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 and a physical lack of fossil fuels mean that continuing to fuel cars by internal combustion, in the long term, is unviable. To combat this it is necessary to look at other methods of powering vehicles. One such option is the electric powered car and this is reflected in the large amount of support and R&D monies that government and other bodies are investing in this technology and the underlying support infrastructure of charging points and supply.**

At the moment the main ergonomic difference between electric and fossil fuel cars, beyond the physical driving of the vehicle, is the comparative lack of range for the electric car. In the first tranche of cars trialed in this project the range was limited to approximately 30miles for each charge cycle. A range of this level means that the driver must now be more fundamentally aware of the remaining distance they may travel, and how they may best utilise this range to accomplish their driving goals for the day. The comparative cost of small journeys (whether environmental or monetary) becomes less important and the increased danger of running out of charge on large journeys becomes more so. The different usage algorithm now employed by the driver will lead to a different behavior within the electric vehicle. So in switching from fossil to electric there is not only a switch in the physical capabilities of the car but also be a fundamental change in how information from the car is processed to make driving choices and also in the type of information required. To monitor this change in behavior and how we may exploit or nurture it, it is necessary to gather data from the car and the driver and to exploit the data.

This has been accomplished within this project by instrumenting a series of electric cars and monitoring each vehicle in all aspects of their working life. This is achieved through the use of a communications system connected to the CAN bus within the vehicle and a GPS system linked to a wireless data transmitter. Data from a variety of sources within the car is considered including regenerative breaking, charge cycles plus driving information including speed and acceleration. By considering all the data collected through the car, by automatically placing and sorting the data within a database and by careful comparison with driver surveys it is possible to build up a quantitative picture of how the cars are used in a typical day to day scenario. Examples of the analysis which can be derived from the raw data include typical trip lengths, distribution of trip lengths through the day, distribution of trip lengths correlated to the battery charge left and general changes in behavior using the car.

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? Before projecting forward, we need to look at how emissions have increased over the years. Figure 1, based on DfT data, shows emissions from transport over the last 50 years. The blue (long) line shows land based emissions since 1956, whilst the shorter (red) line shows the contribution national water and air-based transport have contributed since this data was made available from 1990.

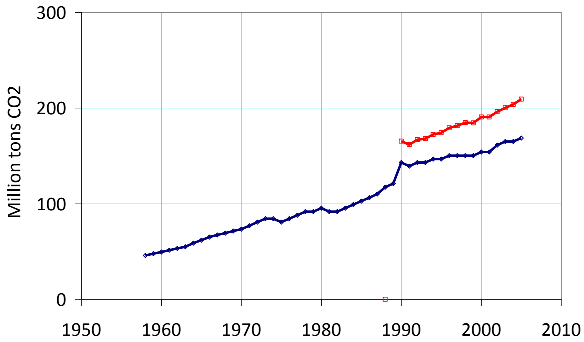


Figure 1: Emissions from UK transport sector

The projected trend forward to 2050, illustrates that with a *business as usual*, CO_2 emissions from the transport sector, could be about double those measured for 2010. More importantly, an 80% reduction in comparison with 1990 is equivalent to a reduction of 92% compared with an extrapolation of this trend as shown in figure 2.

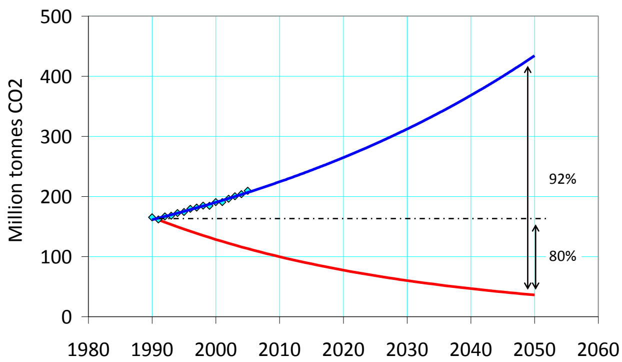


Figure 2: Extrapolation of transport emissions trend

This shows two stark realities about transport: this is one of the few areas of the UK economy where CO_2 continue 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. 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.

Electric cars offer numerous environmental benefits over traditional internal combustion cars; they less carbon per km than fossil fuel cars, 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 and they are also cheaper to run.

However, they also have certain disadvantages. They typically have a lower top speed, less range and also a longer refuelling process. 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 varying users utilise electric cars in their 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 green house gas emissions attributed to transport is critical to future policy formation and thinking [4].

The Trial

This paper provides a brief summary of the research which investigated the performance of a fleet of electric vehicles, provided to us 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 [5]. The vehicles supplied for the trial had the following specification:

Make	smart (Mercedes)
Model	Fortwo Electric Drive
Motor power	20 kW
Energy storage capacity	15 kwh
Battery chemistry	Sodium Nickel Chloride
Top speed	Restricted to 60 mph
Charge supply	13 amps at 240v

This trial was a precursor to further trials of electric vehicles which will be undertaken in the North east under the Switch-EV project which is a £10.7 million project within the north east which will oversee the deployment of 35+ electric passenger vehicles as well as the infrastructure required to fuel and maintain them. This project is funded by the TSB and ONE NE with the vehicles and infrastructure will be 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. To test the prototype data collection system and server and analysis tools for this project, the opportunity to test 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 being available to trial in September 2010, [1].

Figure 3 The Zytek electric vehicle can be seen here. The power train is derived from a molten salt battery implemented in a smart car.

Switch-EV 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 objectives of the trial is essentially to determine what barriers exist to electric vehicles becoming a mainstream road-vehicle technology within a few years, thus key issues to investigate include:

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

Data that will be collected (and indeed was for the CENEX Smart Vehicles included):

- Every Journey (time, distance, route)
- Performance of Vehicle
- Driving Style
- Battery performance and battery management system
- Effect of road topology
- Effect of congestion on performance
- Users and business perceptions of use
- Impacts (economic, emissions, energy, GHG, etc.)

The hard data on the cars will be derived from the CAN 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 in the vehicle.

Data Collection and the Database

The data logger deployed in the project is a modified version of a device provided by Comesys Europe Ltd. The logger connects to the CAN bus through the vehicles OBD port. The logger has been designed to take some external analogue and digital inputs. These inputs include 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.

Data is continuous but 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, whilst it takes place every minute when the ignition is off. This is because when the ignition is off the only information available is charging information through the AC supply and the slow drain of current needed to keep the battery warm. 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. However the measurement is currently limited to 1hz with ignition on to reduce the amount of data which needs to be transferred.

Variable	Ignition Off	Ignition On
GPS position		✓
Time/Date	✓	✓
AC Supply Connection	✓	
AC Heater Request	✓	
AC Heater State	✓	
HV Battery Current	✓	✓
HV Battery Voltage		✓
HV Battery Depth of Discharge		✓
Break Pedal Pressed		✓
Light On		✓
Rear Window Heater		✓
Outside Temperature		✓

Table 1 The different variables recorded in different regimes are specified so that no extraneous data is recorded and sent when there is no need.

The data is transferred when the ignition state switches from on to off, or off to on. Typically this means that the data from a single trip (where the ignition was on) would be transmitted at the end of the trip and the data from a charging event would be transmitted at the start of a trip.

To save the bandwidth when transmitting the data a simple raw byte format is used. Each time period measured is encoded in the raw byte format then concatenated. For example the first two bytes of the transmitted data indicated the logger ID number; the next six indicate the date, then GPS data, etc. After the data for a single time period has been sent, the system repeats. Although this format saves space within the data stream it is not a fault tolerant coding system hence it is necessary, after transmission, to fault check all data. If any results are flagged up in the data stream then the entire segment of data for that particular time period is discarded.

Other more subtle errors are picked up once the data is contained within the database. An ORACLE database server is used to store the data after it has been transmitted from the data loggers in the car. Other more subtle errors will be picked up at this stage. Typically these errors will be where the data shows an unphysical discontinuous change which is not incorrect in itself but only demonstrates itself when compared to the previous results for that particular data set. An example would be a drastic change in location of more than 100M over the course of 1 second.

It is possible to correct errors of this sort by either using a previous "good" result (e.g. for outside temperature) or by interpolating between the two closest "good" results. An example would be interpolating between two positions to derive the data for a position where the GPS data is incorrect.

As well as manually identifying errors in data it is also desirable to create an automatic system for identifying errors, to remove the necessity of user intervention which will become overly onerous for large data sets. Any automatic system will separate errors into one of three varieties:

1) Data segment is corrupted: This will lead to the program dropping that particular segment.
2) Data segment is in the correct format but incorrect: An attempt will be made to interpolate between previous data sources to correct the data.
3) Data is incorrect but not correctable: The data segment is kept and the issue is flagged for user intervention.

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 electric vehicle differs from a normal combustion engine in several ways and, specifically, in how the car must be driven for maximum efficiency. Unfortunately very little research has been carried out on the specifics of driving electric vehicles and hence it has been necessary to start developing metrics which will enable the comparison

An example of this is in the different methods of breaking used within both systems. In a combustion engine the inefficiencies derive from keeping the car travelling at a higher speed for longer before using the friction breaking. In contrast, an electric car with regenerative breaking will not only benefit from the efficiency of not driving the car at a higher speed than necessary but also the regenerative effect of the brakes. Although care must be taken not to apply the brakes harder than necessary as this will switch the brakes from a regenerative braking regime to a friction braking regime.

This is one example of the way in which the efficiency of an electric vehicle will differ from a combustion car. Other differences 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 of range which the use ancillary vehicle features will have, heaters, headlights etc. Hence to successfully monitor driving styles and driver efficiency when using the new breed of vehicles it will be necessary to develop different criteria for assessing the drivers.

Perhaps the most fundamental functional difference between combustion and electric cars (barring power train and fuel type) is in the reduced range of the electric car compared to petrol/diesel. The cars used within the first section of the trial all had a range of approximately 40miles, depending on conditions. A reduced range, and comparative difficulty of refuelling compared to a normal car means that much greater attention must be paid to the battery level remaining 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 there is also less ability to refuel the vehicle mid trip.

Driving efficiency in this project is defined by the mileage currently being experienced by the vehicle. However, driving efficiency 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 mileage as 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 forms accessible from within the data base. Such data may include congestion derived from SCOOT data, meteorological data or topography data.

To further extend the utility of the database it would be desirable to allow the database to make recommendations to driving style/possible routes. 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 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. Whilst a detailed model of a single driver will not be viable using the (relatively) small number of trips it may be possible to broadly characterise a driver into different categories such as “efficient”, “range wary”, “aggressive” or “cautious”. All such models of driver behaviour currently available are for petrol/diesel cars with no systematic review of such behaviour in electric cars.

One of the unique advantages of this project 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

To analyse the data for this project the data has been split into three forms, a summary of each individual trip, an individual trip and an aggregated summary of each 30 second section of data. The split into 30 second data was used so that enough data would be generated so that a general idea of the how the vehicles perform could be ascertained.

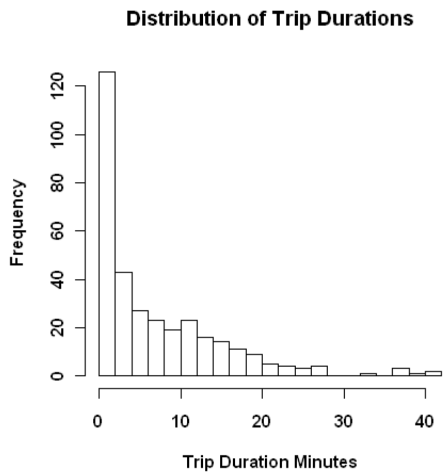


Figure 4 The typical distribution of trip durations is shown here. The majority of trips in this instance take place in the sub 1 minute regime. However due to the nature of the trials from which this data was derived it is likely that these trips are not trips undertaken with a journey in mind but rather users simply trying out the car.

From the data show above it can be seen that the majority of trips undertaken with the electric vehicles are short trips less than 10 minutes, with an approximately linear drop off to 30 minute duration. This distribution of trip lengths is different 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 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 beyond the requirements of their job.

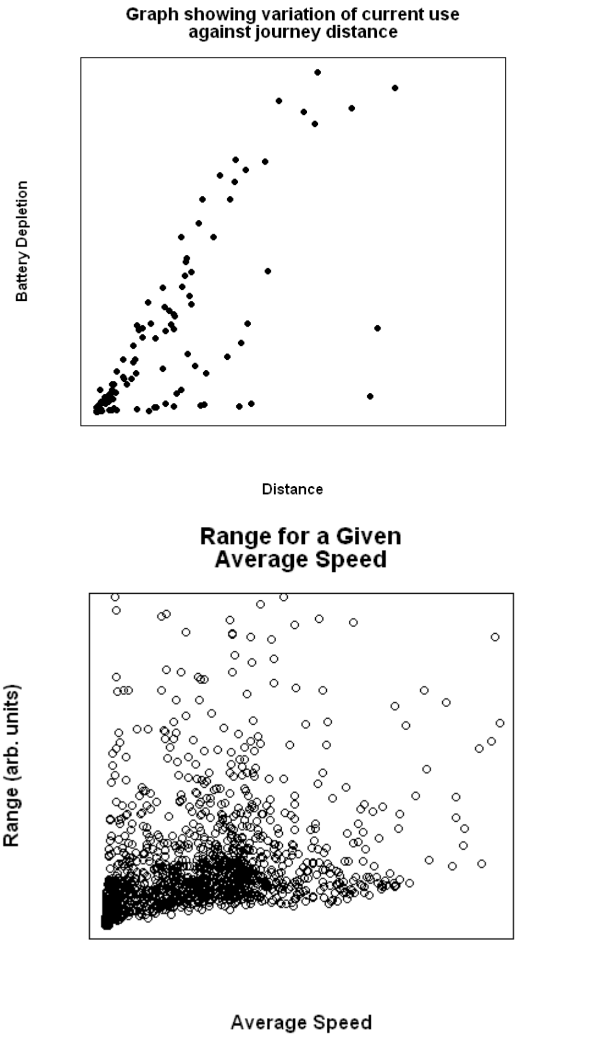
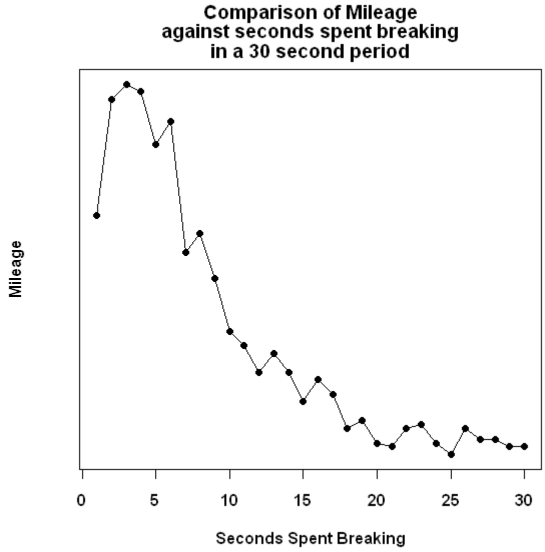


Figure 5 The two graphs above show related information, the top graph shows the total battery depletion as the total distance driven in a journey increases, the bottom graph shows the mileage change as the speed over a 30 second time is changed. It can be seen that there appears to be a decrease in the rate of increase of battery depletion for longer distance journeys and there is an initial increase in mileage as the speed increases followed by a decrease after a certain point.

Figure 5 shows two results which lead to the same conclusion. In figure 5 the battery depletion initially increases fairly linearly as the total distance increases, however at longer distances travelled the battery starts to increase at a lower rate. The conclusion we can draw from this is that long journeys require comparatively less power than shorter journeys. It may be hypothesised that this results is due to the car's increased efficiency when in a "cruising" mode. Essentially the car is more efficient at covering distance when it is continually driven over a given distance rather than when it is undergoing a stop-start pattern which is more common with a shorter journey. Figure 5 shows the reason why this may be the case. The data shown is the average speed over a 30 second period against the average range over that 30 second period. Despite the large effect of other variations on the car it is possible to see a definite speed for which the range is at a maximum. For this car the most efficient speed is approximately 30 mph. Hence it may be surmised that the most efficient journeys will occur when the vehicle spends the majority of this time within the most efficient regime. Typically this will be for longer journeys when the vehicle has more opportunity to reach and sustain cruising speed, which is a result which is borne out by the previous data in



3b.

Figure 6 The greatest efficiency (mileage) is generated when the brakes are used sparingly over the course of a journey segment.

Figure 6 shows that the range over a 30 second period varies quite significantly with the number of seconds spent breaking. As the time spent breaking increases the range of the car decreases substantially. However there is an increase in range from 1 second to 2 seconds and no difference between 2 seconds and 4 seconds. It is likely that the low range at the very low levels of breaking (0 seconds breaking) is due to the car moving off from stationary. For this situation the car would have a low mileage due to the slow speeds at which it was travelling, but it would also show no time spent breaking. The reduction in mileage for large volumes of time spent breaking 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 breaking. 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.

A driver's knowledge about the range remaining to the car is directly related to two things; the depth of discharge of the battery, indicated by a dial on the dashboard, and the proposed future mileage of the car. To increase the range of the car the driver may make a conscious decision to drive in a more efficient manner, assuming the driver has all the knowledge required to achieve this. So it is expected that the driving style of the electric cars will show an increased range as the depth of discharge increases due to the change of driving style of the driver.

The initial step is to test this hypothesis against all drivers to see if there is a general tendency within the test group for the efficiency to increase as the depth of discharge increases. The efficiency and depth of discharge data was taken from a summary of the 30 second data due to the level of noise within the data.

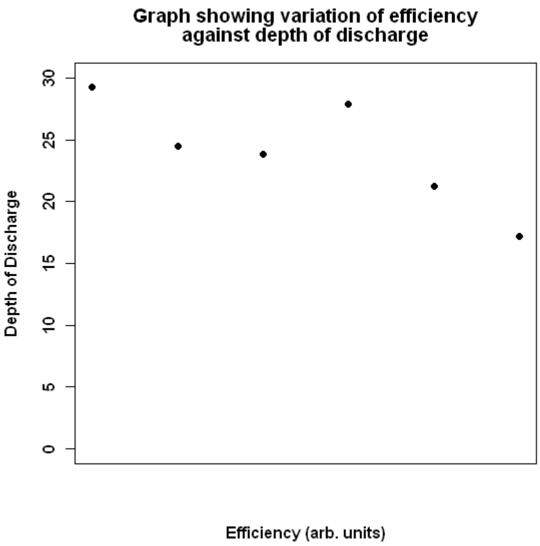


Figure 7 As the depth of discharge decreases it is expected that the driver will take steps to increase their efficiency.

It can be seen from figure 7 that there is only a very weak tendency for this, with it being possible to state that efficiency increases as depth of discharge increases only at the 50% confidence interval. So at the moment it is not possible to state with any degree of certainty that the drivers alter the power consumption based on the driver's knowledge of the power remaining within the car. There are several reasons why this effect cannot be observed in a statistically reliable way.

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.
3) The sample is too small and varied to derive the results of a relatively subtle variation such as driver variability.

As a final example, an individual trip was examined visually to determine if there are any features which will require monitoring that do not necessarily show up in a gross statistical analysis. The trip chosen here is from a demonstration at the Metro Centre, Gateshead, UK. The participants were all members of the public who had either pre-registered their interest in driving an electric vehicle or were interested passersby.

Figure 8 The basic pattern of consumption and regeneration over the course of a single journey can be seen here. It can be seen that the majority of distance is undertaken with consumption with only a small proportion using regeneration.

Figure 8 shows how consumption and regeneration vary over the course of a single trip. Generally speaking it can be seen that regeneration events take place when there is a topographical variation in the path of the vehicle. However it is necessary to more closely examine the trip to determine whether the regeneration is due to a breaking event at the decelerating approach to a corner or when the vehicle is descending and the breaks are being continually applied to limit acceleration.

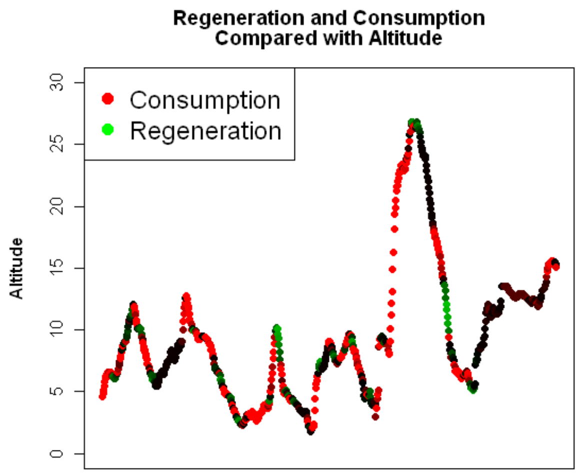


Figure 9 Regeneration event are indicated in the topographic map here by a green indicator. There is a tendency for the larger regenerative events to occur on the downhill section.

Figure 9 shows that although there are small regenerative events which occur when the vehicle is not on a downhill segment, the majority of the events and particularly the largest regenerative events occur on the down-hill segments. Although this is a brief analysis of a single journey it does indicate that the majority of the regenerative events, for an untrained user, are highly dependent on topography and perhaps are not amenable to training.

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 is the first stage of a wider development of an infrastructure for the widespread testing end evaluation of electric vehicles and other eco-friendly vehicles in the North east of England. 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, presented at the last RTIC conference [3], the change in actual traffic emissions can be constantly, monitored over time, to determine the contribution to their reduction that electric and other low carbon vehicles could make to the North east. To this end figure 10 shows a google map of the location of these pervasive sensors in the test area.

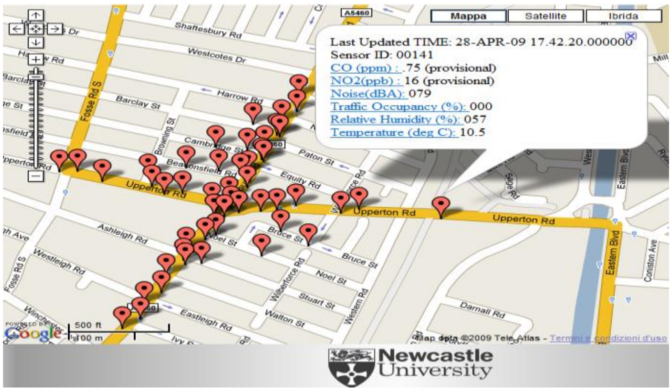


Figure 10 A Google map showing the location of pervasive sensors

It is also possible to provide a real-time congestion overlay which will provide a record of the level of congestion that an electric vehicle is experiencing on that part of the vehicles journey and hence the possible impact the traffic levels may have on battery drain, recharge and general performance [2]

Conclusion

For the initial analysis here it can be seen that there are numerous metrics which may, for an extended and more comprehensive data set, be used to categorise the driver of an electric vehicle and, more specifically, track the change in behaviour exhibited by the driver. Trips length distribution will tend to be a function of the intended utility of the vehicle rather than the behaviour of the driver and hence will not be useful to indicate changes in actually driving behaviour, but they may be useful to indicate differences in driving attention. Driving efficiency may be measured by two metrics; an instantaneous range at any given point in the trip and a power consumed per km for any given trip. It is likely that when more data is collected the instantaneous range will be used to indicate how a driver reacts to specific situations whilst the power consumed per km per trip will be used to indicate driving efficiency for identical trips. Currently both instantaneous range and individual trip data show essentially the same results; that there is a mid range of speed where the vehicle is driven at its most efficient and it is this range which any driver wishing for efficiency should aim for.

Finally it is also seen that the less time spent breaking, the more efficient the resultant drive. This, along with the tentative conclusion that regenerative breaking occurs on the downward portion of inclines rather than breaking at corners/traffic, leads to the conclusion that for maximum efficiency the vehicle should be kept in motion for as long as possible with as little breaking as possible, except where necessary. Currently it is unknown what the scope is for increasing regenerative breaking through driver intervention.

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