



Master Thesis:

Charging behaviour of Dutch EV drivers

A study into the charging behaviour of Dutch EV drivers and factors that influence this behaviour

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Abstract

Electric mobility provides promising developments with regard to sustainability problems such as CO₂-emission, air pollution and rising fossil fuel prices. However, as a result of the rapid growth of electric vehicles in the Netherlands, challenges are expected for a broad implementation of charging infrastructure in the Netherlands such as electricity peak demand problems and charging point availability. The electric vehicle (EV) user is with his charging behaviour an important parameter in a well-functioning charging system. This research therefore aims at understanding what this charging behaviour looks like and what factors constitute this behaviour, which may help to develop strategies for promoting a more efficient utilization of the charging infrastructure. This research is based on an analysis of a database consisting of data from 965.414 charging transactions, and interviews with 16 Dutch EV drivers. A literature review is performed in order to synthesize the various perspectives on EV charging behaviour, in which six dimensions are identified that conceptualize the concept charging behaviour. These dimensions are the charging point location, the charging point type, the frequency, time of day, duration, and the energy transfer of the charging transaction. These dimensions are, according to the literature, influenced by driver-, vehicle- and environment-related factors. The results show that a large share of EV drivers show a routine charging behaviour, in which charging decisions are based on convenience and habit instead of battery level information. EV drivers show similar charging profiles in which clear peaks are visible at times on which EV drivers start and stop charging transactions simultaneously. EV drivers commonly use charging points that are already known to them, and the battery level does not influence charging decisions of EV drivers. Also, the majority of charging transactions last much longer than required, indicating inefficient use of charging points. Furthermore, EV charging behaviour does not differ between urban and rural Dutch areas. These results implicate that, in order to avoid electricity demand peaks, either the routine charging behaviour could be influenced by use of training and education, or technological solutions such as smart charging technology could utilize the potentials that are present in current Dutch EV charging behaviour such as long charging durations during the night and during work-hours. With regard to charging point availability, the EV driver could be stimulated to unplug the EV when the charging transaction is completed, and semi-public charging points could be used more during the night.

Introduction

Electric mobility provides promising developments with regard to sustainability problems such as CO₂-emission, air pollution and rising fossil fuel prices (Franke & Krems, 2013a). Electric vehicles have a small carbon footprint, have less impact on air quality and are cheaper to drive than conventional cars (Leurent & Windisch, 2011). A growing number of Dutch consumers consider buying an electric vehicle and sales of domestic electric vehicles in the Netherlands have been rising from 1100 in December 2011 to more than 37.300 in June 2013 (RVO, 2014). However as a result of this rapid growth of electric vehicles, challenges are expected for a broad implementation of charging infrastructure in the Netherlands (Eggers & Eggers, 2011). These challenges are, among others, adapting the electricity infrastructure to the volume of new electricity demand, the availability of parking spots facilitated with a charging point and the availability of sufficient charging infrastructure (Pearre et al., 2011; Rijksoverheid, 2011; Liu et al., 2014). In order to overcome these challenges, charging infrastructure improvements and policy adaptations are needed. One solution for the electricity increased demand problem could be the development of smart-charging infrastructure: An intelligent and dynamic electricity infrastructure in which electricity producers can influence EV charging demand (Banez-Chicharro et al., 2013).

However, the potential of such solutions, and the performance of the charging infrastructure in general is dependent on how the system is set up and how the system is used (Franke & Krems, 2013a). The user' charging behaviour (e.g. chosen charging location, frequency, duration of charging) is an important parameter in a well-functioning charging system (Kelly et al., 2012; Kristoffersen et al., 2010; Banez-Chicharro et al., 2013). Knowledge of charging behaviour by users is therefore key in improving the charging infrastructure. Users face challenges in using the charging infrastructure such as range anxiety and long charging times (Smart et al., 2013). Users adapt to these challenges in different ways and some users adopt different charging patterns than others (Franke & Krems, 2013a; Schroeder & Traber, 2012). Understanding what factors constitute this charging behaviour may help to develop strategies for promoting a more efficient utilization of the charging system (Franke & Krems, 2013a).

Several studies on charging behaviour by EV drivers have been undertaken. However, studies that focus on understanding EV driver charging behaviour use small data sample sizes (Franke & Krems, 2013a; Jabeen et al., 2013; Smart et al., 2013) and are often very limited, either geographically or in EV diversity. Due to these limitations, generalizations from these results are impossible. Furthermore, given that no quantitative scientific research on EV driver charging behaviour has been performed with data from the Netherlands, little is known on charging behaviour of EV drivers in the Netherlands specifically. This is relevant as the Netherlands is seen as a frontrunner in electrical mobility (Rijksoverheid, 2011). In this research, a large scale dataset is used on charging transactions by Full Electric Vehicle (FEV) and Plug-in Hybrid Electric Vehicles (PHEV) drivers in the Netherlands, collected by several Dutch regional governments and businesses that are involved in (plug-in) EV's, and aggregated by the Netherlands Enterprise Agency (RVO). The size of the dataset, involving 956.579 charging transactions and 67% of all Dutch EV drivers (RVO, 2014), as well as the geographical diversity, provides a more reliable base for understanding the factors influencing the charging behaviour of EV drivers in the Netherlands.

Aim & Research Question

This research aims at giving both quantitative and qualitative insights in charging behaviour of EV drivers in the Netherlands and the factors influencing this behaviour by answering the main research question:

“What does the charging behaviour of FEV and PHEV drivers in the Netherlands look like, and what are the factors influencing this behaviour?”

In order to answer the main research question, several sub-questions have to be answered:

- 1: *According to literature, of what dimensions does EV charging behaviour comprise and what factors influence this behaviour?*
- 2: *What do the Dutch EV charging behaviour dimensions look like?*
- 3: *How do the factors influence Dutch EV charging behaviour?*

In order to synthesize the various views and perspectives on EV driver charging behaviour, a literature review on charging behaviour will be needed. This review will shed light on the dimensions which constitute charging behaviour, possible factors influencing this behaviour, and relevant relations among these influence factors and charging behaviour dimensions. These dimensions, factors and relations will be described and analysed, based on a charging transaction database comprising of 965.414 charging transactions in the period of January 2013 – April 2014 in the Netherlands, together with 16 interviews with Dutch EV drivers.

Demarcation

The performance of the charging infrastructure is evidently dependent on how it is used. This is why this research will focus on the charging behaviour by EV drivers. As the emphasis is on charging behaviour, only plug-in EV's (FEV's and PHEV's) will be taken into account. Due to the Dutch context in which the research is performed, this research is concerned with the charging behaviour of domestic FEV and PHEV drivers in the Netherlands. Also, since the charging behaviour will be analysed in a Dutch context and with Dutch data, the interviews will be limited to Dutch residents only.

Scientific relevance

The results from this research will hold scientific relevance in several ways. First, a deeper understanding of the factors influencing charging behaviour in the Netherlands is provided, a subject that has not yet been researched. Second, this understanding of charging behaviour could provide a first step for further research concerning how this charging behaviour by EV drivers could be influenced to better facilitate an efficient use of charging infrastructure. Third, results from this research will contribute to the field of innovation science as it provides insights in how users cope with, and adapt to, an emerging technology. Fourth, current literature on charging behaviour varies tremendously among scientific strands, and an overview has not yet been constructed. The literature review of this research will provide this overview of perspectives on charging behaviour.

Societal relevance

A reliable charging infrastructure is key for the transition towards a more sustainable mobility system. Results from this research will help to tackle several EV related problems. First, insights in charging times, frequencies and durations may help smoothing out the peak loads on the electricity infrastructure by informing electricity producers on the distribution of EV transactions in time (Pearre et al., 2011; Liu et al., 2014). Second, new insights in the use of charging points may help improve the availability of charging infrastructure by informing EV service providers on EV charging behaviour. This will provide a first step in identifying the potential for charging related business models. These business models could lead to further growth of EV charging infrastructure and provide better service to users, better charging infrastructure efficiency, and more competition which could lower prices (Rijksoverheid, 2011). Third, insights on the use of public charging points may help tackle challenges surrounding public charging points and the availability of charging-point-facilitated parking spaces by informing local governments on what charging times to expect for any public charging point.

Literature Review

Charging behaviour

In the context of EV's, the term charging behaviour could be seen as an umbrella term for all interactions between an EV user and an EV charging point. Given that multiple scientific disciplines have studied the topic from multiple perspectives, definitions and descriptions vary tremendously between the strands in literature (Jabeen et al., 2013). This makes it hard to develop a clear explanation for 'charging behaviour', as this would risk excluding relevant views or evidence on the subject. In order to synthesize these various perspectives and elaborations, a systematic literature review is performed which will provide an answer to sub-question one. This way of systematically describing views on charging behaviour aims to minimize bias through literature searches of published studies (Bryman, 2008; Transfield et al., 2003).

Literature review strategy

For the literature review the scientific online search engine Scimedirect (<http://www.sciencedirect.com>) was used, which contains peer-reviewed scientific literature only. The use of specific keywords alone was not enough to reduce the amount of relevant literature to a manageable size, as the key words 'Electric vehicle charging behaviour' would result in 5000+ results, mainly on chemistry and physics related topics on the charging behaviour of EV batteries. As these chemistry, physics and technology related articles would contain information on charging processes, instead of the user behaviour, these had to be excluded. Adding the keyword 'user' excluded several relevant articles that came up the first search and was therefore no option. Using the four keywords in a search, and excluding all chemistry and physics journals containing more than 6 search results per journal reduced the articles to a remaining amount of 632 articles. When these results were sorted by Scimedirect based on the 'relevance' with regard to these four keywords, the titles of the first 200 articles were manually scanned based on whether or not they would contain information on the charging behaviour of users with regard to FEV's and PHEV's, after which the abstract was read with the same criterion. The scanning consisted of discarding all articles with keywords related to chemical substances or electromagnetic processes and incorporating articles with keywords related to user behaviour, charging behaviour or driving behaviour related to EV's. This resulted in a selection of 25 articles that have been included in the review, which are stated in appendix A.

Literature review structure

These charging behaviour related articles describe a wide range of charging behaviour dimensions, and factors that could influence this charging behaviour. This literature review will therefore start with a chapter on the dimensions which construct 'charging behaviour', which will shed light on what charging behaviour is, followed by a chapter on the various factors that could influence these charging behaviour dimensions and that are touched upon in literature. From literature, six charging behaviour dimensions and eight influence factors have been identified. Additionally, several relevant relations have been identified that emerged from literature. Combined, this chapter is the answer to sub-question one.

Charging behaviour dimensions

Charging point location

The charging point location dimension concerns the type of location where a vehicle is charged. In literature, three main locations are distinguished: home charging, work charging and public charging (e.g. car parks or shopping malls). Research by Graham-Rohe et al. (2012) on new EV drivers from England show that charging was perceived simpler than anticipated, mainly as a result of the possibility to charge the car at home whenever it was parked there. Related literature confirms this notion (Skippon & Garwood, 2011; Ewing & Sarigöllü, 2000; Jabeen et al., 2013). Charging points at home had the general preference of EV drivers over other charging points, as availability was guaranteed and it reduced the need for drivers to adapt daily plans to facilitate the charging transaction (Axsen & Kurani, 2012; Caperello et al., 2013; Jabeen et al., 2013). Jabeen et al. (2013) state that users only decide to charge at work or at public charging points for specific reasons. Charging at work or in public may involve extra costs and charging at public points may require additional planning. However, a charging point at the work space is convenient and public charging points may also be conveniently placed near shopping centres or transport hubs, often offering the privilege of a reserved/free parking bay (Jabeen et al., 2013). Bradley and Quinn (2010) state that most EV drivers have the capability to charge at home and at work, and possibilities for charging at public facilities will grow as EV sales and technologies develop. With regard to the problem of electricity peak demand, EV drivers are preferred to use work or public charging points apart from the home charging point (if they have one) (Banez-Chicharro et al., 2013). In this way, charging the EV's might be more spread out and peak problems could be reduced (Banez-Chicharro et al., 2013; Kristoffersen et al., 2010).

Charging point type

The dimension 'charging point type' relates to the type of the charging point that is used in the charging transaction. In this research, two main types are distinguished: conventional charging points (delivering a power equal or lower than 22 kW) and fast-charging points (delivering power above 22 kW). Within the conventional charging points, five power outputs are distinguished in this research: 2.3, 3.7, 5, 11, and 22 kW (Oplaadpalen.nl, 2014). Both Pearre et al. (2011) and Schroeder and Traber (2012) state that the need of EV drivers to reduce charging times would suggests a preference for the use of high-power or fast-charging points whenever they are available, if the EV technology is even able to use fast-chargers. However, as fast charging points require an infrastructure that can cope with the high electricity demand, all private charging points are of the conventional type, and fast-charging points are still rare. The notion that EV drivers tend to prefer fast-charging points is acknowledged by Neubauer et al. (2012). However they add a warning that regular use of these high-power charging points could negatively affect the EV battery life and depth of discharge of the battery. With regard to the problem of charging point availability, one would prefer EV's with larger capacities to use the high power charging or fast chargers and smaller capacity EV's the conventional lower power charging points. This would reduce charging duration which could improve availability for other users.

Charging frequency

The frequency of EV charging transactions concerns how often an EV is charged. An article by Smart et al. (2013) reports charging behaviour findings from a Chevrolet Volt (PHEV) project in North America showing that these Volt drivers charged their PHEV on average 1,46 times a day and that 80% of these vehicles were charged more than once a day. The charging frequency however varied tremendously between a minimum of once a week and a maximum of 3,2 times a day (Smart et al., 2013). Franke & Krems (2013a) conceptualize EV charging behaviour in the concept of 'User-Battery-Interaction (UBI)' as developed by Rahmati and Zong (2009). They state that the EV charging behaviour by drivers can be attributed an 'UBI-score'. A low UBI-score suggests the driver is not actively interacting with the battery and charges the EV routinely (e.g. daily when returning from

work) and a high UBI-score suggests the driver actively monitoring battery levels and making charging-decisions based on this information (Franke & Krems, 2013a). With regard to charging frequency, drivers set charging routine are less likely to take full advantage of battery resources. The charging frequency of drivers actively monitoring the battery is strongly related to the mobility intensity of the EV. Smith et al. (2011) state that from a sustainability perspective, a high charging frequency is preferred as this would require smaller batteries. This would however require high charging point density, well balanced and well planned mobility behaviour. With regard to electricity peak problems, EV drivers preferably decide to charge the EV based on battery level information instead of routine behaviour (Franke & Krems, 2013a). Routine behaviour is inflexible and based on convenience, which complicates adapting the behaviour in order to reduce inefficiencies. Frequent charging, with lower energy transfer per transaction, could actually have a relieving effect on the charging infrastructure, when compared to EV's charging less often, with high energy transfers per transaction, and during peak demand periods.

Charging time of day

The dimension charging time of day concerns at what time in the day the charging transaction takes place. As mentioned before, EV's are often charged whenever they are parked at home. Research by Smith et al. (2011) on battery size optimization shows that the majority of EV's is parked at home from 21:00 until 7:00. Also, the average commuter EV is parked at work from 09:00 until around 15:00. Research by Kelly et al. (2012) on PHEV charging behaviour adds that on average the EV charging load on the electricity grid starts building around 16:00, that a charging peak in the electricity grid is seen around 21:00, and that the EV charging load on the grid ends around 04:00, confirming that users commonly charge during the night. With regard to both electricity peak problems and infrastructure availability, one would prefer a more dispersed pattern. If the overall charging pattern shows peaks, meaning that large amounts of electricity are demanded within small amounts of time, which is costly from the energy provider's point of view (Banez-Chicharro et al., 2013). This also means that a large number of EV drivers simultaneously prefer to charge at a given point in the day, which renders the availability of charging points to be inefficient and insufficient (Benysek & Jarnut, 2011). EV drivers starting their charging transactions in the evening enables EV's to charge over a longer period during the night during which electricity demand from non-EV purposes generally is low.

Charging duration

The dimension of charging duration concerns the amount of time a charging transaction takes. Research by Graham-Rohe et al. (2012) and by Hindrue et al. (2011) found that the long charging times were one of the most dominant EV disadvantages that were perceived by EV drivers, especially compared to a 5 minute gasoline refill. The duration of the transaction is dependent on the vehicle battery and the charging point type. Skippon and Garwood (2011) show that 78% of the starting EV drivers would consider up to € 360 investment in their private charging point to reduce charging time with 5 hours, and €2400 investment for a 7 hour reduction. These findings show the need for drivers to either reduce the charging duration, or to better incorporate this charging time in daily life. With regard to the electricity demand problem, long duration times (8+ hours) could provide potential. This is because commonly, a charging transaction for a full battery does not require 8 hours of charging. Therefore, longer periods in which the EV is connected to the charging point enable the flexibility and the potential for smart-charging technology: The electricity producer may choose to delay the transaction until the electricity demand has dropped (Banez-Chicharro et al., 2013). However, for availability problems of charging points shorter transactions are best, as this brings more potential for the charging points to be used efficiently.

Energy transfer

The energy transfer dimension concerns the amount of energy that is added to the EV battery during the charging transaction. Research by Smart et al. (2013) showed that for a quarter of the charging transactions, the battery was nearly depleted when starting the transaction, the other three quarters of transactions were nearly homogeneously spread between 10% and 100% of battery levels. In over 90% of all charging transactions the battery was full or nearly full when disconnecting the EV. Comparable results were shown in the research by Franke and Krems (2013a). These findings suggest that EV drivers monitor the battery levels actively and base their charging decisions upon this information. This then again suggests that, next to charging frequency, the energy transfer/battery capacity ratio per charging transaction of drivers with routine charging behaviour is smaller than EV drivers that monitor battery levels more actively. As an actively monitoring EV driver would bring more potential for electricity demand problems (Franke & Krems, 2013a), one would prefer energy transfer values to be close to the battery capacity of the EV.

Factors influencing charging behaviour

Inspired by the previously mentioned research by Franke and Krems (2013a) in which EV charging behaviour is conceptualized as user battery interaction (UBI), the factors that emerge from literature that influence charging behaviour are, for structuring purposes, divided in three factor categories: Factors related to the driver, factors related to the vehicle and factors related to the environment.

Driver related factors

Range anxiety

A common notion in EV charging literature is range anxiety. This factor describes the fear of the driver for not reaching their destination before the EV battery is depleted. Multiple articles state range anxiety as the main challenge for EV drivers (Hindrue et al., 2011; Eggers & Eggers, 2011; Nilsson, 2011; Franke & Krems, 2013b; Ozaki & Sevastyanova, 2011). These range anxiety concerns are also visible in the research by Eggers and Eggers (2011) in which a model is constructed aimed at predicting consumer EV adoption. This model shows that consumer adoption would strongly increase if the EV battery range is increased, illustrating the importance of range anxiety. This anxiety leads to drivers structurally overestimating their range needs, including a so called 'range safety buffer' (Franke et al., 2012). Franke and Krems (2013b) state that customers have been found to prefer vehicles with considerable higher range availability than strictly needed (Franke & Krems, 2013b). This discrepancy brings concerns because larger batteries mean lower cost effectiveness and a larger ecological footprint (Franke & Krems, 2013b). Also, range anxiety has direct consequences for charging behaviour as drivers tend to charge more often and longer than needed. The range safety buffer could be reduced when consumers actively manage their daily distance budgets and develop heuristics to plan their journeys, or when the risk of being incapable of finding a charging point in time is reduced by the addition charging points (Franke & Krems, 2013b).

Planning

The planning factor relates to actively matching the driving plans with the charging opportunities by EV drivers prior to driving. Effective charging considerations by EV drivers could reduce the range safety buffer and range anxiety, and could also improve the battery charging efficiency by EV drivers (Hahnel et al., 2013; Franke et al., 2012). However, these considerations are seen as a major disadvantage by EV drivers in comparison to conventional cars (Graham-Rowe et al., 2012). Additionally, Hahnel et al., (2013) state that drivers are only partly able to accurately predict their mobility behaviour, which negatively affects the user friendliness of the EV. Results by Hahnel et al. (2013) show that drivers tend to predict their trips on the same day or one day ahead, which leaves little room for planning with regard to charging. Both research by Franke and Krems (2013b) and Hahnel et al. (2013) underline the relevance of the user's EV experience in coping with its possibilities and limitations.

Mobility pattern

This factor refers to the mobility pattern of the EV driver. Several articles underline the importance of a well-balanced and predictable mobility pattern for charging behaviour (Pearre et al., 2011; He et al., 2009; Hahnel et al., 2013). Adaption of the mobility pattern to the EV capabilities is also important. Smart et al. (2013) find that in their EV driver sample in North America, more than 62% of EV drivers were able to accomplish their daily driving needs on one fully charged battery but that the other EV's required charging on more than one occasion a day. Smart et al. (2013) find that charging frequency and battery levels are also influenced by the degree in which EV drivers were taking on fuel economy as a challenge. The character and intensity of the EV drivers' mobility pattern is therefore a relevant factor.

EV experience

This factor concerns the amount of experience EV drivers have in coping with EV limitations and possibilities. The amount of experience EV drivers have, has consequences for how they cope with EV technology: range anxiety and the range safety buffer decrease as drivers are better at estimating range needs and EV range capabilities, and mobility behaviour becomes more routinized with regard to charging considerations (Franke & Krems, 2013b; Hahnel et al., 2013; Smart et al., 2013).

Vehicle related factors

Battery size

The battery size factor is related to the amount of energy that can be stored in the EV battery. Battery size is a much researched topic in the field of EV mobility. As mentioned before, from a user's point of view the battery must be as large as possible, negatively affecting the environmental impact (Smith et al., 2011; Lieven et al., 2011). Franke and Krems (2013a) state that vehicle features and capabilities influence charging behaviour. The battery size influences charging behaviour in that a larger battery requires longer charging time, and more energy to charge. However, a larger battery also requires a lower charging frequency, depending on the mobility intensity of the EV.

Vehicle range

The factor vehicle range relates to the range the vehicle can drive on a fully charged battery. This factor is related to, but not the same as, the battery size factor, as a large heavy vehicle with the same battery will have a smaller range than the smaller lightweight vehicle. As vehicle range increases, range anxiety and mobility behaviour change, which has implications for charging behaviour (Eggers & Eggers, 2011; Pearre et al., 2011).

Vehicle type

The vehicle type factor relates to whether the vehicle is a plug-in hybrid, or a full electric vehicle. Given that PHEV's have the option to drive with an empty battery, and the FEV's do not, one could expect the range anxiety, safety buffer and therefore the charging behaviour to differ between these vehicle types. This is confirmed by findings from Kelly et al. (2012) and Franke and Krems (2013a) that this difference in car features results in differences in charging behaviour.

Environment related factors

Charging point density

Charging point density relates to the amount and coverage of charging points in the surroundings of the EV. The availability of a charging point is an important issue for EV drivers. The availability and coverage of charging points in the surroundings reduces the need for planning and reduced the range anxiety, as there's always a charging point close by (Kelly et al., 2012). Skippon and Garwood (2011) state that the amount of EV charging opportunities is strongly related to population density, a notion that is acknowledged by Schoeder and Traber (2012). Kelly et al., (2012) show that urban and rural vehicles show different charging profiles, as the charging peak caused by rural vehicles on the electricity grid is 19% greater than urban vehicles, suggesting that rural vehicles reach lower battery levels when commencing charging.

In figure 1, an overview is provided of all dimensions and influence factors that have been identified from EV charging behaviour literature.

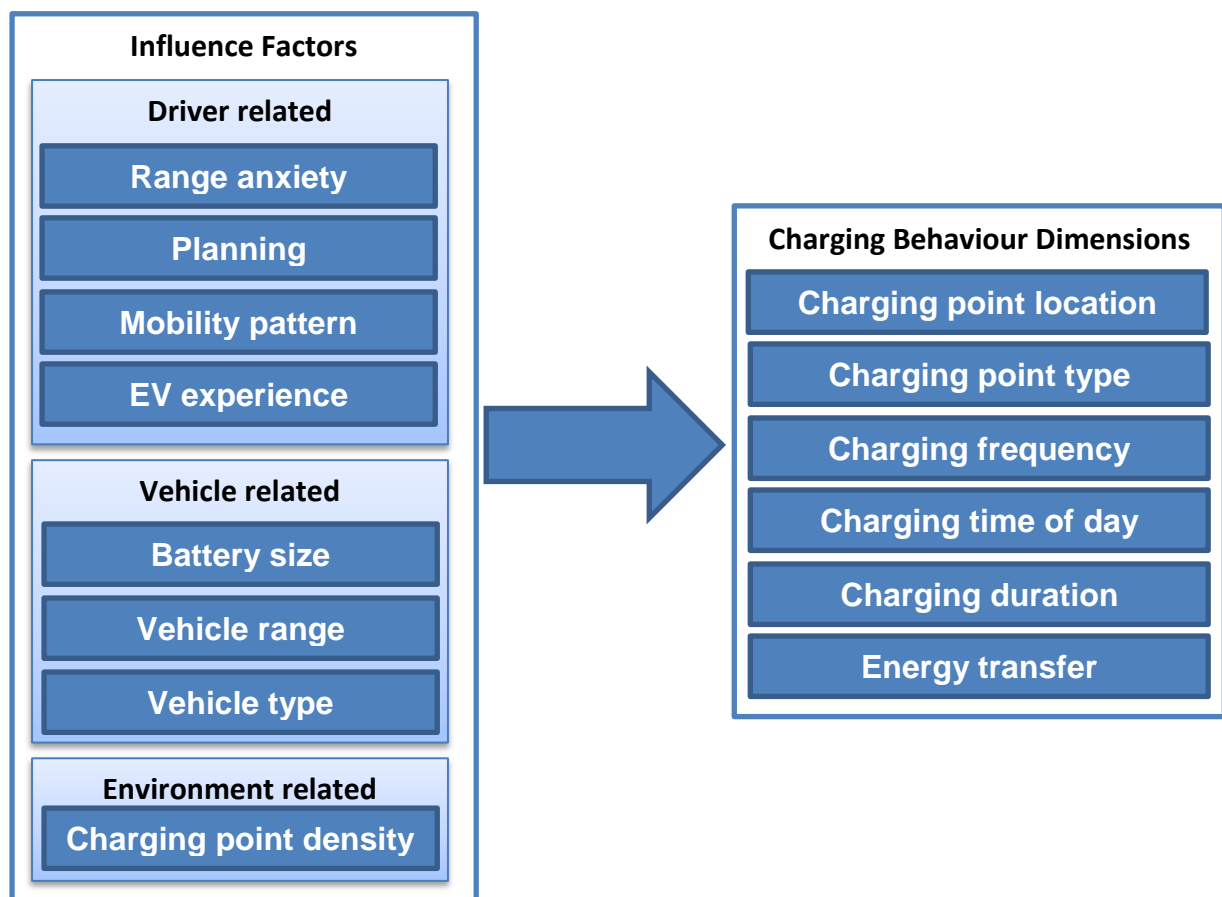


Figure 1: Overview of all influence factors (left) and charging behaviour dimensions (right)

Relations

From the literature review, several dimensions and influencing factors have emerged. Moreover, several relations between these have become apparent and deserve further explanation in this research, as these relations complement the insights in how the factors influence charging behaviour. These relations will be stated and explored below.

Charging frequency – energy transfer

A much stated relation is the relation between charging frequency and energy transfer (Smart et al., 2013; Franke & Krems, 2013a). Franke and Krems (2013a) state that as the charging frequency is higher, the charging transactions tend to start with a less depleted battery. This suggests that as charging frequency is higher, less energy is transferred per charging transaction. With regard to electricity peak problems this relation is relevant as high charging frequency patterns with lower energy transfer per transaction are an option for relieving the electricity infrastructure.

Charging duration – energy transfer

The relation between charging duration and energy transfer is interesting with regard to the charging point availability problem. Many local governments provide free parking spaces with a charging point for EV charging, as long as the EV is being charged (RVO, 2012). However availability problems arise, and this relation sheds light on use and misuse of these spaces. This topic also addresses the parking space availability problem: if the EV's are parked on a public space, do they actually charge?

Charging point type – energy transfer

Because fast-charging points are public points that in general are not very conveniently placed (e.g. car dealers, near highways) and still require 20 minutes to charge an average battery, the use of these points requires more planning and adaptation by the EV driver. This suggests that EV's capable of using fast-chargers, are only fast-charged when the need for charging is high: a low battery level (Schroeder & Traber, 2012). Obviously, these fast-charging points transfer energy in less time than a conventional point, so this suggests that a relation is present between charging point type and energy transfer. This relation is relevant with regard to peak-load problems, as the use of a fast-charging point heightens the load peak in comparison to conventional charging. However, if there is a correlation between the choice for charging points with a certain power output and the energy transfer per transaction, charging duration and the availability of charging points is improved.

Battery size – energy transfer

Further research on the relation between EV battery size and energy transfer will provide valuable insights in charging behaviour. If the ratio of energy transfer vs. battery size in a charging transaction is large, this is an indication of the battery being fully charged each time. If the ratio is small, this either means that the car is only charged for a short time or that the battery was rather full at the start of the charging transaction. As EV drivers are preferred that actively monitor battery levels, one would prefer charging transactions to be close to the battery capacity (Franke & Krems, 2013a).

EV experience – range anxiety

According to literature, a reduction in the overestimation of range needs occurs as EV experience grows (Franke & Krems 2013b). This means that drivers are better able at predicting their vehicle range in relation to their range needs, which reduces the need for a safety buffer. A reduction of this buffer could improve charging behaviour with regard to energy demand and peak load problems.

EV experience – charging frequency

According to literature, as drivers have more EV experience, their charging behaviour becomes more of a routine and they are better able to cope with the limitations of EV technology (Franke & Krems, 2013b; Hahnel et al., 2013; Smart et al., 2013). This routine behaviour should have consequences for charging frequency, as the driver is better able to estimate the capabilities of the EV, and charge it

accordingly. However, routine charging behaviour brings concerns for efficient use of battery resources and electricity peak demand problems (Franke & Krems, 2013a). The exact character of the relation is unclear: Do experienced drivers charge more or less regularly? This relation is relevant because understanding this relation might enable stimulating a better EV experience through education, which might influence charging behaviour.

Vehicle range – charging frequency

Eggers and Eggers (2011) and Pearre et al. (2011) state a relation between range anxiety and charging behaviour. A larger vehicle range would reduce range anxiety and influence charging behaviour. The stated influence on range anxiety suggests a change in the frequency of charging. However, the character of this influence is unclear. Therefore this relation must be further explored, as EV ranges keep increasing, with a negative effect on load-peaks.

Charging point density – charging frequency

Kelly et al. (2012) state that as charging point density increases, range anxiety decreases, as there is always a charging point close by. This relation is interesting as it brings a geographical factor to charging behaviour: will charging behaviour change as the environment changes? The character of this influence is also unclear: Either drivers in high charging point density areas charge less frequent as they are confident that a charging point is available when the battery is depleted, or they charge more frequent due to the abundant charging opportunities.

Research Methods

Research design

From the literature review, charging behaviour dimensions and factors influencing this behaviour have been identified. Also, several relevant relations have been identified that require further research. For analysing the charging behaviour dimensions, the charging transaction dataset is used. From this dataset, also the vehicle related and environmental influence factors were analysed. However, as the dataset did not include information on the driver-related factors, a series of interviews was conducted to analyse these factors. All relations were analysed using the dataset, except for the relations involving a driver-related influence factor, which were analysed using interviews. This resulted in the research being divided into two research methods: a quantitative data analysis based on charging transaction data and a series of qualitative interviews with EV drivers in the Netherlands. These two parts complement each other and deepen the insights in what EV charging behaviour in the Netherlands looks like, what exactly these factors are and how the relations occur. In this chapter, first the data collection methods and all related methodological considerations are discussed. After that, the operationalization is discussed for quantitative and qualitative methods separately, in which the processing and analytical use of the data and interviews are elaborated. Finally, the reliability and validity considerations are discussed.

Quantitative data collection

For the quantitative analysis of the charging behaviour dimensions and the environment and vehicle related influence factors, a charging transaction dataset was constructed. This dataset consists of several characteristics of individual charging transaction data that are shown in table 1. The data was collected from several regional governments and national EV charging service providers, which collect the data directly from the charging points and use it for monitoring and service purposes. The initial request for sharing this data by the organizations was performed by RVO senior advisors, as they already had contacts with the organizations. Then an e-mail was sent describing the required data details and in some cases a face-to-face meeting was set up in order to come to an agreement. In return for the organizations sharing their data, they will be sent a copy of this report. In this way, they can see the charging behaviour analysis that stretches beyond their own dataset and charging

service providers can use this to improve their business and services, and also regional governments can use it for monitoring and designing policy. This method of contacting organizations personally worked well, as all organizations that were approached and that were able to share data (some regional governments did not manage the data themselves) eventually agreed to share their data. When an agreement with the organizations was reached, the data files were sent in Windows Excel formats, as this allowed for effective data management. With regard to the time-span of the data, it was difficult to set a certain time-span as the negotiations took some time and data was shared over a large period of time. Given that including the most recent data was considered valuable for the research, the request was to share several months of the latest data available. This resulted in a time span of January 2013 to April 2014, with the majority within the period of January – April 2014. The data characteristics of which the charging transaction dataset exists are shown below in table 1:

Table 1: charging transaction data characteristics

| Charging transaction data characteristics |
|--|
| Standardized charging point ID Code |
| Street name |
| House number |
| Postal code |
| Municipality |
| Standardized ID code of user charging pass |
| Date and time of start of transaction |
| Date and time of end of transaction |
| Total duration of transaction |
| Total energy transfer of transaction (kWh) |

In addition to this charging transaction dataset, several other data were added from different external sources. First, the number of public and semi-public charging points per four digit postal zone in the Netherlands and the surface of these postal zones in square kilometers was added, originating from Oplaadpalen.nl(2014) and BridGis (2014) respectively. Also, the battery capacity in kWh for the five most sold FEV and five most sold PHEV car models is added, originating from websites of EV manufacturers.

Confidentiality

The charging transaction datasets consist of privacy sensitive information as well as, at least for the commercial organizations, commercially sensitive information. This is because the dataset allowed to see which EV driver was charging where at given points in time, as well as analysing business results through the charging transactions. Therefore, in order to allow for ethical and confidential data analysis, confidentiality agreements had to be reached prior to sharing the requested data. The agreements that have been agreed upon and that will be respected in the rest of this report are:

- The data are not shared with anyone other than the researcher unless given written permission from the organization contact persons of the organizations involved in the data.
- In this research the data are strictly publicized in aggregated form so that the publicized data cannot be traced back to involved persons or the data-sharing organizations.
- Some participating organizations are allowed to check the report before it is published in order to check the researcher’s compliance to these agreements.

These agreements have several important implications for this report. First, the participating data sharing organizations will not be specifically mentioned in this report so that, for instance, geographical charging behaviour results cannot be traced back to individual participating municipalities or companies. Second, results on the geographical aspects of charging behaviour will be limited to meso-level (provinces and/or regions), making it impossible to zoom in on micro-level aspects (cities and/or streets). Thirdly, because license plate data cannot be shared by the organizations due to privacy considerations, the only remaining method to differentiate the electrical vehicles in the dataset is by using the ID codes of the charging pass that EV drivers use when initiating a charging transaction. This brings a potential error in the data analysis, as the pass is used to identify the user and not the EV itself, leaving the possibility that a single pass can be used for different EV's. However, all involved charging service providers, as well as several experts in the field of electrical mobility stated that given the current state of the EV market in the Netherlands, this margin of error can be neglected as that almost all charging passes are used for one single electrical vehicle. Therefore this assumption is maintained in this research. This assumption, combined with the charging pass ID's and the amount of energy transferred, allows to extract whether several charging passes are attributed to FEV's or PHEV's. These methods will be further discussed in the quantitative operationalization section.

These agreements also have implications for the validity and reliability of this research, as these agreements reduce the transparency in data sources and the dataset itself. However, in order to ensure the validity and reliability of this research, several precautionary measures have been taken that will be further discussed in the quality of the research section.

General dataset outline

Several aggregated characteristics describing the size and content of the resulting dataset are shown in below in table 2.

Table 2: Aggregated dataset characteristics

| Characteristic | Value |
|--|--|
| Data time span | January 1 st 2013 – April 30 th 2014 |
| Individual charging transactions | 956.579 |
| Charging points | 11.448 |
| Charging points identified as Public | 1938 |
| Charging points identified as Semi-public | 1198 |
| Charging points with unidentified type | 8312 |
| Charging pass ID's | 24.115 |
| Charging pass ID's identified as PHEV | 6213 |
| Charging pass ID's identified as FEV | 83 |
| Charging pass ID's with unidentified vehicle type | 17.819 |
| Average duration of all charging transactions | 7:29 hours |
| Average charging duration of PHEV's | 7:40 hours |
| Average charging duration of FEV's | 8:10 hours |
| Average energy transfer of all charging transactions | 7,05 kWh |
| Average energy transfer of PHEV's | 5,90 kWh |
| Average energy transfer of FEV's | 13,00 kWh |

Qualitative data collection

For the analysis of the driver related influence factors and the relations involving driver related influence factors, a series of semi-structured interviews with Dutch EV drivers has been performed. The use of semi-structured interviews allows the researcher to steer the interview towards discussing characteristics related to driver-related influence factors as identified from literature, whilst keeping the possibility for the respondent to discuss less related topics of interest that are new and unexpected to the researcher and that could be of interest for the research. All but one of the interviews were performed face-to-face on a location convenient to the respondent, as the use of face-to-face interviews was considered the best way to observe respondent reactions and allowed the researcher to ask relevant follow-up questions. One interview was done by telephone as this had the respondents' preference for scheduling reasons. The goal of the interviews was to help understand the content and influence of the driver influence factors. Despite the current ratio of 6 PHEV's for each FEV sold in the Netherlands (RVO, 2014), the emphasis in respondents was on FEV more than on PHEV drivers, for two reasons. First, as PHEV drivers have an alternative to electrical driving, the driver related factors of range anxiety and planning will be of less influence to the charging behaviour as they are not solely dependent on the electrical driving mode of the vehicle. Therefore these interviews will be of less value to understanding these factors. Second, with a FEV battery capacity being twice to seven times larger than a PHEV battery capacity, charging a FEV is much more demanding for the charging infrastructure, both in energy transfer and in charging duration. This makes it important to understand how and why FEV drivers cope with charging their vehicle with regard to driver influence factors. In total, 16 interviews were performed with a length of around 30 minutes. The last two interviews did not seem to add significantly to the data content, which suggests data saturation, resulting in a total amount of 16 interviews, which was considered appropriate for this research. For approaching EV drivers for interviews, two consecutive approach strategies were used. Firstly, EV drivers were approached in the personal and professional network of the researcher using an appeal for plug-in EV drivers on the social networking site Facebook and the professional networking site Linked-In. This led to interviews with three PHEV drivers and two FEV drivers. Additionally, appeals for PHEV and FEV drivers were placed on the Dutch Linked-in groups for drivers of the most sold FEV (Tesla Model-S) and the most sold PHEV (Mitsubishi Outlander) in the Netherlands (RVO, 2014), as well as the Dutch electrical driving digital forum Forum Elektrisch Vervoer Nederland. This led to an additional 11 FEV drivers. No additional PHEV drivers responded to the several appeal messages. All responses were answered with an e-mail describing the research, the goal and procedure of the interview, and a request for an appointment. All 16 interviews were performed between April 22th 2014 and May 21th 2014.

Ethics

Respondents were asked to share personal information such as mobility behaviour, EV purchase considerations and their home address. In order to ensure a safe and ethical interview procedure, several measures have been taken.

- For reason of processing and reliability, the interviews were recorded. The researcher asked the respondent for permission prior to starting the recording.
- The respondents will not be named in this report, and personal information such as age, addresses or employer will not be published.
- At the start of the interview, the researcher stated that the respondent is free not to answer questions. At the end, the researcher asked if anything had been asked which should not be used.

General interview sample outline

Several aggregated characteristics describing the sample of interview respondents are shown in below in table 3.

Table 3: General interview sample outline

| Characteristic | Value |
|-------------------------------|--|
| Total amount of interviews | 16 |
| Gender | 14 males (87,5%) and 2 females (12,5%) |
| Average age | 49,6 Years |
| Average plug-in EV experience | 6,1 months |
| FEV total | 13 |
| FEV Model | 10 x Tesla Model-S 85kWh 2 x Tesla Model-S 60 kWh 1x Renault Zoë |
| PHEV | 3 |
| PHEV Model | 1 x Mitsubishi Outlander 1 x Volvo V60 1 x Toyota Prius Plug-in |
| Form of EV ownership | 13 x business ownership 2 x lease 1 x private ownership |

Quantitative operationalization

The quantitative analysis on the charging behaviour dimensions and the vehicle and environment influence factors as well as the analysis of all relations that do not contain driver influence factors was performed by using the Windows Excel 2010 and SPSS 17.0 data handling software. For processing the raw data as provided by regional governments and charging service providers, Windows Excel was used which allows large amounts of data to be filtered on errors and missing values, as well as the recoding of data so that the several initial data files can be combined in one data file with a uniform data format. This software is able to handle large amounts of data and is able to produce descriptive and analytical statistics in quantified data. These descriptive statistics helped to describe the dimensions and influence factors of Dutch EV charging behaviour and the analytical statistics helped to describe and analyse the relations. As the elaboration on all quantitative dimensions, factors and relations require either descriptive statistics in order to describe the dimension (e.g. mean, range, outliers) or inferential statistics in order to analyse the relationships and account for randomness (e.g. correlations, independent sample T-test, regression) SPSS is a useful tool.

Raw data preparation

When all databases were combined, 1.015.558 charging transactions were included. However, before the data could be used for analysis, the provided databases of raw data had to be combined and prepared for analysis by fixing and deleting errors. This was performed in several steps. The first step concerned reorganizing the datasets, which consisted of two related but somewhat different formats, into one uniform format. Then, step two was to manually fix as many data errors or missing values as possible. Step three was to process the data using filters that were designed to delete errors as made by the charging point while registering the charging transaction. Below in table 4, these filters are shown and a short explanation is provided.

Table 4: Data preparation filters

| Filter | Explanation |
|--|---|
| Energy transfer larger than 95 kWh | The largest EV car battery is 85 kWh and a 90% efficiency make transactions larger than 95 kWh electrical trucks or errors (332 in total) |
| Energy transfer of 0 kWh | Charging 0 kWh is no charging transaction and considered an error (38.165 in total) |
| Energy transfer with negative kWh value | Negative kWh is an error (137 in total) |
| Energy transfer smaller than 0,1 kWh | Such small transactions result in outliers and are not considered relevant charging transactions (4323 in total) |
| Date errors (in the future or far in the past) | These dates lay outside of the data time span (7188 in total) |

Combined, these filters deleted a total of 50.145 transactions, which is 4,9% of the original amount of charging transactions. The fourth and final step of preparation was adding or constructing several additional data columns from the original data format. Two columns were added to the dataset from external sources: the number of public and semi-public charging points and the surface in square kilometers per four digit postal zone. One column was constructed from the data: the day in the week for each transaction date.

Another constructed column was the identification of charging passes as a FEV or a PHEV pass. This was required as the participating organizations did not have these identification data and were not allowed to share license plate data due to privacy restrictions. It proved impossible to extract EV models from the data, but identifying charging passes as FEV or PHEV was possible. This was done using the list of battery capacities in kWh for the 5 most sold FEV's and the 5 most sold PHEV's in the Netherlands, the charging pass ID column and the energy transfer (in kWh) column. The charging pass ID's allowed for identification of individual EV's in the database and the energy transfer gave an indication of how much energy goes into the EV battery. All charging ID's with forty or more transactions in the database were identified. Then the three largest transactions in energy transfer were selected. If these three transactions had less than 0,5 kWh difference, the maximum value could be considered an indication of the kWh capacity of the battery. When this average amount was compared with the list of battery capacities, it became evident that a cutoff value of 17,5 kWh enabled to differentiate between PHEV (below 17,5 kWh), and FEV (above 17,5 kWh) capacities. All charging pass ID's that had less than 40 transactions, or where the 3 largest transactions differed more than 0,5 kWh were considered too unreliable for the indication of an EV type, and remained unknown as to what EV type was charging. This resulted in an indication for an EV type in 62% of the transactions, and 38% remained unknown. The maximum values for the charging passes that were identified as PHEV or FEV will be used as indicator for the battery capacities for these vehicles. In this way, the correlation between the battery size and the energy transfer can also be measured.

Quantitative indicators

With the resulting dataset, the analysis was performed on the charging behaviour dimensions and the vehicle and environment influence factors. The main goal of this research is to provide insights in what the charging behaviour of Dutch EV drivers looks like, and what the influencing factors for this behaviour are. In order to describe what EV charging behaviour in the Netherlands looks like, all six charging behaviour dimensions and related relations will be analysed and described using the charging transactions dataset. The indicators for these dimensions and factors are stated in table 5 and 6 respectively.

Table 5: Measurement indicators for each charging behaviour dimension

| Dimension | Quantitative Indicator | Measurement |
|-------------------------|--|-------------|
| Charging Point Location | Charging point type (Private/Work/Public) | Nominal |
| Charging Point Type | Power Output | Scale |
| Charging Frequency | Frequency of charging per charging pass ID | Scale |
| Charging Time of Day | Time of day per charging transaction | Scale |
| Charging Duration | Duration of charging transactions | Scale |
| Energy Transfer | Energy transferred to EV battery (kWh) | Scale |

Table 6: Measurement indicators for each quantitative influence factor

| Category | Influence Factor | Quantitative Indicator | Measurement |
|--------------------|------------------------|--|-------------|
| <i>Vehicle</i> | Battery Size | EV battery capacity (kWh) | Scale |
| | Vehicle Range | EV maximum range (Kilometers) | Scale |
| | Vehicle type | Registered as an PHEV/FEV | Nominal |
| <i>Environment</i> | Charging Point Density | Charging Points/square kilometer in four digit postal zone | Scale |

Charging behaviour dimensions and influence factors measurement

In order to answer the second sub-question what the charging behaviour dimensions look like, all six dimensions will be analysed quantitatively from the database separately. Also, all vehicle- and environment-related factors are analysed quantitatively. Several descriptive statistics for each dimension and influence factor will serve as base for these analyses. As the dimensions and factors vary both in characteristics and measurement level (nominal/ordinal/scale), the analysis strategies and operational considerations will be discussed below for each dimension separately.

Dimensions

Charging Point Location

The charging point location (private/semi-public/public) is identified by comparing the charging point ID codes in the database to the charging point ID codes of the Opladpalen.nl database. No identification of private points proved possible due to lack of information on these charging points. In order to show the difference in charging behaviour between public and semi-public charging points, frequency graphs are presented with the start- and stop times of transactions during the day, for public and semi-public charging points separately. In addition, average duration and energy transfer values are calculated for the two categories to allow comparison. Furthermore, the dispersion in different charging locations per charging pass occurring in the database is shown in a pie-graph. This will bring insight in to how many different and what kind of locations EV drivers use in charging their EV.

Charging point type

Using the Opladpalen.nl database, 2356 charging points were identified in how much power they supply. This resulted in five categories: 2,3 kW, 3,7 kW, 5 kW, 11kW and 22 kW. No fast chargers (supplying above 22kW) were identified using this method. A frequency table is produced in order to show the distribution of these power outputs throughout the charging transaction database. Then, in order to understand how these different charging points are used with regard to charging, average transaction durations and average energy transfers are calculated per power output category.

Charging Frequency

For showing the average charging frequency, a frequency graph is presented. In order to correct for the databases not having the same timespan, the average frequency for each charging pass is measured only for the weeks that these passes occur in the database. Next to the graph, descriptive statistics are added so that the data characteristics are clear.

Charging time of day

For the charging time of day, frequency graphs are produced for the amount of transactions starting and stopping per minute of the day. A division is made between working days and weekend days, as it could be expected that working days show a working day pattern and weekend days show a more dispersed pattern. The graphs are discussed using the times on which peaks occur.

Charging Duration

For the charging duration dimension, a frequency graph is produced showing the amount of charging transactions per charging transaction duration (in minutes). The peaks and valleys in this graph will help to discuss this dimension.

Energy Transfer

For this dimension, a frequency graph is produced showing the amount of charging transactions per kWh of energy transfer. This graph will show the dispersion and the most common energy transfer amounts. The peaks and valleys of this graph are discussed and an additional graph is produced showing the difference in energy transfer dispersion between PHEV and FEV chargers.

Factors

Vehicle related factors

As an identification of the EV model proved impossible, this factor cannot be discussed in depth. Only a division between FEV's and PHEV's was possible. A table is produced showing the 5 most registered PHEV's and FEV's, and the related battery capacity in order to show what the EV fleet in the Netherlands looks like, and what capacities are related to these models.

Environment related factors

Using the Oplaadpalen.nl and the BridGis database, a map is produced showing the charging point density per Dutch province. Based on this map, the differences in charging point density in the Netherlands is discussed.

Quantitative relations measurement

In order to provide an answer to sub-question three, how factors influence EV charging behaviour, a quantitative analysis is performed on the influence factors in the vehicle and environment categories and several quantitative relations. In these analyses, descriptive statistics will also be important as they show the central tendency and distribution of the underlying data. The same descriptive statistics will be used as the behaviour dimension analyses. However, in addition to describing the factors, the presence and strength of the relations must also be measured. All quantitative relations are relations between two scale (interval) variables, with one exception. This is the vehicle range – charging frequency. The vehicle range could not be identified for the charging transactions, and will therefore be analysed using the identification of the PHEV/FEV passes. This turns this relation into a relation between a binominal measurement and an interval measurement. For measuring the relationship between two scale (interval) variables, Pearson's Correlation is used, which measures the extent to which the variables are linearly correlated. For measuring the nominal-interval relationship, an independent samples T-test will be used, which allows to test for significant difference in means between the two groups.

Qualitative operationalization

The qualitative analysis on the charging behaviour dimensions and the driver related influence factors as well as the analysis of all relations that contain driver influence factors is performed by use of semi-structured interviews with EV drivers in the Netherlands, and manually coding the interview transcripts. The interview questions were constructed using indicators that were identified in scientific literature discussing the driver influence factors, as stated in table 7.

Table 7: Measurement indicators for each qualitative influence factor

| Category | Influence Factor | Qualitative Indicator |
|---|------------------|-------------------------------------|
| <i>Driver related influence factors</i> | Range Anxiety | Perceived fear for depleted battery |
| | | Overestimating range needs |
| | | Valuing a large vehicle range |
| | Planning | Planning heuristics |
| | | Coping with EV limitations |
| | Mobility Pattern | Mobility regularity |
| | | Mobility intensity |
| | EV experience | Years driving an EV |
| Perceived ability to cope with limitations of EV technology | | |

Combined, these indicators led to an interview question list as stated in appendix B. As all respondents were Dutch native speakers, all interviews were performed in Dutch. The quotes that are used in the results section are translated to English. All interviews were recorded and transcripts of the interview recordings were typed out the same day. When all interviews were completed and transcripts were finished, the coding process began.

The coding process was performed by use of axial coding; using pre-established categories in which codes could be placed. These categories were the qualitative indicators as shown in table 7 plus indicators on the charging behaviour itself. However, as the interview process was designed so that new and unexpected insights could also be added, code-subcategories were added in the coding process to accommodate these insights in a more specific group. This resulted in the coding scheme that is presented in Appendix C.

All transcripts were read by the researcher. Of each sentence, the researcher decided whether the sentence was related to charging behaviour. If this was the case, the sentence was added to an existing code sub-category if possible, and otherwise a new sub-category was added to accommodate the sentence. This process resulted in the use of 33 sub-categories containing a total of 499 entries of one or multiple sentences. When analysing the results per influence factor, all codes in the sub-categories that fall under this factor were read by the researcher. In this way, a general view was created of how the results of this dimension were. Then, commonalities and patterns were sought within these dimensions, so that overarching results could be derived. When these patterns were identified, the meaning of these patterns were described using quotes from interview respondents. Also, surprising and unexpected insights that require further attention are be discussed.

Quality of the research

In order to ensure the quality of the research the validity and the reliability of the research have to be ensured (Hancké, 2009). The validity of the research is concerned with whether the concepts as defined in this research proposal are correctly expressed in the measurements used, and the reliability is concerned with the stability of the measurement (Hancké, 2009). The validity of this research is ensured by strictly using concepts and insights that have emerged from the above mentioned literature review, of which the search strategy and sources are clearly stated. Basing all dimensions, factors and relations on these insights ensures that former literature strengthens the validity of this research. The indicators used from the data are chosen based on insights and elaborations from earlier studies on charging behaviour. In the interview coding process these literature insights have also been used so that this part of the research is grounded in literature as well. The reliability, the stability of measurement, is ensured in this research despite limitations that have emerged due to the confidentiality agreements. The reliability and correctness of the research methods, data handling and data interpretation have been discussed with, and ensured by, several data-management and charging transaction experts with the participating organizations. The reliability is ensured in this research because all steps taken and considerations that have been encountered are clearly stated and elaborated. This enables other researchers to replicate the methods used. As to the use of data and the transparency of data sources, this is more difficult due to confidentiality agreements. However, anyone wishing to replicate this research using the same data and the same data sources, is free to contact the researcher on the contact addresses on the front of this report. The researcher can then ask for permission from these data contributors for sharing this information. This may help to bring transparency to the dataset and sources. However, in accordance with the confidentiality agreements, for all issues in data sharing or the naming of sources, permission has to be granted by the sources themselves.

Results

The dimensions, factors and relations are divided between quantitative and qualitative measurement methods. Therefore, for structuring purposes, this results chapter will be divided between these two measurement methods as well. First, the charging behaviour dimensions and quantitative factors and relations are described, followed by the qualitative factors and relations. Whenever the elaboration on the quantitative dimensions, factors and relations is restricted due to data and/or analysis limitations, further insights will be used from the interviews where possible.

Charging behaviour dimensions

Charging point location

In the charging transaction database, 1938 charging points were identified as public, meaning the charging points are accessible and usable for anyone as they are placed in the public domain. 1198 points were identified as semi-public, meaning that the charging point is placed on private domain such as the parking lot of businesses or other organizations but is also available to visitors or external users. The location of the remaining 9190 points were unknown as the charging points details were missing or were not compatible with the Opladpalen.nl database. On average, public charging points showed 155 charging transactions per charging point in the database, whilst the semi-public had an average of 59. This could be expected as semi-public will most likely only be used during workdays and during office hours, which is also visible when analysing the time of day on which transactions are started and ended, divided between public (figure 2) and semi-public points (figure 3), as shown below.

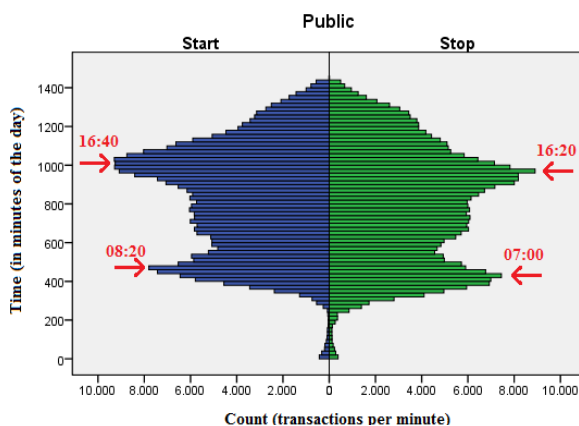


Figure 2: the count (X-axis) of public charging transactions starting (left) and ending (right) per minute in the day (Y-axis)

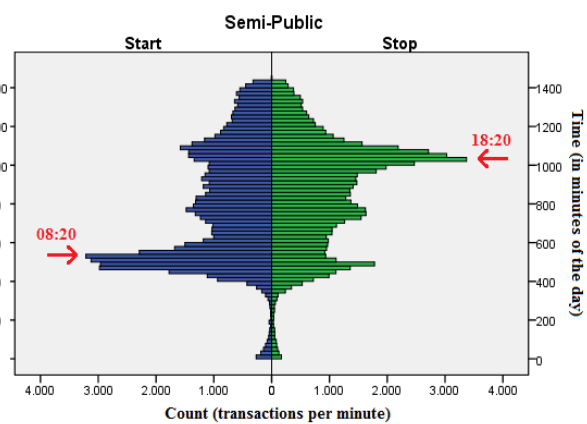


Figure 3: the count (X-axis) of semi-public charging transactions starting (left) and ending (right) per minute in the day (Y-axis)

The time of day on which public transactions occur differ from semi-public charging transactions. Public transactions seem to reflect a working day rhythm of EV drivers, which will be further elaborated in the time of day dimension. The semi-public charging clearly shows a peak in transaction starts around 08:20, and an end peak at 18:20, also reflecting office hours. The semi-public points however, lack the ending peak in the morning and the starting peak in the evening which are visible in public charging transactions. The average transaction duration and the average energy transfer are comparable. The average charging durations for public and semi-public transactions are respectively 6:40 and 06:15 hours, and the average energy transfer are respectively 8,3 and 7,8 kWh.

Analysing charging behaviour for private charging points proved impossible. Not only were the participating organizations unwilling and sometimes legally unauthorized to share this privacy-sensitive information, they also have limited information on these private transactions. As there is no need for the EV drivers to share private charging data, the data is not actively monitored. Only when the EV driver uses online back-office services or automatic cost registration for lease-drivers, the data is shared digitally. This lack of charging point location knowledge is a valuable result in itself. As most EV drivers tend to charge at home, a large amount of energy is used from these points. If the monitoring of these points is difficult, the share of the peak demand issues that is induced from home-charging remains under the radar and could only be analysed through the total energy use of homes, without the possibility of singling out the EV charging demand.

From the interviews, an overall preference for home charging is perceived. This was largely due to the convenience of using the time the car is charging effectively, knowing the point is always available and the experience with and knowledge of the charging system. EV drivers that do not have a private parking spot available at home are dependent on public charging. However, while using these public points, the EV drivers also encounter several restrictions in the use of these points. In urbanized areas, the car may not be parked in the EV parking spot if it is not charging, which brings the need to move the car. Also, the charging point is not always placed near the home of the EV driver that had applied for the charging point, and the availability of the point is uncertain. This leads to EV drivers that did not have a private charging point at home, and had the ability to charge at work, to prefer work-charging over home charging as the availability is more predictable and the charging time could still be used effectively. PHEV drivers also have the option not to charge the battery whenever the public charging point is unavailable, and all PHEV drivers state that not charging the car had the preference over the hassle of looking for another charging possibility.

When looking at the distribution in charging locations per EV in figure 4, the following results show. 46% of all charging passes in the database only charge at one location. 41% charges at between 2 and 5 locations and 13% at more than 5 different locations. From this analysis, several insights arise. First, for a large share of EV drivers, their charging behaviour is based on routine: they charge at limited amount locations and do not deviate from these known locations. Secondly, the share of EV drivers that rely on planning ahead with regard to EV charging point is very small as they are likely to be using an unknown charging. Only one percent has more than 20 locations, and even only four percent has more than 10 locations. This suggestion of routine brings concerns with regard to charging point availability problems, as EV drivers are very static in the locations where they charge and will therefore be less likely to search for alternatives. However, it could also mean that currently the availability of charging point is less of a problem, as EV drivers are not forced to use other charging points due to their preferred charging point being occupied.

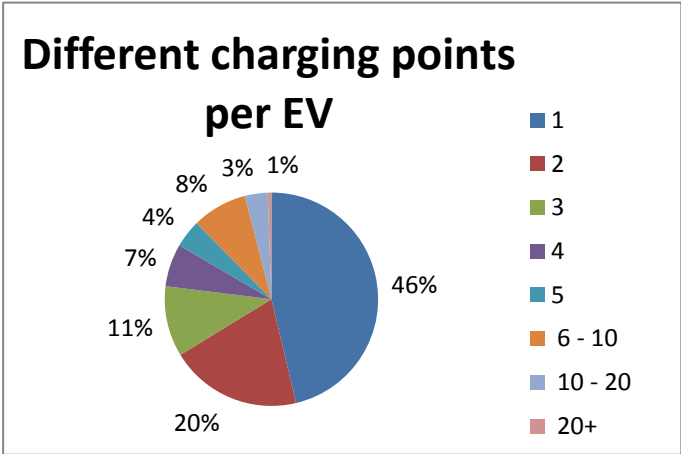


Figure 4: Amount of different charging points used per charging pass, in percentages.

Charging point type

With regard to the charging point type used, a difference is made between five different charging point types, ranging from 2,3 kW to 22 kW. The analysis of the charging behaviour of fast-chargers proved difficult, as the amount of fast charging locations is still limited, the locations have not been used often, and the operating companies do not wish to share charging transaction data due to the competition sensitive character of the data. Below, in table 8, an overview is provided of the charging point types that were identified in the database using the Oplaadpalen.nl (2014) database.

As shown below in table 8, the majority of charging points that were identified in the database are 11kW charging points (72,2%). In reality, when looking at the Oplaadpalen.nl database, 11kW charging points account for 67% of public and semi-public charging points in the Netherlands, followed by 3,7 kW points with 19%.

Table 8: Overview of counts and percentages of charging point types as identified in the database.

| Power output | Charging points | Percentage | Transactions | Percentage |
|--------------|-----------------|------------|--------------|------------|
| 2,3 kW | 25 | 0,81% | 1639 | 0,45% |
| 3,7 kW | 700 | 22,71% | 37156 | 10,16%% |
| 5 kW | 111 | 3,6% | 4407 | 1,20% |
| 11 kW | 2225 | 72,17% | 322145 | 88,05% |
| 22 kW | 22 | 0,71% | 526 | 0,14% |
| Total | 3083 | 100% | 365873 | 100% |

When analysing the difference in use between these charging point types, shown below in table 9, several aspects arise. First, the 11kW charging points, the most common charging points in the Netherlands, are used most frequently. This could be explained by the fact that these are primarily public charging points. As semi-public charging points are commonly only available during office hours, and only for authorised users, they will be used less often than public charging points that do not have these restrictions. Second, the use of the 2,3 kW outputs seems to deviate from the overall trend both in duration and in energy transfer. Thirdly, as the power output of the charging point is higher, overall the duration of the transaction is shorter (apart from the 2,3 kW output). This result indicates that drivers do monitor the battery level while/after charging, as charging transactions with a higher power output use less time. Also, as the power output becomes higher, the average energy transfer becomes higher as well (again, apart from the 2,3 kW).

Table 9: Overview of the average occurrence frequency, duration and average energy transfer per charging point type

| Power Output | Transaction frequency per point (count/week) | Average duration (minutes) | Average energy transfer (kWh) |
|--------------|--|----------------------------|-------------------------------|
| 2,3 kW | 61 | 229 | 8,38 |
| 3,7 kW | 53 | 407 | 6,24 |
| 5 kW | 40 | 402 | 7,32 |
| 11 kW | 141 | 395 | 8,33 |
| 22 kW | 24 | 252 | 8,57 |

Charging frequency

When analysing the frequency with which the EV drivers in the database charge their EV, several aspects arise which will be further discussed using figure 5 and table 10 as presented below. When analysing the charging frequency, it became evident that results were dependent on which charging passes were taken into account in the analysis. It is probable that the majority of charging points in the database are public and semi-public charging points, and that the number of private charging points in the database is limited. This means that EV's that are regularly charged at home will not show as much as EV's that are dependent on (semi-)public charging. The absence of home charging EV's may reduce the average charging transactions drastically. This would therefore not represent the actual average charging frequency of EV drivers. Strictly using passes that occur more regularly could correct for this discrepancy. Therefore, figure 5 shows three lines of the count of charging ID passes per charging frequency value (in charging transactions per week). The three lines refer to which passes are taken into account: All passes (0+), passes occurring more than 10 times in the database (10+) and more than 20 times (20+).

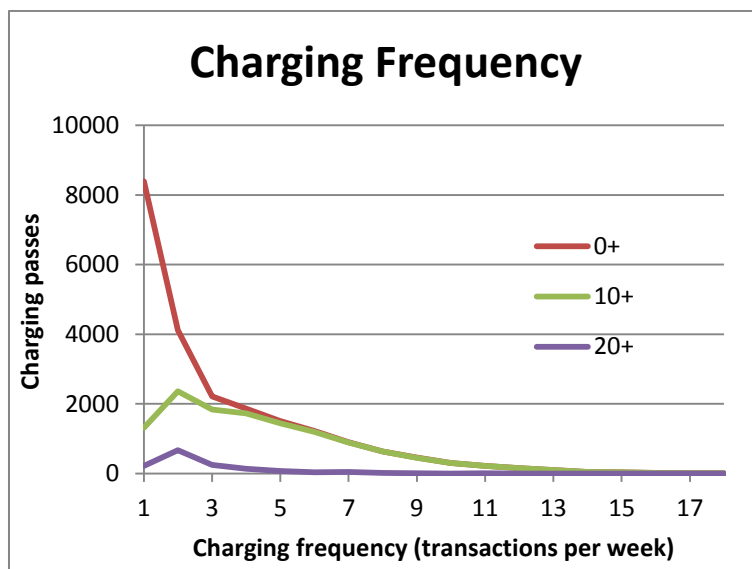


Figure 5: The counts of charging passes occurring 0+, 10+ and 20+ times in the database with the average amount of charging transactions per week.

Table 10: Descriptive statistics of charging frequencies, using the 0+, 10+ and 20+ data filters.

| | 0+ | 10+ | 20+ |
|--------------------------|-------------|-------------|-------------|
| Average frequency | 3,23 | 4,61 | 2,78 |
| Std. Error | 0,02 | 0,03 | 0,05 |
| Median | 1 | 2 | 2 |
| Std. Deviation | 2,81 | 2,97 | 1,72 |
| Sample Variance | 7,92 | 8,84 | 2,97 |
| Range | 36 | 36 | 13 |
| Min. | 1 | 1 | 1 |
| Max. | 37 | 37 | 14 |
| Pass ID Count | 22.216 | 12.767 | 1.462 |

When looking at the analysis with all charging passes (0+), several aspects arise. A high count value is seen at 1 times a week, with a sharp decline when frequency gets higher. This could be explained due to the fact that weeks in which passes were not occurring in the database are not taken into consideration in calculating the average frequency. This was done to correct for the difference in time span for the different databases, and results in a high count for low frequency numbers. As the occurrence value is higher (10+ and 20+), the count values of charging once and twice a week drop, probably due to excluding the home-charging EV drivers. An exact average charging frequency for all EV drivers in the Netherlands proves impossible due to the lack of private charging points, which results in private charging transactions remaining unknown. When all passes are considered, the average charging frequency is 3,23 transactions per week. With the 10+ value, the average charging frequency is 4,61. An average between 3,23 and 4,61 seems to reflect findings from interviews, but seems to be less than findings from the literature, which suggest that EV drivers would charge their EV every day (so that the average would be towards 7). Three main insights can be derived from the figure. First, when the 20+ passes are considered, a charging frequency of 2,78 is seen. As 20+ passes will most likely be dependent on public charging infrastructure in daily life and will therefore always

show up in the database, one could say that EV drivers that are dependent on public charging infrastructure have a charging frequency average of around 2,78 times a week. Secondly, it is visible that only a small share of EV drivers (13 % of all passes) have an average charging frequency of 7 (once a day) or higher, which does not reflect the results from Smart et al. (2013) in which a percentage of 80% daily chargers is found. Thirdly, it is probable that a large part of EV drivers has never charged at a public charging point, or has charged there only once. 14% of the charging pass ID's occurring in the database occur only once, and 33% occurs less than 5 times. The expectation therefore is that the share of EV's that are rarely publicly charged is much larger, as all ID's that have never publicly charged may not be included in the database at all. These findings implicate that commonly, EV drivers charge far less than every day, which suggests less routine than seen in the charging point location and charging point type dimensions.

Charging time of day

When analysing the time of day on which charging transactions take place, a difference is made between working days (figure 6) and weekend days (figure 7), as one could expect regular patterns to be more visible on working days. In the weekends, the EV could be used more often on irregular leisure trips and unexpected impulsive trips, which would show a less strict pattern. The starting and stop times of all charging transactions in these two categories are shown in minutes of the day (0 minutes is 00:00, 720 minutes is 12:00 and 1.440 is 00:00 again). Also, times of relevant emerging peaks are provided.

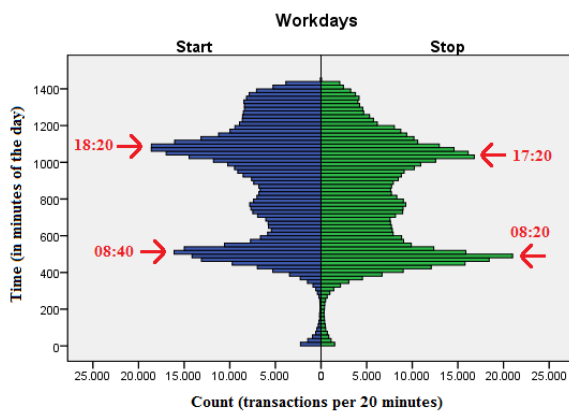


Figure 6: Count of working day transaction start (left) and stop (right) times per minute of the

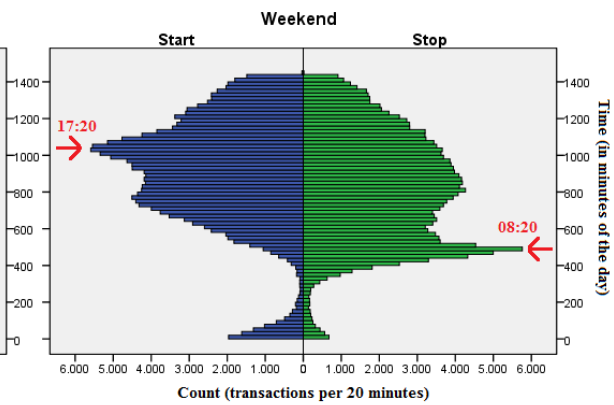


Figure 7: Count of weekend transaction start (left) and stop (right) times per minute of the

The workday picture shows results that match the expectations from literature. As the day starts, a peak of transaction endings is visible at 08:20, which could represent EV drivers ending their nighttime transaction (during the night, almost no transaction changes are visible) and going to work. Then, at 08:40, a peak of transaction starts is visible. This peak could represent people arriving at work or place of destination and plugging in their car again for a daytime charging transaction. Then at the end of the day, the same pattern emerges: at 17:20 a transaction end peak which could represent people leaving work and at 18:20 a transaction start peak which could represent people arriving home.

The weekend picture clearly shows a more dispersed pattern. Although transaction activity in weekend nights is low, it shows more activity than workday nights. At 08:20 a peak in transaction endings is seen. The start of transactions in the weekend is dispersed all over the day, with a peak at 17:20. Overall, several insights can be derived from the figure. First, it is probable that a considerable share of EV drivers do charge their EV overnight, as the 17:30 charging transaction start peak is not followed by an end-peak up until 07:20 the next day. This would bring the flexibility necessary for smart charging technology application. Also, charging at work, or at least in office hours, seems to be done by a considerable share as well, as a starting peak at 08:20 and an end peak at 18:20 seem to reflect this behaviour. Furthermore, the peak demand issues as described in literature seem to be a

viable risk, as the pattern of all EV drivers shows clear peaks in which many EV's are plugged in in a small amount of time. In the weekend, this risk seems to be smaller, as charging activity is more spread throughout the day. Despite not being able to track precise electricity demand throughout the day using the database, this analysis suggests that the electricity demand for EV charging is particularly high around 08:40 and 18:20 on workdays.

Charging duration

Following the time of day analysis, the charging duration analysis in figure 8 also shows patterns that match expectations. Below, figure 8 is provided in which the duration of all charging transactions is shown with the amount of minutes the transaction lasts.

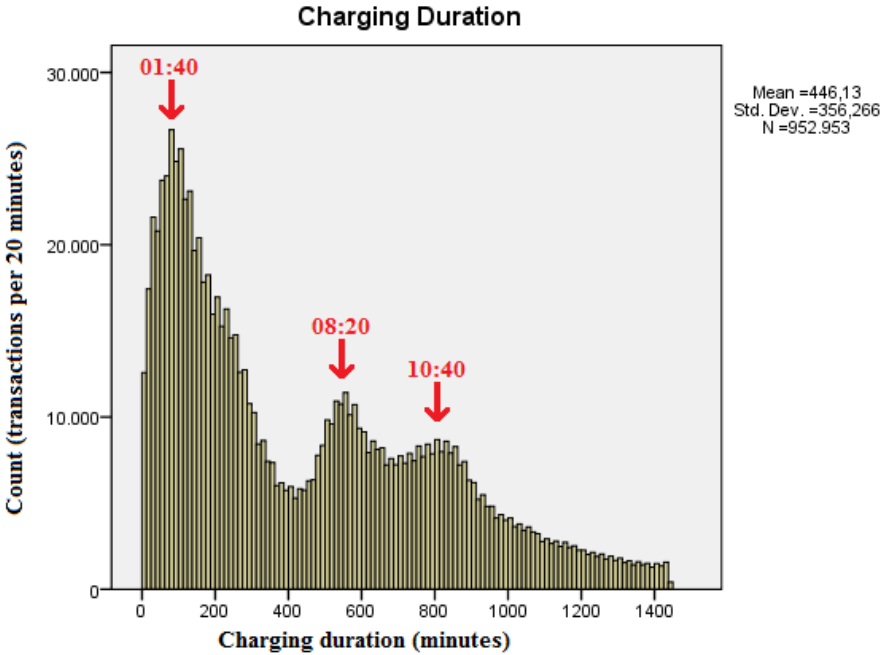


Figure 8: Count of transaction durations per minute.

When further analysing the duration of the transactions, three peaks are visible: durations of around 01:40 hours, 08:20 hours and 10:40 hours. The first peak, which roughly starts around 0 minutes (00:00), ends around 200 minutes (03:20) and includes 35% of all transactions, will mostly represent casual transactions that commonly are less planned, or charging transactions for which EV drivers have limited time available.

The peak on 08:20 hours duration (between 450 and 600 minutes, 12% of transactions) could represent work chargers, as a typical workday would be from 8:30 to 5:30 (as visible in the time of day dimension), which is 8 hours. When the average starting and end times of all transactions lasting between 450 and 600 minutes are analysed, the average starting time is 12:15 and the average end time is 13:15. Although these times do not represent the 8 hour gap itself, they are around the middle of the day, which indicates daytime charging.

Moreover, the peak on 10:40 (between 750 and 900 minutes, 10% of transactions), could represent nighttime chargers, as these long lasting transactions could reflect the length of the night (e.g. 22:00 – 08:00). When the average start and end times of the transactions within this peak are analysed, the average starting time is 18:10, and the average end time is 08:40. These times also do not clearly represent the 10 hour gap, but do clearly reflect the nighttime-charging times, with a start early in the evening and an end early in the morning.

The insights that can be derived from this analysis add to the insights from other dimensions (time of day, charging point location, charging point type). First, it is confirmed that a share of EV drivers charge their EV at night, as was visible in the time of day dimension. The 10:40 hour peak reflect the

start and end times one expects for nighttime chargers. It is also confirmed that a share of EV drivers charges at work or during office hours, as was visible in the semi-public use figure in the charging point location dimension.

When the duration of the transactions is related to the theoretical required duration of the charging transaction, the following figure 9 shows.

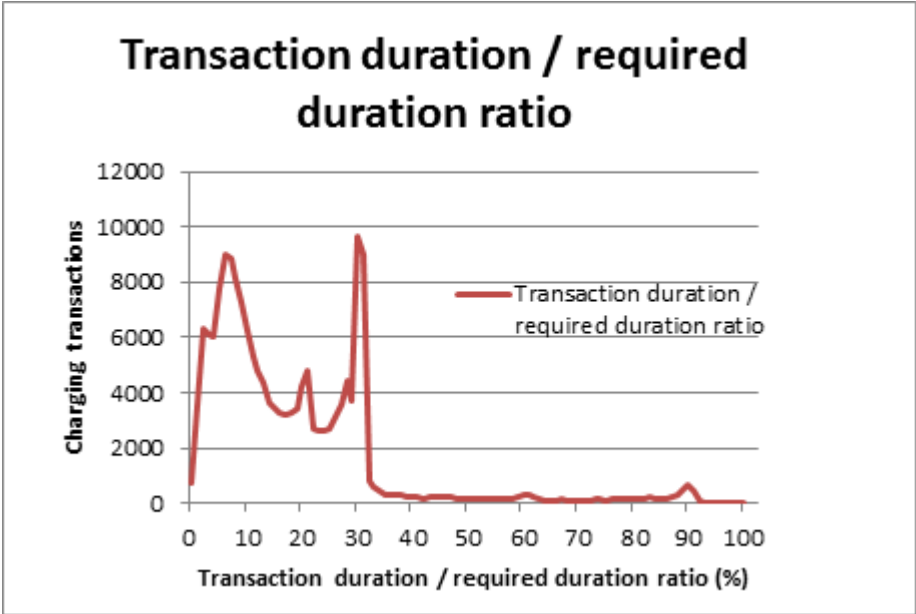


Figure 9: the ratio between the actual and the required charging transaction duration in count of transactions (y-axis) per percentages (x-axis).

The theoretical required duration of the transaction is calculated by dividing the energy transfer of the transaction by the energy output of the charging point. When analysing this ratio, 92 percent of all transactions have a ratio score of below 32%. This means that 92% of all charging transactions are connected to the charging point for up to three times longer than they are theoretically required to. With regard to the charging point availability problem, this is shows that availability could be improved by stimulating EV drivers to end the charging transaction when the desired energy has been transferred. If charging durations are better adapted to the required duration, existing charging infrastructure could be used much more efficiently.

Energy transfer

Energy transfer analysis has revealed several relevant aspects of the charging behaviour of EV drivers. Below, figure 10 is provided showing the count of charging passes per kWh of energy transfer. Table 11 shows the corresponding descriptive statistics. The counts of energy transfers above 13 kWh, with a maximum value of 84 kWh, were very low (only 0,006% of transactions was larger than 13 kWh). Therefore the figure below is shown in the range of 0 – 13 kWh.

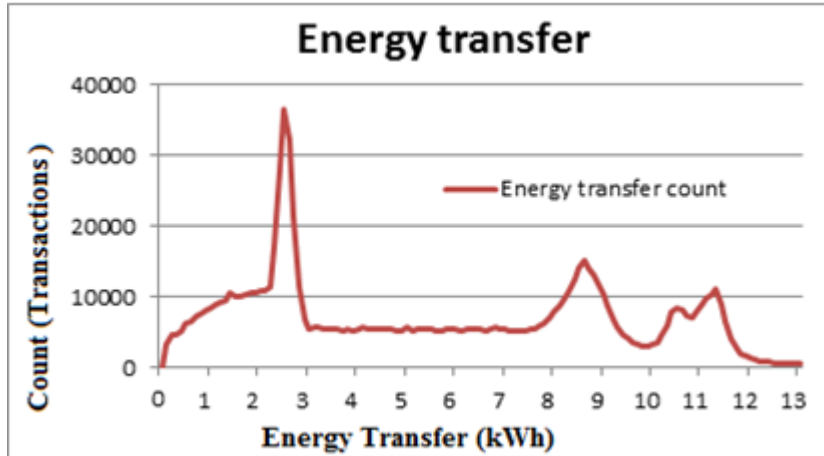


Figure 10: counts of occurring charging pass ID's per kWh energy transfer between 0 and 13 kWh.

Table 11: Energy transfer descriptive statistics

| | |
|-----------------|---------|
| Average | 6,34 |
| Std. Error | 0,01 |
| Median | 6 |
| Std. Deviation | 5,64 |
| Sample Variance | 31,79 |
| Range | 84 |
| Min. | 0 |
| Max. | 84 |
| Sum | 6067230 |
| Count | 956579 |

It becomes visible that four peaks are present: 2,5 kWh, 8,6 kWh, 10,5 kWh and 11,3 kWh. Next to the peaks, also the straight line between 3 and 7,5 kWh stands out. Overall, the average energy transfer for all transactions is 6,34 kWh. The presence of these strong peaks could be attributed to PHEV's having low batteries when being plugged in. As a large majority of Dutch EV's are PHEV's, and with PHEV's it is easy to empty the battery during driving, it is probable that PHEV's often charge from an empty battery to a full one. This should result in many PHEV's charging comparable amounts of energy, showing a peak. Despite the Dutch EV car park consisting of 24% EV's with a battery capacity higher larger than 13 kWh (RVO, 2014), only 0,006% of all transactions was larger than 13 kWh. This shows that these large capacity EV models are often charged at home, and are, when using public or semi-public charging facilities, only charged partly.

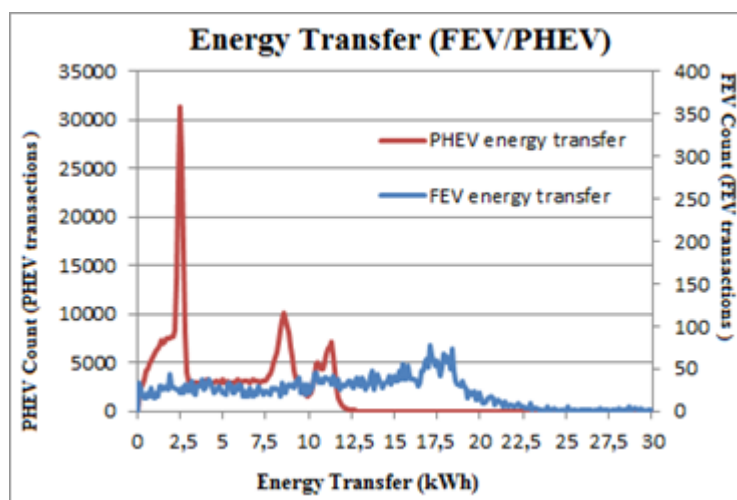


Figure 11: Charging pass ID's per kWh energy transfer between 0 and 30 divided between PHEV (Left y-axis) and FEV (Right Y-axis) passes.

Figure 11 shows the difference in energy transfers for PHEV and FEV charging passes. Here, one can see that the PHEV's are identical to that in figure 10, showing the dominance of PHEV passes in the database. FEV charging however, shows a more even distribution between 0 and 12 kWh, and peaks around 17 and 19 kWh. This is can be related to several FEV capacities, such as the BMW I3 (19 kWh), Renault Zoë (22 kWh), and Nissan Leaf (24 kWh).

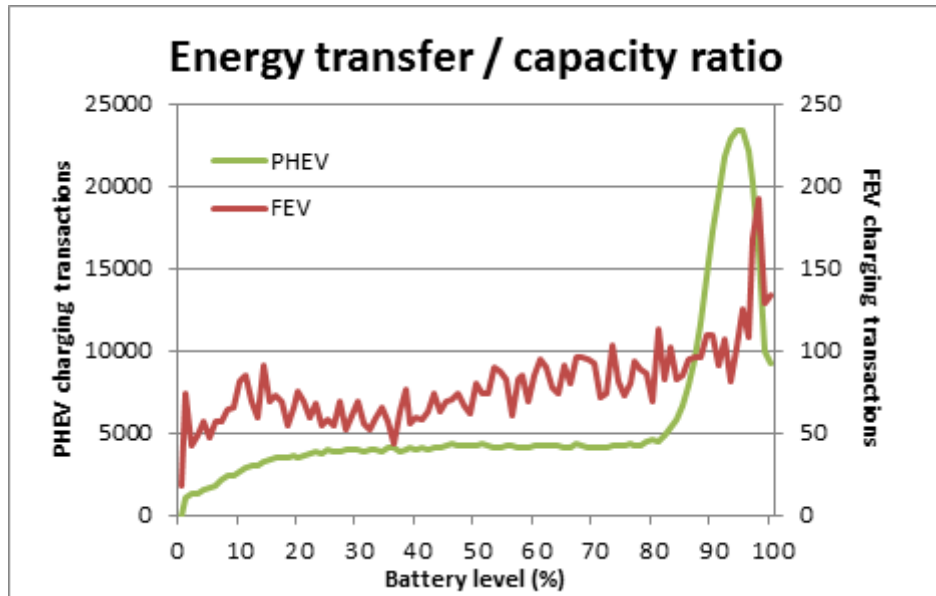


Figure 12: the energy transfer / capacity ratio in transaction counts for PHEV's (y-axis left) and FEV's (y-axis right) per percentage (x-axis).

When the energy transfer is compared to the capacity of FEV's and PHEV's, figure 12 emerges. The EV capacity is calculated using the maximum energy transfer value of charging passes identified as PHEV or FEV. From the figure, several insights emerge. First, 44% of all PHEV charging transactions charge an energy amount of above 85% of the battery capacity. This is visible in the PHEV line, where a strong peak is visible above 85%. This could be expected as PHEV's are easily driven empty, and therefore often charge close to their capacity. Next to the peak, the battery levels are spread almost evenly between 0 and 85%. As for the FEV's, the battery levels are spread almost evenly between 0 and 100%, especially when the scale difference in this analysis with the PHEV's are considered. These results are comparable to findings by Smart et al. (2013) in which a quarter of transactions was charging of depleted batteries, and the remaining three quarters were evenly spread between 10% and 100%. The results from this analysis once again show routine charging behaviour, in which the battery level of the car does not seem to be a relevant factor in making a charging decision. FEV battery levels are spread equal over all transactions, as is the case with PHEV, except for batteries that have been driven empty.

Quantitative influence factors

Vehicle related factors

Due to the lack of data on which EV model is charging, charging transaction data can only be differentiated between PHEV's and FEV's. However, for an indication of the EV car park and corresponding capacities, the table 12 is created.

Table 12: Registration numbers of PHEV's and FEV's in the Netherlands on 31-05-2014, with corresponding battery capacities (Source: RVO, 2014)

| | Most registered # | Registrations on May 31st 2014 | EV model | Battery Capacity (kWh) |
|------|-------------------|--------------------------------|----------------------|------------------------|
| PHEV | 1 | 12.319 | Mitsubishi Outlander | 12 |
| | 2 | 8.231 | Volvo V60 | 12 |
| | 3 | 4.942 | Opel Ampera | 16 |
| | 4 | 3.923 | Toyota Prius | 4 |
| | 5 | 1.060 | Chevrolet Volt | 16,5 |
| FEV | 1 | 1.578 | Tesla Model S | 85/65 |
| | 2 | 945 | Nissan Leaf | 24 |
| | 3 | 620 | Renault Zoë | 22 |
| | 4 | 376 | SmartForTwo | 13,2 |
| | 5 | 295 | BMW I3 | 19 |

Environment related factors

When the charging point densities (charging points per km²) per Dutch province are shown in a map of the Netherlands, some differences are visible, as shown in figure 13. Provinces with a high population density (Zuid-Holland, Noord-Holland, Utrecht) have a higher charging point density, in line with the expectations of Skippon and Garwood (2011). Provinces with lower population densities such as Zeeland, Groningen, Drenthe and Friesland also have a lower charging point density. The difference between the highest charging point density of 2,55 points per km² and the lowest of 0,09 per km² is large. This leaves open the possibility of this density having an effect on the residents adopting another charging behaviour. Moreover, in less populated areas, one could expect car use to be more intense, as facilities are further apart. The effect of charging point density on charging frequency is further analysed in the corresponding relations section.

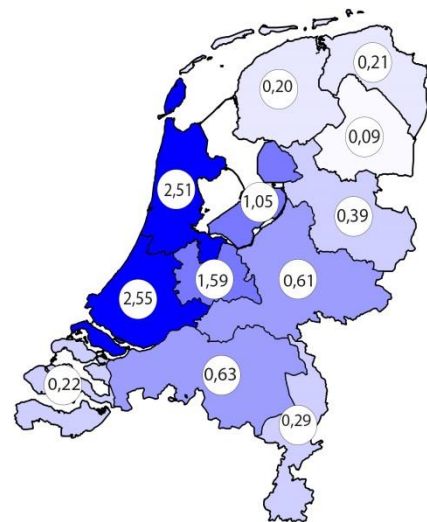


Figure 13: Charging point density per Dutch province (Charging points/ Km²) (Source: Oplaadpalen.nl, 2014; BridGis, 2014)

Quantitative relations

Charging frequency – energy transfer

When analysing the correlation between the charging frequency of drivers, and the energy transfer, a small negative significant correlation (-0,166) has been found to be significant in the analysis, as shown in table 13. This means that as the average charging frequency of EV drivers increases, the average energy transfer decreases. This is in line with the expectation of Franke and Krems (2013a), stating that higher charging frequency users commonly charge with a less depleted battery. Despite the correlation being small, this result could be of importance for relieving the electricity infrastructure, as higher charging frequencies with lower energy transfers per transaction could relieve electricity demand peaks, and spread out the EV charging demand across the day.

Table 13: correlation statistics for charging frequency – energy transfer relation

| Charging frequency - Energy transfer | |
|---|--------|
| Pearson Correlation | -0,166 |
| Sig. (2-tailed) | 0,000 |
| N | 764941 |

Charging duration – energy transfer

A significant correlation is found between the duration of the charging transaction and the amount of energy that is transferred during the transaction as shown in table 14. However, for a relation that is this obvious (if the transfer takes longer, more energy is transferred), one would ideally want a correlation of 1, meaning that the EV is not plugged in any more than required for charging the EV. A correlation of 0,287 means that for a considerable share of charging transactions, the duration of the transaction has little correlation with the energy that is transferred. This means that the charging point and the related parking spot often are occupied longer than needed. This is an important result for charging point availability issues: having a higher charging duration – energy transfer correlation would improve the availability of charging points by reducing the time the charging points are taken by EV's that are not charging.

Table 14: correlation statistics for charging duration – energy transfer relation

| Charging duration – Energy transfer | |
|--|--------|
| Pearson Correlation | 0,287 |
| Sig. (2-tailed) | 0,000 |
| N | 220445 |

Charging point type – energy transfer

A very small correlation is found between the power supply of charging points and the energy transfer from these charging points in charging transactions as shown in table 15. The correlation is 0,018, which is negligible and surprisingly low given the clear difference in average energy transfer per charging point type, as shown with the charging point type dimension, table 9. According to this statistical test, if the power supply of a charging point increases, the amount of energy per transaction only marginally increases. This means that the battery level and/or battery capacity of the EV does not seem to have an effect on the EV drivers' choice in which charging point type will be used for the charging transaction as was expected from the energy transfer dimension analysis. EV drivers do not seem to base their choice for a charging point based on the power output, which is surprising, as charging a large capacity vehicle with a low power output charging point may increase the required charging duration drastically.

Table 15: correlation statistics for charging point type – energy transfer relation

| Charging point type - Energy transfer | |
|--|--------|
| Pearson Correlation | 0,018 |
| Sig. (2-tailed) | 0,000 |
| N | 323859 |

Battery size – energy transfer

When the Pearson's correlation between the battery capacity and the energy transfer is calculated for these EV's, a significant correlation of 0,642 is found, as shown in table 16. This is quite a large correlation, as an increase in energy transfers could be attributed for 64% to an increase in battery size. This suggests active battery monitoring by EV drivers, as was suggested by Franke and Krems (2013a). However, when figure 12 is considered, in which the energy transfer / battery capacity ratio was shown, it is clear that this correlation is caused by PHEV's charging empty batteries. The energy transfer of 44% of transactions was higher than 85% of the battery capacity, due to the PHEV's empty battery influence. Despite this correlation being strong, this is no sign of active battery monitoring by EV drivers.

Table 16: correlation statistics for battery size – energy transfer

| Battery Size – Energy transfer | |
|---------------------------------------|--------|
| Pearson Correlation | 0,642 |
| Sig. (2-tailed) | 0,000 |
| N | 591617 |

Vehicle range – charging frequency

Similar to the battery size – energy transfer relation, this relation was tested between the nominal value of charging passes identified as either PHEV or FEV and the corresponding charging frequency (of all charging passes occurring more than 10 times). The results from the independent samples T-test are shown below in table 17.

Table 17: correlation statistics for battery size – energy transfer relation

| PHEV / FEV | | N | Mean | Std. Deviation | Std. Error Mean |
|------------|------|------|-------|----------------|-----------------|
| FREQ | PHEV | 7946 | 4,564 | 3,0596 | ,0343 |
| | FEV | 92 | 3,611 | 2,7897 | ,2908 |

With a Levene's test P-value of 0,119 and a corresponding significance of 0,03, it is statistically proven that the means of these two groups differ significantly. This means that the PHEV charging passes occur more frequently (with an average value of 4,56 times a week) than FEV charging passes (3,61 times a week). This could mean that PHEV drivers charge more often than FEV drivers. Although PHEV drivers are not solely dependent on electrical mode for arriving at the destination, the capacities of the batteries are also smaller than FEV's. Therefore it could be expected that, as a PHEV battery is empty much faster, the charging frequency is higher. However, it could also mean that FEV drivers commonly charge their EV at home and therefore do not show up as often in the database. As the purchase prices of FEV's are considerably higher than PHEV's, it could be that FEV drivers fall in a income category with a higher tendency to buy a home and own a private charging point than PHEV drivers. The explanation for this relationship remains uncertain and will require further research

Charging point density – charging frequency

The analysis of the relation between the charging point density of a four digit postal code zone and the charging frequency of EV drivers charging in these areas resulted in a very small, negligible correlation of -0,048 as shown in table 18. The notion that EV drivers charge more or less often, depending on the density of charging points in the area is not visible in the dataset. The suggestion of Kelly et al. (2012) that this geographical influence is a relevant factor is not visible in Dutch charging transaction data. This could be explained by the fact that the Netherlands is a small and densely populated country. Therefore, also in less populated areas, there always is a charging point, or even just a wall plug available. This notion is also confirmed in the interviews as drivers did not seem to recognize this geographical influence on their charging behaviour, as well as by the location spread per EV as shown in figure 4. EV's commonly use a limited amount of different charging locations, which reduces the influence of the density of available charging points in the area.

Table 18: correlation statistics for charging point density – charging frequency relation

| Charging point density - Charging frequency | |
|---|--------|
| Pearson Correlation | -0,048 |
| Sig. (2-tailed) | 0,000 |
| N | 6723 |

Qualitative influence factors

The qualitative influence factors were analysed using interviews with EV drivers. These factors are qualitatively analysed and further elaborated below.

Driver related factors

Range anxiety

With regard to range anxiety, results of the interviews show that whether EV drivers are anxious about range and the energy level of the car battery, is strongly dependent on the type of car. For FEV's the range, the cars' range predictability and the length of individual journeys is relevant. First, on the type of car, a strong difference is visible between FEV and PHEV drivers, as PHEV drivers always have a combustion engine alternative. None of the PHEV drivers stated to recognize this 'anxiety'. All PHEV drivers however stated that they were more aware of the battery level and economical driving styles than they expected to be in advance. In practice this meant that PHEV drivers aimed at maximizing the regeneration of energy from the brakes. Some PHEV drivers tried to plan ahead as to which parts of the journey could be driven in electrical and in conventional mode. Moreover, one PHEV driver regularly turned on the cars' 'eco-mode', despite not understanding what this mode was for. As for FEV drivers, the presence of range anxiety was strongly related to the range of the vehicle, the reliability of the FEV's range prediction and the length of individual journeys. The influence of range of the vehicle is visible in the difference between Tesla model-S 85 kWh drivers (range +/- 380 kilometers) and smaller FEV models (between 130 and 300 km range). All Tesla 85 kWh drivers stated that they monitored the vehicles' range and performance, but more for fun or out of interest. With a 380 km range, all drivers stated that there was no anxiety involved, as almost all trips within the Netherlands are possible, as well as the return trip. When vehicle ranges were smaller, almost all FEV drivers acknowledged that they recognized the anxiety. Upon vehicle purchase, all these FEV drivers calculated their mobility intensity, and accounted for a range difference between manufacturer claims and in practice. However, despite these efforts, the smaller range was perceived as increasing the risk of running low. However, these drivers also stated that this anxiety reduced over time. One driver stated:

“At the start I certainly had this fear. However, as confidence grows, you get to know the possibilities, your cars' performance, and you learn to adapt”

All FEV drivers of smaller range-cars added that the prediction of the car computer of the range of the vehicle was experienced as accurate and correct, which decreased the range anxiety of these drivers. One Tesla driver, formerly driving a smaller range FEV stated:

“I’m not easily afraid, but the range prediction of that thing was a mess. The car was great to drive, but when I drove ten kilometers with a 170 kilometers range prediction, the prediction dropped to 110 kilometers. It made me uncomfortable, so the Tesla is a great improvement.”

With regard to this range prediction, all FEV drivers stated to trust the prediction, which reduced the need to actively monitor the range and performance of the car.

Overall, from the interviews it became visible that range anxiety of EV drivers is strongly dependent on whether the EV is an PHEV or FEV, on the vehicles’ range and the reliability of the range prediction of the vehicle.

Planning

With regard to planning, again the type of car had an influence, as well as the range of FEV’s. None of the PHEV drivers actively planned their journeys with regard to electrical driving. They stated that there was no need for planning and that the appointment was made so the trip had to be made no matter what. One PHEV driver stated that the need to plan trips prevented him from buying a FEV:

“This is why I do not want to drive full electric. I do not want to go through that trouble. The apps rarely work, the charging point projection on the map is not accurate as well as whether or not the charging point is occupied.”

All but one FEV drivers stated to plan their journeys actively. Especially when long trips or long appointments were expected, FEV drivers used apps and navigation to calculate ranges and search for charging points. Short appointments were not worth the hustle, as only limited energy could be added to the FEV. Larger range FEV drivers did this more as a precaution and smaller range more out of need, however all came up with comparable apps and measures in planning these trips. One Tesla 85 kWh driver stated that within the Netherlands, there was no need for him to plan and that he would not drive abroad with his Tesla, which takes away the need to plan.

When considering the predictability of the mobility pattern, FEV drivers tend to fall into three categories. The first category, containing seven FEV drivers, states that their mobility pattern is so predictable, that day-to-day activities do not require planning. When trips are planned, these are incidental longer trips outside of the regular pattern. The second category, containing three FEV drivers, despite having an unpredictable mobility pattern do not feel the need to plan day-to-day activities as the distances still are small. They state that their unpredictable mobility is still within the capabilities of their regular charging behaviour and require no adaption or active planning. The third category, containing two FEV drivers, state that the unpredictable pattern in combination with long distances require them to actively plan trips. Although so far they do so successfully, EV range limits have almost been reached on several occasions.

Overall, the planning activity of EV drivers with regard to charging is dependent on the type of car, the range of the car and the mobility intensity of the driver.

Mobility pattern

When analysing the influence of the mobility pattern, the emphasis of the literature is on the adaption of the mobility pattern to the EV limits. With the interview respondents, this is rarely the case. The regular pattern stays in place and, in most cases, is difficult to adapt due to regular locations and appointments the drivers have to attend. Most EV drivers, predicted their mobility

pattern and considered it when purchasing the car, and they are therefore able to keep the same mobility pattern. In some cases, small adaptations are made such as having a foldable bike in the trunk of the EV, to cycle from an available charging point to the appointment, however such adaptations are rarely the case.

EV experience

All but two respondents had between 5 and 7 months of EV driving experience, with the remaining two having 9 months and one year of experience. With the interviews being performed in april/may 2014, the majority of EV's were purchased in the last two months of 2013. Most drivers had an advanced knowledge on the technological systems and capabilities of the EV, and many of them learned these things while already driving the car and looking up further information in the internet. This allowed them to reason why the EV performance would change under certain conditions, and why a certain charging behaviour was better for the lifetime of an EV battery. As mentioned before, the respondents were approached using EV related Linked-in pages and internet forums, therefore all drivers were member of such a digital environment. Reasons for this membership were sharing knowledge and experience among users of the same EV model, getting the latest news on the EV, and posing problems that occurred during use. This way of digital communication was perceived as a valuable source of information and an addition to getting used to EV driving and charging.

Qualitative relations

EV experience – range anxiety

This relation is partly visible in the interview results. When asked if range anxiety changes as EV experience increases, nine respondents said that it did, and seven did not recognize such a relation. Several patterns are visible in the results for this relation. First, the three PHEV drivers did not recognize a change in range anxiety over time, as they state that they started out with no range anxiety and that this has not changed since. Second, FEV drivers with higher ranges were mild on perceiving any development in range anxiety, as they were more confident on the large EV range and the EV's range prediction. Of the Tesla 85 kWh drivers, six confirmed a relation, but four did not. Of those who perceived the relationship, the explanation was that development of routine and estimating range and energy use were drivers for reducing range anxiety. The four drivers who did not perceive a connection between experience and range anxiety did not perceive range anxiety in the first place. Third, the FEV drivers with lower ranges were very explicit in stating that they did find that range anxiety decreases as EV experiences increases. Developing routines in driving and charging the car, increasing the understanding of the technology and improving range and distance estimates contributed to decreasing the range anxiety.

EV experience – charging frequency

Results for the relation of EV experience and charging frequency seem related to results for the relationship between EV experience and range anxiety: PHEV drivers and high range FEV drivers do not perceive this relation, and low range FEV drivers do. Overall, all EV drivers state to have a routinized pattern in charging their EV. This routine means that a development over time is only marginal. Drivers stated that this routine was in place quite fast after purchasing the EV. Commonly one or two weeks of trial and error were perceived, after which the driver was satisfied with the routine and did not change anymore. One PHEV driver received an EV training upon purchase. He commented:

“I received an ‘eco-training’, which was fun. An hour long drive with an expert, teaching about energy regeneration using the brakes, charging, driving. We drove rural, urban, highway. I learned all kinds of things, which really helped me going in charging the car”

For the three PHEV drivers routine was the only argument for not perceiving this relation. For high range FEV drivers, routine was also the main argument. However, some of these drivers indicated that probably their charging behaviour was different at the beginning, but more to test how charging works and to show relatives instead of being led by range considerations. Of the low range FEV drivers two of the three were explicit in perceiving this relationship. At first, they were anxious on the battery not being full, and charging 'just in case'. As one driver put it:

"I used to charge on every possibility. However you learn to understand and estimate the range of the car. This requires preparation, but this becomes much more easy and relaxed over time"

Conclusions

This research aimed at answering the research question: What does the charging behaviour of FEV and PHEV drivers in the Netherlands look like and what are the factors influencing this behaviour? The analysis of what charging behaviour is, and what factors influence this behaviour has been provided by use of a literature review. What this behaviour, and the influencing factors look like in practice in the Netherlands has been described in the results section, based on a quantitative database with nearly a million charging transactions and 16 qualitative interviews with EV drivers. In this way, a full picture is drawn of the charging behaviour of Dutch EV drivers. Several aspects arise that will be discussed below.

Results showed that most EV drivers adopt routinized behaviour with regard to charging their EV. This is in line with the 'low user battery interaction' concept by Franke and Krems (2013) in which routinized EV chargers show inflexible behaviour and are less likely to take full advantage of battery resources. With regard to location, two in three EV drivers charged on one or two locations only, which indicates that EV drivers use charging points they already know, and do not differ from them. It also emerged from interviews, that a strong preference for home charging was perceived by EV drivers, as they valued the convenience of a private point over the use of public points that could be broken, occupied, and more expensive. From the data it is probable that a large part of EV drivers has never charged at a public charging point, or only once. However, a data analysis of private charging transactions proved impossible as the location, status and use of the charging point often is unknown to the service providers, which renders monitoring of private EV use impossible. With regard to charging time of day, clear peaks of starting and stopping charging transactions are visible on working days, which shows that many EV drivers have a similar charging routine, as is in line with findings from Smith et al. (2011). This routine behaviour also emerged from the charging duration, in which peaks for daytime and nighttime charging are visible. Results on charging frequency show that EV drivers that are dependent on public charging, charge on average 2,78 times a week. Overall, 13% of EV drivers charge once a day or more. If the charging frequency of EV drivers is higher, the energy level tends to be lower. When looking at the energy transfer, two aspects of routine behaviour are observed. First, the battery level of both PHEV's and FEV's does not have an influence on charging decisions. Charging transactions are evenly spread among battery levels, except for PHEV's that start charging with an empty battery. However driving a PHEV battery empty is quite easy, and does not suggest active monitoring of the battery level. Also, the EV battery capacity has no influence on a drivers' decision to charge on a high or low power charging point.

An important reason for this routine behaviour is that EV drivers perceive little range anxiety in the use of the EV and do not feel required to monitor battery levels and charging opportunities. Only FEV drivers with smaller ranges perceived the need to actively monitor the battery level, out of anxiety not being able to reach the destination. PHEV drivers relied on the conventional driving mode if the battery ran out and high range FEV drivers trusted they had enough range to go anywhere in the

Netherlands on a full battery. However, unlike findings from Hindrue et al. (2011) and Eggers and Eggers (2011), even the low range FEV drivers only actively planned their charging behaviour if their mobility pattern was both unpredictable and common trip distanced were long. In other situations, they relied on routine, trust and the predictability of their mobility. All EV drivers stated that a reliable range prediction on the EV dashboard had a large effect on reducing range anxieties and building trust. EV drivers perceived that their charging routine is developed during the first two weeks after purchase, during which a trial and error period builds towards a convenient and sufficient charging pattern. Training and education during this period, such as an Eco-training, has large positive effects on the drivers' understanding of the EV technology and limits, and could steer towards a more active charging routine for EV drivers.

Although these EV charging routines do not necessarily have to be inefficient, indications have emerged that suggest they are, especially with regard to the electricity demand and the charging point availability problems in the future. Results show that, contrary to findings from Garwood (2011), nine in ten charging transactions last up to three times longer than is required to charge the EV battery. This shows that charging points are occupied much longer than needed. Furthermore, the lack of influence of battery level and capacity upon charging decisions and which charging point type to use also suggest inefficiency. Apart from the charging routines, other inefficiencies were visible. For instance, semi-public charging points showed low and inefficient use due to the accessibility being limited to office hours, leaving them unused during the night and early morning.

With regard to geographical aspects, no influence of charging point density on charging behaviour was found, contrary to Kelly et al. (2012). The charging point density had no influence on charging frequency, which was also confirmed by the EV driver interviews. EV drivers stated that within the Netherlands, charging points always were available almost everywhere, even in rural areas. If this was not the case, there always were alternative electricity sources available such as conventional wall plugs near homes or even high-power wall plugs near industrial businesses. Within the Netherlands, the provinces Zuid-Holland and Noord-Holland have the highest charging point density, followed by Utrecht and Flevoland. Drenthe has the lowest score with 1 charging point every 11 square kilometer.

Recommendations

Several recommendations can be derived from this research. With regard to the electricity peak demand problem, it has become clear that many EV drivers charge based on routine, with clear charging start and stopping peaks, especially during work days. In order to minimize these problems, one could either attempt to change the charging behaviour routines of EV drivers, or try to utilize the potential of smart charging technology to make EV charging behaviour more efficient. When influencing the EV charging behaviour, the negative relation between charging frequency and energy transfer could be utilized. By having EV drivers charging more often, with smaller energy transfers per transaction, EV induced electricity demand peaks are reduced and spread out. This could be done by stimulating EV drivers to charge more often, and on more occasions (e.g. home, work, shopping center, grocery store, etc.). This influence could be achieved through education and training of EV drivers in coping with their EV. However, as interviews have shown, EV drivers commonly shape their charging routine in the first two weeks after EV purchase. This brings the need for training and education to be offered upon or even before EV purchase, so that a routine has not yet been constructed. Second, according to Banez-Chicharro et al. (2013), there is potential for smart charging technology, given the current charging behaviour of EV drivers. Not only do many EV drivers connect for longer periods during the night, a considerable share also connects to the charging points for long periods during work times. This enables electricity producers to influence and control the charging procedure, and still provide the EV driver with a fully charged battery. Finally, the monitoring of

charging behaviour on private charging points should be improved. This is the location on which most EV drivers charge, however charging service providers have limited knowledge on the location of the charging point (private/semi-public/public), little available data on private charging transactions, and therefore unable to monitor and research EV induced electricity demand from private homes.

With regard to the availability of charging points, several recommendations can be made. It has become visible that currently, the availability of charging points is not a big issue as EV drivers are not forced to use different charging locations. However, in order to prevent availability issues in the future, two possibilities have emerged. First, incentives could help to limit the time an EV is parked at a charging point to the time the EV is charging. The charging duration dimension showed that a large part of charging transactions last shorter than 3 hours, which could be a viable cut-off point for EV parking policy. This would however decrease the potential for smart-charging technology, as this will decrease the longer charging durations required for smart-charging. Also, the low use of semi-public charging points during the night provides a potential solution to availability issues.

Discussion

For this research, 956.579 charging transactions from 11.448 Dutch charging points have been analysed, and 3 PHEV and 13 FEV drivers have been interviewed. In the data analysis, it proved impossible to identify which of the charging points were private, as well as which were fast-chargers. This was due to lack of available data required for identification of these charging points. It proved therefore impossible to state the influence of private charging and of fast charging on charging behaviour. Furthermore, due to privacy restrictions, the EV model could not be identified, which left the influence of car capacity and car characteristics limited to differences between FEV's and PHEV's.

As for the interviews, PHEV drivers were underrepresented when compared to the PHEV/FEV ratio in the Netherlands. This was due to the low response rate of PHEV drivers on the interview requests in the Linked-in groups. In the FEV driver group, Tesla drivers were overrepresented. As Tesla's have the largest available range of FEV's in the Netherlands, their charging considerations could be different to smaller range FEV's. Also, using Linked-in brings the risk of selecting only the enthusiasts, which would steer the results towards a positive outcome.

This research has several theoretical implications. First, the literature review has shed light in the various insights and perspectives from literature on the concept of charging behaviour of EV users. This is also the case for the influence factors on charging behaviour of EV users that emerge from literature. Furthermore, the data analysis has shown how charging transaction data can be used for in depth analysis of EV behaviour with regard to charging. The addition of qualitative interviews has shed light on how EV users cope with the new, mostly unknown technology. This research has revealed several opportunities for further research. First, this research could also be conducted by following the EV driver instead of the charging points. By interviewing and monitoring the same EV driver, one could connect the qualitative and quantitative insights to one EV driver. This would guarantee that no other charging locations remain unknown in the database, as was the case in this research. Also, more detailed research could be conducted on the charging profiles of EV drivers. This requires detailed data on how the transactions take place over time, instead of only the total duration and total energy transfer per transaction, as was the case in this research. Detailed insights in how these transactions occur will help further understand electricity demand peaks, and the potential for avoiding them.

Acknowledgements

First, I would like to thank my supervisor at Utrecht University, Dr. Jacco Farla, who has supported me throughout my thesis. His patience, knowledge and attention to detail has helped me to stay on the right track and carry out this research, whilst still allowing me to work in my own way. Our discussions assisted me to answer my own questions, come up with new ideas and recover from mistakes. I would also like to thank my RVO supervisor Philippe van der Beesen, who has assisted me to settle in the RVO office, helped me in my communication with organizations and who offered me great advice in how to tackle data problems and negotiation issues. His help, even during the birth of his first child, has enabled me to really exploit the possibilities that the dataset offered. Furthermore, the feedback from my second reader Dr. Floortje Alkemade has kept me from getting lost in the broad topic that EV charging behaviour is. Also, my RVO colleagues Suzan Reitsma and Sonja Munnix have been essential in the research process. Being experts in the field of Dutch electric mobility, their feedback, contacts and ideas have shaped this thesis tremendously.

Furthermore, I would like to thank all organizations and all EV drivers that have contributed to this research. My contacts at the organizations have given me great advice, and have invested time and effort in helping me perform my research. Without your data and your expert advice, this research could never have happened. As for the EV drivers, many thanks for cooperating in the interviews. The many enthusiastic responses to the interview requests have really helped and motivated me. I thank you very much for making and taking the time to elaborate on driving and charging the EV, and even offering me to drive in it.

Finally, I would like to thank Teresa, my family, my friends and fellow students for helping me in all sorts of ways. Thank you for supporting me throughout the thesis period.

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Appendix B: Interview question list

Mocht ik iets vragen waar u geen antwoord op wilt geven staat u dat volledig vrij en aan het eind zal ik dit ook nog een keer vragen.

| | |
|--------------------------|--|
| Naam | |
| Leeftijd | |
| Geslacht | |
| EV model | |
| Particulier/lease | |
| Woongemeente | |

EV ervaring

- **1:** Hoe lang rijdt u al een elektrische auto?
- **2:** Hoe bevalt het rijden in een elektrische auto in het algemeen?
- **3:** Wat was voor u het belangrijkste argument voor de elektrische auto?
- **4:** Laadt u uw auto wel eens op?
 - o **4.1** Hoe bevalt het opladen van uw auto?
- **5:** Kunt u uitleggen hoe u uw auto doorgaans oplaadt?
 - o Hoe vaak?
 - o Waar?
 - o Wanneer op de dag?
- **6:** Heeft u de indruk dat u goed weet hoe de techniek van de EV werkt?
- **7:** Heeft u de indruk dat u goed om kan gaan met het elektrische bereik van de auto?

Mobiliteitspatroon

- **8:** Heeft uw mobiliteitspatroon een regelmatig karakter?
 - o **8.1** Ja: Kunt u beschrijven hoe een gemiddelde dag van uw elektrische voertuig eruit ziet?
 - o **8.2** Nee: Kunt u in het algemeen beschrijven hoe het elektrische voertuig doorgaans wordt gebruikt?
- **9:** Kunt u aangeven hoe groot de afstanden zijn die met de auto worden gereden?
- **10:** Bent u doorgaans goed in staat om uw mobiliteitspatroon te voorspellen met betrekking tot het laden van de auto?

Range Anxiety

- **11:** Maakt u zich tijdens het rijden zorgen over het hoeveelheid energie die er in de accu zit?
 - o **11.1:** Zo ja, kunt u uitleggen wanneer u dit gevoel ervaart?
 - **11.1.1:** Kunt u uitleggen hoe dit gevoel zich uit?
 - o **11.2:** Zo nee, waarom niet?
 - o **11.3:** BEV: Heeft u ooit met een lege batterij langs de weg gestaan?

BEV: Een bekend gevolg van deze zorgen dat de elektrische rijder zijn eigen benodigd bereik overschat door als het ware een veiligheidsbuffer in het benodigde bereik in te bouwen.

- **12:** Herkent u dit fenomeen van overschatting van uw benodigde bereik?
- **13:** Had u achteraf voor uw gebruik ook een auto met een kleinere accu kunnen kopen?
 - o Zo ja: wat waren de redenen om dit niet te doen?
 - o Zo nee: Hoe heeft u de keuze voor dit voertuig dan genomen?
- **14:** Hoe belangrijk was het bereik van de auto als aanschafargument?

Planning

- **15:** Doet u aan planning van uw reizen met de auto, met het oog op het bereik van de auto?
 - o **15.1** Zo ja: Kunt u omschrijven hoe deze planning in zijn werk gaat?
 - **15.1.1:** Heeft u de indruk dat dit plannen helpt in het verlagen van de zorgen omtrent bereik?
 - o **15.2** Zo nee: Houdt u er in enige zin rekening met dat uw mobiliteit blijft afgestemd op het bereik van de auto?

Relations:

- **16:** Heeft u de indruk dat naarmate uw ervaring met elektrisch rijden groeit, dat u minder actief bezig hoeft te zijn met het bereik en laden van uw EV
 - o **16.1** Zo ja: Wat voor verandering is dit dan?
- **17:** Heeft u de indruk dat naarmate uw ervaring met elektrisch rijden groeit, er iets veranderd in hoe vaak u uw auto oplaadt?
 - o **17.1** Zo ja: Wat voor verandering is dit dan?

Dank voor uw tijd en uw antwoorden. Heb ik iets gevraagd wat niet gebruikt zou mogen worden in het onderzoek?

Adres voor toesturen van rapport:

Straat + nummer: []

Gemeente: []

Postcode: []

Appendix C: Interview coding scheme

| | |
|--------------------------|---------------------------|
| Basic information | Name |
| | Age |
| | Gender |
| | FEV/PHEV |
| | EV model |
| | EV ownership |
| | Home location |
| | Perceived EV range |

| Category | Nr. | Code |
|------------------|--------------------------------|---|
| EV experience | 1 | EV driving duration (months) |
| | 2 | EV driving satisfaction |
| | 3 | Main purchase argument |
| | 4 | EV charging satisfaction |
| | 6 | Technological EV knowledge |
| | 7 | EV range coping |
| | Charging pattern | 4 |
| 5 | | Charging location |
| | | Charging frequency |
| | | Charging time of day |
| * | Arguments charge point at home | |
| Mobility pattern | 8 | Mobility pattern general |
| | | Mobility regularity |
| | 10 | Predictability mobility |
| Range Anxiety | 11 | Mental state energy driving |
| | 11,3 | Have had empty battery |
| | 12 | Overestimation of needed range |
| | 13 | Purchase arguments this EV |
| | | Hesitation of smaller battery |
| | 14 | Importance of range in purchase |
| | * | Urban - Rural difference |
| * | Why no FEV? (For PHEV's) | |
| Planning | 15 | Planning yes/no |
| | 15,1 | Planning strategies |
| Relations | 16 | EV Experience- range anxiety yes/no |
| | | EV Experience - range anxiety |
| | 17 | EV Experience Charging behaviour yes/no |
| | | EV Experience - Charging behaviour |
| Other | * | User groups |
| | * | Software application |
| | * | Peak problems |
| | * | Image |
| | * | Foreseen problems |