Travel Behaviour and Society 32 (2023) 100572

Contents lists available at ScienceDirect

Travel Behaviour and Society

journal homepage: www.elsevier.com/locate/tbs

Cooperative behaviour at public electric vehicle charging stations

J.R. Helmus [a,b], R. Wolbertus [a,*]

[a] Department of Urban Technology, Faculty of Technology, Amsterdam University of Applied Sciences, the Netherlands
[b] Computational Science Lab, University of Amsterdam (UvA), Amsterdam, the Netherlands

ARTICLE INFO

Keywords:
Electric Vehicles
Charging
Common-Pool Resource
Cooperation
Reciprocity

ABSTRACT

Underutilised charging stations can be a bottleneck in the swift transition to electric mobility. This study is the first to research cooperative behaviour at public charging stations as a way to address improved usage of public charging stations. It does so by viewing public charging stations as a common-pool resource and explains cooperative behaviour from an evolutionary perspective. Current behaviour is analysed using a survey (313 useful responses) and an analysis of large dataset (2.1 million charging sessions) on the use of public charging infrastructure in Amsterdam, The Netherlands. In such a way it identifies the potential, drivers and possible obstacles that electric vehicle drivers experience when cooperating with other drivers to optimally make use of existing infrastructure. Results show that the intention to show direct reciprocal charging behaviour is high among the respondents, although this could be limited if the battery did not reach full or sufficient state-of-charge at the moment of the request. Intention to show direct reciprocal behaviour is mediated by kin and network effects.

1. Introduction

With an increase in the number of electric vehicles (EVs) on the road, cities are struggling to facilitate sufficient charging infrastructure for these vehicles. This is crucial as sufficient charging infrastructure is a necessary condition in EV purchase decisions (Ling et al., 2021). Especially in dense urban areas, access to public infrastructure is vital as many EV drivers do not have access to private charging (Hall et al., 2018; Macioszek, 2019). Cities are searching efficient roll-out strategies for charging infrastructure that should facilitate different user groups such as taxi's, shared cars and city logistics (Macioszek, 2020). Roll-out strategies are long-term decisions as investments are costly and payback terms long. Policy makers face risky decisions while balancing the interests of different stakeholders (Bakker et al., 2014; Wolbertus et al., 2020), but putting off the decision could hamper the transition to electric mobility. Initial roll-out deployment has started in many cities for early adopters, but cities are now looking at ways to scale charging infrastructure.

Public charging stations can be considered a Common-Pool Resource (CPR) which are non-excludable and subtractable (Andersson et al., 2021, Helmus et al., 2019). They are open to anyone, but its use prohibits the use of a different EV driver. Typically, in a CPR there is limited central steering of behaviour, which allows bottom-up cooperation strategies to emerge from individuals (Gollwitzer et al., 2018; Helbing & Yu, 2009). With growing number of stations on the street, EV charging should be considered as a network infrastructure (Helmus et al., 2019). Within this network, EV drivers may both compete and cooperate for limited resources. Simulations have shown that perturbations as a result of competition in the EV system have shown match those of other complex systems (e.g., healthcare (Bar-Yam, 2006), transportation system (Glombek, 2018; Ottens et al., 2006). Yet, while both competition and cooperation may be present the charging network, most simulations of EV charging systems only take into account the competition for EV charging systems while assuming utility maximisation behaviour from their agents.

In this research we focus on cooperative charging behaviour, which we define as a deliberate action of an EV user (A) to share charging resources with another EV user (B). More specifically, user A provides cooperative behaviour to B and B receives cooperative behaviour from A. This action involves the disconnection of an EV by an EV user and re-parking (in the vicinity) of the CP while allowing another EV user to connect to freed socket. The disconnection and re-paring may either occur upon request of another EV user or may be initiated by the users themselves. This type of cooperation may not only improve effective use, it also improves efficiency of charging points, as ratio between charging time and connection time increases as well. A side effect of neighbours sharing charging facilities is that it may improve social cohesion (Caperello et al., 2013).

* Corresponding author.

https://doi.org/10.1016/j.tbs.2023.100572
Received 8 June 2022; Received in revised form 10 February 2023; Accepted 11 February 2023
Available online 18 February 2023
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Fig. 1 (a) illustrates the following pattern of cooperation. An EV user A arrives at 17:30 with the intention to park until the next morning 8:00. At 22:00 EV user B arrives at the CP finding it occupied EV A. User B contacts user A with a request to cooperate. Upon agreement for collaboration user A removes its EV and user B connects. In the charging data (Fig. 1 (b)) we can see this behaviour as a disconnection time of A followed by a short pause after which B connects to the same CP, as later is defined in this paper within a period of maximum 15 min.

While platforms that facilitate cooperative charging behaviour are known to exist in (Dutch) practice (Geurts, 2022), research on the dynamics of social interactions between EV drivers at charging locations has largely been missing. Such dynamics could proof to be important for efficient use of charging stations. Data on charging behaviour indicates that charging stations are used very inefficiently; charging stations are known to be only occupied for charging below 40–60 % of the time, of which 25 % is used for actual charging of the vehicle (Desai et al., 2018; Wolbertus et al., 2016). New etiquette (Caperello et al., 2013) on how to use public charging stations is still being shaped in the early phase of the transition to electric mobility. Insights into the emergence and effects on utility of social dynamics is important for policy makers both in determining the size and location of charging stations.

Policy makers aim to minimize the number of charging stations to optimize the business case (Schroeder & Traber, 2012) for chargers and to minimize the impact on public space and parking pressure of other inhabitants. Sharing of charging stations among EV drivers could reduce the need for charging stations. Joint use of charging stations requires cooperation between EV drivers, a topic that so far has hardly been studied in the literature. This paper is the first to address the topic conceptually and to provide insights both from stated and revealed data.

This research is setup as follows. We first put our research in the context of existing literature on both charging behaviour (Section 1.1 and cooperation in complex systems. From the set of existing literature, we collect factors that lead to patterns of cooperation (Section 2 Theoretical approach). These factors are used to design a survey on social charging behaviour (Section 3). We then display and explain the results of the survey (Section 4.1). From the results of the stated behaviour, we

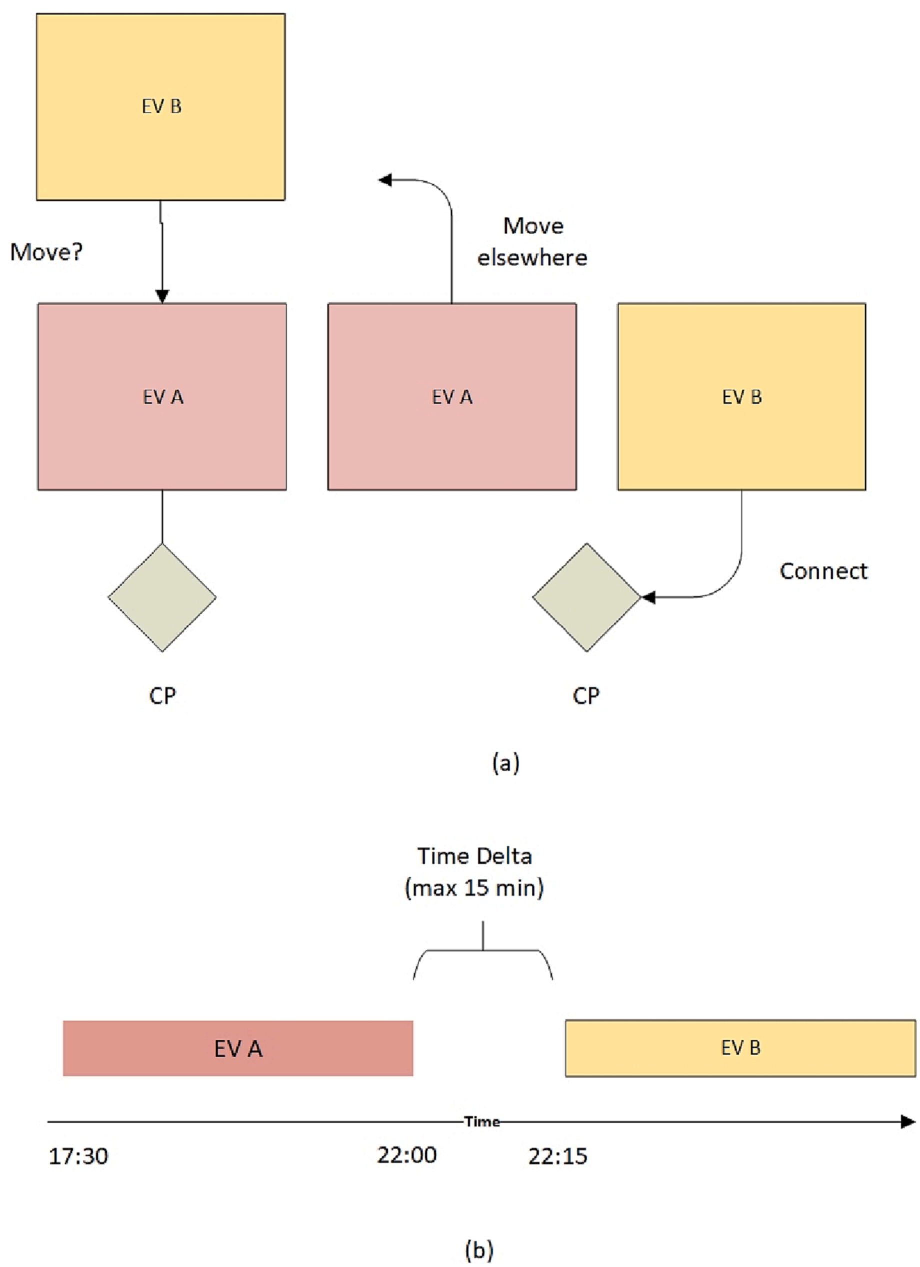

Fig. 1. Schematic visualisaton of cooperative charging behaviour.

apply filters real-world public infrastructure charging data to analyse patterns of social network formation (section 4.2), Finally, we draw conclusions and look forward to future research (Section 5).

1.1. Previous works

Cooperative behaviour in CPRs has been a subject of research in complex systems modelling (Bousquet et al., 1998; Künnecke & Finger, 2018; Ostrom, 2008; Wilson, 2002), game theory (Ostrom et al., 1994) and social experiment studies (Anderies et al., 2011). Studies have successfully described phenomena in other socio-technical systems CPRs in which interactions between actors in the systems are important. Simulation models have pointed at the spontaneous emergence of cooperative behaviour in noisy systems where agents are success driven (Helbing & Yu, 2009). Results from this research show cluster formation of agents that are willing to help each other. While existing CPR research shows similarities with charging infrastructure (e.g, common pool of electricity), the differences such as the limited access points to the common pool and the time-based user activities (charging) set apart this research from earlier work.

Charging behaviour has been researched since the first uptake of electric vehicles and is seen as deliberate behaviour of EV users to refill their EV at a preferred charging location (e.g., home of public, work) for a specific amount of time. Depending on the subject of research charging behaviour includes the following actions: locate a charging point, drive to specific charging point, check occupancy, in case of occupancy find an alternative, connect to charge, disconnect and the reconnection process after a certain amount of time or kilometres driven. Early work explored the interaction between battery size and decision of EV users to initiate a charging transaction. A large part of literature on charging has focused on the relation between the arrival time, state of charging and the connection duration (Almaghrebi et al., 2019; Morrissey et al., 2016, Philipsen et al, 2015) battery size of the EV may affect the times between sessions and therewith potentially the willingness to share charging points (Vermeulen et al., 2018).

Research by Delot et al. (2013) proposes an algorithm and a protocol for sharing parking spot information between vehicles and between parking spots and between vehicles and parking spots. A central concept of this research is the likelihood of two drivers encounter given arrival and departure times. This may relate to potential overlap and encountering of different types of EV users (office charging versus residential overnight charging) (Helmus et al., 2020). This paper builds upon this research, as it is now known that alternative parking spots are potential factors for willingness to act socially to another EV user. Yet, a parking spot with an EV charger and without are not functionally similar, and thus should be seen as an unbalanced exchange.

Cooperative behaviour in EV charging can only exist if their certain social rules or etiquettes surrounding the use of charging stations. Given that EV charging is relative new behaviour, such social norms are still being formed. Caperello et al. (2013) interviewed EV drivers and found that the lack of such etiquette had sometimes prohibited them from using a charging station either by a gasoline vehicle occupying the spot or other EVs staying connected to long. As well, in the situation in which it was possible to unplug other cars from the charger, it was often unclear if one was allowed to do so. Communication between EV drivers was possible in the form of a 'Charging protocol' that indicated that drivers were allowed to unplug after an indicated time.

Elbanhawy & Price (2015) looked at such etiquettes within a workplace setting and found that 'bay blocking', keeping the charger occupied if fully charged, is a problem in the workplace, but that the behavioural heterogeneity makes it difficult to set a single set of behavioural rules. Communication between EV drivers is necessary. Similar results for the workplace were found by Smith (2016) and Nicholas & Tal (2013). Such communication was studied by Plenter et al. (2018) for sharing private charging infrastructure with others.

In the public realm work by Schürmann et al. (2017) has shown that if EV drivers optimally communicate with each other, the number of public sessions in a single neighbourhood can increase by a factor of 7. Additionally, efficient use of charging stations increases between 21 % and 46 %. Such results sound very promising, yet drivers might not be willing to cooperate, either because they are not able to or for example surrounding parking pressure would make it difficult to find another free parking spot (Wolbertus and van den Hoed, 2017a; Wolbertus and van den Hoed, 2017b).

1.2. Contributions

Previous work has indicated the cooperative charging can be a good option to increase the effective utilisation especially in the workplace. So far, research on how for such practices are actually taking place in the public space is missing. This work contributes to literature in the following ways: This paper provides a theoretical framework for cooperative charging behaviour. Using a framework for cooperation from Nowak (2006a), Nowak (2006b), it is explored which aspects of it can be applied with EV charging. For each of the different ways to cooperate it is studied how much is applied in practice in a survey among EV drivers. It is investigated which ways of cooperative charging are most common and which barriers prevent EV drivers from cooperating. Additionally, it is studied how these intentions and barriers translate into cooperation on the basis of revealed charging behaviour. These results give an indication how well the stated behaviour is also seen in the use of charging stations and what the actual need for cooperative behaviour is.

2. Theoretical approach

Cooperation between individuals or organisations is one of the key elements of complex systems (K. H.; van Dam et al., 2013). Complex systems are defined by the fact that its elements interact with each other which may lead to network formation (Arrow et al., 2000; Cuesta et al., 2015; Mureddu et al., 2018). These interactions can be different forms of cooperation. Cooperation can be important to optimise the use of CPRs such as public charging stations (Andersson et al., 2021). In this paper the five different ways to cooperate from an evolutionary perspective defined by Nowak (2006a), Nowak (2006b) are applied to the case of EV charging. This section explores the theoretical foundations of such behaviour and analyses how this can be applied in EV charging based on an overview of the current literature.

2.1. Kin selection

From an evolutionary perspective, it could be useful that a person favours to cooperate with a relative over anyone else. Game theory research has shown that the closeness of players in multiplayer games affects their willingness to cooperate with other (Depping and Mandryk, 2017; Vella et al., 2017). The closer the member, the more likely-one is to cooperate. Such behaviour could also apply to EV charging. Practical cases could imply family members to be allowed to use private charging infrastructure and EV drivers that are more likely to free public charging stations when requested by family members instead of strangers.

2.2. Direct reciprocity

Direct reciprocity is defined as an exchange between two non-related individuals on a repeated basis. Given that cooperation happens on a repeated basis, it could beneficial for an individual to cooperate in the expectation that the other will cooperate the next time as well (Helbing & Yu, 2009). Such strategies are best known in the form of the repeated prisoners' dilemma in which the so-called tit-for-tat strategy is one of the more effective strategies (Axelrod, 1980). In this strategy the person chooses to cooperate at first after which it copies the behaviour of the other person after each choice.

In EV charging such strategy could also apply when two drivers want to make use of the same charging station. If one the drivers has completed his charging session, she would be requested by the other driver to move her car to a regular parking spot. The driver would expect that if something similar would happen the next time the other driver will do the same. Given that there is no direct punishment to not move the car, the driver would have to trust the other to reciprocate the action. Interaction with EV drivers can be facilitated through a charging protocol on a card behind the windscreen (Caperello et al., 2013) or digital applications which allow contact to users that are currently charging (Plenter et al., 2018).

2.3. Indirect reciprocity

Besides cooperation with other EV-drivers in which a direct request to move the car if charged is given, the EV driver could also move their car without a request or they move the car for a random visitor of whom the chances that they will meet again are small. Such altruistic behaviour is seen as indirect reciprocity (Nowak, 2006a; Nowak, 2006b). The motivation for the donor to remove their car is the reputation of the person at hand. She hopes that the act is seen by persons in her network, which boosts her reputation. At a later stage, other EV-drivers are more willing to help this person because of a positive reputation. For EV charging the observability of such an act is rather low, it would be therefore be questionable if such dynamics would work.

Other motivations for such altruistic actions are the setting of group norms. Research by Seinen and Schram (2006) shows that group norms can develop through the exhibition of such behaviour. In this research the EV driver wants to signal that removing your vehicle once fully charged is the social norm. Besides a positive signal, the EV driver could also start to point at negative behaviour such as the hogging of charging stations (Wolbertus and van den Hoed, 2017a; Wolbertus and van den Hoed, 2017b).

2.4. Network reciprocity

Direct reciprocity does not take into account that persons have different type of relations with each other. Besides family members, such as in kin reciprocity, people have friends, colleagues, acquaintances, neighbours etc. with whom they have closer relations than others. Such social and spatial dependencies influence the choice for reciprocity (Floría et al., 2009). The relations between persons can best be described in a network in which the nodes of the persons and the edges are the relations between the individuals. Depending on the size, strength and shape of the network the decision to cooperate or defect could also have an impact on the relation with other individuals in the network.

Within EV charging several situations could be relevant, such as sharing charging stations within a workplace setting. Given that relations with colleagues could be stronger than visitors, those working at the company would be more likely to share a charging station with colleagues (Elbanhawy & Price, 2015; Nicholas & Tal, 2013; Smith, 2016). In the public realm, charging stations are shared by multiple households in a certain neighbourhood. Given that these persons are more likely to meet on other occasions than others, cooperative behaviour would be more likely among them.

2.5. Group selection

The idea behind group selection is that groups that cooperate are more successful than groups that don't. While previous look at the benefits at an individual level of cooperation this concept looks at how different groups compete to survive. The better a group is organised the more likely they to survive.

Within the EV charging space, selecting groups is not evident. Potentially such groups could form along the lines of brands, especially if brand-specific charging infrastructure is available. Opening this infrastructure to all could potentially decrease benefits of owning a specific brand, thus belonging to a group and decrease the comfort of these drivers. Similarly, disputes might arise between plug-in hybrid (PHEV) and full electric vehicle (FEV) drivers as their interests differ. While PHEV drivers could see charging as convenient and cheaper FEV drivers see charging as essential which might spark disputes about the 'right' to make use of a charging between these groups.

On the other hand, one could look at EV drivers and drivers on gasoline as groups that are competing for the same parking space (Babic et al., 2018; Wolbertus and van den Hoed, 2017a; Wolbertus and van den Hoed, 2017b). Media reports suggests that debates can be heated (Hookham, 2017; Richtel, 2015). Cooperation within the group could be crucial to withstand pressure from the other group. An example is organised lobbying with government officials for beneficial parking layouts and enforcement (Bonges & Lusk, 2016; Steinhilber et al., 2013). Sufficient charging infrastructure is important for the 'survival' rate. The main reason for discontinuance of electric vehicles was a lack of charging infrastructure, especially a lack of home charging or a public substitute for this (Hardman & Tal, 2021).

3. Methodology

This research aims to provide insights for policy makers on cooperative charging behaviour. A survey is designed to focus on the different aspects of cooperative behaviour. The survey focusses on the first four aspects of cooperative behaviour as these involve measurable actions by the individual. Group selection processes are far more complex and surveys are not well suited to study this phenomenon. Besides stated evidence of cooperative behaviour this research also provides insight into revealed cooperative behaviour. This gives a possibility to give insight into how often such behaviour is necessary and to which extend stated behaviour can also be observed in practice.

3.1. Survey design and data description

The survey aims to gather data on the first four concepts of cooperation. Introductory questions revolve around basic information on the charging behaviour of the EV driver such as the type of vehicle, the use of public charging stations and the willingness to walk to charging stations. Questions on direct and indirect reciprocity are asked on a both a discrete (yes–no) and 0–100 percent scale. Additional questions involve potential barriers to not showing cooperative behaviour. Questions on kin selection and network reciprocity are asked on a five-point likert scale to see how much different kind of relations influence the willingness to cooperate. Additionally, the way in which EV drivers communicate with each other is addressed in the survey. Group selection has been left out of the analysis as there is no clear application of the concept in public EV charging that is accessible to all as described in our theoretical evaluation.

Besides questions on their own choices, participants are also asked how often their requests to clear a charging station has been answered and by whom. Participants are also faced with open-ended questions to further motivate their answers when they choose to not cooperate. As well they have the opportunity to express what they see as the right charging etiquette. An overview of the relevant questions in this questionnaire for this research has been added to Appendix A.

Participants for the questionnaire were recruited online through advertisement on diverse social media channels (primarily LinkedIn and Twitter). The questionnaire was in Dutch and English, although the primary focus was on Dutch participants. Participation was voluntary, anonymous and there was no form of incentive. The questionnaire was open for 3 approximately 3 weeks in February/March 2020.

In total 507 respondents filled in the survey. In total 313 (62 %) responses were complete enough to be used within this research. Summary statistics are given in Table 1. The majority of respondents drives a full electric vehicle. This is in contrast with the number of vehicles registered in the Netherlands in which at the time of the survey 37 % was

Table 1
Descriptive statistics on vehicles and charging behaviour of respondents.

Type of vehicle	Full electric (90.3 %)Plug-in Hybrid (5,4%)Non-electric (4,3%)
Charging at type of charging station	Home (48.4 %)Public (29.6 %)Semi-public (11.4 %)DC (10.6 %)
Mean % of charging attempts that fail due occupied charging stations	18.4 %

a plug-in hybrid vehicle. Drivers indicated that in 18 % of the times they tried to charge this was not possible due to occupied charging stations.

The majority of charging is done at home, with a significant share for public charging, due to EV drivers not having a driveway or garage. Out of 385 users 51 % indicated to use private charging as most used charging mode. And 21 % indicates to charge mostly at public AC charging. The spread of charging sessions by EV users over AC public, DC, private and semi-private charging the of respondents corresponds with the distribution of sessions in, see Fig. 2(a). It is therefore concluded that the population of our respondents are sufficiently representative for the EV community in the Netherlands.

3.2. Revealed cooperative behaviour

3.2.1. Data gathering

Data on charging behaviour on public charging stations (Alternating Current, up to 11 kW) in the city of Amsterdam, the Netherlands has been gathered during a two-year period between January 2018 and December 2019 (Table 2). The municipality in the past has mainly placed charging stations at the request of new EV drivers (Helmus et al., 2018). Despite being placed on request, charging stations are public. Charging stations usually have two outlets. Charging stations can be accessed through the use of an RFID card or tag. This RFID card number is used as an anonymous identifier for the user. Public charging stations within the city are often used as a replacement for home- or workplace charging as most parking is also done on-street. The following data on the charging sessions is gathered.

Table 2
Charging Data.

Data	Unit
Location	Coordinates (Latitude, Longitude)
ChargePoint ID	Unique identifier for charge point
RFID ID	Unique identifier for EV driver
Start Time	Date and time of day
End Time	Date and time of day
Energy charged	kWh

3.2.2. Data manipulation

To exclude possible faulty charging sessions, data of charging sessions that last at least 5 min and in which more than 0.01 kWh is charging are included. This research focuses on regular users of the charging network in Amsterdam. This done to prevent incidental cooperative behaviour from visitors to be included in this analysis. Charging sessions by shared vehicles, taxis or at fast charging stations are not accounted for as it is hypothesized these types of users are far less likely to engage in such behaviour. Data is being included in the analysis if an EV drivers (represented by its RFID) is available at least 30 times. Note that regular users could show cooperative behaviour towards a visitor and such results are included here. The battery capacity of an EV is the maximum energy charged in a single charging session by an EV driver. Charging speed is determined using the highest charging speed (Energy/Time) observed across all charging sessions. See Wolbertus & Van den Hoed (2018) for a detailed calculation of the charging speed. With the use of the charging speed the actual charging time of the session is calculated.

Cooperative behaviour is studied in three ways. Direct reciprocity is defined when a new charging session starts at the same charging station and socket within 15 min after the end of the same charging session (as also shown in Figure XX lower part). These 15 min is the rounded average (actually 13,5 min) from the questionnaire (See Appendix A, Q15). Indirect reciprocity is defined as removing the EV from the

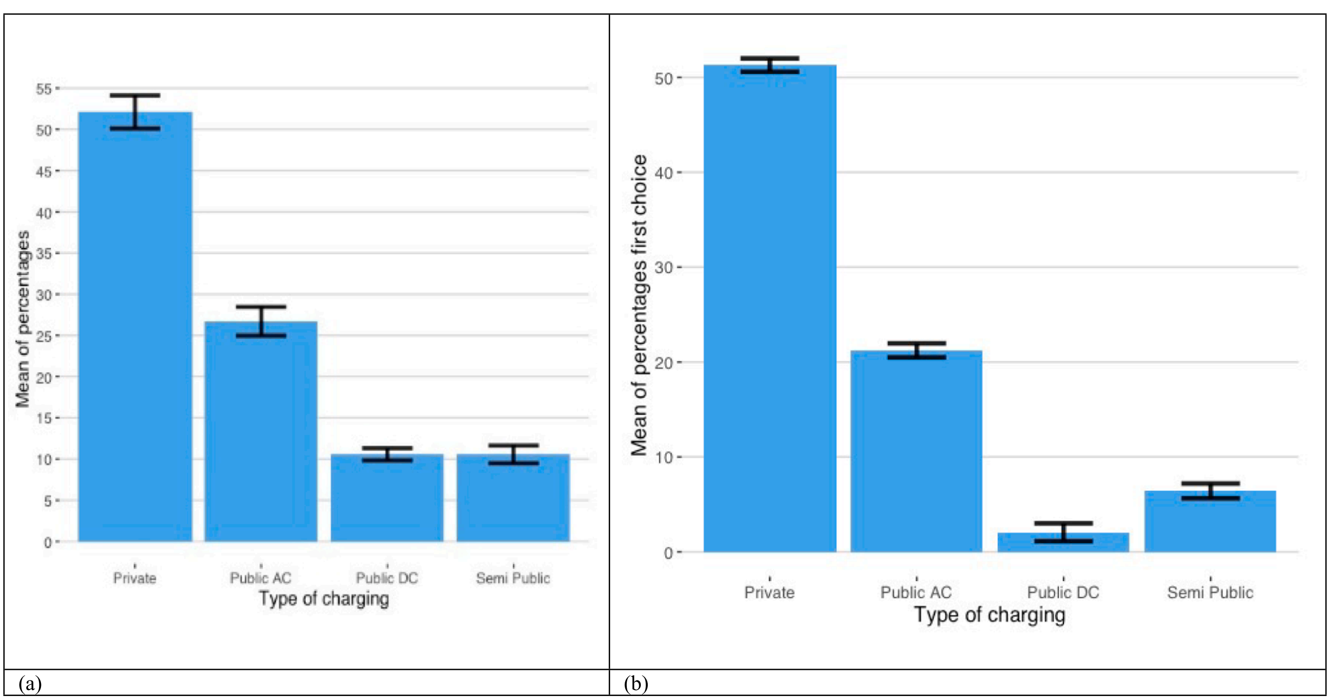

Fig. 2. Overview of charging modes over respondents: (a) mean values for modes over all respondents; (b) percentage of dominant charging mode per user over population.

charging station with 1 h after the actual charging session. The latter definition could leave some room for some sessions being defined as reciprocal while this might be coincidence. Given this nature, additional attention shall be paid to the repetitive aspect of such behaviour. Network reciprocity is analysed with respect to the neighbourhood the EV driver lives or works in. The neighbourhoods are defined at three levels (see section 4.2.3). It assumed that the most used charging station is close to home or workplace of the EV driver. The EV driver is assigned to a certain neighbourhood where that most used charging station is located. Network reciprocity is studied given the home neighbourhood of the EV driver. Given the anonymous nature of the data, other types of reciprocity cannot be determined from this data.

3.2.3. Descriptive statistics

During the period 2.138.542 charging sessions were registered at 1689 public charging stations in Amsterdam. 78.770 unique RFIDs from charging cards were used of which 12.678 RFIDs were registered at least 30 charging sessions. Electric cars were on average 9,6 h connected to charging station of which 2.3 h were used to actually charge the car. In this time on average 10.9 kWh was charged. An overview of the start (left) and end (right) time distributions is given in Fig. 3.

4. Results

4.1. Survey results stated cooperative behaviour

4.1.1. Direct reciprocity

From the respondents 67 % replied that they had moved their car once at the request of another EV driver. On average this was done in 39,5% of the cases if another driver had requested to get access to the charging station. The distribution of how often one would move their car is however widely dispersed indicating different motivations for (not) doing so (Fig. 4).

The effect of perceived inconvenience of EV users due to occupied charging points on their willingness to cooperate with other EV users is addressed next. Regarding the tendency of perceived inconvenience by other EV users that occupy charging stations it can be noted that there is a subtle but significant relation between EV users that are mainly show direct reciprocity and indirect reciprocity. There is a subtle but significant relation between EV users that provide indirect reciprocity and the rate of perceived inconvenience (sample size 352, Effect size (Cramers V) 0.190, p-value 0.0125). This implies that the more frequent EV users perceive inconvenience, the more willing they are to provide direct reciprocal behaviour.

The importance of factors affecting their willingness in (Fig. 5) reveal that three factors have been mentioned to be important: (i) battery level, (ii) the presence of a not occupied alternative parking spot and (iii) reciprocal behaviour of other EV users. The alternative parking spot is highly left skewed with a large standard deviation. This suggests that for some contexts the alternative parking spot is not an issue as parking pressure may be low in certain locations, or that EV users swap parking spots. The reciprocity is normally distributed with a larger standard than battery size.

When asked why one would not move the car (Table 3) most repsondents indicated that their battery was not fully charged. When asked what fully charged is, only 46.5 % indicate that it actually should be fully charged. The majority (86.5 %) thinks that have charged enough for the next trip should be sufficient. 44 % of the respondents indicate that if charging is avialable during the next trip to complete it, this should be sufficient enough to detach the EV from the charging station. Indications of reciprocity ("I don't know the other person" or "No one has done so for me") score remarkably low on reasons to not move the car. Practical issues such as a lack of time of other parking space are mentioned more often. Those in the else category mostly answer that they have not encoutered such a situation or have no way of coming into contact with different EV drivers.

4.1.2. Indirect reciprocity

From the respondents 87 % indicated that they had disconnected at least once from a charging station once fully charged without having a direct request from another EV driver. This is remarkably higher than for direct reciprocity. It is hypothesized that the major barriers do not apply here, since EV drivers will only replace their car if these do not apply. This however does not happen in more 32 % of the charging sessions on average. The distribution shown in Fig. 6 shows that the respondents indicate that they don't do so more than 50 % of the charging sessions at public charging stations. As expected, none of the respondents provides indirect reciprocity without direct reciprocity.

A closer look at the respondents that answered both the questions on providing cooperative charging behaviour to others and receiving form others is found in Table 4. From this table it can be seen that there is a stronger positive reciprocity effect (45.4 %) than negative (31.2 %) reciprocity. Moreover, 33.3 % (72 out of 216) of the EV users provide cooperative charging behaviour to others, without receiving the same cooperative charging behaviour. This may point at the idea that cooperative behaviour relates to normative values.

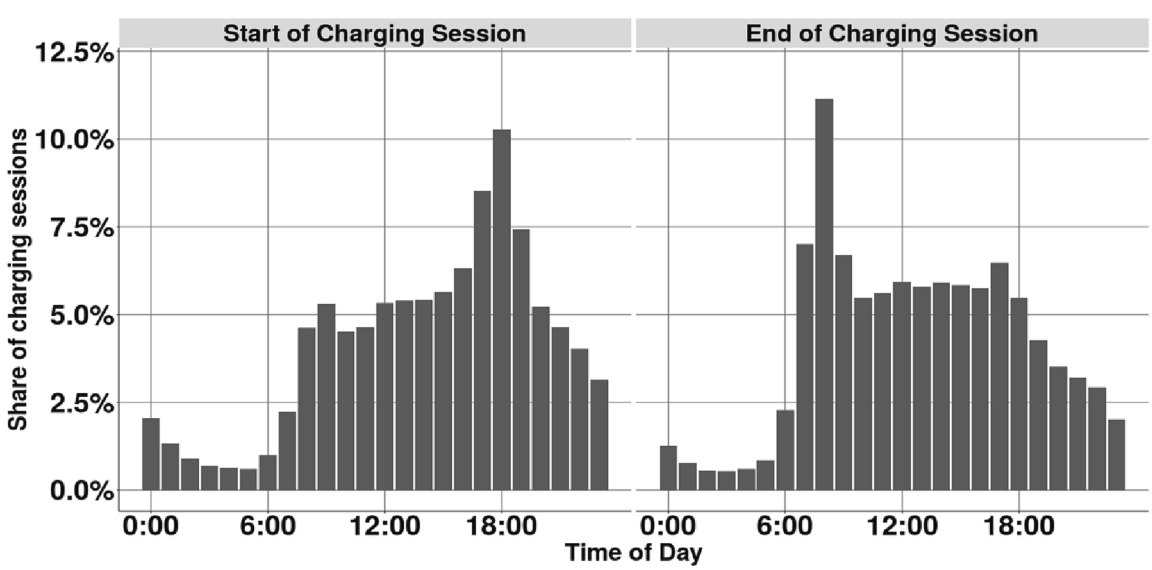

Fig. 3. Distribution of start and end times throughout the day.

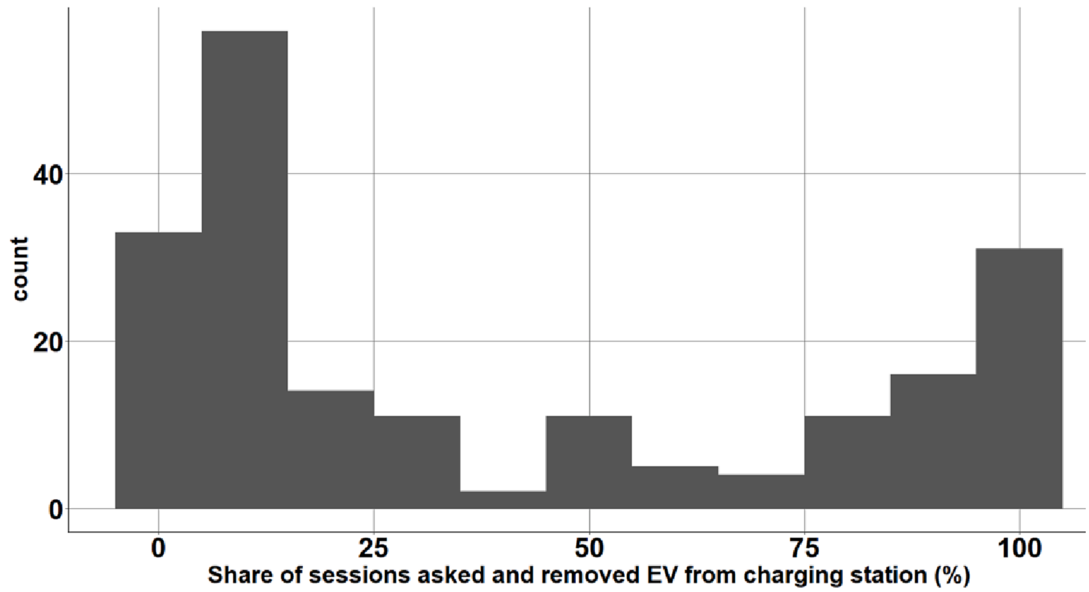

Fig. 4. Distribution of times survey respondents removed their car if asked.

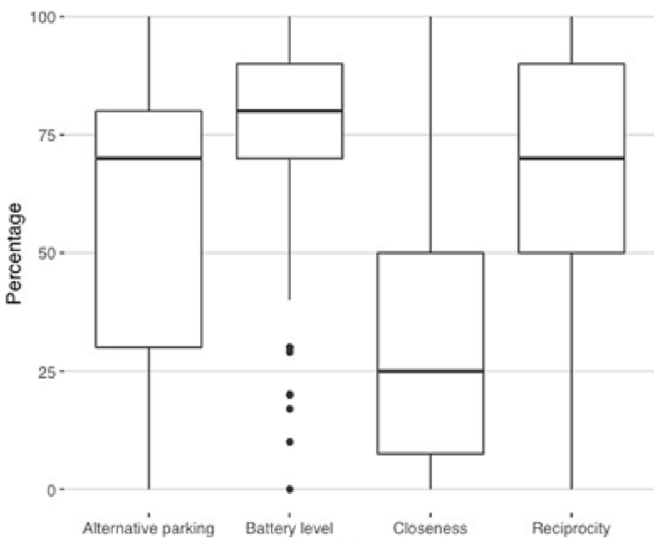

Fig. 5. Distribution of prerequisites to remove vehicles.

Table 3
Reasons to not move the EV if asked.

Reason	% of respondents
Battery not fully charged	19 %
No time	6,6%
Lack of other parking option	5,7%
I don't know the other person	2,5%
No one has done so for me	0,6%
Never charge at public charging stations	7,3%
Else	9,2%

4.1.3. *Kin & network reciprocity*

As shown in Table 5. and supported by the results of the Chi-Square analysis ($X^2(170,8) = 17.195$, $p = 0.02814$) EV drivers are more likely to replace their car for family and friends than for neighbours of the friends of neighbours. There are however no statistical differences between any of the other type of social relations ($X^2(170,8) = 9.5285$, $p = 0.2997$) indicating that kin reciprocity is stronger than network reciprocity. Such differences are not seen across the different type of social relations due to relatively high number of EV drivers that indicate to always remove their car if requested. Only for family and friends they do so more often.

The effect of cooperative charging behaviour to other EV users appeared to be widely spread. A large group (25 %) indicated to benefit from this behaviour 1 out of 20 sessions. A group of 15 % indicated to benefit 1 out of 10 sessions. Interestingly, a subset of 9 % of EV users indicate that 1 out of 2 sessions can proceed due to social charging behaviour. This large subset may be causes by a locality of scarcity for charging points.

There appears to be no significant relation between the percentage of use at public charging points and the percentage of sessions that EV users can charge due to receiving social charging behaviour (P-value 0.881, Pearson's r 0.0132, R-Squared 0.000175). A group of 17 % indicate to not benefit from social charging behaviour.

4.2. *Revealed cooperative behaviour*

4.2.1. *Direct reciprocity*

Out of the 2.138.542 charging sessions, 128.918 sessions (6 %) have less than 15 min between end and start of the charging sessions. This could indicate contact between the EV drivers to make room for the charging station when needed. To exclude incidental behaviour from this analysis, only charging sessions in which the same two users are involved are included. Users that are shared vehicles and taxi drivers are also excluded in this analysis. Only 7667 of the charging sessions (0.4 %) are noted as cooperative behaviour. This is far less than indicated in the results of the survey. These sessions come from 2267 unique users in the network. From the regular users (12678; at least 30 charging sessions in the period) this represents 17,8%. Although lower than the 67 % in the survey, this is still a significant share of the users that are willing to cooperate multiple times.

The underutilised potential of cooperative behaviour is substantial. As noted, 94 % of all charging sessions are not ended within 15 min after charging has finished. When looking at a broader period (2 h) this is still 52 % of all charging sessions. On average the actual charging time is approximately 3 h (29 % of time connected), while the time connected is 10.5 h. Even when considering that is not convenient to remove the car in the late evening or night (~40 % of sessions), there is still substantial room for freeing charging stations from idle sessions.

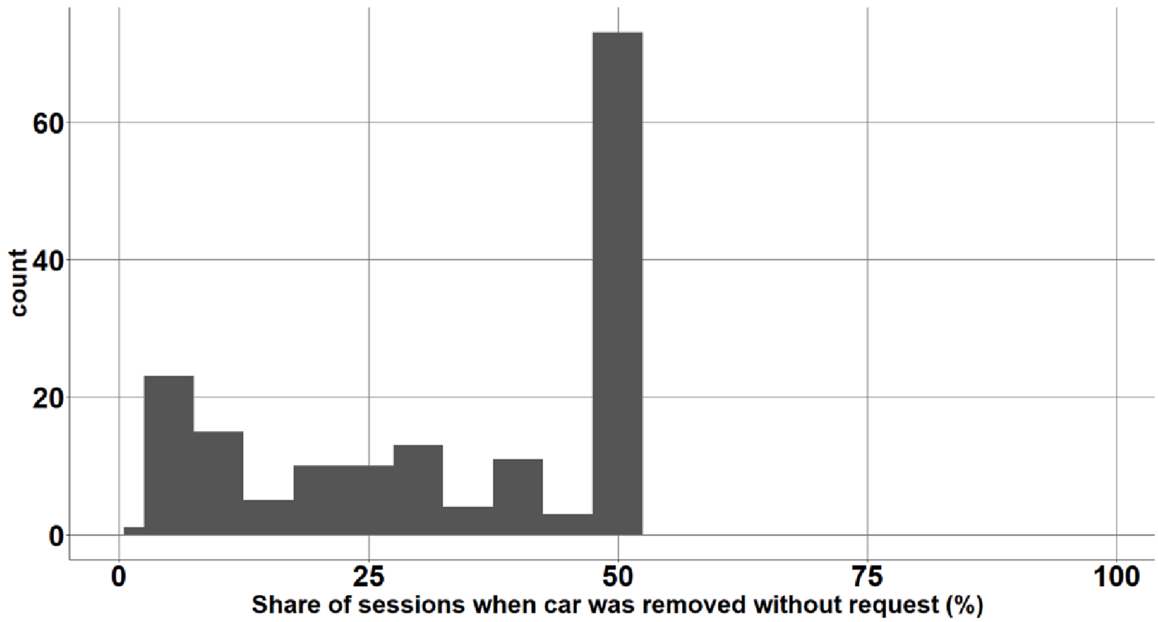

Fig. 6. Distribution of sessions of survey respondents that removed their car once fully charged without request.

Table 4
EV User removes car for other user.

	Yes	No	Total
Yes	144 (45.4 %)	2 (0.6 %)	**146**
No	72 (22.7 %)	99 (31.2 %)	**171**
Total	**216**	**101**	

Table 5
Frequency table for how often EV drivers would replace their vehicle for different kind of social groups.

How often do you replace your EV for:	*Family/ Friends*	*Neighbours*	*Friends & Family from neighbours*	*Visitors*
Always	*80*	*65*	*58*	*65*
Often	*31*	*33*	*28*	*28*
Regularly	*19*	*30*	*18*	*19*
Sometimes	*24*	*29*	*41*	*26*
Never	*16*	*22*	*30*	*21*

4.2.2. *Indirect reciprocity*

Indirect reciprocity is defined as removing the EV from the charging station once the battery has been fully charged. The results show charging sessions that have ended within one hour after the energy transfer has stopped. This is considered reasonable time to allow the EV driver to react to the signal that their battery is fully charged. In total 30.4 % of all charging sessions are ended within one hour after being fully charged. Among frequent users (at least 30 charging sessions) this is only 18.4 %, among non-frequent users this is 83.3 %. Given that the average connection time of these non-frequent users is only 5.5 h, much shorter than the total average, it can be concluded that this high percentage among non-frequent users is mostly a result of that the users only visit the city and therefore stay parked for a short time, which is not necessarily a result of reciprocal intentions.

Similarly, among frequent users the distribution of charging sessions across the day in which they show indirect reciprocal behaviour substantially differs from regular charging patterns (see Fig. 2). Fig. 7 shows if the location at which the EV driver charges (and removes his car once finished charging within an hour) differs from the most used location. In 64 % of these charging sessions the driver does not charge at his favourite station, but is visiting somewhere else in the city. Compared to

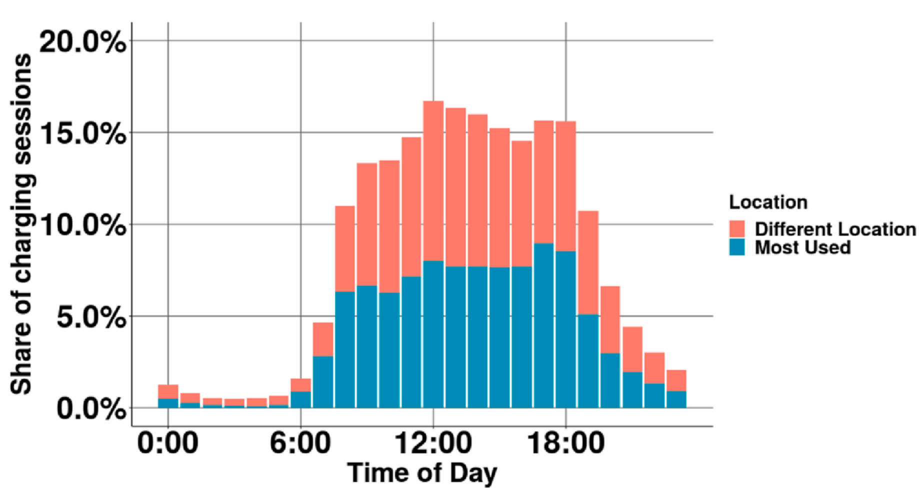

Fig. 7. Distribution across the day of charging session with indirect reciprocal behaviour at most used or different location.

43 % on average this shows a different intention of the parking and charging behaviour instead of indirect reciprocal behaviour. To narrow the it down to regular behaviour only charging sessions of frequent users in the same sub-district as the most used charging station is analysed.

Among those charging sessions (736,881) 16.2 % have the characteristics of indirect reciprocal behaviour. This is far less than the 87 % indicated in the survey. One of the major reasons for such a lower percentage is likely the time of day at which the battery finishes charging (Fig. 8). The majority of charging sessions end in the evening or during the night. EV drivers are far less inclined to remove their car at these times of day. Also, the share of charging sessions that indicate such behaviour decreases significantly during these times, possibly due to higher parking pressure during these times as indicated in the survey results. The spike in share of indirect reciprocity early in the morning most likely indicate charging sessions that take the entire night to charge. These drivers could either go to work or actually clear the charging station for drivers that are coming in.

4.2.3. *Network reciprocity*

To study the effect of the network reciprocity among neighbours is studied. Districts are defined at the District, SubDistrict and SubSubDistrict level in Amsterdam. Amsterdam has 7 districts, 99 subdistricts and 481 SubSubDistricts. Amsterdam had 872.757 inhabitants on the 1st of January 2020.

Fig. 9 shows that share of interactions of EV drivers that live or work in the same district for the different district levels. The x-axis shows the number of interactions that the EV drivers have. If interactions are not very common for EV drivers to work of life in the same neighbourhood, network reciprocity is not considered important. But if the number of interactions increases it becomes very likely for EV drivers to live or work in the same neighbourhood. The results show that if interactions are common this most likely between those that live or work in the same neighbourhood at the SubSubDistrict level. Networks are considered more important if the EV driver wants to cooperate with a different EV driver to make a charging station available. The EV drivers are also much more likely to meet each other if they mainly reside in that area.

Similar results on network reciprocity can be seen in Fig. 8 in which the network is shown. Interactions are not only between two different drivers but can involve multiple EV drivers. In Fig. 10 the network is shown for at least three interactions between users. The figure shows that multiple networks exist out of more than two users, although most networks have one central users. The network in the centre of the figure shows multiple users providing the same service for each other, clearly indicating interactions between them. Out of the 251 nodes in the network 79 (31 %) are in a network more than one edge. Most networks involve users from the same district, in line with the results from Fig. 7.

5. Conclusions

This paper has conceptualised cooperative behaviour at public charging stations along the cooperative strategies in an evolutionary perspective within a common-pool resource. The paper shows that the framework from Nowak (2006a), Nowak (2006b) containing five different cooperative strategies can be applied on this case as well, with the exception of group selection in which it is more likely that electric vehicles drivers as group compete with gasoline driven vehicles. It is therefore concluded that these general principles of cooperation can also be applied in this case study.

These different forms of cooperation among EV drivers are studied in two different ways: Through a survey and by looking at a large set of charging data from public charging stations in Amsterdam. In this way not only stated intentions but actual behaviour could also be measured. Overconfident self-reporting and sample bias are controlled for by cross-referencing the results from the two different methodologies.

Results show that the intention to show direct reciprocal charging behaviour is high among the respondents, although this could be limited if the battery did not reach full or sufficient state-of-charge at the moment of the request. Intention to show direct reciprocal behaviour is mediated by kin and network effects. Familiarity with the cooperative party enhances the chances of showing such behaviour. This result is found in both the stated and the revealed charging behaviour, in the latter continued cooperation between EV drivers was much more likely if they lived or worked in the same neighbourhood. Other findings in the revealed data showed that the intention to cooperate was not found to match actual cooperative behaviour. This was both true for cases of direct and indirect reciprocity in which stated intentions are a factor three times higher than observed behaviour. From this we conclude that there is room for potential increase of cooperative behaviour in public charging infrastructure. Using our survey results, policy makers may define interventions to initiate cooperative behaviour.

Results also indicated the significant effect of cooperative on the receiving EV user. From the rates of both the receiving as well as the providing number, we conclude that social charging behaviour may add to the business case of public charging infrastructure. Increased

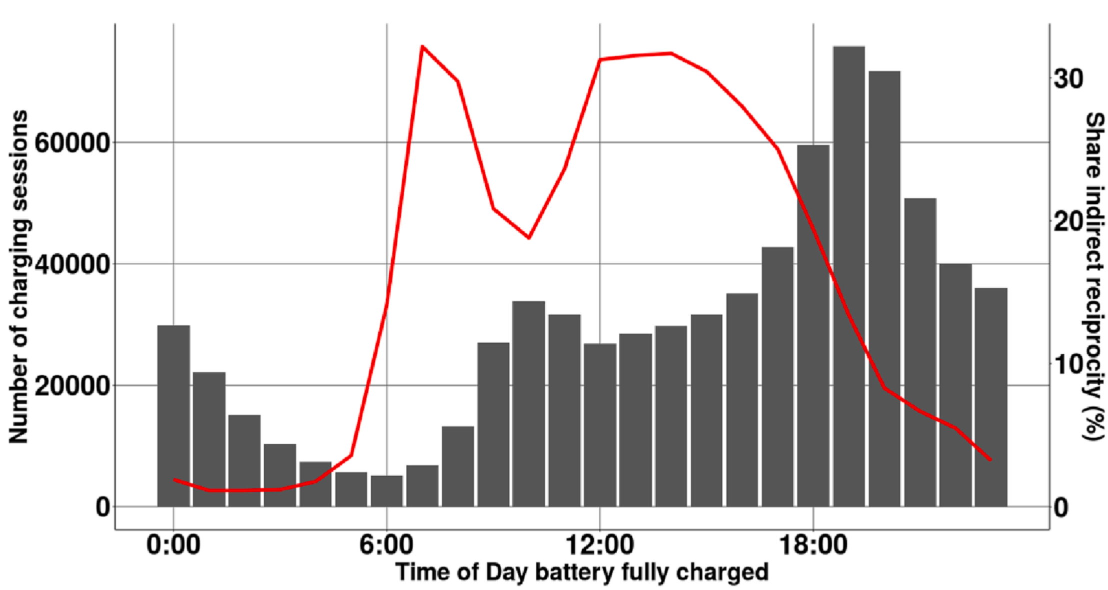

Fig. 8. Number of sessions (black bar) fully charged across the day and share of indirect reciprocal behaviour (red).

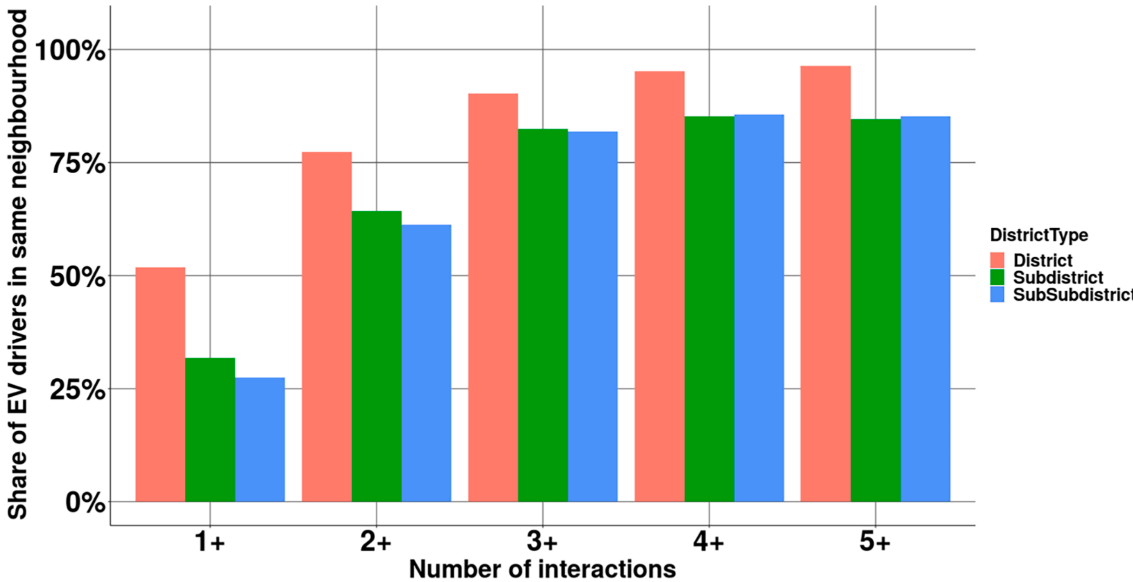

Fig. 9. Share of EV drivers in the same district (at different levels) with increasing number of interactions.

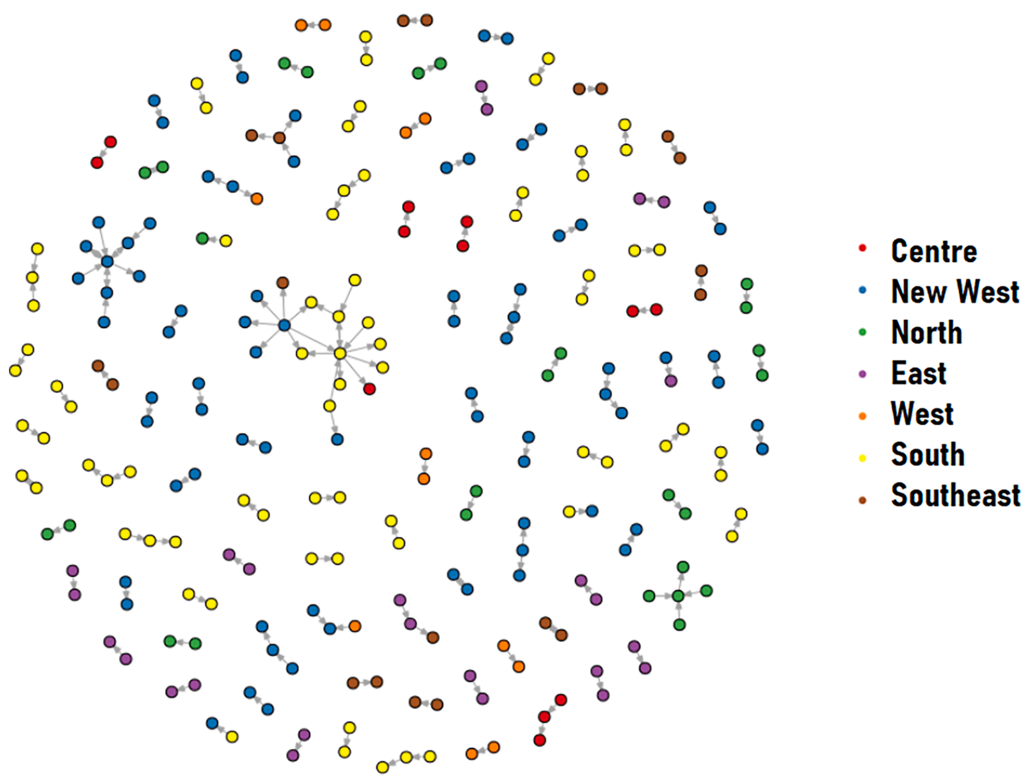

Fig. 10. Network of EV drivers cooperating with each other. Colours indicate the district of where the EV driver charges the most.

cooperative behaviour could lead to less idle time at charging stations. A rough estimation based on our numbers is that 20–50 percent increase of charging point utilization may be possible. This number may increase if social charging behaviour would be incentivized, given that our only takes into account voluntary behaviour.

The difference between stated and revealed behaviour can be explained by three dominant factors. First, sample selection of respondents. As the survey was advertised on social media and among members of EV driver associations, it could be expected that self-selection bias was found to be present. Secondly, over-confidence among EV drivers about their cooperative behaviour is likely to be present. Finally, it is expected that cooperative behaviour is not yet needed in many situations as sufficient charging infrastructure is available in the sample that was selected. Findings also show that due to the timing of charging sessions (many finish late evening or early night) there is no need for cooperation, and it is very unlikely EV drivers would move their car at that time of day. This was not made explicit in the survey which could explain the gap between stated and revealed cooperative behaviour.

Policy makers could use these results to promote cooperation between EV drivers in their cities. This could be done by facilitating easy contact between EV drivers through promoting digital applications.

Charging stations should be connected to these applications to provide live updates on the occupancy and allow (initial anonymous) contact between the relevant drivers. The city could promote the use of these applications by referring to them on the charging station themselves. Given the survey results such a campaign could focus on creating community of EV drivers because EV drivers are more likely to show cooperative behaviour if they are known with recipient. Additionally, concerns about available parking should be mitigated by allowing EV drivers to park with certainty and without additional costs in city parking garages. As well, social norm setting on indirect cooperative behaviour could be an important motivator for such behaviour.

Results both from the revealed and stated preferences show that users see charging infrastructure as network both physical as socially. This does not only have implications for cooperative behaviour at these charging but also for roll-out strategies of charging infrastructure. Infrastructure planning should not only look at the area that a certain charging point serves, but rather look at the network implications of installing charging points at new locations. This could create new physical and social networks which lead to optimisation of charging infrastructure use.

The results however show that the intention to cooperate is high and could also be observed in reality. Cooperation between those that live in the same neighbourhood, and make most frequently use of the same charging stations, could very well be sustainable. Facilitation of communication about a finished charging session and the possibility to request to remove a car from a charging station should be facilitated by the charging point operator. Remarks from respondents showed that such communication was lacking. In the future, with for example the use of discrete choice experiments it could be explored which factors play the most dominant role in such choices, which could be used to design communication applications for the EV driver. Cooperative behaviour could increase EV charging station turnover and facilitate the growth of electric driving at relatively low cost. As the willingness is high among EV drivers it can be advised to facilitate and promote such behaviour especially in neighbourhoods with relative high EV adoption.

CRediT authorship contribution statement

J.R. Helmus: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **R. Wolbertus:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition.

Declaration of Competing Interest

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

Acknowledgement

This research is a part of the Future Charging project funded by SIA RAAK (NWO). Project number: RAAK.PRO03.128. I am grateful for the collaboration and data provision from all partners involved.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tbs.2023.100572.

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