Master Thesis

To what extent can Dutch car drivers use a BEV for their personal car trips

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Summary

This report contains the research performed into the possibilities of Battery Electric Vehicles (BEV).

Road transport is responsible for many problems with air quality, climate change and oil dependence. Despite increased costs of car ownership and usage the share of the car in personal trips has increased with nearly 50% between 1980 and 2007. Despite cleaner cars the CO2 emission has increased by 33% in the same period. An alternative is the Battery Electric Vehicle (BEV). It has no tailpipe emission and can be green depending on the source of electricity.

There are some significant drawbacks, a short range, long recharge times and not many recharge locations. With the improvements in lithium battery technology in the last decade the BEV becomes a more serious alternative. Tesla, Nissan and other car manufacturers have introduced an electric car and are getting a small market share. The range of around 150 km is still small compared to a range of 700 km for a Combustion Engine Vehicle (CEV).

Literature shows that the short range of a BEV is seen as a major drawback by many people. On the other hand researchers found that people are not good at estimating their own range need because it not necessary when driving a CEV. Data from BEV owners shows that their annual driven distance is close to the average annual distance driven by CEV owners. To look past the initial resistance van den Brink et al. (2011) looked at eight week of trip diaries from car drivers. They found that 5% of one car households could use a BEV for their trips based on their trip diaries. The BEV range they assumed was only 75 km and the dataset of trip diaries came from the 1980s. Distances traveled by car have increased by almost 50% since 1983 and the range is at least 100 km for most BEVs.

A dataset that is more recent is the Dutch Mobile Mobility Panel (MMP). It contains trip diaries from around 700 respondents for a period of two weeks and four weeks. The data is collected on personal level which means that when a respondent would be able to make all car trips with a BEV it does not necessarily mean that a BEV can replace the car because there is no data of other household members who may also have used the car. It provides the opportunity to look at the effect of fast charging, charging along the road and adaptations from car drivers.

The goal of this research is: To study the relation between Battery Electric Vehicle (BEV) improvements, adaptations from drivers and the possibility to make all personal car trips with a BEV by a data analysis of personal trip data from the mobile mobility panel (MMP)

To prepare the data for the analysis the following steps were taken: finding all the zip codes from the origin and destination. Find the trip distance with a zip code distance matrix and remove all double trips. Around 10% of the trips had a different origin of a car trip than the destination of the previous trip. Because the respondent must have traveled between the destination of the previous trip and the origin of the current trip and he has used the car in both trips it is assumed that the trip was made but not registered. The missing trip is imputed because it is considered that the respondent has made the trip.

Each BEV has a different range and recharge possibilities. In the analysis a set of ranges is evaluated between 75 km and 700 km. The most important recharge location is at home. Not everyone has the possibility to park a BEV on own terrain. The data does not provide information about who can recharge at home and who cannot. Van den Brink et al. (2011) determined that around 40% of

addresses in the Netherlands have the possibility to recharge a BEV. The same percentage is used in this research. The respondents who have the possibility to recharge at home are chosen based on the urban density of their home address and their income. Low urban density and high income are associated with a higher change of being able to recharge at home.

To determine the potential of the BEV every respondents trips are analyzed. Every respondent starts with a BEV with a full battery, when a car trip is made the distance is subtracted from the battery. When the respondent is at a location where there is the possibility to recharge the battery is recharged. If the battery is never empty during the two or four weeks the respondent could use a BEV for his personal trips. When the battery becomes empty during a trip the respondent cannot use a BEV for his personal trips.

The first analysis is to evaluate the differences between two week data and four week data. Two week data is less expensive to gather but four weeks may contain more information. When everyone has the possibility to recharge at home, the percentage of respondents who can use a BEV for all their car trips is 44% with two week data and 28% with four week data. This is with a BEV range of 100 km. Occasional long trips may not be registered in two weeks but they are registered in the four week data. Four weeks provides more information and is therefore used for the other analyses.

There are three basic scenarios distinguished:

1. Everyone can recharge at home
2. 40% can recharge at home
3. 40% can recharge at home and everyone at work

With a BEV with a range of 100 km the percentage of all respondents who can use a BEV for all their trips is 21% in scenario 1; 9% in scenario 2; and 13% in scenario 3.

The improvements of the BEV that are evaluated are charging along the road and fast charging. The effect when everyone recharges along the road during their longest trip increases the percentage of respondents who can use a BEV for all their trips with 30% to 40% compared to the basic scenarios. This is with a BEV range of 100 km. The effect decreases for BEVs with longer ranges. Charging twice at fast at home and at work shows a small increase between 0% and 5% compared to the basic scenario for both BEVs with a short range as with a long range.

The changes in travel behavior from respondents are an alternative mode of transport for one long trip and an alternative mode of transport for all trips shorter than 15 km. When respondents use a BEV for all car trips except the longest trip the increase is almost 50% compared to the basic scenarios. This is with a BEV range of 100 km. The effect decreases for BEVs with a longer range. When respondents use a BEV for all car trips except the trips shorter than 15 km the increase varies between 17% for scenario 1 and 37% for scenario 3. This is with a BEV range of 100 km the effect decreases fast for BEVs with a longer range.

The improvement of charging along the road has a large effect for BEVs with a range of 100 km but the effect decreases for BEVs with a longer range. This makes it harder for investors in public charging places to determine how long their stations will be profitable. Compared with other literature of van den Brink et al. (2011) the basic scenarios have the same pattern. The differences can be explained by the fact that van den Brink only uses one car households and this research used personal car trips. This research also uses more recent data which could explain differences.

The results of this research show that the market for BEVs is still small. However most respondents make only one or two trips in four weeks where the range of a BEV is not sufficient. When they are prepared and have the possibility to recharge along the road or find an alternative mode of transport they could use a BEV for all their other car trips.

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1. Introduction

1.1 Current problems with road traffic

Road transportation is an essential part in the movement of persons and goods throughout the world; it also plays a major role in three global problems: air pollution, climate change and oil dependence.

Road traffic (persons and goods) are responsible for a large part of the total air pollution caused by human activity in the Netherlands. Cars have become more fuel efficient in the last 30 years and better engine management systems and particulate filters have caused a decrease in CO, NO_x and PM_{10}. The levels are however still high as can be seen in table 1. According to Statistics Netherlands (CBS) road traffic is responsible for 24% of the NO_x and 19% of the PM_{10} matter in the Netherlands (Table 1). A report by the World Health Organization (WHO) states that the situation is worse in urban area's mainly because of the concentration of car traffic and because of the low effectiveness of catalytic converters in the initial minutes of engine operation (M Krzyzanowski, Kuna-Dibbert, & Schneider, 2005). The WHO also blames car traffic for an increased risk of death particularly from cardiopulmonary causes and an increase in the risk of developing an allergy. Furthermore the WHO reports a significant increase in the risk of myocardial infarction following exposure of exhaust gasses.

Pollutant	%
CO_2	16.9
CO	45.8
NO_x	24.3
PM_{10}	19.1

Table 1:share of road traffic in air pollution, caused by human activity (Statistics Netherlands, 2012)

Road traffic is responsible for a 17% of the CO_2 emission caused by humans. CO_2 is the largest contributor to the greenhouse effect. The amount of CO_2 in the atmosphere has increased by 36% since the beginning of the industrial revolution. The greenhouse effect causes a climate change with global warming that will result in sea level rising because of melting ice caps and a decrease of drinking water.

The economical outlooks for car traffic are deteriorating. Oil prices have seen great fluctuations; the price increased around 40% between 2010 and 2013[1] but dropped by 50% at the end of 2014. There are expectations that the demand for oil will further increase especially by upcoming economies in South America and Asia which will lead to an increase in oil prices. The price of oil has a direct effect on the prices of car fuels and therefore the costs of road transportation.

There are two main solutions to overcome these problems: A decrease of road traffic or the usage of other kinds of fuel that are more sustainable. To come up with measures to decrease road traffic is hard; Figure 1 shows that despite the increased costs of car fuel, car ownership and congestion the

[1] A barrel of Brent oil on Sept 20th 2010 cost $78,61. On Sept 23th 2013 it cost $108,59 an increase of 38,1%

number of kilometers driven by car increase faster than the total kilometers traveled in the Netherlands. Also in absolute distances the car is by far the most used mode of transport.

Figure 1 shows that in the last 28 years changing behavior towards other modes is not the case, contrary kilometers driven by car increase faster than other modes of transport. The share of car traffic has never been this high, 49 percent of all distance traveled is by car. Despite better fuel efficiency the CO_2 emission of cars has increased with 33% since 1985(Statistics Netherlands 2012). A change towards other modes in the coming years seems therefore unlikely to happen at a large scale, the car has too many benefits for personal use.

	Average number of car trips per day	**%**	**Cumulative %**	**Cumulative average number**
Total trips	0,88	100		
0 - 1 km	0,03	3,41	3,41	0,03
1 – 3.7 km	0,23	26,14	29,55	0,26
3.7 – 7.5 km	0,19	21,59	51,14	0,45
7.5 – 15 km	0,16	18,18	69,32	0,61
15 - 30 km	0,14	15,91	85,23	0,75
30- 50 km	0,08	9,09	94,32	0,83
50+ km	0,07	7,95	102,27	0,90

Table 2: Average number of trips per person per day as car driver in the Netherlands in 2012. (Source: Statistics Netherlands)

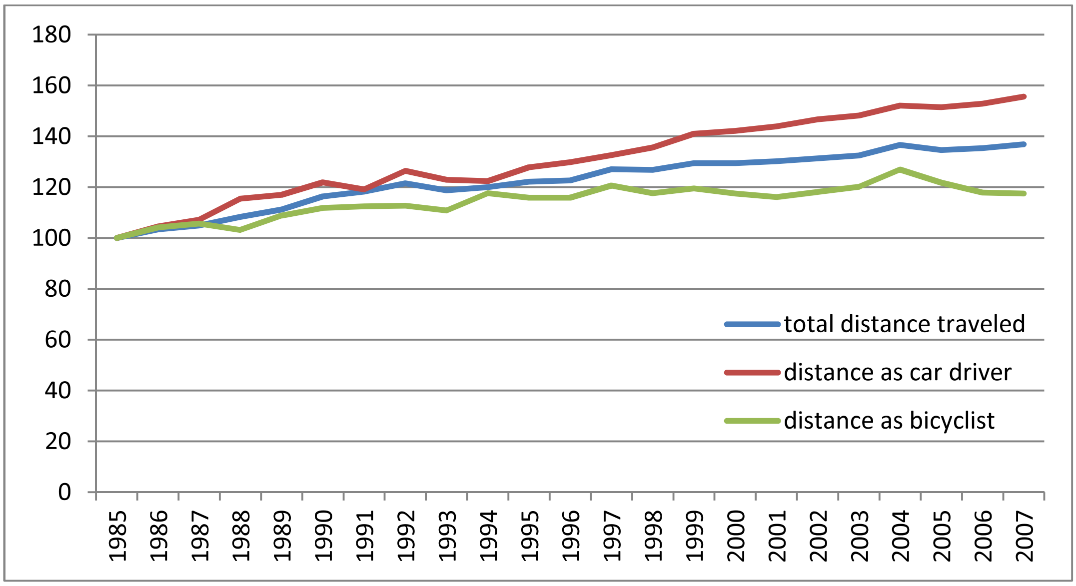
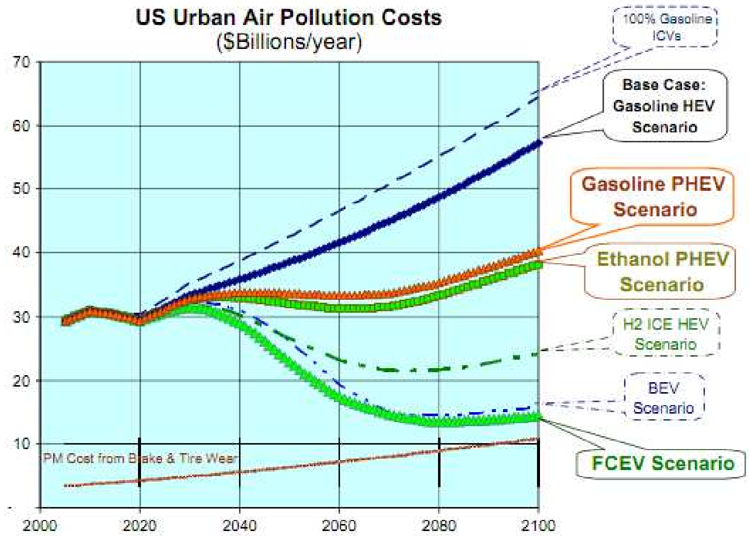


Figure 1: Percentage increase in yearly distance traveled per mode in the Netherlands[2] (1985 = 100)

[2] This way of measuring traffic performance has stopped in 2012 and replaced by traveled kilometers in the Netherlands which is, due to a different method, not directly comparable, Statistics Netherlands did not publish traffic performance data after 2007 and before 2012 on their website.

To overcome problems with air pollution, oil dependence and possibly climate change it is worthwhile to look at cleaner vehicles that do not depend on fossil fuels. Several concepts are developed and introduced in the last years; the most important one is the battery electric vehicle. Figure 2 shows that the predicted values of decrease of air pollution, the introduction costs and overall vehicle costs makes the BEV one of the most environmental friendly and cost effective car for distances shorter than 160 km. To decrease the amount of air pollution to levels before 2002 we need electric vehicles and/or hydrogen vehicles. (Thomas, 2009)



ICV=Internal Combustion Vehicles; HEV=Hybrid Electric Vehicle; PHEV= Plug-in Hybrid Electric Vehicle; H2 ICE= Hydrogen Internal Combustion Engine; BEV= Battery Electric Vehicle; FCEV= Fuel Cell Electric Vehicle

Figure 2: costs of air pollution for alternative vehicle scenarios in the 21st century(Thomas, 2009)

1.2 The Battery Electric Vehicle (BEV)

The BEV has a long history. In the first decades of the automobile history at the end of the nineteenth and beginning of the twentieth century car manufacturers developed several BEVs. These electric vehicles had many benefits; they were easier to start and were quieter than the internal combustion engines of that time. Over the years the BEV lost its position due to better availability of gasoline and stronger internal combustion engines. The first successful competitor for the Combustion Engine Vehicle (CEV) came after lithium-ion batteries were developed and became cheaper. Toyota introduced the Prius in 1997 in Japan which was still a CEV but had a small lithium battery that got its power from the gasoline engine. The vehicle used the electric engine on lower speed in city traffic because it was more efficient than the combustion engine. The Plugin Hybrid Electric Vehicle (PHEV) was the next step; it had a larger battery that could be recharged at home with a normal electricity plug. The cooperation between electric and gasoline became more complex because the combustion engine could recharge the battery and also help to drive the wheels while the electric engine drove the wheels with power from the battery but could also recharge the battery with regenerative breaking. When the battery was depleted the vehicle could run on gasoline alone. The next step was the Battery Electric Vehicle (BEV) which had no combustion engine, only an electric engine and a battery. Several car manufacturers have earned a small market share with a

BEV, Tesla is probably the most famous but the Nissan Leaf, Renault Zoe and Mitsubishi i-MiEV have also some success. The RDW which registers motor vehicles in the Netherlands reports that there are 6 825 registered BEVs in the Netherlands at 31/12/2014, this is nearly 1 electric vehicle on a thousand motor vehicles in the Netherlands. (Rijksdienst voor Ondernemend Nederland, 2015)

The next chapter describes what other researchers have done to investigate the problems of the BEV that prevent it from getting a larger market share. It shows also what the characteristics are from the current BEV drivers. It will explain how new research can help to see what the effect of developments of the BEV are on the potential of BEVs in the Netherlands and what the effect of adaptations from drivers is on their ability to use a BEV for their trips.

2. Potential of the BEV

This chapter describes the research that has been done on the perception and potential of the BEV. When we look at the research that has been done, it can be distinguished into three categories:

- Opinions and attitude towards the BEV
- Characteristics of owners of a BEV
- Analyses of trip data in relation to the potential market for BEVs.

This chapter describes the most important results of these three categories and end with arguments why this research could help to improve the understanding of the potential of the BEV.

2.1 Attitude and perception

Attitude towards a BEV is a broad topic and hard to quantify. In surveys, interviews and focus groups different terms are used and different questions are asked to capture the attitude towards a BEV and its attributes. The purpose of this type of research is to estimate when people are willing to buy and use a BEV and to capture the issues that hold respondents back from buying a BEV. In focus group studies often broad questions are asked like: “Do you think a BEV is better for the environment than your current vehicle?” Focus group members can discuss these questions with each other in groups consisting of 6 to 20 people. Stated preference questionnaires, especially the ones that want to capture the value of a BEV to people, draw specific scenarios to capture the willingness to pay for different attributes of a BEV. The type of questions may vary but the main objective is to capture the attitude of conventional vehicle drivers towards electric vehicles. With the opinion of conventional vehicle drivers researchers try to estimate the potential for the BEV and address the most important drawbacks according to the respondents.

The important issues that respondents have with the BEV according to these attitude studies are firstly the purchase price. When people look at the price of a BEV it is generally higher than conventional vehicles with the same size, engine power and luxury, due to the battery pack. It is expected that the prices will decrease the next years because the manufacturing costs of lithium-ion batteries will decrease. When looked at lifetime costs instead of purchase costs the Nissan Leaf, a Japanese BEV, was cheaper than a conventional vehicle according to the Electric Power Research institute (figure 3). The researchers defined lifetime as 150.000 miles driven for both vehicles. The driving was simulated with American travel data to estimate how the vehicle was used and how long it took to drive the lifetime distance. They included occasions where the range of a BEV was too short and people had to rent a gasoline vehicle, these are the replacement costs. (Alexander & Davis, 2013)

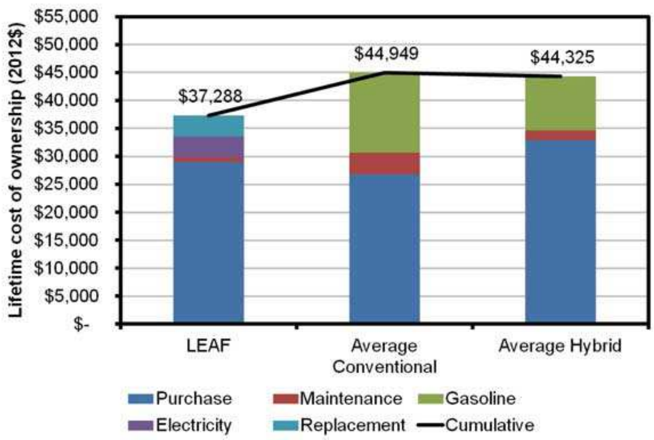


Figure 3: Lifetime costs of a BEV, CEV and Hybrid Electric vehicle (HEV) (Alexander & Davis, 2013)

The figures are an average and individual cases may be different but in general more researchers found that when consumers buy a vehicle, they do not have the basic building blocks of knowledge assumed by the model of economically rational decision-making, and they make large errors estimating gasoline costs and savings over time. (Turrentine & Kurani, 2007)

The second important problem with current BEVs is the range. Several researchers addressed this problem. VDE (2010) concludes after asking 1000 Germans older than 14 years that “The average German resident considers 353 km driving range to be acceptable”. Bunzek (2011) finds “European respondents require 308 km driving range on average”; after asking 1900 Europeans from 7 different countries. Others report similar conclusions according to Franke & Krems, (2013). When we look at the current range of BEVs, the Nissan Leaf has a reported range of 200km and in practice around 120 km. The Tesla model S has a reported range of 500 km, in practice it is around 350 km but it has a price of 85.000 euro, too expensive for most car buyers.

A third issue is recharging. People with BEV experience like the idea that they never have to find a gas station but can recharge at home overnight. However the possibility of charging at home is almost a necessity. Hidrue, Parsons, Kempton, & Gardner, (2011) did a stated preference study where respondents had to value different attributes of a BEV like driving range and recharge time. They conclude that people who could recharge at home were 3.3 times more likely to consider a BEV when they buy a new car. Researchers that let people test drive BEV for more than a day all provided an option to recharge at home (Franke & Krems, 2013, Graham-Rowe et al., 2012). The speed of recharging is also a point of concern. With a battery size of 22 kWh (Nissan Leaf) or 85kWh (Tesla model S) it takes 6 hours to 20 hours to fully recharge an empty battery with a standard home electricity connection of 3,6 kW. According to Pol & Brunsting, (2012) the ability to recharge a BEV at home in 1 hour instead of 8 hours reduced the resistance against a BEV with 20%.

Due to the short range and the long recharge times a BEV seems not ready to replace conventional vehicles. However, according to research by (Franke & Krems, 2013) the average minimum required range was only 168 km when respondents could test drive a BEV for three months. The average maximum daily range of the respondents was 185 km, which brings the range that respondents want close to the range respondents need. Similar research was done by Graham-Rowe et al., (2012) they let respondents drive a BEV for 7 days and held interviews afterwards. Especially the long recharge time and the different places to recharge were seen as negative but changed to less negative with experience and adapting to a new schedule. These two studies from Franke & Krems, (2013) and Graham-Rowe et al., (2012) showed that many people who are not familiar with BEVs have trouble indicating what range they need with a BEV. The cause for the problem with personal required range is that with a conventional vehicle drivers do not deal with daily distance budgets. (Franke & Krems, 2013)

Attitude research indicates that the unfamiliarity of respondents with electric vehicles is partly responsible for the negative image they held regarding the BEV. These studies give a good indication what the largest drawbacks are of the BEV however in individual cases the BEV might be a serious alternative for a CEV.

2.2 Owners of a BEV

People who see a BEV as serious alternative are the ones who bought a BEV. For them the price, range and recharge locations is not a problem. The question is, are they different from conventional vehicle drivers who see so many problems with a BEV. Two studies looked at the group of BEV owners, one in the California (USA) (Clean Vehicle Rebate Project, 2013) and one in Norway (Haugneland & Kvisle, 2013).

In both groups the majority has an opportunity to recharge at home. 90% of Californian respondents have a residential charger and 71% of them parked in their own garage. 85% of Norwegian respondents can charge in their own garage or parking lot and 10% has access to charging in the shared apartment building where they live. They drove on average not significantly less than conventional vehicle owners. BEV owners drove on average 28 miles per day CEV owners 31miles per day in California. In Norway BEV owners drove 13.800 kilometers per year and CEV owners 15.000 kilometers per year. Owners of a BEV have a significantly higher income than average in Norway. In California 67% earns more than $100.000 per year while only 29% of conventional new car buyers have that income. BEV owners have more than one vehicle in their household. 85% of the BEV households in Norway had more than one car. 94% of the respondents in California had another conventional vehicle.

The results of these studies seems to indicate that short range is not a reason for owners to use the vehicle less. Most of them had a second car. It is expected that it made it easier to overcome the range anxiety. However Nissan offered in Norway the possibility to use a conventional vehicle for 20 days per year. The characteristics of these groups are not necessarily the characteristics of people who will drive a BEV, these are the early adopters who are willing to take a little more risk and inconvenience to use a new technology. The group of potential BEV users is larger than this group of early adopters. Research shows that some common barriers to the adoption of any new technology include lack of knowledge by potential adopters, high initial costs and low risk tolerance, (Egbue & Long, 2012) .

2.3 Travel behavior research

Another way to look at the potential of the BEV and to look past the initial resistance due to unfamiliarity is the travel behavior of conventional car drivers. The expectation is that drivers who would have to make minimal adjustments to their normal travel behavior when they would drive a BEV are more likely to use a BEV.

Two studies looked at travel behavior and the possibility to use a BEV as replacement for the conventional vehicle. The first one is by Weiss, Chlond, Heilig, & Vortisch, (2013). The researchers used different data sets and combined them to get the daily distance traveled for a year. The initial dataset consist of respondents from the German mobility Panel (MOP). The MOP consists of one week trip diaries from households. A group of respondents from the MOP was asked to join TANKBUCH, were they filled out how many miles they had traveled and how much fuel they used every time they refueled their car during 8 weeks. The group that was part of the MOP and Tankbuch consisted of 2438 households. The researchers extrapolated this data to make a yearly profile of the cars within the households. According to the researchers one week of trip registration is not enough to get a good sample of long distance trips. For some households this would mean that one long distance trip during the registration week would give an overestimation of long distance trips when the data is extrapolated. For other households there is a chance that no long distance trip was made during the registration week which means that when the data is extrapolated there would be an underestimation of long distance trips. To correct the underestimation respondents had to say whether a day within the registration week was normal or particular. This would correct for the first problem. To add long distance trips to the yearly profile the researchers used INVERMO a data set of long distance trips (>100km) collected from interviews with 17.000 people about socio-demographic situation and long distance trips. After this preparation of data they looked at daily distance per car. The researchers assumed that everyone can recharge every night at home. When a car had no days in one year that it traveled more than 100 km it was suitable for BEV replacement; when 1 to 4 days had distances larger than 100 km it may be suitable for replace; when there were more than 4 days a year were the car traveled more than 100 km a day the car was not suitable for replacement.

The other travel behavior research was done by (van den Brink, Kieboom, van Meerkerk, & Korver, 2011). They used two datasets. The first is the Mobility Research Netherlands (MON) from 2008 it consists of 1 day trip registrations of 14.000 households and the second is the Longitudinal Movement Research(LVO) that consist of 8 weeks trip registrations from 1700 households from 1984-1989. The advantage of the MON is that the registration was collected per household which gave a good insight in car use. However the data is only one day per household; which means that there is a chance that no long distance trip was made during the registration day and when the data is extrapolated there would be an underestimation of long distance trips. The LVO has eight weeks of trip data but no information about who has used which vehicle in multi-vehicle households. In their analysis van den Brink et al. (2011) assumes, as Weiss et al.(2013) did, that drivers do not adapt their behavior. The data of MON and LVO are both trip diaries, the researchers could evaluate every trip to determine whether or not it could be made with a BEV. It also gave the opportunity to look at different recharge places as at home and at work. They conclude that based on 8 week data, a BEV range of 75 km and when 40% can recharge at home, 5% of the respondents can use a BEV as their only vehicle. The potential would be 10% if drivers would find an alternative mode of transport once a month.

2.4 Possibilities for new research

These two studies by Weiss et al. (2013) and van den Brink et al. (2011) are interesting, the BEV is still in development: The range of a BEV is still improving and the number of public charging places and the possibilities to charge a BEV at work increases as well. In the last 30 years the distance traveled by car has also increased significantly. The data from the LVO that van den Brink et al (2011) used might therefore not be realistic anymore. New research with current data could give a better representation about the current potential for the BEV and also look at the effectiveness of fast charging, public charging points and adaptations by car drivers. Furthermore is it interesting to look at the differences between this research, Weiss et al. and van den Brink et al.

Travel behavior research only looks at the usage of a BEV, the purchase price which is also an important disadvantage is another type of research because it requires information about the willingness to pay and the requirements people have for a new vehicle.

There are different methods to look at travel behavior and BEVs. Between Weiss et al. 2013 and van den Brink et al. 2011 there is a tradeoff between the travel observation period and the information about the trips. Weiss et al. (2013) used one week of trip diary data but concludes that it is too short and therefore uses also data from less detailed sets over a longer period to get a dataset that covers one year of travel data. Van den Brink et al. (2013) used 8 weeks of trip diary data and were able to evaluate every trip and could look at different recharge locations. Weiss et al. could only use overnight recharging and daily traveled distance because they had not enough trip details to look at specific locations. The combination of detailed travel data of one year is expensive to gather, and not always necessary. Many trips are made every day or every week, more data does not provide more information.

The method used by van den Brink would be a good way to determine who can use a BEV to make all car trips. It provides the opportunity to look at different recharge locations and can determine which trip or trip sequence would not be able to make with a BEV. The most important factor in that kind of research would be the data.

Research by Pasaoglu, Zubaryeva, Fiorello, & Thiel, (2013) presented requirements for a dataset are for a study to the impact of BEVs. They argue that at least one week of drive patterns of passenger cars is necessary. With a shorter period of drive patterns there is a chance that no long distance trip was made during the registration period and when the data is extrapolated there would be an underestimation of long distance trips. In the case of a BEV this is essential because one trip that is longer than the range of a BEV could mean that a respondent is unable to use a BEV as alternative to his conventional vehicle.

Besides the days of trip diaries that are necessary there are other requirements to the data. It should be representative for car drivers in the Netherlands and should include details in the trip information that makes it possible to determine whether or not the respondent can use a BEV. The most important are: trip distance to determine whether or not a trip can be made with the range of a BEV; locations of origin and destination to determine whether or not the BEV can be recharged there; time that the trips have been made to determine how long a BEV can be recharged between trips. The important part of a travel behavior research is the data set.

Data that covers a large part of these requirements is the Mobile Mobility Panel (MMP).

The MMP is a project that registers the trips of around 600 respondents for multiple weeks with a smartphone app. Trip characteristics like the time of leaving and arriving, mode of transport and motive are automatically determined by the app. To improve the accuracy of automatic registration respondents are asked to verify the registered trips afterwards.

The panel data satisfies most requirements from table 3. It includes trip diaries from around 600 respondents; it is individual data of two or four weeks. It has the time, origin and destination of every trip which means the parking details are known. It has some information about the socio-economic features of respondents. Living area is included and the geographical coverage is the Netherlands. The vehicle details are missing but it is mainly interesting for the electricity consumption of BEVs and not necessary for BEV potential. So far it means that the mobile mobility panel is applicable to study the impact of BEVs. However it does not implicate what kind of research to BEV potential it is suitable for. The fact that it has individual data means it is harder to do a study to the replacement of vehicles since there are probably more household members who use the same vehicle and may be more often than the panel respondent.

Compared with Weiss et al. is this data more detailed which gives the opportunity to look specifically at recharge locations and whether or not a trip can be made with a BEV instead of days. Compared with van den Brink et al., (2011) this research looks more detailed into adaptations and recharging on the road with data longer than one day.

The next paragraph will describe the objective of this data analysis research with the MMP.

2.5 Research Outline

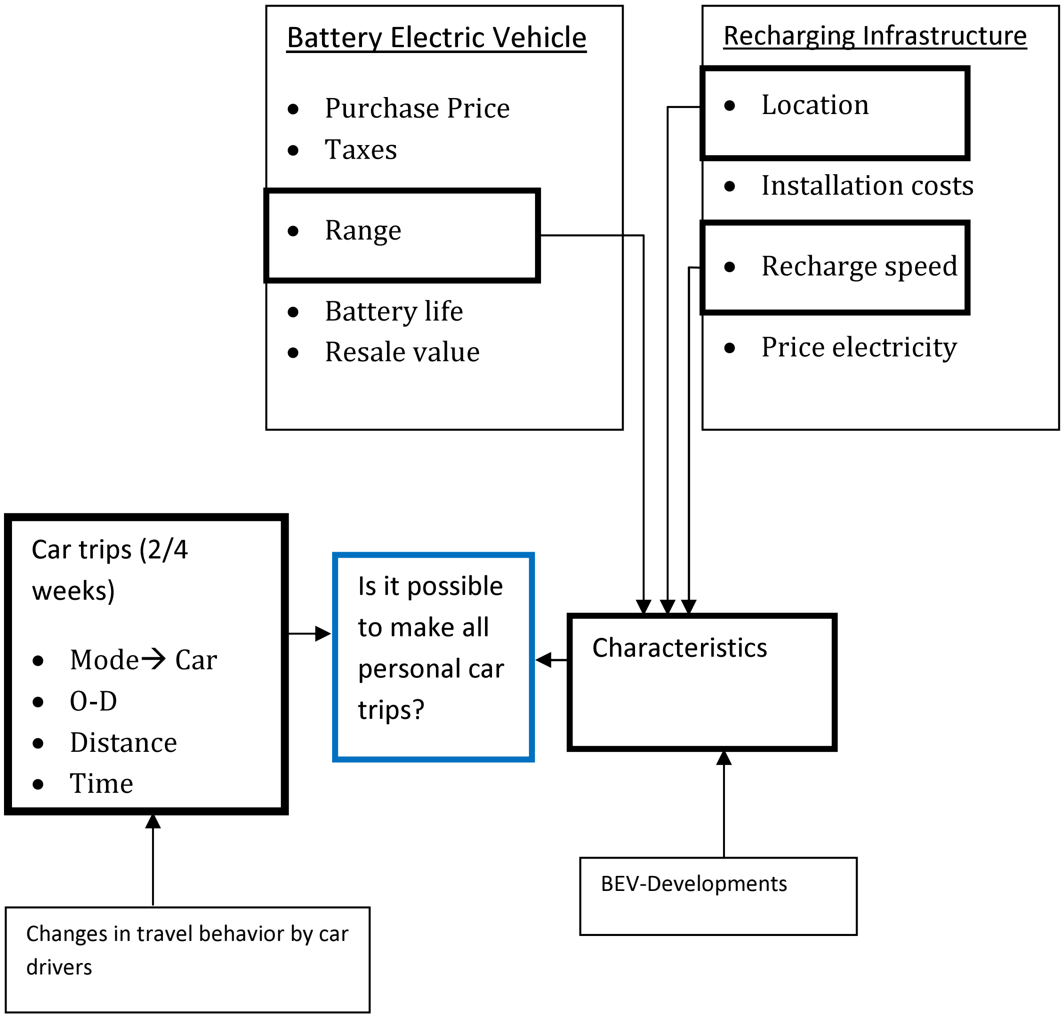
In the previous paragraphs the current research of BEV is described. It showed that to study the effects of BEV improvements on the possibilities to make trips with a BEV a data analysis could give a better insight. The MMP has the characteristics to be used as source for the trip data as representation of the travel behavior in the Netherlands. This research will focus on the possibilities to make all personal car trips with a BEV. The goal of this research is:

To study the relation between Battery Electric Vehicle (BEV) improvements, adaptations from drivers and the possibility to make all personal car trips with a BEV by a data analysis of personal trip data from the mobile mobility panel (MMP)

In order to study the possibility of making trips with a BEV instead of a CEV it is important to identify the most important differences between a BEV and a CEV. Looking at the characteristics of a BEV and the perception of respondents from different studies mentioned in chapter2.1 the problems of a BEV are its range, the possibilities to recharge and the time it takes to recharge. These differences have also showed improvements, particular Tesla has come up with a fast charge network along highways and BEVs with a longer range.

Personal trips are studied because the MMP does not contain further information about the household or the vehicle. The study to evaluate the possibilities to replace the CEV with a BEV for personal trips can give insight in the effect of BEV improvements. However the possibility to use a household's second car is not possible with this dataset. On the next page is a model of the research that will be described further in this report.

Research Model:



2.6 Research questions

The research question can be derived from the different parts in the model. In the first place it is important to define the characteristics of a BEV and its recharge infrastructure. Specifically the range, recharge speed and recharge locations. The question is:

- What are the current characteristics of BEVs and the possibilities to recharge them?

The second part is how the BEV and its infrastructure are developing. What are the improvements to the characteristics mentioned before:

- What are current developments to improve range, recharge facilities and recharge speed of a BEV?

On the other side is the personal trip data from the MMP. There is data from two weeks and data of four weeks.

- To what extent is two week of trip registrations adequate to determine the possibility to use a BEV for all personal trips compared to four week data?

With on one side the characteristics of a BEV and on the other side the personal trip data from the MMP The analysis can be performed to answer the question:

- To what extent can respondents make all their personal car trips with a current BEV?

And after that study the effect of improvements on the ability to make all personal trips:

- What is the influence of improvements of the BEV and its recharge infrastructure on the number of respondents that can make all personal car trips with a BEV?

And lastly look at the effects of adaptations in travel behavior by respondents :

- What is the effect when respondents change their travel behavior on the ability to make all their personal car trips with a BEV?

The first step to answer the research questions and to perform the data analysis is to prepare the data. The next chapter first describes characteristics and limitations of the data and how to prepare it for data analysis. The information in the data determines what can be analyzed and how.

The next step is to define the relevant characteristics of a BEV and what kind of developments are modeled in the analysis. In this part are the scenarios defined for the analysis.

After the data is prepared and the scenarios are defined the method of the analysis will be explained. It will describe how the scenarios are used to determine who can use a BEV for his personal car trips.

3. Data description

An important part of this research is the trip data. The data is not exclusively collected for this research therefore it must be examined to what extent it is suitable for a BEV analysis. This chapter describes what the characteristics of the data are and how it will be prepared for the BEV analysis.

3.1 Characteristics and limitations

The current results of the MMP are two data sets one consist of two week trip registration from 646 respondents and a data set consisting of four week trip registration from 785 respondents.

The two week data is gathered in two batches; the first batch was between April 30th and May 13th. The second batch between june 14th and june 30th. The respondents used a smartphone with an app that recorded the trips that a respondent made during the monitoring weeks. The app used GPS, WiFi and cell-ID to mark the locations and sends these location points to the back-end system. The system translates the data to trips with a place and time of origin and destination, mode of transport and motive. The respondents are asked to validate their trips at least once every three days. They can add, delete, split or merge trips and they can modify the characteristics of their trips like time, location, mode and motive. An example of two trips is in table 3

Day	Month	Year	Depart hour	Depart Minute	Arriving Hour	Arriving Minute	Zip Origin	Zip Destination	Address Origin	Address Destination	Mode	Motive
21	5	2013	10	14	10	34	1000 XX	1100 YY	Hoofdstraat 1, Amsterdam	Kerkstraat 9, Amsterdam	Car	To home
22	5	2013	16	35	16	50	1200 ZZ	1100 YY	Kerkstraat 9, Amsterdam	Molenstraat 11, Amsterdam	Bike	Shopping

Table 3: Example of two trips from the Mobile Mobility Panel

The content and quality of the data determine what kind of analyses can be done and what conclusions can be drown from the analyses. There are three important aspects of the data: the representation, the trip information and the respondent information.

The representation is important because it is only possible to draw conclusion about the current possibility for BEVs in the Netherlands when the respondents of the MMP are representative for current car drivers in the Netherlands. Secondly the monitoring period of two or four weeks should represent general travel behavior of a longer period because car owners do not use a car two or four weeks but every week of the year.

The mobile mobility panel contains all trips from the respondents on a personal level. It was gathered in 2013 and 2014. First insights show that the MMP data has roughly the same modal split and travel time distribution as OViN. The fact that the data is gathered on a personal level means that it is only possible to draw conclusions based on personal trips. When a respondent can make all his car trips with a BEV it does not necessarily means that he can replace his car with a BEV because a car can be shared with other household members or in multi car households a person may use different cars for his car trips. For this research only the car drivers from MMP are used, a respondent is a car driver when he has made at least one car trip in the two or four weeks of data gathering. When a respondent has made no car trips it is assumed that the respondent does not have a car.

To determine if a respondent can make his personal car trips with a BEV it is important to know all his car trips from the monitoring period. Most respondents have registered and validated all their trips however some did not participate the full two or four weeks. This could lead to overestimating the potential of BEVs because the respondent could have made trips that are not possible to make with a BEV but these are not registered. Therefore this analysis only uses respondents with enough verified days. A verified day is a day that a respondent has validated afterwards to separate it from days where no car trips were made. When the MMP data is prepared for the analysis it will be compared with the car trips from the OViN database from statistics Netherlands for trip distance distribution to see if there are differences between the two data sets and whether or not there is an under registration of certain car trips.

The second point is the trip details. Necessary information is trip distance to evaluate if the trip can be made with a BEV and the location where the car is parked between trips to evaluate if the BEV can be recharge there. The important details of a trip can be seen in table 3. the locations and time make it possible to follow every respondent and use locations where the respondent can recharge a BEV. The distance of every trip is not present in the data but because the origin and destination of every trip are known it is possible to obtain the trip distances. There are three location identifiers: address, zip code and GPS-coordinates. Each of those has can be used to calculate the distance between origin and destination. Running the trips through an online route planner however is not possible because the data cannot be transferred outside the CenterData server. Another possibility is to use a zip code distance matrix. This matrix contains the distance between each zip code area in the Netherlands.

A third point is the information about the respondent. For BEV research it is useful if the home address of a respondent is known. At home is the most important recharge location for a BEV. With the trip motive “to home” it is possible to find the home address of the respondent. However not everyone can recharge at home. For people who cannot park a car on their own terrain it is hard to recharge a BEV at home. The data contains no information about the home address; research by van den Brink et al. determined that at around 40% of houses in the Netherlands a BEV could be charged at own terrain.

The next paragraph contains the preparation of the data for the analysis. It describes how the respondents with enough verified days are selected; how missing trip details are obtained and if the data is representative.

3.2 Preparation process

The first step is to select the respondents that will be used for this research. There are two criteria to decide who is useful: the first one is that they should have enough registered days. The registration period was two and four weeks but not everyone registered every day. A registered day means that a respondent has verified the automatic GPS registration and has answered the day questions; it does not mean that any (car) trips have been made that day by the respondent. The second criterion is that the respondent has made at least one trip as car driver. When a respondent has made no car trips he is not selected because it is assumed that he has no car. This research only looks at using a BEV as replacement for a CEV. For the two week data we selected only users with 10 or more verified days because that would give enough respondents and a period that is long enough. For the four week data at least 24 days has to be verified by a respondent to be selected.

To analyze who can use a BEV for all his personal trips it is important to evaluate every car trip a respondent has made. The first step is to fill the locations of every origin and destination. There are three location indicators: The GPS locations from the automatic registration, the address filled in by the respondent and the zip code. It is not possible to obtain distance by GPS location because for the privacy of the respondents the data cannot be processed by any internet based service. We will therefore use a zip-code information file that has the addresses belonging with a zip code and the GPS location of the center of the zip code. The zip code file will be used to find the zip codes belonging to the addresses or GPS locations. With the zip codes as location indicators it is possible to obtain distance with a zip-code distance matrix. The matrix has the distance between every four numbers zip code in the Netherlands.

The next step is to remove double registrations. Sometimes the same trip is registered twice; it means the date, time and locations of two trips are the same. It is not possible to make the same trip twice at the same time, it is expected that the second trip is not made by the respondent an therefore the second trip will be removed as a registration error.

Further, sometimes the origin of one trip is not the same as the destination of a previous trip. An example of such a location gap is in table 4. The trip between the destination of the first trip and the origin of the second trip has to be made because the car is used in both trips by the same respondent. It is likely that the trip has been made but the GPS device has not recorded the trip and the respondent has not seen it or forgot to fill it in with the verification. Therefore we will add any missing trips.

Day	Month	Year	Depart hour	Depart Minute	Arriving Hour	Arriving Minute	Zip Origin	Zip Destination
21	5	2013	10	14	10	34	1000 XX	1100 YY
22	5	2013	16	35	16	50	1200 ZZ	1100 YY

Table 4: Example of a missing trip

With the completed trip sequence we will look how good the data describes the travel behavior in the Netherlands by comparing it with travel behavior research from Netherlands Statistics.

It is expected that recharging a BEV will mainly happen at home. It is therefore important to identify the home address of the respondents. To find the home address of each respondent we use the trip motives because it distinguishes trips to home. Whenever a trip is to home or to the zip code that belongs to home it is identified as a recharge location for that respondent. Whenever the respondent is at home the BEV charges there until the battery is full or when a new trip begins. The same identification applies to finding the work address. The only difference is that a respondent could have multiple work addresses, in that case only the most visited work location is a recharge location.

The adaptations from respondents namely an alternative for the longest trip and an alternative for all short trips can be modeled by removing the longest trip or all short trips from the car trip sequence since they are seen as made with another mode.

3.3 Data preparation

Obtaining missing zip-codes and distance of trips

The data from the mobile mobility panel is gathered by GPS device. Afterwards the respondent had the possibility to verify, remove or alter trips. Sometimes the GPS-device registered two trips while it was one trip or it missed part of the trip because it had not yet found the location of the respondent. All trips are saved in a data file and each trip has a code indicating if the trip was later added, removed or merged. For this analysis the trips that are necessary are the trips that are made by the respondent. We use therefore only the trips that the respondent has verified afterwards. Trips that are registered by GPS have an address, zip code and GPS-location of the origin and the destination. When respondents add, edit or merge trips they often fill in only the address, each with his or her own description of the address.

The two week data is obtained during the first two weeks of May 2013 and the last two weeks of June 2013. This includes the invalid trips, some are merged or removed by the respondent after the trips were automatically registered by GPS. The removed and trips that were later merged are still in the data file but are not useful for this analysis because we are only interested in the trips that have been made by the respondents. We only use the trips that are saved after a going-over by the respondent; The four week data is obtained during four weeks from April 8th 2014 and four weeks from June 10th 2014. The format of the data is identical to the two week data.

Every trip has an origin and a destination; this means every trip has to have two location marks. There are three sources that indicate the origin and destination of a trip: the GPS-code, the zip-code, the address or location description filled in by the respondent. Every source has empty fields but almost every trip record has at least one location source. The best way to identify locations and obtain distances with this data is by the zip codes. Table 5 shows how many zip codes are missing in the data file for the two week data, the four week data has roughly the same percentage of missing zip codes.

	Total trips	Trips without a zip code	Trips with 1 zip code	Trips with 2 zip codes
Total	25679	7700	84	17895
Added trips	2123	2114	0	9
Merged trips	26	26	0	0
Edited trips	23530	5560	84	17886

Table 5: Trips en zip codes from the verified two week data

Missing zip codes can be found through the address that the respondent filled in and the GPS-codes that were registered by the GPS-device. The following methods are used to find the zip codes:

1. Search per respondent for addresses that are the same. Apply the most occurring zip code to the trips with missing zip codes.
2. Look in the address fields of trips without a zip code to see if a zip code was filled in in the address field.
3. Separate address fields by comma and find the addresses with a street name and a city.
4. Separate address fields by dot and space ; then find the addresses with a street name and a city.

5. See if there is a street in the home town of the respondent that matches the address field.
6. Look only at place names in address fields and use the central zip code of that place
7. Look if there is a GPS-code of the trips and find the closest zip code.

The reason why GPS-does were checked last is that the location filled in by the respondent would give a better location than GPS because it could have taken some time to find the respondents location which would result in a GPS-code of origin that would not be at the place of origin.

The result of this missing zip-code process is that now 96% of the trips have two zip-codes instead of 70% in the original trip file. Remaining empty zip code fields are foreign addresses, address fields with just “supermarket” or comparable words.

	total trips	trips without a zip-code	trips with 1 zip-code	trips with 2 zip-codes
Total	25679	320	673	24686
Added trips	2123	123	237	1763
Merged trips	26	5	0	21
Edited trips	23530	192	436	22902

Table 6: Trips and zip codes after filling in empty zip code fields in the two week data

With a zip-code distance table the distance of each trip with two zip codes can be calculated. For the origin of a trip with no zip code the zip code of the destination of the previous trip is taken. If the destination has no zip code the next origin is taken. For remaining trips the distance is estimated according to the duration of the trip and the average distance-time class. See appendix D.

Imputation of car trips

The 25.579 trips from the two week data and the 61.516 trips from the four week data are all modes combined, for electric driving we are only interested in the car trips. More specifically, only car trips as driver. A passenger can be in his own car when he lets another household member drive but he can also be in another car for example with carpooling. Therefore we only use car trips as driver, passenger characteristics are too uncertain. We don’t know if all car trips as driver are made by the main car user or that other household members use the car more often than the respondent. There is no possibility to obtain more information about household characteristics of the respondents or about their car ownership besides the trip information file.

There are 10692 (verified)car trips as driver in the two week data and 27944 car trips in the four week data. 130 times the same trip is registered twice in the two week data and 766 double trips in the four week data. The same trip (date, time and locations are the same) cannot be made twice therefore the second (and sometimes third) registration are removed. There remain 1066 trips that have a different origin than the previous destination in the two week data and 3239 trips in the four week data. An example of a missing trip is in the table below:

Day	Month	Year	Depart hour	Depart Minute	Arriving Hour	Arriving Minute	Zip Origin	Zip Destination	Motive
21	5	2013	10	14	10	34	1000XX	1100YY	To home
22	5	2013	16	35	16	50	1200ZZ	1100YY	To home

Table 7: Example of a missing trip

The cause of the missing trips is uncertain. Maybe the trip was not registered by GPS or the respondent filled in the journey to a location but forgot to fill in the journey back home. Figure 6 shows the share of each distance category for the verified trips and for the trips that are missing in the two week data. The missing trips occur more in the distance categories between 2,5 and 10 kilometers and the long trips over 50 kilometers but they both have the same pattern. The missing trips do not seem to belong to a certain category of trips. The four week has similar results and are included in Appendix B.

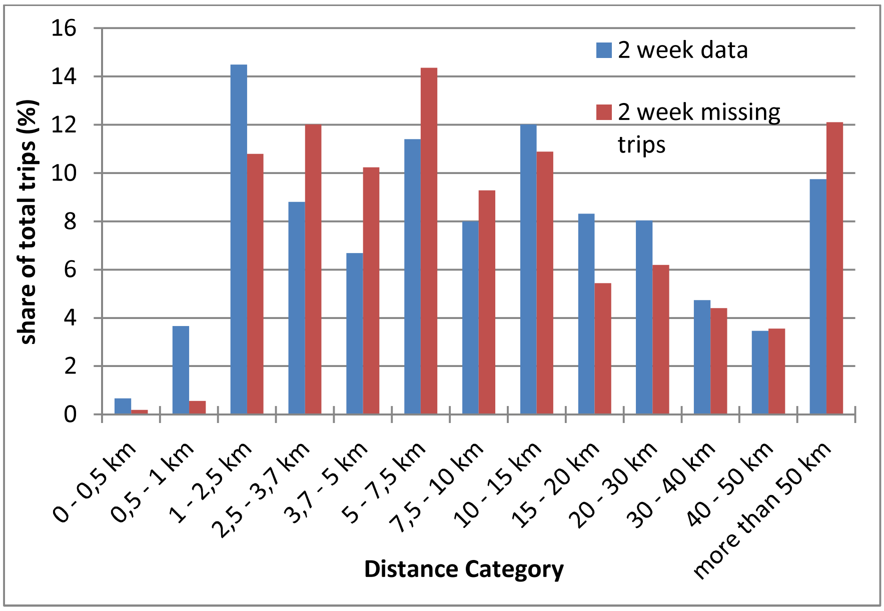


Figure 4: Comparison of two week data without the missing trips and the missing trips from the two week

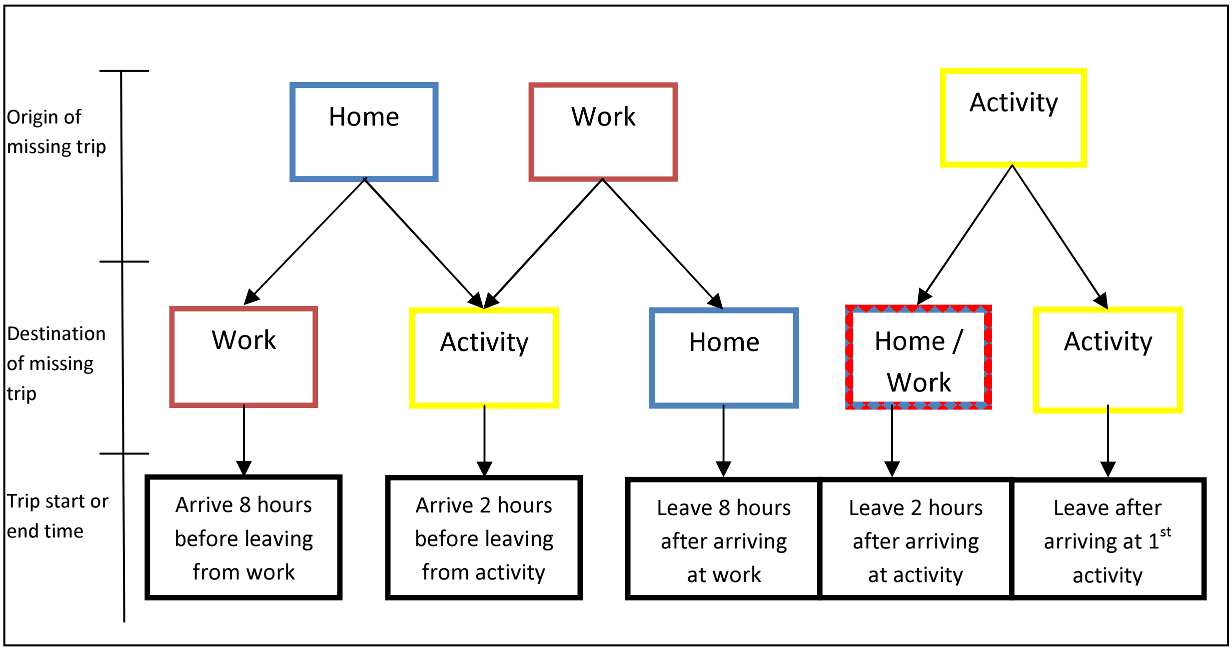
From the perspective of trip sequence the trip between the destination of the first trip and the origin of the second trip as shown in table 7 has to be made because the car is used in both trips by the same respondent. Therefore we add the missing trips. The origin and destination may be known but the time of leaving the origin and arriving at the destination is not; only that it is between the two known trips. In the case of BEV analysis activity time is an important aspect to know because it depends on the location and the amount of time that is spend at that location whether or not the battery can be recharged and how much. To determine the time of each missing trip three location types are distinguished : Home, Work and Activity. The reason for this distinction is that being at home is no activity while the other destinations are visited to do an activity like work or shopping.

Assumptions:

- There is only one trip between the first destination and the second origin.
- Activity duration is two hours.
  Activities have different motives and the duration of an activity is different for every respondent. Even for one respondent an activity like shopping can take 5 minutes to get a crate of beer or several hours to get new clothes. Activity duration is therefore even per motive impossible to trace back. We chose for an arbitrary two hours per activity for imputed trips.
- A working day is eight hours. The data shows that most trips to work arrive between 8 and 10 am and that most next trips are between 4 and 6 pm. See appendix C for details
- Travel time is based on distance and average (median) speed for that distance class. Travel time is important because the longer the travel time the less time is left to recharge the vehicle. Because of some outliers in the speed categories, due to improper distance or trip duration, we chose for the median for it is less sensitive to outliers than the average.
- Respondents home is defined as address with most motives "to home" from a respondent.
  This definition of home means that trips with motive to home but with a different destination address are not seen as trips to home. The reason is that there is a lot of improper motive labeling in the data. With a too broad definition of home, the possibilities to recharge a BEV in this model would not represent the possibilities in reality.
- Respondents work is defined as the address with the most motives "to work" from a respondent. Some respondents have more than one work address, but it is unlikely that they can recharge at every location.
- The respondent is the only driver of the vehicle during an activity. Theoretically it is possible that a respondent drives to an activity with someone else and he is passenger from the activity to home. First it is hard to verify whether or not this occurs. Secondly, it is the vehicle that is interesting, who drives is less important because the vehicle is making kilometers.

Process

The figure below shows a schematic view of the process of imputation of missing car trips.



The origin of the missing trip is by definition the destination of the previous trip. The destination of the missing trip is by definition the origin of the next trip.

A working day takes 8 hours; if a trip from home to work has to be imputed the arriving time at work will be 8 hours before the next trip when he leaves work. The time between activities is not important for this research because location is only important for the recharge time which can only be at home and work.

The missing car trip is the table below.

Day	Month	Year	Depart hour	Depart Minute	Arriving Hour	Arriving Minute	Zip Origin	Zip Destination	Motive
21	5	2013	10	14	10	34	1000XX	1100YY	To home
22	5	2013	16	35	16	50	1200ZZ	1100YY	To home

Table 8: Example of a missing trip

The respondent makes a trip from a location with zip code 1000XX to 1100YY which is home, and the next trip is from 1200ZZ to 1100YY (again to home). The respondent has traveled most likely from 1100YY to 1200ZZ between those two trips. 1100YY is the home location and 1200ZZ an unknown location where an unknown activity takes places. When we follow the scheme above (origin is Home, destination is Activity) the arrival of the trip is two hours before the departing of the next trip (this way the activity takes 2 hours).

The departing of the missing trip is than the arriving time minus the travel time. The new trip sequence becomes then:

Day	Month	Year	Depart hour	Depart Minute	Arriving Hour	Arriving Minute	Zip Origin	Zip Destination	Motive
21	5	2013	10	14	10	34	1000XX	1100YY	To home
22	**5**	**2013**	**14**	**20**	**14**	**35**	**1100YY**	**1200ZZ**	
22	5	2013	16	35	16	50	1200ZZ	1100YY	To home

Table 9: Example of an imputed trip

Remaining unknown trip distance

The only trips left with no distance are the trips were a zip code is still missing or with a non-Dutch zip code. The trip has been made and it could give a larger possibility of electric driving when these trips were omitted. Therefore we estimate the trip distance based on the time traveled. The relation between travel time and distance is obtained from the other trips. From time classes an average distance is obtained which is then used for the trips with one or two invalid zip codes. For the time-distance relation see appendix D.

Validation of Data

The goal of this analysis is to look at the possibility to use a BEV for all personal trips and the effect of improvements and adaptations in the Netherlands. Therefore the data should be a reflection of the trips made in the Netherlands. To validate the data from the mobile mobility panel the data from Statistics Netherlands (CBS) is used. CBS asks respondents to register their trips for one day in their Research on Movements in the Netherlands (OViN). We only use the data from car drivers from the mobile mobility panel; therefore we will compare the data for distance frequencies of car drivers from OViN and the mobile mobility panel. Figure 5 describes the differences between the mobile mobility panel 2 week and 4 week data before the imputation of missing trips and the data from OViN. The largest differences are in the 0,5 -1 km and the 5-7,5 km. The distances that were obtained from the MMP used 4 digit zip code information. It means that all intra zonal trips had a distance of the average radius of the zone. It could be that the average radius of the zone is often between 0,5 and 1 km while the made trip was shorter or longer. This would also explain why the category below and above (0-0,5 km and 1-2,5 km) have a higher occurrence in OViN than in MMP. For this analysis it is not very important because the difference from the actual trip distance and the distance from the zip code matrix would be maximum of 2 km; 2% of a BEV range.

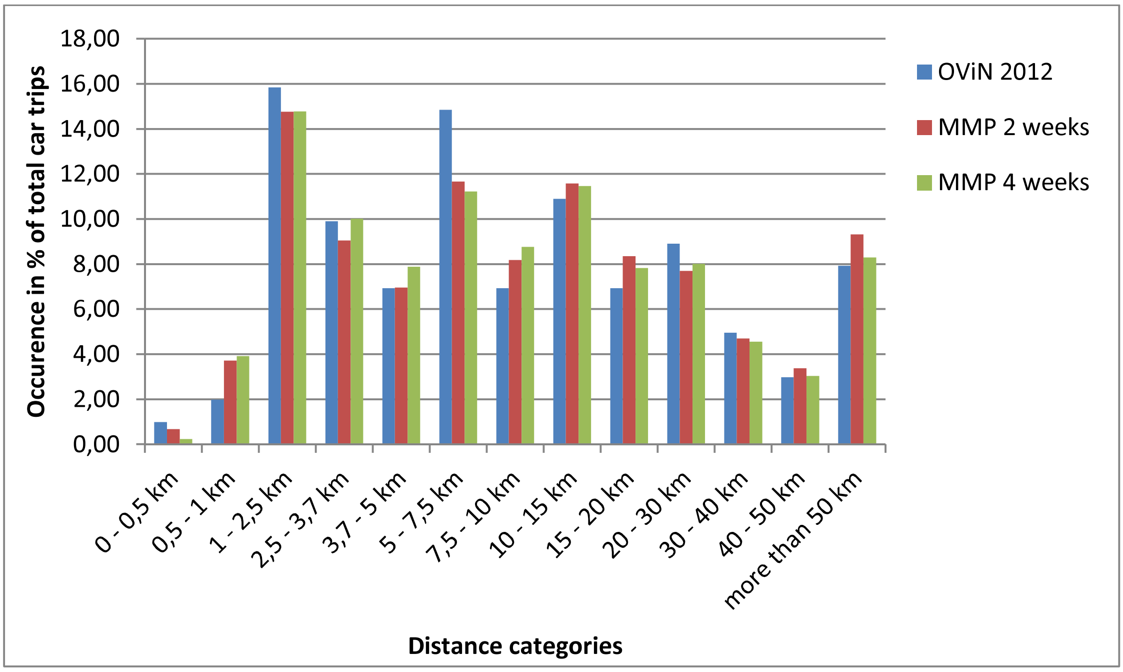


Figure 5: Trip distance frequency distribution of car drivers from CBS and MMP

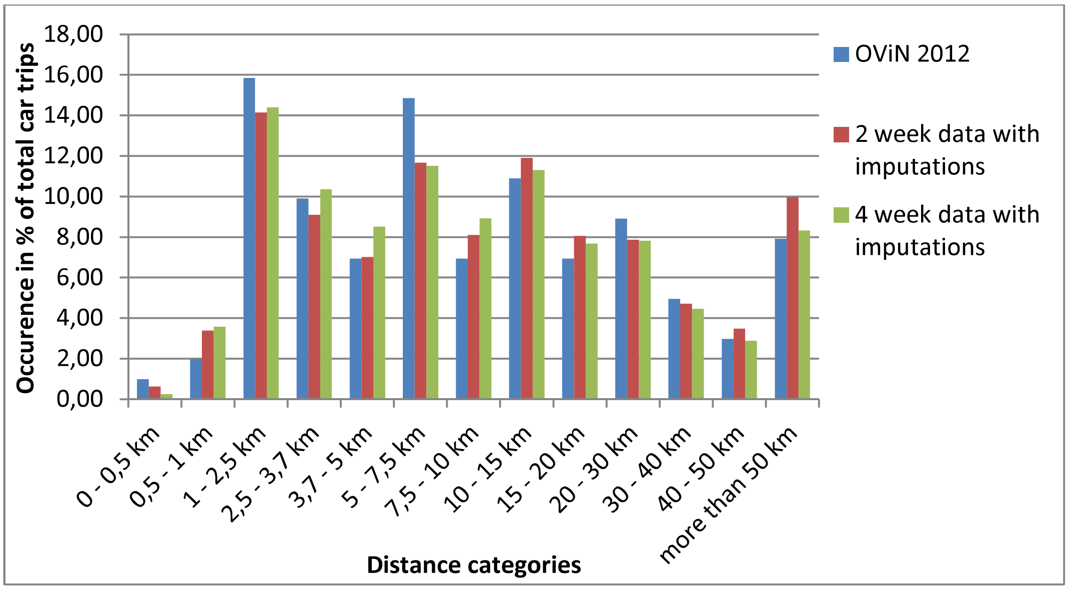


Figure 6: Trip distance frequency distribution in CBS and the MMP with the missing trips included

The MMP with the missing trips does not change the figure much. The cause is the low share of missing trips, around 10% of total trips. The distribution of missing trips follows the pattern of the mobile mobility panel data, see figure 6 on page 29. The category 5-7,5 km is occurs less often in the MMP data but occurs significantly more in missing trips from the MMP in figure 8. However this seems coincidental because the other OViN peak in figure 7 is the 1-2,5 km and occurs significantly fewer times in the missing data from the MMP, figure 8.

Another way of validating the data is to look at the average trips per person and the distance per person in table 10

	OViN	MMP 4 weeks	with inputations	MMP 2 weeks	with inputations
Trips per person per day	0,97	1,16	1,30	1,02	1,12
Distance per person per day (km)	15,07	20,85	23,23	20,06	22,29

Table 10: Trips and distance per person per day according to CBS and MMP with and without imputations

The MMP has more trips per person per day without the imputations this increases also the distance per person per day because the distance distribution over the trips is comparable between OViN and MMP (figure 5 & 6). The absence of foreign trips in OViN could be a reason why it is lower than the MMP data. In the MMP are at least not all foreign trips excluded. Another reason could be the way of obtaining data. OViN asks to fill out all trips for one day while the MMP used GPS to record the trips and it could be improved by the respondent afterwards which could reduce the number of unrecorded trips that have been made. If that is the case the MMP would describe the travel behavior in the Netherlands better than OViN would. All in all seems the mobile mobility panel a good data set for this analysis because it accurately describes the travel behavior in the Netherlands and it has the necessary information to use in a data analysis to study the possibility to use a BEV for personal trips.

4. BEV characteristics

This chapter describes the characteristics of current BEVs, the recharging infrastructure and developments of the BEV and recharging infrastructure. The characteristics described in this part are used as characteristics of BEV's in the analysis. There are three parts: the first is about the range of a BEV and what influences the range. The second part is about recharging location and costs. The third part is how these characteristics are used in the analysis to what extent respondents can use a BEV for their trips.

4.1 Relevant characteristics

In the first place it is necessary to determine what the characteristics of a BEV are. Range, recharge speed and recharge location are the indicators that are used to determine whether or not a person can make his trips with a BEV. These indicators are not static; Every BEV model has a different range and different technology to recharge the vehicle.

Range of an BEV

Several tests have been developed to estimate the range of a BEV. The European Union uses the NEDC (New European Driving Cycle) to estimate the range. Many critics say that the cycle gives a too optimistic range for BEVs that can never be achieved by ordinary users. Table 11 shows the range of some BEVs according to the NEDC. A successor of the NEDC is currently being developed by the EU, Japan and India to harmonize the determination of energy consumption by vehicles. As of this moment there is no test used at a large scale that can determine fuel or electricity consumption. To determine the typical range of a BEV there are two methods available: realistic test scenario reports and measured data from users.

The institute for power trains and automotive technology (IFA) in Vienna has put four BEVs to the test to determine the range under different conditions. Three factors are being distinguished: temperature, speed and road gradients.

High speed:

IFA has tested several electric vehicles: Nissan Leaf, Smart Fortwo Electric, Mercedes A-klasse E-cell, and the Mitsubishi i-MiEV. With the result of every BEV they made a profile of an average electric vehicle.

The electricity a vehicle needs to maintain a certain speed increases significantly with the speed of the vehicle. The NEDC values predict a use of between 12 and 16 kWh/100 km. IPAT results show that 16 kWh/100 km is only possible at a steady speed below 70 km/h.

Brand	Type	Capacity in kWh	Radius in km (NEDC)
Mitsubushi	i-MiEV	16	150
Nissan	LEAF	24	230
Tesla	S (85)	85	500
Tesla	S (60)	60	375
BMW	i3	22	160
Renault	Zoe	22	210
Smart	Fortwo	17,5	140

Table 11: Range of different BEVs according to NEDC tests

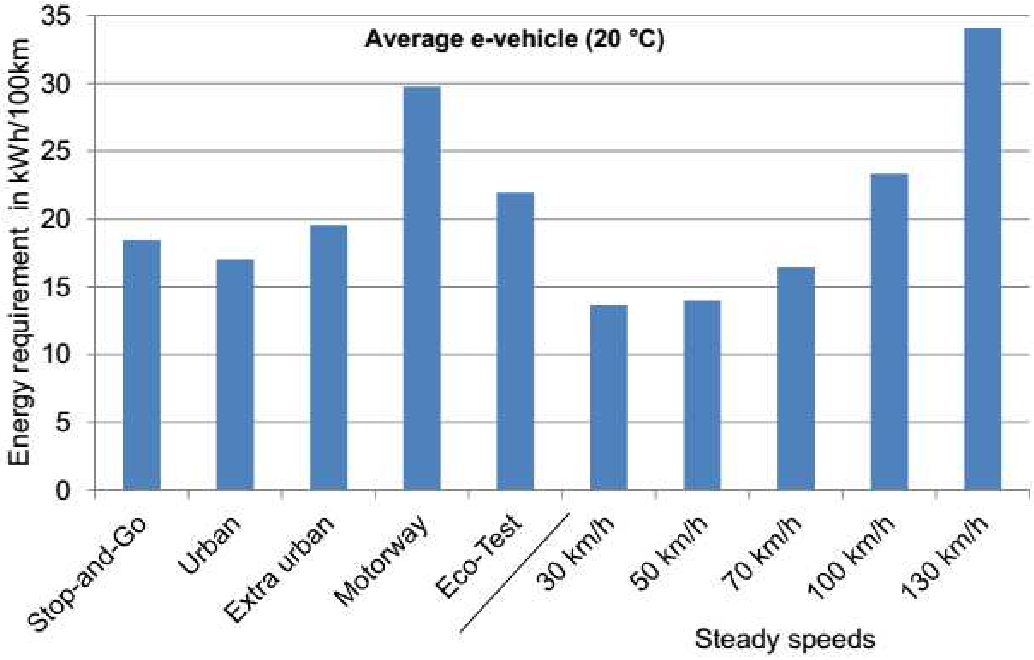


Figure 7: Energy requirement of the average e-vehicle as a function of the driving situation on a road gradient of +/-2% and an ambient temperature of 20° C (without heating and without air conditioning) in kWh/100 km (Geringer & Tober, 2012)

Temperature

The best operating temperature for a BEV is around 20°C. When temperature drops the capacity of the battery decreases and the heating system requires more energy. The capacity of the battery decreases with 40% at -20°C under normal operating conditions compared to a temperature of +20°C. Hot weather has also an influence on the capacity of the battery because the battery cooling unit and the airco require energy. The airco is an optional feature but the battery needs to be cooled down to prevent damage to the battery from overheating. The range at 30°C will decrease with 15% compared to the range at 20°C. The temperature inside the vehicle was set to 22°C using heating or air conditioning systems. IFA did not test with different inside temperatures but is likely that the temperature difference between outside and inside temperature gives an indication for the required energy.

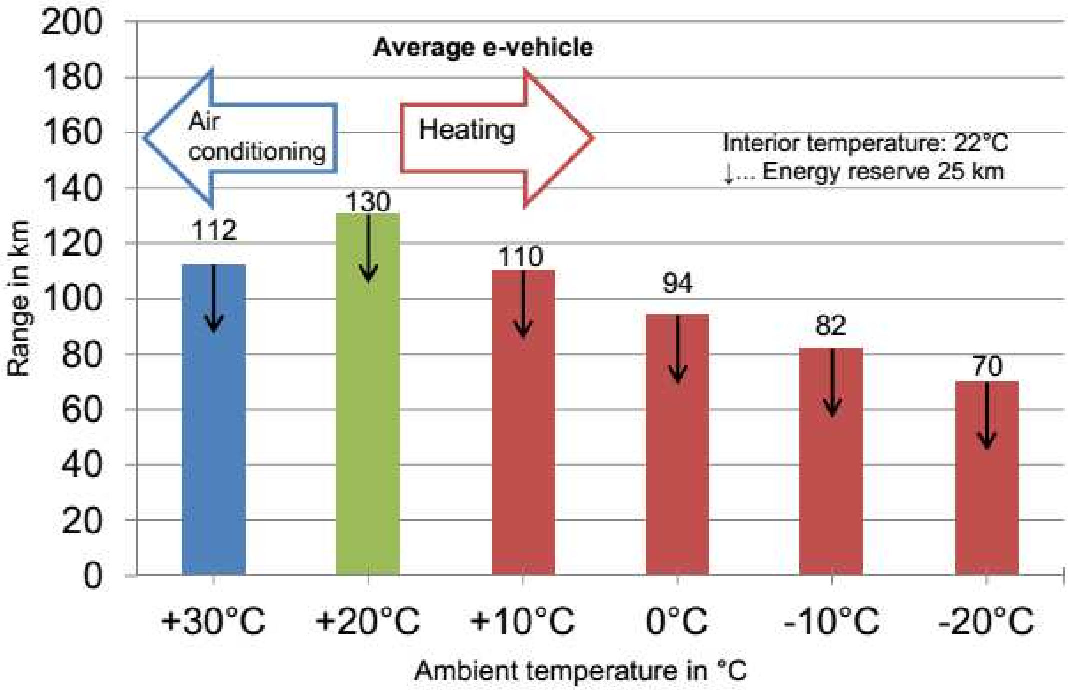


Figure 8: Range of the average e-vehicle as a function of the ambient temperature in the eco-test on a road gradient of +/-2% (Geringer & Tober, 2012)

Road gradient

IFA tested the vehicles at different road gradients to assess the influence of hills on the range of a BEV. Table 12 shows the eco-test results with the Nissan Leaf. The decrease in range is around 33% when the road has a constant gradient of +2%. Most trips however will cover both uphill as downhill parts; the decrease in range on those trips would be around 5% according to the tests.

Nissan Leaf

Eco-Test	Reichweite	Reichweite bei 0% Steigung <km>	Reichweite bei +/-2% Steigung/ Gefälle <km>	Reichweite bei +2% Steigung <km>	Reichweite bei -2% Steigung <km>
	+30°C	99	95	66	166
	+20°C	106	101	69	189
	+10°C	94	90	64	154
	0°C	81	78	57	122
	-10°C	68	66	50	97
	-20°C	58	56	43	79

Table 12: Range of a Nissan Leaf at various temperatures and slopes

Developments

The most important development to increase the range is the battery technology. There occasionally reports on new technologies that can recharge batteries within seconds and new materials that can store much more energy. These technologies are far away from technical implementation. The largest improvements come from the lithium-ion battery. This battery exists since the 1990's and has improved significantly. The amount of energy that can be stored per kilogram of battery has increased from 80Wh in 1991 to 200Wh in 2005. The price of batteries has dropped to 0,4 dollar per Wh and is still decreasing. (Anderson, 2009) Further range improvements at lower costs are expected at least in the coming decade. In that light it is interesting to see to what extent drivers' benefit from larger batteries. At certain level everyone can make their daily trips with a BEV foreign or holiday trips excluded; at that point it seems not effective to further increase the size of the battery. What the maximum capacity of a battery and thus the maximum range of a BEV will be in the future is uncertain but it is unlikely that the range will be higher than the range of a current CEV.

Conclusion Range

There are three range influencers besides the capacity of the battery: Speed, temperature and road gradient. Different speed scenarios are not useful since a vehicle rides at different velocities during a trip and it can be different for every trip. It is likely that owners of a BEV do not analyze every possible trip in such detail that different velocities and therefore different electricity usage is calculated. An average scenario like the eco-test seems more realistic to use in the data-analysis. Based on the eco-test a realistic range is 100 km. This is with a BEV with a battery of 22 kWh.

Temperature has a significant effect on range. A decrease in range of 40% during extreme cold weather compared to 20 degrees Celsius is measured by IFA. A bad weather range of 75 km is realistic according to test results and will be used for a bad weather scenario in the data-analysis.

Road gradient is not a large issue in the Netherlands and it is likely that a BEV with a full battery will drive as much uphill as downhill. The influence on range is negligible according to IFA results and will therefore not be a part of the data-analysis. For the future it is worthwhile to see the effect of range increase by improved battery technology. It is unlikely that the battery will ever have a capacity that results in a range longer than a current CEV which is around 700 km.

Recharging a BEV

Electricity is widely available in the Netherlands often as 3.6 kW (230V, 16A) alternate current (AC). Batteries of Electric vehicles work with direct current (DC). This means that a plug from home socket to car battery is not possible. A BEV has an AC/DC converter that converts the alternating current from the electricity grid to direct current that can charge the battery. The speed at which the battery recharges largely depends on the converter of the BEV and on the type of electricity from the grid.

1phase/3phase

A home outlet in the Netherlands often delivers one phase, 230V, 16A electricity. Some people have a three phase electricity connection at home that can deliver 400V. Public charging poles are often three phase 400V power and deliver 11kW with 16A. Some public poles even have a 32A connection that can deliver 22kW.

All hybrid electric vehicles and some of the BEVs can charge only at one phase. Tesla and Renault BEVs can also charge with three phase electricity. At home there is often no difference between the charging rates for a BEV since it delivers only one phase 16A. At public charging poles there is a difference. Since one phase BEVs can only use one of the three phases. Instead of 11kW they can only charge at 3.7 kW at 22kW points the maximum rate is 7,4 kW.

Converter

The exact maximum rate at which a BEV can charge depends also on the AC/DC converter in the car. A converter that can handle higher power is more expensive and is only used at public charge places. The BMW i3 and the Nissan Leaf from 2011 and later have a 6.6kW converter. This is the maximum power that it converts to direct current. It means that at a 22 kW public charging pole it charges at one phase with a maximum of 6,6 kW. Most hybrid electric vehicles like the Prius or the Volt/Ampera have a 3.3 kW converter.

AC/DC

The above mentioned rates apply only for alternating current. When direct current is available a BEV often charges much faster. The fast charge poles provide direct current; it means that the electricity is converted from AC to DC in the charge unit instead of in the vehicle. The Nissan Leaf for example can charge at a maximum of 44 kW at standard fast charge stations. Tesla can charge even at 90 kW at Tesla's super charge stations.

Plugs

Plugs for electricity are different around the world. Every continent or country can have a different pug and different power rates at their home socket. BEVs are no exception. Different cars require different pugs for each type (AC and DC) of charging. The process of standardization is slow; currently there are at least three different incompatible plugs and Tesla with its own standards.

There are currently three plugs for AC-charging but they are easy to interconnect. European cars use a Mennekes plug, USA and Japan use a j1772 plug and there is the standard Schuko plug that fits in every home socket. The difference is that Mennekes can handle three phase charging and the other plugs one phase charging.

There are two different standards for DC-charging, the SAE-Combo and CHAdeMO. CHAdeMO is de DC-standard for Japanese cars. SAE-Combo is a new standard with a connection for AC (Mennekes) and DC charging in one plug. SAE combo is the connection for European BEVs like the BMW i3. Tesla has its own standards but develops plugs that are compatible with the other plugs. Other cars however cannot use the charge units developed by Tesla.

Brand	Type	plug AC	Plug DC	AC/DC converter (kW)	1 or 3 phase AC	DC capacity (kW)
Mitsubishi	i-MiEV	j1772	CHAdeMO	6,6	1	50
Nissan	LEAF	j1772	CHAdeMO	6,6	1	50
Tesla	S (85)	Mennekes	Tesla	20	3	120
Tesla	S (60)	Mennekes	Tesla	20	3	120
BMW	i3	Mennekes	SAE Combo	7,4	1	50
Renault	Zoe	Mennekes	-	43	3	0
Smart	Fortwo	j1772	-	3,3	1	0

Table 13: Charge connections and capacity for different BEVs in Europe

Costs of recharging

The costs of charging depend on the amount of electricity that is charged or the time at a charging unit. The consumer price for electricity is around 22 cents per kWh. Charging at public charging units costs between 21 and 25 cents per kWh depending on charge card subscription. Fast charge is paid per hour and costs around 13 euro per hour. The costs are not further incorporated in the analysis.

Location of recharging

The most important charging location is at home. It is convenient because a car is often parked there long enough to recharge the battery. However it is not possible for everyone to recharge at home. van den Brink et al., (2011) looked at the possibilities to recharge at home in the Netherlands. They concluded that it was possible for around 40% of the population. Charging at work is a possibility that is also mentioned by van den Brink et al., (2011). A typical working day is eight hours, long enough to recharge a BEV. For people with a home-work distance that is over half the range of a BEV recharging at work could mean they can make their trips with a BEV. There is no information about the companies where respondents work. But the effect of the possibility to recharge at work can be modeled.

Charging at other places is also possible. Fastned and ElaadNL are two parties that focus on charging stations along the road and at public parking spaces. These locations can be interesting for people who make trips longer than the range of a BEV or people that park at train stations or city centers. Tesla installs their own charging network for Tesla's BEVs along European highways.

Conclusion charging a BEV

Each BEV model charges at a different rate with a different plug. Home electricity is the same for almost all people in the Netherlands: 230V, 16A, AC thus 3,6 kW. Charging anywhere else like at the workplace or at shopping malls is different for every vehicle and depends also on the charging unit. Currently DC-charge units are scare in the Netherlands and most public charge units can deliver 11kW AC but it is 3-phase electricity. 1-phase electricity vehicles charge at 3,7 kW at such units. In the near future with more fast-charge DC units 50 kW charging is realistic for on the road charging. At home or at work recharging with three phase may be possible for some people, the recharge rate would vary between 3,7 and 11 kW depending on the AC/DC converter of the vehicle and the possibility to charge three-phase. For the analysis we take a recharge speed twice as fast, this would be 7,4 kW.

The main location to recharge is at home. Another recharge location is at work because the vehicle is parked there for several hours and a car is often used to go to work.

4.2 Scenarios

From the data and the BEV characteristics and development scenarios are composed to evaluate the effect of different BEV developments on the possibility to make personal car trips by car drivers.

The first step it to evaluate the data sets. While four weeks of data contain more information than two week data it is more expensive to collect. When the effect of four week data is only small the benefit of more data does weigh up to the costs of collecting it.

The first scenario is a basic scenario. The basic scenario can be altered to evaluate the effects of technology improvements or adaptations in travel behavior. The factors that can be altered for technology improvements are range, recharge location and recharge speed.

Home is the most important recharge location the car is usually parked there overnight. Work is a second recharge location because when a car is used in home-work trips it is parked there during a large part of the day. To model this three basic scenarios are used: The first basic scenario let everyone recharge at home. This is not the most realistic scenario not everyone can recharge a BEV at home. In the second basic scenario 40% can recharge at home. The third basic scenario assumes that 40% can recharge at home and everyone at work.

The characteristics of recharging at home and work are with a standard home electricity connection at 3,6 kW. The basic scenarios contain an evaluation of different ranges. The lowest is 75 km and the highest is 700 km, this corresponds with a battery size between 16,5 kWh and 154 kWh. The fuel efficiency and the recharge speed are not altered by the battery size. It means a BEV with a range of 100 km recharges from empty to full in 6 hours. In other words at home the battery gets 16,7 km range per charging hour for every battery size.

The other scenarios are technical improvements of the recharging infrastructure. First the effect of fast charging. The recharge speed depends on the BEV and the recharge location. In the basic scenarios the recharge locations are at work and at home. The recharge speed is 3,6 kW. In the fast charge scenario the recharge speed is doubled to 7,2kW both at home and at work. This could have a positive effect on the number of respondents who can make all their car trips with a BEV. It is expected that it will have a larger effect on BEVs with a large battery because they have a longer recharge time. A BEV with a range of 200 km would take 12 hours to recharge from empty to full at normal speed. With the 7,2kW the recharge time is only 6 hours. The other characteristics of BEVs and infrastructure are the same as the three basic scenarios.

The next improvement of the basic scenarios is recharging along the road. The number of charging stations along the road is increasing. Fastned and others companies build recharging stations mainly along highways. It is not expected that people use them as the only recharge location but rather for an occasional long trip. The reason is that recharging along the road is not very convenient. A trip needs to be interrupted and it takes some time to recharge the battery. Fast recharging along the road is therefore important. The roads respondents take to get from origin to destination is unknown. It is therefore not possible to know when they pass a recharging station. Instead respondents recharge once during the longest trip they have registered. The departure or arriving times are not adjusted to the recharging event. The longest trip is cut in half and at the end of the first half the BEV gets a full battery. The other characteristics of the BEV, recharging locations and trips remain the same as in the three basic scenarios.

The following scenarios model the adaptations that respondents make in their travel behavior. The first analysis is to look at the problems that respondents have when they use a BEV for all their trips in the first basic scenario where everyone has the possibility to recharge at home. This will give insight in how many times respondents would get an empty battery when they use a BEV for all their car trips. In the previous scenario a respondent could not use a BEV when they have an empty battery. This time when the battery is empty it is instantly recharged and the respondent continues with making trips. This will show how many times a respondent has problems with the BEV. The next step is to look what the causes are for these problems. Two causes are distinguished: a respondent makes a trip that is longer than the range of a BEV and the respondent makes a series of trips shorter than the range but cannot recharge in between.

The first adaptation respondents make is to use an alternative mode of transport for one long trip. The alternative could be public transport or a rental car or a CEV provided by the BEV manufacturer. The availability of public transport for each respondent is not known and it is not possible to use respondent data outside the Centerdata server to get public transport information. Therefore it is assumed that everyone has an alternative for their longest trip. This can be public transport, carpooling, rental car, etc. In the model the longest trip is not made with a BEV. The other trips do not change. The characteristics of BEV and recharge location and speed are the same as in the three basic scenarios.

The second adaptation is an alternative for short trips. A reason that respondents cannot use a BEV for all their car trips is that they make many short trips and there is no time or location to recharge between trips. An alternative could be that they use an (electric) bike for short trips. In the model all short trips (<15 km) are not made with a BEV. The other trips do not change. The characteristics of BEV and recharge location and speed are the same as in the three basic scenarios.

5. Analysis method

After the characteristics of a BEV and the recharge infrastructure are determined and the personal trip data from the MMP is clean and appropriate for analysis the next step is to perform the analysis. The goal of the analysis is to find out to what extent people can use a BEV for their personal car trips.

The model will look at each respondent to find the necessary range for the respondent. This way it is possible to see how many of the respondents are able to make their personal trips using a BEV with a given range. The parameters that can be changed are the speed at which the BEV recharges and the location where the BEV can be recharged. This is done according to the scenarios based on the characteristics of the data and the characteristics of a BEV and recharging infrastructure.

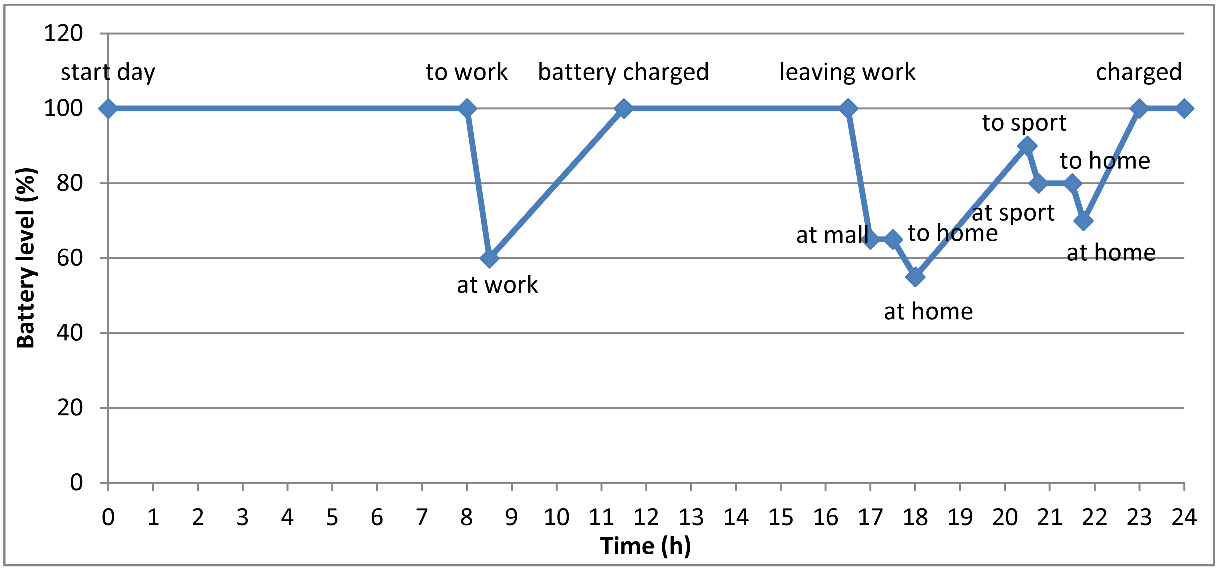


Figure 9: Example of one day of BEV driving for a respondent with charging at home and at work

Every run of the model the necessary range begins at zero then each trip from a respondent will be made by adding the distance of the trip to the necessary range of the BEV. When the respondent is at a recharge location the current range is reduced with a speed belonging to that recharge point until the range is zero or the next trip begins. After the last trip is made the maximum range is the necessary range for that respondent.

The first step is to see what the difference is between two week data and four week data. Four week data is expected to be better because the chance of missing a trip longer than the range of a BEV is smaller when the monitoring period is longer. On the other side may two weeks capture most of the travel pattern. There is always a change that one occasional long trip is not made during the registration weeks, but it likely that such a trip is made less than once every four weeks and that it depends on willingness of an individual to recharge on the road if it is acceptable.

The next step is to make an estimation which respondents can recharge at home. The data does not provide information about the home address. We chose to use the urban density of the home address and the income of the respondent to decide whether or not a respondent is able to recharge at home. It is expected that a higher income is needed to buy a house that has the possibility to park a car at own terrain. Also a house in the city center, a highly dense area, with an own parking space is rarer and more expensive than a house with parking at own terrain on the country side; it means that a high urban density decreases the change to have the possibility to recharge a BEV at home. The analysis from (van den Brink et al., 2011) assumes that 40% of the houses in the Netherlands have the possibility to recharge a BEV at home. In this model we assume that around 40% of the respondents can recharge at home and living in a high dense area and a low income decreases the change of recharging at home while a higher income and a lower urban density increases the change to recharge at home.

Then other possible recharge locations are evaluated to see what their effect is. Possible locations are at work, along the road or at other public recharge points.

Next we will vary the recharge speed and see whether or not it has an influence on the ability to make trips with a BEV. (twice as fast at home and at work)

Last we will also look at what the effect is when the respondents change their habit. When they are able to have an alternative for a long trip or an alternative for short trips.

6. Results

Method

To determine the possibilities of electric driving for respondents of the mobile mobility panel we use only respondents with 10 or more verified days for the two week data and 24 or more verified days for the 4 week data. A verified day is where the respondent filled in the questionnaire after the trip registration. This is to distinguish days where no trips were made from days were no trips were registered.

To determine who can drive electric there are a few assumptions

- The battery is full when first trip begins
- Recharging happens linear
- When there is the possibility to recharge the battery is recharged
- A respondent can drive electric if the battery is never empty during the registration period

Every respondent's trips are analyzed. The distance of a trip is subtracted from the current battery level. When the destination of a trip is a recharge location the battery is charged until the battery is full again or until the next trip begins. Recharging is never negative; some trips start before the next trip is finished. This causes a negative time between trips. Recharging would cause the battery deplete instead of recharge. In such case the recharge is zero. An example of one day analysis for one respondent is in figure 9. The battery of his BEV is depleting when he drives, it recharges when he is at a recharge location and remains the same when he is not driving and not recharging.

Data	Two week	Four week
Respondents	591	652
Minimum verified days	10	24
Verified respondents	441	483
Verified but no car trips	58	49
Verified with car trips	383	434

Table 14: Data characteristics

In the two week data there are 441 respondents with ten or more verified days. 58 of them have made no car trips during the monitoring weeks. This is 13%; it is assumed that these respondents have no car. The other 383 people have made car trips and have more than 10 verified days. These 383 respondents are used in the calculations. Respondents without a vehicle are not interesting for this analysis because it looks at the replacement of car trips. The four week data has 434 respondents with 24 or more verified days who made car trips.

Basic scenario 1, everyone charges at home

Scenario 1 is used for the first test to see who could use a BEV for their trips. In this scenario everyone has the possibility to recharge at home. The recharge speed is 3,6 kW.

When everyone could recharge their vehicle at home 169 respondents (44%) of the 383 verified car owners could drive a vehicle with a 100 km radius. Figure 11 shows the percentage of verified car respondents who can drive a BEV with different radius of action. The recharge speed is the same for every range at 3,6 kW, based on six hours recharging to get 100 km radius of action.

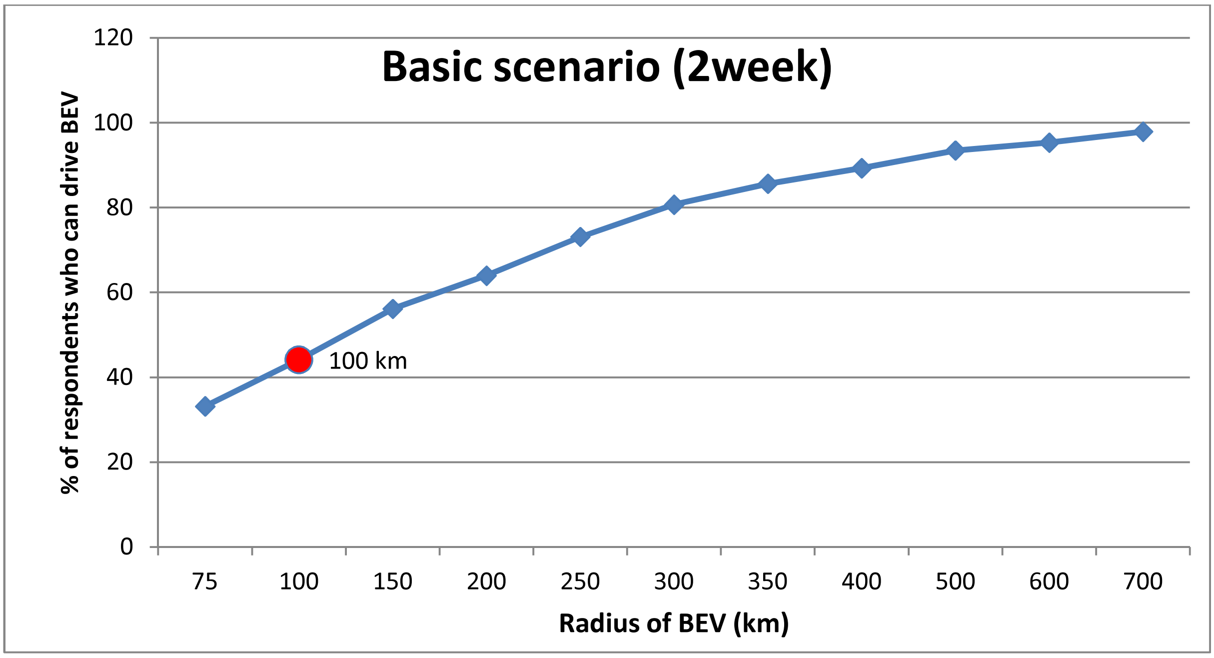


Figure 10: Percentage of verified car owning respondents who can drive a BEV with a different radius of action of a BEV, highlighted is the percentage of respondents that can drive a BEV with a radius of 100 km

Two or four week data registrations

The longer the observation period the more likely it is that all the different kind of trips from a respondent are registered. Collecting the data is expensive and time consuming therefore it is important to find the shortest period of data that covers the various kind of trips that a respondent has made. Is two weeks of data enough to estimate whether or not respondents can make their trips with a BEV? Figure 12 shows the difference between 2 week and four week data for basic scenario 1 where everyone can recharge at home. In two weeks 44% of the respondents could make all their car trips with a BEV with 100 km radius, in four weeks this is only 28% of the respondents. The explanation is that some occasional long trips happen less often than once every two weeks but are covered within four weeks. There may also be trips that are made less often than four weeks. This is a smaller problem because one adaptation in two weeks is far more than one adaptation every six weeks. For the remaining analyzes the four week data is used. Figure 12 also shows a diminishing effect of a longer registration period for BEVs with a higher range. This can be explained by the fact that events were a BEV drove more than 500 km before recharging are very rare even in four week data. A longer registration period show a larger effect because the change of making such a trip once a year is not unlikely but it is an incident and the consideration of using another vehicle for vacation is different from using another vehicle once every four weeks.

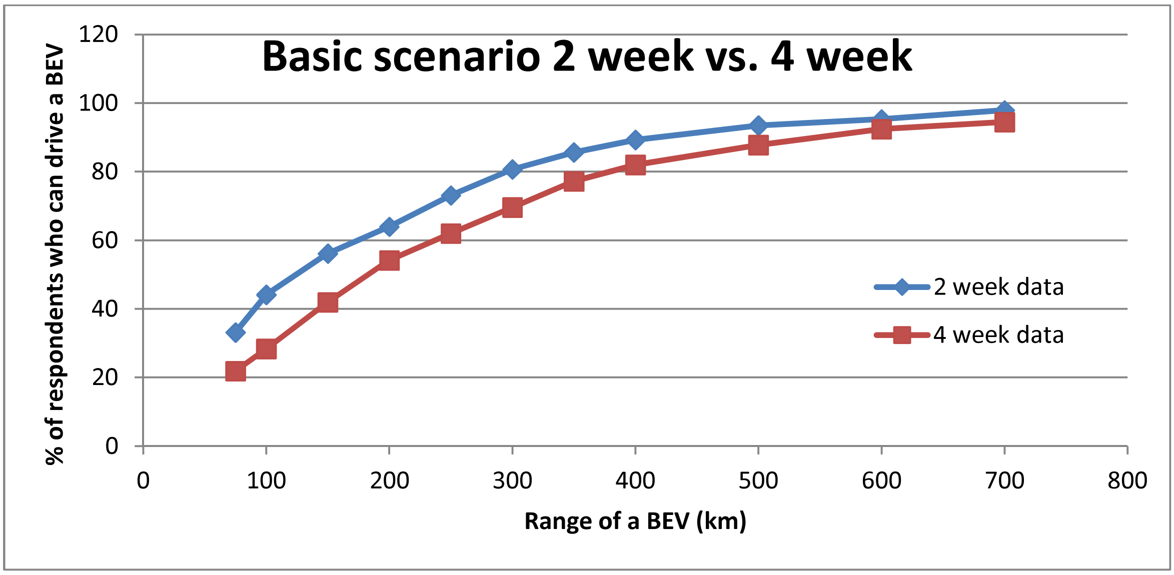


Figure 11: Percentage of verified car owning respondents who can drive a BEV with a different radius of action of a BEV in the two week data and the four week data

Basic scenario 2, 40% can recharge at home

So far it was assumed that everyone could recharge at home because it is a necessary condition to be able to drive an electric vehicle. In reality not everyone is able to recharge at home because they have no private parking space. There is no information about the home situation of the respondents, so it is not possible to determine exactly who is able to recharge and who is not. (van den Brink et al., 2011)has made an estimation in their research that 40% of all households in the Netherlands is able to recharge a BEV at their own place. The houses where recharging was possible are the larger houses like farms free standing and semi-detached houses. These houses are generally more expensive, also depending on the location; in the city center such a place would be more expensive than on the country side. From the respondents of the mobile mobility panel we used their income and the urban density of their home address to determine if they could recharge at home. It is expected that a higher income and a lower urban density increases the change to be able to recharge at home. When table 16 is applied to the respondent s of the panel 174 of the 434 respondents were able to recharge at home, this is 40,1%. Respondents who cannot recharge at home cannot drive a BEV. Some respondents are not able to recharge at home but they drive, in the whole registration period, less than the range of a BEV it means they would not have an incident and could use a BEV. However at some point they need to recharge so they are excluded from the group of respondents who can drive a BEV. The recharge speed is still 16,7 km/h

The effect is of course that the people who could make their trips with a BEV drop significantly.

		Urban density of home address (houses/km^2)		
		<500	500-1500	>1500
Monthly gross household income (€)	0-2000	-	-	-
	2001-4000	V	-	-
	4001-6000	V	V	-
	>6000	V	V	V

Table 16: Table to determine who can recharge at home ("V") based on income and urban density

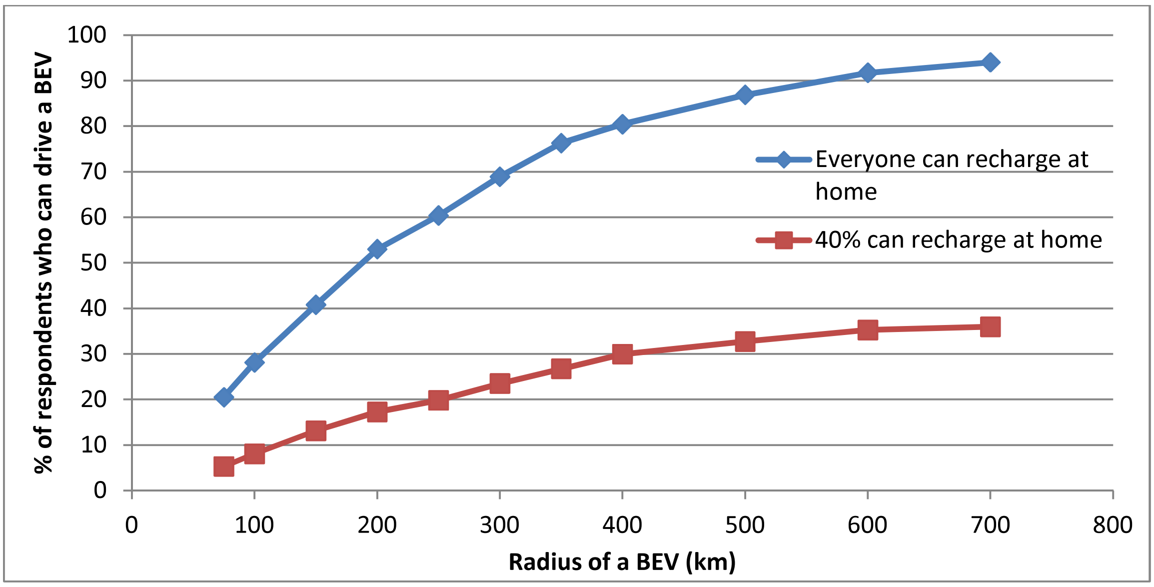


Figure 12: Percentage of respondents that can make all their personal trips with a BEV when everyone can recharge at home and when 40% is able to recharge at home.

The question is if there is a difference between the group who is able to charge at home and who is not able to charge at home. When the range is 100 km 8% of all the respondents can drive a BEV and recharge at home. 29% of the respondents who can recharge at home can also use a BEV for all their trips. Basic scenario 1 showed that 40% of all respondents can use a BEV for all their trips. The share of respondents who can use a BEV for all their trips is lower for the group of realistic home recharges than for all the respondents. The conclusion is that respondents who can recharge at home are less likely to be able to use a BEV for all their trips.

Figure 14 shows which part of the respondents is able to drive a BEV and able to recharge the vehicle at home with a BEV with a range of 100 km. From the group of people that is able to drive a BEV 70% is not able to charge at home. From the group that is not able to drive only 56% cannot charge at home. It means that in the group who can drive a BEV fewer respondents have the possibilities to charge at home. An explanation could be that people living in high dense urban areas make shorter trips because work, friends, shops etc. are closer to home. This means they can drive a BEV without a problem but they do not have the space at their home to recharge the vehicle. People living in less dense areas often have the space to recharge a BEV on own terrain but make longer trips because work etc. is further away from home.

There is however one remark, the yellow square in figure 14, in the group of people who can drive but cannot recharge at home, are respondents who can drive a BEV, cannot recharge it at home but drive in fewer than 25 km/week. The group represents 36% of the people who can drive a BEV but are not able to recharge at home. This is interesting because they may not have a problem with the inability to charge at home. They are excluded but they might not have a problem with once a month finding a public recharge facility, for example near train stations, the city center or at work. When a respondent parks there one a month all trips could be made with a BEV.

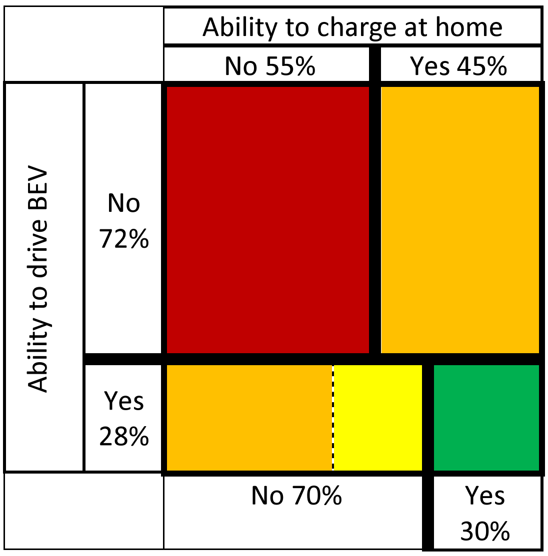


Figure 13: the percentage of respondents that can both recharge at home and make all their trips with a BEV

Scenario 3, work as charging place

Another important recharge location can be at work since most people spend a large part of a working day at work. Figure 15 shows the results when respondents can also recharge at work compared to scenario 1 where everyone can recharge at home and scenario 2 where 40 % can recharge at home. When all respondents can also charge at home (scenario 1) adding work as charging place has almost no effect on the number of respondents who can make all their trips with a BEV. Compared to scenario 2 the effect of adding work as charging place for all respondents has a significant effect especially for BEVs with a large range.

The reason that charging both at home and at work does not increase the BEV potential is likely that home-to-work trips are often not that long and that home-work-home distance is within the range of a BEV. The cause of the larger effect when 40% can recharge at home is that there is a large group that can only recharge at work. Together with the people who can recharge at home this is a significant group. Respondents from the 36% who drove less than 100 km in four weeks but could not recharge at home (figure 13) and have a job fall in this category. The people who could drive a BEV when the only recharge place is at work increases when the range of a BEV increases. In that case they can probably make their weekend trips without recharging, drive to work on Mondays and recharge there.

The respondents who could benefit from charging at work as addition to charging at home are the ones with a home to work distance between half the range of a BEV and the range of a BEV. When the trip to work is smaller than half the range of a BEV one could go to work and back to home without recharging. When distance would be larger than the range of a BEV the trip could not be made at all, regardless of the possibility to recharge at work. When we look at the home-to-work distance of the respondents in table 17 only 31 (7%) has a home to work trip that is longer than 50 km (half the range of a current BEV). For 4 of them the trip is longer than 100 km, they would not be able to reach their work. The 27 (6%) who would be able to make their home-work and work-home trips when they could recharge at work only benefit when they make no other trips that are longer than 100 km.

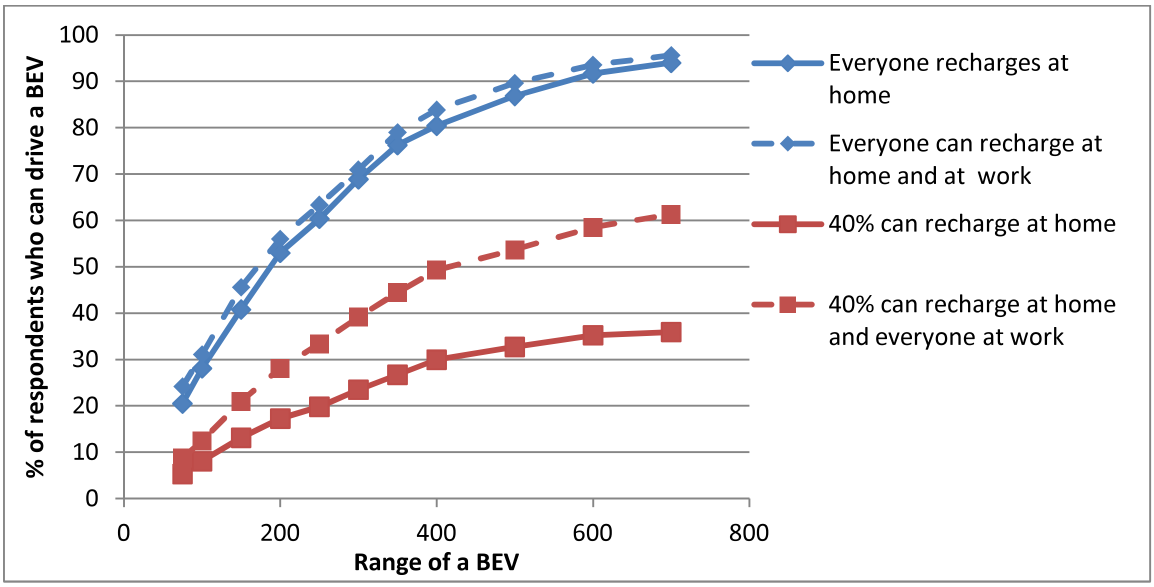


Figure 14: Effect of recharging a BEV at different locations

Home-work distance	# of respondents	% of respondents
no work trips	115	26,5
0 - 37,5 km	264	60,8
>37,5 km	55	12,7
>50 km	31	7,1
>75 km	11	2,5
>100 km	4	0,9

Table 17: Distance from home to work for different respondents

Improvements

In this part we look at the effects of improvements of charging on the road and fast recharging. The results are presented as effect of the improvement on the scenarios 1-3 from the previous paragraphs.

Charging on the road

An improvement is the possibility to charge along the road during a long trip. As mentioned before recharging takes some time. This means it is unlikely that people want to use this possibility very often. Figure 16 shows what the effect would be on the scenarios 1-3 when people can recharge their vehicle also once in the four week period, half way their longest trip.

Figure 16 shows that the effect is significant for every scenario and shows a small peak for vehicles with a range of 150 km. When the range of the BEV is lower many people would make too many trips that are longer than the range; one time recharging on the road is not enough to make all trips by BEV. When a BEV has a range above 150 km the effect becomes smaller because more trips can be made by only recharging at home or at work, recharging on the road is not necessary anymore for many respondents.

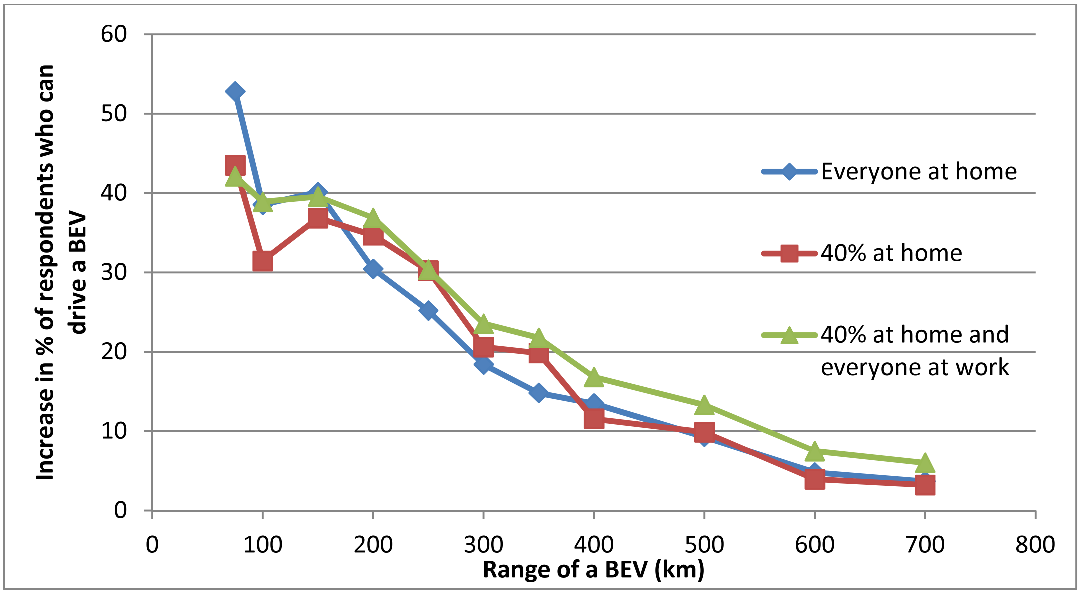


Figure 15: Effect of recharging on the road on the scenarios 1-3.

Improvements, Recharge speed

Recharging a BEV takes much more time than refueling a normal car. This part looks at the effect of charge speed on the possibility to make a trip with a BEV. Recharging happens most of the time at home or at work For the cases where recharging happens on the road it is hard to determine the effect. BEV-owners have to interrupt their trip and wait for the vehicle to recharge; the need for fast recharging on the road is therefore high. The need for fast recharging at home or at work is less clear. When a vehicle is charged overnight at home, normal recharge speed is fast enough for a range up to 200 km; that would take 12 hours to recharge from empty to full. For a BEV with a longer range the recharge time could be the bottleneck in events were the driver would drive distances that are close to the range for two days in a row. At work there is possibly less time to recharge since a normal working day is eight hours. For recharging during the day and maybe at night, it might help to recharge the battery to a higher level in a shorter time.

Figure 17 shows the effect of fast charging at home and at work addition to scenarios 1-3. It shows that there is an effect, but very small and always less than 10% on the different scenarios. The peak at 100 km for scenario 2 where 40% can recharge at home is due to the small sample, in absolute numbers it adds three people to the 38 who can drive a BEV and recharge at home. Only for BEVs with a range equal or larger than 500 km for the people who could charge at work there is a significant effect. For a BEV with a range smaller than 150 km it is likely that the recharge time is fast enough to fully recharge the battery. A larger battery means it takes more time to recharge the battery with the same speed, which explains the effect of fast charging for larger batteries. When respondents have the possibility to recharge at home the effect becomes smaller. This means that fast recharging at home has almost no effect and fast charging at work only for the respondents who cannot recharge at home and have a BEV with a range above 400 km.

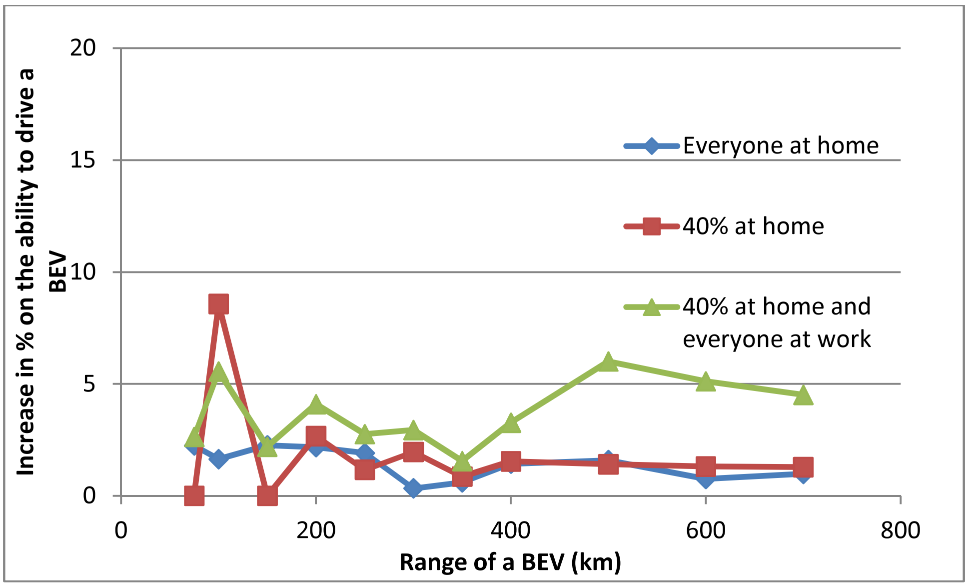


Figure 16: increase in potential to scenarios 1-3 of charging twice as fast at home and at work

Adaptations

Respondents who could make all their trips with a BEV can still experience problems with an occasional long trip. Other respondents may make only one trip in four weeks that is too long, or they are not long enough at home to recharge the battery enough. This part looks at the incidents that respondents have in four weeks and whether or not adaptations by respondents can help to prevent the incidents.

An incident is when the battery is empty during one of the trips in the four week period. At that moment the battery is instantly recharged and the respondent continues the trip. When the battery becomes empty again within the four weeks it is marked as a second incident and the battery is recharged again and the process is repeated until the four weeks are over.

Figure 18 shows the percentage of respondents with one or more incidents when their BEV has a specific range and everyone can recharge at home. With an increasing range up to 200km there is a growing number of respondents with only one incident in four weeks. The cause of the incidents can be different, for some it may be a trip that is longer than the range for others a number of shorter trips with no possibility to recharge.

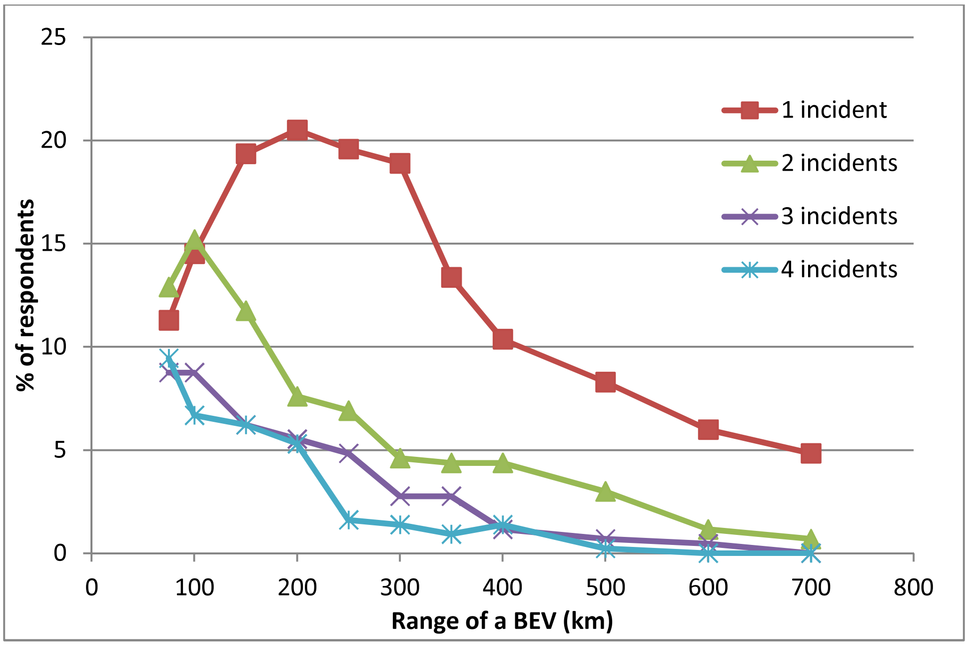


Figure 17: percentage of respondents that have one or more cases of an empty battery when they use a BEV to make their car trips.

So far it was assumed that respondents had the same travel behavior with a BEV as with a CEV. For many of them it meant that they were not able to make all their trips with a BEV. However it is not unlikely that some respondents have the possibility to make one of their car trips with another mode and as result they can make all their other car trips with a BEV. The adaptations that were modeled are one alternative for the longest trip in the registration period and an alternative for all short trips (<15km).

Alternative for a long trip

Besides the improvements to the BEV and the infrastructure it is also possible for drivers of a BEV to change their driving pattern slightly. So far we assumed that respondents kept to their driving pattern. The first adaptation is an alternative for a long trip. Because the range is often a problem finding an alternative for a long trip could mean that all other trips could be made with a BEV. An alternative could be public transport, carpooling, or a rental car. Research to the possibility and effect of public transport for each respondent individually was not possible. It is assumed that it had no further effect on other trips or activities.

Figure 18 shows the increase for each of the three scenarios when the longest trip is not made by car. There is no significant difference between the scenarios. All scenarios show a diminishing effect when the range of a BEV increases. The cause is that when a respondent has a BEV with a longer range there are fewer trips that cannot be made and the chance of making a trip longer than the range is smaller.

There is not much difference between an alternative for a long trip (figure 19) and recharging on the road (figure 16). Both scenarios mitigate the effect of one long trip.

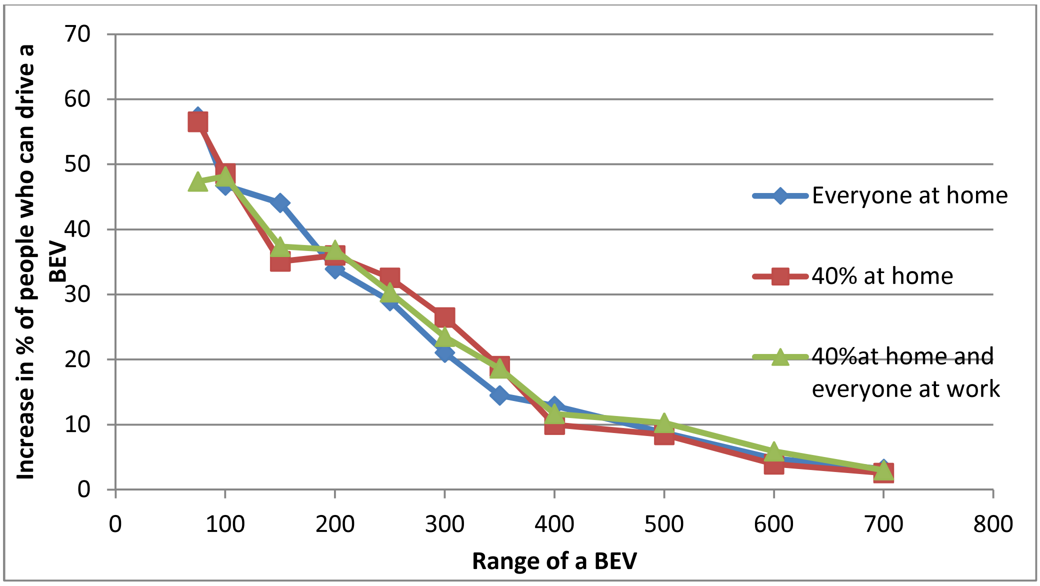


Figure 18: Effect of removing longest trip

Alternative for short trips

Another possibility for adaptations from drivers is to make short trips with another mode of transport like an (electric) bicycle. This seems not very effective because the long trips are considered problematic not the short trips. On the other hand are the most trips made by car trips shorter than 15km. Table 18 shows that almost 69% of all car trips are shorter than 15km. It is expected that it has only an effect when a significant number of short trips is made with another mode. Therefore figure 20 shows the effect on the scenarios 1-3 when all trips under 15km are made with another mode.

The effect of making all short trips with another mode of transport is high for BEVs with a short range. When the range increases to 150 kilometer the effect decreases fast. The cause for this is that with short ranges the combination of short trips can be a problem, the longer the range the smaller the influence of short trips combinations and a larger effect of a single long trip. Compared to the alternative for one long trip (figure 18) the effect is around half the effect for a BEV with a range of 100 km. For a range between 200 and 300 kilometer the effect of one long trip alternative is between 20 and 35% while the effect of all short trips alternative is maximum 15 % and mostly below 10%.

trip length (km)	# of trips	% of trips
total	30417	100
<15	20941	68,85
15-50	6946	22,84
50-100	1751	5,76
>75	1332	4,38
>100	779	2,56
>150	293	0,96
>200	79	0,26
>250	30	0,10
>300	17	0,06
>400	7	0,02

Table 18: occurrence of different trip lengths

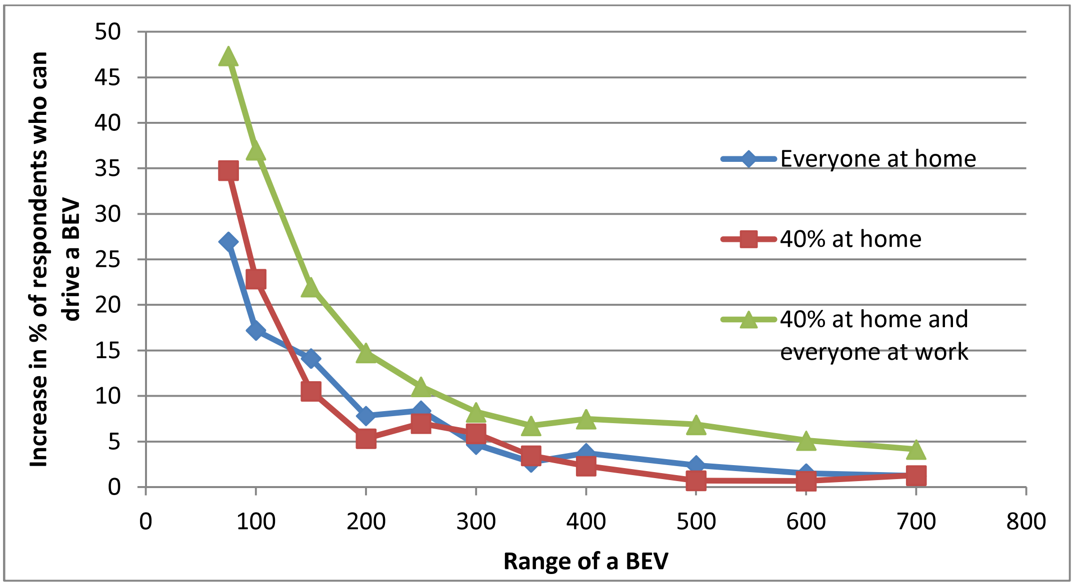


Figure 19: Effect of removing trips <15 km

7. Conclusion

This chapter describes the conclusion of the research performed. It will give an answer to the research question from chapter 2.6 and compare the results to other findings in literature. Lastly it will evaluate the implications of this research.

Research questions:

<u>What are the characteristics of a BEV and what are the current developments to range, recharge locations and recharge speed?</u>

Different BEVs come with different battery sizes and therefore have different ranges. The NEDC which is a European test to determine the characteristics of a BEV with standardized tests is not good at providing a realistic range. Research by Geringer & Tober,(2012) provides a more realistic range. Currently that range is for most BEVs 100 km. The decrease in price of Lithium-ion batteries will lead to batteries with a larger capacity in the future which is currently visible in the Tesla BEVs.

There is a wide range of standards of recharge facilities. Tesla, Nissan, Renault and BMW have different plugs for different current (AC and DC). European and national government are making steps towards standardization but it required another plug (Combo) and Tesla is still building its own recharge stations along the road while other companies are doing the same. This makes it complicated for people with a BEV to determine where they can recharge and at which speed. The situation at home is in the Netherlands quite clear, a 240 V 16 A outlet is standard and it is capable of recharging a BEV without much adaptation.

<u>To what extent is two week data good enough to describe travel behavior compared to four week data?</u>

According to Pasaoglu et al., (2013) one week data is required for this kind of data analysis. When two week data is compared to four week data it shows significant changes to the number of respondents that is able to make all their trips with a BEV. One cause for this is respondents who make an occasional long trip that is not captured in two week data but does show up in the four week data. The implication is that the respondent can drive a BEV according to two week data but cannot drive a BEV in four week data. Furthermore, four week data provides the opportunity to model the effect of smaller adaptations. One adaptation in four weeks is different from one adaptation in two weeks, this analysis is only possible with four week data. A longer registration period has the opportunity to model even smaller changes but is also more expensive to carry out. With a longer registration period the single long trip can be regarded as an incidental trip like a holiday and there are other ways like a questionnaire to evaluate whether or not respondents accept certain alternatives.

<u>To what extent can respondents make all their personal car trips with a current BEV?</u>

When in a realistic scenario 40% has the opportunity to recharge at home and use a BEV with a range of 100 km, 8% of all respondents can use a BEV for all their trips. When everyone can recharge at home this increases to 28%. There are BEVs with a larger range like Tesla with a range in practice of 300 km. This would increase the potential to 25% when 40% can recharge at home and 70% when everyone could recharge at home. Charging at home is necessary to drive a BEV however 7% may drive so few kilometers that they can do without charging at home but charge at work or at a public place once a month.

Charging at work as addition to charging at home has only a small effect because 87% of all respondents have a home work distance that is shorter than 37,5 km. It means that the distance is short enough to make home-work-home trips without recharging. Respondents that do not have the possibility to recharge at home can sometimes use a BEV for all their trips when they can recharge at work. That group increases when the range of a BEV increases.

What is the effect of improvements of BEV infrastructure on the possibility to make all personal trips with a BEV?

Charging along the road could definitely help drivers to make their trips. It increases the potential between 30% and 40% for a BEV with a range of 100 kilometer when respondents charged along the road one a month during their longest trip. The effect of charging along the road decreases when the range of a BEV increases. This makes it harder for investors in public charging to determine how long their stations will be profitable.

Fast charging will help along the road since it isn't the planned destination for a trip but only delay for drivers. Fast charging at home has almost no effect. It seems that overnight charging is long enough even for BEVs with higher ranges. Fast charging at work has a small effect on BEVs with a long range but probably only for people who cannot recharge at home.

What is the effect of adaptations by respondents on the possibility to make all personal trips with a BEV?

For a BEV with a range of 100km almost 50% more respondents can make their remaining with a BEV when they have an alternative for their longest trip. This effect remains at or above 30% for BEVs with a range below 300 km. This applies to all scenarios with different recharge possibilities.

69% of all car trips are shorter than 15 kilometer. When respondents use an alternative mode for these short trips (<15km) it increases the number of respondents who can use a BEV for their remaining trips with 25% for a BEV with a range of 100 km. The effect decreases fast for BEvs with a longer range; it has an effect of less than 10% with BEVs with a range of 300 km.

Results compared with literature

Two other studies looked at the possibility of drivers to make their trips with a BEV. German researchers (Weiss et al., 2013) from the Karlsruhe Institute for Technology (KIT) used different data sets to determine the daily distance respondents drove for a year in Germany. They found that 13% never drove more than 100 km a day and should be able to use a BEV for their trips. 16% needed to have 1 to 4 adaptations per year. They assumed that everyone could recharge at home. This analysis concluded that in 4 weeks when every respondent could recharge at home with a BEV range of 100 kilometers 28% can use a BEV for all their trips. The advantage of this study is that it has a more detailed data for four weeks but there is a chance that an occasional long trip like a holiday is not captured in the four week data. The less detailed data from KIT does incorporate the occasional long trip and the number of respondents that need between 0 and 4 occasional long trips a year they found is 31%.

With the remark that it looks at two different countries with different data and assumptions when a respondent recharges at home the results are almost the same. It would mean that four week data is good to capture the regular trips.

van den Brink et al., (2011) researched the possibility of one car households to make their trips with a BEV in the Netherlands with 8 week data from the 1980s. It is not clear what information they used to select the 40% that could recharge at home. The results from their research and this research are compared in table 19.

Range of BEV (km)	% that can recharge at home	% of households that can make all their trips (van den Brink et al., 2011)	% of respondents that can make all their trips (this research)
75	100	15	20
75	40	5	8
150	100	47	40
150	40	19	12
300	100	83	70
300	40	33	22

Table 19: Comparison of results between van den Brink et al. (2011) and this research

The differences are that they looked at trips from one car households while this research looked at personal trips. The result is that van den Brink et al. has a lower percentage with a BEV range of 75 km but a higher percentage with a BEV range of 150 and 300 km. A part of the difference can be explained by the difference between one car households and individuals in travel behavior. Households are likely to have more trips because more than one person can use the car compared to the trips of an individual person. On the other hand the average yearly kilometers driven as car driver have increased by 50% since the 1980s. How these numbers exactly influence the results is not clear since they would have the opposite effect. An analysis with households would likely lead to a smaller percentage of BEV suitable respondents but data from the 1980s would led to a larger percentage because the total driven distance is shorter.

Implications

The results of this research show that the market for BEV is still small. It confirms the theory that people who are able to drive a BEV have a smaller chance to be able to recharge at home. The cause is that people who live in high dense urban areas drive fewer kilometers but often to not have the space to recharge at home.

This research also found that recharging on the road is a difficult business case. When BEVs have larger batteries fewer drivers will need to recharge on the road because the range of their BEV is sufficient to make most of their trips. The exact effect is hard to estimate because it is also expected that more people will buy an use a BEV when the range increases. Furthermore larger batteries can charge more electricity which is good for owners of public charging stations.

When BEV manufacturers provide and promote alternatives for the occasional long trips the group of potential customers will increase because there is a large group that had only a few incidents in the registration period.

8. Discussion

This research has some limitations. Because of the characteristics of the data the focus of this research was individual respondents. Trip data on household level would provide a better view on the usage of a vehicle. A car can often be used by all household members with a driver's license. The effect would be that that a vehicle made more kilometers with data on household level than with data on an individual level. Household information could also provide information about a second car when it is distinguished in the data. When a household has a BEV as first car and a CEV as second car the CEV would be a good alternative when the trip cannot be made with a BEV. These analyzes are not possible with only individual data.

The MMP data does not have information about the home address of respondents. To determine who is able to recharge at home the household income and the urban density of the home address was used. The percentage that could recharge at home was based on the research of van den Brink et al. (2011). They looked at the housing situation in the Netherlands and distinguished types of houses (free standing, semi detached, farms, etc.). Every housing type was given a recharge chance and based on the number of each housing type they determined that 40% of the Dutch households could recharge at home. The combination of income and urban density fitted to the 40% of van den Brink et al. is not very precise. It has implications for the conclusion that people who drive more than average have a higher chance of being able to recharge at home. It is in line with the expectation from literature but not an exact figure due to the home recharge estimations.

Due to the privacy of the respondents was not possible to check whether or not a respondent had the opportunity to use public transport as alternative for a long trip. The conclusion from this research is that one alternative for a long trip is enough for a large group to be able to make all other car trips by BEV. Whether the respondent has the possibility to make the trip with public transport remains uncertain.

Trips that are often seen as problematic to make with a BEV are holiday trips. The possibilities to recharge along the road increase but a BEV would have to stop a few times to recharge and that will take some time. It is not necessary to have holiday trip data to estimate the effect because it depends on the individual what his alternatives are. Holiday trips are not made very often and a questionnaire could provide information if people would accept to recharge a few times along the road. Maybe they rather have a CEV alternative, perhaps provided by the BEV manufacturer like BMW already does.

This research did not look at the purchase of a BEV. Some researchers assume that people who drive fewer kilometers than average drives are not the ones that buy new cars. The secondhand market is still small for BEVs and there is a risk that second hand buyers have to replace the battery because the capacity decreases over the years. This is of course also a problem for people who sell their BEV second hand because it will decrease its value. Some manufacturers let BEV buyers rent the battery to take away the risk for the consumer.

9. Recommendations

This research is only a small part in the field of BEV-research. In this report are the effects described of improvements of a BEV on the share of respondents that can make all their car trips with a BEV. This report also describes the effect of small adaptations by respondents on the possibility to make all their car trips with a BEV. The question remains who is prepared to make adaptations and do people in reality see the possibilities of a BEV? Being able to make all car trips with a BEV is only one part, considering to buy a BEV is another part that is important to research. Are drivers that are able to use a BEV for their trips prepared to buy a BEV and what are they arguments pro and contra?

Another question is what kind of improvements do people prefer? What is the tradeoff between 50 km range increase and one adaptation per month for example.

To make a better estimation about how many cars can be replaced it is worthwhile to look at household trips and if households with more than one vehicle are able to replace one of them for a BEV. It would also be interesting to look at the alternatives people have in reality when a trip is too long. This research showed that making one adaptation in four weeks has a large effect on the share of respondents who are than able to make their other car trips with a BEV. But do people have an alternative? And is that for their longest trip or is it easier to use another mode for short trips?

Incidental trips or holiday trips remain uncertain. Questionnaires and focus group results show that the ability of making holiday trips with a car or pulling a caravan is important, even if it happens only once a year. The possibility to rent a CEV may be provided by the BEV manufacturer can be a solution. On the other hand the demand for a CEV rental car may not be evenly distributed over a year. In the summer holiday de demand will be higher than in January, can a BEV manufacturer still provide a CEV during that period?

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Appendix A

Figure 1 shows the average speed of each distance class. The upper value of each class is next to the average speed and the lower value is the number above the upper value. The table is made from the car trips in the MMP that have a origin, destination and travel time. The table is used to determine the average speed of a missing trip. The distance is obtained from the destination of the previous trip and the origin of the next trip. The distance is used to determine what the average speed of the missing trip is and from there the travel time is determined.

Distance class upper bound	Average speed of the distance class
0	0
1	5
2	12
3	22
4	27
5	29
6	30
7	36
8	32.5000
10	38
15	42
20	48
30	52
40	62
50	66
60	72
70	74
80	79.5000
90	78
100	82
120	86
150	91
200	91
350	109

Figure 1: Average speed per distance class

Appendix B

Figure 2 shows the distant distribution of the four week data and the missing trips from the four week data. It has roughly the same pattern as the two week data on page 29.

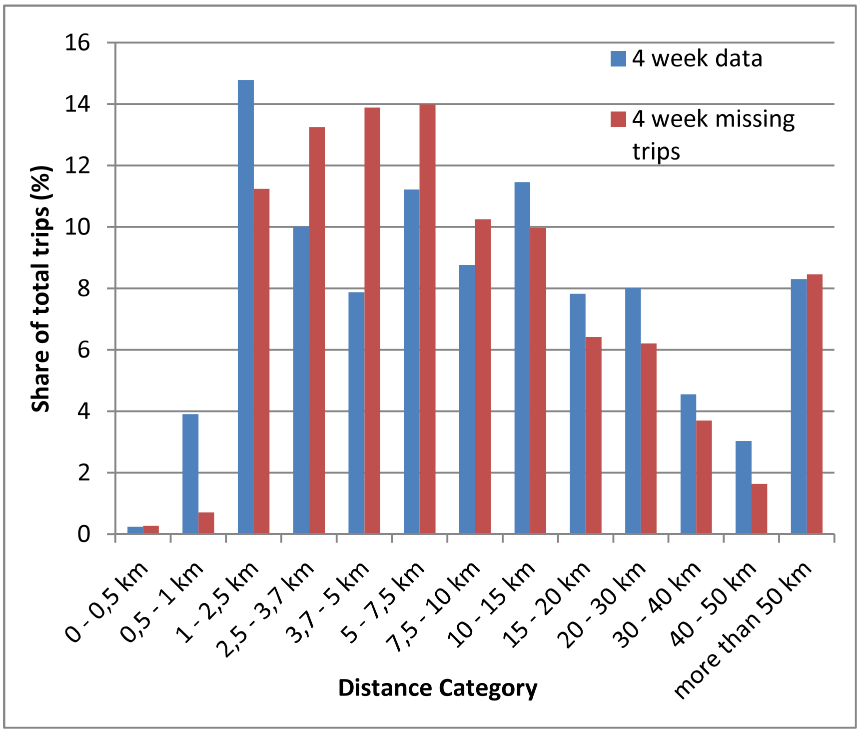

Figure 2: distribution of distance categories in the 4 week data without the missing trips and the 4 week missing trips

Appendix C

Figure 3 shows the time at which respondents of the mobile mobility panel arrive at and leave from work. The time most people arrive at work is between 7 and 9 in the morning. People leave mainly between 4 and 6 in the afternoon.

Hour of the day	People arriving at work	People leaving work
0	2	3
1	3	1
2	5	1
3	2	1
4	4	2
5	23	4
6	72	9
7	335	8
8	358	8
9	136	19
10	46	33
11	31	37
12	55	81
13	81	42
14	69	62
15	47	124
16	16	211
17	14	268
18	16	76
19	18	27
20	8	17
21	13	29
22	6	24
23	7	24

Figure 3: Working hours of respondents

Appendix D

Figure 4 describes the average distance that is traveled for different ravel time intervals. The upper value of the time interval is next to the average distance and the lower bound is the value above the upper bound. The figure is used to determine the distance that is traveled when an origin or destination or both zip codes are missing from the data. In that case the travel time of a trip is used to determine the distance of the trip.

Time in minutes	Average distance in km
0	0
1	0.9800
2	1.6600
3	2.5400
4	3.8400
5	4.3500
6	6
7	6.8300
8	7.1700
10	8.5300
15	10.4500
20	16.7700
30	21.3700
40	32.4600
50	41.1700
60	53.6200
70	62.3900
80	71.9100
90	81.6800
100	92.4200
120	108.4400
150	122.4300
200	166.8600
350	207.4600

Figure 4: average distance per time class