Electric Vehicle Driving Style and Duty Variation Performance Study

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Abstract— Cenex, the UK’s centre of excellence for low carbon and fuel cell technologies, is currently deploying electric passenger cars and vans throughout the UK in a series of Government funded low carbon vehicle trials. This study, produced in partnership with Millbrook Proving Ground, investigates comments and concludes on energy consumption in electric vehicles with varying driving styles and driving duties. At Millbrook, the electric vehicle (EV) track cycle is designed to represent real world driving duties over city, rural, hill and high speed circuits. It is shown that the drive efficiencies over the EV track cycle vary significantly by driver and the largest variations are noted on tracks with the highest opportunities for regenerative energy capture. To further study the regenerative energy, a model is developed and the percentage of potential vehicle energy recovered during deceleration is quantified. This model is also used for assessing the efficiency of input energy used to propel the EVs over the EV track cycle, where a diesel vehicle is also tested over the same circuits to allow a baseline for the data. The track results are contrasted with energy consumption data from real world vehicle trials and the vehicle range, efficiency and CO\(_2\) performance from trial activity is reported. Comparison is drawn on interactions with drive efficiency and regeneration performance observed under real world conditions with that achieved during track testing. The study completes with an analysis on the effect of range anxiety quantifying the State of Charge (SoC) where users appear reluctant to start an electric journey and the effect SoC has on drive efficiency demonstrating how users modify their driving style to conserve energy when SoC reduces.

Keywords— “Electric vehicle”, “Regenerative braking”, ”Vehicle trial”

1. Electric Vehicle Deployment in the UK

Electric vehicle activity is gaining significant momentum in the UK with 2010 seeing the nationwide deployment of electric vans and passenger cars through UK government initiatives such as the Low Carbon Vehicle Procurement Program and the Ultra Low Carbon Vehicle Demonstrator. Alongside this the UK is announcing a series of cities that are rolling out mass deployment of electric charging infrastructure as part of the Plugged in Places scheme.

Cenex, the UK’s centre of excellence for low carbon and fuel cell technologies, was established with support from the Department for Business, Innovation and Skills to promote UK market development and competitiveness in low carbon and fuel cell technologies for transport applications and plays a role in delivering a number of UK low carbon vehicle and infrastructure deployment initiatives.

In this paper Cenex and Millbrook Proving Ground, a UK vehicle development, demonstration and test centre, comment and conclude on energy consumption in electric vehicles with varying driving styles and driving duties. Test track results are contrasted with energy consumption data from real world vehicle trials and the vehicle range, efficiency and CO\(_2\) performance from trial activity is reported on together with an analysis of range anxiety issues.

The results published in this paper are part of an ongoing Smart Move \([1]\) EV deployment trial in which Cenex is studying the performance and acceptance of electric vehicles into public and private sector fleets with the aim of informing and promoting the uptake of electric vehicles. Informing users of the most appropriate duties for and methods of maximising range of electric vehicles is crucial to their market acceptance and success. This paper further quantifies how drivers can interact with electric vehicles to enhance their range performance.
2. The Smart ED

This study is focused on the smart ed (electric drive), a two seater pure electric passenger car (Figure 1) developed by Daimler and Zytek and deployed at a pre-commercialisation stage for a UK wide trial commencing in late 2007. The smart electric drive uses a 12 kWh (usable power) Sodium-Nickel-Chloride ‘Zebra’ battery coupled to a brushless DC permanent magnet electric machine limited to 20kW.

![Figure 1: The smart ed electric vehicle](image)

Following the success of the initial smart ed market trial Mercedes-Benz UK in 2010 released its latest model Smart ed with improved range and power delivery characteristics for market trials. The new Smart ed uses a 16.5kWh lithium-ion battery and delivers up to 30kW from the electric drive motor. The vehicle is due to go into full series with production in 2012. Cenex will be deploying six 2010 release Smart eds, the study of which will be the focus of further research, dissemination and promotion of EV capabilities. The vehicle and tests detailed in this paper are conducted on the original model smart ed, not the new (2010) lithium ion version.

3. EV Track Cycle Performance Evaluation

To investigate the influence of driving style and duty on energy use, a drive cycle was developed using four sections of track at Millbrook Proving Ground. A brief description of the track used follows:

1. High speed circuit (HSC); a 3.2 km circular circuit where the EVs were accelerated to the maximum velocity possible before beginning deceleration to come to rest in a predefined parking location. There were a total of four sections of acceleration, deceleration and rest on the circuit.
2. City course (City); a 1.4 km circuit representative of urban city driving environment. The circuit is based on European cities with a varied range of speeds up to 48 km/h with numerous stops, including reverse parking, and posted speed limits.
3. Hill route (Hill); a 4.5 km route where the drivers were asked to maintain 30-35 mph on two hill circuits incorporating varying gradients, the steepest on this cycle being 11.6%.
4. Handling circuit (HC); a 2.7 km circuit representing tight corners typical of rural UK B roads. Drivers were instructed to limit the speed of the vehicle to 35 mph.

The total cycle duration was approximately 25 minutes. Figure 2 shows the layout of the complete test track with the relevant circuits highlighted.
3.1 Driver Selection and Range Variation

A pre-selection process was established which allowed a wide spread of driver types and driving styles to be taken forward for detailed track analysis. The aim was to have a selection of driving styles that would be representative of the driving techniques of the general population. Six drivers were selected from an initial pool of 25 who, through completing a total of over 140 monitored journeys whilst performing routine work and home travel, represented a spread of the most efficient to the least efficient driving styles.

Figure 3 shows the energy consumed from the initial pool of drivers measured by percentage of the vehicle’s state of charge (SoC) consumed per mile of driving. A spread of approximately +/- 1% SoC/mile from the average energy consumption of 1.9% SoC/mile is observed. This yields an average theoretical range of 53 miles (85 km) for this vehicle - a reduction of 25% in range when compared to the 114 km the vehicle achieved during laboratory Range testing to ECE R101.

When looking at individual driver behaviour, the most efficient driver averaged 1.5% SoC/mile and the least efficient 2.8% SoC per mile. This gives a theoretical range of 35 to 67 miles (56 to 107 km) for this vehicle, or 52% range variation between drivers.

3.2 EV Track Cycle Energy Use

The six drivers selected for the study were instructed to drive using their standard driving style. Figure 4 below presents the energy consumed over the cycle by driver and circuit section. It shows that the energy consumed for different drivers varied considerable for the same cycle and is significantly influenced by the circuit type.
The variation between individual drivers in each circuit demonstrates the effect driving style has on energy consumption showing a maximum differential of 91% in energy consumed between the best and worst drivers over the high speed circuit, which is reduced to 19% on the hill circuit. The ranking of driver efficiency is generally consistent over each circuit.

From a closer look at the data points the following comments characterise the variation in drive efficiency for each circuit:

1. High speed circuit: positive accelerations are at full throttle and consistent between drivers, but significant drive efficiency variation is seen from the range of decelerations applied.
2. City course: variation mostly exists in the drivers’ point of deceleration and acceleration from corners, braking events and reactions to posted speed limits.
3. Hill route: the gradients required full throttle for all ascents and coasting was generally applied for descents. This resulted in more consistent driving styles and energy consumption.
4. Handling circuit: the smooth and progressive nature of this circuit also resulted in more consistent driving styles. The majority of variation occurred in drivers choosing whether or not to achieve the maximum allowed speed during the different circuit sections and how long to maintain the maximum speed between corners.

### 3.3 Energy Efficiency Calculations

To assess the effect of different driving styles and circuits on regeneration and motoring performance a method to determine vehicle energy efficiency was established. Energy was recorded from the electric drive motor output terminals of the vehicle measuring the power flows achieved during both motoring and generating. This means efficiency losses in power electronics, energy conversion from charge supply and vehicle hotel loads, which are not the focus of this study, are excluded. A vehicle road load model (sum of rolling resistance, frictional and aerodynamic forces) was then applied to determine the theoretical maximum energy required to provide vehicle motion, or available from braking by regeneration.

When energy flow is positive (+ve), the energy transfer efficiency represents the proportion of power that is actually being supplied by the motor relative to the theoretical amount of kinetic energy required to power the vehicle.

When energy flow is negative (-ve), the energy transfer efficiency represents the proportion of energy actually transferred to electrical energy by the motor (acting as a generator during regeneration) relative to the theoretical maximum amount of energy that is recoverable from a braking event.

This efficiency analysis was applied to the HSC, City and HC circuit, where the effects of gradient would not require further calculation due to the flat construction of these circuits. Figure 5 below summarises the calculated efficiency of motoring power (+ve) and regeneration power (-ve) for each circuit and the standard deviation as a percentage of the mean for the energy data in each drive event.
From the data above it is shown that there is comparatively little variation in the efficiency of positive energy transfer between the drivers and circuits, whereas the negative energy, or regenerated energy, is highly influenced by driver and circuit. These attributes are further examined in Figures 6 and 7 below which detail a HSC drive trace for the least and most efficient drivers respectively plotting motor power, speed and calculated road power.

Figure 5: Energy transfer efficiencies

Figure 6: Speed and energy trace of least efficient driver

Figure 7: Speed and energy trace of most efficient driver
The speed and energy traces above shows that the least efficient driver uses full throttle acceleration and brakes harshly throughout the high speed circuit, whereas the most efficient driver has much gentler rates of acceleration and deceleration. Despite the behavioural differences in acceleration the motoring (positive) efficiency only differs by 4% between drivers, that is 80% and 84% respectively. During the deceleration phase the most efficient driver used no friction braking and achieves a calculated regenerative energy capture efficiency of 93% compared to only 15% for the most aggressive driver. Similar characteristics were also found in the City and HC circuit analysis albeit to a lesser magnitude but more frequent due to the higher instances of start / stop activity. Overall the average efficiency of motoring was 79% compared to 41% for regeneration.

3.4 EV Track Cycle Regeneration Rates

The data discussed in section 3.3 above can be displayed as the amount of drive cycle energy regenerated as a percentage of energy consumed [-ve/+ve] during a journey. The variation in regeneration performance by driver and circuit is displayed below in Figure 8.

The following comments characterise the variation in regeneration performance for each circuit. It is worth noting that driver 3 teaches on the eco driving course at Millbrook proving ground and clearly integrates these practices into his normal driving style.

1. High speed circuit: Significant energy is available for regeneration due to high speed decelerations; there is a large variation in regeneration performance due to the different blends of friction braking applied between the drivers.

2. City course: The low speed stop/start course allows for little variation in energy regenerated from popular driving styles. However, driver 3 recaptures 87% more energy than the average of the other drivers suggesting specific eco driver training would significantly increase energy capture.

3. Handling circuit: Little variation in performance shows that the naturally more progressive and uninterrupted nature of UK B roads limits the amount of variation in regeneration available throughout the range of driving styles applied.

3.5 Journey Efficiency and Regeneration

Figure 9 shows the average journey efficiency (in km/kWh) plotted against the average power regenerated (expressed as a percentage of power consumed) for each circuit. This demonstrates the improvements available through maximising the amount of regenerative energy capture when a deceleration event is required.
From the most efficient to the least efficient driver the improvements in journey efficiency for the City, HC, and HSC equate to an improvement of 47%, 13% and 90% respectively, which corresponds to an increase in range of 40 km, 11 km and 77 km when calculated from the average range established during driver selection tests. Clearly in the case of the HSC repeated acceleration and deceleration cannot be extrapolated to represent a real-world driving scenario, hence neither can the 77 km range improvement, but this does however effectively demonstrate the amount of energy wasted in isolated over-aggressive braking events.

3.6 Diesel Efficiency Comparison

To benchmark the results for the smart EV drive efficiency analysis, a diesel smart Cdi was tested over the EV track cycle and energy efficiency calculations were applied using the same methodology as section 3.3, albeit with a CAN based fuel logger used to give real time fuel consumption during the tests and the input (motor) energy derived from the amount of diesel fuel used. Figure 10 below shows energy efficiency obtained from test drivers over the EV track circuits. For this conventional vehicle no energy is recaptured under braking, therefore the negative (deceleration) phases yield an efficiency of zero.

The chart shows a consistent pattern for the two vehicle drive technologies with clear groupings corresponding to the different track circuits. Overall road energy for the diesel is slightly lower than that of the EV primarily due to the lower weight of the diesel vehicle. During positive energy transfers the efficiency is higher for the EV, and the variation lower, for the EV at 70% to 90% compared to 5% to 33% for the diesel. It should be noted that the EV energy input was measured at the electric drive motor terminals and therefore losses in the charge process and battery to motor transmission are not included. Both drive technologies are at their least efficient operating point during low speed stop start operation simulated on the City circuit.
4. Real World Performance Evaluation

The track based experimentation section of this paper evaluates the impact of driver behaviour and vehicle duty on the efficiency of energy transfer in an EV. The subsequent sections of this paper present data captured from the same model smart EV as used for the track analysis during real world vehicle use. Here, the total variation in range and drive efficiency is assessed and also displayed in terms of its impact on CO\textsubscript{2} emissions associated with EVs. Other issues such as the effect that range anxiety has on driver behaviour, which are not practically studied in a controlled track environment, are also analysed. Comparison is drawn between regeneration performance observed under real world conditions and that achieved during track testing.

The real world data used was collected during the deployment of four electric smart vehicles into public and private sector fleets in the North East of England as part of the UK government funded Smart Move trial [1]. Vehicle data was logged and analysed using telemetry reporting systems developed by Newcastle University’ Transport Operations and Research Group.

4.1 Real World Range and CO\textsubscript{2} Performance

The extrapolated range and emissions logged during the Smart Move trial are detailed in Figure 11 below. The emissions are determined from UK electricity factors provided by the Department for Environment, Food and Rural Affairs [2].

The extrapolated average range of the vehicle obtained during the Smart Move trial was 72.4 km, with emissions of 81.4 g CO\textsubscript{2} / km for UK grid mix electricity, which reduces to 45 g CO\textsubscript{2} / km if using combined heat and power electricity or 0g CO\textsubscript{2} / km for renewable energy tariffs,. The emission factors used were 544.2, 301.1 and 0 g CO\textsubscript{2} emitted per kWh of electricity respectively.

![Extrapolated range and CO\textsubscript{2}](image)

Figure 11: Range and CO\textsubscript{2} during the smart move trial

As shown above, the range and therefore the CO\textsubscript{2} emissions of the vehicles varied significantly during the Smart Move trial which can be accounted for through a number of factors including hotel loads (parasitic energy demands on a vehicle not directly contributing to distance), driving style, terrain, acceleration/deceleration rates and journey speed.

4.2 Real World Regenerative Braking Analysis

Figure 12 below shows the power and battery SoC behaviour from a typical 25 minute journey during the Smart Move trial. When the vehicle is motoring the energy value is positive and while the vehicle is in a state of regeneration the energy value is negative. The chart demonstrates the frequent stop start regeneration events available in inner city traffic during the first ten minutes and then higher power regeneration events which occur during higher speed coast down and braking. Note also the increased depletion rate of SoC during the higher speed events.
The journey detailed above consumed 2.13 kWh while motoring and regenerated 0.21 kWh, giving a regeneration rate of 9% for the trip. The average regeneration achieved in all the logged journeys over the trial period was 11.3%, with values ranging from 3 to 29% depending on journey conditions. This compares to the average regeneration rate of 16% during the track testing designed to simulate real world drive scenarios. Obviously the Smart Move trial and test track duties differed, also the real world trial measured power at the battery terminals, therefore incurring motor, power conversion and hotel load losses. It is also relevant to comment that the average regeneration rates achieved on the test track could be reduced in real world driving since the external effects of traffic flow and management reduce the ability of a driver to maximise regeneration due to the unpredictability of vehicle traffic.

4.3 Journey Efficiency and Regeneration

This study has shown that driving techniques can be optimised to significantly increase the power regenerated during deceleration. The relationship between journey efficiency and power regeneration examined during the track testing showed that journeys with an increased percentage of regenerated energy were more efficient. Figure 13 below shows the inverse of this is true when a number of real-world random and unique journey patterns were analysed in the Smart Move trial.

The chart above demonstrates why the effect of driving style is best assessed under track conditions. The less repeatable nature of real world journeys and routes coupled with variation from interactions from other traffic and traffic management controls does not allow a focused analysis on the potential efficiency improvement available through modification of driving style under test track conditions. Braking is obviously an essential part of driving, but an opportunity to increase range exists through modification of driving style to reduce wasted energy. This can be achieved primarily through more progressive and predictive driving reducing which reduces excessive acceleration and any unnecessary braking and secondly through educating users of the most effective ways of maximising regeneration rates through driving style.

4.4 Range Anxiety

A contributor to the perceived available range of electric vehicles is the range anxiety which affects users when considering the suitability of using an EV for a potential journey. The extrapolated average range during the Smart Move trial was 72.4 km. This assumes that the battery is used to capacity during a journey. In reality, and depending on a
driver’s perception a personal level of comfort will exist in the degree a user is willing to discharge the vehicle battery during a journey. Range anxiety is particularly relevant at present as public recharging infrastructure volumes are low.

Figure 14 below shows the battery state of charge at the beginning of the journeys. Only 7% of journeys were undertaken when the battery was showing less than 50% state of charge.

![Figure 14: Battery state of charge at the start of Smart Move trial journeys](image)

Range anxiety can be further demonstrated through Figure 15 below. This shows that there is a relationship between journey efficiency and the state of charge of the battery at the end of the journey. The trend suggests that users begin to modify their driving style as the vehicle state of charge reduces to less than 50%.

![Figure 15: Relationship between journey efficiency and end SoC](image)

In considering the implications of this finding, it is important that to remember Smart Move consisted of a large number of short duration drive events with different users, intended to maximise the exposure of fleets and the public to EVs. Ongoing trials in the UK such as the Ultra Low Carbon Vehicle Demonstrator will allow users to become familiar with their EVs over longer periods, which is likely to have a marked effect on the issue of range anxiety.

5. Conclusion

This study found that when the smart EV was used by a pool of 25 regular drivers at Millbrook Proving ground, an average range of 56 to 107 km between drivers was achieved. Six test drivers, representing the most to the least efficient drivers in the group were selected to take part in a more detailed study, covering test track sections designed to represent real world driving scenarios.

The journey efficiencies over the EV track cycle varied significantly by driver and the largest variations were noted on tracks with the highest opportunities for regenerative energy capture. Through developing a method to calculate the theoretical maximum amount of vehicle energy available for regeneration and to provide motive power, the variation in both regeneration energy efficiency and motoring efficiency was determined. On average the efficiency of providing the vehicle with motive power was 79% and under deceleration events 41% of available energy was captured. The range in motoring efficiency was 67 to 85% whereas the range in regeneration energy efficiency was 15 to 93%. The study highlighted the advantages of driver training for regular EV users as driver 3, who teaches eco driving at Millbrook,
achieved an average of 87% more energy regeneration than the other drivers over the City driving circuit. Further analysis showed that the most efficient journeys (measured in km/kWh) were also those that maximised regeneration.

A diesel smart comparator vehicle was driven over the EV test cycle and the results highlight the clear efficiency advantages available in an electric drive train. During positive energy transfers the calculated efficiency is higher and variation narrower for the EV at 70% to 90% (excluding energy storage and electrical conversion losses) compared to 5% to 33% for the diesel. Both drive technologies were shown to operate least efficiently during low speed stop start operation simulated on the City circuit.

Regeneration performance studies also qualified the amount of energy regenerated as a percentage of energy consumed [-ve/+ve]. Averaged regeneration rates of 16% were seen during the test track studies compared to 11.3% in a series of fleet trials in the North East of England. This reduction in regenerated drive energy may reflect the less predictable scenarios of public roads where traffic flow and management reduce the degree of predictable and progressive driving achievable.

The average extrapolated range from the Smart Move trial was 72.4 km, with emissions of 81.4 g CO₂ / km for UK grid mix electricity, which reduces to 45 g CO₂ / km if using CHP electricity or 0g CO₂ / km for renewable energy tariffs.

Finally, when studying range anxiety issues from the Smart Move trial data it was observed that only 7% of users undertook journeys when the range was below 50%. In addition, drive efficiency improved when the SoC reduced to 50% suggesting that users begin to modify their driving style as the vehicle state of charge reduces to below a perceived comfortable level.

6. References


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