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Methods of evaluating electric vehicles from a user's perspective – the MINI E field trial in Berlin

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In the present paper we propose a methodological framework for user studies on electric vehicles (EVs) and present first results from a 1-year field study conducted in the Berlin metropolitan area. The objective of the current field study is to develop, adjust and apply psychologically founded methods of assessing the acceptance of EVs in everyday use.

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Based on these methods, it will be possible to identify factors influencing the acceptance of EVs and to outline changes, for example in attitudes or behaviour, of participants during their participation in test trials. Accordingly, we identified four pillars that are decisive in user evaluation of EVs: mobility, human-machine interaction (HMI), traffic and safety implications and acceptance. Results from the first study period indicate that a great part of daily mobility needs are satisfied although range of EVs is limited. Attitudes towards EVs are predominantly positive. As expected, ecological aspects such as CO₂ emissions play an important role in the evaluation of EVs.

1 Background

As a key solution to addressing the challenges of currently increasing energy demands, electric vehicles (EVs) charged with renewable energy have been the subject of intense discussion. However, barriers in technology, such as price, size of batteries, and limited range are issues that have hindered overall acceptance and large-scale marketing of EVs.

Although EV field trials have a long tradition, knowledge of how users experience EVs is lacking. The goal of the present research is to further explore user experience through the application of a wide range of methods. Additionally, our research aims to develop recommendations for the design of EV systems while maximizing environmental benefit. Underlying this research is the idea that efficiency of such new technology essentially depends on how users interact with an EV system.

Apart from studies that largely focus on technical feasibility, some EV studies explicitly address user expectations and preferences [1]. In this context it has been argued that preferences of EV novices do not necessarily reflect the true preferences of actual EV users [2]. Therefore, it is essential that the evaluation of EVs is based on long-term user experience. Accordingly, the present study, which is based on the project entitled "MINI E

Berlin – powered by Vattenfall”, accounts for this issue. The project is one of the biggest field trials on EVs to date and has been set up in close collaboration with Vattenfall Europe and the BMW Group. An overview of the whole project and its implications for the industry can be found elsewhere [3, 4, 5], the present paper focuses on the user evaluation of EVs.

2 Objective

The current study examines whether electric mobility systems are useable and satisfying in daily life in their present form, i.e. without additional major technological developments. The research objective of the present study consisted of two main goals:

- Integrate previous research methods on EV user behaviour while applying a variety of new methods to analyze user perspectives.
- Define valid evaluation criteria for the assessment of impact of EVs on user behaviour, the environment and the mobility system.

We propose a pillared structure to describe user evaluation of EVs. This is arranged according to four organizing principles: mobility, HMI, traffic and safety implications and acceptance. The structure, which is displayed in Fig. 1, may serve as a fruitful framework for conducting further user research on EVs.

<<Insert figure 1 here>>

2.1 Mobility

The first pillar 'mobility' deals with how individual mobility is affected by EV usage (Fig. 1). On average, Germans travel 39 km per day [6]. Previous user studies on EVs [e.g. 7] showed that users can adapt to limited range. Other studies suggest that experience per se does not necessarily change desired range. Golob and Gould [8] used 'travel diaries' to record daily mobility. Although users in their study reported driving <50 miles (<80.5 km) a day, they still expected the EV to cover a distance of 100 miles (160.9 km) or more. Studies on EVs with novices indicate that there are concerns related to range [9]. Possible explanations for overestimated range needs might be due to general misconceptions of mobility needs and to lack of in-depth experience with EVs [2].

Concerning mobility, several research questions need to be addressed: Can users rely on EVs to fulfil their daily needs? What are the characteristics of trips that exceed an EV's capacities? In this context, the limited range of EVs should be dealt with in detail. Are today's EVs suited to meet the majority of daily commuting needs? Are the barriers that have hindered overall acceptance in the past psychological in nature?

2.2 Human-machine interaction (HMI)

The second pillar in our suggested structure deals with the 'human-machine interaction' (HMI) (Fig. 1). Only few studies have evaluated the interface of other electric drive vehicles. Notably, these have examined the consumption of information in plug-in hybrid electric vehicles (PHEVs). Findings suggest that in some cases interfaces were too complex and abstract thus leading to confusion and, in several cases, to ignorance of required information [10]. Further, Barkenbus [11] stresses the importance of feedback as a crucial element in energy-efficient driving behaviour, especially in EVs.

HMI is decisive in the evaluation of complex, unfamiliar technological systems such as EVs. Notably, the concept of electricity in the car evokes questions not only about safety, but also about energy consumption: For example, what relevant parameters should be displayed in an EV? 'How should the driver be informed about these important parameters? There are some particularly critical questions, such as, do drivers understand the importance of energy-efficient driving in an EV and what sort of feedback can best encourage such driving? Further, how should the remaining charge in the battery be displayed such that drivers are able to make full use of it while minimizing range anxiety?

In addition to in-vehicle information, the charging process is also an important part of the HMI. Charging issues are two-fold: first, users must interact with a charging infrastructure, i.e. a 'wallbox' installed at the driver's home or at a public charging station. Second, they must deal with the EV's battery and its limited capacity. To describe that kind of interaction, Rahmati and Zhong [12] introduced the term 'human–battery interaction (HBI)'. Exploring the interaction with the battery, they found two different charging types: habit and interface-dependent chargers. Gärling and Johansson [13] also recorded the state of charge at the beginning and end of each charging process to describe charging behaviour predominantly related to limited range.

Summarizing, several questions arise: How is charging integrated in the daily routine of users? What is the usability of the charging stations? Is charging duration a barrier for users? What conditions lead to participation in 'managed charging', a process developed by the energy provider in order to utilize the potential of renewable energy?

2.3 Traffic and safety implications

The third pillar covers the 'traffic and safety implications', if EVs are widely used. The lack of engine noise in EVs translates into a potential hazard, particularly for the hearing impaired, blind pedestrians and children. An analysis of incidence rates of pedestrian and bicyclist

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crashes with EVs revealed that incidents with hybrid electric vehicles (HEVs), which emit substantially less noise in electric mode, mainly occur at low speeds. Manoeuvres such as deceleration, stopping, entering or leaving a parking space were especially critical [14].

Previous research on the low noise level of EVs/HEVs has focused heavily on pedestrians. In our research, we also recommend accounting for a driver's perspective and behaviour. In particular: How do EV drivers evaluate low noise levels? What are their experiences in this regard? Which road users are at risk and what strategies do drivers suggest addressing this issue? Detailed findings on acoustics from the first study period are reported elsewhere [15].

Another feature, which is unique in battery-powered vehicles and might also have implications for traffic and safety, is the regenerative braking system. During braking manoeuvres, such a system recaptures the vehicle's kinetic energy and transfers it back to the battery [16]. The deceleration caused by the system is significant and affects the driving task. This could ultimately impact EV drivers themselves as well as drivers of other vehicles. That is, others might be surprised when the dynamics of adjacent vehicles differ from what they are normally used to. For example in a traffic queue it might seem that the EV in front always braked sharply.

The usage of regenerative braking is closely linked to eco-driving, which is also addressed in the third pillar, traffic and safety implications. If eco-driving strategies are applied by a large number of drivers, this could have considerable effects on traffic flow. As already applied to driving behaviour with internal combustion engine (ICE) vehicles, the idea of eco-driving promotes energy-efficient driving behaviour, such as accelerating moderately and driving at a constant speed [11]. Findings on fuel efficiency suggest that aggressive driving or inefficient use of regenerative braking in HEVs can result in a more than 30% decrease of fuel efficiency. Such variations in driving strategies seem to have a much smaller impact on fuel

efficiency in ICEs [17]. Nevertheless, when interpreting these data the structure and control strategies implemented in the hybrid drive train have to be taken into account, as well [18].

These findings clearly emphasize the need to assess how drivers adapt to driving with EVs. In particular: How do drivers deal with the low acoustic cues of EVs? How do drivers integrate regenerative braking in their normal driving behaviour? Furthermore, driver awareness of eco-driving and strategies applied in energy-efficient driving should be evaluated.

2.4 Acceptance

'Acceptance', the fourth pillar, involves research issues on a more global level. Only few publications have examined the acceptance of EVs and variables for measuring acceptance vary. Attitudes and purchase intentions [7, 19] were mostly used as indicators for acceptance. Preference studies supplement general attitude measurements by providing relative importance of EV attributes for the future market. Studies on stated preferences or purchase intentions for different vehicle models show high utilities, for example for range and maximum speed [1, 20].

In research on Advanced Driving Assistance Systems (ADAS) acceptance is also a widely discussed topic, although a clear definition of acceptance is missing. Van der Laan, Heino and de Waard [21] provide a simple scale for measuring two dimensions of acceptance – satisfaction and usefulness. This 9-item scale is broadly used to evaluate ADAS [22].

The Theory of Planned Behaviour (TPB) [23] is another frequently used framework. According to this theory, behaviour is predicted by individual evaluation of behaviour (i.e. attitudes towards the behaviour), perceived social beliefs (i.e. subjective norms) and individual control beliefs (i.e. perceived behavioural control). Arndt and Engeln [24] included these factors in their concept and argued that behavioural intentions and acceptance

concerning driving assistance systems are also influenced by, for example willingness to pay. In sum, a wide range of methods is necessary to gain an overall picture of how people evaluate today's EVs and to explore different influential factors.

Perceived environmental benefits of EVs are widely discussed in the literature. That is, they are perceived as more environmentally friendly than ICE vehicles even though the electricity used for recharging is generated in coal-fired plants. However, there is a great demand for renewable energy to charge EVs [25]. Heffner et al. [26] argued that many HEV buyers regard their vehicle as a symbol of environmental protection and do not report specific environmental goals. In many studies, environmental concerns were not shown to significantly influence acceptance of alternative fuel transport [27, 28]. Although environmental concerns showed an effect in some preference studies, factors such as price and performance were still of higher influence [20].

After-sales services, which might also have an influence on purchase intentions, were explicitly not addressed in this study as service concepts of manufacturers are still in development.

3 Methods

3.1 Time bar of the field study

The present large-scale field study is split into two 6-month periods, each comprised of a different sample of 40 users with an EV in their household. Additionally, 10 EVs were integrated in a so-called 'fleet setting', which will be reported elsewhere. During each period of the study, possible changes in attitudes, experiences and behaviour were detected during three points of data collection: before participants receive their car, after 3 months of usage and upon return of the car. The time bar of the field study and the applied methods are displayed in Fig. 2.

<< Insert figure 2 here >>

3.2 Participants

More than 700 people applied for the first period of EV use via an online application. Requirements for study participation were: residence in metropolitan Berlin, willingness to take part in scientific surveys, willingness to pay the monthly leasing rate, available garage space, suitable power supply, and other technical conditions. After establishing eligible applicants ($N = 161$), the sample ($N = 40$) was selected according two main selection criteria: First, expected kilometres driven with the EV, such that half of study participants planned to drive >250 km in 1 week, the other half planned to drive less with the EV. Second, the number of cars in the household was defined according to the hybrid household

hypothesis [28]: Either the EV would be the only car in the household or the EV would be integrated in the household's fleet of vehicles (i.e. hybrid household). Based on the fact that only few applicants expected to be a single-car household, the sample includes 31 hybrid and 9 EV households. A detailed description of the sample has been published elsewhere [29].

3.3 Test vehicles

The study vehicle was a standard MINI Cooper converted to a battery-powered vehicle with a lithium ion battery pack. Powered by a 150 kW electric motor and a peak torque of 220 Nm, the two-passenger vehicle is capable of reaching a top speed of 152 km/h. The vehicle's regenerative braking system transfers kinetic energy from the EV's momentum back into the battery. Participants could recharge their EV at a wallbox installed at home or at one of the public charging stations located in the city of Berlin. To fully charge an empty battery about 4 h was required (32 A). Under ideal conditions, a range of 250 km could be achieved on a single charge. Further technical data on the vehicle can be found online [30].

As depicted in Fig. 2, a variety of methods were applied in this study. To gain a better understanding of how these methods have been developed or adjusted, the four-pillar structure in Fig. 1 serves as an organizing framework.

3.4 Methods in each pillar

3.4.1 Mobility

A key objective during initial telephone contact with users was to foster a good participant–researcher relationship and to gather data about user expectations. In addition to questioning participants about their motivation to take part in the study, users were asked to comment on their expectations related to EV use in daily mobility. Following the telephone interview, participants were sent a travel diary to record their mobility behaviour prior receiving an EV.

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During the second interview - prior to vehicle handover – participants' mobility patterns were discussed in detail. Travel diaries were developed based on methods employed in German nation-wide travel surveys [31]. Specifically, following a main-user approach, only the participant was asked to log all trips conducted during a 1-week period. The travel diary included variables such as exact time of departure to, and arrival at, destination; length and duration of each trip; and purpose of each trip.

The travel diary was also completed after 3 and 6 months. Hence changes in daily mobility patterns due to EV usage could be detected. As indicated previously, range is a prominent issue in discussions about EVs. To address this issue we developed a trip decision game to quantify comfortable range and subjective buffers set by users. The trip decision game was administered three times throughout the study and is described in more detail elsewhere [32].

The quantification of mobility patterns of urban EV drivers relies heavily on the analysis of objective user data. In the present study all vehicles were equipped with data loggers. Mobility parameters, such as trip length, daily mileage and charging cycles were also recorded. On the basis of these objective data, it was possible to record daily vehicle miles travelled (VMT), as well as detect changes in long-term vehicle usage.

3.4.2 Human-machine interaction

Several methods are used to evaluate the displays and the need for information in EVs. As in research on PHEVs [10] and battery indicators [12], in-depth interviews were implemented three times during this study. User interviews are informative in terms of both first impressions and important issues related to test driving an EV. Furthermore, interviews provide mental models of the system, related requirements, and enable the identification of problems in EV use. These qualitative data are supplemented by the quantitative data of questionnaires, which are also administered three times. The System Usability Scale [33] Cocron, P., Bühler, F., Neumann, I., Franke, T., Krems, J.F., Schwalm, M., & Keinath, A. (2011). Methods of evaluating electric vehicles from a user's perspective - the MINI E field trial in Berlin. *IET Intelligent Transport Systems*, 5(2), 127-133.

was applied to globally assess the usability of EV-specific displays and public charging stations. Additionally, questionnaires contained items regarding information visualization, system knowledge, usage patterns and experiences, all of which indicated requirements and further information needed. While driving the EV for the first time, participants were asked to think aloud [34]. The transcribed protocols provided detailed information about first impression of the vehicle, its handling and the user–vehicle interface.

Charging behaviour was examined three times via charging diaries. Participants used the EV-based charging diary to record data on location of charging, state of charge before and after the charging process and motives for charging. Charging diaries allow drawing specific conclusions about individual charging patterns. Additional charging data, for example, expectations and experiences concerning long charging durations as well as usage of public charging stations, were collected via questionnaire.

Similar to the study by Rahmati and Zhong [12] on HBI, interviews and questionnaires were applied to gain a better understanding of user's mental models of batteries: Users were asked to report on their expectations, knowledge and concerns regarding battery lifetime, battery indicator design, as well as experience with the battery. Both methods were applied before users received the EV, after 3 and after 6 months of usage. Furthermore, questionnaire items helped to identify participants' charging type, similar to Rahmati and Zhong's findings.

3.4.3 Traffic and safety implications

In-depth interviews were also applied in our research on traffic and safety implications and provided valuable insights into user concerns and experiences regarding low noise emissions of EVs. Additionally, questionnaires were administered three times. Finally, drivers also evaluated possible solutions designed to address the acoustic issue.

To gain a better understanding of how participants actually drive EVs, driving style was measured with a translated version of the Driver Style Questionnaire [35], which has been utilized in studies on behavioural adaptation in response to new technology [36]. Moreover, acceptance for regenerative braking was assessed via the van der Laan Acceptance Scale [21]. Additionally adapted items on trust [37] were included. Eco-driving was assessed through a newly developed scale consisting of 10 items. Data from questionnaires and interviews were supplemented and validated by data loggers, which chart, for example speed, acceleration, deceleration and energy consumption.

3.4.4 Acceptance

As a standard instrument for measurement of acceptance the van der Laan Acceptance Scale [21] was adopted. It consists of nine semantic differentials and reliably measures satisfaction as well as usefulness. In addition, a 7-item scale was developed and a single-item measurement [38] was additionally used to specifically measure attitudes towards EVs. These items are described in detail elsewhere [39].

Underlying the explorative character of the previous study, factors according to the TPB [23] were additionally assessed using 19 items. Behavioural intention, or 'purchase intention' in our study, was investigated by three items. Indicators of actual behaviour were recorded by data loggers and travel diaries. Data loggers recorded driven kilometres and frequency of vehicle use over the entire period of the study. Travel diaries contained data about driven kilometres, frequency of EV use during a 1-week period and reasons why the EV has not been chosen.

Willingness to pay (WTP) was assessed using the van Westendorp method [40], as proposed by Arndt and Engel [24]. This method is a well-proven instrument, which is used to calculate optimal price range by trading off price against quality of a product.

Environmental benefits and independence from oil are considered the major advantages of EVs. Before the EV was handed over to participants and after 3 months of driving the MINI E, participants were asked to report on the greatest advantages of EVs. To interrogate user's attitude towards climate protection and renewable energy, additional instruments were included in interviews and questionnaires [41]. Additionally a short scale measuring environmental concerns was utilized in each questionnaire [42].

To assess preferences, which are also crucial for the acceptance of EVs, a choice-based conjoint analysis was implemented three times. In 15 separate trials respondents could choose an appropriate EV from among three alternatives, or refuse all. The different products were described by four aspects, the specifications of which were randomly assigned by a computer. Experts rated factors that were varied in previous preference studies [e.g. 1, 20, 27] and decided on four most relevant factors: range, CO₂ emission, charging duration and monthly leasing rate.

4 Results

Data from the questionnaire applied before EV use indicate the following most important reasons for taking part in the study ($M > 5.00$ on a 6-point Likert scale): to test something new and innovative, to support the development of a new technology, and due a great interest in technology and to a belief that the electric drive is a future technology. Moreover, with participation in the study, they expected to contribute to environmental protection and achieve independence from oil. Further, an important motive reported by participants was to test whether EVs are an alternative to conventional cars.

Due to the methodological scope of the present paper, only selected findings are presented in more detail. Global findings from the pillar HMI suggest that drivers are not yet used to

electricity in vehicles and should be supported accordingly. Relating to the pillar traffic and safety implications, drivers not only appreciate reduced noise emissions of EVs and but also report few safety-related critical situations due to low noise levels. Detailed findings from the pillar traffic and safety implications are reported elsewhere [15]. An overview of the findings from the pillars mobility and acceptance is provided below.

4.1 Mobility

Before vehicle handover, the majority of participants expected to be constrained by the limited range of the EV. Survey data after 3 months of EV use indicate that for more than 94% of users a range of 140–160 km is sufficient for everyday needs, especially within the urban area of Berlin. Users estimated a mean maximum driven range of 150 km. When queried on target range values, participants reported <100 km as insufficient, ≥200 km as sufficient and 250 km as optimal as for range. Sixty-eight percent of users rated the flexibility of an EV as high as that of a conventional vehicle. Further survey data indicate that about 80% of daily trips could be done with the EV. If cargo and passenger space were not limited due to battery size, participants could imagine making >90% of trips with the EV. Similar results can be seen analyzing the travel diary data: Only 14% of the total number of trips driven in 1 week could not be done by the EV due to its restrictions (e.g. cargo space).

Users appraised range as a resource to which they could successfully adapt and that satisfied most of their daily mobility needs. However, some indicators were found that suggested suboptimal range utilization. These factors will be described in detail elsewhere [32].

4.2 Acceptance

First results show that attitudes towards EVs, measured using a 6-point Likert scale, are mainly positive. Attitudes remain positive during the first 3 months of EV use, in which there

is even a tendency towards a more positive assessment. Results of the van der Laan Acceptance Scale [21] provide a similar picture: On a continuum ranging from -2 to 2, usefulness reached a score of $M = 1.4$ ($SD = .452$), indicating well-rated practical aspects. Data concerning satisfaction showed similar results: With $M = 1.63$ ($SD = .476$), users assessed the EV as highly satisfying. Preliminary results showed high purchase intentions among users after 3 months of EV use: About 97% of participants indicated that they wanted to drive an EV in the future. Based on experience with the EV, 75% of users reported that future car purchases would include more eco-related issues. More than 95% of users believed that renewable energy should be used for charging EVs. Only 33% of users approved of nuclear energy to charge EVs, and only 8% would accept charging with energy from coal-fired power plants.

5 Discussion

In the present study, an extensive package of methods was applied to account for all relevant issues affecting acceptance and suitability of EVs in everyday mobility. To categorize relevant issues in users' evaluation of EVs, we proposed a four-pillared structure. This structure involves highly relevant topics and may serve as a framework for conducting future studies on user behaviour with EVs. In this context the methodology is not only applicable to hybrid households, but also to other settings, such as households, which only rely on an EV. Differences between certain user groups could be first identified qualitatively and then tested quantitatively via questionnaires and experiments. While other factors may play a role in user evaluation (e.g. after-sales services), our structure serves as a basis for further discussions on conducting user research in EVs.

Although our study sample might not be representative of the whole population due to self-selecting processes and other limiting factors (e.g. environmental consciousness, income and education), it provides valuable insights into preferences and attitudes of a technologically minded target group.

Preliminary results of the first two points of data collection in this study indicate that there appears to be high acceptance and purchase intentions among the EV test drivers. Hence, there may be a sizeable market potential for EVs given their current state of development. Users' concerns about limited range were reduced with experience whereby range was judged to be sufficient. Thus, a range equivalent to conventional ICE vehicles may not be required, at least for drivers in metropolitan areas. As the low noise levels are experienced as very attractive, this feature should be maintained in future EVs irrespective of potential sound designs to warn other road users. The concept of electricity in relation to energy consumption bears complexities for users. Users should be supported with adequate interface designs. Ecological aspects such as CO₂ emissions and the utilization of renewable energy play an important role in the evaluation of EVs and should therefore be capitalized on as a prominent and transparent feature of future EV concepts.

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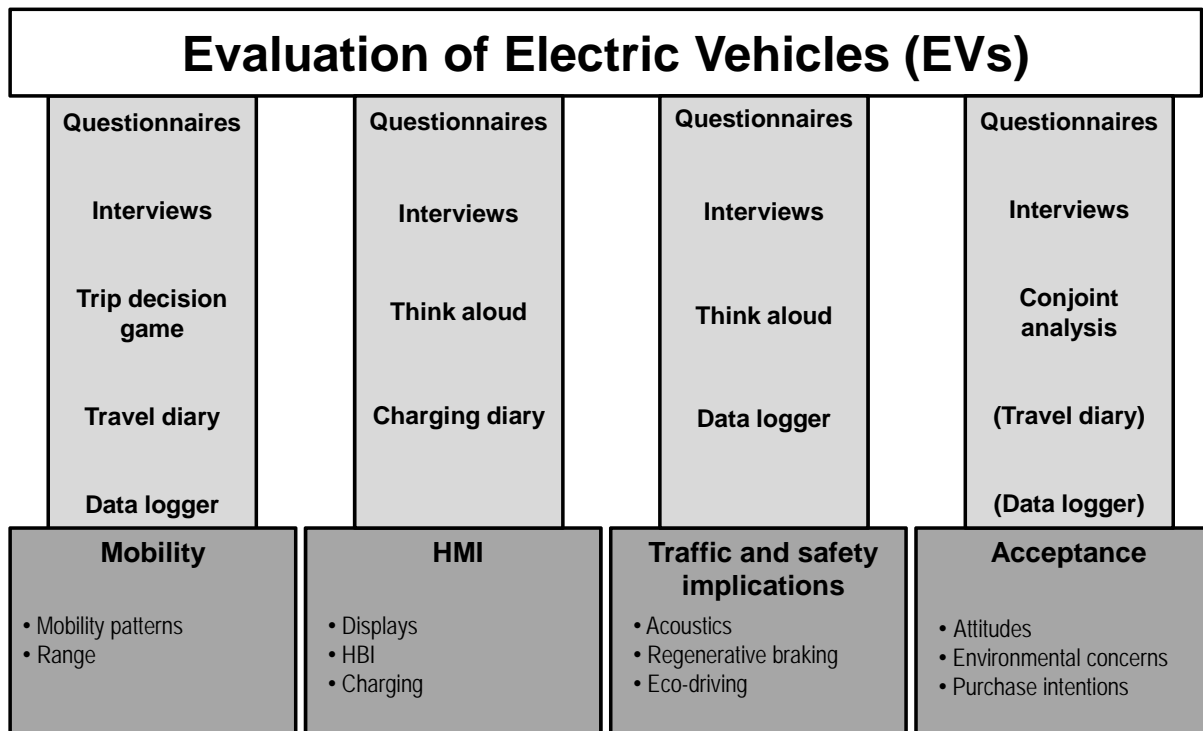


Figure 1 Four pillars in the psychological evaluation of EVs

First period of 6 months with 40 users in private setting

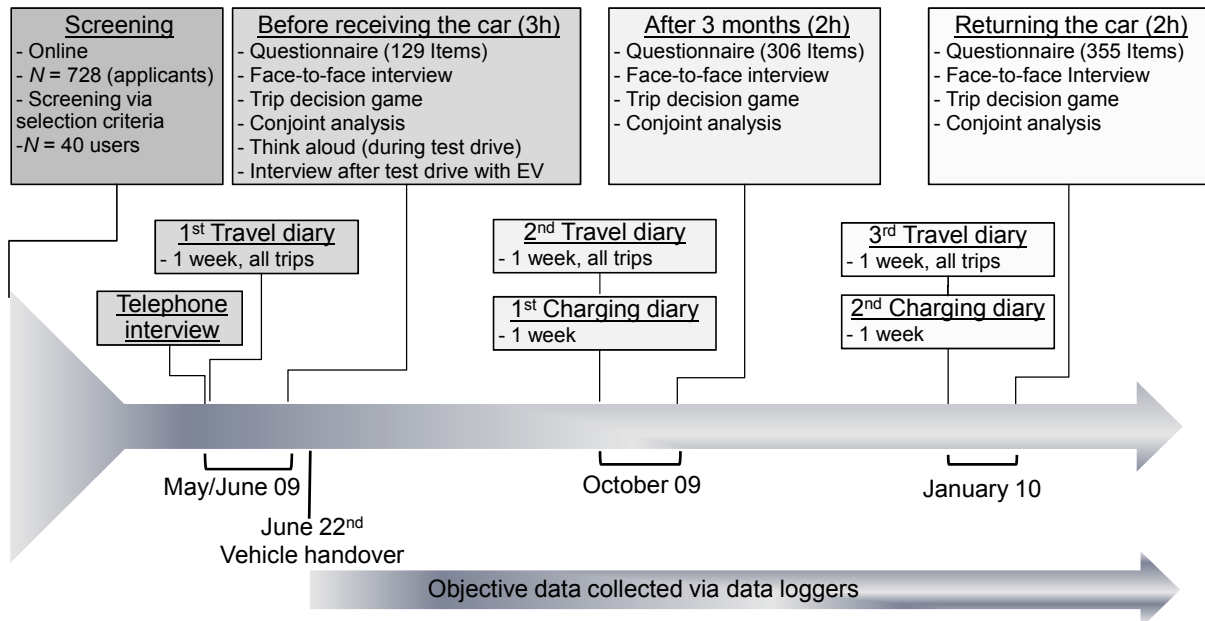


Figure 2 Time bar of the applied methods in the field study