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Conditions for electric vehicle taxi: A case study in the Greater Stockholm region

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ABSTRACT

This study investigates the usability of electric vehicles (EVs) in a taxi company in Greater Stockholm, Sweden. By investigating cost and revenue data of both electric and conventional taxi vehicles, as well as by interviewing taxi drivers and carriers, an assessment has been made of the financial and operational implications of using EVs in a company's taxi fleet. Both the drivers' and the carriers' perspectives have been examined. The main findings are that the investigated e-taxis have a similar or lower Total Cost of Ownership and slightly higher profitability than the investigated conventional taxis. For taxi drivers, using e-taxis implies more advanced planning and revenue service time being sacrificed for charging. However, certain customers' preferences for EVs, as well as benefits such as corporate clients favoring e-taxis and a zero emission priority queuing system at Stockholm's main international airport (partly) compensate for time devoted to charging. In order to facilitate increased use of e-taxis, more fast charging facilities should become available at strategic locations. Besides that, there are signs that carriers' lack of information about the opportunities and consequences of shifting towards e-taxis hamper a wider deployment of e-taxis.

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Electric vehicle; taxi; Total Cost of Ownership; driving patterns; taxi stakeholders; case study

1. Introduction

Despite the environmental benefits of a transition towards zero-emission vehicles, the diffusion of electric vehicles (EVs) is still relatively slow (Muneer et al., 2015). Range limitations (Franke et al., 2017), charging (Egbue and Long, 2012), and cost issues (Larson et al., 2014) have been found to be important barriers. However, EVs have significantly lower operational costs, so the total cost of ownership (TCO) of EVs is in some cases competitive with that of internal combustion engine vehicles (ICEVs) (Hagman et al., 2016). This entails that use cases with high annual mileage and relatively short trip lengths, such as taxi companies, could be particularly attractive for a switch to EVs. The short turnover time of taxi vehicles enables a relatively fast transition towards EVs. Moreover, as many taxi vehicles drive intensively within densely populated areas, switching to electric taxis (e-taxis) has relatively high potential to improve urban air quality compared to an average private vehicle being replaced by an EV.

Several experiments and full-scale implementation of EVs in taxi companies are currently taking place. In certain cities and areas, the number of e-taxis has already reached high levels. Besides that, policy measures are taken in several cities. For example, in Shenzhen, Taiyuan and Beijing, mandates have been implemented to enforce that all new taxi vehicles will be EVs (Dunne, 2017). A similar measure will be in place in London from 2018: Transport for London (TfL) has decided that from then, all new taxis should be capable of driving emission free (Vaughan, 2017). In Europe, experiments with e-taxis take place in many other cities (e.g. Lambert, 2017; Vokou, 2015). E-taxis also seem to be popular specifically for connections between airports and city centres. For example, in Amsterdam, 167 Tesla vehicles provide taxi services between Schiphol airport and the city of Amsterdam in cooperation between a taxi company, a transport coordination company and Tesla (Vernooij, 2014). In Stockholm, there are similar driving factors aiming to make the international airport Arlanda more sustainable by incentivizing lower emitting ground transportation (Swedavia Airports, 2017).

Despite the fact that in more and more places, e-taxis are being used, insight into and specific understanding of the consequences of using EVs in taxi companies from the point of view of both taxi drivers and carriers is limited. The aim of this article is investigating both social and financial implications of introducing e-taxis based on data and experiences from the internal stakeholders of one of the largest taxi companies in Sweden, Taxi Stockholm. It is investigated whether e-taxis are an economically viable alternative in the Greater Stockholm area using a TCO and profitability

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analysis of both e-taxis and ICEV taxis. It is also investigated whether there are differences in actual driving patterns between e-taxis and ICEV taxis and whether taxi drivers have to adapt their driving and recharging patterns. Lastly, crucial e-taxi barriers for carriers and drivers, as well as potential solutions to these barriers are explored.

2. Background

Most studies investigating EV adoption have focused on private users (e.g. Rezvani et al., 2015). Besides instrumental characteristics, symbolic and hedonic attributes play an important role in the processes leading to EV adoption (Schuitema et al., 2013). For company cars, generally instrumental attributes such as purchasing price, fuel use and maintenance are considered to be most important for vehicle choice. However, Sierzchula (2014) studied the reasons for companies to adopt EVs and concluded that the most important factors that are mentioned there are willingness to test new technologies and public image.

The number of studies focusing on EV adoption in taxi fleets is rather limited and in these studies, the financial feasibility is central. For example, a recent study has been published (Kim et al., 2017) about the feasibility of EVs in taxi companies in Seoul. In that study, it was found that the operating distances of the e-taxis were lower than that of the Liquid Petroleum Gas (LPG) taxis that are the most frequently used taxi vehicles in Seoul. The results of a financial analysis showed that for private taxi companies, e-taxis are financially feasible, whereas for corporate companies, they are not. It was estimated that the financial feasibility would be much better in case the driving range would increase from 125 to 150 km, which implies that the object of this study has a relatively short range. The Seoul case can further be characterized by a relatively high number of boardings per day (with weekday averages between 22.3 and 27.8) and 97% of the trips were shorter than 20 km. 80% of the daily distances were below 300 km.

In another, simulation based feasibility study specifically about the return on investment of e-taxis, it was assumed that all revenues of a certain work shift would get lost after depletion of the battery (Carpenter et al., 2014), which is a worst-case scenario, as it disregards the possibilities of fast charging and continuing the work shift. Nevertheless, this study concluded that it can be profitable to have a fleet of 500 e-taxis (Nissan Leaf) in the San Francisco area.

Zou et al. (2016) analysed the driving patterns of 2,550 electric taxis currently in service in Beijing. One of the observed differences in driving patterns was that these vehicles rarely roam on the streets searching for customers, but instead take customers that have pre-booked a trip. Moreover, the average distance driven by e-taxis is with 117.98 km much lower than the average distance driven by ICEV taxis (249.3 km). These results imply that using EVs in taxi companies might come with considerable revenue losses. This finding contrasts with a simulation study of the potential of EVs in the Chinese city Nanjing (Yang et al., 2016), stating that with a sufficient fast charging network, up to 56% of the taxi vehicles can be replaced by e-taxis without the need of any driving pattern changes. In a study using agent-based simulation of e-taxi fleets, it was shown that e-taxis using Nissan Leaf under normal circumstances would function quite well. Only in situations where there is a sudden increase in demand, the use of ICEVs is more appropriate from a system perspective. This study looked at the system as a whole and it was discussed whether the dispatching of taxis should be based on stage-of-charge of the vehicles instead of their ranking in the queue (Bischoff and Maciejewski, 2014).

Due to their intensive use, e-taxis require a good and extensive charging network. Tu et al. (2016) investigated the optimal location of charging infrastructure specifically from the point of view of e-taxis. A spatial-temporal optimization model has been created taking into account the dynamic demand for charging. Abdalrahman and Zhuang (2017) investigated the planning of charging infrastructure, thereby also taking the energy demand effects into consideration.

Financial feasibility of e-taxis is crucial in order to make voluntary shifts towards the use of e-taxis. This entails an understanding of costs, where TCO is a useful tool (Ellram, 1995) as well as revenues in order to calculate profitability differences between different drivetrain technologies. The revenues depend on internal and external factors. The internal factors are based on the characteristics of EVs and the external factors are based on decisions of utility companies, policy makers and other external stakeholders. There are several more stakeholders than those for whom vehicle ownership and thus TCO are most relevant, each of whom having different objectives and conditions. Drivers, for example, might have different objectives than carriers, because they do not have to make capital investments but rather invest their time. On the other hand, both carriers and taxi drivers have the incentive to maximize revenues in order to maximize profits and wages, respectively, especially if wages are directly linked to revenues. Knowledge about these aspects related to the adoption of e-taxis is limited. Aligning driver and carrier needs and incentives are crucial for the adoption of e-taxis. Current high demand for taxi drivers in Sweden enables dissatisfied drivers to relatively easily switch to other taxi carriers or companies. This might differ from market to market, but it is reasonable to assume that user (driver) involvement is important for the adoption process of EVs in taxi companies. Moreover, many carriers are drivers as well. Therefore, this study will emphasize both social and financial perspectives of e-taxis for carriers as well as for taxi drivers. The main contribution of this paper is its interdisciplinary approach, where the results of an economic TCO analysis are combined with an analysis of driving patterns as well as qualitative analyses based on the internal stakeholders' perceptions of profitability, driving and charging patterns, working conditions as well as their perceived strategies to optimize their revenues. This holistic approach allows getting a much deeper understanding of the opportunities and challenges of using EVs within taxi companies in a supportive environment.

3. Case study: taxi Stockholm

This case study is based on a close interaction with Taxi Stockholm, the largest taxi operator in Greater Stockholm. Stockholm has a deregulated taxi market with free pricing. Taxi Stockholm is an economic association owned by ∼880 carriers that operate about 1600 taxis in the Greater Stockholm area. In total, around 6000 taxis are operating in Greater Stockholm. Taxi Stockholm earns revenues by collecting fixed and variable fees from its members (carriers). Although each carrier is a separate entity, Taxi Stockholm has a high degree of control of the taxi operations of each carrier. For example, there are restrictions for what types of taxi vehicles can operate within Taxi Stockholm. This approach with a high level of control is common in the traditional taxi industry as well as for start-up ride hailing services such as Uber or Lyft where the drivers operate their own vehicles. 13 long-range e-taxis (Tesla Model S85) are currently in operation in Taxi Stockholm. Tesla Model S is the only EV that currently fulfils Taxi Stockholm's base requirements in terms of range and comfort, although a test fleet of shorter range Renault Zoe EVs with restricted driving routes was launched in Taxi Stockholm during October 2017. Top management at Taxi Stockholm has publicly expressed a desire to increase the number of e-taxis in the near future.

A network of charging stations (∼1000 charging points divided over 155 charging stations) is available in Greater Stockholm, including fast charging stations of several utility companies and Teslas Supercharger station which is located between Stockholm and the international airport Arlanda. For fast chargers, an amount has to be paid per minutes, whereas charging at Teslas Supercharger station is free for Tesla cars that were registered before 2017. The Greater Stockholm area has ∼2 million inhabitants (SCB). The climate in Stockholm is characterized by four distinct seasons with short springs and autumns, mild summers and occasional snow and subzero temperatures in winter (Sweden, 2017). Stockholm thus has similarities with numerous cities and regions in northern Europe and North America in terms of size and climate conditions.

Two specific policies influence the operations and demand of e-taxis in greater Stockholm. Firstly, at Arlanda, the international airport of Stockholm, there is a queuing system based on vehicle emissions and drivetrain technology. E-taxis have the shortest queueing time and can pass the queue in many cases. Moreover, all taxi vehicles have to comply with CO_2 emission standards in order to be allowed to make airport pick-ups (Swedavia Airports, 2012). The second policy is called Nollzon (Zero zone); a novel private (non-profit) initiative aimed at boosting the demand for e-taxis. Hotels, corporations and other large employers that have joined Nollzon will automatically provide e-taxis priority in the taxi booking system from their address, at no additional cost to the customer. Nollzon has currently 734 premises and seven operating taxi companies (including Taxi Stockholm) signed up to the system. Most companies are situated in the Greater Stockholm area (Nollzon, 2017).

4. Methodology

4.1. Data

For this article, a mixed methods approach has been used consisting of three parts. Firstly, Taxi Stockholm has provided data about all bookings of 24 selected vehicles (9 EVs and 15 ICEVs using fossil fuels and biogas), as well as data on the level of a work shift for these vehicles. Pick-up time, drop-off time, locations for pick-up and drop-off, distance with and without customer, as well as the fare have been registered for each booking. In the work shift dataset, there is information about the total revenue of each work shift, the starting time and ending time as well as the total distance and the distance with customer. The selected vehicles have been used for at least the period April 2016–March 2017, which entails that the data from all eligible EVs at Taxi Stockholm has been used. In April 2016, only nine EVs were in use at Taxi Stockholm. Since seasonal effects were deemed important, 1 year data for nine EVs was preferred over having data for the full number of EVs in use in March 2017 (13) during a relatively short timeframe. Regarding the ICEVs, vehicles have been selected based on whether they can be booked with a so-called Premium attribute, as the EVs can be booked with this attribute as well. Otherwise, the selection of ICEVs was random. In the quantitative analyses for this article, a typology of the driving patterns of the e-taxis versus the conventional taxis will be presented, using descriptive statistics as well as hypothesis tests (Chi-Squared test and *t*-tests for independent samples).

Secondly, vehicle cost data has been provided by some of the carriers and have been complemented with external cost data. With this cost data, as well as information about revenues and driver wages, a TCO model and a profitability model have been constructed, which will be described in the following subsection.

The third data source for this paper consists of semi-structured interviews that have been carried out with taxi drivers, some of whom being carriers as well. Taxi drivers having driven at least 50 work shifts with one of the selected vehicles during the period April 2016–March 2017 have been invited for an interview. Eleven interviews have been done during the first half of June 2017 (6 e-taxi drivers and 5 conventional taxi drivers). Through the use of semi-structured interviews it has been secured that the same topics are brought up for each interviewee, while also allowing interviewees to bring up topics that they consider

Table 1. Interview topics taxi drivers.

Background information	Age, experience Taxi Stockholm, private car use
Charging behavior	When
	Where
	How (type of charging) Consequences for work
Range	Experiences range limitations
	Decline customers because of range limitations
	Influence of weather conditions
Demand and income	Airport trips and knowledge queuing system
	Nollzon and knowledge
	Comparison revenue EV versus ICEV
Driving behavior	Differences in driving behavior and reasons
Customers	Feedback from customers

particularly important. The list of topics for the interview is described in Table 1.

The interviews have been transcribed and coded. Conventional content analysis (Hsieh and Shannon, 2005), where the coding categories are directly derived from the text data, has been conducted. Based on a categorization of the codes, a synthesis of the elements related to the topics of this paper, as well as their interrelationships has been made. The use of mixed methods allows to not only get insight into cost and driving patterns, but to also get more insight into drivers' experiences and input for analyzing particular cost and driving patterns.

4.2. TCO and profitability model

The TCO model used in this article has been constructed in two steps. The first step consists of identifying the different cost factors incurred to taxi carriers related to owning a particular vehicle model. The second step consists of extracting, computing and extrapolating the cost data into a coherent TCO result. In contrast with the driving pattern analysis the TCO analysis was separated into three vehicle drivetrains (electric, biogas and diesel hybrid); since each drivetrain has its own distinct cost structure. The April 2016–March 2017 distance and revenue data was converted into mean values for each drivetrain and was extrapolated to a full ownership period, in order to illustrate a baseline use case scenario for each drivetrain.

A sensitivity analysis was then carried out for each drivetrain base case, illuminating the effect of variations in vehicle distance and purchasing price on TCO. Three scenarios for vehicle distance were tested in relation to the base case; 20% shorter total distance, 20% longer total distance and equal distance for all three drivetrains based on their combined distance mean value. Vehicle distance is assumed to cause variation in fuel costs, service costs, wages and revenues. The effect on other parameters such as tyres has been omitted since data have been imputed on an annual basis rather than on distance. For purchasing price one scenario was tested against the base case, where purchasing price for the e-taxi was set at the same level as the most expensive ICEV taxi. This represents a scenario where e-taxis have reached purchasing price parity with ICEV taxies. Purchasing price is assumed to cause variability in depreciation and interest costs.

Efforts have been made to limit the use of assumptions and instead rely on real cost data incurred during the ownership of existing taxi vehicles based on external data sources as well as information provided by Taxi Stockholm and some of its carriers. Fuel and electricity prices were computed by extrapolating the mean price payed by the taxi carriers from April 2016 to March 2017, which was then multiplied with the average fuel/electricity consumption for each drivetrain, based on real world data from a an online crowd source service (Spritmonitor, 2017). Insurance, service, and tyre costs have been provided by Taxi Stockholm carriers. Interest costs have been computed through an annual instalment model provided by a large financial institution that finances many vehicle purchases within Taxi Stockholm. Tax rates were accessed through the Swedish Transport Department (Transportstyrelsen, 2017). In Sweden, a subsidy of 40,000 SEK (~€4000) is available for the purchase of an EV, which is also available for vehicles in commercial use.

Several assumptions and limitations were nevertheless necessary. Ownership period was set to 36 months, which is a common but not a regulated ownership period for taxi. Costs for reparations were not included due to lack of comprehensive data. Depreciation was estimated through an online vehicle valuation service (Bilpriser, 2017), since all of the vehicles in the sample are still in operation, actual depreciation is as of yet not known. Lastly, the charging patterns for the e-taxis are assumed to be evenly distributed between home charging, free fast charging at Tesla's own charging station and paid fast charging at one of the commercial fast charging operators in Greater Stockholm.

4.2.1. Total cost of ownership model

The cost of purchasing, owning, and operating a taxi vehicle entails several different cost factors for the taxi carrier, direct as well as indirect costs such as opportunity costs. The TCO model used in this article is confined to the direct costs associated with vehicle ownership. Potential indirect costs will be delineated in the qualitative section of the paper. After consulting several carriers, it was concluded that the cost factors to be included in a taxi TCO are approximately the same as the cost factors for private ownership. The model used in this article has therefore been inspired by the private ownership TCO model used in Hagman et al. (2016), with the addition of tyre cost, as tyres for taxi vehicles need to be frequently replaced. All costs used in the model are excluding VAT, unlike in the TCO for private consumers. The following equation defines the calculation approach:

$$\mathrm{TCO} = (\mathrm{PP} - \mathrm{RP}) + \mathrm{Fc}(\mathrm{TKD}) + \left(\frac{\mathrm{rP}}{1-(1+\mathrm{r})^{-\mathrm{N}}}\mathrm{N} - \mathrm{P}\right) + \mathrm{IC} + \mathrm{SC} + \mathrm{TC} - \mathrm{S}$$

TCO is the total cost of ownership for the ownership period, PP is purchasing price, RP is reselling price at the end of the ownership period. The difference between *PP* and *RP* equals the depreciation of the vehicle during the ownership period. FC is fuel cost per kilometre, *TKD* is total kilometres driven, *r* is monthly interest rate, *P* equals the amount borrowed and *N* is the number of monthly interest payments. The total interest cost equals

$(rP/(1\text{-}(1+r)^{-N}))N\text{-}P$, *IC* is insurance cost, SC is service cost, TC is tyre cost, GT is government taxes, and *S* is government subsidies.

4.2.2. Profitability

In an unregulated taxi market with free competition such as the Swedish market, profitability is of crucial importance. It is beyond the scope of this article to calculate overall carrier profitability. Therefore, the calculation approach used in this paper is adopted in order to isolate vehicle specific profitability. The following equation illustrates our approach:

$$EBIT = R - W - TCO$$

EBIT equals earnings before interest and taxes for a specific vehicle, R is vehicle revenue, W are wages to drivers of the vehicle and TCO is total cost of ownership. Revenue and wage data are provided by Taxi Stockholm through their booking and work shift data as well as from the provision (wage) agreements of their drivers.

5. Results

5.1. Driving patterns

In this Section, the driving patterns and work shift patterns of e-taxis are compared with those of conventional taxis (diesel, gas or diesel hybrid vehicles). The basis of this analysis is the driving pattern and revenue data of nine e-taxis (Tesla) and 15 conventional taxis during one year. A summary of the results is listed in Table 2.

5.1.1. Use intensity

Over the course of a year, 4241 work shifts by e-taxis (9 vehicles; 1.29 work shifts per vehicle per day) and 6385 work shifts by ICEV taxis (15 vehicles; 1.16 work shifts per vehicle per day) have been registered at Taxi Stockholm. A work shift has been defined as a time period being logged in the system with the same driver and having had at least one customer. On average, the e-taxis have driven 260 km per work shift, while the ICEVs have driven 240 km per work shift. Within the groups of e-taxis and ICEVs, there is a large variation. The average distance per shift per e-taxi varied between 208 km for the e-taxi with the lowest average distance and 310 km for the e-taxi with the highest average distance per shift. For the ICEVs, the average distance per shift varied between 196 and 311 km. About 64.9 and 63.9% of the average distance per shift consisted of kilometres with customers. Even though e-taxis need to be charged, which takes a considerable amount of time, the prioritization of e-taxi rides due to the Nollzon scheme and at the airport Arlanda, in combination with the for EVs relatively high range of Tesla taxis, are likely to be contributing factors to the average distance per shift for EVs to be slightly (8%) higher than the average distance per shift for ICEVs. Moreover, sometimes taxi drivers make detours in order to charge their EV, which might be another contribution to a higher average shift distance. Finally, as trips from and to Arlanda are relatively long-distance and e-taxis are relatively likely to take these trips, the average distance per shift is likely to be slightly higher. However, the range of average distance per shift values among the e-taxis is very similar to the range of average distance per shift values among the ICEVs.

Table 2. Summary statistics driving patterns.

Variable	Value EV	Value ICEV	*p*-value
Number of work shifts	4241	6385	na
Number of vehicles	9	15	na
Number of work shifts/vehicle/day	1.291	1.166	na
Mean distance per work shift (in km)	259.806 km	240.071 km	<0.001
% of paid distance	64.9%	63.9%	<0.001
Mean revenue per work shift (in €)	€334.32	€340.20	0.016
Mean work shift duration (in h)	9.351 h	9.824 h	<0.001
Hourly driver salary (in €)	€15.29	€14.81	na
Hourly revenue (in €)	€35.63	€34.52	<0.001
Revenue per paid km (in €)	€2.14	€2.38	<0.001
Revenue per customer (in €)	€33.43	€31.59	<0.001
Number of customers per work shift	10.478	11.311	<0.001
Number of customers per hour	1.120	1.157	<0.001
Maximum distance for a booking (in km)	102.9 km	355.3 km	na
Maximum distance for a work shift (in km)	697.9 km	944.7 km	na

5.1.2. Revenues

The average revenue per shift of the analyzed e-taxis is with €334.30 less than the average revenue of the analysed ICEV taxis (€340.20; *t*-test, $p = 0.016$). However, because of the fact that the average work shift duration is lower, the revenue per hour is higher for e-taxis than for ICEV taxis (€35.60 versus €34.50; *t*-test, $p < 0.001$). The reason for this difference is the higher average revenue per customer (€33.40 versus €31.60; *t*-test, $p < 0.001$). E-taxis are more likely to drive to or from the airport of Stockholm than ICEV taxis (11.6% of bookings versus 9.4%, Chi Squared test, $p < 0.001$), and trips to the airport are relatively long and relatively cheap per kilometre. The price per paid kilometre is lower for e-taxis than for ICEV taxis. Also, the average number of customers during a work shift differs: On average, during one work shift 10.48 customers are transported by the e-taxis, whereas 11.31 customers are transported by ICEV taxis during one work shift. Important to note is that taxi drivers' income is based on the revenue they get, as the wage is provision based, even though there is a minimum wage at Taxi Stockholm. Therefore, the revenue for each work shift is directly related to the wage of taxi drivers.

5.1.3. Pick-up zones

There are a few reasons why the pick-up zones for e-taxis might be different from those of ICEV taxis. Firstly, there are fast chargers in some specific zones, so vehicles charging at these zones might be more likely to get a booking from these zones afterwards. Secondly, some specific organizations having a Nollzon attribute prioritize e-taxis. Taxi drivers being in these zones are more likely to get these specific bookings, and because of this policy, taxi drivers might increase their stay in these zones. Also Arlanda, the international airport of Stockholm, is a zone where EVs have relatively more pick-ups than ICEVs.

There are statistically significant differences between the pick-up locations of e-taxis and ICEV taxis (Chi-Square test, $p < 0.001$). Some central areas have more e-taxi pickups, whereas other central areas have less. There seems to be a correlation between the zones with many hotel facilities and e-taxi pickups. For one of the central zones (Radiohuset/Karlaplan), the proximity to a fast charging station might play a role. The western part of Stockholm is less frequently served by e-taxis as would be expected. Generally, in the northern corridor between the international airport of Stockholm (Arlanda) and the city of Stockholm, the e-taxi is overrepresented, with an extraordinary high number of pick-ups from Upplands Väsby, in the proximity of the Tesla Super Charger, where Tesla cars that have been bought before 2017 can charge for free. Another potential factor is the high number of Nollzon companies in the north of Stockholm.

5.2. TCO and profitability

The results for the three TCO and profit base scenarios are depicted in Table 3. Tesla Model S85 and Mercedes-Benz E300 Hybrid have a similar TCO of €56,524 and €56,123 respectively, whereas the Mercedes-Benz E200 NGT has a TCO that is 3.5–4.3% higher. In terms of TCO per kilometre, the Tesla Model S85 will give its owner a cost advantage of 24 and 16% compared to the Mercedes-Benz E300 Hybrid and the Mercedes-Benz E200 NGT, respectively. The profitability computation reveals that the Tesla Model S85 has a 9–32% higher total EBIT than that of the Mercedes-Benz vehicles, as well as a higher profit margin. However, EBIT per km is 9% higher for the Mercedes-Benz E200 NGT compared to the Tesla Model S85 and the Mercedes-Benz E300 Hybrid, due to higher revenues per km.

The sensitivity analysis in Table 4 reveals that the Tesla Model S85 has the lowest TCO/km in all four scenarios. The largest relative TCO benefits can be seen in the equal purchasing price scenario (36–46% lower TCO), followed by the scenario with 20% longer driving distance (17–29% lower TCO). In the equal distance scenario, the Tesla Model S85 has the same TCO/km as the Mercedes-Benz E200 NGT (8% lower compared to the Mercedes-Benz E300 Hybrid). Tesla Model S85 has the highest EBIT in all scenarios except in the scenario when all three vehicles are assumed to have equal total distance, where the Tesla Models S85 has the lowest EBIT.

Table 3. TCO Results and Profitability (36 months' ownership).

Model	Tesla Model S85 (2014)	Mercedes-Benz E300 Hybrid (2014)	Mercedes-Benz E200 NGT (2014)
Total km	367,377 km	278,004 km	319,758 km
Purchasing price	€61,284a	€34,160	€30,400
Depreciation	€30,926	€22,038	€18,508
Fuel	€9,350	€19,052	€24,076
Interest	€3,910	€1,654	€1,472
Insurance	€5,713	€3,013	€3,013
Service	€2,100	€8,146	€9,241
Tyres	€4,416	€2,112	€2,112
Taxes	€108	€108	€108
TCO	€56,524	€56,123	€58,530
Revenues	€448,477	€369,536	€427,450
Wages (-)	€249,798	€205,828	€238,086
TCO (-)	€56,524	€56,123	€58,530
EBIT	€142,156	€107,585	€130,834
Profit margin	31.7 %	29.1 %	30.6 %
TCO/km	€0.154	€0.202	€0.183
Revenues/km	€1.22	€1.32	€1.34
EBIT/km	€0.387	€0.387	€0.41

[a]Government purchase subsidy of €4,000 have been deducted.

Table 4. Sensitivity analysis TCO.

Model	Tesla Model S85 (2014)	Mercedes-Benz E300 Hybrid (2014)	Mercedes-Benz E200 NGT (2014)
Case 1: 20% shorter total distance (fuel, service, wages, and revenues)			
TCO	€57,337	€53,535	€51,659
TCO/km	€0.195	€0.241	€0.202
Revenues	€358,782	€295,628	€341,960
EBIT	€101,607	€77,432	€99,832
Case 2: 20% longer total distance (fuel, service, wages, and revenues)			
TCO	€60,571	€64,369	€63,808
TCO/km	€0.137	€0.193	€0.166
Revenues	€538,173	€443,443	€512,940
EBIT	€177,844	€132,080	€163,429
Case 3: All vehicles same total distance (Fuel, service, wages and revenues)			
TCO	€57,949	€63,210	€57,919
TCO/km	€0.180	€0.196	€0.180
Revenues	€392,729	€427,632	€430,060
EBIT	€116,034	€126,235	€132,601
Case 4: E-taxi same purchasing price as ICEV (depreciation and interest cost)			
TCO	€42,207	€58,952	€57,734
TCO/km	€0.115	€0.212	€0.181
Revenues	€448,477	€369,536	€427,450
EBIT	€156,472	€104,756	€131,631

( ) Vehicle costs and/or revenue affected by the change in case input variable.

5.3. Perspective of taxi drivers

From the perspective of taxi drivers, the working environment and the daily revenue are the crucial elements influencing the interviewed drivers' satisfaction with e-taxis. In the following subsections, a summary of the interviews is described.

5.3.1. Working environment

Because of the need for charging, more planning is required from taxi drivers. This increases stress during the work. On the other hand, charging time can be combined with a break. "The Tesla forces you to take a lunch break, which is a good thing. I know a good Asian restaurant close to a charging station," (male, 31 years) according to one of the interviewees.

The comfort level of Teslas is considered to be satisfactory, even though the comfort of other commonly used taxi vehicles in Stockholm (Mercedes and Volvo) is considered to be higher. The suspension is not the same, so especially at speed bumps the Tesla has to slow down much more than other vehicles. The seats of the Tesla are considered to be relatively good and the fact that the vehicle is quiet is highly appreciated by the interviewees.

More social contact with customers is an often-mentioned positive effect. Most customers are enthusiastic about riding a Tesla and are more talkative. On average, they also give more tips. Even though many customers ask the same questions, these social contacts are appreciated by all of the interviewed e-taxi drivers and one of the interviewees even considered them as the second most important advantage of driving a Tesla.

Conflicts and envy of ICEV taxi drivers have often been mentioned as negative effects of driving Tesla taxis. Five out of six interviewed Tesla drivers have experienced these types of conflicts that occur quite frequently, especially when customers surpass ICEV taxis queuing up to enter a Tesla taxi. Sometimes other taxi drivers request Tesla drives to tell the customer that there are other vehicles first in the queue. The general attitude among Tesla drivers is however that the customer has chosen the Tesla, and he or she has the right to do so. *"What else can we do? Should we question the customer? Is that what our company stands for?" (male, 31y)* one of the interviewees wondered.

5.3.2. Revenues

As the wage of taxi drivers largely depends on the revenues generated, revenue per hour is a crucial factor for taxi drivers to accept switching to an e-taxi. Two main reasons have been mentioned negatively affecting the revenue of e-taxis. Firstly, revenue is affected by declining trips. In many cases, drivers do not know the destination of the trip at the moment a booking is made. Therefore, the available range might not be enough. Some interviewees declared that they have never been forced to decline any trip, whereas other interviewees declared that they have to decline trips fairly frequently. Secondly, revenues are affected by charging time during the work shift. Especially in case a vehicle is used for two work shifts per day, there is not enough time to charge the vehicle between work shifts. Even though it is up to the carriers to decide on a policy about charging status, all interviewees told that it is expected to leave the vehicle with 250–300 km of battery range to the next driver. As the total distance during a work shift is largely variable, it is usually necessary to charge during or after a work shift. Most interviewees declared that they need around 1.5 h per work shift for charging the Tesla. However, if charging takes place during quieter hours, waiting for customers, or during lunch time, time losses can be reduced.

Most popular are work shifts with many trips within Stockholm city: short distances and relatively high kilometre fees. Even though trips to the airport of Stockholm (Arlanda) are very common, they are not considered to be very popular from Tesla drivers' point of view: the "revenue per range rate" is relatively low. The airport is located 42 km from the city centre. If it is not possible to get a return trip, a customer going to the airport decreases the available range by ~84 km. If instead, e.g. 5 shorter trips were done within 84 km, more revenue would have been collected with the same decrease of available driving range.

Low temperatures as well as a more aggressive driving style have a negative influence on the available range according to the interviewees. The degree in which taxi drivers consider low temperatures to decrease the available range varies: according to one interviewee, the vehicle needs to be charged three times more per day, whereas another interviewee called the effect of low temperatures "surprisingly small".

Nollzon and the queuing system in Arlanda airport are considered successful to favour electric taxis and compensate for time losses during charging events. Firstly, the Nollzon scheme is considered to result in more trips if the e-taxi is nearby. Some of the interviewed taxi drivers explained to have a good overview over the locations of these Nollzon companies, trying to be in these areas as often as they can. Secondly, the queuing system at Arlanda is considered to result in significantly lower waiting times at the airport. Some of the e-taxi drivers said that they often get a return trip from Arlanda. However, due to the fact that there is a peak in the number of passengers to the airport during the night, whereas there is a peak in the number of passengers from the airport during the (late) evening, there is a temporal mismatch.

The effects of the EV on the daily revenues are unclear: some interviewees explained that they had to work longer in order to get the same daily revenue, whereas other interviewees explained that the efficiency of driving an e-taxi is higher due to the benefits connected to Nollzon companies and the queuing system at the airport Arlanda. All interviewees agreed that they received more tips than before they started driving the e-taxi.

5.3.2.1. Knowledge ICEV taxi drivers.

Generally, ICEV taxi drivers are less aware of the opportunities and limitations of driving a e-taxi: even though they have a moderate or relatively good knowledge about certain elements such as Nollzon and the point system at Arlanda, they do not have the same picture and sometimes even have misperceptions about the possibilities and limitations of e-taxis. For example, two taxi drivers driving ICEV taxis thought that the range of the e-taxi would be certainly enough for all trips during one work shift, whereas this does not seem to be the case. There are different views on whether the travel patterns would be different if e-taxi would be used instead of the current taxi vehicle. Two ICEV taxi drivers indicated that they would be able to make exactly the same trips, whereas another driver indicated that many times he would have to decline trips due to lack of range.

5.3.2.2. Barriers.

The following main barriers have been identified by both e-taxi drivers and ICEV taxi drivers: The upfront investment of an e-taxi is very high compared to that of an ICEV taxi vehicle. Besides that, the service and guarantee procedures should be looked over, because Tesla has a shorter guarantee period than Mercedes-Benz or Volvo. Thirdly, better facilities are needed close to the charging stations in order to make it more attractive to combine charging with for example lunch breaks. *"A charging station is not a gas station," (male, 26y)* one of the drivers said. And another driver said: *"Some fast charging stations are located at strange places. At night, these are not really the place to be, it is a bit suspicious. What are you doing here at night?" (male, 55y).*

5.4. Perspective of carriers

From the perspective of the carrier, vehicle economy is by far the most important factor, even though it has been mentioned that many carriers also have a personal interest in EVs as a new technology. Among the interviewees, some taxi drivers were also carriers. Generally, the knowledge about the TCO of e-taxis compared to ICEV vehicles is not very advanced and in many cases, the information that carriers have is incomplete. Generally, there is a sense for considering the significant decrease in fuel cost, which can be used to compensate the higher amortization cost. However, to which degree these factors cancel out is unclear to them. Nevertheless, carriers using Tesla seem to be satisfied, as several carriers are planning to replace their Tesla by a new Tesla or to increase the number of Tesla in their fleet. Common points of worry are the construction quality and the service centre. There is only one service centre in the Greater Stockholm region where Tesla's can be repaired, and there are relatively frequently problems with the handles at the right passenger seat. Even though the experiences differ, the service is considered to be significantly worse than usual for vehicles that are used in taxi companies. Moreover, as the guarantee period for Tesla is only valid for 80,000 km (less than a year in taxi) as opposed to 3 years in most contracts for the ICEV taxi vehicles being used; there is a high uncertainty about the costs for reparations and service.

6. Discussion

6.1. Feasibility of using e-taxis in greater Stockholm

Generally, the use of e-taxis in Greater Stockholm seems to be feasible, considering the degree of usage and profitability of these vehicles. For carriers, the mean e-taxi is slightly more profitable over the course of the ownership compared to biogas or diesel hybrid taxis, due to lower TCO and longer driving distances. On km basis e-taxis have the lowest TCO but are not as profitable as biogas vehicles. Moreover, e-taxis have slightly higher distance per work shift. When controlling for multiple scenarios related to distance and purchasing price it can be inferred that e-taxies would generally have lower TCO and higher EBIT compared to the ICEV taxies, although e-taxis need longer relative driving distances to compensate for lost revenues due to time spend charging. The equal purchasing price scenario depicts a probable future situation where falling battery and manufacturing costs have lead e-taxis to purchasing price parity in relation to ICEV taxies. The effect of which is a TCO that is up to 46% lower compared to ICEV taxis.

Duration of work shifts done with e-taxis is on average slightly shorter, which might be partly due to range limitations. However, during the work shift the vehicles' revenue per hour is slightly higher, which is also benefiting taxi drivers. That the results in this paper differ from previous findings (Kim et al., 2017; Zou et al., 2016) is likely due to longer range for the e-taxis used in this study. The context of operating a taxi in Stockholm is different compared to that in megacities in Asia; with fewer daily customers, a higher propensity for pre-booked trips and longer trips. It can be concluded that the feasibility of e-taxis at present is context dependent, but also important to emphasize is that under the right circumstances long-range e-taxis can be utilized more efficiently than ICEV taxis with a subsequent positive effect on profitability.

Figure 1 displays a synthesis of the interview data related to taxi drivers' revenue and interdependencies between the different elements that have been mentioned.

According to the interviews, the benefits of e-taxis at the airport Arlanda and with organisations connected to Nollzon are necessary to compensate for revenue losses due to charging time and range limitations of the e-taxi. The taxi drivers are unsure if these two mechanisms cancel each other out or whether it is a net benefit or a net cost for the driver. In essence, this depends on the planning and optimizing abilities of the individual taxi driver. Based on the aggregate revenue data, it appears that the wage per hour is somewhat higher for e-taxis drivers. Nevertheless, as taxi drivers have to be much more aware of the range limitations of e-taxis and strategies to optimize their work shifts, their work shifts tend to be more stressful. Therefore, coping behavior of taxi drivers seems to be a crucial factor for a successful adoption of e-taxis.

Based on the interview data, it can also be concluded that there is a lack of information about e-taxis; their profitability, specific requirements, and limitations. Conflicts could arise between carriers and taxi drivers, as their objectives partly differ. For example, spending additional time per work shift in order to get the same revenue due to the need of charging would have much more negative implications for a taxi

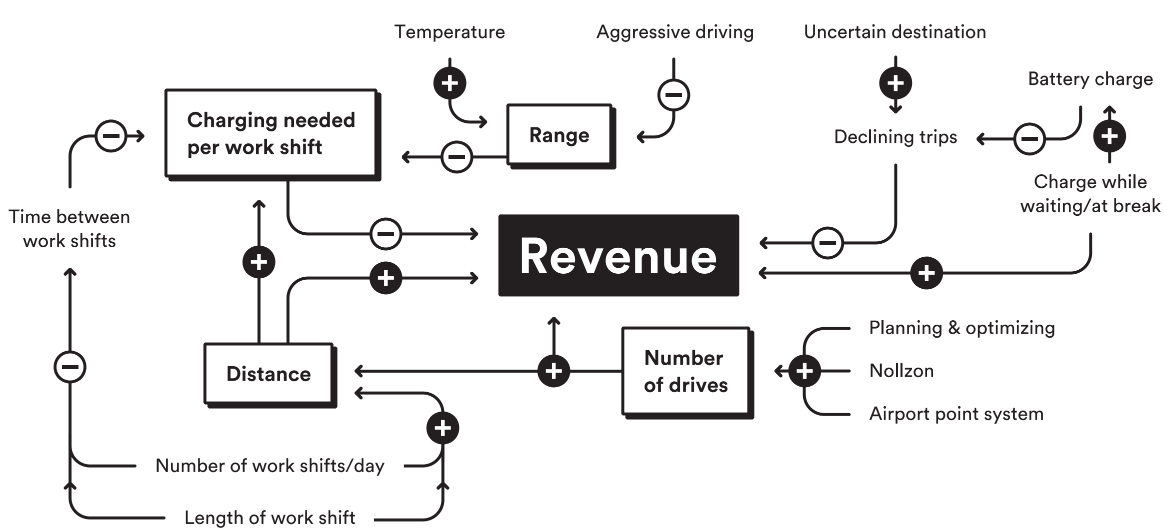

Figure 1. Synthesis interview data taxi drivers.

driver than for a carrier. The degree in which hourly revenues are negatively affected depends on both the circumstances under which the taxi drivers are operating (time-of-day, demand variation over time and space, legal frameworks) and the strategy of the taxi drivers. A plausible solution could entail that carriers spend some of their additional profits to compensate drivers for time spent charging, if it would turn out to be that taxi drivers cannot compensate the time needed for charging by more effective taxi operations using a smart driving and charging strategy. It might be useful to give taxi drivers using e-taxis an additional education where they learn to optimize their revenue given their specific circumstances. A large scale implementation of e-taxis requires a large number of taxi drivers willing to start driving e-taxis with all behavioral changes it entails, which means that all relevant stakeholders should be willing to cooperate. If in the future different types of EVs will be used, the picture of profitability is likely to change. An example is the use of smaller e-taxis (Renault Zoe) within Taxi Stockholm, that recently started being in operation. Based on the first months' experiences, these vehicles positively affect the TCO, whereas the burden on taxi drivers is much higher due to the fact that fast charging (50 kW or higher) is not possible with these types of vehicles. Currently, Renault Zoe is in use for service rides in combination with general Nollzon rides between morning and afternoon rush hour. This situation requires even more that the balance of carriers and drivers is re-considered.

The feasibility of using e-taxis in other urban areas is likely to depend on the driving patterns in these areas, as well as on the available charging infrastructure. Relatively short trips, combined with a good coverage of charging infrastructure facilitates the use of e-taxis. Supporting mechanisms in a competitive environment are also important factors, especially in situations where the vehicle needs to be charged during hours that could have been productive. Combining charging time with breaks or during hours of the day with low demand would decrease the risk for missed revenues due to the fact that e-taxis are used.

6.2. Policy implications

Due to the fact that currently, revenues are lost due to time spent on charging and declining customers, benefits such as Nollzon are currently considered to be necessary and ought to be expanded in a strategic way. For example it would be desirable to analyse common destinations of trips originating from Nollzon companies, in order to stimulate other companies close to these locations to also subscribe to Nollzon. Expanding Nollzon to private customers also has the potential to incentivize e-taxis further.

Taxi companies could consider whether it is worthwhile to encourage a labor division between e-taxis and ICEV taxis, where e-taxis are to a higher degree encouraged to take trips inside of the centre of Stockholm. As e-taxis have most favorable conditions in urban areas (low speeds, braking often), and as less range is needed for a work shift in case shorter trips at a lower speed are done, less time is needed to charge e-taxis during work shifts and the taxi can be used in a more cost-effective way. Moreover, the air quality improvements can be optimized as well in this way. The results in this paper could also have valuable practical implications for the taxi industry. Information that e-taxis are financially competitive could encourage uninformed and risk averse carriers to consider e-taxis in their operations. Additionally, an e-taxi driver training program has the potential to improve the efficiency of e-taxi operations.

6.3. Limitations

In this study, no detailed information is available about the location and duration of each charging event. Therefore, it is not possible to have a more precise estimate of the average time losses due to charging. Besides that, no detailed information is available about the degree e-taxi drivers need to decline trips. Difficulties in extracting repair costs for the e-taxis also pose a problem; expansive reparations post-warranty could have a significant impact on both the TCO and profitability calculations. Another limitation of this study is the limited number of e-taxis that are available at Taxi Stockholm and the fact that only Tesla Model S is in use. Therefore, the results of one year driving data are influenced by individual characteristics of the taxi drivers that have made use of Tesla taxis.

6.4. Future research

Based on the results of this study, an analysis will be made of the potential of an increased number of EVs in taxi fleets. Based on this analysis, communication will take place with the relevant stakeholders (carriers, taxi drivers, utilities, and governmental institutions) aiming to optimize the conditions for an enlarged e-taxi fleet that aims to maximize the benefits for all relevant stakeholders. An increased number of e-taxis is assumed to have important implications on the capacity of charging infrastructure and the degree in which e-taxis get priority for airport rides and rides connected to Nollzon. Based on usage data for charging infrastructure and rides ordered with the Nollzon attribute are analysed in order to hypothesize future capacity constraints in case of a higher market share of e-taxis. Subsequently, a stated adaptation experiment will be conducted, where taxi drivers and carriers indicate their behavioral adaptations reacting on different scenarios constructed together with relevant stakeholders such as charging operators, as well as based on the analysis of the usage data described above. These scenarios represent different potential future developments (regarding market share of e-taxis, decisions of EV charging infrastructure providers and policy measures) having implications on the driving and charging conditions of e-taxi drivers.

7. Conclusion

In this case study, the use of electric taxis in Greater Stockholm has been investigated from a financial and operational perspective. Based on the results, the following conclusions can be drawn:

- E-taxis can be used in Greater Stockholm without sacrificing profitability. The profitability of the mean e-taxi is higher compared to the analyzed biogas and diesel hybrid taxi vehicles due to lower vehicle TCO and longer driving distance. This was also verified when controlling for scenarios with lower and higher relative total distance and in a future scenario with parity in purchasing price, but not when e-taxis and ICEV taxies have equal total distance.
- The e-taxi vehicles have longer total distance than the natural gas and diesel hybrid vehicles. The revenue per work shift is slightly lower because the average work shift duration is shorter. However, the revenue per hour is higher for e-taxis.
- Most taxi drivers using e-taxis need to charge their vehicles during the work shift, especially in case the vehicle is used in double work shifts per day. By planning charging events at quieter times or by combining charging with lunch breaks, part of the charging time can be absorbed. Another part can be compensated by system benefits such as Nollzon and the point system at Arlanda airport, decreasing the waiting time between customers.
- At this moment, benefits such as Nollzon are important if not necessary for both e-taxi drivers and carriers. Besides this, good charging infrastructure is needed in order to minimize detours connected to charging. In order to facilitate a larger scale deployment of e-taxis, carriers should be informed about the opportunities and consequences of adopting e-taxis in order to make a more informed decision.

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