Effects of Electric Vehicle Deployment on Energy Demand and CO2 Emissions

V. Suresh, P.T Blythe, Graeme Hill, Yvonne Huebner, Andrew Robinson
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Abstract

The transport sector is one of the major consumers of fossil fuels and uses a significant amount of the global energy supply. The drive to reduce greenhouse gas (GHG) emissions from transport is pushing the motor industry and governments to consider alternative fuels for road transport. Several energy vectors have been discussed in the past including hydrogen and electricity. The uptake of electric vehicle in the existing fleet of vehicles has positive impacts in the reduction of emissions and reduces the carbon footprints by moving in to greener transport. However, the energy generated to charge the electric vehicles consume fossil fuels. Each country adopts different policies to generate electricity from various sources such as renewable, coal, gas or nuclear power stations. In this work, we will describe our strategic research in monitoring and evaluating one of the biggest electric vehicle deployments in north east of England.

The evaluation will summarize the effects on energy consumption through different driving styles, external effects (weather, topology, congestion) and charging behaviour impact on the energy requirements from grid. Key challenges for many nations will be discussed in the context of reports such as the Stern Report and other international studies into GHG emissions, climate change, energy and transport.
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About the authors

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Abstract:

The transport sector is one of the major consumers of fossil fuels and uses a significant amount of the global energy supply. The drive to reduce greenhouse gas (GHG) emissions from transport is pushing the motor industry and governments to consider alternative fuels for road transport. Several energy vectors have been discussed in the past including hydrogen and electricity. The uptake of electric vehicle in the existing fleet of vehicles has positive impacts in the reduction of emissions and reduces the carbon footprints by moving in to greener transport. However, the energy generated to charge the electric vehicles consume fossil fuels. Each country adopts different policies to generate electricity from various sources such as renewable, coal, gas or nuclear power stations. In this work, we will describe our strategic research in monitoring and evaluating one of the biggest electric vehicle deployments in north east of England. The evaluation will summarize the effects on energy consumption through different driving styles, external effects (weather, topology, congestion) and charging behavior impact on the energy requirements from grid. Key challenges for many nations will be discussed in the context of reports such as the Stern Report and other international studies into GHG emissions, climate change, energy and transport.

Introduction:

Road transportation has been the major consumer of fossil fuels for more than a century where the access to travel and the movement of goods using motor vehicles has transformed society into a mobile, global economy underpinned by the ability to travel. Clearly the benefits of mobility are huge and open up economic, cultural and societal opportunities to all. Given the fact of finite fossil fuels availability coupled with the unprecedented increase in demand for vehicles in the new economic powerhouses such as China, India and Brazil trigger a rethinking of the current transport sector reliance on fossil fuels. Secondly, concerns on greenhouse gas emissions and the role of the transportation sector drives to move toward a greener transport. These are the simplistic drivers pushing the motor industry and governments to consider alternative means of fuelling vehicles, with one key alternative being the use of electricity to power vehicles.

Electric vehicles are by no means a new technology. The first electric-powered cart was built by a Scotsman, Robert Anderson in the 1830’s; in 1897, the Electric Carriage and Wagon Company of Philadelphia had built a fleet of New York City taxis. Moreover years 1899 and 1900 were the high point of electric cars in America, as they outsold all other types and in 1910 in London there were some 6,000 electric cars and 4,000 commercial vehicles registered. Not to mention in 1899 the Belgian, Camille Jenatzy, set a land speed record of more than 100 km/h in an electric car, La Jamais Contente. [1] However like all inventions, the time and environment has to be right for wider adoption and the perfect storm of fossil fuel reserves; security of supply and climate change concerns have brought electric vehicles (EV) to the forefront of an e-mobility revolution.

Policy context for Electric Vehicle Deployments:

The automotive industry is essential to the EU economy. It is a €550 billion turnover industry with a strong commitment to manufacturers of world-leading, high-tech automobiles in Europe. It is the engine of the manufacturing industries, one of the biggest employers in Europe, the largest investor in innovation and R&D, and a formidable export force. In addition, transport accounts for about 7% of GDP and for over 5% of total employment in Europe [3]. However, there is a growing urgency to mitigate the negative impacts from transport on the environment. Transport still depends on fossil fuels, which not only contribute significantly to greenhouse gas emissions, but also have negative implications for the security of energy supplies. In order to meet the EU’s climate change targets of reducing GHG emissions by 20% by 2020, transport has to make a transition towards lower and zero-emission vehicles and a different concept of mobility need to be introduced. Many European regions have therefore started to promote electric vehicles in order to meet their carbon reduction targets, air quality targets and noise reduction targets, as well as to prepare themselves as possible manufacturing bases for electric vehicles and their associated support infrastructure with the knowledge-base and R&D skills to support this.

On a national level, the UK strategy takes a multi-modal approach to transport in its quest to reduce carbon emissions and the wider environmental impact of the sector. The Department for Transport’s ‘2011 strategy: UK Transport Policy: Creating Growth, Cutting Carbon - Making Sustainable Local Transport Happen’, reaffirms the need to make public transport more attractive if it is to offer a viable alternative to car travel. Key to this is improving end-to-end journeys, and the Government is taking the lead on challenging train, bus and car hire companies to consider what measures can be put in place to enhance the whole journey experience for users. Financial incentives are available for those purchasing electric vehicles. In total, the UK Government has pledged over £400 million to support the uptake of ultra-low emission vehicle technologies. Amongst those measures is the ‘Plugged in Places’ scheme, which is a £30 million initiative to
Demand for Electric Vehicles:

The introduction of the electric vehicles into the market is complimented with government tax credits in the range of £5000 in UK and $7000 in US. The green technology is argued for a rapid uptake in certain regions of the world. The current market is very small and is expected to grow quickly. The forecast by international management firm PRTM estimate future sales of electric vehicle and all other vehicles as shown in the Figure 1.

![Figure 1: Global Vehicle Sales (Millions of Units) 2010-2020, Source (PRTM 2010)](image)

The forecast predicts the sales of full electric vehicles, hybrids and PHEV in the quantity of 40 million vehicles. The market share of the electric vehicles will be roughly 50% of total vehicle demand. Total Battery Consulting (TBC) predicts the EV and PHEV market to be around 200,000 vehicles in 2015 and around one million for 2020. According to International Energy Agency (IEA), EV/PHEV stock on a trajectory would exceed 200 million by 2030 and one billion by 2050. This trajectory electric vehicle introduction in the market is a key element to achieve G8-supported, IEA blue map to reduce the CO2 emissions to 50% from the current level in 2050 in comparison with 2005 levels.

The greener transport initiative is supported by major cities such as London and New York. New York started a trial of 375 taxis with HEV. The whole fleet of 13,000 New York taxis will be replaced from 2014 over a period of ten years [20]. The transport for London introduced 106 diesel-electric hybrid buses from 2006. The current program is to introduce 300 hybrid buses by 2012. San Francisco replaced 50% of the taxicab with HEV. Boston mandated the fleet of 1825 taxi to be converted to hybrids by 2015. Other cities such as Vancouver, San Antonio, Arlington, Cambridge (Massachusetts), Hamburg, Phoenix followed the green footprint.

<table>
<thead>
<tr>
<th>City</th>
<th>% of new car sales</th>
<th>Number of electric vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>9</td>
<td>~70,000</td>
</tr>
<tr>
<td>Paris</td>
<td>7</td>
<td>~62,000</td>
</tr>
<tr>
<td>Shanghai</td>
<td>5</td>
<td>~26,000</td>
</tr>
</tbody>
</table>

![Figure 2: Demand for electric vehicles in large cities. Source: McKinsey Electric Cars](image)

Large cities prove to be an ideal test track for the electric vehicle launch, catalyzing the policy maker’s incentive and cost effective mode of travel. The environmental friendly aspect of electric vehicles in terms of carbon emissions and cleaner air quality motivates the increase in electric vehicle sales. The demand analysis conducted by McKinsey Quarterly reveals the projected demand of 6% increase in New York and less than 1% increase in Shangai [27].

Adoption of electric vehicles in growing economy such as China, India would create a huge increase in electric vehicle sales. With the growth in the market need, the gap between the capacity and demand of vehicle production in terms of battery availability, resources and charging infrastructure cannot be ignored. The availability of electricity in developing countries acts as a barrier for the deployment of electric vehicles.

Impact of Electric Vehicles on Rare Earth Metals:

The electric vehicles, hybrid vehicles and other greener options for transport are expected to grow in this decade. The core components to drive the engines use neodymium, dysprosium, lanthanum and few more. The metals listed falls...
under the category of earth's rare metals. Most of the digital devices and the green technologies use indium and niobium that are increasingly high in demand from global industries. The low carbon economy has triggered technologies to rely heavily on the metals that were of very little interest to the industry 10 years ago. The British geological society (BGS) [10] has published the chart and the list of earth's rare metals and the major countries with the reserves of the mineral availability. The highlights of the 52 list elements at high risk are illustrated in BGSRiskList2011 [10]. Reuters[17] reports suggest the demand for the rare earth metal supply in the range of 40,000 metric tons per year within next several years. The magnets used on the motors of the electric vehicles use neodymium. The price of the magnets determines the cost of the vehicles.

The ubiquitous presence of these elements in technological gadgets vary from mobile phones, wind turbines, flat screen television, rechargeable batteries, electric cars and others drives the demand for the mining of rare earth metals. Recycling of the rare metals used in few electronics would be more expensive and energy-intensive [12].

Electric vehicle battery use Lithium to store energy. The current lithium production is around 20,000 tons of contained lithium material. The main producers of lithium are Chile, USA, Argentina, China, Russia and Australia as illustrated in the table 1. The 'reserves' are defined by USGS does not signify extraction facilities or operative production facility. ‘Reserves’ indicate the recoverable material. The ‘reserve base’ could be economically extracted at the time of determination. The data from global vehicle forecast suggest 60M cars being manufactured each year. Existing Lilon battery for electric vehicles require 1.4 to 1.5 kg of Lithium carbonate equivalent per KwH capacity. The total amount of lithium carbonate to replace 50% of the fleet would require at least 432000 tons of lithium production that will be 25% more than global lithium production [19].

Environmental implication of the usage of rare earth metals has driven various researches in the area of complimenting the innovative strategies in low carbon vehicles. The technology strategy board, UK, has invested in projects such as “Low cost, scalable low rare earth electric motor”[13] and “High Torque density switched reluctance drive system for low carbon vehicles” [14]. Newcastle University center for advanced electric vehicles plays an important role in the latter project. Unlike the current motors relying on the neodymium and dysprosium, the new motors from this research will use steel replacing the use of the rare earth metals. Another promising area of research to save rare earth metal is highly efficient separation of lithium chloride from seawater using membrane technology [27]. The cost for the extraction process is currently overridden by research in South Korea. The Korean Institute of Geo Science and Mineral Resources (KIGAM) has passed the technology to steel maker POSCO to commercialize. An offshore plant and production line is being set up to extract 30 tonnes of lithium annually by 2014 and mass production is likely to start in 2015 [26].

**Battery Performance and Materials:**

The current electric vehicle battery cost between $800-$1000/kWh which leads to 30-50% of the cost of the electric vehicles. The lithium-ion batteries are the most suitable in the current vehicles due to the high energy density and power per unit of battery mass, making it lighter compared to the Ni-MH/ Ni-Cd batteries. Energy density is the key for the better operation of the battery and to store the energy for the longer duration. NiMH batteries can be damaged under discharge conditions. If one cell in a multiple assembly discharges completely, other cells may reverse its polarity and permanently damage the battery. Lead acid batteries are very heavy and last only for few years. The energy density indicates the capacity and the run time of the battery.
The NiMH batteries hold 90Wh/kg, metal hydride hold 29 Wh/Kg, lead acid hold 30-40 Wh/Kg and 110-170 Wh/Kg for Lithium ion battery. The memory effect in Ni-Cd/Ni-MH batteries has less energy capacity and discharge shallowly (Yoshino, 2008) [15] as illustrated in Figure 3. Lithium-ion batteries offer the

![Graph showing energy density and power density for different battery types](image)

Figure 4: Power(acceleration) and energy (range) by battery type (source: www.electromedia.com)

Nanotechnology research shows promising potential material development to increase the performance of the batteries through higher energy density, power and safety. Carbon nanotube (CNT) is anticipated as the next generation anode material for future lithium-ion batteries. CNT is expected to improve performance of the battery by a factor of 10 [22]. The charging of the battery can be improved using Lithium Titanate Oxide as anode, to charge a 35-kWh battery pack in 10 minutes [23]. A nano-sized separator in the battery enhances the safety because of its robustness and stability in high temperatures [24]. The Georgia Institute of Technology developed new silicon and carbon nano-composite anode materials to replace a conventional graphite anode (cellular News 2010) demonstrating fives times increase in the energy capacity. Rice university developed coaxial cable, which is cobalt oxide cathode (NCA) stored inside the CNT. The compound of CNT and NCA improve battery performance significantly [25]. CNT is expected to play a major role in fuel cells, solid metal hydride acting as fuel cell catalyst for hydrogen storage material and lithium ion battery. Arizona State University is researching in Metal-Air-Ionic Liquid(MAIL) batteries promising lower cost, long life using oxidation of metals to yield energy. Ultracapacitors is another area of research used for energy storage to supplement batteries to accept high inputs from regenerative braking.

Research Motivation:

Significant impact is anticipated due to the Electric Vehicles deployment on the local electricity distribution system. Key work on smart grids and smart metering is underway to help support the Electric Vehicle introduction and level out the likely peak-demands for electricity by private households and business. Most important is the attitude of the potential purchasers of electric vehicles, and whether they perceive EV’s ‘fit for purpose’ for their mobility needs, with most EV’s having a maximum range of a 100miles on a full battery charge. To understand this we must analyze the driving and recharging behavior. The charging infrastructure is required at home, work-place, public and commercial premises to support the introduction of electric vehicles. In depth research on the effects of driving style, topology of road network, weather conditions and traffic conditions on the performance and range of electric vehicles is very crucial to fill the knowledge gap and disseminate the findings to potential users customized for the individual needs.

To achieve this, we need to gain a true understanding of how electric vehicles are going to be used. It is therefore necessary to monitor as much of their day-to-day drive cycle as is possible. This is not something, which can be achieved purely through “artificial” test track trials, nor through extrapolation of data from other vehicles. The only method available for producing the amount of data needed is through large scale, on street, public trials of electric vehicles. The North East of England, as a region, has been host to multiple EV projects and trials.

To date there have been two completed instrumented trials of EVs in the North East and one of which is ongoing. The two completed trials were Smart Move 1 [4] and Smart Move 2[9] was conducted by CENEX (the Centre of Excellence for low carbon and fuel cell technologies).
Currently there is a large-scale trial of EVs entitled Switch-EV [5]. Switch-EV is a region-wide project running from 2011 to 2013, which is currently overseeing the deployment of more than 40 vehicles within the region. The vehicles deployed are supplied by a range of companies from international vehicle manufacturers down to local businesses.

**Technology Infrastructure for Research:**

To understand the research objectives and to overcome barriers for the gradual rise of an electric vehicle economy, a supportive technology infrastructure is currently operational to provide the quantitative evidence. We have implemented an integrated eScience infrastructure to compliment our strategic vision for the electric vehicle research.

Each individual vehicle on trial is fitted with the state-of-the-art pervasive sensing systems that track its temporal and spatial movements across the country. The systems are monitored in real time with data loggings every second in our central server.

The key performance indicator (KPI) for tracking and monitoring the vehicles are centered around filtering, transformation and most importantly aggregation of information from multiple systems such as geographic positioning systems, vehicle OBD (on-board diagnostics), CAN (controller area network) messages, traffic control systems and external conditions such as weather. The processing and monitoring infrastructure is designed to operate in both the offline and online mode. Under the offline/batch-processing mode, the KPI’s are calculated at the end of each day, week or a month according to the user needs. In an online mode, a workflow triggered system called eScience Central [6] is used to disseminate the information on each individual trip made by the vehicles.

**ARCHITECTURE:**

The technology architecture is built based on the cloud computing infrastructure to analyze, disseminate and store the data collected from nearly 45 vehicles. The eScience Central is developed as a result of four years of research to provide a generic data analysis platform for scientific applications. The prime importance of the usage of the platform within the project is listed below:

- Store the data collected from all the vehicles.
- Interactively explore the data by giving access to close group of users.
- Analyze the data using workflows
- Share the data and services with secure access.

The data is stored using cloud computing and provide the processing capacity to access the resources according to the demand. The sharing of data and services is provided with a remote access to the users irrespective of the location. To exploit the data in an effective manner three recent trends in the computing is adopted as below:

- **Software as a service**: The platform (eScience central) is delivered as a website accessible from any browser. Features are created to automatically upload the data from the vehicles at the end of each trip. The vehicle suppliers, data analysts and decision makers are give access to the data in a controlled environment.

- **Cloud Computing**: To scale the system according to the number of concurrent users, size of the uploaded data, the system uses cloud computing to provide a cost effective solution to deliver the results.

- **Social Networking**: The system adopts approaches from social networking applications to support the sharing of data and receives feedback from the users providing a rich collaborative environment of interaction.

The system architecture is illustrated as shown in the picture below:
Later, while the paper that describes the results is in the publication process, the scientist may give the editors and reviewers access to the data. Finally, once the paper has been published, the scientist may allow full access to the data, workflows and results. This process of opening the data to wider audiences is likely to depend on the work practices of the scientist and the general attitude to open publication in their scientific community. In some extreme cases, patient confidentiality or other privacy concerns may prevent any sharing of the original data.

After reading the publication, another scientist may be interested in whether his own data might also lead to the same scientific conclusions. He uploads his new data into eScience Central and analyses it using the workflow referenced in the paper. He then uploads a new, improved analysis service he has written and uses it to re-analyse the original data to see if any new, publishable results are produced. Keeping the original data available after publication may also encourage new avenues of research which were not considered at the time of the original paper. For example, the availability of the Enron Corpus has stimulated a diverse range of research into email and Social Network Analysis [7].

**DATA ANALYSIS:**

The detailed quantitative and qualitative analysis will provide answers to key policy questions about the future impact of EVs. In the past two years of our research, Newcastle University is monitoring the electric vehicles usage in the north east of England. The total energy usage from the grid due to electric vehicles is approximately 11,595kwh with 2199 charging events. On an average approximately 8000 journeys were driven by the electric vehicles in a period of 8 months. The data analysis drills down in to each and every individual journey to provide an insight on the usage of electric vehicles.

The key objectives for the data analysis is to monitor the following issues associated with the electric vehicles:

- Performance and usage of electric vehicles
- Charging performance and battery life
- Charging occurrences
- Driving influences
- External influences
- Impact on traffic
- Impact on Environment.

To meet the objectives, the control area network in the vehicles are fitted with sensing equipment to measure the following parameters:

- GPS co-ordinates of the drive events
- Speed
- Instantaneous current & voltage consumption in the battery
- Battery depth of discharge
- Hotel Loads (Air condition status, Windscreen, Doors, Indicators, Lights)
- Braking events
- Gear position
Data analysis is based on a published methodology [6] to determine usage patterns of electric vehicles from different drivers, environment and external conditions. These patterns are revealed from data extracted through the data extracted from controlled area networks (CAN) of the car from smart move [4] trials and SwitchEV trials [5].

The system architecture consists of the hardware embedded within each vehicle, sampling the controlled area network (CAN) and the battery management system (BMS) at a rate of 1Hz. The primary data acquisition system act as a data logger which captures the events from the CAN bus and BMS. The information about each individual journey is captured based on the ignition on and off status. Basic rule base is created to detect the anomalies in the recorded data. The malfunctioning based on equipment or system faults are detected using a set of data processing rule base. The random errors arising out of the signal interference during lack of GPRS or other scenarios are not modeled in the rule base.

The individual event e from vehicle sensors S, location information c, battery state of charge D, current I, voltage V are measured in the regular sampling intervals. Each observation of the logger has (S, L, D, e, T, I, V) at a given instance of time. The typical scenario to create a rule base are explained below:

DEDUPLICATION: The removal of duplicate events from the logging system such as waiting in a traffic signal is mandatory to overlay on the GIS. However, the system will need the energy consumption to assess the carbon footprint and the energy consumption. The dissemination system will need recording of one occurrence of the event but performance assessment system will need to record the micro events in a given window of time frame, if the location information are similar ie.. L = L_{x+1}, the observation is dropped.

ANOMOLY DETECTION: The spurious signals arising due to in-vehicle system interference or GPRS/GPS interference could result in the erroneous voltage, current and the state of charge variation. Under a condition of I > 125 or V < 150 or (D_{x+1} - D_{x})/100 > 0.3, the observations are dropped.

TEMPORAL SYNCHRONISATION: To achieve heterogeneous data integration such as traffic control system, V2V systems and others, the temporal synchronization of the timestamp is achieved in the rule base to correct the drift in observations and further correlation of the data is undertaken.

SPATIAL SYNCHRONISATION: The GPS locations collected from the logging systems need to be overlaid with the charging locations to understand the charging pattern of the vehicles. The GPS tend to drift from the real positions from the road leading to the map-matching scenarios [7].

**BATTERY PERFORMANCE:**

The battery management system (BMS) is a very important feature in the electric vehicle that acts as a component within a multiple cell battery pack. The BMS monitor the state of charge within the vehicles, identifies the operational parameters such as range and also ensure the safety of the battery during the charge/discharge cycles. Cycle life is defined as the number of the charge and discharge a battery can perform before the storage capacity of the battery reduces to 80% of it original capacity. The life of lithium battery is typically around 1000 cycles [29]. The cycle life of the battery has an optimum operating temperature of around 10 to 40 degree Celsius. The current required to charge or discharge the battery cell is indicated by “C” rate. The lower the “C” rate of the battery will indicate the increase battery has an optimum operating temperature of around 10 to 40 degree Celsius. The current required to charge or discharge the battery cell is indicated by “C” rate. The lower the “C” rate of the battery will indicate the increase.

To understand the battery charging and discharging characteristics of the vehicles, we took trips from one vehicle for a period of one year. The main aspects of the battery are the range Y and energy usage. During each charging event the percentage of battery charge (α) is measured. The starting state of charge β_{start} and battery state of charge during the end of the charging interval, β_{end} is measured. The percentage of charge α, during each charging event is measured as β_{end} - β_{start}. Energy usage of the battery is measured as ε.

- Energy discharged between charging interval: ε
- Distance travelled between the charging interval: τ
- Percentage of battery charge: α = β_{end} - β_{start}
- Subset of observed range, Y = [Y_1, Y_2, Y_3, ..., Y_{10}]
- Range: γ = ε / τ

The performance of the battery in electric vehicles is based on the type of usage, hotel loads, vehicle type such as HEV, PHEV, EV and others. Modern compact electric vehicles use battery packs around 1800 to 2000 cells [18]. To obtain a larger driving range, electric vehicles need to maintain a lower power to energy (P/E) ratio and higher energy capacity.
To understand the energy capacity and power consumption, statistics on the trips undertaken by electric vehicles is used. We gathered subset of trips in the range of 1 km to 60 km. The battery discharge from the vehicle is stabilized for the journeys with longer distance. The power consumption is optimized during the long journeys. The graphs shown below represent the power consumption for 3 different trips between the range of 50 -100Km, 10-30km and less than 10km range.

The data is extracted from three users driving a particular vehicle during one-month period. The selected journeys from three users are picked in the same route. By selecting the same journey route, a closer observation on the energy loss can be monitored irrespective of the changes in the topology. The first use case is from journeys less than 5km. It has a mixture of peak hour and non-peak hour driving. On an average the energy consumption for a journey is less than 0.2 kWh/Km under normal city traffic conditions.

In the figure 6, trips less than 10 km is selected from a single user. The journey is selected in such a way that route of travel is similar to each other. The energy consumption is categorized in three different ways and illustrated using the colour red, green and yellow. Considering a trip with 2 km distance travelled by user1. There are three different categories where same distance uses 0.55 kWh, 0.3 kWh and 0.2 kWh. The duration of the trip shows, 3 minutes, 3 minutes and 8 minutes. In the two instances, in spite of the same duration, the aggressive driving behavior resulted in 0.55kWh energy consumption. The stop, start conditions based on the congestion of the road caused the journey to prolong to 8 minutes, however, the energy consumption is 0.2kWh. This provides a good evidence to use the electric vehicles under heavily congested situations or in the urban drive.

Figure 6: Energy usage and trip duration (User 1, Distance under 10 km)

The figure 7, provides the statistics for the trips between 20 and 30 km by one user. The average energy consumption for this user is under 5 kWh for a trip. Given an efficient driving behavior, the journey of 27 km can be accomplished in 4 kWh. By considering the cost of the electricity as 10 pence per kwH, the journey cost would be 40 pence. Even in this case, the same distance of 27 km uses variable energy consumption of 5.1, 4 and 3 kWh. The greener driving style has consumed only 3 kWh energy which is the most desirable eco-friendly driving for electric vehicles.

Figure 7: Energy Usage and Trip Duration (User 2, Distance between 20 and 30 Km)

The figure 8, shows the journey between 40 and 60 km. In this category, the average speed of the driving is increased and the energy consumption varies accordingly. The 44km trip in the figure will show 6.2kwh and 9 kWh energy consumption however the trip duration is around 41 and 42 minutes. The 42 minutes trip has a recorded average speed
higher than the other trip leading to more energy consumption. The optimum energy usage requires maintaining the correct average speed throughout the journey especially in a longer distance driving conditions.

![Energy Usage With Distance](image1)

![Energy Usage Based on Trip Duration](image2)

Figure 8: Energy Usage and Trip Duration (User 3, Distance between 40 to 60 km)

**RANGE ANALYSIS:** The above three trips from the three users, are analyzed for the range achieved by the users. The calculation of range is done as mentioned in the mathematical equations described under battery performance section of this chapter. The figure 9, illustrates the range achieved by the trips in comparison to the energy usage and the distance travelled. In lower speed, the range achieved is consistently higher in all three conditions. As the speed increases, the range of the vehicles falls between 4 and 6.

The range achieved by the vehicles is a factor of average speed undertaken in the trip. However, the important factor to achieve a higher range is driving behavior. The eco-friendly driving behavior is very important to achieve optimum range. The following factors are identified as the parameters for the eco-friendly driving behavior.

1. Anticipate the stopping actions by observing the traffic conditions.
2. Use hand brakes instead of foot brakes.
3. Limit the usage of auxiliary controls which consume electricity
4. Plan the journey such as the regeneration through brakes is achieved
5. Capitalize 10% regeneration on normal roads and 30% regeneration on the declines
6. Avoid heavy acceleration
7. Brake over longer period to trigger regeneration
8. Measure the tyre pressure and avoid excessive weight.

By following the conditions mentioned above, on an average 10 to 25 % of energy savings has been obtained. The regenerative braking is activated in a higher proportion when the above-mentioned driving actions are followed.

![Range With Speed](image3)

![Range With Speed](image4)

Figure 9: Vehicle Speed VS Range (3 Users)
GENERAL DRIVING STATISTICS:

The first two basic statistics to be examined are the average distance of journey undertaken and the average time of that journey. These two variables are not, typically, independent as the time for a journey is obviously highly dependent on the length of the journey however it is enlightening to examine both statistics as the average distance of the journey will give an indication as to the typical range of journey lengths for which the vehicle will be used and the duration of the trip will affect both the total power used (through the excessive use of HOTEL loads) and the driver’s perception of the EV.

![Figure 10](image1.png) The data in the two images represents the frequency of the journey durations for the EV. The right image is only for journeys over 1 minute.

A common occurrence when first encountering the EV for the driver is to key on the ignition and then key off a few seconds later. Mainly due to the surprise at the lack of the expected ignition noise which would be present with an IC vehicle. Removing all journey durations below 1 minute reduced this effect whilst retaining all journeys in which the vehicle was used for its intended purpose.

Figure 2 shows linear relationship between both the duration and distance travelled for a journey and the total battery discharge during that journey. However differences between the two plots may be observed. For the Journey Distance against Battery Discharge there is a much tighter variation in battery discharge for a given journey distance but overall the relationship is less linear than in journey duration. This is especially prevalent for the data above a battery discharge of 10%. The R² value for the data is 0.48 for Duration/Discharge and 0.32 for Distance/Discharge when all valid journeys are calculated. However this changes to 0.24 for Duration/Discharge and 0.32 for Distance/Discharge when only journeys under 10% of battery discharge are calculated.

![Figure 2](image2.png)
Hence, for this set of data, the distance of a journey is the best predictor for the total charge to be used when the distance is under approximately 5km, for journeys of a greater length than this it is more accurate to use the predicted duration of the journey. This very simple analysis used a linear polynomial model to match the battery discharge to the duration or distance.

**Energy Grid and Carbon Emissions:**

Electric vehicle usage provides considerable reduction in greenhouse gas emissions. The inexpensive cost to drive in electrified vehicle is the motivating factor for consumers to adopt electric vehicles. On an average, the electric vehicle charged from US grid emit around 115g/km of carbon-di-oxide emissions based on the wheel-to-wheel analysis. The IC engines emit 250g/km under the similar American conditions [ ]. In Europe, the grid emissions calculation varies between each country due to the usage of renewable energy sources. For example, France has clean energy grid where wheel-to-wheel emissions from electric vehicle will be around 12g/km [ ].

In this study, we provide the analysis of the impact from UK energy production through national energy grid. The energy in UK is generated using coal, natural gas, nuclear and renewable energy. We monitor the average gram of carbon-di-oxide per KWhr of electricity generated in UK on a thirty-minute sample. The estimate of carbon-di-oxide emissions from the electric grid is arrived based on the time of the charging of the vehicle. Recharging time of the electric vehicle is very critical to determine the carbon footprint generated by the electric vehicle.

![Figure 11: The images presented here show the variation in battery discharge over different distances and durations.](image1)

In our electric vehicle study, the vehicle charging time and duration of the charging is recorded in the automated process. The energy grid is fed with power stations with varying carbon intensity. To obtain the in depth carbon emission statistics, the charging duration is split to 4 different categories as illustrated in figure 13. The greener source of electricity is available between 10:00 PM and 1:00 AM. The colour in the chart is coded green according to the statistics available for a particular region. Analyzing the charging pattern for the past 10 months of the electric vehicles trial, we conclude each user has different carbon emissions according to the charging conditions. The user 3 has the least carbon emissions based on his maximum charging is between 1AM to 8 AM. The user 8 has the greener charging profile compared to the other users in the study. The user 4 seems to be charging in the early hours of the morning. Given this charging happens in a street where there are more than 5 electric vehicles, this would impact the electric grid. In the mornings, the appliances in home are heavily used as well, so this usage pattern when reflected in higher number of closely located electric vehicle charging is a concern.
The utility and the grid operator have the challenge of providing sustained power delivery to the electric vehicles through the charging stations. The utility companies and the electricity grid need to anticipate the charging pattern of the electric vehicle user. In UK grid, the off peak electricity is supplied through the renewable energy sources. The consumption of the electricity from the grid due to combined demand from consumers would increase the peak time energy usage in some areas. However, the local distribution equipment will be put at risk given several EV users simultaneously charge their vehicle. The charging of electric vehicles is categorized in four different modes. In mode 1, the charging is done using a regular single phase or three phase electric socket. In mode 2, slow charging with additional electric vehicle specific protection is embedded in the charging unit. Mode 3 charging use slow or fast charging points with control and protection specifications as stated in SAE J1772 and IEC 62196. In mode 4, special charger technology for exclusive fast charging option is used. Even in the slower (mode 1 or 2) charging rate, five or more electric vehicle along with the household energy usage can overwhelm the transformer leading to the equipment failure. The research [30] [31] [32] indicates reverse power flow in distribution networks causing bidirectional power flow could damage the network protection systems and phase imbalance.

Penetration of smart meters opens a new revenue stream to charge electric vehicles that would provide incentive to capitalize the under-utilized energy feeds. Under intelligent design of control systems, electric vehicles can provide supply/demand matching and reactive power support [33]. The results of the research [34] show the violation of supply/demand matching and statutory voltage limits leading to power quality problems and voltage imbalance. The power problems are unlikely to exceed the statutory limits if the electric vehicles are charging in widely distributed locations.

The environmental advantages of the electric vehicles will expand further due to the usage of renewable energy usage. The price of the fossil fuel is likely to increase in the coming years whereas the price of electricity is likely to remain the same due to various source of energy generation.

In our electric vehicle study, energy consumption and the distance travelled by the vehicles are recorded. This provides a very detailed results on the total energy consumed in the past 10 months from a subset of 14 vehicles. The distance travelled by 14 vehicles is approximately 84,520 km and the energy consumption is around 24959 kWh.

Energy consumption for each vehicle and the distance travelled is illustrated in the figure 14. The figure also provides the efficiency of the driving achieved by each user in terms of the carbon footprint. Out of the 14 vehicles observed in this study, the user 6 has the least carbon footprint by achieving highest range among the given users. The user 2 has the highest carbon footprint based on the range achieved in the driving. On drilling down to the details, the user 2 has made longer journeys with higher average speed which could have reduced the range of the vehicle.

The analysis of the energy consumption and source of energy during charging provides a very accurate profile of the carbon emissions.
COMPARISON OF IC ENGINE WITH ELECTRIC VEHICLES:

The internal combustion engine based cars use fossil fuels and become a source of carbon emissions. In our research, we analyze the data from various trips carried out in the electric vehicles and modeled the energy consumption with equivalent fuel consumption from an Internal Combustion Engine.

The United Kingdom sets vehicle tax based on the carbon emissions and provide various tools to assess the carbon emissions. All data to calculate the fossil fuel consumption is available to public [36]. The tools provided by the government are available to the public as part of the rationalization program.

Based on the age of the car, the fossil fuel consumption increases and efficiency of the engine decreases over time. The table below denotes the carbon emissions from the new cars available for sale in United Kingdom. The new cars are the one that is currently available to buy or lease from a dealer and not registered under the vehicle certification agency (VCA). The VCA provides certification to vehicles running in UK adhering to global standards such as ISO 9001, OHSAS 18001, ISO TS 16949, ISO14001, ACORN (Environmental Certification) and EMAS [37].

<table>
<thead>
<tr>
<th>Bands</th>
<th>CO₂ emission figure (g/km) *</th>
<th>12 months</th>
<th>6 months</th>
<th>12 months</th>
<th>6 months</th>
<th>12 months</th>
<th>6 months</th>
<th>12 months</th>
<th>6 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band A</td>
<td>Up to 100</td>
<td>£0.00</td>
<td>£0.00</td>
<td>£0.00</td>
<td>£0.00</td>
<td>£0.00</td>
<td>£0.00</td>
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<tr>
<td>Band B</td>
<td>101 - 110</td>
<td>£0.00</td>
<td>£20.00</td>
<td>£0.00</td>
<td>£10.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band C</td>
<td>111 - 120</td>
<td>£0.00</td>
<td>£30.00</td>
<td>£0.00</td>
<td>£20.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band D</td>
<td>121 - 130</td>
<td>£0.00</td>
<td>£60.00</td>
<td>£52.25</td>
<td>£85.00</td>
<td>£46.75</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Band E</td>
<td>131 - 140</td>
<td>£115.00</td>
<td>£62.25</td>
<td>£115.00</td>
<td>£62.25</td>
<td>£103.00</td>
<td>£57.75</td>
<td>£103.00</td>
<td>£57.75</td>
</tr>
<tr>
<td>Band F</td>
<td>141 - 150</td>
<td>£130.00</td>
<td>£71.50</td>
<td>£130.00</td>
<td>£71.50</td>
<td>£120.00</td>
<td>£66.00</td>
<td>£120.00</td>
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</tr>
<tr>
<td>Band G</td>
<td>151 - 165</td>
<td>£165.00</td>
<td>£90.75</td>
<td>£165.00</td>
<td>£90.75</td>
<td>£155.00</td>
<td>£85.25</td>
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<tr>
<td>Band H</td>
<td>166 - 175</td>
<td>£265.00</td>
<td>£190.00</td>
<td>£235.00</td>
<td>£180.00</td>
<td>£99.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band I</td>
<td>176 - 185</td>
<td>£315.00</td>
<td>£210.00</td>
<td>£115.90</td>
<td>£305.00</td>
<td>£200.00</td>
<td>£110.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band J</td>
<td>186 - 200</td>
<td>£445.00</td>
<td>£245.00</td>
<td>£134.75</td>
<td>£435.00</td>
<td>£235.00</td>
<td>£129.25</td>
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<tr>
<td>Band K</td>
<td>201 - 225</td>
<td>£580.00</td>
<td>£260.00</td>
<td>£143.00</td>
<td>£570.00</td>
<td>£250.00</td>
<td>£137.50</td>
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<tr>
<td>Band L</td>
<td>220 - 255</td>
<td>£790.00</td>
<td>£445.00</td>
<td>£244.75</td>
<td>£780.00</td>
<td>£430.00</td>
<td>£239.25</td>
<td></td>
<td></td>
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<tr>
<td>Band M</td>
<td>Over 255</td>
<td>£1000.00</td>
<td>£460.00</td>
<td>£253.00</td>
<td>£990.00</td>
<td>£450.00</td>
<td>£247.50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* g/km = grams of CO₂ produced with each kilometre travelled.

Figure 15: Environmental Emissions from various cars. Source: DVLA, UK

Vehicles are divided into 13 major categories, starting from Band A to Band M based on the fuel consumption and the carbon emissions. Most countries provide mandatory rules to set environmental safety standards.
Based on the energy consumption and the charging profiles collected in the electric vehicles trial, we started a detailed comparison of the electric vehicles with the IC engines. The electric vehicles fall under the band A. The carbon emissions are calculated based on the total energy consumed by the electric vehicle. The same energy usage is used to measure the carbon emissions for various category of the IC engines. The fossil fuels emit more carbon and it is categorized for each vehicle.

Out of the 14 vehicles, we tried to provide a comparison in figure 16, based on the individual vehicle being replaced by the IC engine. For instance if the vehicle identifier 9, in the figure is replaced by IC engine, the statistics will be as follows. Older the vehicles, carbon emission becomes higher. Using the similar methodology, each electric vehicle is replaced with the IC engines and the carbon emissions are calculated as illustrated in figure 16.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Carbon Emissions (measured in tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band A</td>
<td>0.9</td>
</tr>
<tr>
<td>Band B</td>
<td>1.05</td>
</tr>
<tr>
<td>Band C</td>
<td>1.14</td>
</tr>
<tr>
<td>Band D</td>
<td>1.24</td>
</tr>
<tr>
<td>Band E</td>
<td>1.33</td>
</tr>
<tr>
<td>Band F</td>
<td>1.43</td>
</tr>
<tr>
<td>Band G</td>
<td>1.57</td>
</tr>
<tr>
<td>Band H</td>
<td>1.67</td>
</tr>
<tr>
<td>Band I</td>
<td>1.76</td>
</tr>
<tr>
<td>Band J</td>
<td>1.91</td>
</tr>
</tbody>
</table>

Table 1: Carbon Emissions comparison between vehicle types.

To cut down the emissions, many local authorities have declared air quality management areas mainly due to huge traffic and pollution level from transport related fossil fuel usage. The House of Commons Air Quality - Environment Audit Committee report for 2010 indicates 50,000 deaths in the UK annually due to air pollution. Detrimental effects from the

**ATMOSPHERIC EMISSIONS COMPARISON BETWEEN ELECTRIC VEHICLES AND IC ENGINES:**

The United Kingdom emission factors are based on the National Atmospheric Emission Inventory (NAEI) and green house gas inventory (GHGI). Data from both the organizations are compiled by AEA on behalf of the Department for Environment, Food and Rural Affairs, Department for Energy and Climate change, Welsh Assemble Government, Scottish government and Department of the environment for Northern Ireland. The organizations produce 1km²
emission maps under the NAEI system. The emission maps are created based on the emissions from 10 sectors other than transport. The mapped carbon emissions are available to the public at NAEI website [41].

CO and NOx are the most common pollutant arising from the vehicles. The pollution based on the energy consumption and the distance travelled by each vehicle is used to estimate the amount of atmospheric emissions. Electric vehicles are a zero emission, environmentally friendly car. Given the scenario that the petrol vehicle replaces the electric vehicle, we modeled the CO and NO2 emissions as shown in the figure 17 and 18.

The emission varies between the various conditions of driving such as urban, rural and motorways. The three conditions are modeled in our study and the results are illustrated.

![CO emissions for Petrol Vehicles](image)

**Figure 17:** CO emissions when petrol vehicles replace the electric vehicles in trial.

![NOx Emissions For Petrol Vehicles](image)

**Figure 18:** NOx emissions when petrol vehicles replace the electric vehicles in trial.

**CONCLUSION:**

One of the important advantages of Electric Vehicles is their comparatively low equivalent CO2 emission per km compared to traditional engine vehicles. However, different charging patterns can affect the equivalent CO2 emissions due to the daily cycle of power mix used to supply the electricity grid. By closely monitoring how users charge their vehicles, and specifically at what time and for how long, it will be possible to put a definite environmental cost on the power transferred to an EV, and hence to the usage of that EV. The extensive data archival of the electric vehicle trials will provide the impacts on the fossil fuel consumption. Understanding the information from research will allow the infrastructure and policy makers to complement the transport sector with alternative sources of fuels through customized charging times and support systems. By adopting sustainable energy objectives through renewable energy sources, smart metering and smart charging the transport sector can reduce the green house gases and pollutants thereby reducing the amount of fossil fuel usage.

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**REFERENCE:**


[2] Royal Academy of Engineering: EV Charged with potential