# How does the use of a continuously updating database allow for the analysis of a user's changing behaviour in electric vehicles?

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**Abstract** Environmental considerations mean that continuing to use internal combustion is, in the long term, unviable due to availability and cost of the fuel and the environmental effects of their emissions. If full Electric Vehicles (EV) are to be a more sustainable method of transport then some of the perceived problems of EVs must be addressed, such as "range anxiety" and "technical performance". To do this it is necessary to understand how drivers behave in EVs, both through their overall trip statistics and their driving behavior within trips. This has been achieved in this project through instrumenting the EVs with a direct link to the vehicle's CAN bus, a GPS system and a networked link to an always on database. Through analysis of the vehicle data it has been possible to build up a quantitative picture of how the vehicles are typically used. Quantitative examples include trip lengths, trip efficiency correlated to the braking techniques and general driving behavior changes such as improved efficiency at low battery levels. From this work it can be shown that it is possible to monitor electric vehicles and selectively produce derived statistics which can be used to analyse the behavior of drivers.

**Introduction**

To achieve the reductions in $CO_2$ emissions agreed by the UK government, there is a need for an 80% cut in emissions by 2050. From a transport practitioner's (or minister's) point of view the question that must be asked is what would a reduction in $CO_2$ emissions of 80% look like in the transport sector? Figure 1, based on DEC data [1], shows real emissions from transport over the last 20 years and projected data over the next 40 years. The figure shows that the transport emissions have been steadily increasing since 1990, but that there is a sharp reduction due to the recession in 2008.

In figure 1, the projected trend forward to 2050, based on the non-recession growth patterns, illustrates that with *business as usual* $CO_2$ emissions from the transport sector, emissions will be six times higher than the needed cut in emissions from the 1990 level.

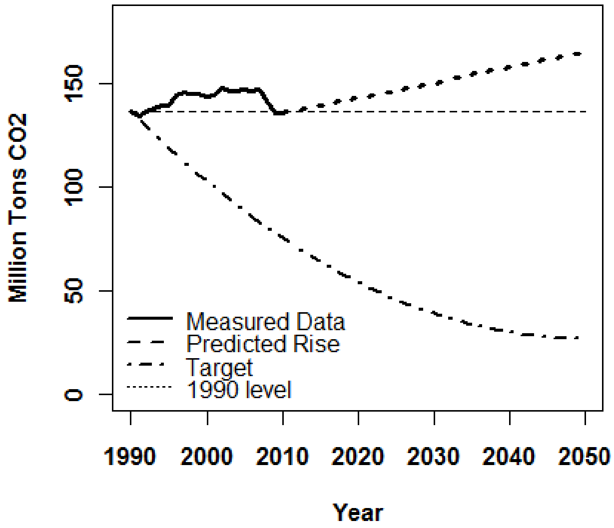


*Figure1: Extrapolation of transport emissions trend.*

This shows two stark realities about transport: this is one of the few areas of the UK economy where $CO_2$ continues to grow and that unless we radically reduce the $CO_2$ emissions from transport we will not, as a country, achieve the reductions that we have signed up to. If we discount modal shift (which will happen – but at its own pace) then the options for moving away from a fossil fuels based road transport economy are limited. Options include: biofuels (of different origins and blends); hydrogen fuel cells; other fuel cells; hybrid, plug-in-hybrid; and full electric vehicles. [2] Each has their pros and cons, most limited by current technology and the availability of refuelling/charging points, which at the moment is leaving hybrids and electric vehicles as the short term options with the emergence of plug in hybrids in the consumer market in 2012.

Electric cars offer numerous environmental benefits over traditional internal combustion cars; they emit less carbon per km than fossil fuel cars during their use [3] and even after a full life cycle analysis [4] they emit no pollutants during their use leading to the possibility that the city of the future will contain no health threatening pollution hot spots [5, 6] and they are also cheaper to run. [7]

However, they also have disadvantages. They generally have a lower top speed (80-90 mph), less range (typical 80-100 miles) and also a longer refuelling process (6-8 hours to recharge a battery using a standard charger, 30-40 minutes with a fastcharger) which can itself have an impact on the local power distribution grid [8]. Whether or not the long term advantages of electric cars will compensate for the short term reduction in functionality is currently an unanswered question. Answering it will require a large and sustained investigation into how EVs are used in day to day life. Nevertheless, the opportunity to explore at an early date the use of this new technology and its potential to contribute to the reduction of transport green house gas emissions is critical to future policy formation and thinking [9].

**The Trial**

This paper provides an introduction to a database/analysis platform for the investigation of the performance of an electric vehicle fleet. Preliminary results from the analysis are presented from the use of the platform with four electric vehicles provided by CENEX (centre of Excellence for Low Carbon and Fuel Cell Technology) as part of their Smart Move trial which took place in North East England between October 2009 and March 2010 [10]. The vehicles supplied for the trial were Smart Fortwo Mercedes with an electric drive train. Each vehicle had a Sodium Nickel Chloride battery with a 15kWh capacity and a restricted top speed of 60 mph

This trial was a precursor to a further EV trial underway in the North East, the SwitchEV project. A £10.7 million project which will oversee the deployment of 35+ electric passenger vehicles as well as the infrastructure required to fuel and maintain them. [11] This project is funded by the TSB and ONE NE with the vehicles and infrastructure supplied by Nissan, Smith Electric Vehicles in partnership with LTI, AVID Vehicles, Liberty Electric Cars and One North East. Newcastle University will oversee the data collection from the vehicles with an aim to assessing driver/fleet behaviour when driving the vehicle and also when interacting with charging points. [12] The CENEX electric vehicles gave the research team the opportunity to prototype and test the data collection and analysis system in advance of the first Switch EV project vehicles which became available to trial in March 2011, [13]. In particular it allowed the opportunity to test the validity of certain Electric Vehicle metrics and to the test the viability of the large scale data collection and reporting system.

SwitchEV is a novel project as it relies on monitoring the vehicles, and the driver’s interaction with the road environment, in a detailed and systematic manner which will allow for the analysis of their patterns of use in a way currently unparalleled within the U.K. The objective of the trial is to determine what barriers exist to electric vehicles becoming a mainstream road-vehicle technology within a few years. These barriers are not just technical but behavioural and attitudinal as well. In addition there is the need for a well-supported infrastructure to support EV charging. To accomplish this it is necessary to test that there is the capability to investigate such issues as:

- Monitor use and performance of vehicles
- Charging performance and battery life
- Charging occurrences (where, how often, what charge before and after etc.)
- Driver influences
- External influences
- To understand issues related to the practical use of electric vehicles
- Impact on traffic
- Impact on the environment

Data directly collected in this trial from the vehicle measurement system included:

- Every journey (time, distance, route)
- General performance of vehicle (efficiency in terms of kWh/km)
- Battery performance and battery management system

By combining this vehicle data with external sources of data and through statistical analysis of the data it is possible to also analyze:

- Effect of road topology
- Driving style (braking frequency, average speed, average acceleration etc.)
- Effect of congestion on performance
- Users and business perceptions of use
- Impacts (economic, emissions, energy, GHG, etc.)

The hard data on the cars, i.e. the data which is collected directly from the vehicle measurement system, is collected from the CAN (Controller Area Network – a high capacity, EM-noise tolerant data bus, now common to all new vehicles) bus of the vehicle and transmitted to a secure database through the use of wirelessly enabled data loggers within the car. This is overlaid with GPS and time data derived from an additional logging unit.

**Data Collection and the Database**

The heart of the ITS system deployed to collect the on-vehicle data is an advanced logger modified from a version of a device provided by COMESYS Europe Ltd. The logger connects to the CAN bus through the vehicles OBD (on-board diagnostics port). The logger has been designed to also take external analogue and digital input including the GPS and time-stamp data as well as a number of analogue inputs from current-clamps which are attached to various electrical systems of the vehicle to measure current flow and battery drain (and regeneration).

The variables measured and the rate of logging is dependent on the state of the vehicle's ignition. With the ignition on the measurement takes place every second, this measurement rate drops to every minute when the ignition is off. When the ignition is off the only information available is charging information through the AC supply and the slow drain of current needed to maintain the battery. Neither of these two variables are expected to vary much in the 1 second regime, hence 1 minute is enough to capture all features of interest.

| Variable | Ignition Off | Ignition On | Data Type |
|---|---|---|---|
| GPS position | | ✓ | Lat/long/altitude |
| Data | ✓ | ✓ | |
| Time | ✓ | ✓ | HH:MM:SS |
| AC Supply Connection | ✓ | | Boolean |
| AC Heater Request | ✓ | | Boolean |
| AC Heater State | ✓ | | Boolean |
| HV Battery Current | ✓ | ✓ | Float |
| HV Battery Voltage | | ✓ | Float |
| HV Battery Depth of Discharge | | ✓ | Float |
| Brake Pedal Pressed | | ✓ | Boolean |
| Light On | | ✓ | Boolean |
| Rear Window Heater | | ✓ | Boolean |
| Outside Temperature | | ✓ | Float |

*Table 1: The different variables recorded in different regimes are shown here.*

The data from the vehicle is transferred to a server at Newcastle University using GPRS, when the ignition state changes, i.e. the data from a single trip is transmitted at the end of the trip and the data from the previous charging event is transmitted at the start of the next vehicle trip. In addition to the in-vehicle data, real-time road and environmental data sources are correlated with the in-vehicle data. Specifically within this project data from a wireless distributed sensor network developed under the MESSAGE project [14] and traffic flow and congestion data from the regional UTMC [15] are used to extend the analysis.

To save bandwidth when transmitting the data a sequential raw byte format is used. The values to be transmitted are encoded in a simple byte format, for example the first two bytes encode the logger ID as a binary number, numerical values are encoded as a two byte decimal and Booleans as a collection of bits. After each measurement period has been encoded and stored, the system will repeat with the next measurement period. Although this format saves space within the data stream it is not a fault tolerant coding system due to the reliance on a continuous, unbroken stream of coherent data, hence it is necessary to fault check all data. If any errors in the data stream are flagged up then the particular measurement period is either discarded or repaired.

Other more subtle errors are picked up once the data is contained within the ORACLE database server that is used to store the data after it has been transmitted from the data loggers in the car. A typical error would be the data showing an unphysical discontinuous change such as a drastic change in location of more than 100m over the course of 1 second. In general such errors are either automatically corrected using the last known good values or through interpolation.

**Metrics for Electric Cars and their Drivers**

The efficient use of electric vehicles requires not only a close monitoring of the physical component, e.g. position or current drain but also a constant monitoring of how the driver interacts with the new vehicle. Using an EV differs from a normal combustion engine in several ways, specifically, in how the car must be driven for maximum efficiency. Unfortunately little research has been conducted on the specifics of driving electric vehicles. [16] Hence it has been necessary to develop metrics for electric vehicles, which are suitable for reporting and analysing EV efficiency.

An example of this is in the different methods of braking used within electric and internal combustion vehicles. In a combustion engine, inefficiencies from braking derive from keeping the car travelling at a higher speed for longer before using the friction braking. In contrast, an EV with regenerative braking will benefit from the efficiency of not driving the car at a higher speed than necessary but also the regenerative effect of the brakes. This may also be analysed by considering the spatial variation in regenerative braking, i.e. consistent spatial locations where vehicles exhibit regenerative braking.

Other differences in efficiency also exist such as the response at low speeds, the lack of gearing within the car, variations in battery charge with temperature and also in the direct effect on range from the use of ancillary vehicle features, heaters, headlights etc. Therefore successfully monitoring both user driving style and user driving efficiency requires different criteria to those more commonly used in assessing driving behaviour/efficiency in IC vehicles.

Perhaps the most fundamental functional difference between combustion and electric cars is the reduced range of the EV. [17] The cars used within the first section of the trial all had a range of approximately 40 miles, depending on conditions. The comparative reduced range and difficulty of refuelling means that greater attention must be paid to the battery level when balanced against the desired trip. Compared to a petrol car there is not only greater chance of running out of fuel before the trip is completed but also less ability to refuel the vehicle mid trip.

For the purpose of this study range is defined by the efficiency currently experienced by the vehicle. However, range is not entirely determined by the driver but also by environmental factors such as congestion, topography or weather conditions. As such it is difficult, to extract the effect that driver efficiency has on the range compared to the actual driving efficiency. To form a complete idea of the driving efficiency it will be necessary to link in the data from the driver with other data accessible from within the data base. Such data may include congestion derived from SCOOT data, meteorological data or topography data. [18]

To extend the utility of the database it would be desirable to allow the database to make recommendations on driving style and most eco-efficient route. But to do this it will be necessary to form a model of how a specific driver may behave when using an electric car. The construction of such a model is underway, underpinned by the data collected in this study and the SwitchEV project, and will entail modelling a driver in such a way as to typify their behaviour under a number of different driving regimes. Such regimes may include different levels of network coverage for charging points, different congestion types, different endpoints etc.

One of the unique advantages of this study is derived from the data handling and storage methods that are used. By transmitting the data directly from the cars using a data logger, to a database which automatically cleans, verifies and stores the data it becomes possible to view the project not simply as an experiment but as a future template for extended data storage techniques.

**Summary of Results**

For this particular group of analyses the data has been analysed in three separate grouping. Initially the data was aggregated on an individual ‘trip’ basis with all trips examined statistically. Secondly, the data was aggregated into 30 second blocks in an attempt to investigate the statistical distribution of driving styles within trips without the excess variation exhibited in higher temporal resolution data. Finally the data was analysed on a second by second basis.

The initial results demonstrate a selection of statistical analyses which can be performed on the current data and, by extrapolation, the statistical analysis which will be available for the much bigger data set available through the SwitchEV project.

**Trip Results**

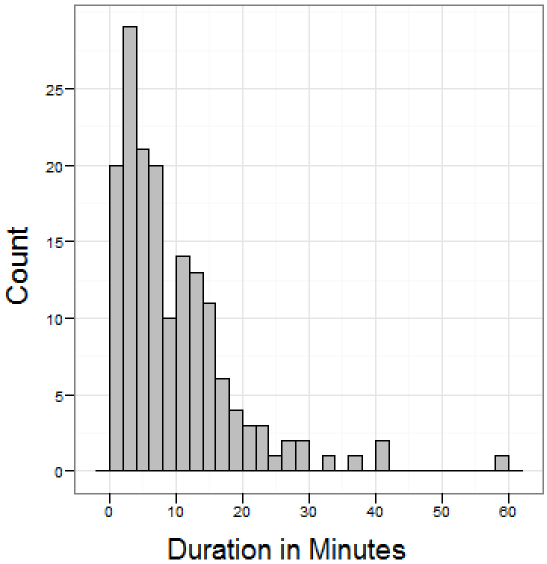


*Figure 2: The typical distribution of trip durations is shown here.*

In Figure 2, it can be seen that the majority of trips are less than 20 minutes.  This distribution of trip lengths is different in scale to that typically derived for petrol/diesel vehicles. This is likely a direct result of the limited range of these vehicles but it is possible that a contributing factor is the end user of the electric vehicles. The majority of the end users for this trial were working for local governments and were unlikely to use a vehicle to travel much. In addition the vehicles were used extensively for ride and driver “taster” events.

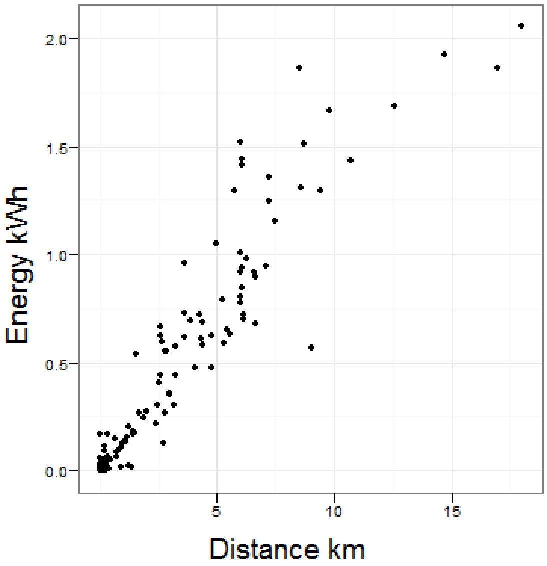


*Figure 3 Energy Consumption per Distance Travelled*

Figure 3 shows that the energy usage for each trip is approximately linearly dependent on the distance, with a slight reduction in energy usage per km for the longer distance trips.

Deriving an accurate picture of the macroscopic usage of electric vehicles will be vital in understanding the environmental benefit of EVs and also whether such vehicles (with limited range) are a suitable vehicle for purchase by a proportion of the population. This information will only be available through the analysis of full trip data.

**30 Second Aggregation Results**

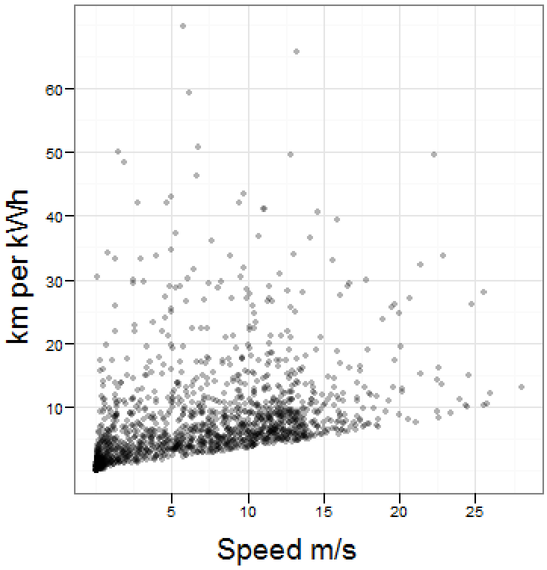


*Figure 4: Vehicle efficiency against Speed*

Figure 4 shows the dependence of instantaneous range (km per kWh) as the average speed varies. It can be seen that there appears to be a reduction in the rate of increase of battery depletion for longer distance journeys and there is an initial sharp increase in range as the speed increases. The reduced range at very low speeds is due to the power overheads of the vehicle. At low speeds the power overheads, which are only dependent on the journey duration, not length, are proportionally bigger than the energy required for movement, which is dependent on distance.

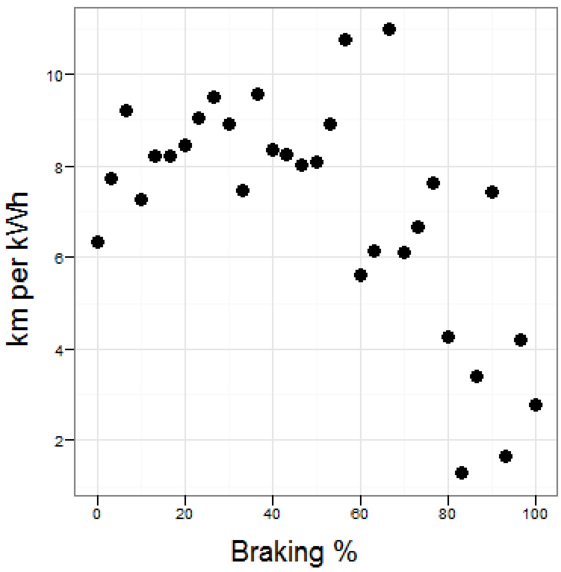


*Figure 5: Efficiency against % time spent braking in a 30 second period.*

Figure 5 shows that the efficiency over a 30 second when compared to the percentage of time spent braking during that period. The braking is determined by a Boolean variable which only records whether the brake has been pressed during any given second.

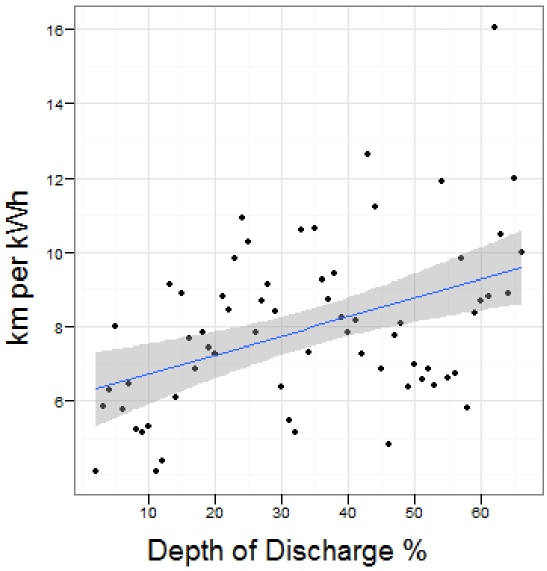


*Figure 6: The change in efficiency against Depth of Discharge is shown here*

Figure 6 shows the average efficiency for each 30 second aggregation with a specific depth of discharge. Despite the large variation it can be seen that there is an upward trend for efficiency with increasing depth of discharge. The fitted line has an $R^2$ of 0.20 with a p value for the fitting of under 0.1%. Due to a lack of data above this point, the 70% is used as the maximum for the depth of discharge.

The results from the example data sets from the 30 second aggregation period show that there is a systematic affect on efficiency from a variety of driving parameters.

One conclusion which may be drawn from this is that a vehicle which spends more time at a higher speed will have a more efficient energy profile. For longer distance journeys, it is likely that there are more sections of the journey which take place at a higher speed and thus the efficiency of the vehicle will begin to increase as the increased energy efficiency at high speeds becomes a factor. This is currently being researched further.

In addition to the dependence on speed it can be seen that efficiency varies quite significantly with the number of seconds spent braking. Initially, as the time spent braking increases the range of the car initially remains fairly constant. It is likely that the regenerative nature of the EV braking allows the EV to brake for short periods of time without a reduction in range. The reduction for large volumes of time spent braking is likely due to stop-start motion of the car when the car is, for example, encountering congestion. When the car is in stop start motion the vehicle will be experiencing a hysteresis effect of the regenerative braking. Essentially the vehicle, in accelerating up to a given speed, will use more energy than it can regain in decelerating down from a given speed.

Finally it can be seen that the efficiency has a weak dependence on the current state of charge. This is expected as qualitatively the EVs should show an increased efficiency due to the driver attempting to drive more efficiently to increase their range.

However the $R^2$ for the linear regression model is 0.20, indicating that the majority of the explanatory power is not captured by considering range anxiety. Although detectable in this data set it is possible that this affect is reduced for the following reasons:

1) The drivers have undergone no training in how an electric car may be driven more economically, thus they may not have the ability to drive more economically.
2) The drivers have been given no incentive to drive more economically barring the inconvenience of running out of power before reaching the next charging point.

The driver’s belief about the range remaining in the car will be dependent on the depth of discharge of the battery as indicated by a dial on the dashboard. However, depending on the familiarity of the driver with the vehicle, it may be possible to adjust for the predicted efficiency of the journey to be undertaken. For example if the driver is on a high speed road then experience will tell the driver that the expected range will be reduced.

**Second by Second Results**

As a final example, an individual group of trips were examined on a second by second basis to determine if there are any features which will require monitoring that do not necessarily show up in a gross statistical analysis. The trips chosen were from a demonstration at the Metro Centre, Gateshead, UK. The participants were all members of the public who had pre-registered their interest in ‘a ride and drive’ experience in an electric vehicle.

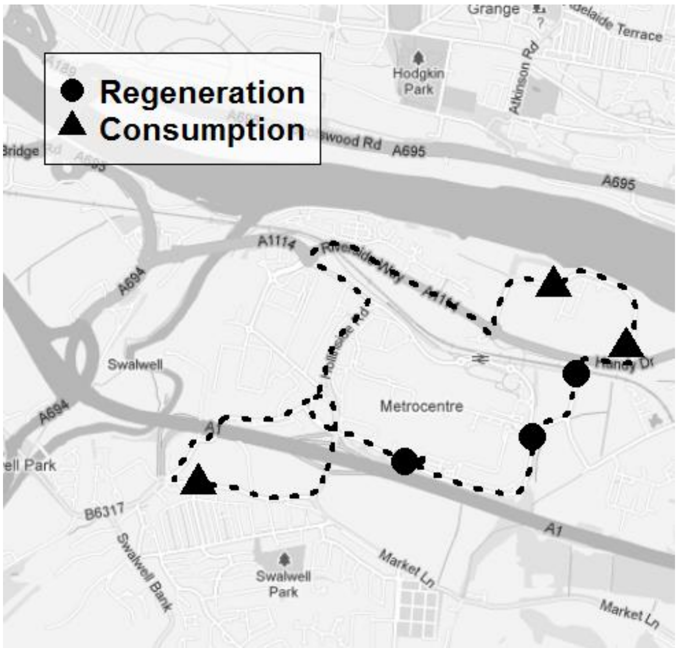


*Figure 7 shows the typical consumption and regeneration events over the course of a single trip.*

Figure 7 shows the regeneration and consumption events for a specific trip around an anti-clockwise circuit. Although the data here is for a specific driver it was found that other drivers behaved in a similar way.

The second by second data shows that regeneration events typically take place when there is a topographical variation in the path of the vehicle. The topographical variation may either take the form of an altitude variation or a forced bearing alteration. Further analysis shows that although there is a probability of a regeneration event at any point in the vehicles path there is a much greater probability when the vehicle is either on a down-hill segment or it is consistently brought to a stop. In the example in figure 8 the expanded position-power map is from a section of the trip where the vehicles are forced to brake before entering a car park.

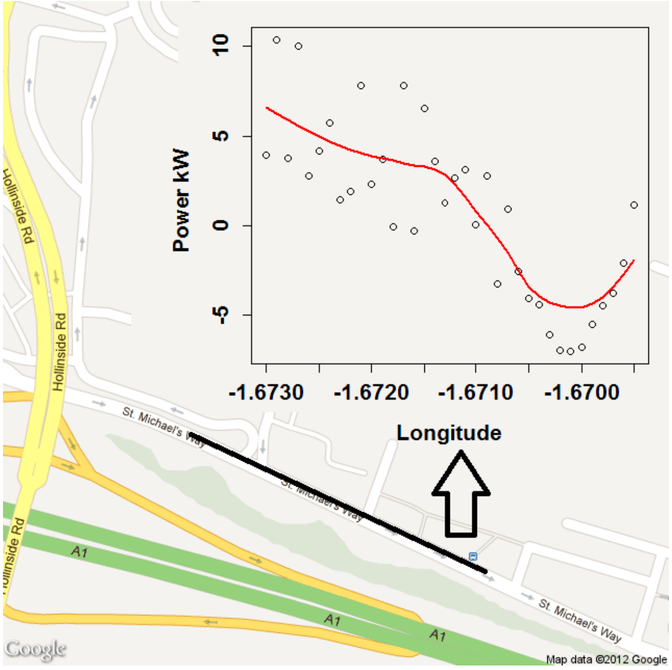


*Figure 8: The regeneration and consumption over a specific section of road is shown here*

What this analysis shows is that there is a great deal of information contained in the second by second data which is unavailable to any other form of analysis, in particular the specific response of electric vehicles to changes in topography or forced speed changes. An in-depth knowledge of such information is vital to properly understand how EVs behave in the real world.

Specifically it also shows that there is information at each scale of analysis which is either not available or not readily analysable.

**Future Developments**

The paper has provided some early results from the data acquisition and analysis system develop by Newcastle University to evaluate the performance of electric vehicles supplied by CENEX. The system developed here was the first stage of a wider development of an infrastructure for the widespread testing and evaluation of electric vehicles and other eco-friendly vehicles in the North East of England, in particular expanding the analysis system for use with the SwitchEV project The next stages of the research will be to integrate the data from the vehicles with other sources so that a richer picture of how these vehicles are impacted by other parameters such as congestion, weather conditions and road topology. Moreover using the pervasive environmental monitoring sensors from the MESSAGE project, the traffic emissions can be constantly monitored, to determine the contribution to their reduction that electric and other low carbon vehicles can make.

The activities in this NE trial was a catalyst to the formation of the ITS (Intelligent Transport Systems) UK working group on EVs, which is exploring how ITS can be deployed to support the roll-out and operation of electric vehicles and their associated recharging infrastructure [19] and also the IET working group who have published a Code of Practice on EV Charging [20] To promote the role of ITS in the evolution of electric vehicles, Newcastle University, on behalf of ERTICO has developed a European Roadmap for the use of ITS in Electromobility, which will inform future EU research programmes in this area [21]

**Conclusion**

This paper provides a snapshot of the early research and first generation ITS architecture developed by Newcastle University for a series of electric vehicle trials in the North East of England. The data presented here utilise data collected from the four Zytek electric Smart cars deployed by CENEX in the NE of England in 2010 to 2011. The infrastructure and data analysis techniques presented here are a proof-of-concept and proving ground for the larger TSB-funded Switch EV trail which went live in March 2011.

It can be seen that there are numerous metrics which may be used to categorise the driver of an electric vehicle and, more specifically, track the change in behaviour exhibited by the driver.

Driving efficiency may be measured by two metrics; an instantaneous efficiency and a total efficiency for any given trip. It is likely that when more data is collected the instantaneous efficiency will be used to indicate how drivers react to specific situations whilst the power consumed per km per trip will be used to indicate driving efficiency for identical trips and for fleet wide statistics.

Finally it is also seen that the less time spent braking, the more efficient the resultant drive. This, along with the tentative conclusion that regenerative braking occurs as a function of topography, leads to the conclusion that for maximum efficiency braking should be reduced where possible, except where necessary due to road or traffic conditions. Currently it is unknown what the scope is for increasing regenerative braking through driver intervention.

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