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Optimal Charging Scheduling for Catenary-free Trams in Public Transportation Systems

Yongmin Zhang, *Member, IEEE,* Zhe Wei, *Student Member, IEEE,* Heng Li, *Student Member, IEEE,* Lin Cai, *Senior Member, IEEE,* Jianping Pan, *Senior Member, IEEE*

***Abstract*—Catenary-free tram with supercapacitor for short-distance travel is an emerging and energy-efficient way of urban transportation. However, a large number of decentralized and high-power charging loads from Catenary-free trams bring new challenges to the power system. In addition, frequent and high-voltage charging may result in a shorter lifetime of the supercapacitor. Thus, how to coordinate the charging processes of Catenary-free trams considering the power system constraint and the operation costs of the transportation system is an important open issue, especially as the charging requirements are time-varying. In this paper, we design a charging scheduling system to manage the charging processes of Catenary-free trams. Then, based on the historical and estimated operation data of Catenary-free trams, we propose a day-ahead optimal charging scheduling scheme to arrange their charging processes and report to the power system on the upper bound of the charging loads. Thereafter, we propose a real-time optimal charging scheduling scheme according to the real-time operation information to update the real-time charging loads of Catenary-free trams, such that a trade-off among the electricity cost, operation reliability and battery lifetime is made to minimize the total operation costs. Finally, simulations have been conducted to evaluate the performance of the proposed charging scheduling schemes and show that the proposed algorithms can reduce the total operation cost by about 28%.**

***Index Terms*—Catenary-free trams, Charging scheduling, Operation cost, Real-time scheduling, Supercapacitor.**

Nomenclature

$A_{i,n}$	Arrival time for tram i at its n-th station.
B_i^{cap}	Battery capacity of tram i.
$\bar{B}_i^{\text{cap}}$	Minimal battery capacity requirement for tram i.
C_1	The electricity cost.
C_2	The battery lifetime-related cost.
C_3	The expected cost for the emergency charging services.
C_B	The cost for replacing the supercapacitors of one tram.
C_E	The cost of one emergency charging service.
$D_{i,n}$	Travel duration for tram i from its n-th station to $(n+1)$-th station.
$\bar{D}_{i,n}$	The expected value of travel duration $D_{i,n}$.
$E_{i,t}$	Energy level of tram i at time slot t.
I	Total number of Catenary-free trams.
$L_{i,n}$	Departure time for tram i at its n-th station.
m	The voltage acceleration factor for the degradation of supercapacitor.
N	Total number of tram stations.
$\bar{p}$	The minimal reliability requirement of the public transportation system.
$P_{i,t}$	Energy that is charged to tram i at time slot t.
$P_{i,t}^{\max}$	Maximal energy that can be charged to tram i at time slot t.
$\bar{P}_t$	The upper bound of the charging loads on the power system.
$\bar{P}_t^*$	An upper bound of the charging loads on the power system that is calculated by the aggregator.
$\widetilde{P}_t$	The total charging load on the power system from all the trams.
$\mathbb{P}_{i,n}$	The probability for tram i arriving at its $(n+1)$-th station successfully after it leaves its n-th station.
T	Total time slots in one time period.
V_0	The reference voltage of the supercapacitor.
$V_{i,t}$	The voltage of the supercapacitor for tram i at time slot t.
$W_{i,t}$	Energy consumption of tram i at time slot t.
$W_i^{\max}$	Maximal energy consumption of tram i at time slot t.
$\widetilde{W}_{i,n}$	Total energy consumption for tram i from its n-th station to $(n+1)$-th station.
$\widetilde{W}_{i,n}^*$	The expected energy consumption that ensures $\mathbf{Pr}\{\sum_{t=L_{i,n}}^{A_{i,n+1}} W_{i,t} \leq \widetilde{W}_{i,n}^*\} \geq \bar{p}$.
τ_0	The expected lifetime of the supercapacitor at reference voltage V_0.
$\tau(V)$	The static lifetime of the supercapacitor at voltage V.

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Y. Zhang is with the State Key Lab. of Industrial Control Technology and Innovation Joint Research Center for Industrial Cyber Physical Systems, Zhejiang University, China, and the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada. Email: ymzhang@zju.edu.cn.

Z. Wei and L. Cai are with the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada. Emails: {weizhe,cai}@uvic.ca.

H. Li and J. Pan are with the Department of Computer Science, University of Victoria, Victoria, BC, Canada. Emails: {liheng,pan}@uvic.ca.

I. Introduction

With the increasing rate of urbanization and growing concerns on the sustainability of using fossil fuel and the global environmental issues, Catenary-free trams, an emerging electric-driving, environment-friendly and energy-efficient urban transportation, are highly desirable for modern urban public transportation systems [1]. In addition, Catenary-free trams offer various benefits compared with conventional tram systems, including low visual intrusion, reduced cost of overhead infrastructure, design flexibility, reduced power usage and better performance in adverse weather [2].

Battery and supercapacitor are two of the most important types of on-board energy storage devices for Catenary-free trams [3]. Battery requires a longer charging time (several hours) and offers a greater cruise range (tens to hundreds of kms) with a limited lifetime, while the supercapacitor requires a very short period of charging time (20–30 seconds) and offers a limited cruise range (several kms) with a long lifetime. Thus, due to the frequent-stops and short-distance features of the modern urban public transportation system, the supercapacitor-based Catenary-free trams are more suitable.

For Catenary-free trams, since their supercapacitors can only be charged at tram stations, a large amount of energy

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should be charged to the supercapacitor during the short dwelling time, thereby the trams can travel to their next tram stations successfully. Without a proper charging scheduling scheme, a large number of uncontrolled charging processes of Catenary-free trams may incur high and time-varying charging loads and bring a new challenge to the power systems.

In the literatures, charging scheduling for EVs has been heavily investigated, e.g., [4]–[6]. Based on the historical data of EVs' charging requirements, several day-ahead charging scheduling schemes have been developed in [7]–[12] to minimize the peak load on the power system. Based on the real-time charging requirements of EVs, [13]–[15] have designed several real-time charging scheduling schemes to minimize their peak loads and reduce the charging waiting time. However, most of these works only considered the electricity cost without the battery lifetime-related and reliability-related costs, and thus are not directly applicable for the charging scheduling of Catenary-free trams, which have high reliability and long-running requirements.

Generally speaking, the lifetime of the supercapacitor and the reliability of Catenary-free trams depend on the energy stored in the supercapacitor. An aggressive charging method may reduce the lifetime of the supercapacitor while a conservative one may risk the reliability of the public transportation system. How to manage the charging process of the supercapacitor has attracted wide attention. Several energy management schemes for energy storage systems have been developed to improve the charging and discharging efficiency as well as the battery lifetime in [16]–[19], and researches on timetable design have been conducted in [20]–[23] to minimize the energy consumption and improve the reliability of the system. However, neither the energy management schemes nor the timetable design can satisfy the real-time charging scheduling requirements of Catenary-free trams.

In this paper, we jointly consider the charging loads on the power system, the lifetime of the supercapacitor and the reliability of Catenary-free trams, and formulate the charging scheduling scheme for Catenary-free trams as an operation cost minimization problem. Based on the historical and real-time operation information of Catenary-free trams, we proposed both offline and online algorithms to calculate an upper bound of charging loads on the power system and manage the charging processes of Catenary-free trams to minimize the total operation cost. The contributions of this paper are summarized as follows:

- We designed a framework for the charging scheduling system, including the aggregator, the tram stations and the power system, to manage the charging processes of Catenary-free trams.
- We developed an algorithm to calculate an upper bound of the charging loads on the power system based on the historical operation data of Catenary-free trams.
- We proposed both day-ahead and real-time charging scheduling schemes to manage the charging processes of Catenary-free trams according to their operation information, such that the operation costs of the public transportation system can be minimized while the system's reliability can be guaranteed.

The rest of the paper is organized as follows. Section II presents the designed framework for the charging scheduling system, including system model, system implementation and charging system. Section III defines the system parameters and formulates the problem as an operation cost minimization problem. Section IV analyzes the necessary conditions for the parameters in the designed system. An upper bound of the charging loads on the power system is given, and a day-ahead charging scheduling scheme is designed in Section V. A real-time charging scheduling scheme is designed based on the real-time information from Catenary-free trams in Section VI. Section VII demonstrates the operational performance analysis based on simulation results. Finally, Section VIII concludes our work.

II. Design of the Charging Scheduling System

In this section, we first propose a framework for the charging scheduling system and then introduce the operation model of the designed system. Afterwards, we explain the implementation of the control strategy in the system.

A. System Design

In general, the designed system model is shown in Fig. 1. The system consists of three participants: the aggregator, the power system and the tram stations, and three elements: the power distribution system between the power system and the tram stations, the communication system among the aggregator and the tram stations, and the communication system between the aggregator and the power system. The aggregator acts as the coordinator, the tram stations act as the energy consumer executing the control strategies and the power system acts as the energy provider.

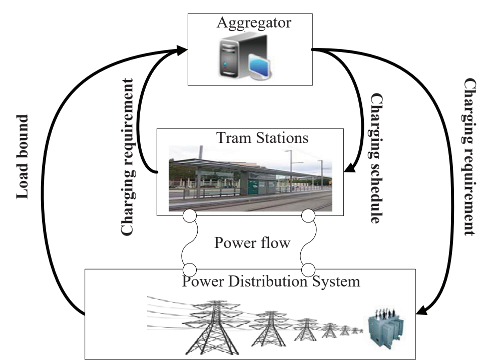

Fig. 1. The operation model of the designed system.

Specifically, each tram station needs to report data related to the charging requirements of Catenary-free trams, i.e., historical operation data in the day-ahead charging scheduling scheme or the real-time operation information in the real-time charging scheduling scheme, to the aggregator. Then, the aggregator needs to estimate the charging requirement of each Catenary-free tram based on the collected information. After that, the aggregator exchanges the charging requirements of all the tram stations with the power system to request an upper bound of the charging loads on the power system. Based on the charging requirements of all the Catenary-free trams and the upper bound of the charging loads on the power system, the aggregator determines the optimal charging scheduling

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scheme and distributes the control strategy to each tram station to minimize the operation cost of the public transportation system. After receiving the control strategy, each tram station executes the corresponding charging processes.

B. System Implementation

Based on the system model, we design an optimal charging scheduling scheme to arrange the charging processes of Catenary-free trams, which can be divided into two steps: 1) offline day-ahead charging scheduling, which determines the optimal charging scheduling scheme as well as the upper bound of the charging loads on the power system based on the estimated charging requirements of Catenary-free trams; 2) online real-time charging scheduling, which updates the charging scheduling decisions based on the real-time operation information of Catenary-free trams. The operation flow chart of the designed system and its communication flows among the charging stations, aggregator and power system can be found in Figs. 2 and 3, respectively. In the day-ahead charging scheduling scheme, the following procedures should be conducted before the operation of the public transportation system:

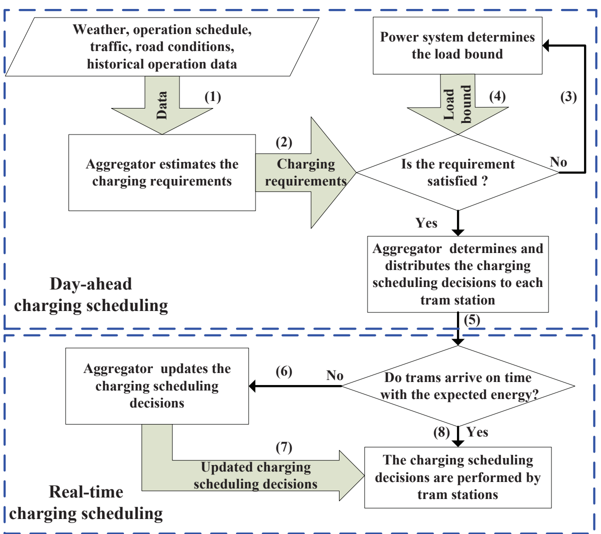

Fig. 2. The operation flow of the designed system.

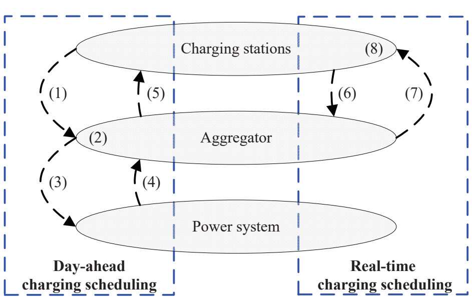

Fig. 3. The corresponding communication flows among the charging stations, aggregator and power system.

1) Each tram station reports the data related to the charging requirements, such as the historical operation data, weather forecast, operation schedule, road conditions and other information, to the aggregator through the communication link between the charging stations and the aggregator, which is shown as (1) in Fig. 3;
2) After receiving the data from all the tram stations, the aggregator estimates the charging requirements of Catenary-free trams in the future time slots and reports the estimated charging requirements to the power system through the communication link between the aggregator and the power system, which is shown as (3) in Fig. 3;
3) Based on the estimated charging requirements, the power system updates its upper bound of the charging loads accordingly through the communication link between the aggregator and the power system, which is shown as (4) in Fig. 3;
4) Based on the charging requirements of Catenary-free trams and the upper bound of the charging loads on the power system, the aggregator determines the optimal charging scheduling decisions and distributes the decisions to each tram station through the communication link between the charging stations and the aggregator, which is shown as (5) in Fig. 3.

In the real-time charging scheduling scheme, the following procedures at time slot t should be conducted:

1) The tram station reports its real-time information to the aggregator when the real-time charging requirement is different from the estimated one through the communication link between the charging stations and the aggregator, which is shown as (6) in Fig. 3;
2) After receiving the real-time charging requirements from at least one tram station, the aggregator determines the optimal charging scheduling scheme based on the updated information, and distributes the charging scheduling decisions to each tram station through the communication link between the charging stations and the aggregator, which is shown as (7) in Fig. 3;
3) After receiving the real-time charging scheduling decisions from the aggregator, each tram station executes the corresponding charging processes.

The "connection" between the day-ahead and real-time charging scheduling schemes is the day-ahead scheduling decisions to be updated in the real-time scheme if needed by the aggregator without the intervention of the power system.

C. Charging System

There exist several different charging mechanisms, e.g., Constant-Current (CC) mode, Constant-Voltage (CV) mode and Constant-Power (CP) mode, to charge the supercapacitor [24]–[26]. In the designed system, the CP mode[1] is employed to charge the supercapacitors when Catenary-free trams are staying at the tram stations. Specifically, when the tram station receives the charging decision from the aggregator, i.e., $P^*_{i,t}$, the aggregator of the charging system will regulate the output current as a function of the output voltage, such that the charging system's output power $P_{i,t}$ equals the desired charging power $P^*_{i,t}$.

III. System Model and Problem Formulation

Considering a public transportation system, there are I supercapacitor-based Catenary-free trams running on tracks

[1]The CP mode provides a constant energy charging rate by regulating the output current as a function of the output voltage.

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along the shared urban streets, and also sometimes on a segregated right-of-way. The supercapacitor can be recharged when the Catenary-free tram stays at the tram station and how much energy should be charged to the supercapacitors will be determined by the aggregator. We aim at optimizing the charging processes of Catenary-free trams to minimize the total operation cost. For easy reference, the important notations are listed in the Nomenclature.

A. System Parameters

Let one day be an operation period, which can be divided into T time slots. Denoted the t-th time slot by t and $t = 1, 2, \cdots, T$. In general, for the public transportation system, there is a regular operation, from which the schedules and running frequency of all the Catenary-free trams can be found. Let i, $i = 1, 2, \cdots, I$, denote the i-th Catenary-free tram, N denote the total number of the tram stations that each Catenary-free tram needs to travel to in an operation period, and n, $n = 1, 2, \cdots, N$, denote the n-th tram station that one Catenary-free tram visits. Let $A_{i,n}$ and $L_{i,n}$ denote the arrival time and the departure time for Catenary-free tram i at its n-th tram station. $[A_{i,n}, L_{i,n}]$ can be treated as the available charging duration for Catenary-free tram i at its n-th tram station.

Let $E_{i,t}$ denote the energy level of the supercapacitor for Catenary-free tram i at time slot t, $W_{i,t}$ denote the total amount of energy consumption for Catenary-free tram i at time slot t, and $P_{i,t}$ denote the total amount of energy charged to the supercapacitor for Catenary-free tram i at time slot t, respectively. Thus, at time slot t, the energy level of Catenary-free tram i satisfies the following constraint:

$$E_{i,t} = \min\{E_{i,t-1} + P_{i,t} - W_{i,t}, B_i^{\text{cap}}\}, \ \forall i, t, \tag{1}$$

where B_i^{cap} denotes the battery capacity of the supercapacitor for Catenary-free tram i. It can be found that the highest energy level of the supercapacitor for Catenary-free tram i at any time slot t cannot exceed its battery capacity.

Since one Catenary-free tram can be recharged only when it stays at the tram station, we have

$$P_{i,t} = \begin{cases} [0, P_{i,t}^{\max}], & \text{if } t \in [A_{i,n}, L_{i,n}], n = 1, 2, \cdots, N; \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

where $P_{i,t}^{\max}$ depends on the charging facilities in the tram stations and the power system.

Let $\widetilde{P}_t$ denote the total charging load for all the Catenary-free trams in the power system at time slot t. The values of $\widetilde{P}_t$ can be given by

$$\widetilde{P}_t = \sum_i P_{i,t}. \tag{3}$$

In order to guarantee the stability and reliability of the power system, an upper bound $\bar{P}_t$ can be issued by the power system. The total charging load $\widetilde{P}_t$ cannot exceed the upper bound $\bar{P}_t$, i.e.,

$$\bar{P}_t \geq \widetilde{P}_t. \tag{4}$$

In general, a small upper bound is preferable by the power system for cost saving. However, a small upper bound of the charging loads may not satisfy the charging requirements of all the Catenary-free trams, and thus may affect the reliability of the transportation system. Hence, in the day-ahead charging scheduling scheme, we will calculate a small upper bound but sufficient for satisfying the charging requirements of all the Catenary-free trams.

Since all the Catenary-free trams cannot be recharged during their travel from one tram station to the next, the energy in the supercapacitor will be consumed when a Catenary-free tram is traveling. In addition, we assume that the energy consumptions for all the Catenary-free trams at the tram stations are 0. Hence, the energy consumption of Catenary-free trams i satisfies the following constraint:

$$W_{i,t} = \begin{cases} (0, W_i^{\max}], & \text{if } t \notin [A_{i,n}, L_{i,n}], n = 1, 2, \cdots, N; \\ 0, & \text{otherwise,} \end{cases} \tag{5}$$

where $W_i^{\max}$ depends on the energy consumption parameters of Catenary-free trams.

Let $D_{i,n}$ and $\widetilde{W}_{i,n}$ denote the travel duration and energy consumption for Catenary-free tram i traveling from its n-th station to its $(n+1)$-th station, respectively. Thus, we have

$$D_{i,n} = A_{i,n+1} - L_{i,n}, \tag{6}$$

$$\widetilde{W}_{i,n} = \sum_{t=L_{i,n}}^{A_{i,n+1}} W_{i,t} = \sum_{t=L_{i,n}}^{L_{i,n}+D_{i,n}} W_{i,t}, \tag{7}$$

where $D_{i,n}$ is assumed to follow a normal distribution with the mean and variance of $(\bar{D}_{i,n}, \sigma^2)$ and $\widetilde{W}_{i,n}$ is assumed to be an increasing and concave function of the travel duration $D_{i,n}$. In this paper, we assume that $D_{i,n}$ for different Catenary-free trams are independent.

Let $\mathbb{P}_{i,n}$ denote the probability that Catenary-free tram i can arrive at its $(n+1)$-th tram station successfully after it leaves its n-th tram station. According to the definitions of the energy level $E_{i,L_{i,n}}$ and energy consumption $\widetilde{W}_{i,n}$ for Catenary-free tram i, the value of $\mathbb{P}_{i,n}$ can be given by

$$\mathbb{P}_{i,n} = \Pr\{E_{i,L_{i,n}} \geq \widetilde{W}_{i,n}\}. \tag{8}$$

In order to ensure the public transportation system operate normally, there always exists a reliability requirement. Let $\bar{p}$ denote the minimal probability of the successful operation for the public transportation system. Thus, the following constraint should be always satisfied:

$$\mathbb{P}_{i,n} \geq \bar{p}, \tag{9}$$

Due to the high reliability requirement of the public transportation system, we set $0.99 \leq \bar{p} \leq 1$ in this paper.

B. Operation Cost Model for Catenary-free Trams

In addition to the business tax, surcharges, management fees and so on, the main business costs, which dominate the operation cost, include the electricity cost, vehicle repairs, wages, etc [27]. For a tram transportation system, in this paper, we consider main parts of the operation cost: the electricity cost, the vehicle maintenance and repairs cost [27], which can be changed by adjusting the charging processes of Catenary-free trams, and the emergency charging service cost.

Firstly, let $C_1(\widetilde{P}_t)$ denote the electricity cost for all the Catenary-free trams at time slot t. Recently, many power

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systems begin to deploy load-based pricing schemes to reduce their peak loads, e.g., electricity spot price [9], Time-of-Use (TOU) pricing [10], and peak load pricing [11], in which the electricity cost not only depends on the total amount of used energy, but also depends on the current aggregated charging load on the power system. We assume that $C_1(\widetilde{P}_t)$ is an increasing, piecewise differentiable, convex function of the total energy consumption $\widetilde{P}_t$ at time slot t in this paper. One example of the electricity cost can be given by

$$C_1(\widetilde{P}_t) = a_1\widetilde{P}_t + a_2(\widetilde{P}_t)^2, \tag{10}$$

where both a_1 and a_2 are positive coefficients. Thus, the total electricity cost during one operation period can be given by $\sum_{t=1}^{T} C_1(\widetilde{P}_t)$.

Secondly, let $C_2(V_{i,t})$ denote the lifetime-related cost of the supercapacitor for Catenary-free tram i at time slot t. [2] According to the voltage dependency found in the existing experiment [28], the inverse power law for the relationship between the lifetime τ and the voltage V is established as

$$\tau(V) = \tau_0(\frac{V}{V_0})^{(-m)}, \tag{11}$$

where $\tau(V)$ (in seconds) is the static lifetime at the voltage V, V_0 is the reference voltage, τ_0 is the expected lifetime at the reference voltage V_0, V is the voltage across the supercapacitor terminals (in volts)[3], and m is the parameter related to the voltage acceleration factor. A careful examination shows that $m = 3.5$ when $V_i \in [0.7V_0, 1.3V_0]$ [28]. Thus, the lifetime-related cost of the supercapacitor at the voltage $V_{i,t}$ is

$$C_2(V_{i,t}) = \frac{C_B}{\tau(V_{i,t})} = \frac{C_B V_{i,t}^m}{\tau_0 V_0^m}, \tag{12}$$

where C_B denotes the financial cost for replacing the supercapacitor of one Catenary-free tram. In this paper, since the voltage level of the supercapacitor for tram i at time slot $L_{i,n}$ reaches a peak value and the supercapacitor's voltage level during $[L_{i,n}, A_{i,n+1}]$ can be formulated as a decreasing function of $V_{i,L_{i,n}}$, we take the lifetime-related cost function as a function of $V_{i,L_{i,n}}$. Thus, the total amount of the lifetime-related cost during one operation period can be given by $\sum_{i=1}^{I}\sum_{n=1}^{N} C_2(V_{i,L_{i,n}})$.

Thirdly, Let $C_3(P_{i,n})$ denote the expected financial cost for the emergency charging services for Catenary-free tram i between its n-th tram station and its $(n+1)$-th tram station. When one Catenary-free tram runs out of energy before arriving at the tram station, an emergency charging service should be provided, which incurs an extra financial cost. Denote the financial cost of one emergency charging service by C_E, which is much higher than the regular charging service. The expected financial cost for the emergency charging services $C_3(P_{i,n})$ can be given by

$$C_3(\mathbb{P}_{i,n}) = C_E(1 - \mathbb{P}_{i,n}). \tag{13}$$

Thus, the total amount of the expected financial cost for the emergency charging services during one operation period can be given by $\sum_{i=1}^{I}\sum_{n=1}^{N} C_3(\mathbb{P}_{i,n})$.

C. Operation Cost Minimization Problem

Now we formulate the operation cost minimization problem for the public transportation system as follows:

$$\begin{aligned}
\textbf{P0:} \min_{P_{i,t}} \quad & \sum_{t=1}^{T} C_1(\widetilde{P}_t) + \sum_{i=1}^{I}\sum_{n=1}^{N}(C_2(V_{i,L_{i,n}}) + C_3(\mathbb{P}_{i,n})),\\
s.t. \quad & \mathbb{P}_{i,n} \geq \bar{p} \quad \forall i,n,\\
& P_{i,t} \leq P_{i,t}^{\max} \quad \forall i,t,\\
& \widetilde{P}_t \leq \bar{P}_t \quad \forall t.
\end{aligned}$$

The objective is to minimize the operation cost of the public transportation system by adjusting the charging processes of Catenary-free trams. The first constraint ensures the normal operation of the designed system. The second and the third constraints give the upper bounds of the charging loads.

In order to solve this problem, we first analyze the requirements of the system parameters to ensure that there exists at least one feasible solution for the operation cost minimization problem. Then, we propose a day-ahead charging scheduling scheme to arrange the charging processes and report to the power system on the upper bound of the charging loads, as well as an online charging scheduling scheme to update the real-time charging loads of Catenary-free trams based on the real-time operation information.

IV. System Parameter Analysis

To support the normal operation of Catenary-free trams, there are some requirements of the system parameters, such as the battery capacity and the minimal upper bound of the charging loads. In this section, we define the lower bound for the battery capacity and an bound of the charging loads.

Battery Capacity Requirement: Let $\bar{B}_i^{\text{cap}}$ denote the minimal capacity of the supercapacitors for Catenary-free tram i. Since the energy level of Catenary-free tram i at any time slot t cannot exceed its battery capacity B_i^{cap}, i.e., $E_{i,t} \leq B_i^{\text{cap}}, \forall i,t$, $E_{i,L_{i,n}} \leq B_i^{\text{cap}}$ should always be satisfied. According to the definition of $\mathbb{P}_{i,n}$, to ensure the normal operation of Catenary-free tram i, $\Pr\{E_{i,L_{i,n}} \geq \widetilde{W}_{i,n}\} \geq \bar{p}$ should always be satisfied. Thus, $\Pr\{B_i^{\text{cap}} \geq \widetilde{W}_{i,n}\} \geq \Pr\{E_{i,L_{i,n}} \geq \widetilde{W}_{i,n}\} \geq \bar{p}, \forall i,n$, should always be satisfied.

Charging Processes Requirements: In order to satisfy the reliability requirements of Catenary-free trams, there exist some requirements for the charging processes of Catenary-free trams, which can be given in the following Lemmas:

Lemma 1: When the battery capacity is large enough, there exists a sufficient condition for the normal operation of Catenary-free tram i, i.e.,

$$\Pr\{E_{i,0} + \sum_{t=1}^{L_{i,n}} P_{i,t} \geq \sum_{n'=1}^{n} \widetilde{W}_{i,n'}\} \geq \bar{p}, \ \forall i,n, \tag{14}$$

[2]Generally speaking, the degradation of the supercapacitor depends on several factors, such as the operation temperature, voltage, and humidity. However, the operation temperature and humidity, as well as the other external environmental factors, cannot be controlled by the charging scheduling scheme. Thus, in this paper, we consider the effects of the voltages, which are more significant than the temperature and humidity, on the degradation of the supercapacitor.

[3]According to the characteristic formula of capacitance, $E_i = 1/2CV^2$ where C is the capacitance of the supercapacitor.

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where $E_{i,0}$ is the initial energy level of the supercapacitor for Catenary-free tram i.

Proof: When the battery capacity is large enough, the energy level of the supercapacitor for Catenary-free tram i at time slot $L_{i,n}$ can be given by

$$\begin{aligned} E_{i,L_{i,n}} &= \min\{B_i^{\text{cap}}, E_{i,A_{i,n}} + \sum_{t=A_{i,n}}^{L_{i,n}} (P_{i,t} - W_{i,t})\} \\ &= E_{i,A_{i,n}} + \sum_{t=A_{i,n}}^{L_{i,n}} P_{i,t}, \\ &\geq E_{i,0} + \sum_{t=1}^{L_{i,n}} P_{i,t} - \sum_{n'=1}^{n-1} \widetilde{W}_{i,n'} \end{aligned} \tag{15}$$

where

$$\sum_{n'=1}^{n-1} \widetilde{W}_{i,n'} = \sum_{t=1}^{L_{i,n}} W_{i,t}, \tag{16}$$

since $W_{i,t} = 0$ when $t \in [A_{i,n}, L_{i,n}]$ and $E_{i,A_{i,n}} = \max\{0, E_{i,L_{i,n-1}} + \sum_{t=L_{i,n-1}}^{A_{i,n}-1} (P_{i,t} - W_{i,t})\}$. In order to guarantee the normal operation of Catenary-free tram i, we have

$$\begin{aligned} & \Pr\{E_{i,L_{i,n}} \geq \widetilde{W}_{i,n}\} \geq \bar{p} \\ \Longrightarrow\ & \Pr\{E_{i,0} + \sum_{t=1}^{L_{i,n}} P_{i,t} - \sum_{n'=1}^{n-1} \widetilde{W}_{i,n'} \geq \widetilde{W}_{i,n}\} \geq \bar{p} \\ \Longrightarrow\ & \Pr\{E_{i,0} + \sum_{t=1}^{L_{i,n}} P_{i,t} \geq \sum_{n'=1}^{n} \widetilde{W}_{i,n'}\} \geq \bar{p} \end{aligned} \tag{17}$$

since the energy consumptions, $W_{i,n}, \forall n$, are independent. ■

Since the $D_{i,n}$ is assumed to follow a normal distribution with the mean and variance of $(\bar{D}_{i,n}, \sigma^2)$ and $\widetilde{W}_{i,n}$ is an increasing and concave function of $D_{i,n}$, we have the following lemma for the charging load as well as its bound:

Lemma 2: In order to ensure the normal operation of the public transportation system, an upper bound of the charging loads for Catenary-free tram i at its n-th tram station can be given by

$$\sum_{t=A_{i,n}}^{L_{i,n}} \bar{P}_{i,t} \geq \widetilde{W}_{i,n}(\sigma\Phi^{-1}(\bar{p}) + \bar{D}_{i,n}), \tag{18}$$

where $\Phi^{-1}(\cdot)$ denotes the inverse function of the cumulative distribution function for a standard normal distribution $(0, 1)$, and $\Phi(a) = b$ and $\Phi^{-1}(b) = a$ always hold.

Proof: Since $D_{i,n}$ is assumed to follow a normal distribution with the mean and variance of $(\bar{D}_{i,n}, \sigma^2)$ and $\widetilde{W}_{i,n}$ is an increasing and concave function of the travel duration $D_{i,n}$, for Catenary-free tram i at its n-th tram station, we have

$$\Pr\{X = \widetilde{W}_{i,n}(D_{i,n})\} = \Pr\{Y = D_{i,n}\}, \tag{19}$$

where X is the variable related to the energy consumption $W_{i,n}$ and Y is the variable related to the travel duration $D_{i,n}$. Thus, for any value of $\widetilde{W}_{i,n}(D_{i,n})$, we can find a unique corresponding $D_{i,n}$ with the similar probability. Let $\widetilde{W}^*_{i,n}$ be the minimal value that ensures $\Pr\{X \leq \widetilde{W}^*_{i,n}\} \geq \bar{p}$ always holds. Thus, an upper bound of the charging loads for Catenary-free tram i at its n-th tram station can be given by

$$\begin{aligned} & \Pr\{X \leq \widetilde{W}^*_{i,n}\} \geq \bar{p} \\ \Rightarrow\ & \sum_{t=A_{i,n}}^{L_{i,n}} \bar{P}_{i,t} \geq \widetilde{W}_{i,n}(\sigma\Phi^{-1}(\bar{p}) + \bar{D}_{i,n}). \end{aligned} \tag{20}$$

■

It can be found that the upper bound $\sum_{t=A_{i,n}}^{L_{i,n}} \bar{P}_{i,t}$ is an increasing function of the reliability requirement $\bar{p}$ and the travel duration $D_{i,n}$.

V. A Day-ahead Charging Scheduling Scheme

In this section, we will design a day-ahead charging scheduling scheme to request an upper bound for the charging loads of Catenary-free trams and arrange the charging processes of Catenary-free trams for each time slot.

Since the upper bound of the charging loads for Catenary-free tram i is a constraint rather than a constant, the upper bound of the charging loads for all the Catenary-free trams can be given by the following theorem.

Theorem 1: There exists an upper bound of the charging loads from all the Catenary-free trams at time slot t, which can be given by

$$\bar{P}^*_t = \min_{\bar{P}_{i,t}} \max\{\sum_{i=1}^{I} \bar{P}_{i,t}\}. \tag{21}$$

$$\text{s.t.} \quad \sum_{t=A_{i,n}}^{L_{i,n}} \bar{P}_{i,t} \geq \widetilde{W}_{i,n}(\sigma\Phi^{-1}(\bar{p}) + \bar{D}_{i,n}), \tag{22}$$

$$\bar{P}_{i,t} \leq P^{\max}_{i,t}. \tag{23}$$

Proof: In order to satisfy the charging requirements of all the Catenary-free trams, the upper bound $\bar{P}_t$ should satisfy the following constraint:

$$\bar{P}_t \geq \sum_i P_{i,t}, \tag{24}$$

According to Lemma 2, an upper bound of the charging loads for Catenary-free tram i at its n-th tram station is an increasing function of $D_{i,t}$, i.e., $\sum_{t=A_{i,n}}^{L_{i,n}} \bar{P}_{i,t} \geq \widetilde{W}_{i,n}(\sigma\Phi^{-1}(\bar{p}) + \bar{D}_{i,n})$. Thus, for the charging loads of all the Catenary-free trams, there exists an upper bound $\bar{P}_t$, which should satisfy

$$\bar{P}_t \geq \sum_{i=1}^{I} \bar{P}_{i,t}, \tag{25}$$

$$\sum_{t=A_{i,n}}^{L_{i,n}} \bar{P}_{i,t} \geq \widetilde{W}_{i,n}(\sigma\Phi^{-1}(\bar{p}) + \bar{D}_{i,n}). \tag{26}$$

In addition, the charging loads for each Catenary-free tram cannot exceed the charging load constraint from the tram station, i.e., $\bar{P}_{i,t} \leq P^{\max}_{i,t}$.

Based on these constraints, in order to request an upper bound for the charging loads on the power system, an upper bound $\bar{P}^*_t$ can be given by solving the problem (21). ■

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By exchanging information between the power system and the aggregator, the upper bound of the charging loads for Catenary-free trams can be determined. Then, the aggregator needs to determine the charging scheduling decisions and then distributes them to each tram station.

Assuming that all the Catenary-free trams will operate under the regular operation on time, the day-ahead charging scheduling scheme can be obtained by solving the following problem:

$$\begin{aligned}\textbf{P1:} \min_{P_{i,t}} \quad & \sum_{t=1}^{T} C_1(\widetilde{P}_t) + \sum_{i=1}^{I}\sum_{n=1}^{N}(C_2(V_{i,L_{i,n}}) + C_3(\mathbb{P}_{i,n})),\\ s.t. \quad & \mathbb{P}_{i,n} \geq \bar{p} \ \ \forall i,n,\\ & P_{i,t} \leq P_{i,t}^{\max} \ \ \forall i,t,\\ & \sum_i P_{i,t} \leq \bar{P}_t^* \ \ \forall t,\end{aligned}$$

where $\bar{P}_t^*$ is given by Theorem 1. The objective function is to minimize the operation cost of the public transportation system during one operation period. The first constraint denotes the operation reliability requirement for Catenary-free trams. The second and third constraints show the upper bounds of the charging load for each Catenary-free tram and all the Catenary-free trams, respectively. For this optimization problem, we have the following properties.

For Problem **P1**, it can be found that all the constraints are linear, and we can proof that the objective function is a convex function of $P_{i,t}$ as follows:

1) Since $C_1(\widetilde{P}_t) = a_1\widetilde{P}_t + a_2(\widetilde{P}_t)^2$ is the electricity cost and $\widetilde{P}_t = \sum_{i=1}^{I} P_{i,t}$, we have $\partial^2 C_1(\widetilde{P}_t)/\partial P_{i,t}^2 = 2a_2 > 0$. Thus, the first part is a convex function of $P_{i,t}$.
2) Since $E_{i,L_{i,n}} = E_{i,A_{i,n}} + \sum_{t=A_{i,n}}^{L_{i,n}} P_{i,t}$, $V_{i,L_{i,n}} = \sqrt{\frac{2E_{i,L_{i,n}}}{C}}$ and the lifetime-related cost is $C_2(V_{i,L_{i,n}}) = \frac{C_B V_{i,L_{i,n}}^m}{\tau_0 V_0^m}$, we have $C_2(V_{i,L_{i,n}}) = \frac{C_B}{\tau_0 V_0^m}(\frac{2}{C})^{\frac{m}{2}}(E_{i,L_{i,n}})^{(\frac{m}{2})}$. Since $m = 3.5$, we have $\partial C_2(V_{i,L_{i,n}})/\partial P_{i,t} > 0$ and $\partial^2 C_2(V_{i,L_{i,n}})/\partial P_{i,t}^2 > 0$. Thus, the second part is an increasing and convex function of $P_{i,t}$.
3) Since $\widetilde{W}_{i,n}$, which is an increasing and concave function of $D_{i,n}$ when the probability is larger than 0.99, has the similar distribution as $D_{i,n}$ and $\mathbb{P}_{i,n} = \Pr\{E_{i,L_{i,n}} \geq \widetilde{W}_{i,n}\}$ is also an increasing and concave function of $D_{i,n}$, $(1-\mathbb{P}_{i,n})C_E$ is a decreasing and convex function of $E_{i,L_{i,n}}$, which is a linear function of $P_{i,t}$. Thus, $C_3(\mathbb{P}_{i,n}))$ is a decreasing and convex function of $P_{i,t}$.

Thus, the objective function is a convex function of $P_{i,t}$ and the operation cost minimization problem **P1** is a convex optimization problem, which can be solved by several existing methods, i.e., `fmincon` function [29] or CVX toolbox [30] in Matlab. We omit the details of how to solve this problem.

VI. A Real-time Charging Scheduling Scheme

Based on the day-ahead charging scheduling scheme, the aggregator distributes the charging scheduling decisions to each tram station. If all the Catenary-free trams arrive at the tram station on time with the same charging requirement as the estimated charging requirement, the tram station will carry out the corresponding charging processes for Catenary-free trams; otherwise, the tram station needs to report the real-time charging requirement and the real arrival time to the aggregator to update the charging scheduling scheme.

Let $\bar{t}$ denote the current time slot, t' denote the time slots, $t' = \bar{t}, \bar{t}+1, \cdots, \bar{t}+M$,[4] and n' denote the set of the tram stations that Catenary-free trams visit in the current or the following M time slots, respectively. If any Catenary-free tram does not arrive at its tram station on time or with different energy level, the following charging scheduling scheme will be carried out to update the charging scheduling decisions:

$$\begin{aligned}\textbf{P2:} \min_{P_{i,t}} \quad & \sum_{t=\bar{t}}^{\bar{t}+M} C_1(\widetilde{P}_t) + \sum_{i=1}^{I}\sum_{n\in n'}(C_2(V_{i,L_{i,n}}) + C_3(\mathbb{P}_{i,n})),\\ s.t. \quad & \mathbb{P}_{i,n} \geq \bar{p}, \ \ \forall i, n\in n',\\ & P_{i,t} \leq P_{i,t}^{\max}, \ \ \forall i,t',\\ & \sum_i P_{i,t} \leq \bar{P}_t^*. \ \ \forall t',\end{aligned}$$

The objective function relates to the operation cost in the current and upcoming M time slots and the first constraint only ensures the normal operation of the public transportation system at the current and a few tram stations in the future.

It can be found that the main difference between the day-ahead charging scheduling scheme and the real-time charging scheduling scheme is the time scale: the day-ahead charging scheduling scheme considers all the charging processes for the whole operation period while the real-time charging scheduling scheme only considers the time slots for the current time slot and a few future time slots. Thus, the problem **P2** can be solved with the similar tools for the problem **P1**. The computation complexity for problem **P2** can be reduced from $O(T^3/\log(T))$ (for problem **P1**) to $O(M^3/\log(M))$.

The proposed scheduling scheme is sketched as Algorithm 1. In the proposed charging scheduling scheme, the aggregator needs to collect the system parameters, such as the capacity of the supercapacitor B_i^{cap}, the reliability requirement $\bar{p}$, and the estimated operation data of Catenary-free trams, including the initial energy level $E_{i,0}$, arrival times $A_{i,n}$, departure times $L_{i,n}$ and energy consumption $W_{i,t}$. Then, the aggregator needs to calculate an upper bound $\bar{P}_t^*$ by solving Problem (21) and report to the power system on the result. Based on $\bar{P}_t^*$ and the estimated operation data of Catenary-free trams, the aggregator calculates the day-ahead charging scheduling decision by solving Problem **P1** and distributes the decision to the tram stations. At each time slot t, according to the real-time operation information of Catenary-free trams, the aggregator updates the real-time charging decision by solving Problem **P2** and distributes the charging decision $P_{i,t}$ to the tram stations. Each tram station executes the charging decision to charge the supercapacitors, such that the operation cost for Catenary-free trams can be minimized.

[4] Where M is a positive constant depends on the performance requirement, larger value of M results in a higher computation complexity and smaller gap from the optimal solution.

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Algorithm 1 Optimal real-time charging scheduling scheme

Initialization $E_{i,0}, W_{i,t}, A_{i,n}, L_{i,n}, T, \bar{p}, B_i^{\text{cap}}$

- Calculate $\bar{P}_t^*$ by solving Problem (21);
- Calculate the day-ahead charging decision by solving Problem **P1**;
- **for** $t = 1, 2, \cdots, T$

  1) Update $E_{i,t}, A_{i,n}, L_{i,n}$;

  2) Calculate the optimal real-time charging decision $P_{i,t}$ by solving Problem **P2**;

  3) Distribute the charging decision $P_{i,t}$ to each tram stations;

  end

return $P_{i,t}, C_1(\widetilde{P}_t), C_2(V_{i,L_{i,n}}), C_3(\mathbb{P}_{i,n})$.

VII. Performance Evaluation

The parameters from the Guangzhou Catenary-free tram system, which consist of 10–12 supercapacitor-powered Catenary-free trams and a total length of 7.7 kilometers tracks with 22 tram stations in one round trip, are adopted in the simulation[5]. The average travel time between two tram stations is 4.5 minutes with a standard deviation $\sigma = 1/3$ minute. The expected energy consumption is defined as $\widetilde{W_{i,n}} = 0.74 * \sqrt{D_{i,n}} kWh$. The charging time at each tram station is 30 seconds and the maximal charging power is $540kW$ ($900V$ and $600A$) [31]. The regular, highest and lowest voltage for each supercapacitor module are $2.7V$, $2.8V$ and $2.3V$, respectively. Each Catenary-free tram is fit with two supercapacitor groups and each group consists of 344 $7000F$ supercapacitors in series. Thus, the battery capacity is $5.24kWh$. We set one time slot as 10 seconds, $\bar{p} = 0.99$, $a_1 = 0.2$, $a_2 = 0.1$, $M = 6$ time slots, $C_B = \$30,000$, and $C_E = \$150$.

In this section, we shows the simulation results for ten Catenary-free trams from 11:14am to 11:54am. "Without scheduling" denotes the charging scheduling scheme, in which the supercapacitor of Catenary-free trams will be charged to full when it stays at one tram station with the highest charging power $540kW$, and "Valley Filling" denotes the charging scheduling scheme, in which the "valley-filling" approach is used to reduce the peak load on the power system under the reliability requirement of Catenary-free trams in a real-time manner [13].

A. Case Study

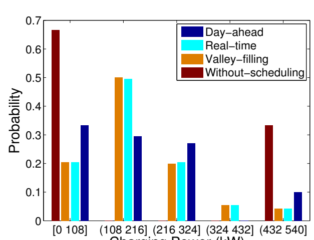

Fig. 4. The distribution of charging powers for all the Catenary-free trams.

Fig. 4 shows the distribution of the charging powers for all the Catenary-free trams from 11:14am to 11:54am. From the simulation results, it can be found that both the proposed real-time charging scheduling scheme and the existing valley-filling charging scheduling scheme can reduce the probability of employing the highest charging power, such that the charging processes of the Catenary-free trams will be smooth, desirable for the power system.

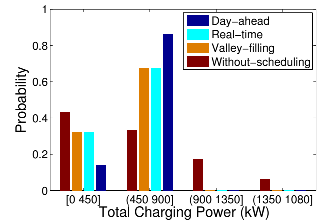

Fig. 5. The distribution of total charging loads from all the Catenary-free trams on Power system.

Fig. 5 shows the distribution of total charging loads on the power system. It can be found that both the proposed real-time charging scheduling scheme and valley-filling charging scheduling scheme can reduce the probability of employing high total charging powers and smoothen the charging power on the power system. Furthermore, the real-time charging scheduling scheme and valley-filling charging scheduling scheme achieve the similar total charging loads to each other. Hence, both of them can reduce the peak load on the power system in an efficient way.

Fig. 6 shows the operation costs, including the electricity cost, the battery lifetime-related cost and the expected cost for the emergency charging services, for the Catenary-free trams at their tram stations. From Fig. 6(a), it can be seen that both the real-time charging scheduling scheme and the existing valley-filling charging scheduling scheme can reduce the electricity cost since they can reduce the peak load on the power system in an efficient way. From Fig. 6(b), it can be found that Catenary-free trams without scheduling have a higher battery lifetime-related cost since they always charge the supercapacitor to full, which incurs a shorter lifetime of the supercapacitors, while Catenary-free trams under the other two charging scheduling schemes have a lower lifetime-related cost since they try to keep energy at a lower level to avoid high peak loads on the power system. Fig. 6(c) shows that Catenary-free trams under the existing valley-filling charging scheduling scheme incur the highest expected operation cost for the emergency charging services. This is because they always keep the energy in the supercapacitor at a low and possibly insufficient level, which satisfies the lower bound of the reliability requirement of the public transportation system without any margin for schedule variations, to reduce the peak charging load on the power system. While Catenary-free trams under the real-time charging scheduling scheme will make a trade-off between the electricity cost and the reliability-related cost, and thus the expected operation cost for the emergency charging services for Catenary-free trams under the real-time charging scheduling scheme can be greatly reduced.

Fig. 7 shows the total operation cost for Catenary-free trams at each tram station and Table I shows the total operation cost for Catenary-free trams under different charging scheduling schemes during [11:14am, 11:54am]. It can be found that

[5]Simulation settings can be found on page http://web.uvic.ca/~ymzhang/

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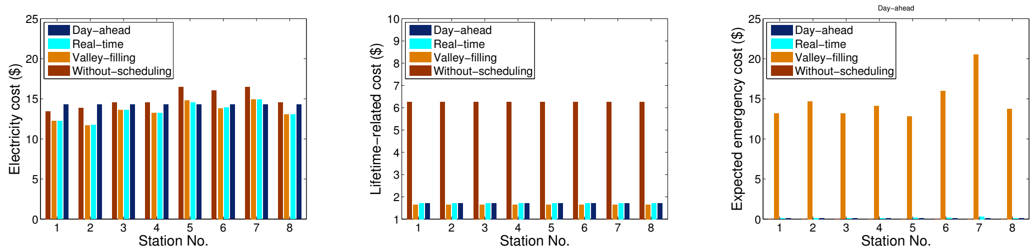

(a) (b) (c)

Fig. 6. The operation costs (in $) for Catenary-free trams under the day-ahead, real-time, valley-filling, and without scheduling scheme, respectively: a) Electricity cost; b) Battery lifetime-related cost; c) Expected emergency cost.

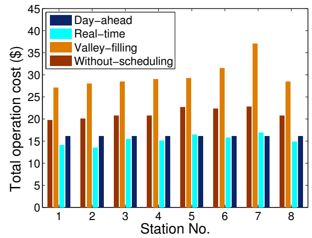

Fig. 7. Total operation cost of Catenary-free trams.

TABLE I
TOTAL OPERATION COST ($)

Schemes	$\sum C_1$	$\sum C_2$	$\sum C_3$	Total cost	Proportion
Day-ahead	114.64	13.71	1.05	129.40	76.1%
Real-time	107.25	13.73	1.19	122.17	71.9%
Valley-filling	107.43	13.14	118.22	238.79	140.5%
Without	119.95	50.01	0	169.96	100%

Catenary-free trams under the proposed real-time charging scheduling scheme achieve the lowest operation cost and reduce the total operation cost by about 28% when compared with the case without scheduling. While the existing valley-filling charging scheduling scheme produce the highest operation cost due to its high expected operation cost for the emergency charging services.

B. Relationship between Parameters and Simulation Results

In order to analyze the effects of the considered slots (M) on the real-time and valley-filling charging scheduling schemes, we change the values of M from 5 to 11 and show the simulation results about the total operation costs and the peak charging load on the power system in Figs. 8 and 9. From Fig. 8, it is observed that, with the increase of M, both the real-time charging scheduling scheme and the valley-filling charging scheduling scheme can reach their near-optimal solutions. From Fig. 9, it can be seen that, with the increase of M, the peak charging load on the power system will not be changed, which means that the peak charging load will not be affected by the value of M when it is large enough.

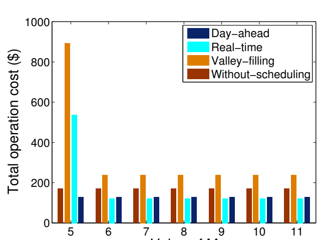

Fig. 8. The effects of M on the total operation cost for Catenary-free trams.

The average computation times for different schemes are shown in Table II. It can be found that the computation time is growing with the increase of M and the optimal solution

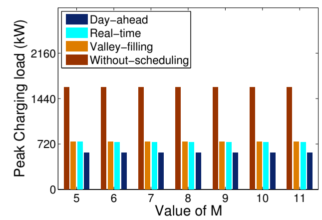

Fig. 9. The effects of M on the peak charging load on the power system.

TABLE II
THE COMPUTATION TIMES FOR DIFFERENT SCHEMES

Schemes		$M = 6$	$M = 8$	$M = 10$	$M = 12$
Day-ahead	$\sim$ 4 hours	-	-	-	-
Real-time	-	0.6 s	1.1 s	1.5 s	2.0 s
Valley-filling	-	0.6 s	1.0 s	1.4 s	1.9 s
Without	$<$ 0.1 s	-	-	-	-

TABLE III
THE DISTRIBUTION OF THE TOTAL OPERATION COST AND THE PEAK LOAD

Schemes	Maximal P_t^*	Mean P_t^*	Minimal P_t^*
Day-ahead	-	291 kW	-
Real-time	490 kW	377 kW	301 kW
Valley-filling	491 kW	380 kW	301 kW
Without	1350 kW	936 kW	588 kW
-	Highest cost ($)	Mean cost ($)	Lowest cost ($)
Day-ahead	-	129.40	-
Real-time	133.34	123.95	115.91
Valley-filling	264.80	241.23	222.50
Without	182.52	172.11	162.91

for the proposed real-time charging scheduling scheme can be obtained in two seconds with a reasonable M, which is acceptable for real-time charging scheduling.

In order to explore the efficiency of the proposed algorithm, we assume that the arrival times obey a normal distribution $(A_{i,n}, \delta_A)$ where$A_{i,n}$ is the expected arrival time and $\delta_A = 1$ time slot. The distributions of the total operation cost and the peak charging load are shown in Table III. It can be found that the real-time charging scheduling scheme can not only reduce the total operation cost by 28% when compared with the case without scheduling, but also reduce the peak load from all the Catenary-free trams. Meanwhile, the scheduler designed for optimizing the charging of battery-based EVs, valley-filling, results in a much higher operation cost due to a higher probability of emergency charging.

VIII. CONCLUSION

In this paper, we addressed the charging scheduling problem for supercapacitor-based Catenary-free trams. First, we proposed a charging scheduling framework, in which the aggregator communicates with the tram stations to collect Catenary-free trams' operational information and distributes the charging decisions to them, and communicates with the power system to require an upper bound of the charging loads during the whole time period. Then, to minimize the operation cost, we proposed a day-ahead charging scheduling scheme, which can arrange the charging processes of Catenary-free trams based on the historical data and report to the power system on the upper bound of the charging loads. Also, we proposed a real-time charging scheduling scheme, which can update the charging decisions according to the real-time operation information of Catenary-free trams. Using the proposed solution, the operation costs, including the electricity cost, the battery lifetime-related cost and the expected cost for the emergency charging services, can be minimized. Simulation results demonstrated the efficiency of the proposed charging scheduling scheme, which can reduce the operation cost of the tram transportation system and the charging peak load of the power system significantly, while not affecting the regular operation of the tram transportation system.

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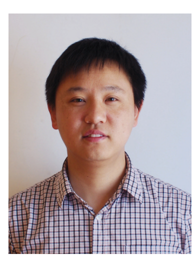
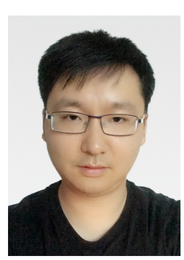


Yongmin Zhang (S'12-M'15) received the PhD degree in control science and engineering in 2015, from Zhejiang University, Hangzhou, China. He is currently a postdoctoral research fellow in both the State Key Laboratory of Industrial Control Technology at Zhejiang University and the Department of Electrical and Computer Engineering at the University of Victoria. His research interests include wireless sensor networks, resource management and optimization, and smart grid. He is a member of the IEEE.



Zhe Wei (S'15) received his B.Sc. and M.Sc. degrees in electrical engineering from Northwestern Polytechnical University, Xian, China, in 2009 and 2012, respectively. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering at the University of Victoria, Victoria, BC, Canada. His research interests include electric vehicle charging scheduling, resource allocation, smart grid, and demand response.

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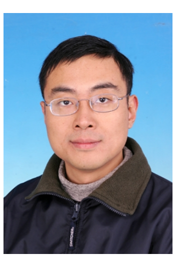
Heng Li (S17)is currently a Ph.D. Candidate in the School of Information Science and Engineering, Central South University, China, where he received his Bachelor's degree in 2011 in Automation. From Nov 2015, he has been working as a visiting research student in the Department of Computer Science, University of Victoria, Victoria, Canada. His current research interests include cooperative control and cyber physical systems.

Lin Cai (S'00-M'06-SM'10) received her M.A.Sc. and PhD degrees in electrical and computer engineering from the University of Waterloo, Waterloo, Canada, in 2002 and 2005, respectively. Since 2005, she has been with the Department of Electrical & Computer Engineering at the University of Victoria, and she is currently a Professor. Her research interests span several areas in communications and networking, with a focus on network protocol and architecture design supporting emerging multimedia traffic over wireless, mobile, ad hoc, and sensor networks. She has been a recipient of the NSERC Discovery Accelerator Supplement Grants in 2010 and 2015, respectively, and the best paper awards of IEEE ICC 2008 and IEEE WCNC 2011. She has served as a TPC symposium co-chair for IEEE Globecom'10 and Globecom'13, an Associate Editor for IEEE Transactions on Wireless Communications, IEEE Transactions on Vehicular Technology, EURASIP Journal on Wireless Communications and Networking, International Journal of Sensor Networks, and Journal of Communications and Networks (JCN), and a Distinguished Lecturer (DL) of IEEE VTS society.



Jianping Pan (S'96-M'98-SM'08) received the bachelors and PhD degrees in computer science from Southeast University, Nanjing, China, and he did his postdoctoral research at the University of Waterloo, Waterloo, Canada. He is currently a professor of computer science at the University of Victoria, Victoria, Canada. He also worked at the Fujitsu Labs and NTT Labs. His area of specialization is computer networks and distributed systems, and his current research interests include protocols for advanced networking, performance analysis of networked systems, and applied network security. He has been serving on the technical program committees of major computer communications and networking conferences including IEEE INFOCOM, ICC, Globecom, WCNC, and CCNC. He is the Ad Hoc and sensor networking symposium co-chair of IEEE Globecom 2012 and an associate editor of the IEEE Transactions on Vehicular Technology. He is a senior member of the ACM and IEEE.