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How do EV drivers adapt their charging behavior to battery size and charging capabilities? A systematic data-driven analysis

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Summary

Charging station infrastructure is designed to meet the demand of electric vehicle (EV) drivers. Prediction of the necessary supply of charging stations is often a data driven process in which charging patterns from current EV drivers are used as an exemplar. These patterns are than extrapolated to estimate future demand. This is a stationary approach to predicting the necessary supply. Battery and charging technology are however continuously changing; new EVs offer larger battery packs and higher fast charging speeds. It can be expected that drivers adapt their charging behavior to the technological capabilities of the car but on the other hand, opportunistic behavior and habits also play a role. So far, little insight has been provided in how EV drivers adapt their charging behavior to these technological factors. Such information is crucial for planning of charging infrastructure in the future. This study analyses how technological factors such as battery capacity and charging speed determine the charging behavior of EV drivers. Using a large database (6+ million charging sessions) on public charging infrastructure and a database with charging profiles of those drivers that have home charging available, it is systematically evaluated how the technological capabilities affect charging behavior. Conclusions are drawn for how this has an impact on infrastructure planning.

Keywords: EVSE, Level 2, Battery, Charging speed, Policy

1 Introduction

Due to a decline in battery costs [1] and more stringent policy measures [2] the sales of EVs is expected to rise soon. Policy makers are looking to optimize the way deployment of charging infrastructure to facilitate growth in charging demand form these new vehicles. In recent years, policy makers have used studies that rely on charging data of early adopters [3][4] to examine how charging infrastructure matches charging demand. However, to assume that these charging patterns match the charging demand of future EV drivers is a static approach.

Due to continuous developments on battery and charging technology, EVs are built with larger ranges and faster charging speeds. Previously, 300km+ ranges were only available in the luxury segment; newly launched models (e.g. Tesla Model 3, Volkswagen ID.3 etc.) make larger driving ranges available for the masses. While, up to now 50kW was the most common fast charging standard, currently available vehicles tout with fast charging speeds from 150 up to 350kW.

Policy makers and businesses try to keep up with sufficient charging infrastructure for the increasing number of EVs on the road. They face uncertain strategic decisions. Uncertainty increases due to rapidly changing technology. This increases the risk of investments into potentially soon-to-be-obsolete technology. Additionally, it is not well understood how charging behavior of EV driver adapts to such technological developments. A systematic analysis about how these technological factors impact charging behavior has been missing.

This research is the first to systematically evaluate how vehicle capabilities (battery capacity and charging power) influence charging behavior. The paper does not assume a one-way relation between vehicle capacity and charging habits but also that availability influences charging choices. With two different datasets on charging behavior (in total more 4 million charging sessions), the analysis compares different vehicle types in their charging behavior such as frequency of charging, unique charging stations used and the ratio of home, workplace, public and fast charging. To investigate the reciprocal relationship the paper uses the second dataset to compare charging behavior of those that do or do not have access to home charging.

2 Literature overview

This literature review addresses previous work in the field of charging behavior on the basis of charging data. A study by the Idaho National Laboratory for example compared charging behavior between Nissan Leaf and Chevrolet Volt owners (2015). They young out that the number of miles is driven is limited by the battery capacity of the car. The plug-in hybrid (Chevrolet Volt) owners drive the same number of electric kilometers as Nissan leaf owners but add additional gasoline driven miles. They also find that Nissan leaf drivers use more out-of-home charging at a larger number of different locations. Similar findings were found in a study by Toronto Atmospheric Fund [6] in which they compared several FEV and PHEV vehicles in their charging behavior. They also find that the average State of Charge (SoC) for PHEVs is lower than for FEV vehicles, indicating the range anxiety among FEV drivers.

Other research on the interaction between technology and charging behavior can mainly be found in modelling the required charging infrastructure. Such models mainly rely on the assumption on when the driver will charge, often related to the SoC of the battery [3], [7]. Increasing battery size would then lead to a lesser need for charging infrastructure. Yet, other research has shown that charging decicions not only rely on the remaining range of the vehicle but rather availability [8], convenience [4] and for eaxmple pricing [9] influence this choice. Using current charging behavior, despite its limitations, is therefore a better proxy for determing future charging infrastructure need. So far, the only modeling approach which has incorporated charging behavior and vehicle characteristics to our knowledge is work by Vermeulen et al. [10] which simulated a city on which all PHEV vehicles were replaced by FEVs. They find that the number of charging session per charging stations decreases with about 15% but that the volume (kWh) charged at these stations increases with more than 100%. This research however only makes a distinction between PHEVs and FEVs, further specification is missing.

Generally, there is need to see how the technological capacities of EVs have an influence on charging behavior. Some distinctions in literature on the differences between PHEVs and FEVs has been given, yet a systematic analysis of different capabilities has been missing. Additionally so far no research has been that distinguishes between the charging options an EV drivers has (e.g. home charging availability).

3 Methodology

This research relies on two big datasets on EV charging systems. The first dataset is on public charging stations in the four major municipalities in the Netherlands (Amsterdam, Rotterdam, Utrecht and the Hague) and the Amsterdam Metropolitan region. It gives a full overview from the public charging station perspective. The second dataset is on individual charging sessions provided by a mobility service provider. A detailed description is given below.

3.1 Public charging infrastructure data

The first dataset contains over million charging sessions on charging infrastructure in the four main cities in the Netherlands (Amsterdam, Rotterdam, The Hague, Utrecht) and the Metropolitan area of Amsterdam. Data comes from public charging stations which are mainly put in place for inhabitants of these cities or those working in the city. Yet, charging stations are always available to all EV Drivers. Charging stations can only be accessed through swiping an RFID-tag. Table 1 gives an overview of the data collected. Data is summarized per RFID (unique user) to provide new insights.

Table 1 Data variables and examples

Variable	**Example**
RFID	60DF4D78
Address	Prinsengracht 767, Amsterdam
Start Connection Date Time	24-04-2015 13:56:00
End Connection Date Time	24-04-2015 17:14:00
Connection Time	2:18:00
Volume	6.73 kWh

Data on the user is collected as follows. Only users (based on their unique RFID-tags) that charged more than 30 times in the period between 2018 and 2020 were considered, otherwise their data was not considered reliable. 15,400 users were identified, for which in total 3,161,036 (93% of total) charging sessions were analyzed. The maximum number of kWh charged over all their charging sessions per user is considered as their battery capacity. We estimate that within a period of two years each EV driver would at least once drive their battery near empty. On top of that, the paper analyses the charging speed per session to determine maximum charging speed. We assume that each EV driver would at least charge once in the given period in which the charging was not done before the car was disconnected. Given that all public charging stations have a maximum power of 3x16A per socket, it is possible to determine whether the car can charge at 1x16A (single phase) of 3x16A (three phase).

3.2 EV driver data

This dataset is charging card data from 19,420 EV drivers in The Netherlands. Data contains all charging sessions in which a charging card is needed to access the charging station. Data on the location, time and volume has been logged anonymously. The data also contains information about home charging stations as some employers would ask their employees to log this data to get a refund for their costs. The data additionally provides information about the type of charging station (private, public, semi-public, fast charging). A total of 1,160,283 charging sessions (94,5% of total) were used for the analysis after filtering for impossible (e.g. negative or >100 kWh) charging sessions or for faulty data (e.g. duplicates of missing time variables).

Data on the RFID level was aggregated in the same way as on the public charging data. Given that only a year of data was available instead of 2 years, only data was kept of users with more than 15 charging sessions.

This left 11609 users (60% of total) and 1.109.719 charging sessions (96% of the total). Users were divided on the basis of battery capacity in the similar manner as with the public charging data. Additionally, it was identified if the user had access to a private charging station at home. Distinction at charging speed was not possible as the power at the charging station could not always be determined.

4 Results

4.1 Public charging dataset

Data was grouped on the basis of battery capacity and the charging speed (single phase (3.7kW) and three phase (11kW)). Descriptive data for each of the groups can be found in Table 2. Cut-offs of the battery capacity were made on the distinction between PHEVs (below 16kWh) and FEVs. For the FEVs equal groups with a difference of 20kWh were made.

Table 2 Descriptive statistics public charging dataset

Battery capacity	Charging speed	Number of drivers	Number of sessions	Mean Volume (kWh)	Mean Connection Time (hours)
0-16 kWh	3.7kW	8,566	1,933,539	5.83	11.50
0-16 kWh	11kW	183	41,351	6.72	9.71
16-30 kWh	3.7kW	1,200	298,158	9.95	10.98
16-30 kWh	11kW	878	190,608	11.61	8.96
30-50 kWh	3.7kW	559	170,940	15.04	12.75
30-50 kWh	11kW	1,570	106,321	15.25	10.96
50-70 kWh	3.7kW	259	50,106	20.09	13.55
50-70 kWh	11kW	932	327,792	25.45	11.10
>70 kWh	3.7kW	141	23,780	29.72	14.41
>70 kWh	11kW	1,100	193,689	34.03	12.16

Figure 1 shows the average unique number of used charging stations per session per EV category. The number of uniquely used charging stations is especially high for small battery FEVs with a low charging speed. This is line with expectations as such cars need more intermediary charging to complete their trips due to limited range. Remarkably this is much lower for group with the same battery capacity but with three phase charging. It could be explained that these vehicles can acquire much more energy per charging session that the single-phase charging. For PHEV vehicles this is reverse. PHEVs, usually tend to use less charging stations as they mostly only charge near home or work. Range limitations are absent for this group. The higher number of unique charging stations for the three-phase group could be explained that they can completely fill the battery in a short charging session and therefore get the benefits of these sessions. The number of cases however in this group is limited.

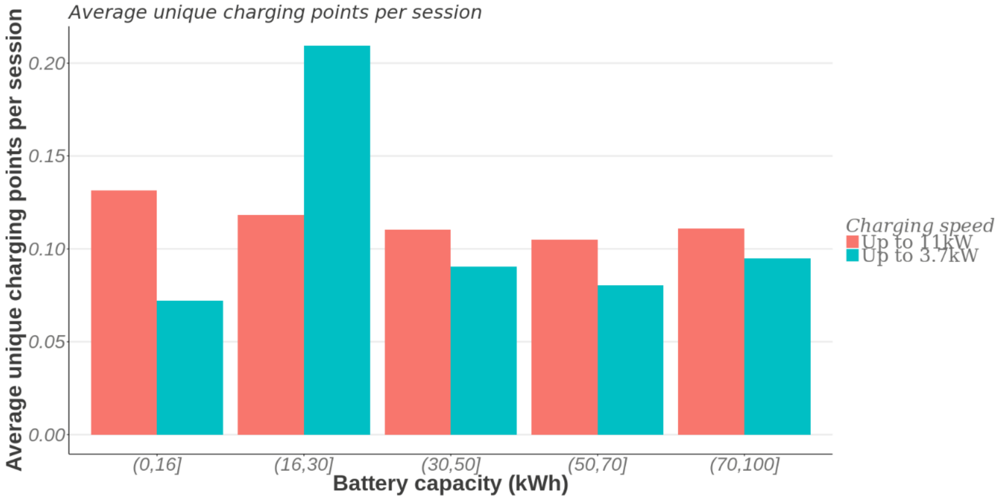

Figure 1 Unique number of charging points per session per vehicle category

The average time connected to a charging station per vehicle category can be seen in Figure 2. The average time connected is relatively high as the charging stations are mainly used for overnight charging. In general, it shows a trend towards longer charging sessions given the battery capacity. This is mainly because cars with a larger battery capacity tend to charge less and therefore mainly use overnight charging. Smaller charging sessions throughout the day are no longer necessary. Within the larger battery capacity vehicle significant differences can be seen depending on charging speed. Single phase (3.7kW) cars tend to charge longer. Those cars need a longer time to completely fill their car and drivers could be waiting until their car is fully charged.

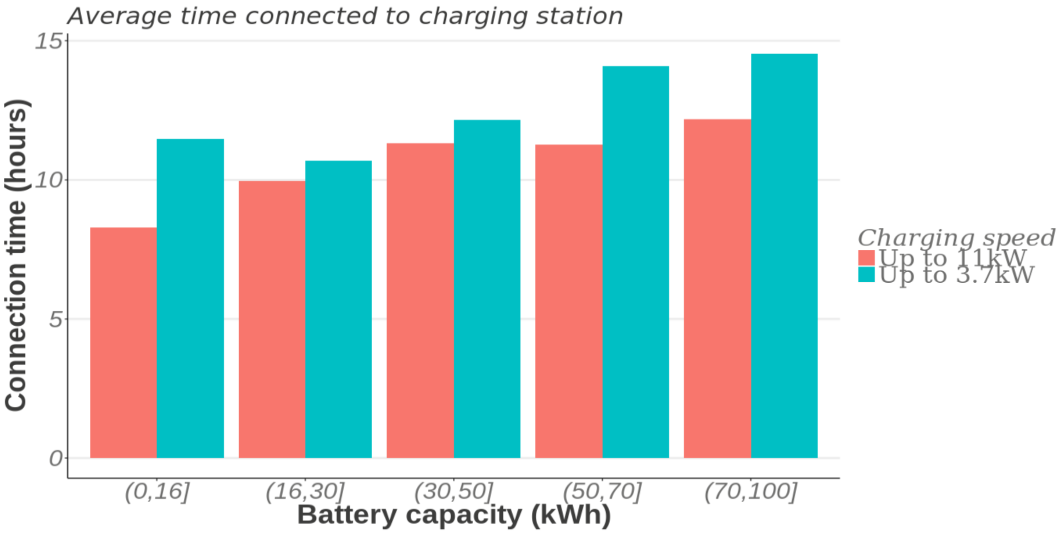

Figure 2 Average time connected to charging stations per vehicle category

The abovementioned dynamics of charging can also be seen in the average number of charging sessions per week per vehicle category. There is a clear trend in a lower number of sessions per week with increasing battery size. This effect is mediated by a lower charging speed, but still holds. Vehicles with a battery capacity over 70 kWh and three phase charging on average only charge 2.77 times a week while 16-30kWh battery packs with single phase charging charge 4 times a week. The latter category is therefore connected nearly 44 hours a week to charging station, drawing just under 40 kWh in the week. The >70 kWh battery packs are only connected just below 34 hours but draw on average 94 kWh per week. The average load of >70 kWh-three phase vehicles on the charging station occupation is therefore relatively low, but their demand of the electricity grid is much higher. >70kWh-single phase cars have the highest burden on charging station occupancy with over 46 hours of time connected to public charging stations a week.

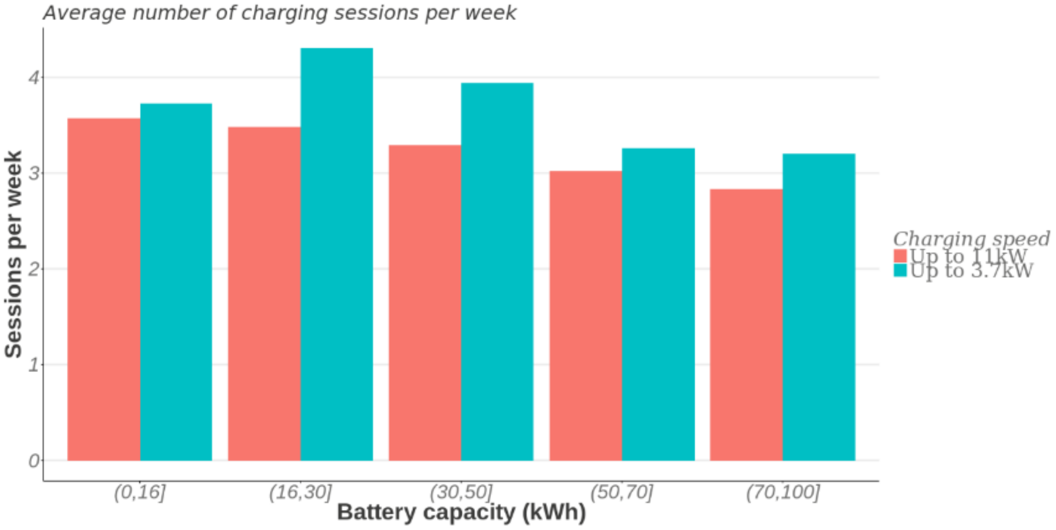

Figure 3 Average number of charging sessions per vehicle type

4.2 EV driver data

The EV driver data reveals more information about the distribution across the different charging modes. Additionally, while the public charging data had no information about home or private charging access, this dataset has to option to compare these two groups. Figures in this analysis always show the results for those without and those with private charging access.

Figure 4 shows the distribution across the different charging stations types for each of the battery capacity groups and split into two for those with or without home charging. It is clear that for those with home charging, the majority of charging is done at home. This is in line with earlier research which has found similar findings in the range of 65-80% [11]. For those without private charging access the use of charging stations is mixed. An equal share of workplace, public and semi-public charging can be seen for most battery capacities. Fast charging is mostly used by FEVs with a small battery capacity, which could be expected due to their range limitations. The use of fast charging is however limited in most groups, with a share below 10%.

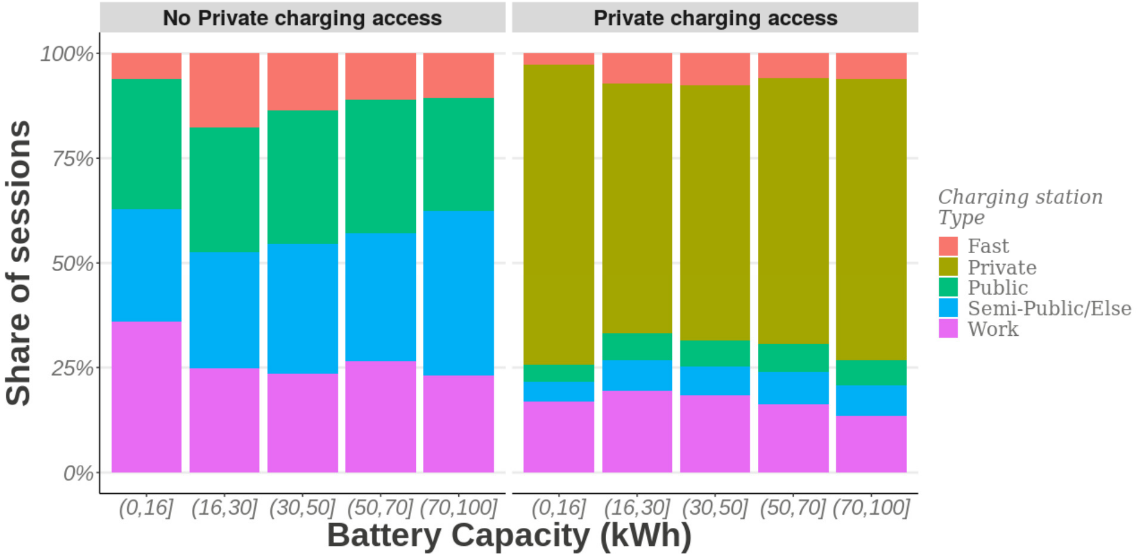

Figure 4 Share of charging sessions per Charging station type

In the Netherlands those without private parking facilitates are often provided to the opportunity to request a charging station near their home at their municipality [12]. This station often serves as a substitute for home charging, although public to everyone. It could be expected that drivers will use this (semi-)public charging close to their home the most. This location was identified by looking at the most used location for each user. As shown in Figure 5 there is still a big difference in how often the most used location is used across those with or without private charging access. For the latter group this is in the range of 40-50%, but for those with home charging this is between 60-80%. Despite this policy of placing charging stations near homes, these drivers still feel that they need to charge at other locations more often, possible in fear of that the charging station is occupied by others.

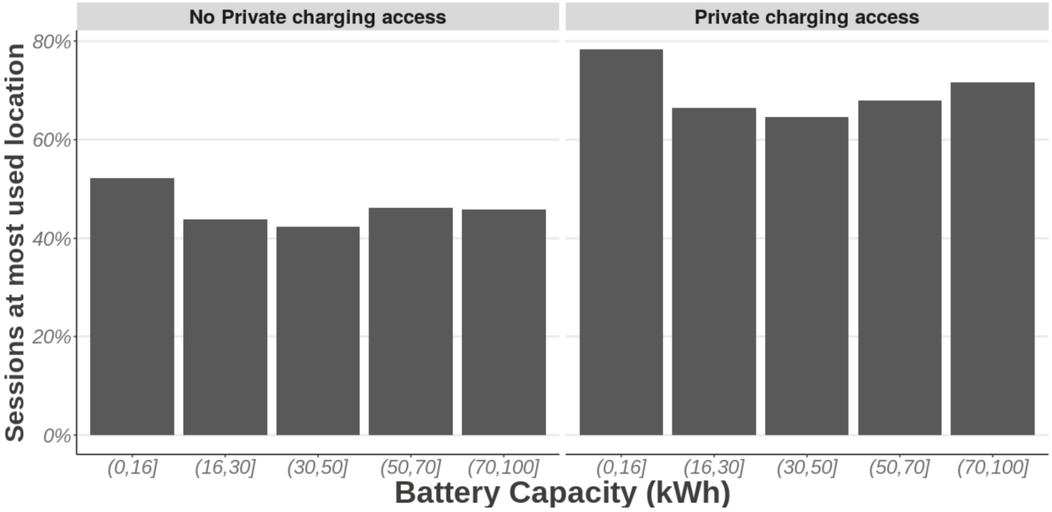

Figure 5 Share of sessions at most used location

Given that users without private charging stations have more away from home charging sessions, Figure 6 provides evidence that they also make more out each sessdfc78ion. Users without private charging access charge about 10% more kWhs per charging sessions than those with. In general, there is a clear trend in increasing transaction size with a large battery capacity, which was also found with public charging stations (Table 2).

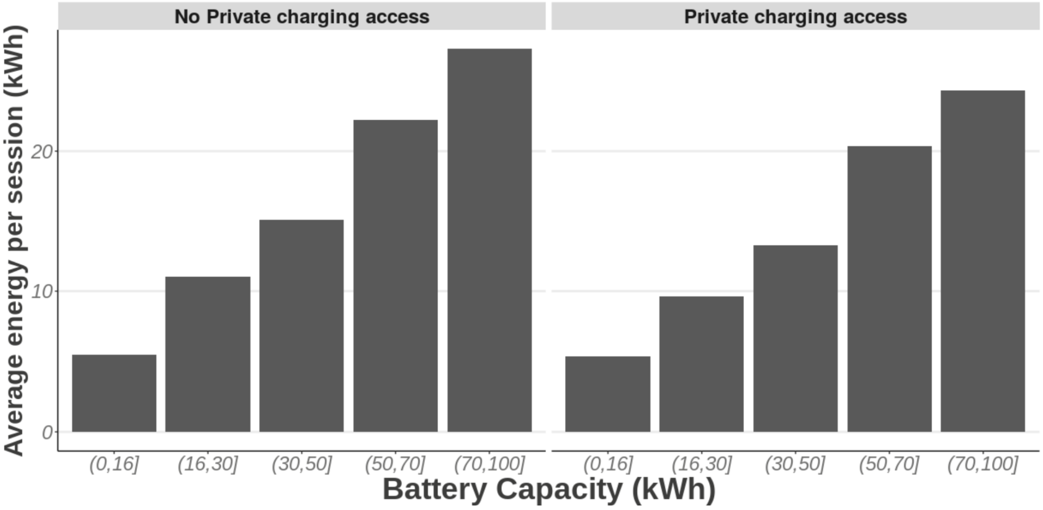

Figure 6 Average energy volume per charging sessions per battery capacity group

Figure 7 shows the average number of charging session per week divided across the several battery capacity groups. As was clear in Figure 4, most users that have a private charging station charge most of their sessions at home. They do so more often, but as shown in Figure 6 this results in a lower transaction volume per session at a time. Those without private charging access also tend to use fast charging stations more often. Note that these numbers are largely in line with those presented in Figure 2 for public charging. For full electric vehicles users without private charging access use a fast charging station about once every two weeks (0.55/week) while those with private charging access use it only once a month (0.22/week). Of those vehicles without private charging access 20% never used a fast charging station. For those with access, this was 33%. Possible explanation for these relative high figures is that Tesla supercharging stations are not registered. It is unclear which proportion of users of charging sessions is missing.

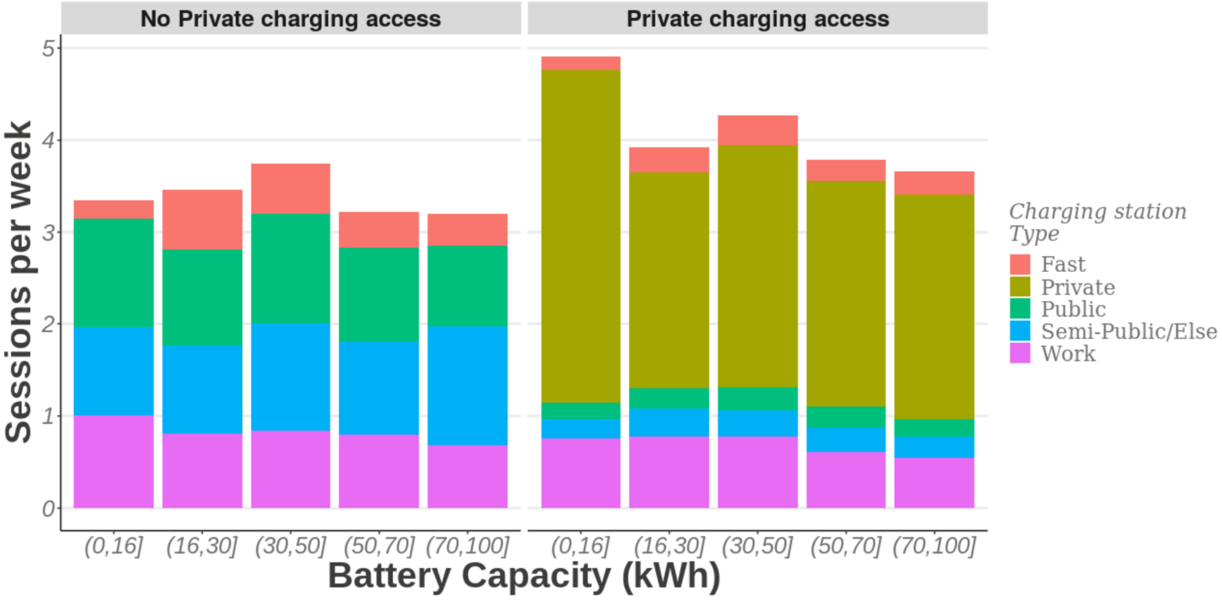

Figure 7 Charging sessions per week per charging station type

5 Conclusions

This research has been the first to systematically analyze the impact of the technological capabilities of EVs in the charging behavior of EV drivers. It is clear that these technological capabilities influence the decision to charge for drivers but also that this an interaction between charging infrastructure availability and the decision to charge. The battery capacity is the most dominant factor on the decision to charge. It however does not influence the number of charging sessions, but also results in more shorter charging sessions in between trips instead of only relying on overnight or workplace charging. There is also clear mediating effect between charging speed (3.7kw or 11kW) and battery capacity. Slow charging large battery capacity vehicles, despite a low number of charging sessions, are connected to a charging station the most, putting the most significant strain on charging stations in terms of occupancy.

The second part of this research has contributed to the understanding of the impact of access to home charging on charging behavior. It is clear that those without, even though they often have a (semi-)public charging station nearby, have different charging patterns than those with home charging. They charge at more different locations and make use of fast charging more. They also charge more energy per session but show fewer charging sessions per week. These drivers more carefully plan their trips and charging to prevent running out of energy.

Policy makers and businesses aim to make their charging infrastructure future proof. This includes predicting which type of vehicles enter the market and how policy measures influence the purchase choices of consumers. Many countries for example limit subsidies on EVs to a certain amount. This would steer purchases towards shorter ranged vehicles in the coming years. This also has implications for charging infrastructure roll-out strategies in terms in the sheer number of sales but also in location choice. Short ranged vehicles have more need for convenient locations at destinations and fast charging stations along the highway or other major roads. Policy makers should also be aware of those that do not have private charging. These have different charging needs that those with access. Not only providing charging near their home as substitute for home charging, but there is also a need for more away from home charging to make up for the uncertainty about the availability of public charging stations.

Future research could focus on the impact of fast charging capabilities and the option to choose for a certain charging mode. It could be that EV drivers with cars that have better fast charging capabilities would prefer such options instead of searching for available (semi-)public charging stations. Additional factors to take into account are price differences in charging. It could be that home charging is preferred due to the relative low cost compared to public and fast charging options. Free charging also attracts a significant number of drivers.

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