



Understanding processes and travel behaviour changes connected to electric vehicle adoption

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Abstract

The use of electric vehicles (EVs) has the potential to increase the sustainability of the transport system, especially in case of unchanged or decreased car use, eco-driving and charging during hours of low electricity demand in case of an electricity generation mix with a large share of renewable energy sources. However, EVs still use much energy and EV-use does not solve problems regarding accessibility, social equity, traffic safety and has only a limited beneficial effect on liveability (e.g. through decreased noise).

The focus of this study is on the process of the transition from conventional vehicle use to electric vehicle use. Economic and socio-psychological theories have been used in order to get more insight into the motivations for people to start using EVs, the process of EV-adoption and travel behaviour, as well as the interaction between car users, the electric vehicle and policy measures. The aim is to better understand the ongoing transition process to EV-use and the potential behavioural implications of this transition.

This study is largely based on a two-wave survey that has been deployed among active car drivers in the metropolitan area of Stockholm, Sweden. In total, 294 respondents have participated in the first wave of the study, while 269 respondents have completed all waves. Besides this survey, one paper of this study is based on another two-wave survey that has been deployed among people renting a car on the island of Gotland, Sweden. In total, 158 respondents have participated in the first wave of this study, while 69 respondents have completed all waves.

Electric vehicle adoption implies a considerable initial investment and a behavioural change because of range limitations. Therefore, the change towards electric vehicle use could be considered as a process rather than an event. Using the Transtheoretical Model of Change (Paper 1), it has been

found that certain socio-economical, behavioural and socio-psychological determinants are correlated with being in a more advanced stage-of-change. Knowledge levels and self-efficacy for electric vehicle use are increasing from stage to stage. The level of response efficacy increases from stage to stage for the non-EV users, but is slightly lower for the group of EV-users that might have a more realistic view of the range and energy use of EVs. There is no direct effect between environmental awareness and stage-of-change, but there is an indirect effect through goal intention to decrease one's CO₂-emissions.

In this study (Paper 2), it has also been found that the respondents using EVs make more trips on average and that they also use the car for a larger share of their total distance travelled. The differences in the number of trips and modal share of the car are statistically significant even after controlling for socio-economic variables, which might imply a rebound effect. The risk for a rebound effect is also explainable because of the fact that the marginal cost of EV-use is considerably lower than the marginal cost of conventional car use. Another potential reason for increased car use is the extremely good image that the EV has. It has been found that the EV is perceived to be more environmentally friendly than conventional cars, which was expected, but also more environmentally friendly than public transport modes.

Policy makers in many countries provide incentives to make EVs more attractive. Using a stated choice experiment (Paper 3), the effects of several potential policy incentives on EV-adoption has been investigated in this study. Both purchase-based benefits and use-based benefits have a significant positive effect on EV-adoption. Purchase-based benefits intervene with the high investment costs of EVs, while use-based benefits intervene with the already low marginal costs of EV-use. Use-benefits, incentives that are given to EV-users in some countries, such as free parking or access to bus lanes, further decreases the marginal cost of EV-use, increasing the risk for rebound effects. On the other hand, the study shows

that use-based benefits do have a large effect on EV-adoption. Including the stage-of-change of the respondents, EV-adoption rates increase in the stated choice experiment for people in more advanced stages-of-change. However, the price-sensitivity decreases for people in more advanced stages-of-change. Also people with a high self-efficacy and response efficacy are more likely to adopt EVs. Seen from a policy perspective, it might be more efficient to provide use-benefits rather than purchase based benefits. However, there is a risk for a rebound effect because of the decrease of the already low marginal costs of EV-use.

Because current electric vehicle users are a small part of the population, future EV-use has also been investigated using stated adaptation methods. Two stated adaptation experiments have been carried out: one concentrating on travel patterns and one on charging patterns.

The first stated adaptation experiment (Paper 4/5) was carried out among all respondents, taking the initial travel patterns registered in a one-day travel diary as a starting point. The respondents got scenarios with a kilometre budget that was based on the travel distances during the one-day travel diary day. In case of shortage of range or perceived range limitations, different behavioural alterations have been selected, among trip cancellation, destination change and change of travel mode towards alternative travel modes were most frequently selected. Non-mandatory activities were more likely to be cancelled, as well as trips for which the public transport alternative is rather unattractive in terms of travel time and number of transfers. In case of abundant range and an electricity cost that is five times lower than the fuel cost per kilometre, a non-negligible number of additional trips has been reported, predominantly leisure trips and shopping trips. Besides, for a number of trips, a modal shift “towards the car” has been registered for a non-negligible number of trips, the majority of them being trips to work or school which are often carried out during rush

hour. So, the existence of a rebound effect under the condition of abundant range has been confirmed.

Charging behaviour has a significant effect on the sustainability of EV-use. The timing of charging events can increase peaks in electricity demand or fill the valleys of electricity demand. In this study (Paper 6), it has been investigated when people prefer to start a four-hour charging event and how temporal price differentiation influences these preferences. Based on this study, it has been found that the afternoon rush hour is by far the most preferred charging time if the price for charging events is fixed throughout the day. However, temporal price differentiation significantly affects preferred charging time. Both the existence and degree of temporal price differentiation matters: different behavioural responses were observed using two different price differentiation schemes: a high level of price differentiation causes the majority of charging events to move to night time.

In the final paper of this thesis (Paper 7), it has been investigated whether electric vehicle rental affects the process of electric vehicle adoption as described in Paper 1. Using a before-after study, the long-term effects of renting an EV on the Swedish island of Gotland has been investigated. The results of this study show that EV-rental does not seem to significantly affect the stage-of-change towards EV-adoption. However, there seems to be a selection effect: the EV is more likely to be selected as a rental car if the rental guest is in a more advanced stage-of-change. Besides, the driving patterns of EV rental cars do not differ much from those of ICEV rental cars, which is an indicator of EVs being adequate for EV-rental in Gotland.

Sammanfattning

Genom storskalig användning av elbilar istället för bränslebilar kan transportsystemets hållbarhet ökas, framförallt ifall bilanvändandet inte ändras eller minskas, ifall bilen laddas under perioder med låg energiefterfrågan, och ifall elen genereras med förnybara energikällor. Elbilar använder dock fortfarande mycket energi det hjälper inte att köra elbil för att lösa problem kring trängsel, social jämlikhet, trafiksäkerhet. Elbilsanvändandet har också bara en begränsad positiv effekt på dräglighet (t ex på grund av minskat buller).

Den här studien fokuserar på förändringsprocessen från att använda vanliga bilar till att använda elbilar. Ekonomiska och socialpsykologiska teorier har använts för att få mer insikter i motivationer för att börja använda elbilar, förändringsprocessen mot elbilsanvändandet och resvanor, och interaktionen mellan bilister, elbilar och policy-åtgärder som kan vidtas. Syftet är att bättre förstå förändringsprocessen mot elbilsacceptans och möjliga beteendemässiga konsekvenser av den här förändringen.

Den här studien har baserats på en enkätundersökning som har genomförts bland aktiva bilförare i Storstockholm. Enkätundersökningen bestod av olika delar för att kunna undersöka förändringsprocessen utifrån olika perspektiv. Totalt har 294 respondenter deltagit i första delen av undersökningen, medan 269 respondenter har deltagit i hela enkätundersökningen. Förutom denna enkätundersökning har en annan tvåstegs enkätundersökning utförts bland människor som hyr en bil på Gotland. Totalt har 158 respondenter deltagit i första delen av undersökningen, medan 69 respondenter har deltagit i hela enkätundersökningen (både före- och eftermätningen).

Elbilsacceptans medför en betydlig investering och potentiella beteendemässiga förändringar på grund av räckviddsbegränsningar. Därför

kan förändringen mot elbilsanvändandet anses som en process snarare än som en händelse. Transteoretiska förändringsmodellen, som analyserar beteendeförändring som en process som består av fem olika faser, har använts (Paper 1), och det har kommit fram att vissa socio ekonomiska, beteendemässiga och socio psykologiska faktorer är korrelerade med att vara längre framme i förändringsprocessen. Kunskapsnivån och self-efficacy för elbilsanvändandet ökar från fas till fas. Genomsnittsvärdet för response efficacy ökar från fas till fas för icke-elbilsanvändare, men är något mindre för gruppen elbilsanvändare som kan ha en mer realistisk bild av elbilens räckvidd och energiförbrukning. Ingen direkt effekt mellan miljömedvetenhet och fas i förändringsprocessen har hittats, men det finns en indirekt effekt genom respondenternas avsikt att minska sina personliga CO₂-utsläpp.

I den här studien (Paper 2) har det också kommit fram att respondenterna som i nuläget använder elbilar brukar göra fler resor och att de också använder bilen för en större del av sitt totala reseavstånd. Skillnaderna i antalet förflyttningar och bilens andel i färdmedelfördelningen är statistiskt signifikanta, även efter att ha kontrollerat för socio-ekonomiska variabler, vilket kan innebära en rebound effekt. Risken för en rebound effekt kan också förklaras på grund av att marginalkostnader för att använda elbil är betydligt lägre än marginalkostnader för att använda vanliga bilar. En annan möjlig grund för ökad bilanvändning är den extremt positiva bilden som elbilen har med hänsyn till miljövänlighet. Det har kommit fram att elbilen anses vara miljövänligare än vanliga bilar, vilket var förväntat, men också miljövänligare än kollektivtrafik.

Beslutsfattare i många länder erbjuder incitament för att göra elbilar attraktivare. Ett stated choice experiment har genomförts (Paper 3), där effekterna av olika möjliga policy incitament på elbilsacceptans har undersökts. Både incitament vid elbilköp och incitament för befintliga elbilsägare när de använder bilen har en signifikant och positiv effekt på

elbilsacceptans. Incitament vid elbilsköp påverkar de höga investeringskostnaderna av elbilar, medan incitament vid elbilsanvändande påverkar de redan låga marginalkostnader av elbilsanvändande. Ändå har sistnämnda incitament en betydlig effekt på elbilsacceptans. Också effekten av respondenternas fas i förändringsprocessen har tagits med, och elbilsacceptans blir ständigt högre för de som är i mer avancerade faser i förändringsprocessen. Å andra sidan minskar respondenternas priskänslighet när de kommer till mer avancerade faser i förändringsprocessen. Också människor med en hög nivå av self-efficacy och response efficacy är mer benägna att byta till elbil. Sett från ett policy perspektiv, det kan vara mer hänsynsmässigt att erbjuda incitament för befintliga elbilsförare snarare än att erbjuda incitament vid elbilsköp. Det finns dock i så fall en risk för en rebound effekt på grund av att de redan låga marginalkostnaderna minskas ytterligare.

Därför att nuvarande elbilsanvändare utgör en väldigt liten del av populationen har framtida elbilsanvändning också utforskats genom stated adaptation metoder. Två stated adaptation experiment har utförts. Ett experiment som handlar om resemonster har genomförts och ett som handlar om laddningsmonster.

Det första stated adaptation experimentet (Paper 4/5) utfördes med alla respondenter. Deras nuvarande resemonster, som hade registrerats i en resedagbok under en dag, togs som utgångspunkt. Respondenterna fick scenarion med en viss kilometerbudget som baserats på totalt reseavstånd med bil för registreringsdagen. Ifall kilometerbudgeten inte räckte till eller på grund av t ex räckviddsångest valdes olika beteendeförändringar; bland annat ställdes resor in, ändrades destinationer för resor och valdes andra färdmedel. Man var mest benägen att ställa in icke-obligatoriska aktiviteter såsom shopping eller att besöka släkt och vänner. Dessutom var man mer benägen att ställa in resor där alternativet med kollektivtrafik är relativt ointressant på grund av lång restid eller många byten. Ifall

kilometerbudgeten räcker till och det finns en stor buffert, med bakgrundinformationen att elkostnaden är fem gånger så låg som bensinkostnaden per mil, har ett icke-försumbart antal extra resor registrerats, framförallt fritidsresor och shoppingresor. Dessutom har man angett att vilja ändra färdmedel från alternativa färdmedel till bil för ett icke-försumbart antal resor. De flesta av de resorna är resor till och från arbetet/skolan, som ofta utförs i rusningstid. En rebound effekt har bekräftats i den här studien i dessa fall att elbilens räckvidd räcker till.

Laddningsbeteende har en signifikant effekt på hur hållbar elbilsanvändning är. Laddtillfällen kan öka trycket på elsystemet under rusningstid eller fylla dalar när efterfrågan är låg. I den här studien (Paper 6) har det utforskats när på dagen man önskar att påbörja ett laddtillfälle på fyra timmar och hur tidsmässig prisdifferentiering påverkar ens preferenser. Den här studien visar att kvällsrusningstimmen är mest populär när det gäller starttid för laddtillfällen, om elbilsladdning kostar lika mycket dygnet runt. Tidsmässig prisdifferentiering har dock en betydlig påverkan på den föredragna tidpunkten för laddtillfällen. Både att det finns prisdifferentiering och hur hög prisdifferentieringen är verkar spela en roll: olika beteendeförändringar registrerades under två olika prisdifferentieringsplaner. En hög grad av prisdifferentiering orsakade en överflyttning av flertalet av laddtillfällen till nattid.

I sista artikeln för den här avhandlingen (Paper 7) har det utforskats om elbilshyra påverkar processen gentemot elbilsacceptans, som har beskrivits i Paper 1. En före-efter studie har gjorts för att utforska långsiktiga effekter av elbilshyra på Gotland. Studiens resultat visar att elbilshyra inte visar sig att påverka processen mot elbilsacceptans. Det verkar dock finnas en självvalseffekt: elbilen har större sannolikhet att väljas ifall hyresgästen redan är i ett längre steg i förändringsprocessen. Dessutom visar körmönstren av elhyrbilar inte skilja sig från körmönstren av vanliga

hyrbilar, vilket är en indikator för att elbilar verkar vara lämpliga hyrbilar på Gotland.

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1 Introduction

1.1 Current transport systems

Transport systems provide accessibility to people in order to perform activities that are located at different locations. Therefore, the demand for transport is mostly a derived demand (Ortúzar & Willumsen, 2011) enabling people to carry out activities. Because of ever faster transport options and the increase of personal motorized vehicle possession (Dargay et al., 2007) people are able to travel further and to reach destinations that could not be reached before. Cities have expanded and people working in a city do not necessarily have to live in that city, but can commute and choose from a wider range of potential housing locations.

However, the last decades it has become more and more apparent that the current transport systems cause problems that are not negligible and should be dealt with. Traffic congestion, transport poverty, traffic accidents, decreased liveability and local and global emissions of exhaust gases are major problems that are directly connected to our current transport system (e.g. OECD, 1996). All over the world, policy makers aim to improve the sustainability of the transport system or to reach a more sustainable mobility.

1.2 Sustainable Mobility Framework

Sustainable Mobility is a widely used term. A classical definition of sustainability by Brundtland is a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). Sustainable Development and also Sustainable Transport is often considered of having three dimensions: an economic, an ecologic and a social (equity) dimension (Campbell, 1996 & Litman and Burwell, 2006).

The economic dimension is translated in the need for a good accessibility. As traffic congestion decreases accessibility, it is necessary to either increase capacity or to manage the use of the current capacity that is available. Also the provision of new alternative transport options or improvement of existing alternative transport options can increase accessibility. Transportation demand management or Mobility Management as a set of strategies to increase the efficiency of the transport system has been embraced as an alternative to the “predict-and-provide” approach that was used before (Goodwin, 1999; Meyer, 1999).

The ecological dimension deals with the resources used and pollution that are inherently connected with the current transport system. The transport sector uses a large amount of fossil fuels and, while other sectors in the economy have decreased their dependence on fossil fuels, the trend of fossil fuel usage for the transport sector is increasing after a temporal decrease in the years 2000 (European Environmental Agency, 2017). Exhaust gases of power plants but most of all tail-pipe emissions contribute to severe health problems, primarily in dense urban areas with many residents and much traffic, where exposure is high (Health Effects Institute, 2010).

The social dimension deals with the humans that either make use of the transport system or are affected by this transport system. Social equity deals with the degree in which everyone has a certain level of accessibility (vertical equity) given everyone’s needs and limitations, as well as the degree in which people with a similar need have a similar level of accessibility (horizontal equity; Litman, 2017). Most importantly, it is crucial that nobody suffers from transport poverty, where the possibilities to carry out activities are severely restricted for a certain part of the population. Traffic safety is another important issue: although in most European countries the situation has improved the last decades, traffic accidents still cost more than one million lives per year globally (WHO, 2013), and a much larger number

of people get severely injured every year. Driving behaviour or the human factor is the main cause of most traffic accidents (Evans, 2004).

Banister (2008) identified four action strategies that improve the sustainability of the transport system:

1. “Reduce the need to travel or substitution of travelling by for example ICT solutions”
2. “Land-use policy measures that reduce the distance”
3. “Transport policy measures that induce a modal shift from the car to alternative means of transport”
4. “Technological innovations that increase the efficiency of the current transport system and standards/measures that regulate the step-wise change towards more sustainable transport systems”

Also, Banister argued for the importance of communicating with different stakeholders and make them be committed to make the transport system more sustainable (Banister, 2008).

1.3 Electric vehicles and sustainable mobility

A technological innovation that can increase the efficiency of the transport system is the electric vehicle, which will be the main topic of this thesis. Electric vehicles (EVs) are vehicles that are exclusively or partially driven by an electric engine. In this thesis, a distinction has been made between a Battery Electric Vehicle (BEV), that only uses electric power, and a Plug-in Hybrid Electric Vehicle (PHEV) that has both an electric engine and an internal combustion engine that can be used when the battery is empty or in case additional power is needed for the drivetrain (Wikström, 2015). HEVs (Hybrid Electric Vehicles such as Toyota Prius) are not considered in this study because of their short electric range and the fact that these vehicles cannot be plugged in. The range of EVs is limited and varies with weather circumstances, driving circumstances and driving behaviour.

Electric vehicles are not new. They have been around for at least as long as ICEVs. However, when the internal combustion engines became better, ICEVs became much more popular than EVs. In several moments of time, EV-adoption was promoted (Høyer, 2008). Important occasions were the publication of the book “The Limits of Growth” by the Club of Rome (Meadows, 1972), oil crises in the 1970’s and 1980’s (Høyer, 2008) and the air pollution issues that resulted in low emission vehicle policies in California in the United States of America (Collantes and Sperling, 2008). After that, interest in EVs sank again, although Toyota made a breakthrough by launching a hybrid electric vehicle, the Toyota Prius, in 1997, which became very popular in the years 2000 (Ottman et al., 2006). The latest years, more and more electric vehicles are produced and sold. Tesla only produces EVs, but most major car manufacturers currently produce or plan to produce either PHEVs or BEVs. Research about EV-adoption has more or less followed this trend, with relatively few studies in the 1990’s and early 2000’s, and a huge increase since 2013.

Electric vehicles have the possibility to improve the sustainability of the transport system, but they are not likely to be a “panacea” solving all problems that are inherent to the current transport system. Accessibility is not likely to improve by replacing conventional vehicles by electric vehicles, *ceteris paribus*. A traffic jam composed of electric vehicles is likely to give a similar time burden to the economy as a traffic jam composed of conventional vehicles, as the time lost in traffic is probably similar. Also regarding traffic safety, there are no indications that electric vehicles as such have any beneficial effect (Verheijen and Jabben, 2010). However, noise levels are likely to go down in case electric vehicles are mass adopted (Verheijen and Jabben, 2010), as well as local air pollution in dense urban areas (e.g. Ferrero et al., 2016), and under certain circumstances can the electric vehicle be considered as an improvement seen from an ecological perspective (Jochem et al., 2016). In the ideal case, the electricity that is needed to charge electric vehicles comes from renewable energy sources

such as wind and water power. However, in a country where the electricity generation mix mainly consists of coal powered power plants, the environmental benefits of EV-use are considerably less (Faria et al., 2013). Also driving style (Knowles et al., 2012) and auxiliary energy users such as heating and air-conditioning systems (Mebarki et al., 2013) have a significant impact on the environmental effects of EV-use, as these factors have a major impact on the electricity use.

As electric vehicles still use a considerable amount of energy, people changing to electric vehicles would in an ideal world striving for a sustainable transport system also drive fewer kilometres and use alternative transport modes such as public transport modes or active modes for part of their current trips, following Banisters action strategies (Banister, 2008). However, if electric vehicles would have a detrimental effect on somebody's mobility level, making it more difficult to carry out the activities that someone wants to do, electric vehicles cannot really be considered to attribute to sustainable mobility neither.

This thesis investigates behavioural changes connected to electric vehicle adoption. These changes are both related to the adoption itself and to the travel behaviour consequences of electric vehicle adoption. The rest of this thesis framework is structured as follows: In Chapter 2, Theories of behavioural change are discussed. In Chapter 3, an Overview of research about electric vehicle Adoption is presented. In Chapter 4, an Overview of research about electric vehicle Use is presented. The Research Questions for this thesis are discussed in Chapter 5, followed by the Methodology in Chapter 6 and the data collection in Chapter 7. In Chapter 8, the Results of the different papers that are included in this thesis are shortly discussed, followed by the Conclusions and Policy Recommendations in Chapter 9. In Chapter 10, a short discussion of possible future research directions is made.

2 Behavioural change

The transition from conventional vehicle to an electric vehicle entails a behavioural change. In this chapter, transport research dealing with behavioural change will be discussed in general. In Chapter 3, research regarding Electric vehicle adoption will be discussed, while in Chapter 4, research regarding Electric vehicle use will be discussed.

Traditionally, behaviours within the transport research field have mainly been studied using the framework of utility maximization (e.g. Ben-Akiva, 1974) to explain people's behaviour. Decision makers face a choice set consisting of a certain number of alternatives, out of which they make a choice for one of those alternatives giving them the highest utility. Which the elements giving utility are, is hidden. The only thing we can observe is the choices that people make.

The utility maximizing framework has been used as the standard methodology used of transport studies considering behaviour and behavioural change. However, in recent decades, the picture of humans having perfect information and always making "rational" choices has been found. The notion of bounded rationality has been introduced, and studies have shown that many people use "satisficing" strategies that do not necessarily select the "best" alternative, but at least an alternative that is "good enough" (Wilkinson and Klaes, 2012). It has also been widely observed that people form habits when repeatedly behaving in a certain way and in a stable context and also the influence of others on someone's behaviour has been found important (e.g. Verplanken and Wood, 2006). Also in transport research, there was a need for studying behaviour and behavioural change from different perspectives and making use of different disciplines. In recent years, it has become more common to incorporate research methods from social psychology in transport research, both regarding driver behaviour and traffic safety research and regarding travel

behaviour and mobility management (for an overview article see Steg, 2007).

Within the fields of sociology and socio-psychology, numerous theories and models have been developed to get more insight into behavioural change. Many of those models have originally been developed to study health-related behaviour, but the last years, an increasing number of studies is using these models in the transport sector as well. In the following subsections, a selection of relevant theories on the individual level and on the environmental level is discussed.

2.1 Individual level

2.1.1 Determinants of behavioural change

A relatively old socio-psychological model that explains behavioural changes is the Health Belief Model (Rosenstock, 1974). This model comprises the following constructs:

- Perceived susceptibility or the perceived risk for a certain consequence of the problem behaviour
- Perceived severity of the consequence of the problem behaviour
- Perceived benefits of actions to reduce the threat of the consequence of the problem behaviour
- Perceived barriers of the new behaviour
- Cues to action that provide people a reason to rethink their current behaviour patterns and possibly change their behaviour

The Protection Motivation Theory (Rogers, 1975) is closely related to the Health Belief Model. This model postulates that the intention to change behaviour is composed of an appraisal of the threats of the current behaviour and a coping appraisal of the new behaviour. The threat appraisal consists of the perceived risk of negative consequences of the behaviour and

of severity of these consequences. The coping appraisal on the other hand consists of self-efficacy and response efficacy. Self-efficacy can be defined as the perceived ability to perform the new behaviour (Bandura, 1978), while response efficacy is the perceived beneficial effect of the new behaviour to decrease the risk and severity of the consequences of the old behaviour. High risk and severe consequences, as well as a high level of self-efficacy and response efficacy, increase someone's intention to change behaviour.

One of the most frequently used theories of behavioural change is the Theory of Planned Behaviour (Ajzen, 1991). This theory can be considered as an expectancy-value theory (Bartholomew et al., 2011) and postulates that intention for certain behaviour is determined by the constructs attitudes, social norms and perceived behavioural control. An attitude is an evaluation of an attitude object, in the case of the Theory of Planned Behaviour an evaluation of certain behaviour. Different from the Protection Motivation Theory, also subjective norms play a role. Subjective norms can be considered as perceived social expectations. The third construct is perceived behavioural control, which is about the ability to perform certain behaviour (Ajzen, 1991) and which is closely related to the construct self-efficacy. Attitudes, subjective norms and perceived behavioural control determine the intention of certain behaviour, which in its turn determines whether someone will actually perform the behaviour. Moreover, there is also a direct link between perceived behavioural control and behaviour. Regardless of the intentions towards certain behaviour, if the perceived behavioural control is low, the behaviour is not likely to occur.

The difference between the Protection Motivation Theory or the Theory of Planned Behaviour and another theory that is called the Norm Activation Theory (Schwartz, 1977) is that the latter theory deals with behaviour that might be good for the decision maker himself, but might have external effects on others. Changing behaviour in that case can be seen as altruistic behaviour. The Norm Activation Theory has also been used in

environmental psychology. According to this theory, the decision maker must first be aware of the problems that are caused by certain behaviour. Then, the decision maker must feel responsible for these problems and develop a personal norm that conflicts with the problem behaviour. First then, the norm is activated and behavioural change is likely to occur. A few studies have integrated the Norm Activation Theory with the Theory of Planned Behaviour (e.g. Bamberg and Möser, 2007) and concluded that the link between personal norm and behaviour is mediated by intentions.

The strength of a theory such as TPB is the fact that it takes motivation, as well as ability and social influences into account. A weakness is that it is a static and rather deterministic theory. It does not take into consideration the fact that behavioural changes occur over time and that intentions may be formed over time.

2.1.2 Processes of behavioural change

Models that consider behavioural change as a process rather than an event are called stage-models, and generally they consider behavioural change as a process consisting of several sequential stages.

A relatively old stage-model that originates from marketing research is the Diffusion of Innovations Theory (Rogers, 1962). This theory has as main constructs four stages, five categories of adopters and five main factors that influence adoption. People that adopt an innovation go through four different stages: “Awareness”, “Decision to use”, “Initial use to test” and “Continued use” of the innovation. Adopters of innovation differ in how fast they adopt a new technology. Innovators are the first ones to adopt innovations and are willing to take financial risks. After the innovators, the early adopters will adopt the innovation, and they will be a role model for the early majority, late majority and laggards that follow them.

Five main factors that influence adoption according to the Diffusion of Innovations Theory are the relative advantage of the innovation compared to the products previously available, compatibility of the new products with the values, experiences and needs of the adopter, complexity of the use of the new product, “trialability” of the product before the commitment of the purchase has to be done and observability or the degree in which the innovation provides tangible results.

A stage-model that has been widely used for studies and interventions is the Transtheoretical Model of Change (TTM; Prochaska, 1991). The origin of the model is from health psychology, but later on, this model has been used in different fields of behavioural change, such as the transport research field, as well. The Transtheoretical Model of Change has as its main constructs five stages-of-change, processes of change, decisional balance and self-efficacy. Because of the combination of constructs from different other socio-psychological theories, the model is called a “transtheoretical” model. In some of the studies within this thesis, the Transtheoretical Model of Change was used.

The process of behavioural change is started if the current behaviour is perceived to be sub-optimal, for whatever reason. People changing their behaviour are assumed to go through five different stages:

1. *Pre-contemplation* where one is not considering changing behaviour and often not much aware of the negative sides of one’s current behaviour
2. *Contemplation* where one is considering changing behaviour, but on a rather abstract level
3. *Preparation* where one is planning to change behaviour on a more concrete level
4. *Action* where one is actually changing behaviour

5. *Maintenance* where one is getting used to the new behaviour after experience with this new behaviour

When changing behaviour, ten processes of change have been identified as playing a role:

1. *Consciousness raising* or increased awareness of the problem behaviour
2. *Dramatic relief* or experiencing feelings about the consequences of the problem behaviour and possible solutions
3. *Environmental Re-evaluation* or reflecting what the effects of the problem behaviour on the physical and social environment are
4. *Self-Re-evaluation*, where the individual re-evaluates his values with respect to the problem behaviour
5. *Self-Liberation* or the choice and commitment to alter the problem behaviour
6. *Helping relationships* or the support of others to change the problem behaviour,
7. *Counterconditioning* or thinking about alternative behaviour and positive attitudes towards that behaviour
8. *Reinforcement Management* or rewarding oneself or being rewarded when making behavioural changes
9. *Stimulus control* or the control about situations that might trigger the problem behaviour
10. *Social liberation* or the provision of alternative behaviour that is supported by society

In the different stages-of-change, different processes of change are usually emphasized. For example, “Consciousness raising” is considered an important process for people moving from the Pre-contemplation to the

Contemplation stage, while “Stimulus control” is more relevant for people that already started to change their behaviour and are in the Action stage.

The third construct of TTM, decisional balance, is the balance between the advantages (Pros) and the disadvantages (cons) of the new behaviour. Individuals that are moving along the stages are assumed to have a decisional balance that is more and more valuing the advantages of the new behaviour and the disadvantages of the current behaviour. This construct is closely related to the construct attitude in e.g. the Theory of Planned Behaviour.

The fourth construct of TTM is self-efficacy according to Banduras definition. Self-efficacy is considered very important when studying behavioural change, because confidence to perform the new behaviour is an important potentially hindering factor for behavioural change. Especially during the Contemplation and Preparation stages, self-efficacy is considered important, because the behavioural change gets more concrete and preparing actions are needed to go from ambition to reality.

There are many similarities between the Theory of Planned Behaviour and the Transtheoretical Model of Change relating to the constructs that are considered important. However, the large difference is the process-approach of TTM. People are assumed to go through a process of change, and before they have internalized behavioural change, they can relapse. Acknowledging this learning process can help to get more insight into behavioural change.

There are some other stage models, such as the Precaution Adoption Process Model (Weinstein, 1988) that consists of seven stages: Unaware of issue, Unengaged by issue, Undecided about acting, Decided not to act or Decided to act, Acting and Maintenance. The names of five of the stages remind much about TTM, however Weinstein et al. (2008) emphasize that

the stages are distinguished by mental state rather than by the time left to action as in TTM.

Bamberg (2013) developed another stage model, called “A stage model of self-regulated behavioural change”. This model consists of four stages: Predecision, Preaction, Action and Postaction, and the borders of each stage are goal intention, behavioural intention and implementation intention. Within each stage, processes consist of constructs of the Norm Activation Model (Predecision stage), Theory of Planned Behaviour (Preaction stage) and the theory of self-efficacy (Bandura, 1978; Action and Postaction stages). Also this model has many similarities with TTM.

Overall, many theories have been developed to study behavioural change. Most of those theories are not completely different from each other, but take earlier theories as a starting point, after which new constructs have been added. An example is the Motivation-Opportunities-Abilities model (Ölander and Thøgersen, 1995) that consists of a combination of the Theory of Planned Behaviour and the constructs opportunity and ability as a refinement of the construct Perceived Behavioural Control. Some other models are a combination of two models that have existed before.

2.2 Environmental level

Individuals must change their behaviour themselves. However, they are affected by other individuals, as well as by organizations and society in a variety of ways. Interpersonal relationships provoke social norms that have an influence on the decisions made by individuals, as discussed in the Theory of Planned Behaviour. Systems theory or just systems thinking is built on the consideration that humans are complex adaptive systems. Humans are part of groups (for example a group of friends), communities (for example a group of people sharing a certain religion) and societies (for example the society of the country an individual is living in). All of these

levels are in their turn also complex adaptive systems (Bartholomew et al., 2011) influencing people's behaviour and behavioural change.

One theory that takes both the individual level and the environmental level into consideration is the COM-B System (Michie et al., 2011). This acronym stands for Capability, Opportunity, Motivation, which are considered to be the necessary aspects for a change in Behaviour. The role of interventions is depicted in the so called Behavioural Change Wheel, that surrounds Capability, Opportunity and Motivation with nine potential intervention functions (Education, Persuasion, Incentivisation, Coercion, Training, Restriction, Environmental Restructuring, Modelling and Enablement), and seven policy categories (Communication/Marketing, Guidelines, Fiscal, Regulation, Environmental/Social Planning and Service Provision) that can help to support people in their process of behavioural change.

2.3 Discussion

Although there are differences between each of the socio-psychological models that have been discussed above, there are large similarities and a major trend of contemporary research is to combine models in order to take all aspects that are known to be relevant into account. Awareness, feeling of personal responsibility, response efficacy, motivation, social support and societal support enabling behavioural change and self-efficacy are main constructs that arise in several of the models. The context in which these models have been developed varies from health psychology to environmental psychology to marketing. However, the identified main drivers of behavioural change are most often very similar.

3 Electric vehicle adoption

3.1 Introduction

Electric vehicle adoption implies in many cases a transition from an internal combustion engine vehicle (ICEV) to an electric vehicle (EV). From a

societal point of view, driving a car that uses fossil fuels can be considered as behaviour causing societal problems, mostly because of the fact that many people drive a car that uses fossil fuels (Greenhouse gas emissions leading to global warming, local air pollution with adverse health effects). However, it is important to mention that when it comes to alternative behaviour aimed at decreasing the societal problems connected to the use of ICEVs, there are several options out of which EV-use is only one option. Driving to destinations that are closer by, stop making trips, choosing different travel modes or even buying a smaller car are all potential new behaviours with a possible beneficial effect, decreasing the problems related to current use of ICEVs and contributing to a more sustainable transport system. On the other hand, these actions may compromise people's mobility level.

From an individual point of view, a person driving an ICEV does generally not cause severe problems for him- or herself, which distinguishes the problem of car driving from problem behaviours like smoking or drinking too much alcohol. From this point of view, the behaviour is only considered as problematic in case this person is aware of the consequences of exhaust gas emissions and in case the person feels personally responsible for those consequences. Driving can be seen as a social dilemma (Van Lange et al., 2013): it has considerable personal advantages to drive an ICEV, but the (negative) consequences have to be borne by everyone.

There are two major concerns that are often mentioned to hamper mass deployment of electric vehicles. Firstly, because of the fact that EVs need an expensive battery package, these vehicles are often more expensive than comparable conventional vehicles. Carley et al. (2013) investigated factors influencing electric vehicle adoption and found that the purchase price is the most dominant disadvantage hampering EV adoption. Secondly, electric vehicles have a limited range and they need to be charged. PHEVs can drive further after the battery is depleted, thereby changing into a normal but rather heavy Hybrid Electric Vehicle (HEV), but BEVs cannot drive any

longer than the range of the battery package without getting charged. Because of the fear of not have enough range for a certain trip of tour, so called range anxiety (e.g. Franke and Krems, 2013), people may not use their entire range in order to always have a certain safety margin. The range of an EV minus safety margin might or might not be enough to cover the distances that somebody currently drives by conventional car. In case the range does not suffice or charging is an issue, changing to electric vehicle cannot only be considered as a purchase but also as requiring certain travel behaviour changes.

Many stakeholders have to be taken into consideration when planning a large scale adoption of electric vehicles. In this study, most emphasis is on private car drivers and the government as a facilitator of EV-adoption. Car drivers can make the decision to adopt EVs or to not adopt them, and after adopting the EV, they will use the vehicle in a certain way. For commercial users, similar decisions have to be made. However, their circumstances differ both regarding use intensity and the way decisions are made. Governments on different levels (local/regional/country-level) aim to reach targets regarding air quality and GHG emissions. They can facilitate EV-adoption by providing charging facilities in public space. Moreover, they can stimulate EV-adoption by providing policy incentives for those who purchase an EV. Because all of those policy-measures have a certain cost, governments must seek public acceptability for EV-policy. Citizens must accept the fact that tax money is used for facilitating and stimulating EV-adoption. Other stakeholders that may influence EV-adoption are car manufacturers, that through price, performance and design characteristics can make EVs more suitable or more attractive to buy. Employers, housing cooperatives, hotel owners and other stakeholders that receive many car users that are parked for a long time can facilitate EV-adoption by providing charging stations. Finally, electricity suppliers must be able to deliver the electricity to charge EVs, which is a challenge both on a local and on a global level.

3.2 Pioneering studies EVs

A pioneer study regarding EV-adoption was made by Kurani et al. (1994), in which the compatibility of the EV in a household with more than one car was studied using what was called “Purchase Intentions and Range Estimation Games (PIREG)”, based on travel diaries. It was considered that EVs have an insufficient range to be considered as the main vehicle or only vehicle in the household, but for so called “hybrid households” having more than one vehicle in the household, there is a viable market for EVs with a range of 60-100 miles. Kurani et al. (1996) also concluded that there is a discrepancy between the results of attitude studies, travel behaviour analyses and stated preference studies. Attitudes towards EVs are rather positive and based on the travel behaviour analyses, the EV would fit with the travel patterns in hybrid households, but stated preference studies predict a very low probability of choosing an electric vehicle. This might be caused by the fact that these vehicles were rather unknown in that time.

Most studies that have been done after can be categorized as either grounded theory studies, studies from the framework of utility maximization, studies following a socio-psychological framework or scenario studies in which people are assumed to change to an EV automatically in case this car is compatible with one’s travel patterns. In the next sub-sections, a short overview of these types of studies is given.

3.3 Grounded theory studies

Grounded theory means that a certain study will not use any existing theoretical framework, but the data are the starting point of the study, out of which patterns, concepts and relations between constructs will arise. As EV-adoption research is a rather new research field, grounded theory has been a rather important method. Examples of studies using grounded theory are Caperello and Kurani (2011) and Graham-Rowe et al. (2012), studying respondents that tried out electric vehicles (PHEVs or BEVs) for a certain

period of time, followed by in-depth interviews. Certain insights that came out from these studies were that the environmental benefits of electric vehicles were not as highly valued as whether EVs can meet personal mobility needs. Moreover, it was expected that electric vehicles get better, which is a hampering factor for electric vehicle adoption (Graham-Rohe et al., 2012).

3.4 Random utility theory studies

As described in 2.1, random utility theory states that choices for a certain product or service are made based on the attributes of these products or services (e.g. McFadden, 1974). Generally, the alternative with the highest utility will be chosen. However, due to several reasons, the choices made are of a probabilistic rather than a deterministic nature.

In many studies investigating electric vehicle adoption, the random utility theory has been used as a framework. For example, Axsen and Kurani (2013) studied the willingness to adopt HEVs, PHEVs and BEVs and concluded that only a few per cent of potential car buyers would consider buying a BEV. Major concerns were both range limitations and the price premium that has to be paid for BEVs. Hidrue et al. (2011) studied the Willingness-to-Pay for electric vehicles and concluded that consumers were willing to pay up to \$16,000 extra for an EV if it had the most desirable attributes in terms of range, performance and comfort. Similarly, Dimitropoulos et al. (2013) and Hackbarth and Madlener (2013) studied the value of additional kilometres of driving range, resulting in a value of \$70 per mile, respectively €16-33 per kilometre. Also for charging time, that is seen as a disutility, several studies have investigated the Willingness-to-Pay for a decrease of charging time (e.g. Hidrue et al., 2011; Hackbarth and Madlener, 2013 & Dimitropoulos et al., 2013).

A major influence is expected from the number of cars in the household (Kurani et al., 1996; Jensen et al., 2013; Karlsson, 2017). Due to the

possibility of car swapping, the limited driving range is significantly less disadvantageous for multi-car households according to these studies.

Rezvani et al. (2015) reviewed a number of studies concerning electric vehicle adoption. In most studies, indeed cost and range were important issues. However, also other technical factors such as performance, safety and carbon emissions, contextual factors such as policy incentives and charging infrastructure and individual and social factors such as lifestyle, environmental awareness, political beliefs, education, gender, age and income played an important role. It also concluded that certain groups are more likely to adopt EVs, such as younger or middle aged people, higher educated people, people that are inclined to adopt new technology in an early stage and people that expect increase in petrol prices in the next five years.

3.5 Studies using Total Cost of Ownership

In order to have insight in the cost structure of EV-ownership and use over a longer period, the so-called Total Cost of Ownership (TCO) has been used. This computation seeks to make clear how the cost structure of ICEVs differs from that of EVs. EVs are more expensive to buy, but less expensive to use due to lower expected marginal costs. After a certain period of time, the lower usage price compensates the purchase premium and EVs can become cost-competitive. For example, Hagman et al. (2016) investigated the Total Cost of Ownership of an EV and an ICEV over an ownership period of three years and concluded that the EV has a lower TCO, if vehicle purchase and registration tax subsidies are incorporated. Other studies show mixed results: in some calculations, EVs have a higher TCO (e.g. Prud'homme and Koning, 2012; Tseng et al., 2013). In an analysis by Al-Alawi and Bradley (2013), however, PHEVs have a lower TCO than ICEVs. As battery costs are declining (Nykvist and Nilsson, 2015b), it is expected that EVs will become more cost competitive. Besides the (expected) value of the TCO, the TCO needs to be used in order to affect electric vehicle

adoption decisions. Dumortier et al. (2015) studied the effects of providing consumers with Total Cost of Ownership calculations. They concluded that information about five-year fuel savings does not have an effect on the ranking of EVs compared to ICEVs, but that providing estimates of the Total Cost of Ownership does increase the likelihood to choose for the EV. Due to the dynamic nature of EV purchase cost and EV adoption, Coffman et al. (2017) recommend on-going studies on both the development of the cost of EVs and their uptake.

3.6 Studies using socio-psychological constructs

Schuitema et al. (2013) indicated that besides instrumental attributes, also hedonic and symbolic attributes play an important role. In several studies, socio-psychological theories such as the Theory of Planned Behaviour (e.g. in Egbue and Long, 2012), Protection Motivation Theory (Bockarjova and Steg, 2014) and the Value-Belief-Norm theory (Lane and Potter, 2007) have been used as a theoretical framework to study electric vehicle adoption. These theories have often been developed for other types of behaviour such as health-related behaviour and general pro-environmental behaviour, as described in Section 2.

3.7 Studies using environmental factors

Although most studies about EV-adoption focus on the individual, there are a few studies that focus on other ecological levels, such as Bakker et al. (2014) reasoning about the interests of different stakeholders in the process of electric vehicle adoption, and a multi-level study by Nykvist and Nilsson (2015a), investigating the reasons why Stockholm is not a leader in EV-adoption. Lack of local initiatives, so that very few people are aware of and have knowledge about EVs was one of the reasons given. Another reason was the ambivalent attitude of policy makers around EVs and EV-policy.

As EV adoption is surrounded by policy incentives in many countries, some studies have included policy measures and their influence on EV adoption

(Lieven, 2015; Helveston et al., 2015; Lin and Greene, 2012; Zhang et al., 2011). Studies focussing on different policy incentives in order to make the effects of them comparable are rare. An exception is Lieven (2015) that made use of stated preference data in different countries.

3.8 EV compatibility

Several studies have made estimations about how much range is needed to accommodate the daily travel needs of different percentages of the current car market. Studies concentrating on EV compatibility (e.g. Pearre et al., 2011; Skippon and Garwood, 2011) investigating the travel patterns of current ICEV users in order to obtain an image of which vehicles could be replaced by an electric vehicle, (tacitly) assuming that travel behaviour is not likely to change as an effect of electric vehicle adoption. The idea of car users whose travel patterns are EV compatible being very likely to adopt an electric vehicle has not been confirmed by EV deployment.

3.9 Research gaps

Even though more and more electric vehicle brands are on the market, the uptake of EVs is still slow and varies considerably from country to country. The hypothesis that EVs will be taken up automatically by everyone for whom they are range-compatible has not been confirmed. Also the current insights into electric vehicle adoption have not led to a major increase of electric vehicle deployment.

As changing to an EV requires a large investment and considerable behavioural changes, it is believed that more insight into EV-adoption can be gained by describing EV-adoption as a process rather than an event, making use of the Transtheoretical Model of Change as well as the Protection Motivation Theory. These theories were described in 2.1.2. The Transtheoretical Model of Change has been selected as a stage model that has been used in many studies related to behavioural change, but not before in the case of electric vehicle adoption. Besides, it is unknown whether

interventions such as temporarily trying out to drive an electric vehicle can forward people to more advanced stages-of-change.

Regarding the effect of policy incentives, it is mostly unknown in which degree policy measures have an influence on electric vehicle adoption and how different policy incentives are valued compared to one another. Moreover, it is unknown whether the effect of policy incentives differs for different people, as a result of e.g. socio-economic characteristics or intrinsic motivation to adopt an electric vehicle.

4 Electric vehicle use

For car drivers, changing from driving a conventional car to driving an EV implies a significant behavioural change. BEVs have to be charged and PHEVs should be charged as well to make most use of their beneficial characteristics. To charge an electric vehicle from empty to full takes significantly more time than to refuel a conventional car. Range limitations might make electric vehicles less suitable for all trips that are currently made by conventional cars, so driving an EV might also imply a change in travel patterns, which might affect people's mobility level. On the other hand, the cost structure of electric vehicle use, with high upfront investment costs and relatively low marginal costs, might also affect travel patterns.

4.1 Change of travel patterns

Electric vehicles have a certain battery capacity and a certain marginal usage cost. The range of an EV significantly influences the possibilities of driving. In case of driving a BEV, a longer driving distance is not possible without a charging event, while in case of driving a PHEV, a longer driving distance means that the vehicle starts using fossil fuel and the vehicle transforms to a rather heavy hybrid electric vehicle.

The limited range of electric vehicles and the fact that charging events take time and charging stations are not everywhere available might cause travel patterns to change. For example, the number of car trips and distance of those car trips might change. On the other hand, it has been found in earlier compatibility studies that current BEVs have a sufficient range for the lion's share of daily trips made (Pearre et al., 2011; Skippon and Garwood, 2011). Within the range limitations of EVs and PHEVs, the marginal cost of car use is comparatively low in comparison with the marginal cost of using a conventional car. The reason for this is the fact that electricity costs less per kilometre than fossil fuels such as petrol and diesel (e.g. in Sweden, see Hagman et al., 2016). Moreover, electric vehicles are more efficient, using less units of energy per kilometre than ICEVs (MacKay, 2009). As the marginal costs of car use decreases, *ceteris paribus*, it is expected that the attractiveness of using the car instead of alternative means of transport increases. Another potential effect is making new trips that have not been made previously, as there might be a latent demand for car trips that were not previously made due to the marginal cost of ICEV use.

As range and marginal cost have opposite effects on electric vehicle use, the question is whether the "average EV user" will drive more or less on a yearly basis. This is an important question, because it determines the external effects that a large scale deployment of EVs is going to have. A car user that switches to an EV and increases his or her car use will have less environmental gains than a car user that switches to an EV and decreases his or her car use. As described in 1.3, the external costs of electric vehicle use are still relatively high. A rebound effect would take place in case vehicle kilometres travelled increases as an effect of electric vehicle adoption. In Small and Van Dender (2005), the existence of a rebound effect of 5-20 per cent was found among people adopting fuel efficient vehicles. Whitehead et al. (2015) also found a rebound effect comparing owners of energy efficient vehicles, be it at a lower level of 3.1 per cent. In this study, Propensity Score Matching was used. The difference between the marginal cost of electric

vehicle usage and conventional vehicle usage is even more pronounced than that of fuel efficient vehicles in general, which entails that a larger rebound effect could occur, disregarding the opposite effect that range limitations might have.

The general approach to predict electric vehicle use is to assume people not to change their travel behaviour when switching to an electric vehicle, unless they are forced to by range limitations. As mentioned in 3.8, Pearre et al. (2011) studied the minimum range that should be available in order to match the EV with people's current travel patterns. Several studies also reason that EV adoption will take place when people are actually able to use it for almost all of their trips. Studies like Tamor et al. (2013) assume that there is a threshold frequency of need for alternative transportation. If the current travel needs of someone surpasses this threshold and alternative transportation has to be selected, then the EV is assumed to not be a viable option. Weiss et al. (2017) investigated the effects of a fleet of electric vehicles using a microscopic travel demand model. Based on both adoption and usage models, taking battery depletion into account, they found that electric vehicle users drive significantly fewer kilometres than internal combustion engine vehicle users. However, this result might be influenced by self-selection effects (people driving less are more likely to adopt an electric vehicle in the model framework), assumptions of the future range of electric vehicles and the fact that only at home charging was allowed.

To the contrary of studies stating or assuming travel patterns to be similar or car driving to decrease, several observational studies found opposite results. In a small scale study, Rolim et al. (2012) found that EV-users change their driving behaviour towards more eco-driving, but on the other hand; they travel more than their non EV-using counterparts. Franke et al. (2012) observed after a field trial that car trips among the participants of the field trial constituted a larger part of the total number of trips than prior to the field trial, which is an indication for electric vehicle adoption to

influence modal split. Similarly, Hjorthol (2013) found that electric vehicle users are less likely to use public transport. Figenbaum et al. (2014) investigated total driving distance with the help of changes of the “insured driving length”. Based on these figures, it was shown that in Norway, 18 per cent of the EV-owners increased driving length after adopting the EV, whereas 6 per cent decreased driving length. The majority (62%) did not change driving length, while for 14 per cent no conclusions can be drawn due to the fact that the values are unknown, mostly because the vehicle was bought less than one year ago.

The question of the severity of changes in someone’s mobility level is a non-trivial question. If people cancel trips, they cannot carry out certain activities, having a negative effect on their mobility level. Besides trip cancellation, for example, if a car driver decides to go for shopping in shopping mall A instead of in shopping mall B because of range limitations, this might also be seen as a decrease in his or her mobility level. Based on the fact that shopping mall B was the initial choice, it can be assumed that a shopping trip to shopping mall B has a higher utility than a shopping trip to shopping mall A. In which degree this change of shopping location limits someone’s mobility level is another question. Still another question is to which degree people know before deciding to adopt an EV for which activities they have to compromise their preferred travel and activity patterns because of range limitations, and whether current preferred activity and travel patterns are stable over time. More trips will increase someone’s mobility level, but on the other hand, a rebound effect would occur.

4.2 Charging behaviour

Besides travel behaviour, charging behaviour is another crucial factor influencing the sustainability of a large-scale transition to electro mobility. The type of charging (fast charging versus destination charging) plays a role, but also the timing of charging events. Charging events can increase peaks of electricity demand, but also be valley-filling in case most charging events

take place when total electricity demand is low. Large scale charging during peak hours has been associated with higher carbon content of electricity generation (e.g. Robinson et al., 2013; Foley et al., 2013 & Sohnen et al., 2015) and cost increases for local distribution networks (Ye et al., 2018).

Knowledge about current electric vehicle users' charging patterns is limited, but based on some studies (Robinson et al., 2013 & Morrissey et al., 2016) a tendency is shown for charging events to be likely to take place during electricity peak hours. In the current situation, this is not problematic due to the limited number of electric vehicles. However, when scaling up, peak hour charging might cause substantial economic and environmental costs. In order to decrease these costs, future electric vehicle users should be stimulated to charge their vehicle during non-peak hours. Foley et al. (2013), Knapen et al. (2012) and Morrissey et al. (2016) have stated that non-peak hour electric vehicle charging would be beneficial. Temporal price differentiation for electric vehicle charging events could be a policy measure that contributes to spreading out electricity demand over the day.

4.3 Research gaps

The fact that many EV-adoption studies assume that one will uptake EVs as soon as those vehicles are compatible with one's current travel behaviour is a clear indication that it is not generally assumed that travel behavioural changes are likely to occur as an effect of electric vehicle adoption. Also for effect studies, dealing with how much energy is needed for a large scale deployment of EVs, current travel behaviour is most often taken as a starting point. Very little research has been done on travel behaviour patterns of presumptive or current electric vehicle users. Weiss et al. (2017) suggested car trip chains of EV-users to be shorter, but this might be due to the input variables of the usage model. Several observational studies have pointed in the opposite direction.

Regarding charging behaviour, relatively little research has been done to investigate the behavioural responses to temporal price differentiation. In some agent based models, a behavioural response to temporal price differentiation is assumed (e.g. Knapen et al., 2012, Hu et al., 2016, Xydas et al., 2016), but these models do generally not take into consideration that different pricing schemes might cause different responses. Moreover, very little is known about the behavioural and socio-economic factors that influence people's likeliness to change preferred charging time.

In general, there seems to be a tendency to predict future travel behaviour and charging behaviour on the basis of current travel behaviour. More insight is needed into the mechanisms behind travel patterns of electric vehicle users, as well as their charging behaviour. Coping strategies connected to electric vehicle use and range limitations, as well as the effect of the lower marginal cost of EV use, have been given little attention until now.

5 Research Questions

The aim of this study is to get more insight into the adoption and use of electric vehicles. The focus of all studies is finding important mechanisms and a reflection on the effects and impacts of these mechanisms for policy making.

In previous studies, several factors influencing EV-adoption have been studied. However, because EV-adoption implies major behavioural changes, especially when adopting a BEV, EV-adoption is assumed to be a process rather than an event. The Transtheoretical Model of Change (e.g. Prochaska, 1991) considers behavioural change as a process consisting of five stages, from Pre-contemplation to Contemplation, Preparation, Action and Maintenance. The actual behavioural change is started in the Action stage. *The main research question of Paper 1 is which socio-economic,*

behavioural and socio-psychological constructs are related with being in a more or less advanced stage-of-change. The main research question of Paper 7 is whether electric vehicle rental has a significant influence on processes of change towards electric vehicle adoption.

Some main characteristics of EVs are a limited range, a high purchase price and a comparatively low running cost or marginal usage cost. As a result, within the range limitations of EVs, it is rather cheap to increase car use. *The main research question of Paper 2 is whether the travel behaviour patterns of EV-users differs from the travel behaviour patterns of conventional car users. The main research questions of Paper 4 are which behavioural alteration is likely to be selected under which circumstances in case of (perceived) range limitations, as well as whether additional trips are likely to be made in case of (perceived) abundant range.*

Policy incentives currently provided in many European countries can increase the attractiveness of electric vehicles. However, in most cases, these policy incentives are directed towards everyone instead of tailored towards different groups. *The main research question of Paper 3 is how effective and efficient different policy incentives to increase EV-adoption are, considering that people are in different stages-of-change and considering potentially influencing socio-cognitive factors.*

Different from the use of fossil fuels, electricity cannot be stored as easily and the timing of charging events is believed to make a difference in case of a large-scale deployment of EVs. *Therefore, the main research questions of Paper 6 are when current and presumptive electric vehicle users would prefer to charge their vehicle, as well as which influences temporal price differentiation has on the preferred charging time.*

	Electric vehicle adoption	Electric vehicle use
<i>User</i>	Paper 1, Paper 3 & Paper 7	Paper 2, Paper 4, Paper 5 & Paper 6
<i>Electric vehicle</i>	Paper 1, Paper 3, Paper 4 & Paper 7	Paper 2, Paper 3, Paper 4, Paper 5 & Paper 6
<i>Government</i>	Paper 3	Paper 6

Table 1: Focus of the papers

Table 1 gives an overview of which papers describe studies connected to electric vehicle adoption and which papers describe studies focussing on electric vehicle use. Besides, it shows whether the user, the electric vehicle and/or the government are focussed on. Papers 1, 3 and 7 are focusing on electric vehicle adoption, while the papers 2, 4, 5 and 6 focus on the use of electric vehicles and the specific characteristics of EVs that are connected with potentially different usage patterns. The interplay between the new technology (the EV), the user of potential user, and the government has been studied in the different papers. Moreover, Paper 3 discusses electric vehicle adoption, but also discusses the dilemma of cost effectiveness versus behavioural side effects of use-based incentives. Likewise, Paper 4 discusses electric vehicle use, but also discusses the fact of range limitations leading to decreased mobility, which is a major hampering factor for large-scale electric vehicle adoption. Policy measures play an important role in Paper 3 and Paper 6, even though all papers discuss policy implications. Paper 5 is a critical assessment of the research design and survey instrument that was used in Paper 4.

6 Methodology

6.1 Interdisciplinary approach

For this study, an interdisciplinary approach was used, combining engineering, travel behaviour, environmental science, transport economics, social psychology and energy systems. The aim is to get a deeper understanding of EV-adoption and EV-use by considering different perspectives from different disciplines. Although the electric vehicle itself is a technological innovation, it is part of a complex socio-technical system including many stakeholders that all have their own interests.

6.2 Socio-psychological theories

Two socio-psychological theories have been used as a framework to study electric vehicle adoption: Protection Motivation Theory and Transtheoretical Model of Change. In the following subsections, the use of these models in this study is described.

6.2.1 Protection Motivation Theory

The Protection Motivation Theory is a motivational socio-psychological theory. Initially, the theory was developed in order to study health-related behavioural changes, but it has also already been applied to electric vehicle adoption (Bockarjova and Steg, 2014). In that study, the authors operationalized the main constructs to be adapted to “slow-onset environmental risks” such as air pollution and global warming. Due to the fact that electric vehicle adoption requires behavioural adaptations, random utility models will not suffice to explain electric vehicle adoption (Bockarjova and Steg, 2014). Even though pro-environmental values can be included, it is important to incorporate the coping appraisal with the new behaviour. Main constructs of the Protection Motivation Theory are Threat Appraisal and Coping Appraisal. Threat appraisal means an appraisal of the risks and severity of the consequences of current behaviour, while the

Coping Appraisal deals with the response efficacy of the new behaviour and the self-efficacy of being able to perform the new behaviour. The constructs of the Protection Motivation Theory have been found to be significantly correlated with the intention to adopt electric vehicles (Bockarjova and Steg, 2014). This theory also reflects the motivation to start using electric vehicles because of environmental reasons, as opposed to because of instrumental, hedonic or symbolic reasons such as in Schuitema et al. (2013).

In this study, the constructs threat appraisal, self-efficacy and response efficacy have been conceptualized into seven point Likert-scale indicators.

6.2.2 Transtheoretical Model of Change

Electric vehicle use is considered to be a learning process that should already start before the actual adoption of an electric vehicle. Without being relatively certain that an electric vehicle would fit with someone's mobility patterns, it is hypothesized that electric vehicle adoption is unlikely to occur. In order to describe this learning process, the stage-model Transtheoretical Model of Change (TTM) has been selected. The Transtheoretical Model of Change consists of five sequential stages-of-change. These stages have been defined as follows:

1. Precontemplation – Not considering to change to electric vehicle use
2. Contemplation – considering to change to electric vehicle use
3. Preparation – planning to change to electric vehicle use in the coming six months
4. Action – having started to use an electric vehicle but not longer than six months
5. Maintenance – having more than six months of electric vehicle use experience

Constructs from this stage-model (processes of change and decisional balance) have been used to define indicators aiming to describe the process towards electric vehicle adoption. There are ten processes of change; most of them have been conceptualized into seven point Likert-scale indicators, some of them overlapping with indicators for the constructs in the Protection Motivation Theory. These processes concern Consciousness raising, Dramatic relief, Environmental reevaluation, Self-reevaluation, Self-liberation, Helping relationships, Counterconditioning, Reinforcement management and Social liberation. Some components, such as “stimulus control”, were considered to be less useful when applying the theory to electric vehicle adoption than for health-related behaviour such as smoking or drinking alcohol, so these processes have not been taken into consideration.

The decisional balance has been conceptualized into indicators concerning instrumental, hedonic and symbolic attributes of electric vehicles that can be considered as positive (pros) or negative (cons) attributes. Lastly, self-efficacy has been conceptualized into indicators concerning fear for limited mobility because of changing to EV-use and whether the EV fits into the current daily travel patterns of someone.

6.2.3 Use of Socio-Psychological Theories in the thesis

The Protection Motivation Theory and the Transtheoretical Model of Change have been used in Paper 1, Paper 3 and Paper 7. Paper 1 is fairly descriptive, and in the modelling part, the stage-of-change (TTM) is used as the dependent variable, which makes the stages-of-change to a way of clustering respondents. Constructs of the Protection Motivation Theory, as well as other behavioural and socio-economic variables have been used as independent variables. For example, it has been investigated whether the respondents in different stages-of-change score higher or lower on constructs of the Protection Motivation Theory. In Paper 3, which is based on a stated choice experiment, the stages-of-change are independent

variables, as well as constructs of the Protection Motivation Theory, socio-economic variables and the attributes of the stated choice experiment (different policy incentives). The dependent variable is there whether the respondent prefers to purchase an EV or an ICEV. In Paper 7, a comparison is made between the stage-of-change of a group of EV rental guests and a group of ICEV rental guests. Moreover, it has been investigated whether electric vehicle rental contributes to moving to more advanced stages-of-change.

The advantage of using stage-models such as the Transtheoretical Model of Change is that these models account for the fact that behavioural change can be a complex phenomenon. In different stages-of-change, different aspects can be of importance and policy measures can take into consideration that people in different stages-of-change are in need for different policy interventions. By investigating socio-cognitive and behavioural differences for people in different stages-of-change, more insight can be gained into potential policy measures that can be tailored towards people in a certain stage-of-change.

6.3 Transport Economics Theory

Literature about the Total Cost of Ownership of electric vehicles shows that EVs can be economically competitive considering the price premium and the compensatory effects of lower fuel and expected lower maintenance costs (e.g. Hagman et al., 2016). Directly related to this different cost structure, it is apparent that the marginal cost of using electric vehicles is lower. This lower marginal cost might have effects on the number of trips made, the destination choice, mode choice and possibly route choice. This all has to do with the generalized cost of travelling. If the generalized cost of travelling by car decreases, it will be cheaper to make additional trips or make trips that are relatively further away. Moreover, it will be relatively cheaper to choose the car rather than alternative transport modes such as public transport modes or active modes.

Mechanisms from Transport Economics Theory have been used in Paper 2, Paper 3, Paper 4/5 and Paper 6. In Paper 2, the marginal cost of driving has been used for the hypothesis that EVs and HEVs might induce traffic within the range limits connected to the battery capacity. In Paper 3, it has been hypothesized that policy makers can intervene with travellers' generalized costs of travelling by providing incentives such as free parking and subsidies/tax rebates (monetary gain) or by giving access to bus lanes (time gain). In Papers 4/5, it has been investigated whether changing to an electric vehicle, under the condition of range abundance, is likely to increase car travelling, and under which conditions this is likely to happen.

6.4 Revealed preference

In Paper 2, revealed preference methods (self-reported travel behaviour) have been used to investigate the difference between current electric vehicle users and current internal combustion engine vehicle users. A one-day travel diary was carried out among all respondents. Due to an oversampling of electric vehicle users, a significant part of the sample consisted of electric vehicle users. A comparison of travel behaviour characteristics (modal share of the car and number of trips) between EV-users and ICEV-users was done, both by descriptive statistics and by using multivariate regression models.

6.5 Stated preference

In the Papers 3, 4, 5 and 6, stated preference methods were used to investigate future behaviour. Stated preference methods can give insight in matters where there is little information to get from current practice. The disadvantage of stated preference methods is the fact that these methods do not entail a real transaction. Behaviour is non-consequential. When studying emerging behaviour, however, revealed preference methods have other limitations and therefore, a combination of revealed preference and stated preference has been used in this study.

In Paper 3, a stated choice experiment was carried out to gain insights into electric vehicle adoption. Instead of exclusively using characteristics of electric vehicles to investigate the willingness to pay for these characteristics, the main topic of this stated choice experiment was policy incentives and their influence on electric vehicle adoption.

In the Papers 4, 5 and 6, two stated adaptation experiments were discussed. The aim of stated adaptation experiments is to elicit behaviour as a reaction to a certain stimulus given by the researcher (Janssens et al., 2009), which is similar to the aim of other stated preference experiments. However, stated adaptation experiments are stated preference experiments with a more realistic anchor point: the respondent's own current behaviour. Stated adaptation experiments have been used in both qualitative (e.g. D'Arcier et al., 1998 & Lesteven, 2014) and quantitative approaches (e.g. Arentze, 2005 & Cools and Creemers, 2011). In Paper 4/5, the stated adaptation experiment is based on the travel behaviour the respondents registered in a one-day travel diary that was part of the first wave of the survey. In Paper 6, the anchor point consists on a stated preferred starting time for a charging event in a reference scenario where the price for a charging event is equal throughout the day. The stimulus given by the researcher consists of a hypothetical electric vehicle with a certain range or kilometre budget for Paper 4/5. For Paper 6, the stimulus consists of two different price distributions for different times of the day to investigate the influence of temporal price differentiation, besides the reference situation (the anchor point).

6.6 Statistical methods

The research methodology used is a theory-driven and quantitative methodology. The basis of the analyses is a number of hypotheses that have been tested. Generally, a combination of descriptive statistical analyses, hypothesis tests and multivariate regression models has been used to explore and analyse the data. For the models that have been estimated,

regression models (Binary Logistic Regression, Ordinal Logistic Regression, Poisson Regression, Tobit Regression and Mixed Logit Regression) and Structural Equation Models have been used. The focus of these models is to explain rather than to predict. Therefore, also non-significant parameters have been discussed in the papers. Much emphasis has been put on comparison of different model specifications. An example is a comparison between a model that estimates the probability of someone being in the Pre-contemplation stage as a function of socio-cognitive, behavioural and socio-economic variables as opposed to a model with only behavioural and socio-economic variables (Paper 1). In the third paper, the Random Utility Framework (e.g. McFadden, 1974) has been used in combination with socio-psychological constructs from the Protection Motivation Theory and the Transtheoretical Model of Change. Also in this paper, a number of models have been estimated to investigate the explanatory value of e.g. the included socio-psychological constructs in this survey.

7 Data collection

For the largest part of this study, a three-wave survey has been designed. The first wave was designed for respondent selection and consisted of a small questionnaire with mainly socio-economic questions. The second wave included questions about socio-psychological determinants of behavioural change according to the Protection Motivation Theory and the Transtheoretical Model of Change, including stage-of-change, decisional balance, self-efficacy, response efficacy and the Processes of Change belonging to the TTM.

The respondents were asked in which stage-of-change they were using four simpler binary questions. Then, using seven point Likert-scale items, constructs of the Protection Motivation Theory and the Transtheoretical Model of Change were measured. Using a standardized summated rating

scale, the values for each construct were computed. Each construct was measured by 2-4 Likert-scale items.

Also, questions were asked about the respondent's travel behaviour pattern, including a one-day travel diary. Besides, there were some questions about the respondent's energy use at home. The final part of the second wave consisted of some socio-economic questions.

The third wave of the questionnaire consisted of a collection of three stated preference tasks.

- The first stated preference task was about EV-adoption in several scenarios of policy incentives that can be taken to make EVs more attractive (free or discounted parking, use of bus lanes, free or paid public charging infrastructure and upfront subsidies).
- In the second stated adaptation task, the respondents get the task to imagine they switch to an EV with a certain range, that can be 60 %, 90 %, 120 %, 150 % or 300 % of their current daily trip length. The respondents were asked whether they would change something in their daily travel pattern in these scenarios, and if there are changes, whether these changes would be about adding or cancelling trips, destination choice, mode choice, route choice and/or departure time choice.
- In the third stated adaptation task, the respondents were asked about their preferred charging time in case of a flat electricity price (reference scenario) or in case of a price that fluctuates in order to decrease peak demand hours.

The respondents have been recruited with the help of a recruitment company. The Swedish Transport Agency (Transportstyrelsen) has provided the addresses of all EV- and PHEV-owners in Stockholm's County. The

recruitment company got the task to recruit respondents from all parts of Stockholm's County and recruit a certain number of respondents within a certain age group, with a certain family structure and with a certain income. The recruitment of respondents took place between September and December 2014. In total, 294 respondents participated in the first and second part of the survey, while 269 respondents have completed all three waves of the survey.

For Paper 7, a separate data collection has been done during summer 2015, summer 2016 and spring 2017. People renting a car from two rental companies on the island of Gotland, Sweden, got an invitation to take part in a survey consisting of two waves. The first wave included socio-cognitive, socio-economic and behavioural questions, including stage-of-change towards electric vehicle adoption. In the second wave, part of the questions were repeated in order to do an after measurement where it was investigated whether people who rented an electric vehicle in Gotland were more likely to move forward in the process of behavioural change towards electric vehicle adoption. In total, 158 respondents participated in the first part of the survey, while 69 respondents completed all waves of the study.

8 Contributions

8.1 Paper 1 - Changing towards electric vehicle use in Greater Stockholm

Paper 1 is an explorative paper that describes the transition from ICEV to EV as a process that consists of different stages. In this study, the Protection Motivation Theory and the Transtheoretical Model of Change have been used to describe the environment related motivation and the process towards EV-use. By describing the socio-cognitive, behavioural and socio-economic characteristics of people that are in a certain stage-of-change, more insight can be obtained about the process of EV adoption and potential variables that can be influenced by policy measures.

The main results of paper 1 were that people who moved to more advanced stages-of-change towards EV-use became more and more positive about EVs, obtained more knowledge about the characteristics of these vehicles and got a higher self-efficacy to use EVs. In the stages before the actual electric vehicle adoption, the respondents in more advanced stages-of-change reported a higher level of threat appraisal of the current transport system and a higher response efficacy of the electric vehicle, while these were at a lower level for the actual EV-users. Including socio-cognitive variables increases the explanatory power of the model considerably as compared to a model with only socio-economic and behavioural explanatory variables. Another finding was that although it was hypothesized that people who have a more varied daily travel pattern including different travel modes are more likely to be able to cope with EVs, people in more advanced stage-of-change had an ever increasing modal share of the car, which is an indication of increased car use for electric vehicle users. In Papers 2 and 4/5, this has been studied in more detail.

8.2 Paper 2 – Electric vehicle users and their travel patterns in Greater Stockholm

Paper 2 zooms in on the travel patterns of electric vehicle users. In this study, the travel behaviour of a group of EV-users and a group of non EV-users was compared using a one-day travel diary. Also, the perception of how environmentally friendly the electric vehicle is compared to other modes of transport was studied. As electric vehicles have a high upfront cost and relatively low marginal usage costs (mainly because electricity use costs less per kilometre than petrol or diesel), the hypothesis was that EV-users might drive more than their non EV-using counterparts, within the range limitations of these EVs. Also the perception of environmental friendliness of electric vehicles might be a driving factor for using patterns.

The most important findings of Paper 2 are that the electric vehicle was perceived to be significantly more environmentally friendly than public

transport modes such as the bus, the metro and the train. Although the EV-users in the sample did not travel significantly further per day, they travelled more kilometres by car and made on average more trips. The fact that the car is chosen for a larger part of the total distance travelled is an indication for a potential rebound effect, where part of the benefits of switching from conventional cars to electric vehicles gets lost because of increased car use.

8.3 Paper 3- The effect of policy incentives on electric vehicle adoption

Paper 3 builds further on the findings of paper 1 and paper 2 and deals with the interaction between EV-users and policy incentives that can be taken to make electric cars more attractive. Different potential policy incentives (subsidies, parking policy, access to bus lanes and charging policy) have been incorporated in a stated choice experiment. Also, the influence of socio-cognitive constructs from the Protection Motivation Theory, as well as the stage-of-change from the Transtheoretical Model of Change, has been incorporated in the analysis of this stated choice experiment.

Based on this study, the conclusion can be drawn that policy measures, both subsidies and alternative incentives, have a significant and positive influence on EV-adoption. People that were in a more advanced stage-of-change were increasingly eager to adopt an EV, and also people with a high self-efficacy and a high response efficacy for electric vehicles were more inclined to choose for the EV. A remarkable result was the fact that the price-sensitivity decreased with stage-of-change, meaning that people in a more advanced stage-of-change are less sensitive to a certain unit of EV-subsidization.

Use-based incentives were relatively effective compared to purchase-based up-front subsidies. The efficiency of local EV-policy incentives not relying on upfront subsidies might be higher because of relatively high part-worth

utility and relatively low costs. On the other hand, those incentives decrease the marginal costs of EV-use even more and may increase car use, leading to rebound effects. Another issue is the credibility of policy incentives that are provided over time. Free parking and access to bus lanes might not be possible to provide many years into the future, depending on the development of EV-adoption. However, when considering the purchase of an EV, the utility of a policy incentive depends on the perceived certainty for the policy incentive to be provided in the future.

8.4 Paper 4- How would you change your travel patterns if you used an electric vehicle? A stated adaptation approach

Paper 4 is a paper describing a stated adaptation experiment aiming to investigate future electric vehicle use. As current electric vehicle users are considered to be early adopters, the disadvantage of the revealed preference approach (as used in Paper 2) is the fact that their travel patterns might be different from that of future EV-adopters. Using stated adaptation experiments among all respondents, this selection effect is less prevailing. Based on people's current behaviour (registered in the one day travel diary), all respondents were provided with a fictive electric vehicle with a certain kilometre budget that was based on their current total driving distance during the travel diary day. The aims were to investigate which behavioural strategies are used to take the range limitations into consideration. In a number of cases, the respondents were provided with kilometre budgets that were not sufficient for all currently made trips. In these cases, we were interested to see which alterations were taken to decrease car use, because different behavioural strategies have different implications on people's mobility level. On the other hand, we were also interested to see whether people are making additional car trips in case they have an electric vehicle with abundant range, as this would entail a rebound effect.

Based on this study, there are indications that range limitations can lead to the cancellation of trips (and activities), leading to a decrease in the mobility

level. The attractiveness of the public transport alternative seems to influence the selected alteration, and non-mandatory activities such as shopping and visiting friends or relatives are most likely to be cancelled. Besides this, a non-negligible number of additional trips have been registered in case of abundant range, leading to a rebound effect. Moreover, for a number of trips the registered travel mode has been shifted from public transport to the car, which would also entail a rebound effect. The fact that a relatively high percentage of these trips consisted of working trips carried out in rush hour leads to the hypothesis that large scale electric vehicle adoption might increase traffic congestion.

8.5 Paper 5- A stated adaptation instrument for studying travel patterns after electric vehicle adoption

Paper 5 is a reflection paper where the stated adaptation instrument that was used in paper 4 is evaluated and discussed. In this paper, the rationale of using stated adaptation experiments for investigating future travel behaviour is described, comparing stated adaptation with other methods such as comparing travel diary data (as used in Paper 2), a longitudinal study of people switching from internal combustion engine vehicle to electric vehicle, field trials or using general theoretical concepts such as price elasticity of demand.

In the evaluation of the stated adaptation instrument, the validity and reliability of the study are discussed. The internal validity is considered to be relatively good due to the fact that the respondents' own travel patterns are the basis for the experiment. The external validity or generalizability is influenced by the provided kilometre budgets. These kilometre budgets were based on a random assignment of a certain percentage applied to the total driving distance during the travel diary day or the total travel distance during the travel diary day in case no car trips were made. In some cases, these kilometre budgets might not be realistic.

The reliability of the study might be negatively affected by the complexity of the choice tasks. Even though some efforts were made to guide the respondents through the experiment, the survey task seems to be too complicated for a subset of the respondents. Moreover, in this study it has been chosen to not allow for out-of-home charging. This might not be realistic, but on the other hand, allowing out-of-home charging implies that driving patterns and stated adaptations can be caused by differences in knowledge about the available public charging infrastructure, which would negatively affect the reliability of the study.

8.6 Paper 6- When do you charge your electric vehicle? A stated adaptation approach

Paper 6 deals with charging behaviour and to which degree current and prospective EV-users are sensitive to temporal price differentiation. Different scenarios have been designed in order to elicit preference for scheduling charging events. In the baseline scenario, the price of a charging event does not fluctuate during the day. Besides this baseline scenario, two scenarios with temporal price differentiation were used, where the price of a charging event is up to 200% more expensive at peak hours than at night hours. The aim was to elicit behavioural responses to temporal price differentiation.

Based on this study, the conclusion can be drawn that temporal price differentiation, even at a relative moderate level, has a significant effect on the timing of charging events. This implies that night time charging is considered to be a rather good substitute for early evening charging, which is currently the most preferred way of EV-charging, in case the price is stable throughout the day. Behavioural change is more likely with a higher level of temporal price differentiation. Also the behavioural response differs: late evening charging is more likely to be selected in case of a moderate level of temporal price differentiation, whereas the absolute majority of charging

events changes to night time charging in case of a high level of temporal price differentiation.

8.7 Paper 7- Electric vehicle rental and electric vehicle adoption

Paper 7 is based on a different research project where the processes of behavioural change towards electric vehicle adoption are further explored. In this project, tourists visiting the Swedish island Gotland are able to rent an electric vehicle or a conventional, ICEV. Based on a survey that is similar to the one in Stockholm, socio-economic, socio-cognitive and behavioural factors are analysed in relation to people's reported stage-of-change. However, in this paper, stage-of-change is measured at two times: at the time of the rental and one year/half a year later.

The main results of this study are that electric vehicle rental is likely to be a measure that attracts people that are already in a relative further stage-of-change, but it does not seem to have a significant positive effect on letting people move forward to more advanced stages of change. Besides, an analysis of driving patterns of a sample of EV rental cars and ICEV rental cars shows that there are no large differences in driving patterns. EV rental cars even seem to be used more intensively.

9 Conclusions and policy recommendations

In the stages-of-change closer to electric vehicle adoption, the knowledge level and self-efficacy of people to adopt EV are higher and people seem to get more confident to start using EVs the closer they come to adoption. The included socio-cognitive variables explained more of the variability in the data than the socio-economic and behavioural variables. Unexpectedly, people that use the car for a larger share of their total distance travelled are more likely to be in a more advanced stage-of-change.

People in the Pre-contemplation stage score significantly lower on Threat appraisal: the assessment of current travel behaviour being harmful and feeling personal responsibility for it. Policy measures aiming at increasing awareness about the adverse effects of our current travel behaviour are likely to be most effective for people in the Pre-contemplation stage. In order to decrease the risk for rebound effects, it should be clearly communicated that electric vehicles can solve some of the issues related to our current driving behaviour, but not all.

Insight in one's own driving and mobility patterns seems to be an important aspect influencing people's confidence to start using electric vehicles. More education can help to increase this insight, for example by giving a clear image of how relatively seldom long-distance trips by car are made, as well as under which conditions it is feasible to make long-distance trips by electric vehicles. Policy measures supporting this are likely to be most effective for people in the Contemplation stage.

For people in the Preparation stage, educational policy measures can also be valuable, be it more concrete. An example of a policy measure is focussing on auxiliary behaviours such as public charging. By providing easily accessible information about all public charging points within a region, as well as their type and which cars are compatible, groups of car users close to EV-adoption can get a better image of how to practically use their EV.

The effect of renting an electric vehicle on moving forward in the process of change towards EV adoption seems to be limited. Rather than that temporal exposure to EV-use stimulates EV-adoption, there seems to be a selection effect, where people that are already in more advanced stages-of-change are more likely to rent an electric vehicle.

EV-users (being in stage Action or Maintenance) make on average more trips than non EV-users and they use the car for a larger share of their total

distance travelled. This might imply a rebound effect if the results can be generalized to a large group of future EV-users. However, due to the fact that the current EV-users are early adopters and because of the fact that this study is a cross-sectional study, the results should be treated with prudence. Nevertheless, the risk for a rebound effect has been confirmed using another research method (stated adaptation). A non-negligible number of additional car trips have been registered: there seems to be a latent demand for more non-mandatory trips such as shopping or leisure trips and for a modal shift towards the car for working trips. Especially the latter is likely to contribute to increased congestion due to the temporal distribution of these trips. In the longer term, a tax system that is based on kilometres driven might be needed to counterbalance the low marginal costs of electric vehicle use, but also the decreasing revenues from petroleum products.

Policy incentives are likely to have a significant effect on EV-adoption. Local, use-based policy incentives might be more efficient than up-front subsidies and registration tax rebates. However, these use-based policy-incentives actually do not take away the high investment costs of EVs, while they decrease the marginal cost of EV-use, which might enlarge the risk for rebound effects.

Also in the use stage, people seem to be highly influenceable when it comes to charging behaviour. Temporal price differentiation has shown to significantly decrease charging events starting in the early evening. Both the fact that there is temporal price differentiation at all and the degree of temporal price differentiation seem to play an important role.

10 Future research

In this thesis, a number of topics related to electric vehicle adoption and use have been investigated. Electric vehicle adoption has been studied in relatively many studies, using different methods and theoretical

frameworks. Future research regarding electric vehicle adoption could concentrate on intervention methodologies, where the insights from the studies that have been carried out can be applied to design interventions aiming at increasing electric vehicle adoption for people in different stages-of-change.

To the contrary, electric vehicle usage and charging patterns is a field of research where very little empirical research has been carried out so far, despite its importance. More research is needed to get insights in the consequences of electric vehicle adoption, both from an individual and from a societal perspective. The impact of EV-adoption on mobility is an important issue, especially if EV-adoption is stimulated or even required for a part of the population, due to e.g. strict environmental zones. This research field will be emerging and this impact is believed to be heavily influenced by technological developments such as larger battery capacity or ultrafast charging stations.

From a societal perspective, the influence of electric vehicle adoption on car use is of importance. Electric vehicle adoption can increase or decrease car use. Also here, technological developments are believed to play an important intermediate role. Based on the results of this study, a new research project will be carried out from July 2018 until December 2020. In this project, the focus will be broader than the user and includes local and national policy besides current and presumptive electric vehicle users. As electric vehicle charging is a key factor facilitating electric vehicle adoption, but also influencing where people park and so which places people visit by car, more insight into the processes leading to charging infrastructure provision is needed, as well as behavioural responses to these choices. Besides charging infrastructure and charging behaviour, more insight is needed into the circumstances under which more car trips are likely to be made. A mapping and quantification of the latent demand for car trips is needed for policy makers to anticipate on future policy measures aiming at decreasing car-

related problems such as congestion, air pollution and accidents. A variety of research methods is needed to inform policy makers on the likely effects of electric vehicle adoption of car use, as well as the likely effects of policy measures that could be taken to regulate changing car use patterns. Stated preference experiments, such as stated adaptation experiments, is one research method that can shed light on changes in travel patterns as a result of electric vehicle adoption. However, with an increasing market share of electric vehicles, the value and importance of revealed preference methods and longitudinal studies will increase.

Charging infrastructure is believed to be a key factor linking electric vehicle adoption, use and charging behaviour together. Therefore, in parallel to this study, I have been involved in two studies where charging infrastructure plays an important role. The first study currently carried out concerns Swedish housing cooperatives. As most of the electric vehicle using respondents indicated to charge their vehicle at home most often, electric vehicle adoption is believed to be facilitated by the possibility to charge at home. In urban environments, however, home charging is often more challenging compared to suburban environments consisting of single-family homes. It is investigated what the attitudes are of the members of Swedish housing cooperatives regarding the provision of charging infrastructure for their tenants, as well as the factors currently hindering large scale provision of charging infrastructure for electric vehicle charging. Another study currently carried out concerns a taxi company that started using electric vehicles in its fleet. Due to their commercial (and intensive) use, as well as their fast turnover, the taxi branch can play an important role as a catalyser of electro-mobility. At the same time, there are specific challenges, both internal and external, with the specific needs of vehicles used in taxi companies. From the perspective of taxi companies, charging is an important issue for taxi companies, as charging time and cost are important factors influencing the profitability of using electric taxis. From a societal perspective, the pressure of intensive EV-users on the emerging network of

charging infrastructure (and the electricity consumption related to charging events) is an important issue.

A distinction can be made between the short term and the long term. In the short term, where electric vehicle market shares are growing but at a relatively low level, electric vehicle adoption is the first issue to be solved. Despite ambitions in many countries of electric vehicles having an important role in decreasing Greenhouse gas emissions, adoption rates are currently low. Car manufacturers work on constantly improving the range and performance, while battery costs are decreasing. Charging technologies, either static (such as ultrafast charging) or dynamic (electric roads), facilitate the use of electric vehicles for longer distances and aim to decrease the time cost connected to charging events. Based on these developments, it is believed that electric vehicle adoption has the possibility to increase to much higher levels than the ones currently observed. In the middle and long term, however, the focus should shift to new system questions related to electric vehicle use. How do we finance our transport system, given the fact that fossil fuels generated high tax revenues? How do we react to changing travel patterns of electric vehicle users, whose car use has become relatively cheaper? Or generally, how do we obtain a sustainable use of electric vehicles?

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List of papers

- I. Langbroek, J.H.M, Franklin, J.P. and Susilo, Y.O. (2017). Changing towards electric vehicle use in Greater Stockholm. *Published in European Journal of Transport and Infrastructure Research.*
- II. Langbroek, J.H.M, Franklin, J.P. and Susilo, Y.O. (2017). Electric vehicle users and their travel patterns in Greater Stockholm. *Published in Transportation Research Part D.*
- III. Langbroek, J.H.M, Franklin, J.P. and Susilo, Y.O. (2016). The effect of policy incentives on electric vehicle adoption. *Published in Energy Policy.*
- IV. Langbroek, J.H.M, Franklin, J.P. and Susilo, Y.O. (2018). How would you change your travel patterns if you used an electric vehicle? A stated adaptation approach. *Submitted to Travel Behaviour and Society.*
- V. Langbroek, J.H.M, Franklin, J.P. and Susilo, Y.O. (2018). A stated adaptation instrument for studying travel patterns after electric vehicle adoption. *Forthcoming in Transportation Research Procedia.*
- VI. Langbroek, J.H.M, Franklin, J.P. and Susilo, Y.O. (2017). When do you charge your electric vehicle? A stated adaptation approach. *Published in Energy Policy.*
- VII. Langbroek, J.H.M., Cebecauer, M., Malmsten, J., Franklin, J.P., Susilo, Y.O. and Georén, P. (2018). Electric vehicle rental and electric vehicle adoption. *Revised version submitted to Research in Transportation Economics.*

Declaration of contribution

- I. The idea of Paper 1 was from joint discussion between Joram Langbroek, Joel Franklin and Yusak Susilo. Joram Langbroek designed the survey with the feedback and help from Joel Franklin and Yusak Susilo. Joram Langbroek prepared the dataset, run the model and wrote the paper with feedback and help from Joel Franklin and Yusak Susilo.
- II. The idea of Paper 2 was from Joram Langbroek. Joram Langbroek designed the survey with the feedback and help from Joel Franklin and Yusak Susilo. Joram Langbroek prepared the dataset, run the model and wrote the paper with feedback and help from Joel Franklin and Yusak Susilo.
- III. The idea of Paper 3 was from Joram Langbroek. Joram Langbroek designed the survey with the feedback and help from Joel Franklin and Yusak Susilo. Chengxi Liu has helped with preparing a generic code that could be adapted to analyze the stated choice experiment. Joram Langbroek prepared the dataset, run the model and wrote the paper with feedback and help from Joel Franklin and Yusak Susilo.
- IV. The idea of Paper 4 was from joint discussion between Joram Langbroek, Joel Franklin and Yusak Susilo. Joram Langbroek designed the survey with the feedback and help from Joel Franklin and Yusak Susilo. Joram Langbroek prepared the dataset, run the model and wrote the paper with feedback and help from Joel Franklin and Yusak Susilo.
- V. The idea of Paper 5 was from joint discussion between Joram Langbroek, Joel Franklin and Yusak Susilo. Joram Langbroek wrote the paper with feedback and help from Yusak Susilo.

- VI. The idea of Paper 6 was from Joram Langbroek. Joram Langbroek designed the survey with the feedback and help from Joel Franklin and Yusak Susilo. Joram Langbroek prepared the dataset, run the model and wrote the paper with feedback and help from Joel Franklin and Yusak Susilo.

- VII. The idea of Paper 7 was from joint discussion between Joram Langbroek, Joel Franklin and Yusak Susilo. Joram Langbroek designed the survey with the feedback and help from Joel Franklin and Yusak Susilo. Joram Langbroek analyzed the data with the help of Matej Cebecauer for the analysis of travel patterns. Joram Langbroek and Matej Cebecauer wrote the paper with feedback and help from Joel Franklin and Yusak Susilo. Matej Cebecauer contributed with Chapter 4.1 and 5.3. Jon Malmsten coordinated the project and contributed with the analysis of the overall evaluation of the rental events. Peter Georén coordinated the project part of KTH and provided feedback in the process of data collection and discussion of the results.

Papers