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Efficient Deployment Design of Wireless Charging Electric Tram System with Battery Management Policy

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Abstract: As an alternative to the environmental pollution problem of transportation means, the application of electric tram is considered in urban areas. However, due to the aesthetic problems occurs by the electric supply line for an electric tram, the wireless charging electric tram may be regarded as an alternative. It can be supplied electricity wirelessly from the wireless charging infrastructure installed on the railways even while moving. For a successful application, it is important to install and operate the overall systems with minimum investment cost. In this study, a mathematical model-based optimization technique, one of the methods of operations research, is adopted to derive the decision-making elements such as capacity and management of battery and allocation of the wireless charging infrastructure. Numerical example shows the optimal capacity and management of battery for a wireless charging electric tram and the ideal installation locations of the wireless charging infrastructures.

Keywords: mathematical model; wireless charging; battery capacity; battery management; wireless charging infrastructure; regenerative braking

1. Introduction

In order to prevent environmental pollution, electric transportation is considered as an alternative to the existing internal combustion engine transportation. There are various types of electric transportation such as electric cars, electric trains, electric motorcycles, electric bicycles, and so on. Above all, electric trams are considered as eco-friendly transportation in urban areas [1]. Electric trams have the advantage of emitting less environmentally harmful compounds while using electricity as an energy source, but there are also some disadvantages too. First, the electric supply line on electric trams is not aesthetically good, and high-height vehicles at an intersection can threaten safety. In addition, the maintenance cost of the electric supply line is relatively expensive, and the tunnel excavation for the electric supply line area requires an additional cost. Moreover, due to the electric supply line, it is impossible to apply various types of trams such as double deck trains, or duplex type trains for both passenger and cargo. To overcome these disadvantages, a wireless charging electric tram has been proposed as an eco-friendly transportation system in urban areas [2].

Unlike conventional electric trams, a wireless charging electric tram can be powered remotely from wireless charging infrastructure on the railway and can store the remaining electricity in the battery. In addition, if a wireless charging electric tram is located on a railway with a wireless charging infrastructure, electricity can be supplied either during a stop or in operation. This makes it possible to design an entire system with a smaller battery than a pure battery-powered electric tram [3]. That is, if the wireless charging technology is applied to the electric tram, the wireless charging infrastructure is installed in the railway to overcome the disadvantage caused by the electric supply line of the existing

electric tram. In addition, it can be operated with a smaller battery than a pure battery-powered electric tram, so that the entire system can be installed with a relatively low cost.

The conceptual structure of the wireless charging electric tram is shown in Figure 1. The wireless charging infrastructure consists of a wireless pick-up device and a power transmitter. The power transmitter is installed between the railway lines and supplies electric power to the wireless pick-up device wirelessly through electromagnetic induction. The supplied electricity is used to operate the wireless charging electric tram, and the remaining electricity is stored in the battery.

Figure 1. Conceptual structure of wireless charging electric tram.

There is a trade-off relationship between the battery capacity of the wireless charging electric tram and the installation length of the wireless charging infrastructure. If the battery capacity is large enough, the wireless charging electric tram will be like a pure battery-powered electric tram. In this case, it is not necessary to install a wireless charging infrastructure at all. On the other hand, if the battery capacity of the electric tram is zero, a wireless charging infrastructure must be installed on all railways. This is the same situation as conventional electric trams with electric supply lines. Therefore, in order to operate a wireless charging electric tram system with minimum investment cost, it is necessary to derive optimal battery capacity and installation length of wireless charging infrastructure.

In this study, operations research, a scientific decision-making technique, is applied to determine the optimal capacity and management of a battery for a wireless charging electric tram and the location and length of a wireless charging infrastructure. Among the various techniques of operations research, a mathematical model-based optimization technique is used to derive the decision variables by modeling the goal as the objective function and the various conditions of the problem situation as the constraint equations.

This paper is organized as follows. In Section 2, related previous studies are announced as the literature review. The description of proposed problem and overall procedure are explained in Section 3. The development of a mathematical model and the numerical examples are presented in Sections 4 and 5, respectively. Finally, findings and insights from this research are provided during concluding remarks in Section 6.

2. Literature Review

This study deals with the efficient system design of a wireless charging electric tram using wireless power transmission technology to replace existing electric trams with electric supply lines. The first theoretical foundation of wireless power transmission technology was from Maxwell's equation by Maxwell in 1862. Shinohara [4] introduced the technology development and research progress since Maxwell's equation in his research. In recent research by Lu et al. [5], it was mentioned

that wireless power transmission technology can be categorized as non-radiative coupling-based charging and radiative RF (radio frequency)-based charging. In addition, non-radiative coupling-based charging consists of three techniques such as inductive coupling [6], magnetic coupling [7] and capacitive coupling [8], while radiative RF-based charging [9] is divided between a directive RF power beamforming technique and a nondirective RF power transfer technique. Since this study is not a technical aspect research, a reference related to wireless power transmission technology is addressed at this part.

The wireless power transmission technology was first applied in the field of electric vehicles rather than other means of transportation. As the world gets more interested in finding a method that can reduce CO₂, people's effort to develop the eco-friendly technology is getting bigger too. Between various eco-friendly resources, electric vehicles with wireless power transmission attract attention [10]. Therefore, there are researches to improve the power receiver technology [11], plans to set wireless charging infrastructure [12], or locate wireless charging lanes for vehicles that can maximize recharged electricity while maintaining small road congestion [13]. However, in order to apply wireless power transmission technology to transportation, it is necessary to transmit a large amount of electric power with high efficiency through a relatively large air-gap. Huh et al. presented a new inductive power transfer system (IPTS) for electric cars with a large air-gap and narrow rail width. They tested the efficiency of their proposed power transfer technology from 10 cm to 20 cm of air-gap and announced that maximum efficiency is 74% at 27 kW output [14]. Wang et al. described the theoretical and practical design issues associated with inductive power transfer systems, and verified the developed theory using a practical electric vehicle battery charger. They proposed a new approach to the design of the main resonant circuit, and the proposed method minimized the deviation of the design expectation due to phase or frequency shift [15]. Huang et al. proposed a hands-free inductive power transmission system for charging batteries in electric vehicles. They explained how to design a power regulator that can guarantee a high efficiency and continuous power flow even though the distance between the bottom of the vehicle and the charge pad may vary depending on the vehicle type [16]. The studies of wireless power transmission technology applied to electric trams are as follows. Fujii and Mizuma [17] analytically studied the characteristics of new electromagnetic devices with propulsion and non-contact power collection capabilities for future wireless trams. The devices they designed operate as linear motors or linear transformers, using finite element method (FEM) and special integral equations method (IEM) for analysis. Lee et al. [18] proposed wireless power transfer (WPT) as a way to effectively solve the energy supply problem of electric railway (ER). To develop such systems, design optimization has been described as a solution that optimizes objective functions (e.g., system mass, transfer efficiency and air-gap) while satisfying constraints such as electromagnetic field (EMF), magnetic saturation and induction. In this paper, an optimization framework for railway WPT system was developed by connecting optimization module and electromagnetic commercial software. In addition, because estimating the SOC (state of charge) of a battery is one of the important techniques in wireless charging electric trams, Miyamoto et al. [19,20] performed investigations about that subject.

The above studies are related to the wireless power transmission technology applied to transportation. For the common use of such advanced technologies in society, it is necessary to study their management aspects, such as construction of systems with minimum investment cost as well as research on technology. However, research on the management aspect of wireless charging transportation has been rarely performed. Though dealing with general electric vehicles, Li [21] reviewed the worldwide development of battery-electric buses from medium-sized vehicles (e.g., 6.7 m) to large vehicles (e.g., 11 m) and described the charging method from low-speed charging mode (e.g., 6 h) to fast charging mode (e.g., 10 min). In addition, he reviewed the worldwide operations of battery-electric buses from real operation cases such as the early 1980s in Denver, Colorado and the early 1990s in Santa Barbara, California, and from less than 20 vehicles in a transit agency to more than 1000 vehicles. Giménez-Gaydou et al. [22] conducted a study on a method for determining the location of charging station for a battery electric vehicle (BEV) in an urban area. This approach addressed not

only an innovative type of location-allocation model, but also BEV charging needs, charging coverage and adoption potential. Ko and Jang [3] dealt with the optimal system design of wireless charging electric vehicle. They developed a mathematical model to derive optimal battery capacity and the length and location of power transmitter for On-Line Electric Vehicle, which is developed by Korea Advanced Institute of Science and Technology (KAIST). In addition, Ko et al. [23] presented different way to generate an optimal design of wireless charging electric vehicle with non-linear cost function. They proposed a mathematical model with the concept of segments for all operation routes and adopt genetic algorithm to calculate the efficient solution. Though the above two studies dealt with the decision of battery capacity and deployment of wireless charging infrastructure, they did not consider regenerative braking nor discuss battery management. There is no research on management aspects of wireless charging electric trams within our knowledge.

3. Problem Description

3.1. Problem Statement

In this study, the optimal system design of wireless charging electric tram is developed to determine the capacity and management of battery capacity and to allocate the wireless charging infrastructure. As shown in Figure 2, it is assumed that a railway is divided as segment level with certain length, l , and each station is located at specific point. Then, if the i th segment is decided to allocate the wireless charging infrastructure, then l length of it can be assigned in the i th segment. The wireless charging electric tram can be supplied the electricity wirelessly when it is operating on that segment. Therefore, the allocation position of wireless charging infrastructure should be decided through a mathematical model.

Figure 2. The concept of railway for allocation of wireless charging infrastructure.

In this example, wireless charging infrastructure consists of both inverter and inductive cable. The inverter receives the electricity and sends it to the inductive cable while the inductive cable receives the electricity and sends the electricity to the wireless pick-up device under the wireless charging electric tram using electromagnetic induction. At this time, a series of inductive cables can be powered by one inverter. However, if the inductive cable is not connected, each inductive cable requires a different inverter.

As mentioned earlier, battery capacity and wireless charging infrastructure have a trade-off relationship. Battery capacity which is installed on a wireless charging electric tram should be derived considering the allocation decision of wireless charging infrastructure. In addition, even if the maximum capacity of the battery is determined, the actual available battery capacity is limited as shown in Figure 3, considering the life of the battery. Therefore, suppose that the maximum capacity of battery is decided as I_{capa} , then the actual battery utilization area is between I_{min} and I_{max} [20,24]. As a result, the maximum battery capacity should be determined considering all those situations.

This study deals with not only battery capacity but also battery management. The battery management policy also affects a significant impact on the entire system [21,25]. In addition, unlike previous studies, regenerative braking is considered when calculating the variations in battery charging level. That is, regardless of the wireless charging infrastructure, the battery charging level can increase by regenerative braking. However, the battery charging level can only be changed between I_{min} and I_{max} , and even if the electric power is supplied by the regenerative braking and the wireless charging, the battery charging level cannot exceed I_{max} . In this case, the supplied electricity cannot be

charged, and it is lost. Therefore, when the wireless charging electric tram starts to operate in the first station, it is best to determine the target battery charging level, I_{target} , as the optimal value between I_{min} and I_{max} . Then, it can prevent the loss of the electricity supplied by regenerative braking and wireless charging.

Figure 3. The concept of actual battery utilization area and target charging level.

3.2. Overall Procedure

The overall procedure to derive an optimal system design of wireless charging electric tram is shown in Figure 4.

Figure 4. Overall procedure for an optimal system design of wireless charging electric tram.

3.2.1. Data Collection

First, it is necessary to collect the physical data of the wireless charging electric tram, such as the weight of the tram, the acceleration and deceleration tendency, the air resistance and so on. In addition, it is also necessary to get data on the length, gradient and inter-station distance of the route on which the wireless charging electric tram will be operated. Although it is not covered in this study, the number of passengers can be considered as additional data to be collected in the future.

3.2.2. Battery Consumption Calculation

Based on the collected data, the values for the power consumed in each segment, the power supplied through the regenerative braking in each segment and the power charged when the wireless charging infrastructure is installed in each segment should be calculated by considering the circumstance of wireless charging electric tram in operation. For more detailed calculations, please refer to Jong and Chang's work [22,26].

3.2.3. Optimal System Design

The optimal system design of the wireless charging electric tram is derived from the mathematical model-based optimization method which is one of the techniques of operations research. Then, the values of decision variables such as maximum capacity, target charging level of battery and allocation of wireless charging infrastructure can be obtained. This is covered in detail in Section 4.

3.2.4. Real Application

Finally, it is enough to operate the wireless charging electric tram system with the value of the derived decision variable. The existing decision variables can be corrected and supplemented in consideration of issues occurring during operation.

4. Mathematical Model

4.1. Notation

To develop a mathematical model, the following variables are defined.

Index

i : Set of segments; overall route is divided by I number of segments ($i = 1, 2, 3 \dots, I$)

Decision variables

I_{capa} : Maximum capacity of battery installed in wireless charging electric tram [kWh]

I_{target} : Target battery charging level before operation at first station [kWh]

$k_{inverter}(i)$: 0–1 binary decision variable; if the inverter is allocated in i th segment, then value of 1, otherwise, value of 0

$k_{cable}(i)$: 0–1 binary decision variable; if the inductive cable is allocated in i th segment, then value of 1, otherwise, value of 0

Variables

$n_{inverter}$: Total number of inverters applied in overall system [unit]

n_{cable} : Total length of inductive cable applied in overall system [meter]

I_{max} : Upper limit of battery utilization area regarding maximum battery capacity [kWh]

I_{min} : Lower limit of battery utilization area regarding maximum battery capacity [kWh]

$I(0)$: Initial battery charging level before operation at first station [kWh]

$I(i)$: Battery charging level after passing i th segment [kWh]

Input parameters

n_{tram} : Total number of wireless charging electric trams in overall system [unit]

$c_{battery}$: Battery cost per unit kWh [\$/kWh]

$c_{inverter}$: Unit inverter cost [\$/unit]

c_{cable} : Inductive cable cost per unit length [\$/meter]

α_{max} : Ratio of upper limit of battery utilization area regarding maximum battery capacity

α_{min} : Ratio of lower limit of battery utilization area regarding maximum battery capacity

$k_{cable}(0)$: Initial value for allocation of inductive cable, which is set as 0

$s(i)$: Electricity supply by wireless charging in i th segment [kWh]

$r(i)$: Electricity supply by regenerative braking in i th segment [kWh]

$l(i)$: Length of i th segment [meter]

4.2. Model Formulation

Minimize

$$n_{tram} \cdot c_{battery} \cdot I_{capa} + n_{inverter} \cdot c_{inverter} + n_{cable} \cdot c_{cable}, \quad (1)$$

subject to

$$I_{max} = \alpha_{max} \cdot I_{capa}, \quad (2)$$

$$I_{min} = \alpha_{min} \cdot I_{capa}, \quad (3)$$

$$I_{min} \leq I_{target} \leq I_{max}, \quad (4)$$

$$I_{target} = I(0), \quad (5)$$

$$I(i-1) - d(i) + s(i) \cdot k_{cable}(i) + r(i) \geq I(i), \quad i = 1, \dots, I, \quad (6)$$

$$I_{min} \leq I(i) \leq I_{max}, \quad i = 1, \dots, I, \quad (7)$$

$$k_{cable}(i) - k_{cable}(i-1) \leq k_{inverter}(i), \quad i = 1, \dots, I, \quad (8)$$

$$k_{cable}(0) = 0, \quad (9)$$

$$n_{cable} = \sum_{i=1}^I l(i) \cdot k_{cable}(i), \quad (10)$$

$$n_{inverter} = \sum_{i=1}^I k_{inverter}(i), \quad (11)$$

$$k_{inverter}(i), k_{cable}(i) \in \{0, 1\}, \quad (12)$$

$$I_{capa}, I_{target} \text{ are positive real numbers}, \quad (13)$$

The purpose of this problem is development of an optimal system design for wireless charging electric vehicle with minimum investment cost. Therefore, the objective function of the proposed mathematical model, Equation (1), is sum of the costs such as battery capacity, number of inverters and length of inductive cable. Equations (2) and (3) are about battery utilization area regarding the maximum battery capacity. Equation (4) is for the target battery charging level at initial operation and should be set between its actual battery utilization area while Equation (5) means that initial battery charging level is has the same value with target battery charging level. Equations (6) and (7) are for the battery charging level variation during the operation of wireless charging electric tram. Battery charging level in passing by i th segment is affected by battery consumption, wireless charging and regenerative braking in i th segment. Equations (8) and (9) are developed to describe the location of each inverter which should be applied in this system by considering the number of separate inductive cables. Equation (10) is about the calculation of length of installed inductive cables while Equation (11) is for counting the number of applied inverters. The remaining Equations (12) and (13) address the decision variables.

5. Numerical Example

5.1. System Parameters

In Korea, because the Pangyo area in Gyeonggi province recently has attracted many IT companies and start-ups, traffic demand is tending to increase in the urban area. In order to meet the traffic demands, one considered alternative is to operate electric trams in Pangyo area. This study tried to design a wireless rechargeable electric tram system with minimum investment cost, assuming that a wireless rechargeable electric tram is installed and operated in this area as shown in Figure 5.

Figure 5. Pangyo area considered to install the wireless charging electric tram system.

The system parameters related to the wireless charging electric tram and wireless charging infrastructure assumed in this numerical example are shown in Table 1.

Table 1. System parameters.

Notation	Meaning	Value
N_{tram}	Number of wireless charging electric tram [unit]	5
$c_{battery}$	Battery cost per unit kWh [\$/kWh]	\$50,000
$c_{inverter}$	Unit inverter cost [\$/unit]	\$5000
c_{cable}	Inductive cable cost per unit length [\$/meter]	\$200
α_{max}	Ratio of upper limit of battery utilization area	0.8
α_{min}	Ratio of lower limit of battery utilization area	0.2
$l(i)$	Length of i th segment [meter]	20

Due to the limitations of the paper, data on the amount of electricity consumption, the amount of regenerative braking in each segment and the amount of wireless charging electricity when there is a wireless charging facility are not mentioned. However, it should be noted that the acceleration, deceleration and maximum speed are set as 1 m/s^2 , -1 m/s^2 and 20 m/s , respectively.

5.2. Computational Result

To perform the computational experiment with the proposed mathematical model and given system parameters, Cplex, a well-known optimal solution generation software, was applied. It is guaranteed to derive optimal solution for mathematical models with a linear programming type, used both in industry and in academia [19,23]. The mathematical model consisted of objective function and constraint equations. On the way to derive the value of the objective function, various constraints reflect the actual circumstance of the problem. Moreover, the devised mathematical model is called out as a mixed integer programming model. Since the model consisted of linear equations, the optimal value can be derived. Therefore, with the adequate mathematical model and proper parameters, the program can derive optimal result through a single execution.

The numerical result was derived as shown in Table 2. The optimal battery capacity was set as 3.2389 kWh while the overall electricity consumption at one round trip of total route described in Figure 5 considering the provided electricity by regenerative braking is 12.5041 kWh. Supposing that a decision maker introduces a pure battery-powered electric tram system instead of a wireless charging electric tram, it is also necessary to calculate the required battery capacity. It can be calculated assuming no wireless charging infrastructure can be installed on all railways; the required battery capacity is then 21.9392 kWh. In other words, the required battery capacity can be reduced to 14.76% by introducing a wireless charging electric tram. Of course, the additional cost of wireless charging infrastructure is required, but the utility of the wireless charging electric tram system can be confirmed considering the fact that the battery itself is an important environmental pollutant.

In addition, target battery charging level before operation at first station was calculated as 1.7997 kWh when the upper limit of battery utilization area is 2.5911 kWh. In the previous study, it was assumed that the amount of battery charging level at the starting point is always regarded as maximum level. However, in this study, the initial battery charging level was reduced to 69.46% of maximum level by applying battery management. Therefore, more than 30% of the potential electricity is saved over the entire battery capacity in case of intuitive full charge.

Moreover, there were eight separate wireless charging infrastructures on overall railways. That is, the total number of inverters was eight while the total length of inductive cables is 1380 m. The inductive cable was allocated between 0 m and 420 m, between 580 m and 680 m, between 960 m and 1040 m, between 1340 m and 1400 m, between 1640 m and 1720 m, between 1960 m and 2040 m, between 2320 m and 2400 m, and between 2680 m and 3160 m as well. All of the wireless charging infrastructures were allocated near the stations; the relative location of each station was 20 m, 640 m, 1020 m, 1380 m,

1700 m, 2020 m, 2380 m, 2760 m, and 3380 m. This is because the speed of a wireless charging electric tram is relatively low near the station, so it can receive more electricity through wireless charging.

Table 2. The result of numerical example.

Content	Value
Total investment cost	\$1,125,725
The optimal battery capacity	3.2389 kWh
Target battery charging level before operation at first station	1.7997 kWh
Total number of inverters	8 units
Total length of inductive cable	1380 m
Location of 1st inductive cable	0 m–420 m
Location of 2nd inductive cable	580 m–680 m
Location of 3rd inductive cable	960 m–1040 m
Location of 4th inductive cable	1340 m–1400 m
Location of 5th inductive cable	1640 m–1720 m
Location of 6th inductive cable	1960 m–2040 m
Location of 7th inductive cable	2320 m–2400 m
Location of 8th inductive cable	2680 m–3160 m

The variation of battery charging level is depicted in Figure 6. Since the maximum battery capacity was 3.2389 kWh, the upper and the lower limitations of battery utilization area were 2.5911 kWh and 0.6477 kWh, respectively. It can be confirmed that the battery charging level varied within that range. For all of the above situations, the total investment cost of the numerical example was derived to \$1,125,725.

Figure 6. Battery charging level variation.

6. Concluding Remarks

There are many attempts to introduce and operate electric trams in certain areas as an alternative means of transportation considering environmental pollution. In this study, the efficient deployment design of the wireless charging electric tram system which can maximize the environmental advantage of the electric tram has been particularly studied. The wireless charging electric tram is an innovative, new-style electric tram which can be supplied electricity wirelessly from the wireless charging infrastructure installed on railways even though it is moving. Therefore, the wireless charging electric tram, which can overcome various disadvantages caused by the electric supply line of a conventional electric tram and reduce the high battery cost of a pure battery-powered type electric tram, has received attention as a new transportation means in an urban area.

Though wireless charging electric trams have many advantages, efficient design of the entire system to minimize the total investment cost is required for successful application. For that, the optimal decision about the maximum battery capacity and the allocation of wireless charging infrastructure

to minimize the investment cost was investigated. In addition, regenerative braking was considered to reflect the accurate electrical flow in the system, and battery management about the initial battery charging level was also investigated for additional electric efficiency. A mathematical model-based optimization technique was adopted to treat those decision-making elements, and Cplex was applied to derive an optimal solution for those decision-making elements.

Through the numerical example, the total investment cost was calculated with the information of decision-making elements such as maximum battery capacity, initial battery charging level, number of inverters and location of inductive cables. By applying the wireless charging electric tram in the Pangyo area described in Figure 5, it can be confirmed that maximum battery capacity was reduced by 14.76% compared to the pure battery-powered electric tram, and initial battery charging level was also decreased by 69.46% with battery management.

For transportation to be operated well, the infrastructure should come first. Especially when it comes to the new technology, a deliberate decision should be made. As can be seen in the results of this research, the battery capacity can be different due to the location of inductive cable and inverters. Since the battery cost is expensive, this research can provide a stable and cost-efficient way to set the infrastructure for an electric tram. However, there can exist various other transportation that consider adopting the wireless charging system. In those cases, more constraints that can reflect certain transportation environments should be devised.

As a further study, various transportation environments and operation policies will be considered. Since there are lots of transportations with different policies, the needed infrastructure for wireless charging electric trams can also be different. For example, there exists public transportation with both normal operation that passes every station, and express operation that bypasses certain designated stations. In this case, diverse constraints should be made. By reflecting the different operation policy of transportation, the practicality of the following research to be done might increase.

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