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Coping with a growing number of e-taxis in Greater Stockholm: A stated adaptation approach

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ABSTRACT

The introduction of electric vehicles in taxi companies has shown that operating electric taxis can be profitable and useful already under current circumstances. However, a significant future increase of electric taxis within relatively short time could impose severe challenges to the system. In this paper, current charging patterns and demand for electric taxi rides were analysed to design future scenarios with a significantly higher number of electric taxis and changes in fast charging technology and pricing. A qualitative stated adaptation experiment was carried out among taxi drivers and carriers in order to explore important human factors for coping with changing driving and charging conditions in scenarios with significantly more electric taxis or potential policy changes. The main findings are that hired drivers and carriers react differently to temporal price differentiation. Hired drivers make more use of faster but more expensive charging infrastructure than carriers do. Speed and convenience of charging events seems to be more important for hired drivers than for carriers. An increasing number of electric taxis is likely to increase the strains on urban public charging infrastructure, thereby stimulating charging at home or at currently less popular charging infrastructure. Moreover, there is a risk that the already existing imbalance between carriers and hired drivers could escalate in the future.

1. Introduction

Zero-emission vehicles such as Battery Electric Vehicles (BEV) have a high potential to decrease climate and health effects related to exhaust gas emissions from the transport sector (Teixeira and Sodré, 2018; Razeghi et al., 2016). The inherent traits of the electric drivetrain, compared to the Internal Combustion Engine Vehicles (ICEV), are especially appealing in urban environments: zero tailpipe emissions, silent operation and higher energy efficiency. In recent years, politicians around to world have laid out plans to ban or severely limit access to ICEVs (especially diesel vehicles) in urban environments in the near future (Campbell and Keohane, 2018; Bennett and Vijaygopal, 2018). This shift in sentiment, combined with continuously decreasing costs of batteries (e.g. Nykvist and Nilsson, 2015) and an increased supply of BEVs in previously underserved vehicle classes (Muzi, 2018) could make a fast transition towards zero-emission vehicles such as BEVs significantly more likely in the near future. Organisations with large vehicle fleets that are intensively used, such as taxi companies, could be important players in the transition towards cleaner means of transport. Besides their intensive use, taxi vehicles are also believed to be most often used in densely populated urban areas. Relatively many vehicles in these areas are taxi vehicles. Therefore, replacing ICE taxis with BEV taxis (hereafter e-taxis) could have a significant positive effect on urban air quality and noise pollution.

In a previous study, it was found that e-taxis could be both economically and practically viable in taxi operations in the Greater Stockholm region (Hagman and Langbroek, 2018). High demand originating from e-taxi priority at Stockholms international airport (Arlanda) and through the novel e-taxi demand boosting initiative Nollzon (Zero Emission Zone, hereafter ZEZ) compensated for e-taxis' higher investment cost and additional time cost needed for charging. Organisations that have joined ZEZ will automatically prioritize e-taxis in the booking system from their address.

The typical taxi fleet on the Swedish market is nearly completely renewed every third year, implying that on average, one third of the fleet is replaced every year. Transitions from one drivetrain to another could thus hypothetically occur within a short period of time in the taxi industry, having a large impact on the transport system and charging infrastructure, especially in urban areas. The market for e-taxis appears ripe for an expansion in the Greater Stockholm area and beyond; high

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profitability and stricter environmental regulations are powerful incentives for taxi carriers to consider replacing their ICE taxis to e-taxis. However, a rapid transition of e-taxis can lead to numerous challenges that could affect the viability of e-taxi operation in the long term. Therefore, it is believed that the relevant stakeholders regarding taxi operations need to be both able and willing to adapt their behaviour in a future with considerably more e-taxis in operation.

In the current body of literature, there is a lot of emphasis on theoretical studies modelling the locations for charging stations in an efficient EV charging network for intensive users such as taxi (e.g. Tu et al., 2016; Jung et al., 2014). Less research has been done on the human and organizational factors affecting the deployment of e-taxis. For example, in Jung et al. (2014), it was assumed that dispatching would be connected and centralised, which does not reflect the Swedish situation which is decentralized and commission based. As a consequence, every taxi driver is incentivized to maximize revenues individually. This can lead to a situation where the user optimum does not correspond to the system optimum, especially in a situation where charging infrastructure becomes scarce. Therefore, it is important to understand how to align driver and system incentives. In other fields, such as the diffusion of cost saving manufacturing equipment, it has been found that human factors are critical. Incentivising workers to adapt their behaviour is indispensable for diffusion of the new technology to occur (Atkin et al., 2017).

The aim of this study is to investigate behavioural strategies of e-taxi drivers and carriers in order to cope with changing demand and charging conditions due to an increasing number of e-taxis. The point of embarkation of this study are the current use patterns of e-taxis and the corresponding capacity of fast charging stations, as well as the e-taxi specific demand patterns originating from ZEZ. Based on these, a stated adaptation experiment consisting of different scenarios has been designed.

This paper aims to answer the following research questions:

1. How do e-taxi drivers change their intended driving and charging patterns in scenarios where e-taxis would be a substantial part of the total taxi fleet?
2. How do e-taxi drivers adapt their charging patterns in scenarios depicting the introduction of policies aimed at improving the capacity of fast charging stations?

In the next section, a literature study is given concerning the use of e-taxis and related challenges. In Section 3, the methodology of this study is elaborated, followed by the results (Section 4). In Section 5, a discussion follows, including policy implications, limitations of the study and suggestions for future research. In Section 6, the conclusions of this study are elaborated.

2. Literature study

Investigating private users and their experiences of electric vehicles during the use phase have received ample attention in the literature thus far (e.g. Hardman et al., 2018). In a recent study exploring early adopters in Sweden it was found that most private EV-users live in single family houses in the suburbs, the majority of them driving between 30 and 100 km per day (Langbroek et al., 2017). Regarding charging behaviour, most users (70%) charge their EV exclusively at home and usually overnight (Vassileva and Campillo, 2017). Only 1% of EV-users have the habit to charge their EV when doing errands i.e. using the public charging network, while 15% stated that they charge wherever they can (home, work and while doing errands). The preference for evening/night charging at home amongst private users has also been found in Hardman et al. (2018), as well as in Langbroek et al (2017). Existing literature indicates that private EV users generally do not rely on the public charging infrastructure, home charging is significantly more important. Nevertheless, a network of public charging infrastructure can psychologically decrease “range anxiety” (Carbon and Gebauer, 2017), thus alleviating limited range as a barrier for EV adoption. Besides that, charging infrastructure in urban areas is frequently used by BEV-users with relatively low driving range, as well as for intensive users (Hardman et al., 2018). Thus, motivating a need for public charging to be built and operated in urban areas.

Professional users such as e-taxi drivers and users of electric light commercial vehicles (e.g. delivery vans) have different use and charging patterns compared to private users, which makes many of them more likely to depend on a daily use of public charging infrastructure. The body of literature on professional users is limited relative to private users. Figenbaum (2018) found that craftsmen’ and service enterprises’ range constraints can be mitigated by the possibility of charging during the day. However, the longer time needed to fast charge a BEV relative to refuelling an ICEV constitutes a significant opportunity cost (i.e. lost revenues) due to lost working time (Hagman and Langbroek, 2018). In a previous study conducted in the Greater Stockholm area it was found that e-taxis drove on average 335 km daily and that e-taxi drivers used the public charging infrastructure extensively, in many cases multiple times a day (Hagman and Langbroek, 2018). In theory, long-range e-taxis such as the Tesla Model S could provide sufficient daily range when charged overnight with a wall box charger. However, the daily reality of multiple work shifts and limited time between work shifts still leads to an extensive use of the public fast-charging network both during and between work shifts (Hagman and Langbroek, 2018), even if Tesla Model S is used. Several studies that have investigated e-taxis have found that due to their intensive use and long daily distance compared to private EVs, the feasibility of e-taxi is heavily dependent on the existence of an extensive urban fast-charging infrastructure. For example, in a simulation study for e-taxis in the Chinese city Nanjing (Yang et al., 2016), it was concluded that with a sufficiently large fast charging network, over half of all taxis could be replaced by e-taxis without the need of any driving pattern changes. In another study using agent-based simulation of e-taxis, it was shown that e-taxis (Nissan Leaf) could be feasible under “normal” circumstances (Bischoff and Maciejewski, 2016). The exception was in situations when there is a sudden demand peak, in which the use of ICE-taxis would be more efficient at the system level. Another aspect that was discussed at the system level is whether the dispatching of e-taxis should be based on stage-of-charge instead of their ranking in a traditional taxi queue (Bischoff and Maciejewski, 2016).

Tu et al. (2016) investigated the optimal location of charging infrastructure considering the presence of intensive use by e-taxis. A spatial-temporal optimization model for determining charging location was created also taking into account the dynamic demand for charging. The results of that study reveal that an optimum is theoretically possible ensuring a high level of service (time in operation) given a certain access to charging services.

However, as demand grows, a full coverage of the road network with an theoretical optimal density of charging stations is not sufficient. Queues are likely to grow at peak hours, thereby causing time and revenue losses for e-taxi drivers. Oda et al. (2017) conducted a study aimed at finding ways of mitigating these congestion problems at fast charging stations in Japan. Based on this study, it was recommended to increase the amount of EV charging infrastructure if the number of charging events at a charging station exceeds 10 per day. As charging events are believed to be random events, influenced by demand patterns and the composition of the e-taxi fleet, it is assumed that some overcapacity is needed to minimise the chance for congestion problems.

Abdalrahman et al. (2017) investigated the planning of charging infrastructure, thereby also taking the energy demand effects into consideration. They found that it is relatively complicated to predict when charging events happen and when significant additional loads on the electric power distribution system are to be expected. Analyses of the use patterns of charging infrastructure could shed light on this. An additional contribution in the field is a paper by Figenbaum (2019) in which it is argued that urban fast charging infrastructure could fulfil two needs; for private users that have forgotten to charge overnight and for professional users such as taxis that need to charge during the day. Only 2% of urban fast charging users charge more than once per day.

Yang et al. (2018) modelled the decision-making process of taxi owners and drivers in Hong Kong and concluded that for owners, the upfront investment costs, rental income and battery lifespan are important, while for drivers, the revenues, rental cost, access time to chargers and battery range are crucial.

A rare example when involving e-taxi stakeholders in the investigation is Scorrano et al. (2020). In their study, that was carried out in Florence, Italy, taxi carriers were interviewed in order to investigate acceptability and cost-competitiveness of e-taxis compared to hybrid and diesel taxis. The results from the study indicate that adoption of e-taxis was primarily driven by regulation in the form of e-taxi licensing agreements. One clear difference between the context in Florence and Stockholm is that carriers in Florence is limited to one vehicle licence, thus drivers are often carriers. In Stockholm, carriers can have several taxis and hired drivers.

A common denominator in previous studies investigating e-taxis is a large emphasis on centralized systems and simulations of optimization, with the exception of the study from Scorrano et al. (2020). A gap in the current understanding is regarding the human aspects of taxi drivers and their change in behaviours due to an emerging e-taxi fleet. This is particularly important when planning for rapid e-taxi growth in a decentralized taxi system. In Stockholm, where the carriers hire taxi drivers, there might be other considerations that are of importance, considerations that will be investigated in this study.

3. Methodology

For this study, a mixed methods approach was used, combining quantitative analysis of charging patterns with qualitative stated adaptation experiments. In order to construct relevant and realistic scenarios for the stated adaptation experiments, the first step was to analyse the current use patterns of the urban fast charging infrastructure and the e-taxi specific demand originating from the ZEZ scheme. The subsequent step was to construct the stated adaptation scenarios, that was the basis for the stated adaptation interviews.

Currently two models of e-taxis are in operation at the case taxi company; Tesla Model S and Renault Zoe, corresponding to approximately 1% of the case company's taxi fleet in 2017. Table 1 illustrates the vehicle specifications in terms of range and charging speed of Tesla Model S and Renault Zoe.

The case context of this study is the city of Stockholm, the capital of Sweden. The Greater Stockholm region has approximately 2.35 million inhabitants (SLL, 2019). Stockholm has two commercial airports; Bromma and Arlanda. Arlanda is by far the largest in terms of number of flights to European and intercontinental destinations. Located 43 km north of downtown Stockholm, Arlanda airport creates an important source for taxi demand, due to its distance from the city and its large volume of daily inbound and outbound flights. Fig. 1 shows the Greater Stockholm region, including the geographical location of Arlanda (top of the map).

Table 1
Vehicle specification.

	Tesla Model S85 (2017)	Renault Zoe (2017)
Battery size	85 kWh	40 kWh
Operating range (NEDC)	500 km	400 km
Maximum charging speed	125 kW (Supercharging)	22 kW

3.1. Charging infrastructure

The drivers of Tesla Model S e-taxis that are in use by Taxi Stockholm make use of three types of charging infrastructure: overnight charging at the garage or home location of the driver or carrier, fast charging at one of the public fast charging stations (50 kW) in Greater Stockholm and charging at Teslas own SuperChargers (125 kW) that are located between Stockholm and the international airport Arlanda. The Renault Zoe e-taxis are primarily used for paratransit services in the early morning and afternoon, while they are in used for general taxi rides during the rest of the working shift. These e-taxis are generally charged at overnight at home/garage or at public (semi-fast) charging stations, at a rate of up to 22 kW.

In order to get more insight into capacity problems at charging stations, data about the use of fast charging stations has been analysed to investigate whether there are any “peak hours” at charging stations. Data has been analysed for the fast charging stations set up by the utility company that supplied data to this study, as well as for Teslas own SuperCharger station that is located approximately halfway between the city centre of Stockholm and Arlanda airport. The data describes the situation between April 1st 2016 and March 31st 2017. Teslas own charging infrastructure is free for Tesla vehicles registered before January 1st 2017. For Tesla vehicles registered after that date, a limited number of kWh per year was still free at the time of the investigation. Once the free limit has been reached, each Tesla vehicle is charged on a per kWh basis. The pricing model at the fast charging stations at the utility company is on per minute basis, where corporate customers such as taxi operators typically have a discounted price compared to private customers.

3.1.1. Fast charging at the utility company

In total, between April 1st 2016 and March 31st 2017, 13,533 charging events with a charging volume of at least 1 kWh have been registered to 464 different electric vehicles. On average, this would imply 29 charging events per vehicle. However, the public charging stations are visited by a relatively low number of intensive users and a high number of users that rarely use the charging station over the course of one year. Out of in total 464 EVs being charged at one of the fast charging stations included in the dataset, 238 only used the charging station 1–3 times over the course of a year. The 10% most intensive users (50 EVs) covered 78.1% of all charging events, whereas the 20% most intensive users (100 EVs) covered 89.1% of all charging events.

The fast charging events took place at different locations within the inner city of Stockholm (36%; 4 locations), outside of the inner city of Stockholm (36%; 7 locations) and at the international airport Arlanda (28%; 2 locations). Charging at the airport was thus relatively popular.

The average charging event took 33 min. 90% of the charging events took less than 60 min. The time between two charging events at the same charging point is highly skewed with an average of 1055 min (17.6 h), a median value of 218 min (3.6 h) and minimum of 2 min. This implies that there are some charging stations with a very low utilization rate, but also indicating that overall, the maximum capacity of the charging station has not been reached yet. Short time values between charging events can indicate queues at the charging station. However, only 4.2% of charging events started maximum 3 min after the previous charging event at the same charging station, while 8.7% of charging events started maximum 10 min after the previous charging event.

Fig. 2 shows that the number of charging events is unequally spread throughout the day, with a peak between 12 PM and 4 PM.

3.1.2. Charging at Tesla SuperCharger

In total, 27,721 charging events were registered where a Tesla vehicle charged with at least 1 kWh. During the period (April 2016-March 2017), 1759 vehicles made use of the charging station. A small number

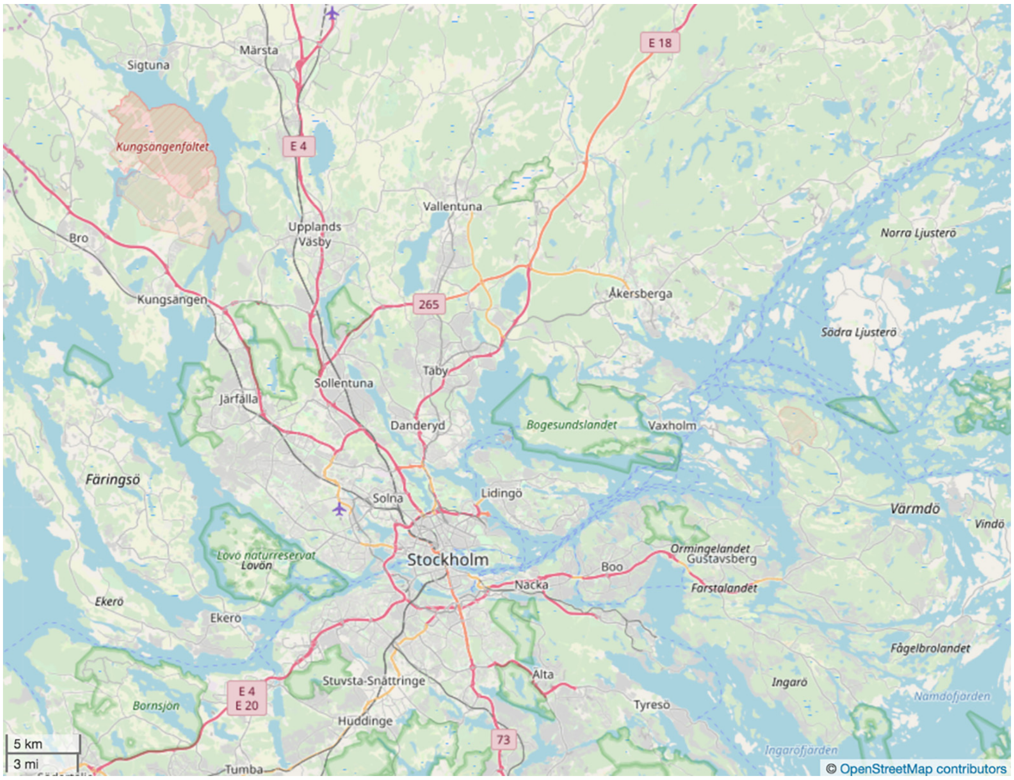

Fig. 1. Map of Greater Stockholm region.

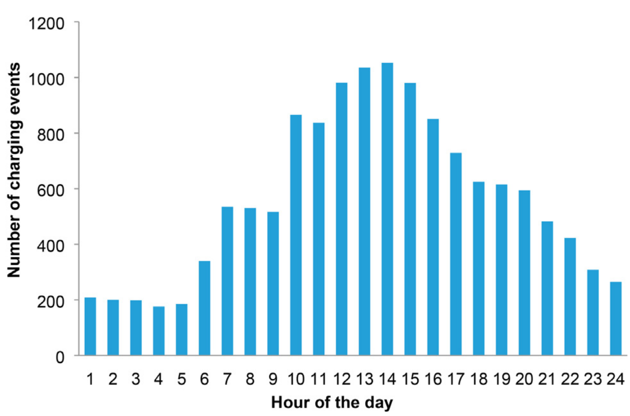

Fig. 2. Temporal distribution of charging events at the fast charging stations of a utility company in Stockholm.

of vehicles can be considered as heavy users, with 50 vehicles counting for 60% of all charging events and 100 vehicles counting for 71% of all charging events. Taxi vehicles count for 15,184 charging events (54.8%) and the maximum 13 Tesla vehicles that were in operation within Taxi Stockholm during this period count for 4739 charging events (17%).

The average charging time was 38 min (SD = 20.1 min). There were indications of queues at the charging station, especially during midday. Fig. 3 indicates the temporal distribution of charging events for all Tesla vehicles, while Fig. 4 indicates the temporal distribution of charging events for only taxi vehicles. Three obvious charging peaks are distinguishable for taxi vehicles: in the early morning, in the early afternoon and at night between 8 PM and 10 PM.

3.2. Zero emission zone

The Zero Emission Zone (ZEZ; Nollzon in Swedish) is a voluntary scheme for companies and organizations that wish to prioritize e-taxis to their customers and employees. The impact of this scheme partly depends on the fact that in Stockholm, it is relatively common to make reservations from a taxi operator e.g. via a phone call or through an app. All taxi orders from the addresses of the participating companies and organizations receives an EV-attribute, giving e-taxis priority for these bookings. The booking system first analyses whether there is any e-taxi in the zone where the order was made. If an e-taxi is present and available, the order is automatically assigned to this vehicle, regardless of its ranking in the virtual queue. By surpassing the queue for taxi orders, carriers/drivers adopting e-taxis can reduce the waiting time per booking, which in turns makes it more attractive to introduce e-taxis in the taxi fleet. A majority of the ZEZ connected companies and organisations are situated in the central areas of Stockholm. Most of the large taxi operators in Stockholm participate in the ZEZ-scheme and the prioritization works internally: if an order is made through one of the ZEZ connected taxi operator's systems, the operator's e-taxis are getting priority over the ICE taxis within the same operator. Therefore, e-taxi rides are even more likely to be pre-booked compared to ICE taxis, which have a higher rate of street pick-ups. The relative importance of bookings and street pick-ups is however dynamic in space and time. For example, street pick-ups are more likely on weekend nights, whereas pre-bookings are more likely at office hours. The taxi company investigated in this case study estimated that approximately 2/3 of their taxi rides are pre-bookings.

It has been analysed how many ZEZ-orders were made over the course of one year, and also how many ZEZ-orders succeeded i.e. when a customer was served by an e-taxi. The data used for the analysis of the ZEZ scheme was provided by the case taxi company and covers the six-month period between 1st of January 2017 to 1st of July 2017.

In total, 108,084 ZEZ orders were made from 195 different zones throughout the Greater Stockholm region. 6013 (5.56% success rate) of those orders were served by an e-taxi.

ZEZ orders are concentrated spatially and timewise. For example, the zone with most ZEZ orders stands for 9.78% of all ZEZ orders. The

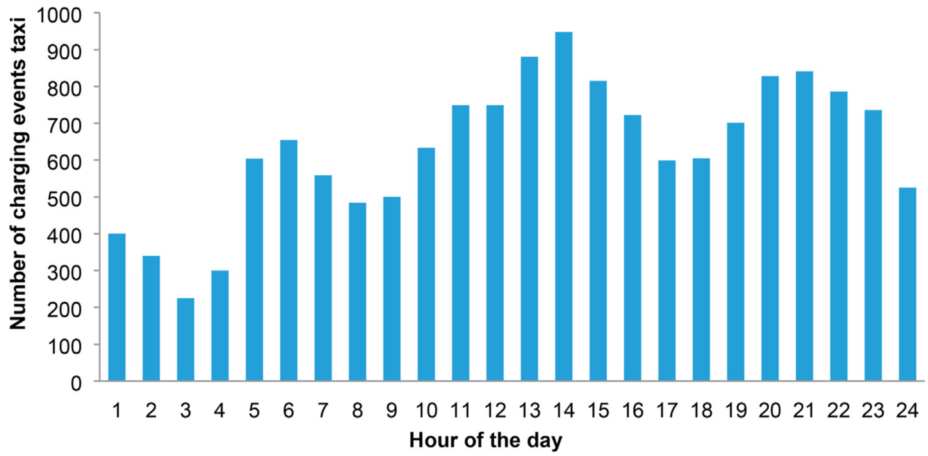

Fig. 3. Distribution over the day (all vehicles at Teslas SuperCharger).

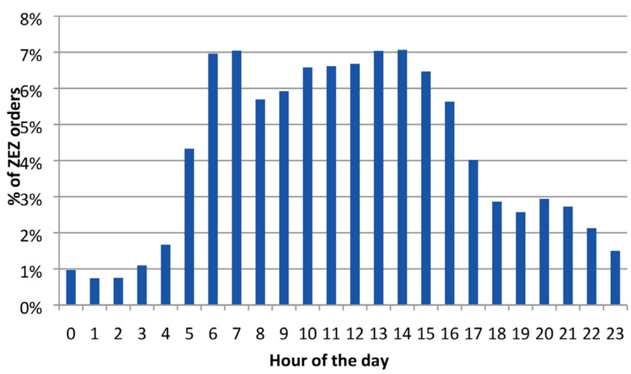

Fig. 4. Distribution over the day (Taxi only at Teslas SuperCharger).

25 most popular zones cover more than 70% of all ZEZ orders and 85% of all succeeded ZEZ orders.

Fig. 5 shows the distribution of ZEZ orders throughout the day. There is a peak in the early morning as well as between 10 AM and 4 PM. In the evening, the number of ZEZ orders decreases and during night hours, relatively few ZEZ orders were made.

3.3. Stated adaptation experiment

Based on the analysis of the usage data of the fast charging infrastructure as well as the analysis of the demand and success rate of ZEZ-orders, scenarios were designed for a stated adaptation experiment. A stated adaptation experiment (e.g. Janssens et al., 2009) takes current behaviour as a starting point and behavioural responses to several hypothetical scenarios are investigated. Compared to other types of stated preference experiments, stated adaptation experiments have a more realistic basis because they are based on real initial behaviour. The stated adaptation experiment in this study was carried out with one-to-one in-depth interviews. The interviews were carried out among 15 taxi drivers, 8 of whom are hired drivers, while 7 are carriers that drive as well. The interviews were between 30 and 60 min long. The interviews consisted of two parts: current driving and charging behaviour and stated adaptation to the described scenarios.

Stated adaptation experiments have been used in both quantitative and qualitative approaches. D'Arcier et al. (1998) considered stated adaptation methodology as a qualitative methodology that can precede other, more quantitative approaches. After 15–20 respondents, the main processes leading to the different behavioural responses are likely to have been captured. Lesteven (2014) also used a qualitative approach, where a travel diary was the basis for in-depth interviews where the respondents had to react to different scenarios related to traffic congestion. Quantitative approaches have been used by e.g. Cools and Creemers (2013), Cools et al. (2011) and Langbroek et al. (2018). The main characteristic of stated adaptation experiments is that there is a base of current travel behaviour, a stimulus from the researcher and a behavioural response to that stimulus.

Based on the charging and ZEZ data the authors identified patterns and future challenges of large scale EV deployment, specifically related to e-taxi operations. The scenarios were constructed with these issues in mind. In this way, two main aspects related to driving and charging behaviour were dealt with: a large increase of e-taxis in operations and potential policies that can alleviate charging and demand peaks during certain hours of the day. The next paragraphs will describe the scenarios that were constructed.

3.3.1. Scenario 1 10% e-taxis

In this scenario, 10% of all taxis are e-taxis, which would be the results if approximately 1/3 of taxi vehicle replacements in the coming year would be e-taxis. An increase of the number of e-taxis at such a rate is likely to have a detrimental effect on the efficiency of e-taxi operations. The additional e-taxis increase the pressure on the fast charging system, even if the charging infrastructure is developed in the same pace as the number of electric vehicles in Stockholm.

3.3.2. Scenario 2 50% e-taxis

This scenario is comparable to Scenario 1, but much more extreme and could, given the current taxi vehicle replacement rate, not occur in theory within at least the coming two years. A situation where half of the taxis are e-taxis would create an increased pressure on the charging infrastructure as well as a significant decrease of the effectiveness of the ZEZ scheme. Following the assumptions of Section 5, the ZEZ scheme is likely to get saturated from a market share of approximately 20% e-taxis.

3.3.3. Scenario 3 Temporal price differentiation at fast charging stations

In this scenario, the coping effects of taxi drivers facing temporal price differentiation at fast charging stations are investigated. Following the logic of congestion charging for making use of the road at busy hours, temporal price differentiation can steer charging behaviour towards less busy hours, thereby decreasing the risk for queues at charging stations. Night time charging will cost 1 SEK (≈€0.1) per minute in this scenario, day time charging 2 SEK (≈€0.2) per minute and charging between 11 AM and 2 PM 4 SEK (≈€0.4) per minute, coinciding with peak demand at fast charging stations.

3.3.4. Scenario 4 Ultra-fast charging stations

In this scenario, it is assumed that the charging infrastructure will be extended by several ultra-fast charging stations that allow for

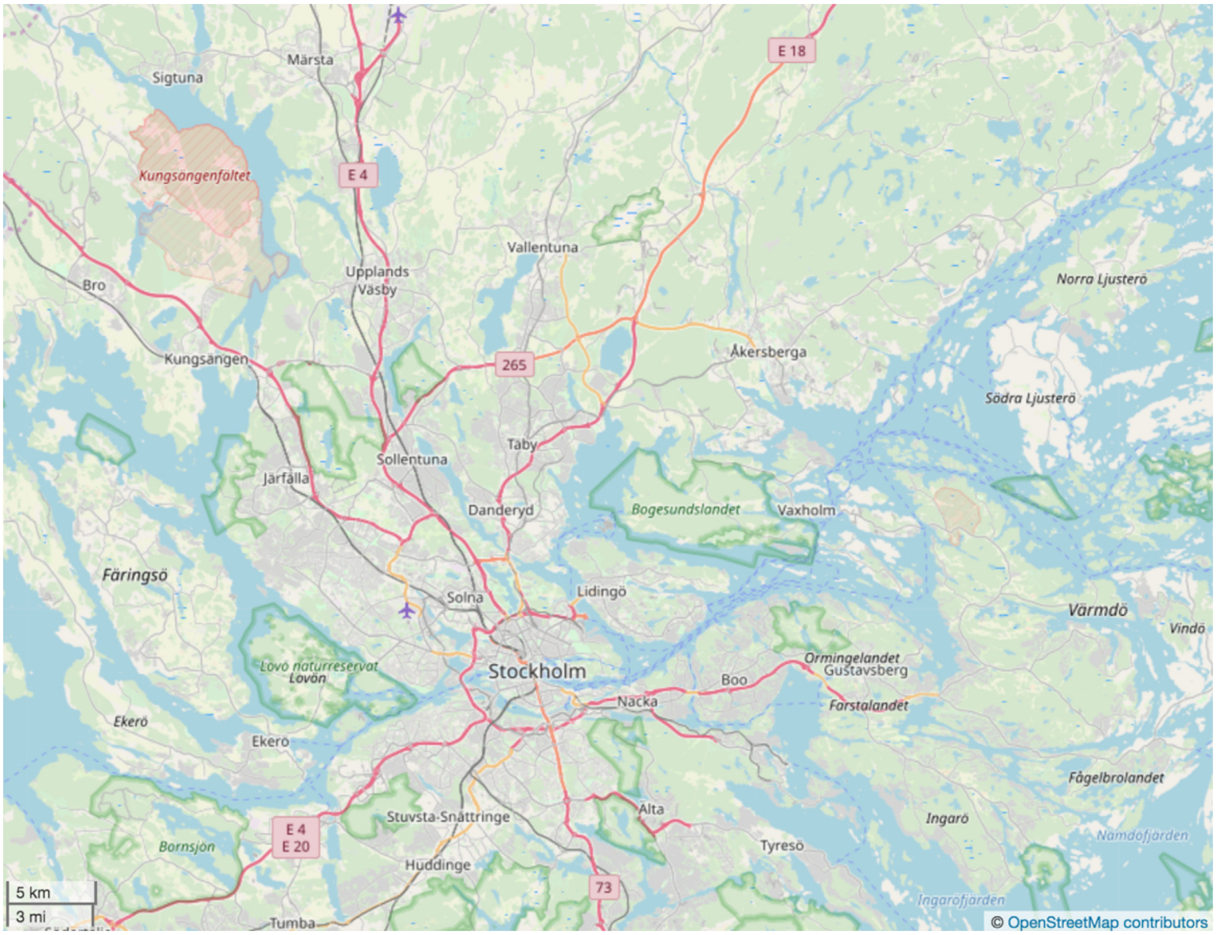

Fig. 5. Temporal distribution of ZEZ orders.

charging the vehicle twice as fast but at a price that is also twice as high per kW. Besides increasing the capacity of charging infrastructure due to an increase throughput, taxi drivers' time losses at charging stations decrease, while the charging costs for carriers increase.

3.3.5. Scenario 5 Queues at charging station

In this scenario, it is asked whether the taxi driver is willing to wait at a preferred charging station, knowing that there is an average queue length of 20 min. This scenario reflects situations that are already apparent at some charging locations and this scenario allows the respondents to reflect on the opportunity cost of waiting for a certain time.

4. Results and analysis

4.1. Current driving and charging patterns

As an anchor point, the current driving and charging behaviour of the interviewees was investigated. In the first part of the interview, the respondents were asked about their current driving behaviour (time of work shift, preferred zones to stay between customers) and charging patterns (timing and preferred locations for EV charging). Table 2 illustrates the driving and charging patterns for each driver and carrier that participated in the stated adaptation interviews.

All respondents mentioned the ZEZ scheme as an important source of taxi orders. 12 out of 15 respondents often stay within the inner city, as they experience that there is a concentration of ZEZ orders there. About half of the respondents indicated that they actively search for ZEZ orders in order to maximize their driving efficiency. Besides the inner city, a few other locations were mentioned where many ZEZ companies are located. In contrast, two drivers mentioned a zone where many taxi rides are ordered, but where no ZEZ companies are located.

Regarding charging strategies, different patterns could be seen across the interviewed drivers. Two of the drivers rely solely on overnight charging. Both are operating Tesla vehicles with single work shift, where overnight charging has proved to yield sufficient range to sustain their complete work shift distance.

For the 13 drivers that need to charge their vehicle during the shift, there are three main strategies mentioned by the respondents. The most common strategy is to charge the vehicle during lunch time. Another strategy is to charge the vehicle during quiet hours, while waiting for customers, which sometimes coincides with their lunch break. This strategy leads to a pattern of relatively many but short-duration charging events. The third strategy is to combine a charging event with going to a fitness club. Some carriers provide fitness club memberships to their drivers in order to make use of the time that is needed for charging. Several of the hired drivers also reflected on the fact that charging is unpaid work time, since their salary is based on the daily revenue gathered.

4.2. Changes of driving and charging patterns

4.2.1. Scenario 1–10% E-taxis

When faced with the scenario that e-taxis would increase fivefold compared to the current situation (from 2% to 10%), a large majority of the drivers and carriers indicated that they would adapt their behaviour to the new situation. Although some drivers had a hard time envisioning the plausible effects of such an increase, most drivers

Table 2
Driving and charging patterns.

Type	Vehicle model	Overnight charging	Fully charged at start of the shift	Distance per shift	Charging strategy
Carrier (V1)	Zoe	Yes	No	250 km	Lunch and quiet hours
Driver (V2)	Zoe	No	No	N/A	Public charging at end of shift
Driver (V3)	Zoe	Yes	No	200 km	At fitness clubs and public charging
Carrier (V4)	Tesla	Yes	Yes	N/A	Lunch, SC between shifts
Carrier (V5)	Zoe	Yes	No	220 km	Mid-day (2 h)
Driver (V6)	Zoe	Yes	Yes	200 km	Lunch
Carrier (V7)	Zoe	No	No	200 km	Lunch
Carrier (V8)	Zoe	Yes	No	210 km	During shift
Driver (V9)	Tesla	No	No	450 km	SC at quiet hours and change of shift
Driver (V10)	Tesla	Yes	Yes	425 km	Several charging events during shift and change of shift
Carrier (V11)	Zoe	Yes	Yes	200 km	Only overnight charging
Driver (V12)	Tesla	Yes	No	250 km	SC and fast charging during shift
Driver (V13)	Tesla	No	No	340 km	During quiet hours, SC and fast charging
Carrier (V14)	Tesla	Yes	Yes	200 km	Only overnight charging
Driver (V15)	Zoe	Yes	Yes	250 km	Lunch

speculated that the number one challenge is related to the public fast charging infrastructure. Referring to the occasional congestion at fast charging stations already in the current situation, many envisioned an almost "chaotic" situation if the number of e-taxis would increase to 10%. As one of the drivers stated:

"*If 10% (e-taxis) would happen tomorrow there would be war around the charging stations*".

11 of 15 drivers stated that congestion and competition for charging stations will be the largest problem. Although a clear need is expressed that the public fast charging infrastructure grows in tandem with the increase in e-taxis, many drivers also indicate that they would take measures to rely more on overnight home charging. Some envision a situation where charging at home is fast enough and that future e-taxis have large enough batteries for sustaining all or close to all work-shift driving needs with overnight home charging. Decreasing energy consumption through eco-driving is also discussed by one of the drivers. The aim of these behavioural measures would be to decrease the dependence on the public fast charging stations to a minimum.

The changing specific e-taxi demand originating from ZEZs is considered less of a problem. Many drivers expect the ZEZ advantage as only a transitional solution that would stepwise erode as more e-taxis roam the streets. As one driver said:

"*When more and more drive e-taxis it will just be like driving a normal taxi today*".

In terms of expected behavioural change the strategy differs between the drivers; several drivers indicate that they would become more active and search for areas where the competition for ZEZ orders is less intense, while others indicate that they would become less active seeking ZEZ orders since they expect the situation to become similar to the current situation for ICE taxi drivers.

4.2.2. Scenario 2–50% E-taxis

The more extreme scenario where 50% of all taxi vehicles are e-taxis was approached in a similar way by many of the e-taxi drivers; they would adapt to the new situation. The expected adaptation strategies however differed slightly compared to the 10% scenario.

A majority (9/15) indicated that the at 50% e-taxis the situation would be very similar to driving an ICE taxi pre-e-taxis. They would go back to their previous strategy of maximizing revenues and decrease their reliance on the demand from ZEZ and Arlanda Airport. As one of the driver stated:

"*I would probably not continue to actively search for ZEZ pre-orders, which i do very actively today*".

However, some drivers believe that an increase in ZEZ locations and demand would simultaneously take place which could compensate for the sharp increase in e-taxis. The consequence of this would be a significant deterioration of revenues for ICE taxi drivers according to several of the interviewees. Some locations such as Arlanda Airport could become virtually inaccessible for ICE taxis. A large fleet of e-taxis could crowd out ICE taxis at the terminals due to their advantage in the point queuing system.

A large share of e-taxis does however not come without significant challenges according to some of the drivers. These challenges are primarily related to range and charging. The most commonly mentioned expected obstacle is severe congestion at the fast charging stations, which need to expand at the same pace as the growth of e-taxis in order to avoid "chaos". If e-taxis range is greatly improved charging issues could also be avoided since little or no fast charging would be needed during the work shift or between work shifts. Some drivers believe that this is a prerequisite for e-taxis to even reach 50% of the taxi fleet. The combined expected effect of less demand advantages and charging issues is enough for three of the drivers to indicate that they would stop driving e-taxis or even retire as a taxi driver.

4.2.3. Scenario 3 – Price differentiation fast charging

Presenting the fast charging temporal price differentiation scenario to drivers yielded the most emotional reaction of all the scenarios. Several drivers became upset with the idea of increasing their charging costs and thus their ability to operate in a profitable manner. Rather they felt that other stakeholders also need to assist in the transition to e-taxis. One driver said:

"*We who are at the bottom, once again need to pay for the whole party, instead they should build more charging stations. I feel used, this is completely wrong*".

In terms of expected change of behaviour, a clear division can be seen between hired drivers and drivers that are also carriers. A large majority of the hired drivers indicated that they would not change charging behaviour despite the introduction of temporal price differentiation of fast charging rates. Their focus is not to minimize costs but rather to maximize revenues, which is reflected in their current charging behaviour. A change in charging behaviour can affect revenues and hence their income. Drivers that are also carriers responded differently to this scenario due to their dual focus on both costs and revenues. Several carriers indicated that the most important advantage of e-taxis currently is the low running cost, primarily the cost of electricity compared to diesel or biogas. Rising charging costs are perceived as a severe threat to the profitability of e-taxis. Therefore, most carriers would change their charging behaviour in order to avoid surcharge pricing, and in some cases, they would also instruct their hired drivers to do the same. One driver who is also a carrier expressed the following:

"*If I buy an EV that is 3 times more expensive, a large part of the profitability depends on replacing fuel costs by investment cost. Paying €0.3 per kWh, EVs would not be profitable".*

4.2.4. Scenario − 4 Ultra-fast charging stations

The respondents were asked whether they would make use of so called ultra-fast charging stations. These charging stations enable faster charging, but the cost per charging event would be higher. The majority of the respondents are interested in having the possibility to charge faster for an increased fee. However, there are times of the day when there is much more need for ultra-fast charging. During lunch breaks, for example, conventional fast charging stations are considered to suffice, whereas during demand rush hours, using ultra-fast charging stations would make more sense. Some respondents explicitly took into consideration that decreasing charging time has an economic value because more taxi rides can be organized if less time is devoted to charging. It is interesting to note that out of 4 respondents saying that ultra-fast charging stations are not worth the additional fee, 3 of them are carriers. Drivers are more likely to make use of ultra-fast charging stations in order to speed up the charging events:

"Carriers provide a provision based salary and expect their drivers to sit in the car and not to have to do anything, 'how beautiful then I don't have to pay the guy even though he is working.' But doing that, they should not be surprised that we become creative when we (drivers) are outside and.. yeah if it costs €1 per minute, whatever, if the charging station is free, we would charge the car there. The cost is not our problem anymore then," as one of the drivers formulated.

Because of the fact that carriers and drivers have partly different objectives, there is a danger that drivers' charging behaviour will not be optimized considering time gains and monetary costs.

4.2.5. Scenario 5 – Queues at charging station

The next scenario deals with information about average queuing time at a charging station. Approximately half of the respondents were found to be willing to wait on average 20 min at a charging station, whereas the other half preferred to continue to another station. A variety of reasons was mentioned: Preferring stable routines or acknowledging that 20 min is not a long waiting time for taxi drivers are reasons to wait, whereas drivers that know other, less well-known stations have an incentive not to wait but to continue to the next station. One driver mentioned that the choice depends on the charging status: if it is possible to postpone a charging event by driving to the next station, this option is preferable. However, if that is not possible, the driver has to wait.

5. Discussion

5.1. Coping with an increasing number of e-taxis in greater Stockholm

In this paper, the capacity and coping behavioural strategies of e-taxi drivers have been investigated through a stated adaptation experiment. The results of this paper indicate that an increase of the number of e-taxis in the taxi fleet is theoretically possible but practically difficult. An overarching theme among the interviewees in the scenarios related to growth of the e-taxi fleet is issues related to capacity of the fast charging system. Limited access and congestion at the charging stations are considered to be the largest bottleneck for e-taxi growth.

Based on the analysed charging data, it can be concluded that charging events are not randomly spread over the day which is also supported by the interviews. This is in contrast to the assumption that charging events are randomly distributed in time, which have been assumed in e.g. Oda et al. (2017). In the current situation, the average utilization rate of the fast charging stations in the Stockholm area were found to be rather low. However, e-taxi vehicles have a significant impact on the public fast charging stations at certain times of the day, primarily during mid-day hours when e-taxis are overrepresented at the charging stations. Thus, a growing fleet of e-taxis can be an important enabler for the build-up of the urban fast charging network due to their many times more intensive use compared to privately owned EVs. The concentrated use of charging stations during some hours of the day is likely to result in queues, which could negatively affect the usability of e-taxis according to the results of the stated adaptation experiment in this study. There are several strategies and policies that have been explored to mitigate these charging capacity issues, being temporal price differentiation, the use of ultra-fast charging stations that both decrease charging time and by doing so increase the capacity of these charging stations, as well as coping strategies such as taxi drivers moving to less busy charging stations in case of queues.

There is a general resistance against temporal price differentiation. Taxi drivers and carriers will not accept that their electricity cost will increase; e-taxis are an attractive option for carriers partly because of the fact that higher investment cost can be counterbalanced by lower marginal costs. Depending on the range and characteristics of the e-taxi vehicle, it is likely that there will be taxi drivers being captive to charge at certain times of the day in order to sustain work shift operations and thus not to compromise their revenues. Therefore, it is probable that there is a need for fast charging operators to provide peak capacity rather than average daily capacity, i.e. the fast charging network is not likely to be fully utilized during the course of a 24-hour period since charging peaks are the results of the driving patterns and demand optimization of taxi drivers. A similar capacity demand can be seen in for example public transportation where the morning and afternoon rush requires significantly more capacity relative to day-and night time. From a local electricity grid capacity distribution perspective, the current fast charging patterns of e-taxis could however be advantageous, since electricity effect peaks at the grid level are usually occurring in the late afternoon and morning. Increased use on the local grid due to fast charging might therefore be better placed at off-effect peak hours, such as mid-day.

Night time charging is not a panacea but can be very helpful for one-shift long range e-taxis. For two-shift e-taxis, as well as one-shift low range e-taxis, charging during the shift is currently needed. Ultra-fast charging that is now emerging is of high potential to decrease charging times and could therefore increase the capacity at peak hours. The result suggests that taxi drivers would use ultra-fast charging primarily at peak demand times even at higher kWh prices, although carriers are more price sensitive than hired drivers.

The imbalance between taxi drivers and carriers is likely to increase with an increasing number of e-taxis. As e-taxi vehicles are likely to become cheaper, while the queues at charging stations are likely to become longer and the chance to be the first e-taxi in the queue of ZEZ is going to be smaller, the operation of e-taxis is likely to become less efficient. The ZEZ scheme gives room for significantly more e-taxis if fully utilized. However, this implies that better information is needed and that the e-taxis spread out over the different ZEZ in another way than what is currently happening. As carriers are likely to profit more from using e-taxis than drivers due lower marginal cost of the electric drivetrain, an increasing imbalance is expected into the future. Currently drivers are not compensated for time spent charging. On the other hand, drivers do not pay for the charging cost and consequently, do not have financial incentives to charge as cheaply as possible. The demand incentives of the policies at the international airport of Stockholm and at the ZEZ companies are currently considered to compensate for time spent charging. However, it is questionable whether the future conditions will also allow the drivers to compensate charging time by a lower waiting time for customers. As long there is a market for both e-taxis drivers and ICE taxi drivers, the working conditions of taxi drivers are crucial for succeeding in higher market shares of e-taxis, since drivers can actively choose which type of vehicle to operate. The mismatch between taxi drivers and carriers is closely related to the Principal Agent problem often used in economics (e.g. Polutnik, 2015) i.e. misalignment in incentives. The e-taxi structure in the Greater Stockholm region investigated in this study is interesting since drivers and carriers have aligned incentives for revenue generation, due to their commission-based salary structure. In contrast, incentives are not aligned in order to minimize marginal costs, which arguably could be one of the largest advantage of e-taxis going forward, as taxi operators are commercial entities. As a consequence, e-taxi drivers are not stimulated to minimize cost related to driving styles and fast charging pricing, as is apparent in the divergent answers between drivers and carriers related to charging cost strategies in this study. Accordingly, a closer alignment in driver and carrier incentives in terms of cost optimization could be a promising policy to decrease overall e-taxi charging cost for the carrier. Such a policy could increase the financial attractiveness of e-taxis for carriers in the long run. This in turn could be an incentive for carriers to augment the compensation structure of e-taxi drivers in case temporal price differentiation and higher kWh pricing for ultra-fast charging were introduced.

5.2. Policy recommendations

Overall, the need for improved dialogue between charging operators and taxi companies has become apparent. Coordinating taxi companies' purchase plans of e-taxis with the build-up and geographical placement of fast charging stations is vital to avoid severe congestion at the charging stations if and when the fleet of e-taxis increase. From internal discussions within the research project where both a charging operator and a taxi company were part, it became clear that this is not done in any systematic way currently.

Providing fitness membership is one way to deal with the imbalance between drivers and carriers that has been found in this paper. When drivers can combine charging time with training added benefits are present, which at least in part can compensate for lost revenues due to charging. Another solution would be to consider charging time as working time, for which a fair hourly wage could be paid.

A plausible mitigation to the challenges related to fast charging and demand fulfilment investigated in this paper could be the development of a route planning system for e-taxis that consider both charging and ZEZ demand in order to optimize each work shift for revenues, costs and fast charging fulfilment.

Even though utility companies are exploring the idea of temporal price differentiation in order to balance demand and supply of capacity at charging stations, it became clear that it is risky to raise fast charging prices too early, at least for taxi operators. The attractiveness of e-taxis heavily depends on the relatively low operating costs. If these costs would increase significantly due to pricing decisions by fast charging operators, the market share of e-taxis could stay at a low level or even decrease over time.

5.3. Limitations

Firstly, this study was a case study, which implies that the generalizability might be limited. Certain aspects depend on the specific characteristics of the Greater Stockholm region or the specific schemes that is in place to prioritize e-taxi bookings e.g. ZEZ and the Arlanda queueing point system.

Another limitation is that in the fast charging data from the utility company, there are no specific taxi classifications for the vehicle type. The vehicles were classified as either professional or private users. Therefore, there is a risk that some professional users other than e-taxis, such as delivery vehicles, were included in the data analyses. However, in the dialogue with the utility company, they argued that a vast majority of the professional users consisted of e-taxis. The consequence of this potential contamination of the fast charging data is a under or overestimation of the use of fast chargers by e-taxis. In addition, did the fast charging data include all e-taxis in Stockholm, not only Taxi Stockholm, thus making an isolation of Taxi Stockholm charging behaviour impossible, although the interviews by and large confirmed the charging behaviour from the fast charging data.

It appeared that the stated adaptation experiment was not fully understood by all of the respondents, who reacted to the scenarios rather than giving indications of how their driving and charging patterns would be likely to change. In some cases, if was sufficient to repeat or reformulate the scenarios and to mention that the focus was on their plausible behavioural changes related to driving and charging. However, in a few cases the respondent simply did not understand how to answer in a given scenario. Due to time constraints, the researchers had to continue the interview without a complete answer to all scenarios in the stated adaptation choice test. As a consequence, some responses were omitted from the analysis, which could negatively affect the robustness of the results.

5.4. Future research

The balance between fast charging capacity and the electricity grid capacity is an interesting avenue for future research. As peak hours of electricity use by e-taxis might be different from the peak hours of general electricity use, it might be the case that e-taxi charging behaviour can act valley-filling on a local and regional scale.

Secondly, the balance between drivers and carriers is an interesting and unresolved issue. It could be investigated how high the compensation ought to be for charging time in order to equal taxi drivers' utility driving an e-taxi and a conventional taxi. If this compensation is too low, there is a chance to end up in a situation where there are not enough drivers willing to drive an e-taxi. If the compensation is too high, the solution is not optimal from the carriers' point of view, which could disincentives their adoption of e-taxis. Also, the value of the suggestion to provide fitness memberships or other perks to drivers using e-taxis could be investigated in more detail.

Lastly, it could be investigated how drivers of e-taxis can be better prepared to optimise their revenues. Driver education can increase insight into charging needs, assistance in finding hidden ZEZs that have a relatively high demand but are seldom visited by e-taxis and other strategies leading to a more efficient e-taxi operation.

6. Conclusions

In this study, the effects of large-scale electric vehicle use in taxi companies have been investigated from a driver perspective. The following conclusions can be drawn based on the stated-adaptation experiment:

1. How do e-taxi drivers change their intended driving and charging patterns in case e-taxis would be a substantial part of the total taxi fleet (10% and 50% of all taxi vehicles)?

Based on this study, it became clear that a significant increase of e-taxis would primarily lead to challenges related to charging. Therefore, taxi drivers with long-range e-taxi vehicles intend to try to facilitate overnight charging more than they currently do, as well as try to make more use of eco-driving to increase range. There are differences in the degree in which the drivers still concentrate on getting ZEZ due to decreased efficacy.

2. How do e-taxi drivers adapt their charging patterns in case of the introduction of policies aiming to make better use of the fast charging stations?

The policy measure of temporal price differentiation is considered to be unfair and likely to decrease the likelihood of further EV-deployment, a clear difference was observed between drivers and carriers. Drivers were less likely to change their charging behaviour than carriers. The willingness-to-pay for ultra-fast charging depends on whether the driver is a carrier as well. Moreover, the willingness-to-pay for ultra-fast charging depends on the time of day: at rush hours, there is a tendency to be willing to pay extra for a higher charging speed.

The willingness to wait for 20 min for a free charging session at a fast charger depends on the context of the situation, as well as the familiarity with the environment.

CRediT authorship contribution statement

Joram Langbroek: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Jens Hagman:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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