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The investigation of the major factors influencing plug-in electric vehicle driving patterns and charging behaviour

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ABSTRACT

All major vehicle manufacturers now have, or plan to have, an electric vehicle model (EVs) on the market. Current EV take up rates are relatively slow, but the main factors that will determine take up rates are complex and unpredictable. A rapid and large increase in the take up rates over the coming years is therefore possible and probable. Such a rapid take up rate, if it occurs, would impact on electricity load and load profiles. Determining what the impacts will be, however, is made difficult as recharging behaviours of EV drivers are not well known or understood in advance. While a number of research studies have reviewed the methods that can be used to control the recharging profiles of EVs, this paper focuses on EV driver recharging behaviours and charging patterns and reviews and presents the major technical, environmental and economical factors that will influence these.

Contents

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1. Introduction

Electric vehicles (EVs) have started to appear on the market. All major vehicle manufacturers offer, or plan to offer in the near future, an EV model. This suggests that EVs could potentially represent a significant portion of the vehicle fleet in the future. High EV penetration rates would have a number of social, environmental and economic benefits, one major benefit being reduced oil consumption and reduced national reliance on imported oil products. Government policies are therefore likely to be geared to encourage accelerating EV take up rates. Accurately projecting EV take up rates at this very early stage in the market, however, is difficult and is made more difficult by the fact that the main determinants of take up rates, such as world oil prices and future battery costs, are unpredictable. This uncertainty of EV take up rates and the possibility of an unexpected surge in EV take up rates at any stage present major challenges for electricity distribution network operators. Rapid high EV penetration rates would result in EV recharging loads increasing to become a substantial part of the overall electricity load. It is not only the number of EVs in the vehicle fleet, but also the recharging behaviour of EV drivers that will determine the degree to which any sudden increase in load will be problematical for network operators. If, for instance, a large number of EV owners started to recharge their EVs at the same time in the day, and that occurred during peak load periods, it would have the potential to increase peak loads and to impact negatively on the reliable operation of the grid. It will therefore important to be able to predict the recharging behaviour of EV drivers, which will be determined in turn by vehicle technology as well as by recharging behaviour

This paper considers EV driver recharging behaviour in terms of time of day, duration and frequency of the recharging events and the electricity required to recharge the vehicle batteries. The major factors that could influence the recharging behaviour and driving pattern are grouped into three domains, named the transport domain (EV penetration rate, charging infrastructure), the vehicle technology domain (battery performance, cost) and the power system domain. These factors are discussed in terms of their likely impact on EV driving behaviour and charging patterns. The results of a trial used to study recharging behaviour are then presented.

2. Electric vehicle study overview

The driving behaviours or patterns of EV owners are likely to be very different to those of conventional internal combustion engine (ICE) vehicle owners, as they will be determined primarily by recharging and recharging management requirements. Currently, the driving behaviours and charging patterns of EV owners are unknown and this creates challenges for both transport planning and electricity planning. In order to manage these challenges it will be essential to obtain a better understanding of how EV drivers' mobility and driving patterns will differ from the current driving patterns of drivers of conventional ICE vehicles as these changes will determine EV recharging electricity loads and, therefore, the extent to which the other potential benefits of EVs, such as reduced emissions, will be achieved.

To address the fundamental concerns about the potential impacts that both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), together referred to in this paper as Plug-in Electric Vehicles (PEVs) or simply as Electric Vehicles (EVs), may have on the electricity grid as well as on environmental and climate impacts, assessing EV driving patterns and recharging is essential and will allow planners to manage the electricity grid to accommodate PHEVs and BEVs. Vehicle manufacturers and climate policy regulators also stand to benefit from a more thorough understanding of recharging behaviour, while battery manufacturers would benefit by being able to more accurately model battery life and cost. For energy planners, the charging behaviour of EVs is an important factor in the integration of EVs to the electric grid, as this will affect the recharging demand, which could become a major component of overall load on the electricity supply system.

The recharging behaviour of EV owners will be determined by various environmental, economical and technical factors, such as the number of EVs being charged (EV penetration trend), the availability of charging infrastructure, charging voltage and current levels, charging time, state of the battery technology, including battery specification, battery lifetime and capacity, which are all considered as technical aspects of EVs [1]. The interconnection between the power supply system, the transportation system and vehicle technology are shown in Fig. 1. Factors relating to each of these three domains will affect EV users' behaviours.

The study of electric vehicle integration and its impact on the electricity grid began in the 1980s. Several studies have been undertaken to estimate EV penetration growth rate in different regions and their potential impacts on electricity loads [2–6]. A common finding of these studies was that unmanaged charging demand is likely to coincide with the overall peak load on the grid [7]. These studies all focused primarily on the question of whether the existing and planned generation capacity would be sufficient to meet the resulting increase in load [8]. A thorough analysis of EV penetration into the regional power grid, for example, was undertaken by the Oak Ridge National Laboratory (ORNL) in the USA. That study found that all regions in the USA would need additional capacity to cover the increase in load.

Other studies have focused on the impact of EV penetration on the high voltage transmission supply infrastructure [6,9,10]. The majority of studies, however, have concentrated on the impact that EV recharging is likely to have at the distribution network level. An evaluation of the potential impacts of BEV and PHEV charging load on the distribution network components and its operation, however, requires a micro-level analysis that takes into account potential variations in spatial diversity of EVs throughout the network as well as temporal diversity in charging patterns and how these relate to the traditional system load [8,11]. The concepts of smart charging and demand response management have therefore been proposed, with the aim of optimising the recharging of EVs in terms of reducing the impacts on the distribution network [11–14].

A number of studies have found that the integration of distributed generation, such as small-scale renewable generators into EV charging infrastructure, could reduce the potential negative impacts that additional EV loads will have on the electricity network [15]. In more recent years, the focus of these studies of EV recharging has shifted towards analysing factors resulting from the EVs' extra load on the grid. The factors include driving patterns, charging behaviour, energy cost optimisation, and battery longevity [16–20].

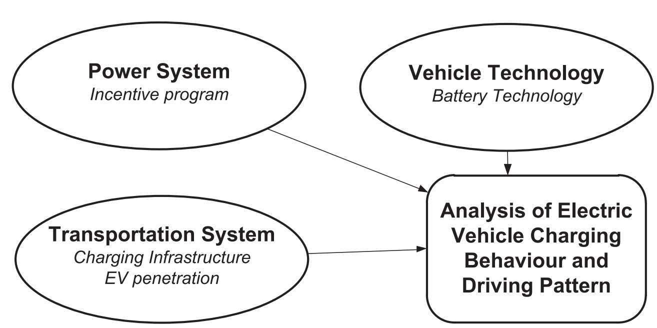

Fig. 1. EV charging behaviour and driving pattern analysis.

3. Factors influencing charging strategy and driving patterns

The recharging behaviours of EV owners will be determined by a number of factors. These can be grouped into three main domains: the transport domain, the vehicle technology domain, and the power system domain. The details of these three domains and the related factors are discussed in the following sections.

3.1. Transport domain

3.1.1. Projected penetration

Transportation is critical to almost every aspect of modern human activity. The current very high dependency of the transportation system on fossil fuels and on oil in particular holds major economic, social and environmental risks. Reducing transportation energy consumption and transportation related emissions will be challenging. Improvements in technology, by themselves, will not be sufficient and behavioural changes will also be essential. Transportation behaviour changes will involve not only choosing a fuel efficient vehicle, but also changing both the way the vehicle is used and driving patterns [8].

The results of recent studies suggest that EV uptake rates are likely to be non-linear [19,21–23]. They are also currently at very low levels and both of these mean that at this early stage in EV market development, future EV penetration levels are difficult to predict. This is reflected in the large divergence of the projections that have been made. The EPRI and Natural Resources Defence Council (NRDC) predicted that PHEV sales would account for 37% of new vehicle purchases by 2020, 52% by 2035 and 62% by 2050 in the USA [3]. The US Department of Energy forecasted that sales of hybrids and PHEVs will reach 50–54% of total sales by 2030 [3]. The Boston Consulting Group and Deutsche Bank, however, have separately forecasted that the electric vehicles in the North American market will make up 1–5% by 2020, based on energy prices and government regulations [24].

This lack of predictability, combined with potentially rapid and large uptake rates under certain conditions or scenarios, holds the potential for unanticipated growth in electricity demand. If the capacity of the electricity supply system is reached rapidly it could have a negative impact on EV take up rates as constrained electricity supply system could slow further EV take up rates. If this occurred, it would that the potential economic, social, and environmental benefits that that a rapid uptake of EVs offers would be delayed.

Several other studies attempted to predict EV market penetration levels. These include studies undertaken by the Massachusetts Institute of Technology (MIT), the Electric Power Institute (EPRI), the National Renewable Energy Laboratory (NREL), the Argon National Laboratory (ANL), the International Energy Agency (IEA) and the Indiana University [22]. The last of these studies revealed that the market factors with largest influence on EV uptake rates are energy prices, battery characteristic (such as safety, reliability and production cost), availability of convenient, affordable recharging infrastructure and the development trend of PEVs compared to competing technologies such as improved fuel efficiencies of internal combustion engine vehicles, conventional hybrids, advanced biofuels, natural gas vehicles, and fuel cell vehicles [25].

Predicting likely EV market penetration rates is made more difficulty by the fact that there are expected to be significant regional differences in EV take up rates. A range of potential market penetration rates have been projected for different regions and a number of countries including USA, Canada, Japan, South Korea, Israel, China. Some European Union Member (EUM) countries have established EV development targets, policies, and plans to deploy EVs successfully as shown in Table 1 [26].

3.1.2. Recharging infrastructure

EV types and locations of EV recharging infrastructure are likely to be a critical determinants of EV market development. The locations of EV recharging stations will influence EV driving patterns. Having access to fast-charging facilities for longer journeys, for example, will encourage members of the public to adopt the EV technology faster.

The results of a study by the Tokyo Electric Power Company (TEPCO) over the period of 2007–2009 suggest that the availability of fast charging stations will be essential in the successful development of EVs and will have a massive effect on user behaviour. It was observed that EV drivers using standard recharging stations returned with, on average, 50% of remaining charge but that when using fast chargers, EV users came back with much less charge remaining in their batteries and also that driving distances increased [27].

In addition to the types of charging infrastructure, the location for EV recharging infrastructure is also categorised by charging power levels of EVs. The EPRI defined three charging levels as shown in Table 2 and these were codified in the National Electric Code (NEC) in 1994, along with corresponding functionality requirements and safety systems [28].

Based on the Society of Automotive Engineers (SAE) terminology, 'level' is defined for North America and term mode is defined in the International Electrotechnical Commission (IEC) standard in Europe. The IEC 61851-1 has defined four conductive charging modes. Modes 1 to 3 are referred to as charging with an on-board charger in the vehicle, while mode 4 refers to the use of an 'off-board charger'. Table 3 lists the four charging modes defined by the IEC.

Level 1 charging is referred to as 'slow charging' and is achieved through a standard 120 V AC, 15 A or 20 A, based on the vehicle technology, battery type, and capacity. This is the lowest common voltage level for residential and commercial buildings in the USA. Recharging time can take anywhere from three to 24 h for PHEVs/PEVs. Level 1 charging is particularly suitable for overnight charging and the charging equipment is usually installed on the

Table 1
Global EV penetration target.

Country	EV uptake target	Country	EV uptake target
North America	37% by 2020; 52% by 2035; 62% by 2050 [24]	UK	350,000 by 2020 [25]
Canada	500,000 by 2018 [26]	Sweden	600,000 by 2020 [25]
Australia	2020: 20% production; up to 65% mass production by 2050 [26]	Spain	One million by 2014
New Zealand	2020: 5% market share; 2040: 60% market share [26]	The Netherlands	200,000 by 2040 [25]
Germany	One million by 2020 [27]	Ireland	2020: 230,000; 2030: 40% market share [25]
France	Two million by 2020 [25]	Japan	50% of new vehicles by 2020 [25]
Belgium	30% by 2030 [28]	South Korea	10% of small vehicles by 2020 [25]
Denmark	200,000 by 2020 [25]	Israel	40,000–100,000 EVs by 2012
Switzerland	145,000 by 2020 [25]	China	Five million by 2020 [25]

Table 2
Types of charging infrastructure based on SAE standard.

Charging level	Level 1	Level 2 (primary)	Level 3 (fast)
Nominal supply voltage (V)	120 V AC (US) single phase/230 V AC (EU)	208–240 V AC single phase	600 V DC maximum three phase
Maximum current (A)	12–15	32	400
Power provided (kW)	1.44	3.3	–
Available infrastructure	Residential/commercial	Residential/commercial	Commercial
Connector type	General outlet	EVSE conductive/inductive	EVSE
Time to charge (h)	4–11/11–36	1–4/2–6/2–3	50% of charge in 15 min
Vehicle technology	PHEVs (5–15 kW h)/EVs (16–50 kW h)	PHEVs (5–15 kW h)/EVs (16–30 kW h)/EVs (30–50 kW h)/EVs	EVs (20–50 kW h)
Branch circuit breaker rating (A)	15 A (min)	40 A	As required

Table 3
Types of charging infrastructure based on IEC standard.

Charging mode	Nominal supply voltage (V)	Single phase	Three phase	Charger type
Mode 1	250 V AC (single phase)/480 V AC (three phase)	Max 16A 3.7 kW	Max 16A 11 kW	On-board
Mode 2			Max 32A 22 kW	
Mode 3			Max 63A 43.5 kW	
Mode 4	–	–	400A DC	Off-board

vehicle and the supply is brought to the vehicle via a standard plug and cord [29,30].

Level 2 charging is usually termed the ‘primary’ and ‘standard’ method for charging the battery of an electric vehicle at both private and public facilities. Level 2 provides alternating current (AC) electricity to the vehicle. It uses a 240 V AC, single-phase, 40 A branch circuit. The vehicle's on-board equipment converts the AC to the direct current (DC) required to charge the batteries with a higher level of safety as required by the NEC. Two types of Level 2 charging equipment have been developed: ‘conductive’ and ‘inductive’ which is generally referred to as the electric vehicle supply equipment (EVSE) [29,30].

Level 3 charging is a high-voltage DC ‘fast charging’ for commercial and public applications. Battery electric vehicles achieve a 50% charge in 10–15 min. This is referred to as ‘fast charging’. Level 3 charging and is intended to be equivalent to refuelling a conventional ICE vehicle at a petrol station [29,30]. Level 3 charging would significantly reduce the charging time, enabling long distance travel. The maximum current specified is 400 A. Level 3 uses an off-board charger system that is serviced by a three-phase circuit at 208 V AC, 480 V AC, or 600 V AC. Charging equipment sizes vary from 60 to 150 kW [29,30].

3.2. *Vehicle technology domain*

3.2.1. *Battery system*

Batteries have key role in EV performance, as the energy consumption is associated with the battery system efficiency. Hence, the in-depth understanding of a battery's system and characteristic is important in the utilisation and functionality of EVs. There are two main components in a PEV's battery system: the battery pack and the battery management system (BMS). The BMS is the brain of the battery pack. It constantly controls the functionality and charge of the battery's cells, monitors the state of the battery's charge, and predicts the actual amount of energy that can be delivered to the load. Since the performance of the battery depends on its useable capacity and internal resistance, this is crucial in lengthening the life of the battery [31]. The battery management functions are defined as three main categories, including protection function, optimisation function, and display and diagnose functions as shown in Fig. 2 [32].

3.2.1.1. Battery pack. In any PHEV architecture, the battery plays a critical role in storing energy from the electricity grid and from the petrol engine (through a generator), as well as transferring energy via an electric motor to maximise efficiency. Ultimately, the commercial success of the PHEV depends on the development of appropriate battery technologies [33].

A battery pack consists of several mechanical and electrical component systems. It contains battery cells that are characterised by different chemistries, sizes, and shapes. The battery cells are connected in series or parallel configurations to achieve the required total voltage and current levels [28].

3.2.1.2. Battery characteristics. To discuss the advantages of one battery technology over others, it is useful to identify the characteristics of an ideal battery. The most important characteristics of an ideal battery are power density, energy density, safety, cost, and durability as shown in Fig. 3 [28].

Energy density is defined as the amount of energy that can be stored in the battery per mass of the battery and is measured in watt-hours per kilogram (W h/kg) or kilojoules per kilogram (kJ/kg). The battery energy density is the most important criterion for an EV because the amount of energy that a battery can store determines the maximum range of the EV.

Power density is the amount of power that the battery can deliver per mass safely without damaging the battery and is expressed as W/m which indicates the efficiency of a battery pack [28].

Safety is defined as being protected from out-of-tolerance operating conditions and is a considerable issue for an EV battery due to the potential risks to drivers and passengers. Undesirable use conditions (off-normal conditions) include electrical short circuit and over voltage (Electrical), thermal runaway, and crush and nail penetration (Mechanical) [34]. The key characteristics of EV batteries are defined in Table 4.

Battery lifetime is defined with respect to both Calendar life and Cycle life. Calendar life is the expected life span of the battery under storage. It can be strongly related to the temperature and State of Charge (SOC) during storage, independent of how the battery is used. Cycle life refers to deep cycle life and shallow cycle life. Deep cycle life is the number of complete charges–discharges that a battery performs in charging mode, which is normally 80%. Shallow cycle life refers to variation in SOC. These frequent

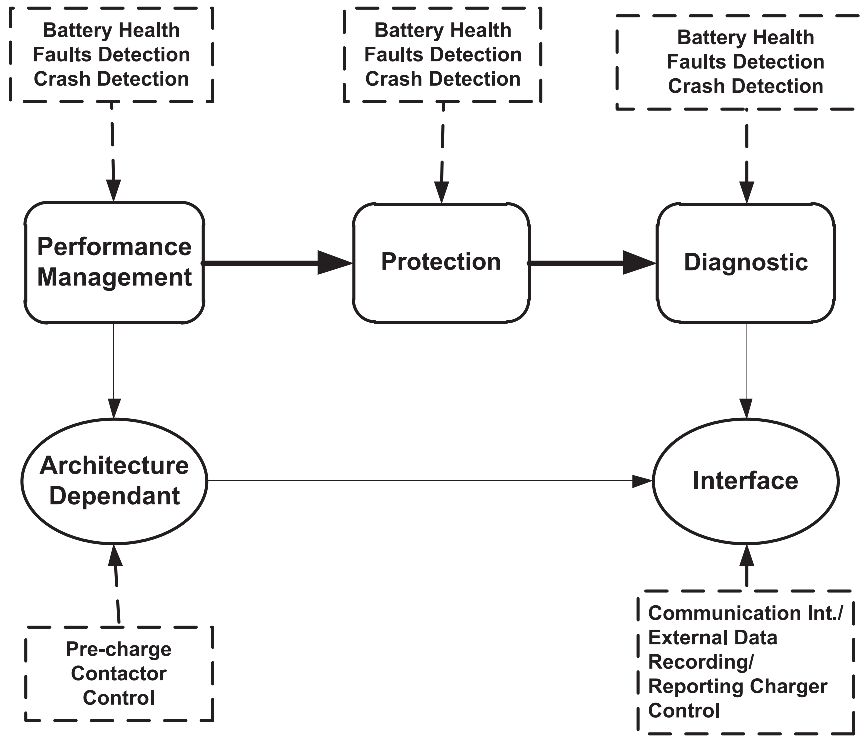

Fig. 2. Battery management function.

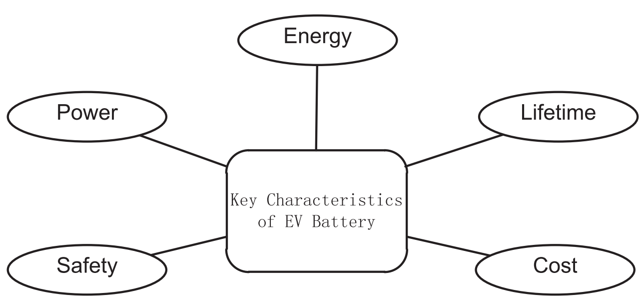

Fig. 3. EV battery characteristics [36].

Table 4
Key characteristics of EV battery [37,38].

Battery key Characteristic	Definition
Energy density	How much energy can be stored in the battery per mass of the battery? The energy density is measured in watt-hours per kilogram (W h/kg) or kilojoules per kilogram (kJ/kg)
Power density	The amount of power the battery can deliver per mass without causing harm to the battery [30]
Lifetime	This usually depends on the energy management of the battery and is defined with respect to Cycle life, Calendar life, Deep cycle life, and Shallow cycle life
Safety	Condition of being protected from out-of-tolerance operating criteria such as over voltage, thermal variation and mechanical shock

shallow cycles cause less degradation than deep cycles, but still affect longevity [35].

State of charge (*SOC*) is the remaining capacity of a battery and it is influenced by its operating conditions, such as load current and temperature [36].

$$SOC = \frac{remaining\ capacity}{rated\ capacity}$$

State of health (*SOH*) is the ratio of the maximum charge capacity of an aged battery to the maximum charge capacity when the battery was new. SOH is an important parameter for indicating the degree of performance degradation of a battery and for estimating the battery remaining lifetime [36].

$$SOH = \frac{aged\ energy\ capacity}{rated\ energy\ capacity}$$

3.2.1.3. Battery cost. Battery cost is the most crucial factor affecting commercial deployment of electric vehicles and has the most significant influence on vehicle price. Hence, electric vehicles and hybrid electric vehicles face the issue of affordability at the cost of performance [35]. The way EV drivers charge their vehicle affects degradation of the battery performance in terms of power, energy capacity, safety and potential replacement cost. Popular models of conventional cars lose 50% to 60% of their initial value (purchase price) after three years. The depreciation rate of EVs is likely to be higher and the cost of replacing the battery in an EV is therefore likely to exceed the depreciated value of the car. This could lead EV owners to operate their EVs at low SOC levels [37].

The safety, durability, and performance of batteries are highly dependent on how they are charged or discharged. Abuse of a battery can significantly reduce its life and can be dangerous. Recent studies have focused on the how driving and charging behaviour (strategy) have influenced by battery lifetime [38]. These studies have shown that driving profile obtained from the EVs' charging behaviour can be used to predict the lifetime of a battery. The analysis of comprehensive lithium-ion battery aging tests shows that high battery SOC decreases battery lifetime, whereas the cycling of batteries at medium SOC has only a minor contribution to aging [18]. Another study of EV deployment on the distribution grid by monitoring real EVs driving behaviour in Germany has shown that charging strategies and behaviour have significant influence on the battery operation [18].

3.2.1.4. Battery technology. The two most common battery chemistry technologies used in EVs are lithium-ion (Li-Ion) and nickel metal hydride (Ni-MH) because both have relatively high energy densities. Lithium-ion technology has the potential to meet the requirements of a broader variety of EVs. Lithium batteries have increased market share due to their lightweight nature and potential for high voltage and slow loss of charge when not in use, which enables them to have higher power than Ni-MH batteries do [39].

A lithium-ion battery has the highest energy density among the entire rechargeable cell chemistries. The main concern in the development of lithium-ion battery packs for EVs is thermal management. The temperature of all cells must be precisely maintained within a few degrees Celsius across the entire pack. Thus, the charging and discharging of a lithium-ion battery should be very accurate in order to maintain an optimum internal temperature to attain maximum performance [7]. Among battery chemistries, lithium-ion has more advantages compared to more mature chemistries, such as Ni-MH. The cell voltage of a lithium-ion battery is three times higher than that of Ni-MH. Lithium-ion battery chemistry has higher energy density per unit volume, which makes it possible to have a lighter and smaller size battery system [28].

The current generation of lithium-ion batteries commonly use a carbon-based anode and a metal oxide cathode. Research on next generation lithium batteries is expected to continue to develop electrode and electrolyte materials that will increase the life and the energy density of the battery while reducing battery size and weight. The most promising options appear to involve silicon, sulphur, and air (oxygen) [40].

The recent battery research efforts worldwide are focused around cell chemistry seeking improved power density, thermal management, lifespan, and stability at a reasonable price. Efforts are directed towards developing customised battery packs for different EVs shown in Table 5 [2].

Table 5
Comparison of Li-ion with Ni-MH battery technology.

Characteristic	Li-ion	Ni-MH
Energy density (W h/kg)	94	57
Power density (W/kg)	540	250
Cycle life (cycles)	> 3200	> 3000

3.2.2. Charging system

To understand the process of charging an EV and to assess the charging strategy of an EV's user, it is essential to have an in-depth knowledge of the safe transfer of energy between the electric utility and an electric vehicle and all components associated with the charging process. Fig. 4 shows an energy transfer system used for electric vehicles [36].

Power is delivered to the EV's onboard battery through the EV inlet to the charger. The charger converts AC to the DC that is required to charge the battery. The charger and the EV inlet are considered part of the EV. A connector is a device that, by insertion into an EV inlet, establishes an electrical connection to the electric vehicle for the purpose of charging and information exchange. The EV inlet and connector together are referred to as the coupler. The EVSE consists of the connector, cord, and interface to utility power. The interface between the EVSE and utility power will be directly 'hardwired' to a control device [41]

Energy Transfer System (ETS) refers to the transfer of electrical energy from the electricity supply network to an electric vehicle. It is responsible for three main functions: to determine when the vehicle and EVSE are ready for energy transfer; to switch and convert AC electrical power to DC; and to control the transfer of energy to the vehicle [28].

Battery charger performance depends on the type and the design of the battery as well as on the characteristics of the charger and the charging infrastructure [42]. EV battery chargers are categorised as 'on-board' and 'off-board' and can have either unidirectional or bidirectional power flow. Unidirectional power flow provides charging from the grid, while bidirectional can charge the battery from the grid and also offer battery power injection to the grid [42]. On-board chargers are divided into two categories, inductive or conductive. Conductive charging systems use direct contact between the outlet and the connector. Inductive

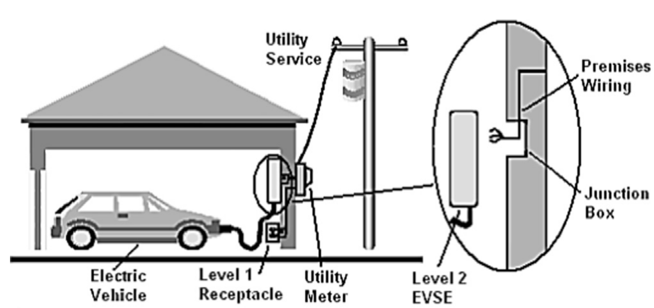

Fig. 5. Levels 1 and 2 of residential charging installation [1].

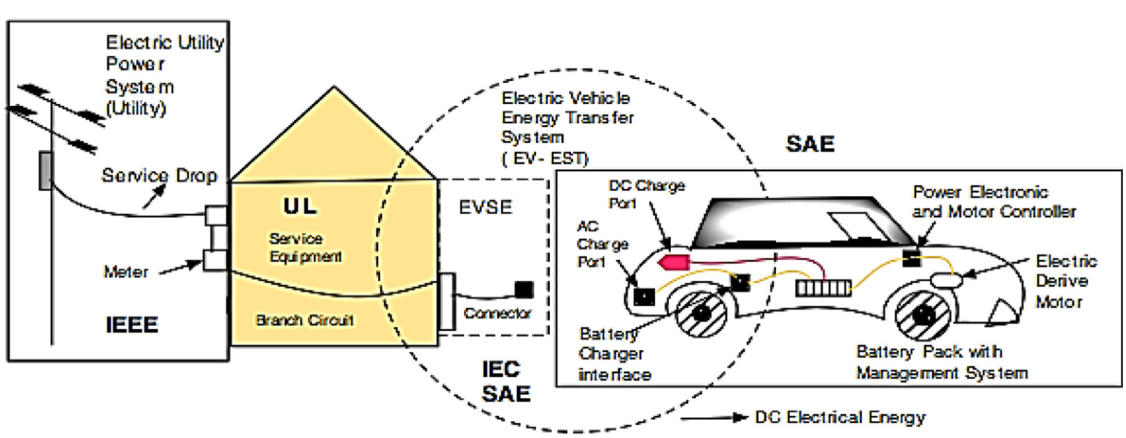

Fig. 4. EV energy transfer system [1].

Table 6
Standards of electric vehicle charging [7].

Standard	Description
National electric code article 625	Electric vehicle charging system
SAE J2293	Energy transfer system for electric vehicles Off-board electric vehicle supply equipment (EVSE) used to transfer electrical energy to an EV from a utility in North America
SAE J1772	Recommended practice for communication between plug-in electric vehicle and power inlet
SAE J1773	Electric vehicle inductively coupled charging
IEC 62196	Plugs, socket outlets, vehicle couplers and vehicle inlets—conductive charging of electric vehicles
IEEE 1547.3	Interconnecting distributed resources with electric power systems
SAE J2847	Provides requirements and specifications on the necessary communication between PHEV and power grids
SAE J2894	Provides the charging equipment operational recommendations for power quality
SAE J2836	Provides the practice for communications between PHEVs and power grids

chargers use a magnetic field to transfer electricity for charging EVs [42].

Electric vehicle supply equipment (*EVSE*) is a device or apparatus for transferring energy to the electric vehicle. The design and deployment of EVSE is an important consideration because many issues need to be addressed, such as charging time, distribution of EVs, and charging process policies. EVSE is designed in two configurations: a specialised cord set and a wall or pedestal mounted box [36]. EV charge cords, charge stands (residential or public), attachment plugs, power outlets, vehicle connectors, and protection equipment are major components of EVSE [36]. The configurations vary from location to location and country to country, depending on frequency, voltage, electricity grid connection, and transmission standards. A charging installation for Level 1 and Level 2 is shown in Fig. 5.

SAE International developed the standard requirements for energy transfer systems and off-board EVSE used to transfer electrical energy to an EV from an electric utility power system. The SAE standard includes two parts:

- Part 1 SAE J2293/1 addresses the functional requirements and system architecture;
- Part 2 SAE J2293/2 addresses the communication requirements and network architecture.

There are various standards regarding the energy transfer, connection interface, and communication requirements for EV charging. Table 6 summarises some of these standards.

3.3. *Power system domain; electricity tariffs*

The major concern associated with a large-scale integration of electric vehicles into (centralised and decentralised) power supply systems is the potential impacts on peaks demand that may result from EV recharging. The first step in reducing the impact on peak demand will be to shift the charging process to time periods when there is low demand on the grid. Studies on the economic and environmental aspects of EVs have shown that EV recharging behaviour can be controlled by encouraging EV owners to charge their vehicle during off-peak charging periods by using various incentive programs [43]. This can be achieved by means of price incentives, pricing response and/or by demand-side management [44].

Demand response programs can be categorised into those that are incentive-based and time-of-use (TOU) price-based [45]. Price-based demand response (DR), including real-time pricing (RTP), critical-peak pricing (CPP), and TOU tariffs, give customers time-varying rates that reflect the value and cost of electricity in different time periods [45]. Incentive-based demand response programs – such as curtailable, direct load control and emergency programs for reliability – pay participants to reduce their electricity consumption (load) at times requested by the program sponsor, triggered by high electricity prices or a peak in demand prices [45,46]. A report by staff of the Federal Energy Regulatory Commission (FERC) showed that peak demand reduction comes mostly from incentive-based DR programs [39]. Hence, it is critical to improve understanding of consumer preferences and to change consumer behaviour through the use of creative incentives by the utilities and service providers to better manage the potential impacts on the grid.

Table 7
Electric vehicle trial projects.

Country	Project name	Year started
USA	The EV project17 electric vehicle (15 Mitsubishi i-MiEVs and 2 Nissan LEAFs)	2009
Australia	REV, (11 Ford)	2010
Germany	ColognE-Mobile, (25 Ford)	2010
UK	SwichEV (44 EVs)	2010
Ireland	Active E, (20 EVs)	2011
Canada	Hydro—Quebec, (30 I-MiEVs)	2011
France	SAVE, 65 Renault—Nissan	2012

A number of interventions can be used to alter the behaviour of EV drivers, including information, incentives, and institutional support. Information and education involves offering incentives of various kinds [47].

4. Investigation and analysis of the interaction of key factors

Of importance is how these factors discussed in the preceding sections interact to determine the complex behavioural patterns of EV drivers. A number of EV trial projects have been undertaken in different countries over recent years. The data from some of these trials are summarised in Table 7 [19,48]. A consistent finding from these trials has been that the positive factors that participants focus on are economic (fuel savings), comfort, and environmental while the negative factors that they focus on are range limitations, recharging times, and higher purchase costs [48]. Limited range of EVs has been found to be the main concern of the EV users [19]. Two key factors, the charging infrastructure and the battery performance, are discussed in greater detail below to indicate the way in which these interactions significantly influence EV charging patterns and driving behaviours. A more detailed discussion on the influence of these two key factors is given in the following sections.

4.1. *Battery performance*

Number of studies have has shown that the energy capacity of EV batteries is sufficient to meet the daily driving needs of most people. The optimal choice of EV battery capacity depends on the distance that the vehicle will be driven between charges. The highest performance of EVs is achieved when the batteries are sized according to the charging patterns of the driver. Three potential complications arise when sizing EVs based on the number of kilometers that drivers travels: if the variance in distance travelled per day is large, then a capacity designed for the average distance may be suboptimal; it is unclear whether it is safe to assume that drivers will consistently charge their vehicles once per day. EVs in the market can finish daily commuting trips without roadside charging [19]. The results show that, for urban driving conditions and frequent charges every 15 km or less, a low-capacity EV sized battery is sufficient for less frequent charging (every 32–160 km) [49]. Journey data shows that the battery range of electric vehicles (EVs) more than covers most users' needs, with most drivers finishing their daily journeys still with charge remaining. Typical users only need to recharge every 2–3 days and choose the convenience of a home charge overnight or at their place of work over 85% of the time [5].

Moreover, the recent development of battery technologies has allowed greater use of the total amount of energy in the batteries. The two dominant battery technologies considered as the most promising candidates for EV applications are nickel-metal hydride (NiMH) and lithium-ion (Li-ion) batteries. NiMH batteries have performed well and have proven reliable in existing hybrids vehicles [50].

Additionally, the majority of PEVs were charged once daily during evening and night hours when the power consumption and the electricity prices are the lowest. Without charging management, EV drivers would charge between 5 pm and 9 pm-placing significant pressure on the power grid at peak hours. By matching real world driving patterns with technical specifications of electric vehicles and charging infrastructure, technical requirements for the batteries' state of charge boundaries have been identified and the actually usable battery capacity is driven. The gap between the minimal and the maximal boundary indicates the range that could be used for load levelling of the power grid or even for vehicle-to-grid applications. It has been shown that due to technical restrictions, the possibilities of utilising electric vehicles for load levelling of the power grid have to be assessed very carefully [51].

4.2. Charging infrastructure

EV trail projects conducted in different countries to date have provided insights into the complex behaviour of EV drivers, and that constrained EV drivers' route choice and charging routine are two critical determinants of EV driving behaviour. Based on the observed project trials data, the analytical results show that the majority of drivers were able to complete their trips without a public charging infrastructure, but that a considerable portion of drivers remain convinced that public charging sites are essential. The potential benefits achievable from selecting optimal charging station locations were quantified and the results indicated that EV users' sense of having to plan their journeys more carefully was reduced with the increase of the experience with the vehicle, especially when the drivers desire to use their EV for longer journeys [52]. Additionally, in relation to charging behaviour, the data of the trail projects has clearly demonstrated that EV users are not motivated to recharge their vehicle's battery at a particular point of depletion; rather they are driven by convenience. It is apparent that there is an opportunity for the users to be plugged-in Ref. [51]. According to the leading providers of electric car charging infrastructure, installing charging stations in a network can provide alternative options for EV users, and that EV drivers travel further, charge their vehicles more often at public locations and are more likely to charge at night when electricity tariffs are lower [23].

Furthermore, the most popular time to charge a vehicle has been found to be overnight. But as most vehicle trip journeys are relatively short (with five average journeys per charge and each trip15 km per day [4]), this allows scope for exactly when the car is charged each night to minimise the cost. Such evidence supports the need for automated intelligent charging technology that would allow EVs to adaptively interact with the distribution grid in an area [5]. If the timing of EV charging can be controlled, e.g. shifting to night-time hours when the demand is low, the effects of charging EVs on the electricity system can actually be beneficial, e.g. charging EVs at night would ensure "fill valleys" in the load curve, more completely using existing generation capacity. Such improvements to the utilisation factor of the generation fleet would reduce the average cost of electricity generation [5].

EV drivers with timed infrastructure can achieve a relatively higher average kilometer between charging compared with those without timed infrastructure. This suggests that timed infrastructure, which also offer slower cost off-peak electricity, is able to decrease not only the opportunistic charging during the day, but also the charging at peak times of the electricity demand [15]. The results also show that irregular charging behaviour could lead to significantly longer distances between charges than the average daily distances would suggest and, conversely, that the extensive installation of charging infrastructure in public parking places would enable charging more than once per day, enabling shorter distances between charges. But daytime across night time charging, geographic location, and effects of marginal changes in electricity demand on the mix of energy sources could all affect implications associated with electrified transportation [52].

Furthermore, the trials data shows that most corporate users had a strong pre-trial desire to have a public charging infrastructure, while private drivers reduced their desire to have a public charging infrastructure [49]. The differences are likely to have been due to the relatively routine nature of the private drivers' journeys where their home charging was sufficient for daily trip as compared to corporate drivers who did not get the opportunity to fully explore the range capabilities of the vehicles they had [23]. In addition, the fact that the distances travelled between two charging events steadily increase across all user groups shows the increasing confidence of the EV users when more journeys are undertaken between charge events. Users' concerns about limited range were reduced with the accumulation of driving experience whereby the range was judged to be sufficient. The data also showed a trend towards the drivers travelling longer journeys over

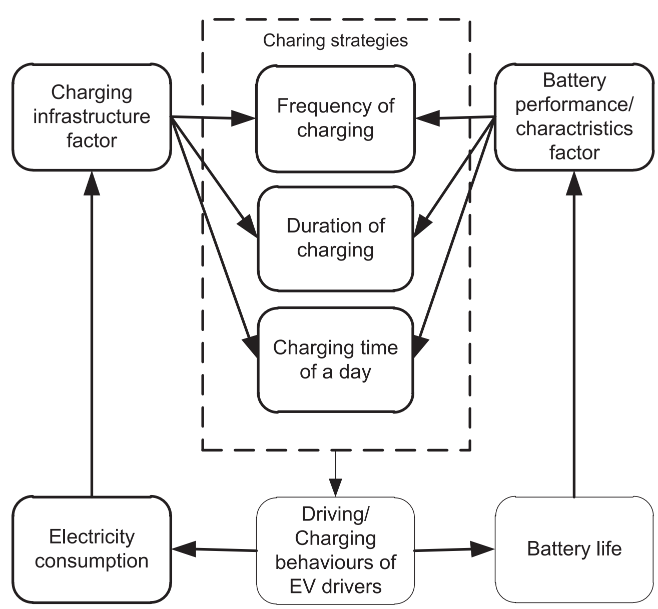

Fig. 6. The flow chart of the purposed system.

time which indicates the increased confidence and the reduced range anxiety [53]. The flowchart of proposed system is shown in Fig. 6.

Collecting information, such as the state of charge, use of external applications (air conditioning, radio, etc.), and the use frequency of these applications is also essential to assess the energy consumption of the EVs and their environmental performance [21].

5. The comparison of charging pattern in term of cost

Aggregators must estimate the amount of energy demand and the available charging periods and accordingly provide the electricity to satisfy the costumer's need for vehicle usage [54], These needs are determined by daily driving patterns, which vary according to time of day, duration and frequency of the recharging events and the electricity required to recharge the vehicle batteries, parking place, parking time, starting and destination points of each trip, number of trips per day, and distance of each trip. These factors directly determine the amount of energy demand and the available charging periods. So, driving pattern models will provide basic information to accurately analyse the charging demand and evaluate the impact of charging load [55].

To characterise power demand, all charging methods are classified into three groups presented in Table 8.

The effectiveness of charging performance has been analysed in a number of studies [51,53–58] that have compared the charging costs and the energy demands of charging in different time intervals for typical charging pattern (unregulated) and optimised charging patterns. The results have shown that the optimised charging pattern significantly reduces the cost and flattens the load curve if the peak and valley time periods are partitioned appropriately. Modelling studies of vehicle usage patterns have also found that usage patterns have significant impacts on the timing and duration of home charging of EVs, and hence on the electricity charging profiles and consequently the wholesale price [55]. The unregulated charge profiles would increase the peak demand while a regulated charging scheme, such as flat valley-fill power, substantially improves the cost of driving and charging of EV and reduces power system cost while maintaining reliability. It has been shown that regulated charging offers a 40% reduction in the daily recharging cost which amounts to a present value of approximately $600 over a ten-year period [55,59].

6. Case study: Observed charging behaviour in a Western Australian trial

In 2010, a plug-in electric vehicle-recharging trial was launched in Perth, Western Australia using 11 EVs and charging infrastructure. This project, conducted by The University of Western Australia's (UWA) Renewable Energy Vehicle (REV) Project team that partnered

Table 8
EV charging strategies [56].

Charging pattern	Description
Unregulated	
Typical charging (unmanaged or unregulated)	Charging begins immediately when the commuter arrives home and plugs-in, incurring the highest recharging cost
Regulated	
Flat valley-fill	Charging is regulated to take place when system demand is lowest, incurring the lowest cost
Smart charging (intelligent)	Charging can be delayed or advanced in time whenever commuters are at home to minimise total system cost based on energy cost or grid capacity

with eleven Western Australia based organisations, has deployed 11 converted Ford Focus sedans and 23 level 2 AC charging outlets distributed across the greater Perth metropolitan area. The UWA team collected and analysed electronic data being logged from the vehicles and recharging stations for the purpose of evaluation and statistical analysis. The telemetry data consist of location, time, movement and charging patterns of EVs (Fig. 7) [60].

This section assesses vehicle consumer driving and charging behaviour, from the vehicle data statistics collected from early driving and charging behaviour of electric Ford Focus drivers. Factors influencing driving patterns and charging behaviour are evaluated to assist deployment of EV mass production, associated regulations and standards.

To accomplish this goal, Ford Focus sedans were converted from petrol to electric vehicles. These converted vehicles utilise a PEV 23 kW capacity battery pack with 130 km driving range. All Ford Focus' participating in the EV charging trial have an on-board 4.8 kW charger that takes four or 10 h to full charge based on the single-phase plug or three-phase plug and European standard IEC 62196 type-2 connector vehicle inlets (Mennekes) which can be used for single phase as well as three phase.

6.1. Project status and methodologies

Driving data are collected from each participating Ford Focus sedan, chargers and charging stations via a telematics system. All vehicles are equipped with GPS tracking units.

Managing the power supply to the electric vehicles requires the knowledge of charge and drive event information. This data is collected through measurements from the vehicles, chargers, and charging stations data loggers. Management of the power supply to the electric vehicles includes the following set of information:

1. Energy consumption of each vehicle is measured via a logger unit, which is tracked by GPS and transmitted back to the server at UWA. For each vehicle, the status of battery level, charging level, energy usage for ignition, air conditioner, heater, and headlights is measured.
2. Where the vehicle is charged.
3. When the vehicle is charged.
4. The power consumption of the vehicle.

The detailed trip log for each vehicle and each participant was formed by using these measurements and through data processing of information regarding journey, charge and parking events. To analyse Ford Focus owners' driving and charging behaviours and the relationship between driving and charging, a summary of the metrics and distribution were calculated. The results were based on the electronic data collected from Ford Focus sedans enrolled in the EV charging trial for the period of six months from August 2012 through February 2013 (Table 9).

The mean and median values shown in Table 9 are statistically important as they represent a large data set of over 3000 logged trips (km) [60]. However, contribution of kilometres from each vehicle is relatively small, the mean represents the average value of total distance driven for the period of six months. The median is the central tendency of the value of distance driven by the vehicles. Therefore, the statistics in Table 9 presents the behaviour of EV drivers who participated in the EV charging trial for the specific period [60].

6.2. Observed results

The aforementioned cases study has been carried out in Western Australia and the observed data was collected and analysed by using the methodologies introduced above. The results are summarised as follows.

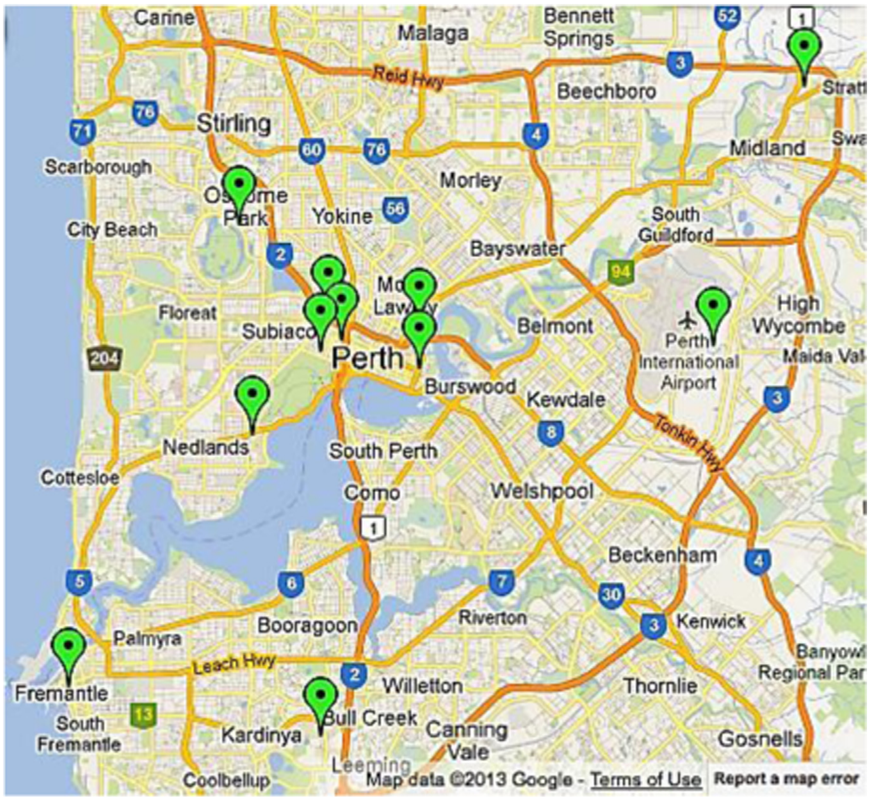

Fig. 7. Western Australian EV charging station network (*Source*: Google maps).

Table 9
Summary of driving metrics.

Number of trips	3,357
Total distance driven (km)	24,791.6
Mean/median trip distance (km)	4.4/7.4
Mean/media distance driven between charging events (km)	8.4/19.6

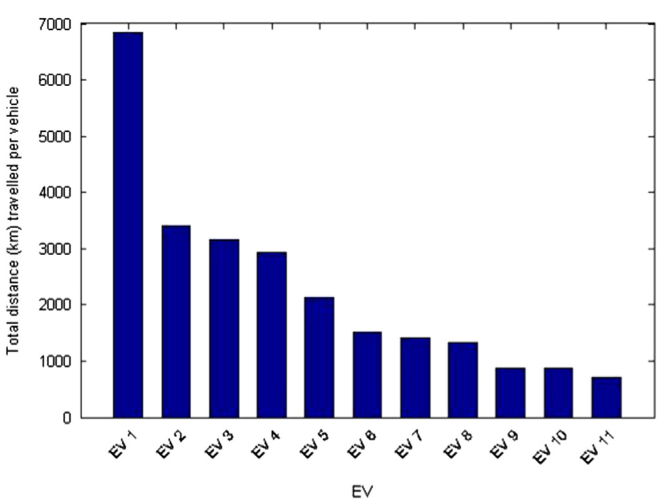

Fig. 8. Total distance (km) travelled per vehicle.

6.3. Observed driving behaviour

Fig. 8 shows the total distance travelled by each vehicle during a period of six months. Fig. 9 shows that over half of all trips were less than 5 km.

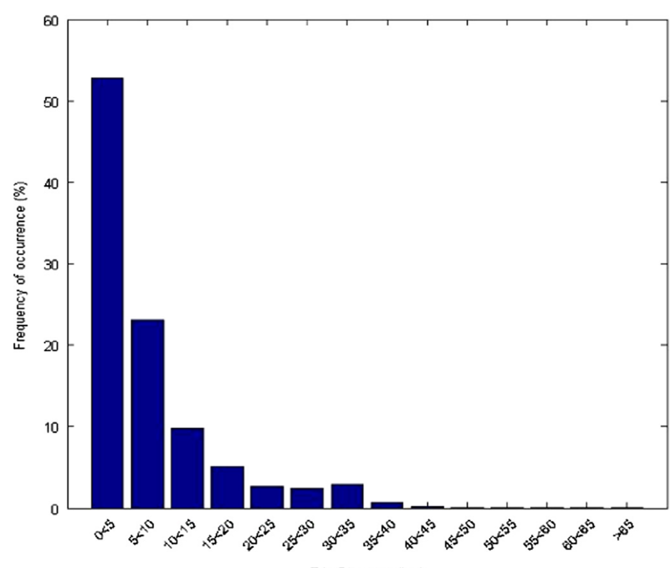

Fig. 9. Distribution of trip distance (km).

6.4. Observed charging behaviour

The recharging behaviour statistics of EVs participating in this trail is shown in Table 10 [60]. The distribution of the average number of charging events performed per day driven for each vehicle is shown in Fig. 10. This shows that drivers frequently charged their vehicle before reaching the battery expected range. It means drivers behave conservatively and limit their driving between charging to avoid the risk of fully depleting their battery before the next charging opportunity. The drivers prefer to use convenient opportunities to charge their vehicle regardless of the available driving range remaining.

Table 10
Charging summary statistics.

Total number of charging events	3357
Total kW h	4341.665
Number of transactions	342
Mean charging transaction time	2:32:56
Energy used in peak (kW h)	1409.57
Energy used in off-peak (kW h)	1243.03

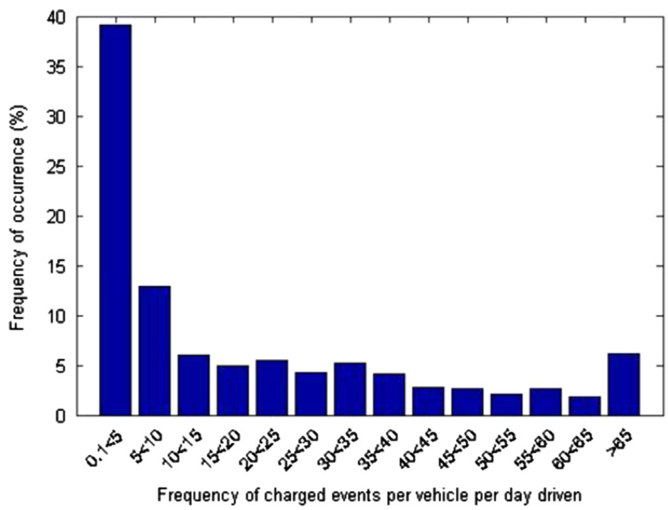

Fig. 10. Distribution of charging events per vehicle (number of charge events per vehicle day driven).

7. Conclusion

Behaviour change is likely to form a critical part of any strategy used to manage the challenges of reducing transport related energy consumption and emissions. Improvements in technology by themselves are unlikely to be sufficient. It will therefore be necessary to encourage not only the adoption of EVs over ICEs, but also to change the way that they use their EVs and their driving patterns. Studies on the electricity availability and power demand illustrates both when the PEVs could have been recharged and when recharging actually occurred. It also can demonstrate how much power is required to recharge these PEVs and when EV drivers prefer to charge their vehicles. The ability to model the recharging behaviour observed in the PEV demonstration is shaped by several factors.

In this paper the charging patterns and driving behaviour of EVs were studied. The factors addressed that can affect the charging behaviour are mainly EV penetration rate, charging infrastructure, EV battery performance and cost and utilities' incentive programs. Two factors were identified as key parameters for shaping the charging pattern and driving behaviour of EVs drivers as integration of electric vehicles: the charging infrastructure and the battery performance. An analysis on battery technology, capacity and performance and charging infrastructure described. The available energy and the lifetime were discussed considering all recent EV trail projects conducted in different countries.

This study has helped to develop understanding the charging behaviour and driving patterns importance for planning future transport systems as well as for the utility sector. From the real driving data collected from the EV charging trial in Western Australia, it was observed how EV consumers utilise their vehicles and how they charge their vehicles enabling a general prediction of the state of charging networks for future developments.

Early analysis of data collected from Ford Focus EVs in the UWA EV charging trial project examined distributions of trip distance, distance driven between charging events and charging event frequency per day. Data indicate that in the trial drivers charged their vehicle frequently maintaining a relatively high battery state of charge. Collected robust data showed the timing of EV recharging is the most vital factor, followed by the location of the recharging station. EVs have the potential either to be difficult for the grid to accommodate or to provide a valuable service, depending on whether vehicle charging can be sufficiently controlled.

As Plug-in Electric Vehicle (PEV) ownership grows, controlling when these vehicles charge becomes an important issue for energy providers. This study shows the comparison of the EVs charging pattern in terms of cost considering TOU, which proposes EV charging method minimising the cost of wholesale energy. Driving conditions affect economic and environmental benefits of electrified vehicles substantially. Hence, charging patterns of EVs have significant implications for network management. It is evident that the optimised charging patterns have significant reduction in the cost of EV users' charging.

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