A Reservation-Based Vehicle-to-Vehicle Charging Service under Constraint of Parking Duration

Shuohan Liu, Qiang Ni, Yue Cao, Jixing Cui, Daxin Tian, Yuan Zhuang

***Abstract*—Electric Vehicle (EV) has been applied as the main transportation tool recently. However, EVs still require a long charging time and thus inevitably cause charging congestion. The traditional plug-in charging mode is limited by fixed location and peak hours. Therefore, a flexible Vehicle-to-Vehicle (V2V) charging mode is considered in this paper. Here, Parking Lots (PLs) widely dispersed in cities are reused as a common place for V2V charging. EVs are divided into EVs as energy consumers and EVs as energy providers to form as V2V-Pairs.**

In this paper, we propose a V2V charging management scheme, which includes a distance-based V2V-Pair matching algorithm and a PL-Selection scheme. As the occupation status at PLs is difficult to predict, to achieve high PL utilization and evenly PL-Selection, V2V charging reservation is introduced. Meanwhile, since EV drivers usually park at PLs within a limited duration, our proposed V2V charging scheme introduces the parking duration to optimize V2V charging under a temporal constraint. We simulate this V2V charging scheme under the Helsinki city scenario. The results prove our proposed V2V charging scheme achieves great charging efficiency (minimized charging waiting time and maximized fully charging times).

***Index Terms*—Electric Vehicle, V2V Charging, EV Charging Optimization.**

I. INTRODUCTION

In recent years, due to a large number of greenhouse gas emissions, the environmental problem has become increasingly prominent [1]. The greenhouse effect is posing a serious threat to people's daily lives. Therefore, Electric Vehicles (EVs) are regarded as major means of transportation to protect the environment as EVs use clean energy [2]. Compared with the traditional internal combustion engine vehicles, EVs produce less greenhouse gas emissions and converse energy more efficient.

Nevertheless, due to the limitation of charging technology, EVs charging time still can not satisfy EV drivers. This brings two challenges in the large-scale deployment of EVs:

(a) In the spatial domain, compared with the refuelling time of ICVs, the charging time of EVs is extremely long [3].
(b) In the temporal domain, EV charging is constrained by the limited Charging Stations (CSs) deployment.

Previous works on EV charging optimization focus on plug-in charging mode [4], where charging service is accomplished by plugging EVs into charging slots (set by CSs geographically deployed in the urban city). Here, EV charging optimization either works on charging scheduling (when to charge) under temporal domain [5], [6] or works on charging recommendation (where to charge) under spatial domain [7], [8].

In charging scheduling optimization, previous works aim to allow more EVs to finish charging at CSs within a limited period (jointly considers the parking duration in the works [9], [10]). Meanwhile, in charging recommendation optimization, previous works concentrate on allocating EVs evenly among CSs, so as to reduce charging congestion. However, urban areas are nearly saturated recently, CSs suffer from high costs in deployment and operation [11]. This restricts further EV charging optimization in the plug-in charging mode.

Therefore, recent works have started to address emerging Vehicle-to-Vehicle (V2V) charging mode [12]. Here, those traditional Parking Lots (PLs) are reused as public places for energy transfer among EVs. In the previous urban planning, PLs reserve plenty of parking space for traffic mediation. Additionally, by deploying DC-DC converters [13], [14], PLs can be applied for V2V charging, other than serving traditional parking management.

EVs are divided into EVs as energy Providers (EV-P) and EVs as energy Consumers (EV-C) [15] in the V2V charging mode. EV-Ps (EVs supplies energy/discharge energy) transfer surplus energy to EV-Cs (EVs request energy/charge energy) through DC-DC converters deployed at PLs. An EV-C and its EV-P are formed as a Vehicle-to-Vehicle charging Pair (V2V-Pair) for V2V energy transfer. Here, the V2V-Pair matching is important in achieving smart and flexible V2V charging behaviours [16]. As EVs have high mobility, major concerns in V2V-Pair matching are EVs' locations and their charging profits. A V2V-Pair matching initiated by EV-Cs would cause demand confusion and uncertainty. Therefore, for a stable V2V-Pair matching, a Global Controller (GC) can be applied to centralized allocate the matching of V2V-Pairs.

Previous works apply the V2V charging mode as a supplement to the plug-in charging mode. This maintains the load balance of the grid and regulates the price of energy [17], [18]. However, the V2V mode can be further applied as an alternative to the plug-in charging mode [19]. Here, PLs in V2V charging mode becomes a potential substitute for CSs in plug-in charging mode, especially that PLs are flexible in location and require a lower operation cost.

Nevertheless, in V2V charging, the charging time of an EV-C exceeds more than an hour [20]. The charging congestion would occur if all converters at a PL are occupied. Therefore, the selection of PL is crucial for any matched V2V-Pair

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[19]. An optimized PL-Selection scheme could alleviate the V2V charging congestion and efficiently use converters at PLs. Here, the availability of the converters will determine whether a PL is available for a matched V2V-Pair. Due to the uncertainty of occupation status of V2V-Pairs at PLs, it is difficult to predict which PL will have potential charging congestion. To solve the above problem, the reservation anticipated enables the GC to estimate the potential charging flow at PLs. Such reservations will avoid allocating V2V-Pairs to PLs with potential charging congestion.

Considering that the traditional plug-in charging mode has practical issues (a rigid requirement for CSs and charging congestion), in this paper, we propose a flexible V2V charging management scheme to alleviate the charging congestion and provide convenience to EV drivers. This V2V charging scheme includes a distance-based V2V-Pair matching scheme and a PL-Selection scheme. In addition, V2V charging reservation and parking duration are introduced. Technically:

1) We propose a distance-based V2V-Pair matching scheme to reduce the EVs' energy consumed on-the-move before the charging of V2V-Pairs starts. Major previous works in V2V-Pair matching rely on preset static data (like in works [17], [18]), nevertheless, the real-time status of EVs is considered in our paper.
2) Furthermore, we propose a PL-Selection scheme. This is different from previous works that focus on V2V charging optimization in a single parking area without considering on-the-move EVs (like in works [16], [21]).
3) As the occupation status at PLs is difficult to predict, EVs are asked to send reservations (different from the work [22]). This helps to predict the occupation status at PLs and evenly allocate V2V-Pairs.
4) Previous works ignore the parking duration constraint (like in works [19], [23]), which is contrary to the reality (drivers park a PL within a limited duration). It is novel in our paper that introduces the parking duration to refer the upper limitation that EVs park at a PL. This allows the GC to intelligently allocate V2V charging requests within the limited parking duration.

In Section II we present the related work, followed by Section III in which the proposed V2V charging management (a distance-based V2V-Pair matching and a reservation-based PL-Selection) is presented. Followed by the performance evaluation in IV, we conclude our work in section V.

II. RELATED WORK

The large-scale application of EVs would cause charging congestion. This needs to be solved to relieve range anxiety of EVs [24]. Major previous research works focus on EVs' static charging at CSs ([6], [24]–[27]). Considering the rigid location and capacity of CSs, they are difficult to handle large-scale concurrent charging requests, especially at peak hours. However, the V2V alleviates the charging congestion during peak hours and is more flexible in charging location selection ([13-14],[18-19],[28-30]).

A. Plug-in Charging Mode (Static Charging at CSs)

Due to the rapid increase in the number of EVs, in plug-in mode, how to optimize charging services at CSs has become the main content of previous works. Here, the optimizations mainly focus on two aspects: the CS-Selection for on-the-move EVs and charging scheduling for parking EVs.

By comparing either on selecting CS with the minimum distance or with the minimum waiting time, the work in [24] proves that selecting CS with the minimum estimated waiting time would avoid waiting too long for EVs in a single customer service. Here, to accurately estimate the minimum waiting time, the work in [25] selects the CS by collecting and combining the number and the remaining charging time of EVs at CSs. The CS-selection scheme in [26] adopts a pricing strategy, which minimizes congestion and maximizes profits by adjusting the price according to the number of EVs at each time point.

The other important research aspect is the charging scheduling when EVs have arrived at CSs. However, most previous works apply the First In First Serve (FIFS) policy to determine charging priority among EVs. That is unrealistic because EV drivers may spend limited time at a CS. The work in [6] presents two scheduling strategies: the Earliest Start Time (EST) and the Earliest Finish Time (EFT). In EST, the order of EVs arriving determines EVs' charging order. In EFT, EVs that can be fully charged in a relatively short time have a higher charging priority. Considering the emergency charging requirement of some EVs (in terms of EVs that have a special duty), the work in [27] proposes a scheduling scheme that considers EVs' heterogeneity. Here, high-priority EVs can get preempted charging services.

B. V2V Charging Mode (Directly Charging between EVs)

Unlike the traditional plug-in mode, a flexible V2V charging mode is proposed in [28], which allows EVs to transfer energy among themselves other than plug-in charging at the grid. At the system level, the work in [29] introduces a cloud-based control system to assign and guide V2V charging. At the hardware level, the work [13] studies bidirectional DC-DC converters for EVs' V2V charging purpose. Meanwhile, by deploying converters, traditional PLs can be reused for V2V charging [14].

Previous works try to optimize the matching of V2V-Pairs. The work [30] applies a maximum weighted diplot matching algorithm to optimize V2V-Pair matching. However, this algorithm is not able to stable match EVs, so the work in [16] proposes a marriage matching algorithm, which considers the status of EVs and ensures all EV-Cs will be matched.

When V2V-Pairs are matched, they require an appropriate PL-Selection decision. Uneven allocation of V2V charging will cause charging congestion problem, and PLs will have potential waiting queues for either EV-C/EV-P. However, only a few previous works have considered the problem of PL-Selection in addition to V2V-Pair matching [19], [22]. In practice, EVs require an optimized PL-Selection algorithm due to the constrained parking resources. However, in the work [22], the occupation status at PLs (for PL-Selection) does not consider the real-time prediction of on-the-move EVs, thus it still fails to maximize the usage of PLs in the network.

In the plug-in charging mode, the reservation is introduced for accurately predicting the occupation status at CSs [8]. The work in [31] further improves the reservation accuracy in the urban environment. Similarly, in V2V charging mode, the GC is able to accurately predict the occupation status at PLs with the benefit of reservations. Then the GC could select an appropriate PL for V2V-Pairs. In the work [19], EVs select the PL base on the travelling time prediction model, charging time estimation model and charging comfortable degree model. However, the above predictions are not based on real-time traffic information and do not consider the time constraint of EVs staying at PLs.

III. PRELIMINARY

A. Assumption

In this paper, we consider a V2V charging under an urban scenario as follow. A GC is deployed to communicate with EVs and PLs. The GC manages V2V charging in a centralized manner. Multiple PLs are geographically distributed in the scenario. Each PL is equipped with multiple DC-DC converters (δ) to allow parallel energy transfer. EVs are divided into EV-Cs and EV-Ps, an EV-C can only receive energy from a paired EV-P. Here, the energy transfer via an EV-P to an EV-C is under a rate of β (constrained by converters).

The freshness of occupation status information is determined by the communication architecture [32]. Such information is particular important in V2V charging [33]. Therefore, the GC and EVs are equipped with a wireless communication module so that they can communicate through the cellular network with a low delay. Additionally, the encrypted communication between EV and GC is applied to ensure the message will not be eavesdropped by others and protect drivers' privacy.

B. Network Entity

An urban scenario is illustrated in Fig.1. Network entities involved are as follow:

EV as energy Consumer (EV-C): An EV-C seeks for V2V charging if its State of Charge (SoC) is below the threshold. Here, the EV-C requires a suitable EV-P to match. Once an EV-C has been matched to an EV-P (in the form of a V2V-Pair) by means of centralized optimization, they both will travel towards the determined PL to enable V2V charging service. Here, we consider EV-Cs would leave the service due to limited parking duration.

EV as energy Provider (EV-P): It is EV with surplus energy providing and transfers energy to EV-C. We assume each EV-P has enough energy to provide multiple times V2V services, deemed as an alternative to the grid.

Parking Lot (PL): Each PL has space for EVs to park. Meanwhile, it provides additional DC-DC converters to allow energy transfer between a V2V-Pair. Multiple V2V-Pairs are allowed to transfer energy in parallel at a PL, but it depends on the number of DC-DC converters. In the worst case, EVs need to wait if all DC-DC converters are occupied.

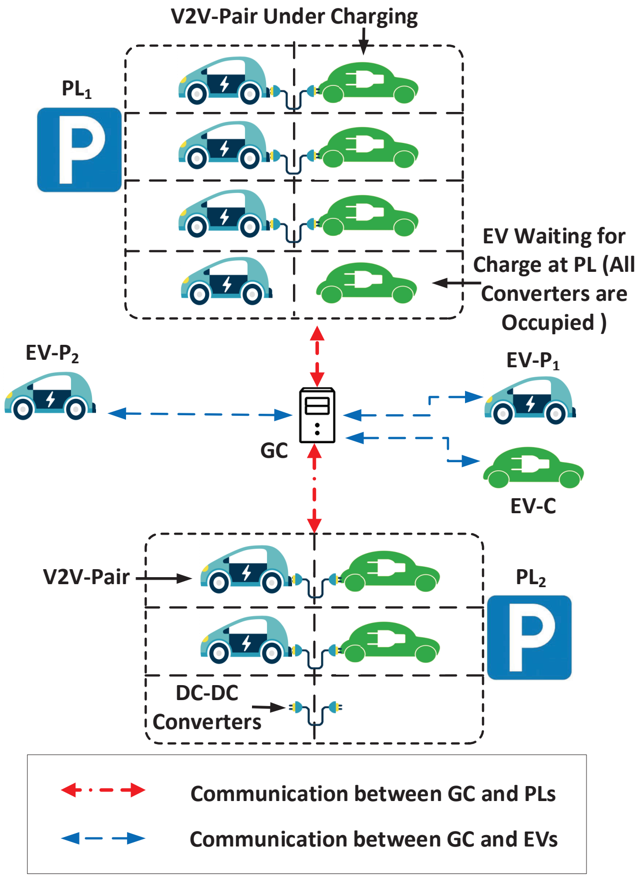


Fig. 1. System Procedure

Global Controller (GC): The GC communicates with PLs and EVs simultaneously in a centralized manner. Here, the GC monitors the local occupation status of V2V-Pairs at PLs. If the GC receives a V2V charging request from an EV-C, it matches a suitable EV-P and arranges the PL-Selection for the V2V-Pair.

C. Proposed V2V Charging Management System

Fig.2 illustrates the procedure for the proposed V2V charging scheme. Here, the GC monitors the local occupation status of V2V-Pairs of all PLs in the charging network. Here, the V2V charging management scheme contains two parts: the V2V-Pair matching process (steps 2,3) and the PL-Selection decision process (steps 4,5).

Step 1: Once an EV-C (EV_r) is driving on the road and its SoC is below the preset threshold, EV_r sends its V2V charging request (contains its location and energy request) to the GC.

Steps 2: When the GC receives the charging request from EV_r, it communicates with EV-Ps to aggregate their current status.

Steps 3: The GC matches an appropriate EV-P for EV_r according to the collected real-time location of EV-Ps, then it replies the V2V-Pair matching result to EV_r and EV-Ps.

Step 4: The GC estimates the V2V charging availability at each PL. This estimation jointly considers PLs' local

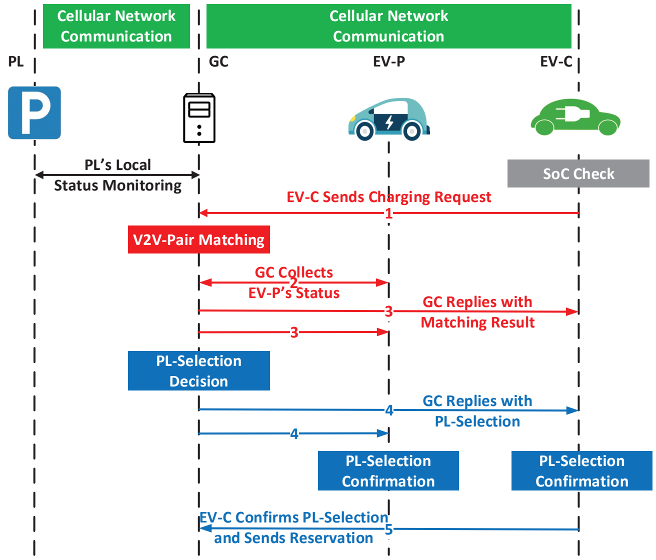


Fig. 2. Time Sequence of V2V Charging

occupation status of V2V-Pairs, EVs parked at PLs waiting for energy transfer and EVs sending charging reservations. Here, the GC replies the PL-Selection decision (the PL with the shortest trip duration) to the matched V2V-Pair of EV$_r$.

Steps 5: The V2V-Pair (EV$_r$ and the matched EV-P) then confirms the selected PL by reporting the reservation to the GC.

D. V2V Charging Reservation Format

TABLE I
LIST OF NOTATIONS

δ	Number of V2V converters at PL
β	V2V Charging power via converters
α	Electric energy consumed per meter
T_{cur}	Current time in the network
T_{ev}^{tra}	EV's travelling time to reach PL
E_{ev}^{max}	Full volume of EV battery
E_{ev}^{cur}	Current volume of EV battery
T_{ev}^{arr}	EV's arrival time at PL
T_{pair}^{arr}	Later EV's arrival time at PL in a V2V-Pair
DIS_{ev}^{ev}	Distance between two EVs (an EV-C and another EV-P)
LIST	List includes available charging time for converters at PL
N_C	Queue of EV-Cs under V2V charging at PL
N_W	Queue of EV-Cs waiting for V2V charging at PL
N_R	Queue of EV-Cs sending reservation to PL
N_P^{ev}	Queue of EV-Ps
N_{PL}	Queue of PLs providing V2V charging
T_{ev}^{fin}	Charging finish time of EV-C
D_{ev}	Parking duration of EV
S_{ev}	Speed of EV
EACT	Estimation of Available Charging Time

The GC accurately estimates the Earliest Available Charging Time (EACT) at each PL. Here, the GC replies the PL with the minimum trip duration (influenced by the EACT) as PL-Selection to EVs. An EV-C is asked to confirm and send a reservation once it receives the PL-Selection decision from the GC. Such reservation is beneficial to analyse PL's occupation status in the near future and prevent EVs from driving towards potential PL hotspots.

The reservation is reported via the cellular network and includes the following information:

⟨**EV-C ID:**⟩ The ID of EV-C which needs charging.

⟨**EV-P ID:**⟩ The ID of matched EV-P in EV-C's V2V-Pair.

⟨**Arrival Time:**⟩ Here, the estimated arrival time T_{ev}^{arr} is given by the travelling time (T_{ev}^{tra}) from EV's current location towards the selected PL plus current time in the network (T_{cur}):

$$T_{ev}^{arr} = T_{cur} + T_{ev}^{tra} \tag{1}$$

⟨**Expected Charging Time:**⟩ The estimated charging time T_{ev}^{cha} of the EV-C, is given by:

$$T_{ev}^{cha} = \frac{E_{ev}^{max} - E_{ev}^{cur} + (S_{ev} \times T_{ev}^{tra} \times \alpha)}{\beta} \tag{2}$$

$(S_{ev} \times T_{ev}^{tra} \times \alpha)$ calculates the energy consumption in EV's travelling, where S_{ev} refers speed of EV-C and α refers to energy consumption per meter.

Here, Table II displays a sample reservation message of EV$_{22}$ sent to the GC.

TABLE II
RESERVATION OF EV-C$_{22}$

EV-C ID	Matched EV-P	Selected PL	Arrival Time	Expected Charging Time
EV-C$_{22}$	EV-P$_{85}$	PL$_{26}$	8676s	3043s

E. Problem Formulation

To alleviate potential charging congestion, we herein propose a V2V charging management solution. To facilitate the problem formulation, we have the following notations:

(a) ξ_l: The V2V charging service time for an EV-C being fully charged at PL l.
(b) ω_l: The average waiting time for each EV-C being fully charged at PL l.
(c) N_{PL}: The queue of PLs in the network.
(d) ϕ_l: Encountered EV-Cs that arrive at PL l.
(e) Ω: Overall V2V charging service time for all EV-Cs taken V2V charging in the network.

Here, the V2V charging service time (ξ_l) is summed by the waiting time (before an EV-C get charged) and charging time. It is worth mentioning, an EV waiting at a PL is due to either the other EV (EV-P/EV-C in the V2V-Pair) has not arrived (arrival latency) or the PL has no converter available (charging congestion). To reduce the V2V charging service time and improve drivers' Quality of Experience (QoE), the problem is formulated as follow:

$$\text{Minimize} \quad \Omega = \sum_{l \in N_{PL}} \phi_l \cdot \xi_l \tag{3}$$

Since the charging time depends on the charging power (determined as a constant by converters), reducing the average waiting time (ω_l) has become the core in the optimization. Ω is minimized if charging demands (ϕ_l) are evenly across all PLs (N_{PL}). Due to the uncertainly in the city scenario, a practical approach is to achieve local optimization for each EV-C. Therefore, the problem of Equation (4) is formulated as follow:

$$\arg \min_{l \in N_{PL}} \omega_l := \{ l | l \in N_{PL} \wedge \forall i \in N_{PL} : \omega_i \geq \omega_l \} \tag{4}$$

Here, we aim to find the optimized PL-Selection for EVs, which minimizes the EV's average waiting time. This will be discussed in detail in Section IV-E.

IV. V2V CHARGING MANAGEMENT

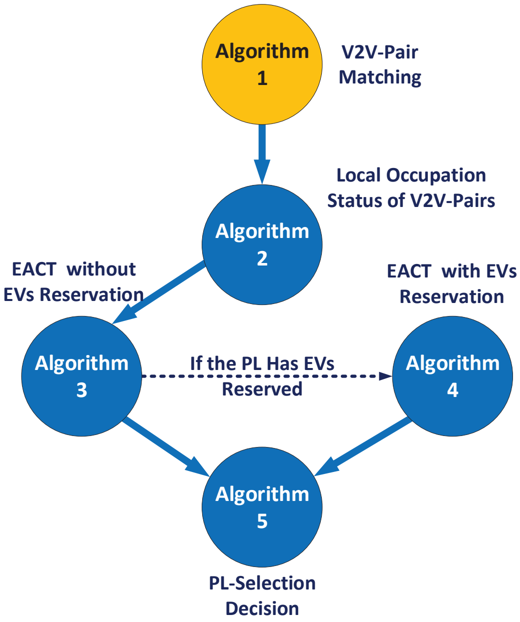


Fig. 3. Computation Logic of V2V Charging Management

Fig.3 illustrates the logic of the proposed V2V charging management scheme. To reduce energy consumed on-the-move before the charging of V2V-Pairs starts, the GC matches V2V-Pairs in Algorithm 1.

There are three types of EVs in V2V charging process:

(a) EVs under V2V charging at PLs (in the queue of N_C)
(b) EVs waiting for V2V charging at PLs (in the queue of N_W)
(c) EVs send reservations to PLs (in the queue of N_R)

In Algorithm 2, the GC calculates the PLs' local occupation status of V2V-Pairs by considering EV-Cs in the queue of N_C, and further sorts the converters in the order of their charging availability in time. Here, the cases a PL without or with receiving EVs' reservations are concerned respectively, as detailed in Algorithm 3 and Algorithm 4. Algorithm 3 and 4 estimate the Earliest Available Charging Time (EACT) at a PL. Algorithm 5 further aggregates the EACT at each PL and selects the most suitable PL for selection.

A. Distance-Based V2V-Pair Matching

When an EV-C (EV$_r$)'s SoC is below the preset threshold, it sends a charging request to the GC. Here, the GC matches the most suitable EV-P (with the minimized energy cost on-the-move) as the EV$_r$'s V2V-Pair. This energy cost calculation is according to the location and availability of EV-Ps.

Algorithm 1 Pair Matching Algorithm

```
1: for ($p = 1; p \leq N_P^{ev}; p++$) do
2:     if (EV-P$_p$ is not matched) then
3:         calculate $DIS_{ev_{(r)}}^{ev-p_{(p)}}$
4:     end if
5: end for
6: EV-P$_p$ ← $\arg\min(DIS_{ev_{(r)}}^{ev_{(p)}})$
7: return EV-P$_p$
```

In the Algorithm 1, the GC communicates with EV-Ps to aggregate their locations. The GC confirms whether an EV-P (EV-P$_p$) has been matched with other EV-C at line 2. If EV-P$_p$ has not been matched, then EV-P$_p$ is determined available, the distance between EV$_r$ and EV-P$_p$ is calculated at line 3. EV-P$_p$ with the minimum distance is returned as the most suitable EV-P, thanks to the minimum energy consumed on-the-move (line 6). Then the GC matches EV-P$_p$ as the V2V-Pair result of EV$_r$ at line 7. This pair matching result is replied to EV$_r$ and EV-Ps to ensure the stability of V2V-Pair matching.

B. Local Occupation Status of V2V-Pairs at PLs

Algorithm 2 Local Occupation Status of V2V-Pairs at PLs

```
1: if no EV is under charging then
2:     add $T_{cur}$ in LIST with $\delta$ times
3:     return LIST
4: end if
5: for ($n = 1; n \leq N_C; n++$) do
6:     if ($(T_{cur} - T_{ev_{(n)}}^{arr} + \frac{E_{ev_{(n)}}^{max} - E_{ev_{(n)}}^{cur}}{\beta}) \leq (T_{ev_{(n)}}^{arr} + D_{ev})$) then
7:         LIST.ADD($\frac{E_{ev_{(n)}}^{max} - E_{ev_{(n)}}^{cur}}{\beta} + T_{cur}$)
8:     else
9:         LIST.ADD($T_{ev_{(n)}}^{arr} + D_{ev}$)
10:    end if
11: end for
12: if ($N_C < \delta$) then
13:     for ($m = 1; m \leq (\delta - N_C); m++$) do
14:         LIST.ADD($T_{cur}$)
15:     end for
16: end if
17: sort LIST with ascending order
18: return LIST
```

Algorithm 2 calculates the local occupation status of V2V-Pairs at a PL. Meanwhile, it further returns a list (LIST) that indicates available time for V2V charging at each DC-DC converter. Here, an EV-C's V2V charging refers to the energy transferring from its V2V-Pair. If there's no EV-C under charging at the PL, the current time in the network (T_{cur}) is added into the LIST with δ to indicate all converters are available from T_{cur}.

The loop operation from line 5 to 11 considers the condition that the PL has EVs under charging. Therefore, a number of converters (size of N_C) are occupied until EV$_n$ (in the queue of N_C) finishes charging. From lines 6 to 10, Algorithm 2 calculates charging finish time of EV$_n$. Note that, EV$_n$'s charging time is limited by the parking duration (D_{ev}). If EV$_n$ can get fully charged before its departure deadline, the EV$_n$'s charging finish time ($\frac{E^{max}_{ev_{(n)}} - E^{cur}_{ev_{(n)}}}{\beta} + T_{cur}$) is added into the LIST at line 7. Otherwise, EV$_n$ has to depart at its departure deadline ($T^{arr}_{ev_{(n)}} + D_{ev}$).

The condition from 12 to 16 indicates that not all converters have EV-Cs under charging. Here, the converters with availability are added into the LIST to indicate they are available from T_{cur}. At line 17, the LIST is sorted in the order of the available time at each converter. Algorithm 2 further returns the LIST at line 18 as the local occupation status at the PL.

C. Estimation of EACT without Reservation

Algorithm 3 EACT without EVs Reservation ⟨LIST⟩

```
 1: sort the queue of $N_W$ according to the FIFS order
 2: if contains EVs waiting for charging then
 3:     for ($i = 1; i \leq N_W; i++$) do
 4:         if (($T^{cha}_{ev_{(i)}}$ + LIST.GET(0)) $<$ ($D_{ev}$ + $T^{arr}_{ev_{(i)}}$)) then
 5:             $T^{fin}_{ev_{(i)}}$= $T^{cha}_{ev_{(i)}}$ + LIST.GET(0)
 6:         else
 7:             $T^{fin}_{ev_{(i)}}$ = $D_{ev}$ + $T^{arr}_{ev_{(i)}}$
 8:         end if
 9:         replace the LIST.GET(0) with $T^{fin}_{ev_{(i)}}$
10:         sort LIST with ascending order
11:         record EV$_i$ into DELETESET
12:     end for
13:     remove EVs recorded in DELETESET, from the queue of $N_W$
14: end if
15: if no EV's reservation for charging then
16:     if ($T^{arr}_{ev_{(r)}} < T^{arr}_{ev-p_{(r)}}$) then
17:         $T^{arr}_{pair_{(r)}} = T^{arr}_{ev-p_{(r)}}$)
18:     else
19:         $T^{arr}_{pair_{(r)}} = T^{arr}_{ev_{(r)}}$
20:     end if
21:     if ($T^{arr}_{pair_{(r)}}$ <LIST.GET(0)) then
22:         return LIST.GET(0)
23:     else
24:         return $T^{arr}_{pair_{(r)}}$
25:     end if
26: else
27:     return EACT with EVs Reservation ⟨LIST⟩
28: end if
```

EV-Cs waiting at the PL are scheduled to charge. At line 1, the waiting queue of N_W is sorted with the FIFS order to ensure more EVs can finish V2V charging within their D_{ev}.

The lines from 2 to 14 consider the condition that there are EVs waiting for V2V-Pair at the PL. Those EVs are scheduled to charge once a converter becomes available. Here, the estimated charging time of EV$_i$ (the EV-C in the queue of N_W) is calculated by:

$$T^{cha}_{ev_{(i)}} = \frac{E^{max}_{ev_{(i)}} - E^{cur}_{ev_{(i)}}}{\beta} \tag{5}$$

To consider whether EV$_i$ is able to be fully recharged before its departure, the lines 5 and 7 calculate EV$_i$'s charging finish time ($T^{fin}_{ev_{(i)}}$) respectively. If EV$_i$ is able to be fully recharged (meets the condition at line 4), its $T^{fin}_{ev_{(i)}}$ is calculated as ($T^{cha}_{ev_{(i)}}$ + LIST.GET(0)). Otherwise, EV$_i$ has to depart at (D_{ev} + $T^{arr}_{ev_{(i)}}$). LIST.GET(0) is replaced by $T^{fin}_{ev_{(i)}}$ to imply the first available converter is occupied by EV$_i$ until $T^{fin}_{ev_{(i)}}$. Then the LIST is sorted in ascending order at line 10. EV$_i$ is recorded into DELETESET and removed at line 13 to indicate that all EVs in the queue of N_W have been scheduled to charge.

If the PL has not received any reservation for charging as the condition at line 15, EV$_r$ will be the first charging sequence when it arrives. However, a necessary condition of starting V2V charging is both EVs in a V2V-Pair have arrived. Therefore, we determine the arrival time ($T^{arr}_{pair_{(r)}}$) of EV$_r$'s V2V-Pair as the later EV's arrival time in the pair. If EV-P$_r$ (EV$_r$'s energy provider in its V2V-Pair) arrives later than EV$_r$, $T^{arr}_{pair_{(r)}}$ is recorded as $T^{arr}_{ev-p_{(r)}}$ at line 17. If EV$_r$ arrives later than EV-P$_r$, $T^{arr}_{pair_{(r)}}$ is recorded as $T^{arr}_{ev_{(r)}}$ at line 19.

Considering that the PL may have no available converter when EV$_r$ arrives (all converters are occupied by EVs in the queue of N_W), it is necessary to compare $T^{arr}_{pair_{(r)}}$ with LIST.GET(0). If EV$_r$ arrives with the first available converter occupied ($T^{arr}_{pair_{(r)}}$ <LIST.GET(0)), then Algorithm 3 returns LIST.GET(0) at line 22 for PL-Selection purpose in Algorithm 5. In the other case, $T^{arr}_{pair_{(r)}}$ is returned at line 24.

If the PL has received V2V charging reservations, the further EACT estimation will be processed in Algorithm 4.

D. Estimation of EACT with Reservation

Algorithm 4 EACT with EVs Reservation ⟨LIST⟩

```
 1: sort the queue of $N_R$ according to the FIFS order
 2: for ($j = 1; j \leq N_R; j++$) do
 3:     if (($T^{cha}_{ev_{(j)}}$ + LIST.GET(0)) $<$ ($D_{ev}$ + $T^{arr}_{ev_{(j)}}$)) then
 4:         $T^{fin}_{ev_{(j)}}$= $T^{cha}_{ev_{(j)}}$ + LIST.GET(0)
 5:     else
 6:         $T^{fin}_{ev_{(j)}}$ = $D_{ev}$ + $T^{arr}_{ev_{(j)}}$
 7:     end if
 8:     replace the LIST.GET(0) with $T^{fin}_{ev_{(j)}}$
 9:     sort LIST with ascending order
10:     record EV$_j$ into DELETESET
11: end for
12: remove EVs recorded in DELETESET, from the queue of $N_R$
13: if ($T^{arr}_{ev_{(r)}} < T^{arr}_{ev-p_{(r)}}$) then
14:     $T^{arr}_{pair_{(r)}} = T^{arr}_{ev-p_{(r)}}$)
15: else
16:     $T^{arr}_{pair_{(r)}} = T^{arr}_{ev_{(r)}}$
17: end if
18: if ($T^{arr}_{pair_{(r)}}$ <LIST.GET(0)) then
19:     return LIST.GET(0)
20: else
21:     return $T^{arr}_{pair_{(r)}}$
22: end if
```

Based on the output from Algorithm 3, Algorithm 4 further calculates the EACT with reservations generated from EV-Cs. Here, N_R is sorted according to the FIFS order. This is the estimated arrival order of EV-Cs in the queue of N_R.

If EV$_j$ (EV-C in the queue of N_R) could be fully charged before its departure (($T^{cha}_{ev_{(j)}}$ + LIST.GET(0)) $<$ (D_{ev} + $T^{arr}_{ev_{(j)}}$)), Algorithm 4 calculates $T^{fin}_{ev_{(j)}}$ as ($T^{cha}_{ev_{(j)}}$ + LIST.GET(0)) at line 4. Otherwise, $T^{fin}_{ev_{(j)}}$ is calculated as (D_{ev} + $T^{arr}_{ev_{(j)}}$) at line 6.

Line 8 replaces LIST.GET(0) with $T^{fin}_{ev_{(j)}}$ to indicate the first available converter is occupied until $T^{fin}_{ev_{(j)}}$. Then line 9 updates the LIST with ascending order to make sure that LIST.GET(0) is still the first available charging time at converters. All EVs that have been scheduled to charge are recorded into DELETELIST and removed from the reservation queue of N_R.

As the V2V charging can only start when the both EVs in a V2V-Pair have arrived, the lines from 13 to 17 compare the arrival time of EVs in a V2V-Pair. If EV$_r$ arrives later than EV-P$_r$, $T^{arr}_{pair_{(r)}}$ is recorded as $T^{arr}_{ev-p_{(r)}}$. Otherwise, $T^{arr}_{pair_{(r)}}$ is recorded as $T^{arr}_{ev_{(r)}}$.

If all converters are occupied when EV$_r$ arrives ($T^{arr}_{ev_{(r)}}$ <LIST.GET(0)), Algorithm 4 returns LIST.GET(0) as the EACT at the PL at line 19. In the other case, EV$_r$ can get directly energy transfer service once it arrives, the EACT at the PL is returned as $T^{arr}_{pair_{(r)}}$ at line 21.

E. PL-Selection Decision

Algorithm 5 PL-Selection Decision Making

```
 1: for $\forall l_{pl} \in N_{PL}$ do
 2:     calculate $T^{min}_{pl,d}$
 3:     calculate EACT$_{pl}$ via Algorithm 3 & 4
 4:     if $((T^{cha}_{ev_{(r)}} + \text{EACT}_{pl}) \leq (D_{ev} + T^{arr}_{ev_{(r)}}))$ then
 5:         $T^{pl,d}_{ev_{(r)}} = T^{cha}_{ev_{(r)}} + \text{EACT}_{pl} + T^{min}_{pl,d}$
 6:     else
 7:         $T^{pl,d}_{ev_{(r)}} = T^{arr}_{ev_{(r)}} + D_{ev} + T^{min}_{pl,d}$
 8:     end if
 9: end for
10: $l^{min}_{pl} \leftarrow \arg\min(T^{pl,d}_{ev_{(r)}})$
11: return $l^{min}_{pl}$
```

Algorithm 5 selects the PL for EV$_r$ with the minimum time spent with an intermediate V2V charging (total trip duration $T^{pl,d}_{ev_{(r)}}$). Here, $T^{pl,d}_{ev_{(r)}}$ is the summation of the duration EV$_r$ spends at the selected PL and the travelling time from the selected PL to EV$_r$'s trip destination ($T^{min}_{pl,d}$).

Here, $T^{min}_{pl,d}$ is calculated at line 2, which refers to the time EV$_r$ travels from the PL to its destination via the shortest path. The EACT at PL (with location l_{pl}) is estimated by Algorithm 3 & 4. There are also two cases considering whether EV$_r$ can be fully charged before its departure.

(a) At line 5, EV$_r$ can be fully charged before its departure, thus $T^{pl,d}_{ev_{(r)}}$ is calculated by ($T^{cha}_{ev_{(r)}} + \text{EACT}_{pl} + T^{min}_{pl,d}$).

(b) At line 7, due to the D_{ev} limitation, EV$_r$ has to depart from the PL no matter it is fully charged or not. Thus $T^{pl,d}_{ev_{(r)}}$ is calculated by ($T^{arr}_{ev_{(r)}} + D_{ev} + T^{min}_{pl,d}$).

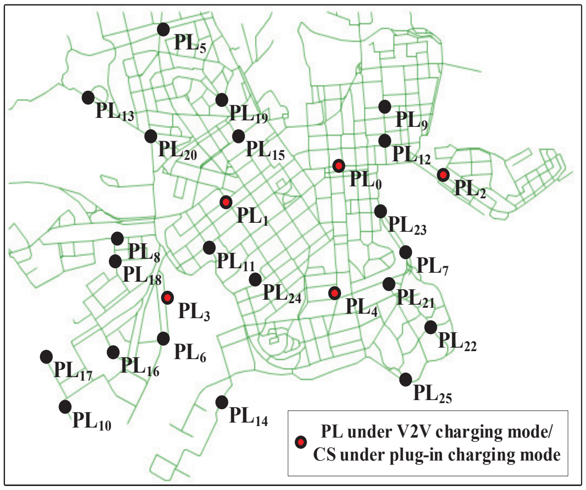
In the loop operation at line 10, Algorithm 5 calculates $T^{pl,d}_{ev_{(r)}}$ at each PL. Then PL with the minimum $T^{pl,d}_{ev_{(r)}}$ will be returned as PL-Selection decision to EV$_r$.

V. PERFORMANCE EVALUATION

A. Simulation Configuration

We use the Opportunistic Network Environment (ONE) [34] to build V2V charging management scenario. The ONE is initially designed for mobile networks. Here, we modify the system to simulate the V2V charging process. In Fig.4(b), the simulation demonstrates the urban area of Helsinki city (Fig.4(a)) with a 4500×3400 m^2 scenario. 26 PLs are geographically deployed in the urban area and each PL is equipped with 4 DC-DC converters. One DC-DC converter allows V2V charging for a V2V-Pair with an energy transferring rate of 15 kW.

(a) The Helsinki City



(b) Deployment of PLs

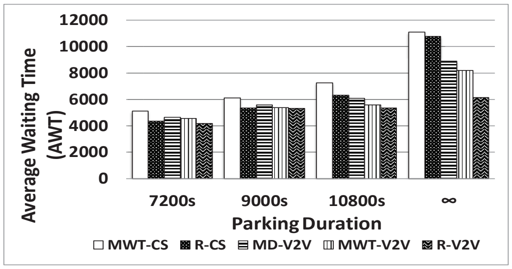
Fig. 4. Simulation Scenario

Meanwhile, to examine the efficiency of V2V charging mode as compared with the plug-in charging mode. We consider another scenario under plug-in charging mode where 5 CSs are deployed in this urban scenario. Each CS is provided with 5 charging slots, using the fast charging rate of 62 kW.

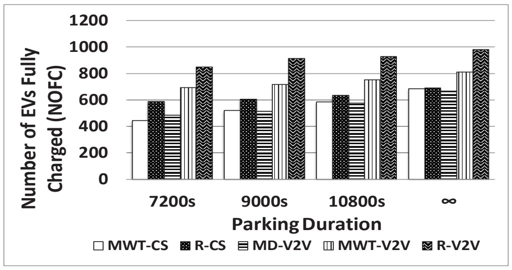
EVs in the scenario are using Coda Automotive [35] with the following configuration: Maximum electricity capacity : 33.8 kWh; Max travelling distance : 193 km; Average energy consumption : 0.1751 kWh/km.

To enrich EV differences in the scenario, three SoC thresholds (30%, 40% and 50%) are set. All EV-Cs' batteries are with full volume when the simulation starts. To simplify the simulation and exam the optimality of V2V-Pair matching, PL-Selection and reservations, we set EV-Ps with a super power, EV-Ps are able to provide repeatedly charging services without intermediate charging. The numbers of EV-Cs and EV-Ps are set equally to avoid a large number of EV-Cs competing with a few number of EV-Ps.

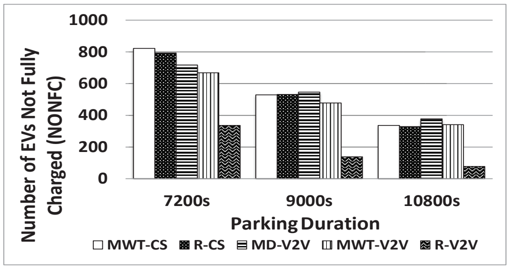
Here, EVs are with $[30 \sim 50]$ km/h variable moving speed, the speed fluctuation reflects the impact of traffic. The EV's destination is randomly selected from a location on the map.



(a) AWT



(b) NOFC



(c) NONFC

Fig. 5. Influence of Parking Duration

Once an EV arrives at its trip destination, it will travel towards the next random selected destination again. If the EV's SoC is below the threshold, it travels towards the selected PL via the shortest path, which is formed considering the Helsinki road topology. The simulation lasts for 12 hours. Here, EVs' location, speed and energy are updated per 0.1s, no matter EVs are at a PL or on-the-move.

B. Comparison Configuration

A reservation-based V2V charging management scheme is proposed in this paper. To compare the efficiency of different V2V charging schemes, the following V2V schemes are evaluated for comparison:

(a) **MD-V2V**: The benchmark scheme with distance-based V2V matching and distance-based PL-Selection.
(b) **MWT-V2V**: The benchmark scheme with distance-based V2V matching and waiting time-based PL-Selection (without reservation).
(c) **R-V2V**: The proposed scheme with a distance-based matching scheme and a reservation-based PL-Selection scheme.

We evaluate two other CS charging schemes for comparison. In CS charging schemes, the number of EVs is set as the same number of EV-Cs in V2V schemes.

(d) **MWT-CS [24]**: Literature work applies the plug-in charging mode for EVs. The GC allocates EVs to the CS with the minimum waiting time.
(e) **R-CS [9]**: Literature work applies the plug-in charging mode for EVs and considers charging reservation. The CS allocates EVs to the CS with the earliest EACT.

The following performance metrics are evaluated:

(a) **Number of EVs Fully Charged (NOFC)**: It indicates the total number of EV-Cs get fully charged. Here, within the simulation duration, each EV-C can be charged for several times.
(b) **Number of EVs Not Fully Charged (NONFC)**: It indicates the total number of EV-Cs can not get fully charged although EV-Cs have arrived at a PL. In extremity, an EV-C may not receive V2V charging before its departure, thus it needs another PL-Selection for charging.
(c) **Average Waiting Time (AWT)**: It indicates the average queuing time for EV-Cs before they get charging service at the selected PL.

C. Influence of Parking Duration

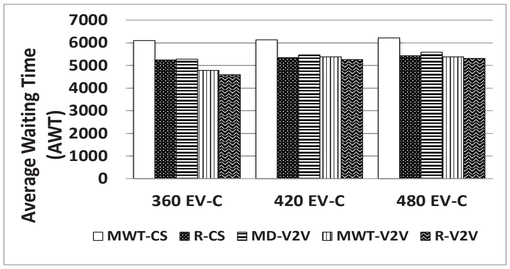
In the first group of simulations, we set the EV density to 840 (420 EV-Cs and 420 EV-Ps) and observe the influence of the parking duration. Here, we set the parking duration to 7200, 9000, 10800s respectively. To further observe the upper limit of charging schemes, we add the results without considering the parking duration (the results with ∞ symbol in the figures).

In Fig.7(a), due to the lack of prediction at PLs/CSs, MWT-CS, MD-V2V and MWT-V2V schemes are unable to prevent EVs from selecting the PL/CS hotspots and suffer from a longer AWT. Here, V2V charging schemes (based on flexible utilization of PLs), with a far lower charging power (15 kW), are able to achieve better charging efficiency than 5 CSs with 62 kW charging power (MWT-CS and R-CS schemes). In the three V2V schemes, the MD-V2V scheme suffers from the longest AWT. This is because the MD-V2V scheme lacks global planning and only considers the location of EV-Cs. This inevitably leads to charging congestion at PL hotspots. As the R-V2V scheme enables the GC to estimate PLs' occupation status accurately (with the benefit of reservations), it is able to better allocate V2V charging among PLs and achieves the shortest AWT. If the parking duration is not limited, the AWT of MD-V2V and MWT-V2V schemes are obviously increased, which also reflects the importance of reservation to charging efficiency.

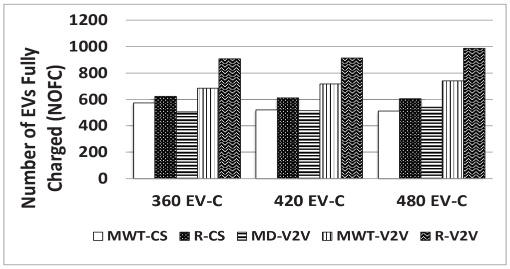
In Fig. 7(b), under V2V charging mode, a longer parking duration reduces the proportion of arrival latency (time waiting for EV-C/EV-P in a V2V-Pair) in one entire charging process. Here, an EV-C has a longer time waiting for its matched pair to get fully charged and thus the NOFC increases. As R-CS and R-V2V schemes ask EVs to send reservations, then the GC has more accuracy in the estimation of EACT than the other schemes. The GC is able to select the CS/PL with a lower congestion level. Therefore, R-CS and R-V2V schemes achieve higher NOFC than other schemes. In Fig.7(c), the R-V2V scheme achieves a lower NONFC than the other schemes.

This benefits from the prediction of potential occupation status at PLs. When the parking duration is extended to 10800s, almost all EV-Cs charging requests can be satisfied.

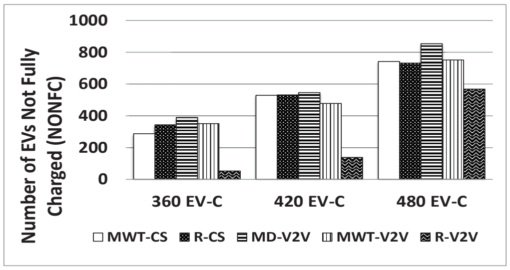
D. Influence of EVs Density



(a) AWT



(b) NOFC



(c) NONFC

Fig. 6. Influence of EVs Density

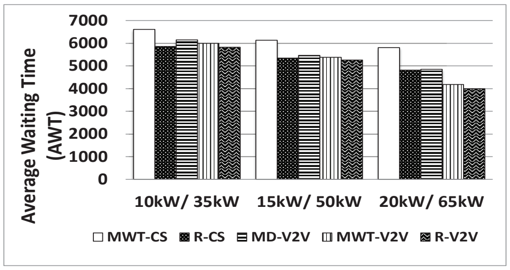
In the second group of simulations, we set EV's parking duration to 9000s and further vary the number of EVs to reflect the scalability of management schemes. Here, the EVs density refers to the number of EV-Cs.

The result in Fig.6(a) shows that the MWT-CS scheme suffers from the longest AWT. However, the AWT can be significantly reduced with the help of reservation in the R-CS scheme. Among three V2V schemes, the MD-V2V scheme suffers the longest AWT. This is because the distance-based PL-Selection would centralize charging requests at PLs in the city centre and thus cause charging congestion. By considering the local occupation status of V2V-Pairs at PLs, EVs are able to avoid PL hotspots. Here, when the number of EV-Cs is 360, MWT-V2V and R-V2V schemes can effectively reduce the AWT. When the number of EV-Cs increases by 480, the R-V2V scheme still achieves the shortest AWT as it considers the potential charging flow.

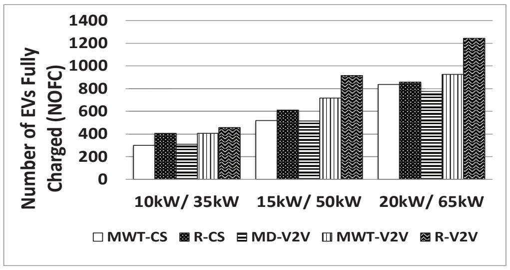
In Fig.6(b), it shows that the R-V2V scheme achieves the highest NOFC. In CS schemes, charging congestion occurs when the number of EVs increases and thus NOFC decreases. However, in V2V schemes, the V2V-Pair matching becomes more flexible when the number of EVs increases. Therefore, the NOFC increases in V2V schemes.

The result in Fig.6(c) also proves the advantage of the R-V2V scheme. When the number of EVs is at a low level (360 and 420 EV-Cs), the R-V2V scheme benefits from the reservations as the GC could accurately estimate EACT at PLs. This effectively avoids EV-Cs charging at PLs with high charging congestion. When the density of EV-Cs increases by 480, reservations still help the GC evenly allocate EVs at PLs and thus maximize the PLs' charging utility.

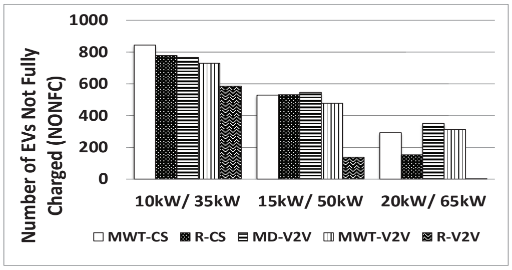
E. Influence of Charging Power



(a) AWT



(b) NOFC



(c) NONFC

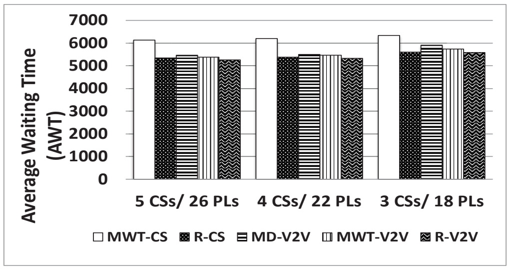
Fig. 7. Influence of Charging Power

By adjusting the charging power at CSs and PLs, we further observe the utility of each charging scheme. Here, we set the parking duration to 9000s and EV-Cs density to 420.

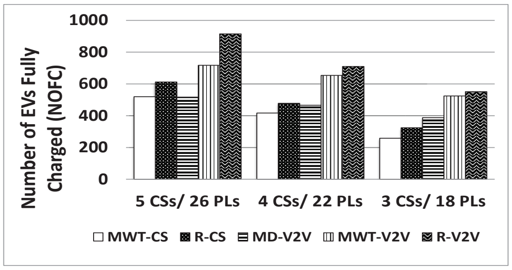
The R-V2V scheme achieves the shortest AWT in Fig.7(a). The increment of charging power reduces the AWT in all charging schemes. However, under V2V charging mode, charging power with a small increase (5 kW) can significantly shorten the AWT. This is because the number of PLs is large, and a small increase of charging power can effectively improve the overall charging performance in V2V charging. Considering the bottleneck in charging technology, V2V charging schemes take great charging efficiency improvement with less charging power increment.

In Fig.7(b), when the charging power increases, the NOFC is significantly increased under V2V charging schemes. And the R-V2V scheme achieves the highest NOFC, because it considers the reservations and efficiently allocates the charging requests at each PL. Note that with the increase of charging power, the NONFC decreases significantly in all schemes in Fig.7(c), and this decreasing trend is more obvious in V2V schemes. When the charging power at PL reaches 20 kW, the R-V2V scheme can ensure that all EV-Cs can be fully charged once they arrive at PLs.

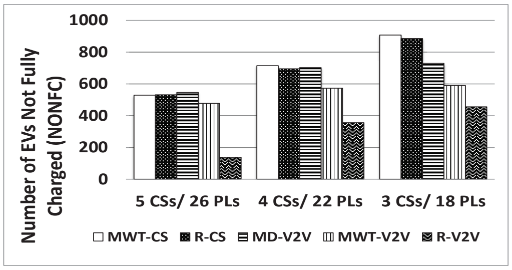
F. Influence of Charging Facility Deployment



(a) AWT



(b) NOFC



(c) NONFC

Fig. 8. Influence of Charging Facility Deployment

To simulate the EV charging under different charging facility deployment, we adjust the number of PLs and CSs in the scenario for simulation:

(a) In the first group of comparison, the number of CSs is reduced to 4. Here, CS_0 to CS_3 in Fig.4(b) can continue to provide charging services. Meanwhile, the number of PLs is reduced to 22. Here, PL_0 to PL_{21} in Fig.4(b) can continue to provide V2V charging services.

(b) In the second group of comparison, the number of CS is further limited to 3. Here, CS_0 to CS_2 can continue to provide charging. The number of PLs is limited to 18. Here, PL_0 to PL_{17} can can continue to provide V2V charging.

In Fig.8(a), a less number of charging facilities means that EV charging is further limited by constrained locations. Therefore, the MD-V2V scheme suffers a significant increase in the AWT. This is because distance-based PL-Selection further aggravates charging congestion at PL hotspots. MWT-CS and MWT-V2V schemes consider the local charging status/occupation status of CSs/PLs and select the CS/PL with the minimum waiting time. To some extent, the charging requests are evenly distributed among CSs/PLs. However, R-CS and R-V2V schemes further consider the reservation information to predict potential charging requests. Therefore, these two reservation-based schemes achieve a lower AWT.

In Fig.8(b), the NOFC reduces with less number of charging facilities. This reflects the dilemma faced by plug-in charging mode when a small number of CSs deployed. Since V2V charging mode can flexibly use preset PLs, V2V schemes can still ensure relatively high NOFC. In particular, the R-V2V scheme achieves the highest NOFC, with the benefit of reservations. In Fig.8(c), V2V schemes achieve a lower NONFC. However, limited by the number of CSs, more EVs depart with not fully charged in plug-in charging mode.

G. Charging Distribution at PLs

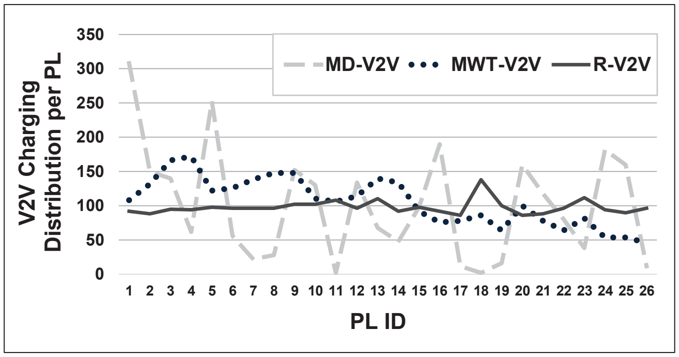


Fig. 9. Charging Distribution at PLs

Fig. 9 shows the distribution of V2V charging at each PL under V2V charging schemes. Here, the parking duration is set as 9000s and the number of EV-Cs is set to 420.

The even distribution of V2V charging at each PL can maximize the V2V charging efficiency. Since the MD-V2V scheme selects PL based on EV's local information (distance from each PL), V2V charging requests are easy to concentrate at some PLs (especially PLs at the city centre). This leads to charging congestion and reduces EV drivers' QoE. In the MWT-V2V scheme, the GC calculates the EACT of each PL. But due to the lack of reservations, the GC cannot accurately predict the potential charging requests. Here, it's inevitable that several V2V-Pairs are allocated to the PL hotspots and thus cause charging congestion.

The R-V2V scheme avoids the above problems. In Fig. 9, the V2V charging distribution at each PL is relatively average under the R-V2V scheme. Therefore, converters at each PL are able to be highly utilized. This guarantees a higher charging efficiency in large-scale EVs deployment.

H. Summary Discussions of V2V Charging

Based on the above evaluations, the proposed V2V charging mode proves its advantages over CS charging mode.

(a) When the number of EVs participating in V2V charging increases (from 360 to 480 EV-Cs), the more EVs get fully charged. This is because V2V-Pair matching optimizes with more EV participators. However, the increase number of EVs in CS charging mode leads to the decrease of charging results (less fully charged EVs and longer charging waiting time).

(b) The V2V charging mode flexibly use PLs under a low charging power (10-20 kW) to achieve a charging result of CSs under a high charging power (35-65 kW). Meanwhile, a small charging power increase (5 kW) in V2V charging mode achieves a large improvement in V2V charging result. Currently, charging power is limited by battery technology, V2V charging mode is conducive to improving the EV drivers' charging experience.

(c) In V2V charging schemes, the introduction of reservation optimizes the PL-Selection. Our proposed V2V charging scheme proves its advantage over simply considering the local PL occupation at PLs. EVs distributes evenly among PLs thanks to V2V charging reservations, which maximizes the use of V2V charging resources in the city.

VI. CONCLUSION

Since range anxiety and spatial limitation of public charging facilities hinder EVs' large-scale application, we propose a reservation-based V2V charging management scheme. It is applied as an alternative to the traditional plug-in charging mode. Here, the V2V charging mode is able to effectively reduce grid fluctuation as it allows directly transfer among EVs.

By means of V2V charging technology, PLs widely distributed in urban areas can be reused as V2V charging places. Here, an EV-P transfers surplus energy to another EV-C (in the form of a V2V-Pair) through the DC-DC converters deployed. To reduce energy consumed on-the-move before the charging of V2V-Pairs starts, the GC monitors EVs' status and global matches V2V-Pairs considering their locations. Meanwhile, to solve where to charge problem for V2V-Pairs, we propose a reservation-based PL-Selection algorithm. Here, the GC selects the PL with the highest charging availability (jointly considers parking V2V-Pairs and reservations).

This paper further evaluates the EVs' charging performance under the plug-in and V2V charging modes. The results show that the V2V charging mode provides more flexibility in urban scenarios, which shortens the AWT and achieves a higher NOFC within the constrained parking duration.

VII. ACKNOWLEDGEMENTS

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