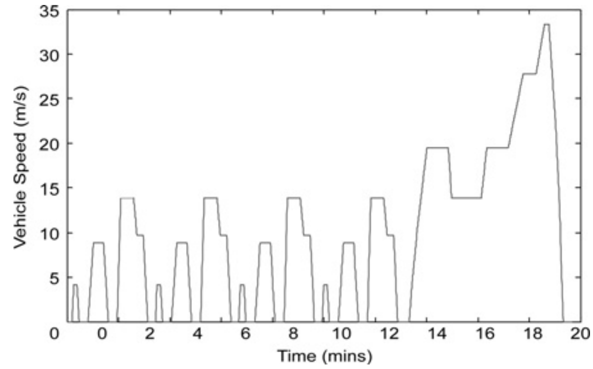

Fig. 4 *Velocity profile of NEDC driving cycle*

trials is manifest in the energy usage. For instance, Fig. 5 shows the real-time battery %SOC during each of the trials, (i)–(v), respectively. The battery %SOC at the start of each trial is 100%. Table 1 gives the final %SOC at the end of each trial. Additionally, Table 1 also shows the mean power from the battery averaged over each trial – this, therefore includes the benefits of regenerative braking and 'engine braking'.

A direct comparison between the 'best' (v) and 'worst' (i) case trials shows that when driving 'aggressively' the vehicle consumes ~57% of the available SOC, compared with ~39% when driving moderately. Under such conditions, the best estimate of vehicle range is between 43 and 64 miles, respectively, depending on driver behaviour. By integrating (with respect to time) the instantaneous power to/from the

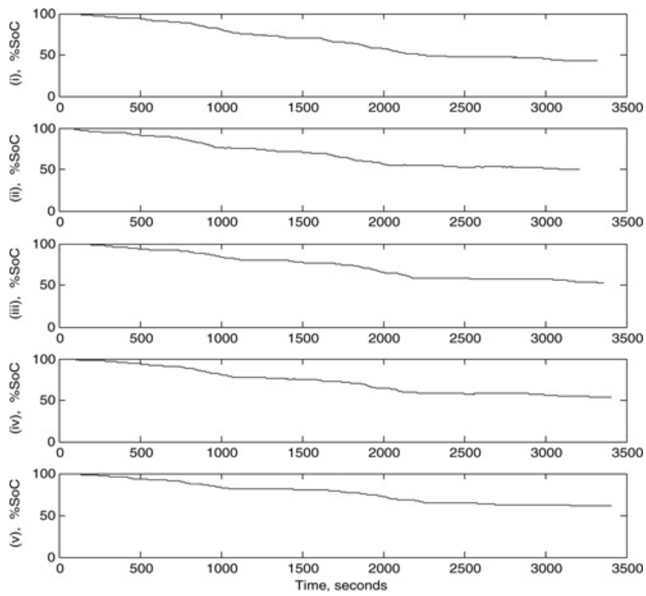

Fig. 5 *Real-time battery SOC (%)*

Table 1 Net energy consumption of each trial (measured at battery)

Trial	Final %SOC	Mean power, kW
(i)	43	5.47
(ii)	50	5.33
(iii)	53	4.95
(iv)	54	4.70
(v)	61	4.21

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battery throughout each trial, it can be shown that trial (v) consumed 4.0 kWh, whereas trial (i) consumed 5.3 kWh, an increase of ∼32.5%.

This also highlights notable differences in effective available battery capacity. Projected over the full %SOC usage, for trial (i) the estimated total ‘useful energy available for driving’ is $(5.3/(1-0.43)) = \sim 9.3$ kWh, whereas for ‘gentle’ driving there is $(4/(1-0.61) = \sim 10.3$ kWh. This compares with the nominal battery capacity of ∼12 kWh. A contributory factor to this is the additional ‘auxiliary’ loading of battery management (fan/cooling, and so on) which has a higher utilisation when the battery is worked harder and is operating at higher temperatures – Fig. 6 shows the temperature profiles for driving cycles (i) and (v). Other contributory factors are also discussed in the next section.

The results clearly demonstrate that more aggressive driving consumes substantially more energy. Typically, ‘aggressive cycles’ incurred greater acceleration into corners resulting in the need for higher deceleration to subsequently slow down the vehicle, and consequently heavier braking activity. This then is in-line with traditional characteristics expected from ICE vehicle counterparts, even with the provision of regenerative braking.

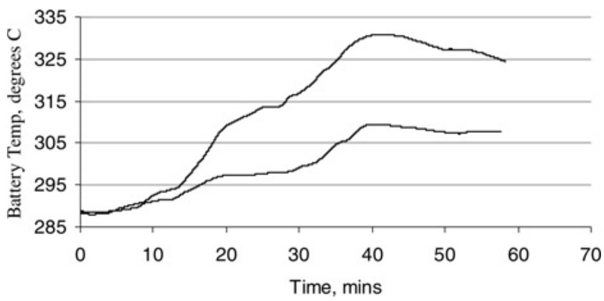

Fig. 6 *Mean battery temperature for trials (i) and (v)*

3.3 Metric for driving behaviour

Fig. 7 shows the acceleration profiles for each of the driving trials (i)–(v), respectively. By consulting the raw data, it is not clear which profile provides the most economical use – indeed (v) which is the most economical, appears to possess one of the more significant dynamic behavioural characteristics. However, from a basic statistical ‘frequency’ analysis of acceleration with bins centred at 0.2 m/s^2, the histogram in Fig. 8 results.

From this, it is clear that although the characteristics of each driving trial is underpinned by relatively low-acceleration behaviour, it is also evident that ‘more gentle driving profiles’ (e.g. trial (v)) contribute more dominantly in the low acceleration/deceleration regions, and the aggressive profiles (e.g. trial (i)) dominate the higher acceleration/deceleration regions. This indicates that a greater degree of braking energy is being lost as a consequence of unnecessary ‘over acceleration’ during the aggressive cycles, along with limited (controlled) regeneration capability during decelerations (typically ∼10 kW max) – see Fig. 9, for instance, which shows the power profile for trial (i). Regeneration in this instance refers to energy recovered from deceleration of the vehicle mass and delivered back to the zebra battery, as indicated by the negative power regions.

Since it is proposed that additional energy usage during trial (i) is, to some degree, related to the (normalised) high acceleration/deceleration content of the driving profile, it is instructive to consider some quantity of merit that measures the ‘spread’ of the histograms about the (common, zero) mean value. A candidate measure is the standard deviation (SD).

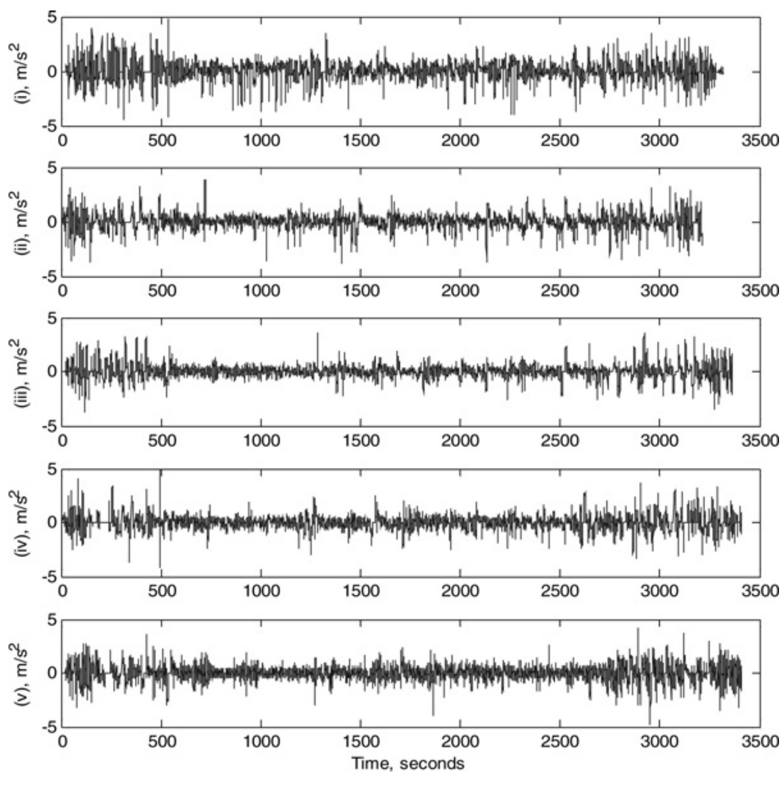

Fig. 7 *Acceleration profile of five driving trials (i)–(v)*

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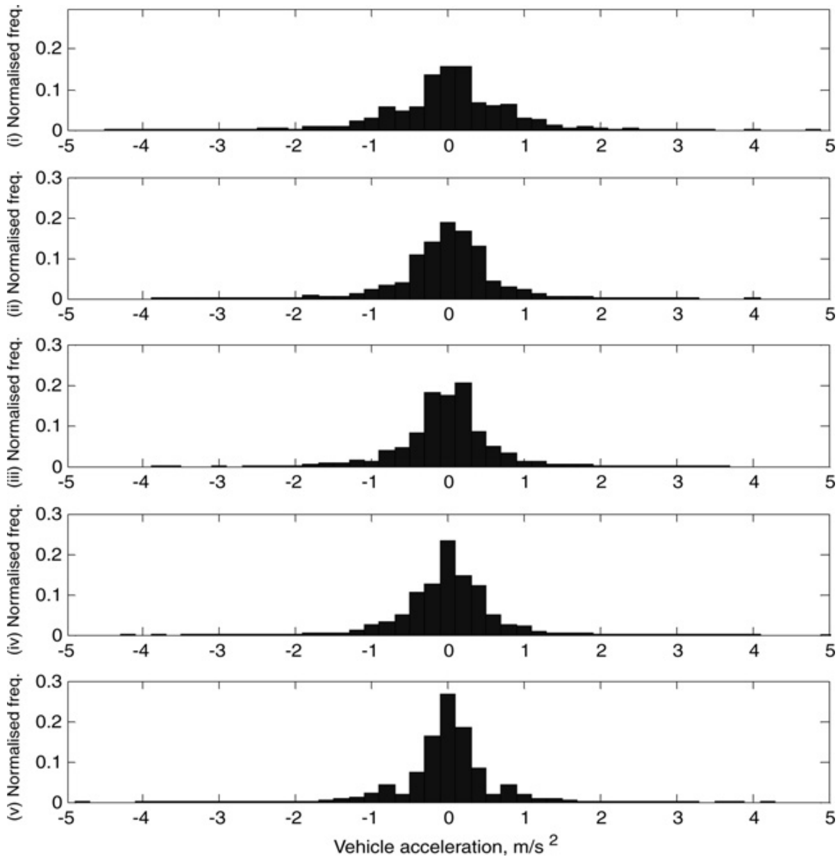

Fig. 8 *Histogram of acceleration profiles (bins 0.2 m/s^2)*

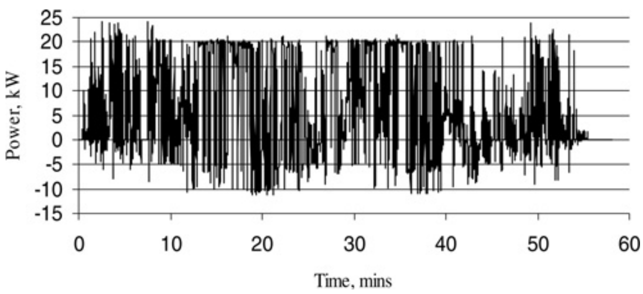

Fig. 9 *Power profile for trial showing limited controlled regeneration throughout trial (i)*

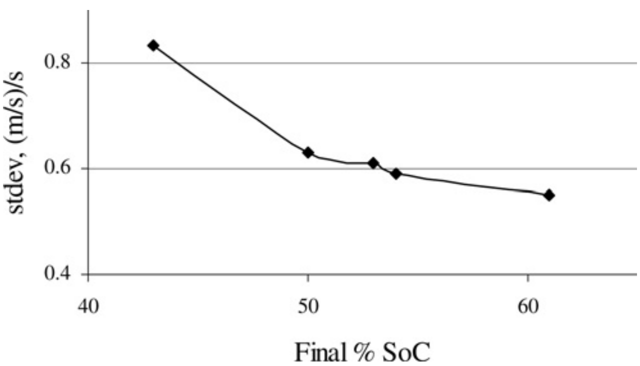

Fig. 10 *Final %SoC against S.D. of acceleration profile*

By way of example, Fig. 10 shows the SD of acceleration for each driving trial, as a function of the %SoC at the end of each trial.

Although non-linear, the results qualitatively suggest that to a first approximation, consideration of the SD (or variance) of acceleration can provide a performance indicator for 'good driving behaviour' in order to maximise energy utilisation, and hence, vehicle range. However, it should be noted that, while the results show a very good correlation between the statistical properties of vehicle acceleration and energy usage, it is important to remember that the results are taken over a common driving cycle, and therefore they should only be considered as a figure of relative merit for driving over that particular cycle. Nevertheless, it is expected that reduced acceleration variance should be considered a good figure of merit for more general driving conditions, even though absolute values should not be directly compared across different cycles. The results also suggests that some care needs to be taken when considering standard driving cycles, since they are often underpinned by long periods of constant speed (zero acceleration) operation. An example is the NEDC. For instance, by comparing the 'real' driving cycle SD (trials (i) and (v)) with that of the NEDC (0.49 with the assigned bins), it is clear, from Fig. 11, that we should expect the NEDC cycle to be very energy conservative compared with real driving conditions. Supporting evidence for this has already been reported in relation to other driving cycles [11].

4 Impact of hotel loads

An advantage of EVs for urban journeys is a reduction of idling losses and emissions associated with congested traffic that can constitute a significant proportion of journey time. Nevertheless, the servicing of auxiliary- and hotel-loads can pose a significant drain on energy that can be largely

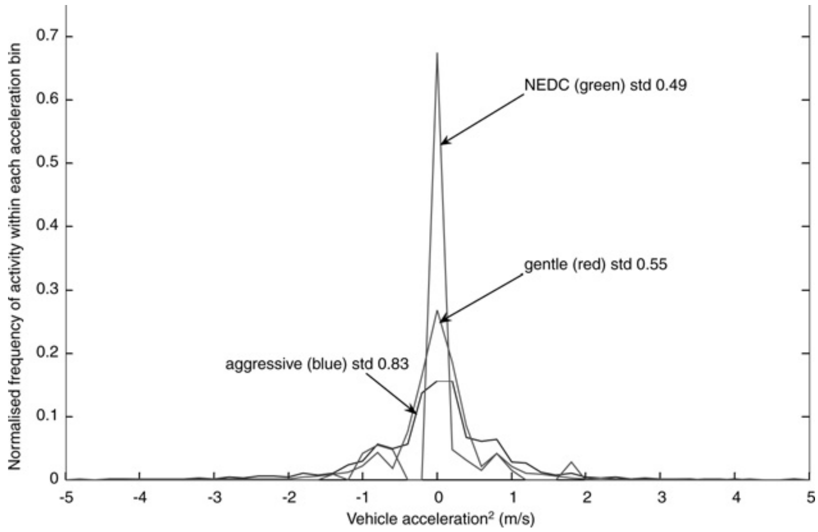

Fig. 11 *Histogram of (i) and (v) data of Fig. 8 replotted at 'bin' centres, along with data from NEDC profile*

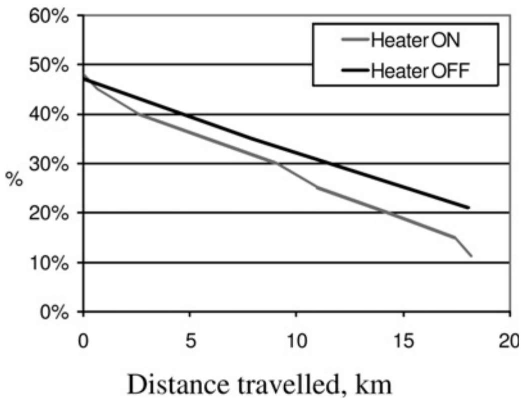

Fig. 12 *Impact of vehicle heating on battery %SOC with, and without, the heater 'on', over the same commuter journey*

independent of driving conditions, and more depending on operation time. Although the use of lights, stereos, wipers, heated back and front windows all contribute to the overall energy audit, over time it is likely that heaters and air-conditioning units will pose the largest energy drain.

For the Smart ED, trials examined the charge depletion associated with cabin heating, finding that the heater uses ~1% SOC for every 3 min of operating time, regardless of initial SOC. This rate of %SOC depletion is found to be relatively constant regardless of driving duty. An example is shown in Fig. 12. The result indicates the potential benefits of improving heat/energy recovery systems to support cabin environment conditions – in this particular case, around 20% savings could be obtained if energy harvesting from other vehicle systems could be employed.

5 Conclusions

This paper has considered the impact of driver behaviour on the energy utilisation of all EVs. Over a common driving cycle results have been presented to show that substantial energy savings can be made by consciously reducing the amount of acceleration and deceleration throughout the driving cycle. Specifically, between trials of the best (v) and worst (i) energy consumption, a difference of $5.3 - 4.0 = 1.3$ kWh was measured over the 40 km cycle. Assuming good charging efficiency, from the UK mixed grid carbon intensity of 0.537 kg/kWh, this amounts to a potential saving of upto $0.537 \times 1.4 = 0.75$ kg of CO_2 (equivalent) over this cycle, from good driving practice – amounting to a saving of ~30 g/km (equivalent). This is underpinned by looking at a basic statistical metric for good driving practice that shows a significant correlation exists between energy consumption and the SD of acceleration, for instance. Although not considered to be applicable to direct numerical comparison across driving cycles, the results do, nevertheless indicate that reducing the statistical spread of demanded vehicle acceleration can provide substantial savings in energy consumption. This also has a beneficial impact on cost to the user – for the trials described herein, cost of aggressive driving could be >30% higher.

Consideration of hotel loads has also been considered, with particular emphasis given to heating in this case – which, along with air-conditioning is considered to be dominant loads. It is apparent from the results that unless technological developments mean that EV battery technologies or supporting systems can provide energy for heating/air-con that would otherwise not be used, the hotel power requirements for EVs and possibly Plug in Hybrid EVs (PHEVs) (during all-electric drive modes) will remain essentially similar, that is, independent of the drive-train technology. Although this is a known issue for ICEs, and impacts on fuel-consumption figures, the relatively low total energy available from pure EVs, at present, means that the accommodation of such loads needs to factored into journey planning and user behaviour. Moreover, the results also suggest that substantial economy and 'fuel' savings that can be accrued by appropriate traffic management by reducing periods of transient acceleration/deceleration and allow longer periods of steady-speed motion, albeit possibly slower overall.

It should be noted that when a pure EV platform has been used as a focus to the study, ultimately the underlying principles are much more widely applicable to hybrid and plug-in hybrid vehicles.

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8 Appendix

Fig. 13 shows driving cycle route for driver behaviour study.

Fig. 13 *Driving cycle route for driver behaviour study*

Sheffield centre (S1 3JD) → A57 towards Manchester (Manchester Road, Rivelin Valley) → Bamford (Hope Valley) → Hathersage (Hope valley) → Sheffield centre (S1 3JD)
The route is chosen to reduce the impact of a non-zero mean gradient over the driving trials