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Analysis of charging behavior when using battery electric vehicles in commercial transport

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Abstract

The use of battery electric vehicles - BEVs in commercial transport may require the integration of recharging during the usual operating hours. This might lead to a conflict between the commercial activity and a non-usability period of the vehicles due to charging. This conflict is an obstacle to the suitability of BEVs. Therefore, the aim of this study is to analyse the charging behaviour of organisations, which already use BEVs in commercial transport. Furthermore, this paper provides conclusions on the feasibility of integrating recharging into the daily routine and the pursued energy-related and temporal charging behaviour.

Keywords: electric mobility; commercial transport; battery electric vehicle; BEV; charging behaviour; state of charge; SOC

1. Introduction

Ten years ago, the German government announced in their coalition agreement an ambitious goal of one million battery electric vehicles - BEVs by the year 2020 (CDU, CSU and FDP 2009). The number of new registrations is continuously increasing, but the latest records as at January 1, 2018 shows that only 53,861 BEV are currently registered in Germany (KBA 2018). The increased use of electric vehicles in commercial transport has great potential. However, research on electric vehicles and their suitability for everyday use in commercial transport under real conditions is still insufficient in Germany (Flämig 2017a; Matt 2018). One of the main barriers that users of BEV mention is the dependence on charging stations and the inflexibility associated with charging as well as the limitations of current battery technologies (Azadfar et al. 2014; Matt 2018).

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Charging battery electric vehicles leads to a conflict of interest in commercial transport. Commercial transport can be differentiated between trips for the carriage of goods only, carriage of persons in commercial context without the carriage of goods (e.g. home calls by doctors), and mixed forms such as customer services, which represent both (e.g. plumber with spare parts) with goods and services (Schwerdtfeger 1976).

From the start of charging, the BEV can no longer be used for these purposes due to the stationary charging. The charging duration equals a period of non-usability, which must be regarded as of special importance in commercial transport. These can be divided into two different categories. On the one hand, periods of non-usability during the usual operating hours of the organisations and, on the other hand, periods outside the operating hours. According to the mobility study "Kraftfahrzeugverkehr in Deutschland 2010 (KiD 2010)", which examined motor vehicle traffic in Germany, the usual operating hours for commercial transport from Monday to Friday are between 6 a.m. and 8 p.m. (Wermuth et al. 2012a). While charging outside operating hours does not require the use of vehicles (but there is a possibility of occurrence), charging during usual operating hours may conflict with the availability of the BEV. This conflict between charging duration and the provision of mileage is an obstacle to the suitability of BEVs in commercial transport.

Nonetheless, charging is a necessity when BEVs are used. In order to be able to integrate these optimally into the daily routine of an organisation, a deeper understanding of the charging behaviour is necessary. The economic activity must be planned in terms of location, time and energy, depending on the current state of charge (SOC) of the battery. A study by Franke and Krems (2013) indicates that a heterogeneous perception of available range regarding the state of charge influences recharging decisions to avoid range anxiety. According to Yang et al. (2016), the initial charge state is the most important factor in recharging decisions and furthermore affects route choices.

Charging behaviour can be divided into two categories: fixed and flexible. The demand in fixed charging behaviour is based on preferred locations and times (Bae and Kwasinski 2012). In commercial transport, these are primarily the company sites if private charging infrastructure is available within the usual operating hours. Flexible charging behaviour occurs during travel and depends on specific recharging opportunities at public charging stations or customer locations (Yang et al. 2016). Schücking et al. (2016) discusses different charging strategies for economical operation of BEVs in commercial applications and highlight the importance of the location in addition to timing and energy demand. The feasibility is also considered by the ratio of driving time to charging time as well as idle time during usual operating hours. The results show that controlled charging strategies must be carefully designed.

Therefore, the aim of this study is to analyse the charging behaviour of organisations which already use BEV in commercial transport. In order to analyse the charging behaviour within the context of a research project, a variety of different BEVs were sampled with logging devices to collect spatial, energy- and time-related data. The individual behavioural reasons of the drivers that might trigger charging behaviour and thus determine the quantitative values are not evaluated in this paper. From the collected data, conclusions on the feasibility of integrating recharging into the daily routine and the predominantly pursued charging behaviour will be deduced.

2. Data basis and methodological approach

This paper is based on data from a long-term study of the research project "Hamburg - Wirtschaft am Strom" (WaS), which was funded by the German Federal Ministry of Transport and Digital Infrastructure. The project examined the use of battery electric passenger cars and light commercial vehicles in commercial transport (primarily carriage of persons in commercial context and mixed forms) in the Hamburg metropolitan area from 2012 to 2017. One of the goals of the funding was to evaluate the suitability of BEVs for everyday commercial use to identify favourable and inhibiting framework conditions for a more extensive vehicle ramp-up (NOW GmbH 2016). A total of 740 BEVs were funded in 367 different organisations, each using one or more vehicles. Of these, 314 were commercial enterprises and 53 were institutions in the public sector, of which 36 were part of the core administration at municipal or state level and 17 were public enterprises (Flämig et al. 2017a). This set of organisations in the project covers 18 of the 21 economic sectors covered by the Federal Statistical Office's system (Statistisches Bundesamt 2008).

The project organisations also differ in the size of their fleets. While 10% owned a micro fleet with just one vehicle, one-third of the organisations had a small fleet of 2 to 5 vehicles or a medium fleet of 6 to 49 vehicles. The remaining organisations had a large fleet of more than 50 vehicles at their company site. The average proportion of electric vehicles in the different fleet sizes was 42.5% in small fleets and 14.2% in medium-sized fleets. At 4.5% and an average of 7 BEVs, the share was lowest in large fleets, due to the high number of vehicles (141 on average) and the associated substitution effort. In micro fleets, only BEVs were used.

Of the 740 vehicles, a total of 160 BEVs from different organisations were sampled using CAN-based logging devices to record charging, driving and energy data. These facilitated reading, decoding and converting the vehicle signals into numerical values, which were transmitted to a central server via mobile radio. The logging device had a separately connected dual antenna for mobile radio and GPS coordinates that was connected directly to the power of the 12V vehicle battery and could therefore "wake up" at any time as soon as the vehicle was used for charging or driving (Flämig et al. 2017a).

2.1. Data basis

In the period between September 2014 and March 2017, driving and charging data were logged from the 160 sampled BEVs. The following five vehicle models and number of vehicles were sampled: 65 Renault Zoe, 27 Renault Kangoo Z.E., 33 Smart electric drive, 32 VW e-Golf and three VW e-Up (Flämig et al. 2017a). On the one hand, the driving database contains GPS based driving profiles for every BEV with an overall quantity of 254,061 trips with a total distance of approx. 1.5 million kilometres. The charging profiles, on the other hand, are based on the energy transmission via charging cable. The charging database contains a total of 26,131 charges with approx. 176,000 kilowatt hours. During the sampling period, the 160 BEVs were used on 45,832 active days (932 different days). An active day is defined in terms of driving and charging activities, which excludes days with no usage of the BEV from the analysis.

The charging data include the spatial, energy and time related values of the logged charging. On the one hand, the energy-related initial state of charge at the beginning and the final SOC at the end of charging were logged. The SOC is relative to the maximum battery capacity of the different vehicle models, which may vary in absolute battery capacity. The evaluation of the SOC allows a vehicle model independent comparability of the energy-related data. It is measured in percentage points, an empty battery is the equivalent of 0% and a fully charged battery equals 100%. On the other hand, a timestamp is recorded when the charging cable was plugged into the BEV at the beginning and another timestamp by unplugging it afterwards or at the moment the SOC reaches 100%. Based on the time difference between both timestamps, the charging duration was calculated.

2.2. Methodological approach

In order to describe the quantitative charging behaviour, the relationship between energy and time related values of all charges has to be analysed. Contingency tables were used to analyse the absolute or relative frequency distributions of two variables with different characteristics. The variables were grouped into intervals to categorise the charges.

Intervals of 10% were selected for the energy-related variables initial and final state of charge. For the temporal integration of charging in the daily routine, the time of day was divided into two hour intervals according to the timestamp for plugging in the charging cable. The duration was divided into one hour intervals with an open category above nine hours due to the average maximum charging duration for a full recharge of the different vehicle models.

As a supporting visualisation method, a colour gradient was used to illustrate heat maps for the frequency distribution. The colour gradation of the three-colour scale is based on the maximum value (red), the 50 quantile (yellow) and the minimum value (green) of the referenced frequency distribution. This highlights the quantity of the various combinations of variables by the respective colour to visualise hotspots in the frequency distribution. Individual colour gradations are applied for the inner frequency distribution of the contingency table and for the outer sums of the different intervals of each variable.

3. Charging behaviour

In the following analysis, the interdependency between the state of charge and temporal integration of recharging in the course of the day is evaluated. As the state of charge decreases, it becomes a necessity to recharge the BEV depending on the remaining range. Therefore, the state of charge should be one of the main triggers for the necessity of initiating recharging. If the daily mileage still to be driven is less than the remaining range (based on the current state of charge), charging can also be delayed (e.g. till the next day). According to the OEM's specifications for the calculated ranges based on the New European Driving Cycle (NEDC), the maximum range for the sampled vehicle models is between 145km and 210km, depending on the different battery capacities (Daimler AG 2014; Renault 2014). However, the actual ranges of BEVs in daily driving situations are affected by the influence of various factors (e.g. temperature, frequent acceleration, use of auxiliary equipment, etc.), which can lead to considerable deviations in certain circumstances (Rahimzei 2015).

In order to evaluate the charging behaviour in the context of commercial transport, the average driving characteristics of the project organisations has to be considered. Table 1 shows the average number of trips per day and the resulting daily mileage and its standard deviation. In addition to the average values for all active days, these are also differentiated by whether the daily mileage was driven with or without recharging on that day.

Table 1. Distribution of active days by charging activity (n = 160 BEV; 254,061 trips; 45,832 active days).

Active days	Number of active days (*days*)	Average trips per day (*trips/day*)	Average daily mileage (*km/day*)	Standard deviation daily mileage (*km/day*)
All active days	45,832	5.5	32.2	30.1
Without recharging	25,146	5.1	27.4	28.1
With recharging	20,686	6.1	37.9	31.0

In 54.9%of all active days no charging was performed. Accordingly, on these days no recharging was necessary to provide the daily mileage. Therefore, the BEVs in the project are averagely recharged on every second active day (not necessarily to be equated with the next day), which can include multiple charges per day. The average daily mileage of all sampled BEVs was 32.2 km with an average of 5.5 trips per day (Flämig et al. 2017a). Comparable commercial vehicles with internal combustion engines in Hamburg drive 65.5 km with an average of 3.2 trips per day (Wermuth et al. 2012b). The difference in the daily mileage is probably due to the introduction of BEVs as a new technology which may result in uncertainty in the usage of the vehicles.

On days with only driving activities and no recharging, the average number of trips per day is about one trip less than on days with charging and driving activities. With 27.4km on days without recharging compared to 37.9km per day, the daily mileage is also approx. 10km lower. Further influence on the daily mileage by the amount of recharging per day is shown in Table 2.

Table 2. Influence of recharging on the daily mileage (n = 160 BEV; 254,061 trips; 20,686 active days with recharging).

amount of recharging per day	number of active days (*days*)	average trips per day (*trips/day*)	average daily mileage (*km/day*)	standard deviation daily mileage (*km/day*)	average duration per charge (*h/charge*)
1 recharge	16,826	5.8	33.9	27.3	3.3
2 recharges	3,333	7.1	52.4	33.2	2.5
3 recharges	438	7.9	67.8	47.8	2.1
4 recharges	71	9.0	72.0	60.7	1.8
5 recharges	14	8.4	158.3	155.0	1.1
6 recharges	4	7.3	349.7	145.9	0.8

The average number of trips per day and the daily mileage show a dependence on the amount of recharging, with the average per day on active days with charging activity being 1.2. On days with exactly one recharge, 5.8 trips per day with a daily mileage of 33.9 km were recorded. With 81.4%of all active days for charging and driving, this charging behaviour represents the predominant share. On the remaining days, multiple recharges were made with two or more recharges per day. The average duration per charge decreases when multiple recharges are made. As the combined charging duration increases, the shorter charges can be integrated at different times during the course of the day.

An increasing number of recharges per day directly affects the related daily mileage. The average daily mileage increases by almost 20 km if the BEV is recharged twice and is with 67.8 km doubled by three recharges per day. Therefore, the average daily mileage would be on the same level as comparable commercial vehicles with internal combustion engines in Hamburg.

Due to the recorded behaviour of the project organisations under the present conditions during the sampling period, the average integration of one or two charges every second active day can be deduced from the daily usage of the BEV in commercial transport. At the same time, it is also shown that considerably higher daily mileage can be reached by the integration of multiple recharges.

3.1. Initial and final state of charge

The energy-related data of the initial state of charge at the beginning and the final state of charge at the end of charging are interrelated as shown in Figure 1. Due to a positive energy gain and thus increasing state of charge when charging, the intervals of the final SOC below the corresponding initial SOC in Figure 1 are non-existent and therefore greyed out.

The predominant charging behaviour is to fully recharge the BEV (above 90% SOC) when it is connected to a charging station, regardless of the initial state of charge at the beginning. The final state of charge shows that the majority of the sampled BEVs are fully recharged (87.5% of all charges). Less than 2.4% of all charges are terminated prematurely before a relatively low-level final state of charge of less than 50% SOC is reached. The remaining 10.1% of all charges end with an increased final state of charge between 50 and 90% SOC. This premature termination of charging with a medium to high-level final state of charge can be described as intermediate charging, which occurs when the BEV is required to provide mileage even though the battery is not yet fully recharged. In these cases, the non-usability period was intentionally interrupted to provide mileage with the current state of charge. This may be due to the higher necessity to pursue commercial transport activities.

final SOC	90 - 100 % SOC	80 - 90 % SOC	70 - 80 % SOC	60 - 70 % SOC	50 - 60 % SOC	40 - 50 % SOC	30 - 40 % SOC	20 - 30 % SOC	10 - 20 % SOC	< 10 % SOC	∑ %	state of charge - SOC
∑ %	87,5 %	3,5 %	2,5 %	2,3 %	1,9 %	1,2 %	0,7 %	0,3 %	0,1 %	0,0 %	100%	**initial SOC**
number of charging processes (n = 26,131)	3.036										11,6 %	**90 - 100 % SOC**
	3.760	99									14,8 %	**80 - 90 % SOC**
	3.648	175	69								14,9 %	**70 - 80 % SOC**
	3.430	172	171	132							14,9 %	**60 - 70 % SOC**
	2.932	158	129	197	161						13,7 %	**50 - 60 % SOC**
	2.202	126	108	114	162	102					10,8 %	**40 - 50 % SOC**
	1.681	95	80	78	80	107	61				8,4 %	**30 - 40 % SOC**
	1.210	55	51	48	59	73	70	39			6,1 %	**20 - 30 % SOC**
	713	21	26	19	31	24	28	39	15		3,5 %	**10 - 20 % SOC**
	247	13	7	14	6	10	16	13	16	3	1,3 %	**0 - 10 % SOC**

Fig. 1. Frequency distribution according to the initial and final state of charge at the beginning and end of charging (n = 160 BEV; 26,131 charges).

One reason for the high amount of full charges is the overall high initial state of charge at the beginning of charging. The average initial state of charge of the sampled BEVs was 62% SOC (Flämig et al. 2017a). In more than two thirds of all charges, the initial state of charge was above 50% SOC and 11.6% of all charges were even initiated with a nearly full battery with more than 90% SOC. Only 2,866 of 26,131 charges (11%) were initiated with a low-level initial state of charge of less than 30% SOC. In terms of the remaining range of the BEV, this state of charge level represents a high necessity for recharging, under the premise described above that the average daily mileage is 32.2 km per day. In this low-level state of charge of less than 30% SOC, approx. 20 to 30km are still remaining for the sampled vehicle models (Flämig et al. 2017a).

A interdependency of the preventive charging behaviour on the size of the vehicle fleet could only be determined to a limited extent. For small fleets, the average initial state of charge of 56% SOC was indeed the lowest, but in the sampled micro fleets with an average of 62% SOC on the same level as for vehicles from large fleets. The average initial state of charge was highest for vehicles from medium-sized fleets at 68% SOC.

The recorded charging behaviour of the project organisations, therefore, contradicts the usual understanding that a lower initial state of charge is common for initiating charges. The project organisations rather act according to a preventive charging behaviour by which charges are already initiated at high to very high states of charge.

3.2. Temporal charging behaviour

Depending on the initial state of charge, different approaches can be pursued for the temporal integration of charging the BEV throughout the course of the day. The charging duration is equivalent to the time-related period of non-usability of battery electric vehicles in commercial transport. These time periods are important for the implementation of charges in the daily routine.

Charging of BEVs during the usual operating hours in commercial transport is feasible (86.2%of all charging activity between 8 a.m. and 6 p.m.) and associated with a rather preventive charging behaviour in sense of the remaining state of charge and duration. In Figure 2, the highest charging activity by the sampled project organisations occurs in the middle of the day between 10 a.m. and 4 p.m. during the usual operating hours. Outside the usual operating hours between 8 p.m. and 6 a.m. a lower share of charging activity is indicated, but is nevertheless verifiable with 13.8%of all charges. One reason for this may be the wide coverage of different economic sectors in which organisations could have varying operating hours.

time of day	00:00 - 01:59	02:00 - 03:59	04:00 - 05:59	06:00 - 07:59	08:00 - 09:59	10:00 - 11:59	12:00 - 13:59	14:00 - 15:59	16:00 - 17:59	18:00 - 19:59	20:00 - 21:59	22:00 - 23:59	∑ %	
∑ %	1,0 %	0,9 %	1,8 %	6,2 %	11,3 %	13,9 %	16,3 %	15,3 %	13,1 %	10,1 %	6,8 %	3,3 %	100 %	**duration**
percentage of charging processes (n = 26,131)	0,2 %	0,2 %	0,2 %	1,3 %	2,4 %	3,9 %	3,8 %	3,3 %	2,3 %	1,3 %	0,7 %	0,4 %	20,0 %	**< 1 hour**
	0,2 %	0,2 %	0,7 %	1,6 %	2,3 %	4,1 %	4,1 %	3,4 %	2,5 %	1,3 %	0,9 %	0,4 %	21,9 %	**1 - 2 hours**
	0,2 %	0,2 %	0,4 %	1,1 %	2,1 %	2,6 %	3,1 %	2,9 %	1,9 %	1,4 %	1,1 %	0,6 %	17,5 %	**2 - 3 hours**
	0,2 %	0,1 %	0,3 %	1,0 %	1,4 %	1,3 %	2,5 %	2,1 %	1,7 %	1,4 %	1,4 %	0,4 %	13,9 %	**3 - 4 hours**
	0,1 %	0,1 %	0,1 %	0,5 %	1,2 %	0,8 %	1,3 %	1,5 %	1,7 %	1,4 %	0,8 %	0,4 %	10,0 %	**4 - 5 hours**
	0,1 %	0,0 %	0,0 %	0,2 %	0,8 %	0,6 %	0,6 %	0,9 %	1,2 %	1,2 %	0,5 %	0,3 %	6,7 %	**5 - 6 hours**
	0,0 %	0,0 %	0,0 %	0,1 %	0,4 %	0,2 %	0,3 %	0,4 %	0,7 %	0,8 %	0,5 %	0,3 %	3,7 %	**6 - 7 hours**
	0,0 %	0,0 %	0,0 %	0,1 %	0,2 %	0,1 %	0,2 %	0,3 %	0,4 %	0,6 %	0,5 %	0,2 %	2,7 %	**7 - 8 hours**
	0,0 %	0,0 %	0,0 %	0,1 %	0,2 %	0,1 %	0,2 %	0,2 %	0,3 %	0,3 %	0,2 %	0,1 %	1,6 %	**8 - 9 hours**
	0,0 %	0,0 %	0,0 %	0,1 %	0,1 %	0,1 %	0,2 %	0,3 %	0,3 %	0,4 %	0,3 %	0,1 %	2,0 %	**> 9 hours**

Fig. 2. Frequency distribution according to the time of day and duration of charging (n = 160 BEV; 26,131 charges)

Over the course of the day, a slight shift in the share of charges with increasing charging durations becomes apparent. Short and medium charging durations are initiated at the beginning or middle of the usual operating hours and longer charging duration towards the end of the day. With increasing charging duration, the highest percentage per interval combination is at the same time of day or later than in the previous duration interval. As a result, the following conclusion can be derived. The longer the charging duration, the later in the day the charges are initiated.

In their recorded charging behaviour, the project organisations tend towards relatively short and medium charging durations. Overall 20% of the recorded charges were shorter than one hour and the most frequent charging duration interval with 21.7% was between one and two hours. The average charging duration of the sampled BEVs was 2 hours and 58 minutes with a standard deviation of 2 hours and 17 minutes (Flämig et al. 2017a). A total of 73.3% of all charges lasted less than 4 hours with the highest percentage combinations between 10am. and 4pm. The charges are implemented within the usual operating hours and the resulting conflict between the provision of mileage and the implementation of charging is therefore accepted. On 18% of all days with charging activity, two or more charges were made on the same day. The average daily charging duration increases with two charges to 4 hours and 56 minutes and with three charges to 6 hours and 13 minutes (Flämig et al. 2017a). In these cases, two or more recharges are initiated at different times during the day to increase the possible daily mileage or to maintain the BEV at a high state of charge level. This results in multiple time periods of non-usability that have to be considered.

Charges with a single duration of four hours or longer are with 26.7% overall less frequent among the sampled BEV. In the frequency distribution a postponement in the charging duration intervals in the period between 4pm and 8pm becomes apparent. The relative proportion within the charging intervals, however, is considerably higher at these times of day. For example, the 0.6% between 6pm and 8pm for charging durations of 7 to 8 hours equals 22.3% of all charges within this duration interval. Long charging durations at this time of day cause the charges to end outside the usual operating hours and are initiated as overnight recharges for the next day.

4. Conclusion

The aim of this paper was an energy and time related analysis of the charging behaviour of organisations in the research project “Hamburg - Wirtschaft am Strom” (WaS) using battery-electric vehicles in commercial transport. For this purpose, the energy-related initial and final state of charge were evaluated and the interrelation to the time-related integration of charges in the course of the day as well as the charging duration were determined.

The initial evaluation of the driving characteristics in the context of commercial transport has shown that the BEVs had a lower average daily mileage than comparable commercially used vehicles with internal combustion engines. However, a comparable level can be reached by an increasing number of recharges per day. Furthermore, considerably higher daily mileages are possible by the integration of multiple charges over the course of the day. The average integration of one or two charges every second active day was deduced for the evaluation of the interrelated charging behaviour.

The analysis of the charging behaviour has revealed that the project organisations have pursued a rather preventive charging behaviour when using BEVs. The majority of charges were already initiated at high to very high initial states of charge and the BEVs were predominantly fully charged. A premature termination of charges, because the BEVs were needed for the provision of mileage, was very rare. A charging behaviour oriented to the necessity of recharging due to a low-level state of charge was predominantly avoided. The BEVs were plugged back into the charging stations if the opportunity permits it, regardless of the initial state of charge. With a small number of BEVs in the fleet, the recorded charging behaviour was feasible, but with appropriate scaling for the integration of large electrical fleets, the behaviour may have to be readjusted. The limitation to one sampled BEV per organisation prevents the comparison of charging behaviour within the commercial fleet of the organisation.

Regarding the time-related charging behaviour, a generalisation of the temporal integration in the course of the day was not entirely homogeneous. But based on the preferred time of day, the charging of BEVs during the usual operating hours in commercial transport was feasible with different approaches. While short and medium durations of charges were initiated rather in the morning until the afternoon, charges with long durations are postponed to the end of the usual operating hours. The upcoming deployment of higher-performance charging technologies will reduce charging durations and therefore the resulting non-usability periods of BEVs. This will reduce the conflict between charging and the provision of mileage, which could improve the suitability of BEVs in commercial transport.

In addition to the conclusions on charging behaviour, further research is needed. In order to be able to make more differentiated statements about behaviour when using BEVs, a combination with a similar analysis of driving behaviour would be beneficial. The described charging behaviour could be enhanced by a spatial evaluation of the geographical distribution of charging on company sites or on public infrastructure.

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