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Electric drive vehicle deployment in the UK

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Abstract

The UK stands ready to examine the electrification of road transport. Following a growth in UK petrol-electric vehicles, and strong policy signals supporting decarbonised road transport through electrification, Cenex the UK's first Centre of excellence for low carbon and fuel cell technologies, has examined the deployment of electric drive vehicles in conjunction with the University of Sheffield.

This paper presents analysis of an electric vehicle deployment focusing on the smart ed, including laboratory and in use road and user perception analysis. The study found consistent range performance across laboratory drive cycles, but differing real world performance, where range and duty alter significantly. The high impact of 'hotel' loads is shown and equivalent CO_2 emissions and fuel costs are calculated, showing that good environmental and cost performance is linked to high rates of utilisation. The user perception study highlights strong and weak areas of the vehicle performance compared to a conventional vehicle, and finally limited data from the Mitsubishi i MiEV is included as a comparator vehicle where equivalent CO_2 emissions and fuel costs were found to be below conventionally powered vehicles.

Keywords: ZEV (zero emission vehicle), EV (electric vehicle), vehicle performance

1 UK electric drive

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. 11% of new vehicles now sold in the UK have CO_2 emissions below 120g/km [1]. But the vast majority of these vehicles are petrol and diesel powered and the use of electric drive in the UK has played a small part in this shift. Figure 1 illustrates the growth in 'Alternatively Fuelled Vehicle' registrations in the past nine years and clearly demonstrates sharp growth in petrol electric hybrid car sales. However, these registrations are still limited against the 2008 new petrol and diesel registrations of 1,187,360 and 928,605 respectively. [1]

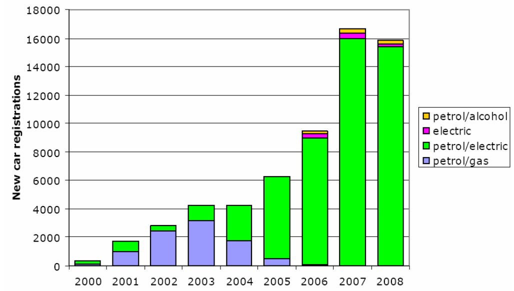

Figure 1 - UK new alternatively fuelled vehicle registrations [1]

Figure 1 also shows the very low level of pure electric drive (ed) vehicles registered in the UK each year, with only 179 such vehicles sold in 2008. However, recent UK policy analysis has highlighted electric drive as a potential technology capable of decarbonising road transport.[2]

Building on the Stern [3] report, commissioned by the UK government in 2005, which examined the economics of climate change, the 2007 King [4] review looked specifically at low carbon cars. In examining the role of road transport in the UK, which currently accounts for approximately 22 per cent of the UK CO_2 emissions, the King report commented that a 60-80% reduction in CO_2 per kilometre 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.

To promote this shift to electric drive transport, the review recommended: '*Bringing existing low emission technologies from "the shelf to the showroom" as quickly as possible*' and '*ensuring a market for these low emission vehicles*'. [4]

Cenex, the UK's first centre of excellence for low carbon and fuel cell vehicles, is at the forefront in deploying low carbon vehicles and will play a vital role in the electrification of UK road transport. As part of this remit, Cenex has supported and participated in the deployment of the first 100 smart ed vehicles, and plays an active role in the assessment of new electric vehicle technology.

2 The smart ed

Developed by Daimler and Zytek, the 2008 smart ed is a pure electric drive two seater passenger car. These vehicles are at a pre-commercialisation stage where 100 have been built for a UK wide trial. The electric drive train is fitted by Zytek into a 'glider' vehicle from Daimler, where the internal combustion engine would have been and accommodation is made for the high voltage battery, in the area previously housing the gasoline tank.

The smart electric drive 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 20kW to preserve battery capacity. Delivering approximately 300V, with a high gravimetric energy density (~120Wh/kg) the Zebra battery does not suffer from battery memory issues and is well suited to electric drive operations [5]. However, the Zebra battery operates at high temperatures (270-350 degrees C) with cell chains being interconnected and packaged within a sealed, vacuum insulated, air-cooled modular casing. Despite this insulation the battery requires a portion of the operational energy to maintain temperature, or draws a continual current when plugged in. The Zebra pulse power capability is appropriate for typical electric vehicles acceleration profiles, at around 1.5 the rated energy (170W/kg), and offer significantly increased cycle life ≈3500 nameplate cycles when compared to lead-acid batteries. The electric machine is sized to provide sufficient acceleration through a standard smart gearbox (fixed in 2nd gear), and acts as a generator when the vehicle is on coast down or under braking, to give a 'regenerative' braking functionality.

3 smart ed laboratory range testing

Full range testing was completed in accordance to ECE regulation 101[6] procedures on the smart ed over the prescribed NEDC cycle, the Artemis Urban and the Artemis Road cycles as shown in Figure 2 Figure 3 & Figure 4. The Artemis Urban and Road Cycles were developed within a European funded 5th framework project coordinated by TRL Ltd. in the UK. The R101 test gave 114 km range. Over the Artemis Urban cycle the vehicle achieved 114.68 km, and over the Artemis Road cycle the vehicle achieved 105.66 km. It should be noted that all cycles showed approximately linear state of charge (SOC) decline against time.

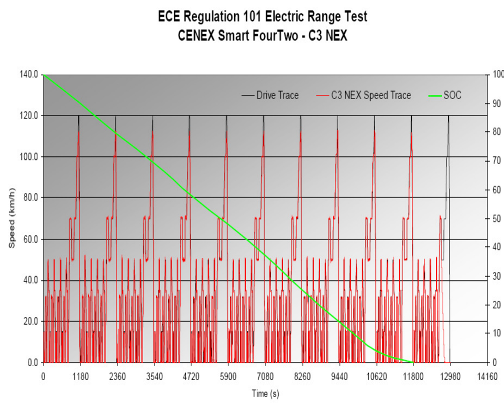

Figure 2 - Regulation 101 electric range test

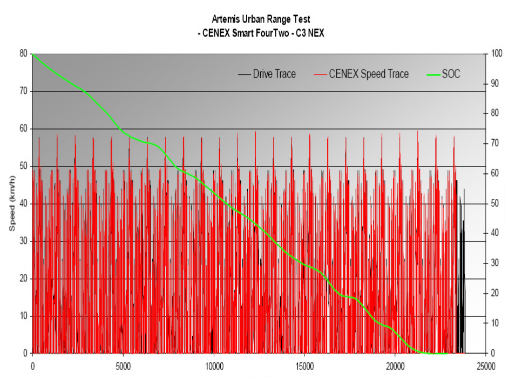

Figure 3 - Artemis urban range test

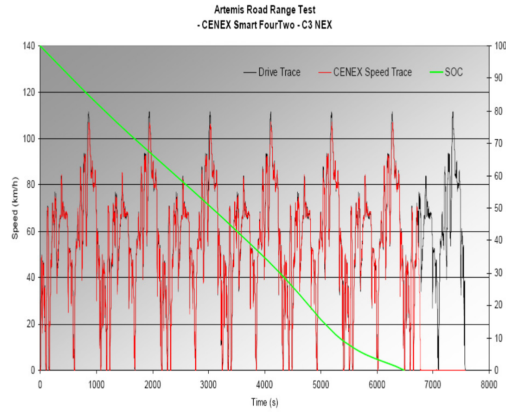

Figure 4 - Artemis road range test

4 smart ed laboratory energy consumption testing

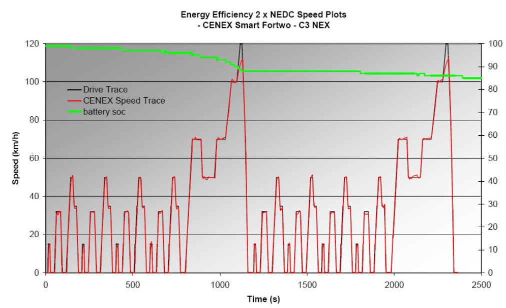

Figure 5 – NEDC cycle

Following the defined R101 test procedure, the vehicle achieved an energy consumption rating of 0.29 kWh/km. On completion of the two consecutive NEDC cycles the vehicle took just under 1.5 hours to achieve its full state of charge. During this period the vehicle consumed a charge energy of 2.89 kWh and hence would have achieved 0.14 kWh/km energy efficiency. The difference between this and the official figure after 24 hours is that the vehicle consumed a further 3.38 kWh of electricity in the remaining 22.5 hours to keep the batteries balanced and at the correct temperature. This represents approximately 150W of continuous power draw.

5 Operational characteristics

Operational deployment analysis of the smart ed has been collected by Cenex over a period of six months (October 08 - March 09). The vehicle covered approximately 2000 miles, with five regular drivers, and 27 additional appraisal drivers. The vehicles have been mainly used for short commutes and data was logged both driving and charging. The following sections present the salient points from the study.

5.1 Charge/discharge characteristics

The recharging of domestic electric vehicles in the UK is limited by supply constraints (3kW, 230Vrms in the UK). The high temperature nature of the Zebra battery leads to a specific charge behaviour, where a fully discharged battery will require internal pre-heating prior to charge. Figure 6 documents a 13 hour charge with approx. four hours pre-heating prior to significant charge being taken on-board as available SOC.

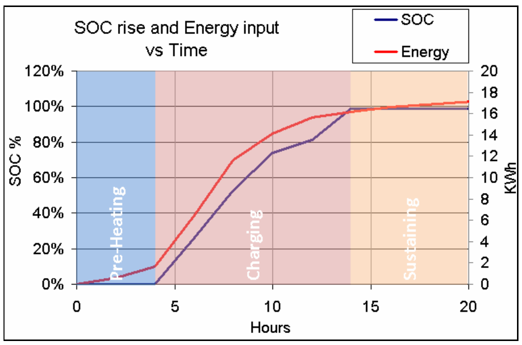

Figure 6 - Charging characteristics

However, when using the vehicle on a regular daily basis such 'pre-heating' is not necessary, and typical full-charge times are in the region of eight hours. Zebra battery modules are essentially maintenance free units with zero self-discharge i.e. Ah charge in = Ah discharge out. However, the high operating temperatures can lead to charge decay as a consequence of maintaining the battery's internal temperature within operational bounds. Figure 7 shows the required energy input to maintain 100% SOC over ~ seven hour period.

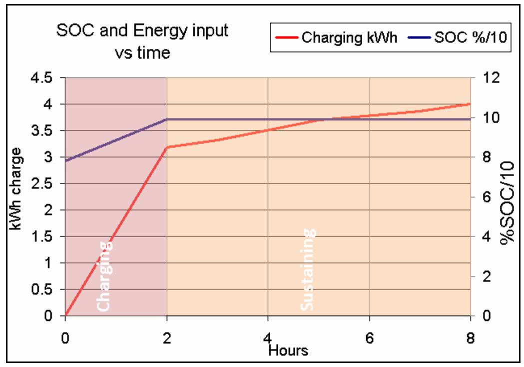

Figure 7 - Charging characteristics maintaining SOC

Over time, it is found that a mean power requirement of ~133W is necessary for sustaining SOC. If power is not available from an external source (i.e. through normal charging) the battery module must use its stored energy for sustaining the internal temperature, with a consequential accumulative reduction in user-available SOC which is shown in Figure 8.

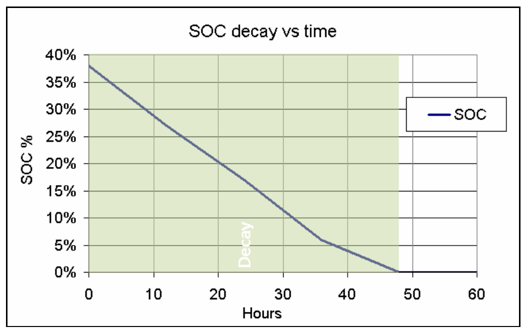

Figure 8 - Charge decay

5.2 Power delivery and regeneration

Examining a typical logged trip, we can detail the instantaneous power supplied from and regenerated to the battery, as detailed in Figure 9. In this instance, whilst the peak power demand regularly reaches ~20kW the overall mean supplied power over the full duty is only 5.6kW, of which ~6.6kW is mean motoring power and ~1kW is the mean regeneration power back into the battery (i.e. ~13%).

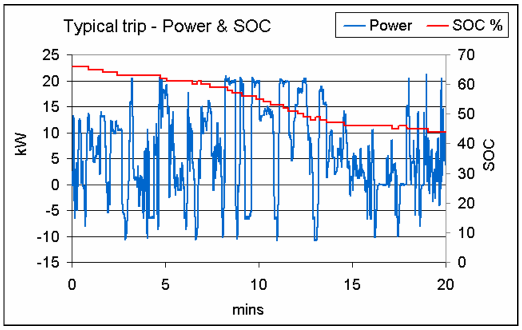

Figure 9 - Power and regeneration characteristics

5.3 Range analysis

Examining individual driving cycles provides a 'snap-shot' of vehicle behaviour. To examine vehicle characteristics, analysis has been undertaken across multiple trips and differing duty cycles. Figure 10 shows (SOC vs. distance travelled) results from 12 different driving cycles, starting at various initial battery %SOC, for a variety of journey distances. The figure shows that the gradient of SOC decline is consistent across trips and distance, mirroring the laboratory range test performance. This indicates that the %SOC consumed per unit distance travelled is effectively constant (over non-trivial journey distances) and the rate of %SOC usage is not significantly affected by the initial %SOC of the battery. We therefore have the ability to predict range for this user on 'non-trivial duties' with some confidence.

Whilst SOC decline is predicable on long trips, reducing the distance base to single miles alters the picture. Figure 11 shows a scatter diagram of the incremental distance travelled (miles) per 1% reduction in SOC, plotted against the absolute battery %SOC that the reading was taken at, for the same 12 trips presented in Figure 10. From the results it is evident that over short distances significant differences in %SOC usage occur.

From, Figure 11 the standard deviation of the data is 0.16 about the 0.48 mean, which highlights an issue for current EVs in general. Specifically, by comparison with traditional ICE vehicles that have relatively long absolute ranges (typically between 300-900miles), the relatively low average range of current EVs means that, to promote user confidence, greater precision is required for estimating the remaining vehicle range. For example, whilst it is acceptable to estimate the range of a typical vehicle to perhaps ±16miles on long journeys from an expected mean of 300miles, when the mean vehicle range is 50miles similar error bars are 'less comfortable'. In this particular case, however, for non-trivial duties the battery technology provides consistent behaviour and good estimates of remaining range are readily obtained.

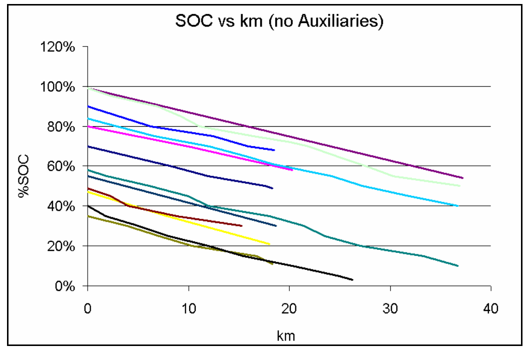

Figure 10 - 12 duty cycles SOC vs. distance travelled

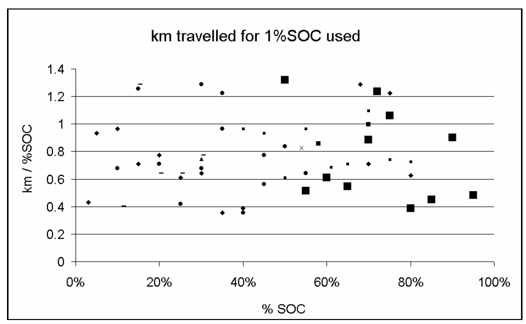

Figure 11 - 12 duty cycles miles travelled for 1% incremental SOC used vs. absolute %SOC

Figure 12 shows variation of extrapolated average range by driver for three sample drivers, and Figure 13 shows variation of extrapolated average range by duty type. With a variation of between 61 and 73km across the three drivers, using the vehicle in similar conditions, the spread remains well within the range variability discussed above, yet demonstrates a clear impact from driving style, meriting further analysis. The laboratory range tests presented in section 3 indicated higher range capability on urban cycles compared to road cycles, which contrasts to this real world data. Such a variation is likely to be due to the limited acceleration and decelerations rates of the test cycle, or due to real world mixed and rural operation at lower top speeds than those required by the road test cycle. Users may choose to avoid high speed operation and routes to ensure range capability.

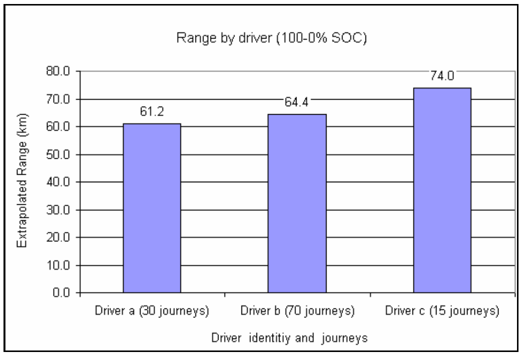

Figure 12 – Extrapolated range by driver

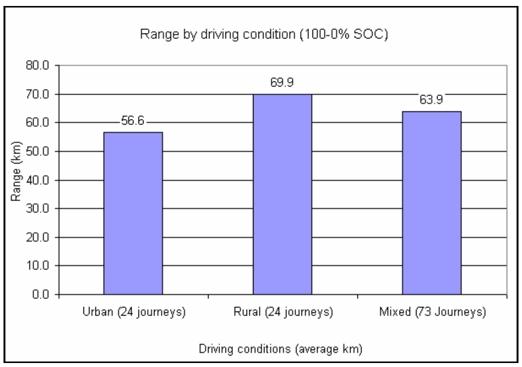

Figure 13 – Extrapolated range by driving conditions

5.4 Hotel loads

An advantage of EVs for urban journeys is a reduction of idling losses and emissions associated with congested traffic which can constitute a large proportion of journey time. Nevertheless, the servicing of auxiliary- and hotel-loads can pose a significant drain on energy which can be largely independent of driving conditions, and more depending on operation time. Whilst 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-con units will pose the largest energy drain.

For the smart ed the Cenex trial examined the charge depletion associated to cabin heating, finding that the heater uses ~1%SOC for every 3min of operating time, regardless of initial SOC. This rate of %SOC depletion is found to be relatively constant regardless of driving duty as shown in Figure 14.

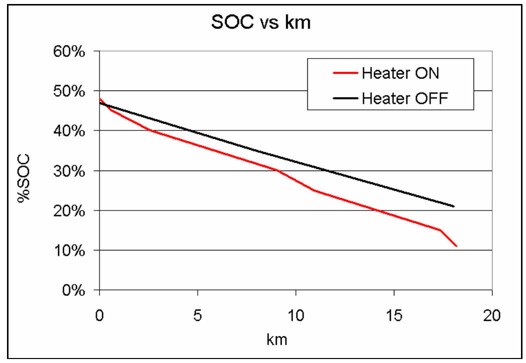

Figure 14 - Impact of vehicle heating on battery SOC with and without heater turned-on over the same commuter journey

Therefore, 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, HEVs and pure ICEs will remain essentially similar i.e. independent of drive-train technology. Whilst 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.

5.5 Equivalent CO_2 & cost analysis

The calculation of equivalent CO_2 and cost for the smart ed is more complex than other EVs due to the chosen battery chemistry. The constant power draw, required to maintain battery operational temperature, means that CO_2 and cost calculations are a function of charge energy and energy consumed to maintain the battery operating conditions. Throughout the Cenex trial, driving and charging data has been collected and so such an analysis is possible. Figure 15 presents equivalent CO_2 emissions for the smart ed plotted against kilometres travelled per hour on charge. The CO_2 equivalents are derived from the current 'rolling average' UK grid mix carbon intensity (0.537kg/kWh)[7] and the projected carbon intensity for 2019 (0.433kg/kWh)[8] based on expected technology roll out in the UK generating sector. So, if the UK is targeting emission figures of <100gCO_2eq/km it is clear that high utilisation rates are required, greater than 4km per charge hour for today's grid mix. To give a specific example, an overnight charge of 12 hours requires daily mileage of 48km to achieve <100gCO_2eq/km.

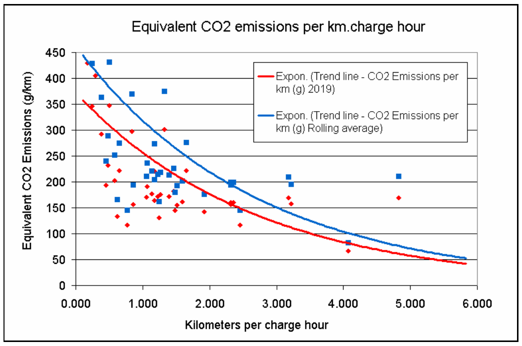

Figure 15 - Emissions per km.charge hour

Table 1 Translates the measured kWh consumption figures for the smart ed trial to UK Pounds cost (£). Based on the UK 2008 average domestic electricity rate of 11.4 pence per kWh, the minimum and maximum £/km costs within the trial are seen to be 1.8 pence and 25.9 pence. Typical UK petrol and diesel fuel costs in April 2009 are 7-8 pence per km. Thus, as with CO_2 emissions the smart ed can deliver significant operational cost savings provided that utilisation rates remain high. Increased running costs compared to petrol and diesel will occur with low utilisation.

Table 1 - smart ed emissions and cost per km

smart ed trial equivalent CO2 and cost					
	kwh/km	Rolling average emissions (g/km)	2019 emissions (g/km)	Charging time (hours)	Cost per km (£)
Min	0.15	82.544	66.555	2.50	0.018
Max	2.27	430.458	347.079	92.10	0.259

6 Comparator vehicle - Mitsubishi i MiEV

The Mitsubishi MiEV is a five door, four seat all electric vehicle powered by a 47kW permanent magnet synchronous motor. Electricity is stored in a 16kWh Lithium-ion battery pack.

The data presented here on the i MiEV has been collected by Cenex over a period of one month (March 09), approximately 500 miles, 40 trips and eight drivers. The vehicles have been mainly used for demonstration and commuting activities and data was collected both driving and charging.

6.1 Equivalent CO_2 & cost analysis

The calculation of equivalent CO_2 for the i MiEV is simpler that the smart ed. The Li-Ion battery pack does not operate at an elevated temperature like the Zebra unit used in the smart. Thus energy is not consumed in maintaining battery operational temperature, and short term charge decay is not an issue. Therefore, CO_2 and cost calculations are a simple function of charge energy used. Figure 16 presents equivalent CO_2 emissions for the i MiEV plotted against kilometres travelled. The CO_2 equivalents are derived from the current 'rolling average' UK grid mix carbon intensity (0.537kg/kWh) [7] and the projected carbon intensity for 2019 (0.433kg/kWh) [8] based on expected technology role out in the UK generating sector.

The average carbon intensity for using the rolling average for the i MiEV is 115gCO_2eq/km and with the 2019 carbon intensity this reduces to 92gCO_2eq/km. It should be noted that a significant spread of results was recorded. It is likely that the lack of definition in measuring SOC has led to the variation shown for short trip lengths. But, for longer trips, considering similar driving conditions were encountered, driving style has had a considerable impact. Nevertheless, the i MiEV delivers low gCO_2eq/km performance for the majority of journeys and the low temperature battery operation removes the high utilisation need found in the case of the smart ed.

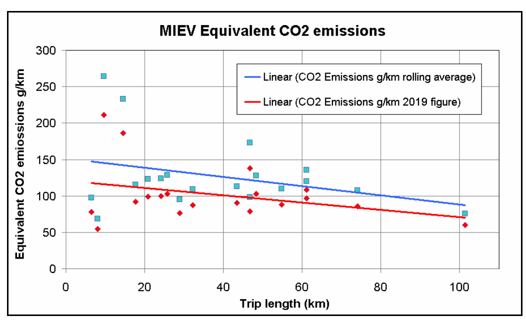

Figure 16 – i MiEV CO2 emissions by trip length

Table 1 Translates the measured kWh consumption figures for the MiEV to UK Pounds cost (£). Based on the UK 2008 average domestic electricity rate of 11.4 pence per kWh, the minimum and maximum £/km costs within the trial are seen to be 1.5 pence and 5.6 pence, where typical UK petrol and diesel fuel costs are 7-8 pence per km (April 2009 prices). Thus the i MiEV in all cases is more cost efficient than a standard petrol or diesel vehicle.

Table 2 – i MiEV emissions and costs per km

MIEV trial equivalent CO2 and cost					
	kwh/km	Rolling average Emissions (g/km)	2019 Emissions (g/km)	Charging time (hours)	Cost per km (£)
Min	0.13	68.57	55.29	1.72	0.015
Max	0.49	264.17	213.00	124.88	0.056

7 User perception

All trial EV drivers completed a user assessment form, which assessed the drivers experience against a variety of criteria. Ratings from 1 to 10 were assigned to each criterion where 1 is considered very poor, 7 satisfactory and 10 excellent. In such an assessment OEM volume products should aim for minimum scores of 7. The results of the smart ed user assessment are shown in Figure 17 below.

The assessments revealed similar themes. Acceleration performance from 0 to 50 km/h exceeded expectations with a superior performance when compared with the smart fortwo petrol model. But, reduced gradient performance was particularly noticeable in the EV. The smart ed is limited to a maximum speed of 95km/h. Some users lacked confidence with the speed restriction which leads to a perceived vulnerability. However, high speed performance is of limited concern as the reduced range at such speeds encourages users towards urban operation, where most trial users agreed the vehicle performed best. The general consensus was that the suspension was too harsh and although the brake performance was good, the braking feel at low rates was unsteady. This may have been due to the interaction between motor regeneration function and the friction brake take over point which are both controlled through the standard brake pedal.

The large analogue SOC display which gave battery feedback from 0 to 100% was generally praised. The majority of users' attitude towards electric vehicles was enhanced because of their experience in the smart ed.

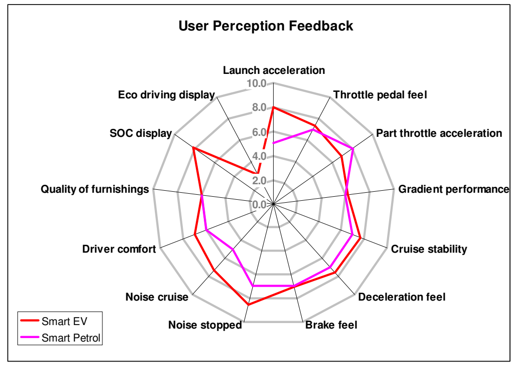

Figure 17 - User perception chart of smart ed vs. petrol model

8 Conclusions

This collaborative paper between Cenex and the University of Sheffield has examined the deployment of electric vehicles, focusing mainly on the smart ed. The study has collected data from a number of differing sources and includes laboratory and road duties whilst examining the reality of an EV deployment.

The study has shown that the UK has experienced a growth in 'Alternatively Fuelled Vehicle' registrations in the past nine years but this growth has been in petrol electric hybrid sales, and the potential of pure electric vehicles is yet to be exploited. Recent UK policy analysis has highlighted electric drive as a potential technology capable of decarbonising road transport, supported by an increasingly 'decarbonised' electricity generating sector.

Laboratory range and energy efficiency tests showed a consistent range performance over the Artimis and R101 cycles of 105-114 km, and an R101 energy consumption rating of 0.29 kWh/km. On the two consecutive NEDC cycles the vehicle achieved 0.14 kWh/km energy efficiency. Due to the high temperature battery chemistry, and hence ongoing power requirement, if the subsequent 24 hour charge period is taken into account the efficiency performance is significantly reduced.

Considering the operational range of the smart ed, for a single user across multiple trips the SOC vs. mileage was seen to be consistent, affording the ability to predict range with some confidence. Through shortening the distance base of the journey, the analysis showed large km by km variations demonstrating the importance of a correct distance base on range predictions.

Looking at the user studies, range variations between drivers were observed, and all drivers experienced a lower range than seen on test cycles. Some reduction would be expected as the test cycles ran to below 0% SOC, but the reductions are significant which suggests that drivers' acceleration and deceleration rates are significantly higher than those of the test cycles. The user analysis showed reduced energy consumption in rural conditions, and greater energy consumption in urban conditions when compared with test cycle data. This result differs from expectation. Further analysis is required, but one possible explanation lies in increased acceleration and deceleration rates in urban conditions, or due to real world mixed and rural operation at lower top speeds and users choosing to avoid high speed operation and routes to ensure range capability.

The study found that the charge depletion associated to cabin heating was ~1% SOC for every 3 min of operating time, regardless of initial SOC.

The real life vehicle trials showed that CO_2 emissions and running cost for the smart ed are highly dependent on utilisation. High rates of utilisation are essential to get the best from the vehicle. When targeting emission figures of <100gCO_2eq/km greater than 4km per charge hour for today's grid mix is required. So, an overnight charge of 12 hours requires daily mileage of 48km to achieve <100gCO_2eq/km. When examining cost based on the UK 2008 average domestic electricity rate of 11.4 pence per kWh, the minimum and maximum £/km within the trial are seen to be 1.8 pence and 25.9 pence. Typical UK petrol and diesel fuel costs in April 2009 are 7-8 pence per km. Thus, as with CO_2 emissions the smart ed can deliver good significant operational cost savings provided that utilisation rates remain high.

A second vehicle the Mitsubishi i MiEV was also assessed albeit with a limited data set. The average carbon intensity for the i MiEV using today's UK rolling average grid mix was 115gCO_2eq/km, with the projected 2019 grid carbon intensity this reduces to 92gCO_2eq/km. Examining cost based on the UK 2008 average domestic electricity rate of 11.4 pence per kWh, the minimum and maximum £/km costs within the trial are seen to be 1.5 pence and 5.6 pence. Thus the i MiEV is in all cases more cost efficient than a standard petrol or diesel vehicle. In addition, due to low temperature battery operation need for high utilisation seen for the smart ed is removed.

Finally trial smart ed drivers completed a user assessment form, which assessed the drivers experience against a variety of criteria. The assessments revealed similar themes. Low speed acceleration performance and noise performance exceeded expectations, with a superior performance when compared with the smart fortwo petrol model. But, reduced gradient performance, higher speed performance and braking feel were all marked down. The majority of users' attitude towards electric vehicles was enhanced because of their experience in the smart ed.

Acknowledgments

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2 Catherine Perrin, Product Manager – Electric Vehicles, Mitsubishi Motors UK

3 Neil Cheeseman, Project Manager – Low Carbon Technology, Zytek

References

1 SMMT CO2 report 2009

2 BERR & DFT electrification report http://www.berr.gov.uk/files/file48653.pdf

3 Stern 2005

4 King 2007

5 T.M. O'Sullivan et al, Zebra battery technologies for the all electric smart car, 2006.

6 For R101 details see - http://www.unece.org/trans/main/wp29/wp29regs/r101r2e.pdf

7 Defra 2008 GHG emission factors, http://www.defra.gov.uk/environment/business/reporting/conversion-factors.htm

8 Market Transformation Programme, Report BNXS01: Carbon Dioxide Emission Factors for UK Energy Use

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