Optimal Location Model of In-motion Wireless Power Transfer System for Trips in Urban-scale Region by Electric Vehicles

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ABSTRACT: The popularization of electric vehicles (EVs) is limited by their driving range and long charging times. To address this, in-motion wireless power transfer systems (WPTSs) are currently attracting attention as a new power supply system. This study aims to propose a new mixed integer programming (MIP) model to determine the optimal locations of WPTSs in urban-scale area. Specifically, we calculate the amount and locations of WPTS necessary and sufficient to achieve substantially zero consumption of energy in urban areas. We also present an numerical example by real data of a typical medium-sized city in Japan.

KEY WORDS: electric vehicle, in-motion wireless power transfer, mixed integer programing, optimal location, urban-scale region

1. INTRODUCTION

In recent years, the use of electric vehicles (EVs) is expected to become widespread[(1)]. To popularize the use of EVs, their convenience needs to be improved, specifically by developing appropriate charging infrastructures. In-motion wireless power transfer systems (WPTSs) have garnered attention as a new power supply system that can solve the problems of EVs[(2)]. Under in-motion WPTSs, EVs receive power while being driven through coils embedded under the road. This allows EVs to charge their batteries without waiting at a charging station, thereby achieving an unlimited driving range.

Though there are limited optimal location models for in-motion WPTS, compared to those for EV charging stations, the number of WPTS researches focusing on locational analysis and economic rationalities is steadily increasing over the last decade. Jang[(3)] provided a comprehensive review of WPTSs related to infrastructure planning, costs, and benefit analysis. WTPS location studies using real-world networks also exist at both the metropolitan and interstate scale. From the metropolitan-scale perspective, Mubarak[(4)] focuses on the Chicago area network and derives the complete flow coverage solution. Yan[(5)] used a mobility dataset collected in Shenzhen, China, and applied kernel density estimation to converge their data. One of the theoretical mainstreams of location models for WPTS is analysis of equilibrium flows considering traffic congestions. In their models, multiple routes are considered, and system optimizations are discussed. For example, Rieman et al.[(6)] formulated a flow-capturing location model with stochastic user equilibrium. Chen et al. [(7)] developed a user equilibrium model considering the relationship between speed, charge amount, and travel time. Manshadi et al. [(8)] considered the interdependence between the electricity network and the transportation network while Liu et al. [(9)] incorporated electricity prices.

This study aims to propose a new mixed integer programming (MIP) model to determine the optimal locations of WPTSs in urban-scale area. Specifically, we calculate the amount and locations of WPTS necessary and sufficient to achieve substantially zero consumption of energy in urban areas. While considering equilibrium flows as in the previous study, acceleration/deceleration patterns were also carefully introduced. We also present an numerical example by real data of a typical medium-sized city in Japan. The energy consumption of the EVs was carefully prepared based on previous studies.

2. METHODS

2.1. Frameworks

In this section, we assume an in-motion WPTS to be an energy-supply infrastructure for EVs and propose a new MIP model to optimize WPTS locations in urban area. First, we summarized the situation where EVs are moving in a region. In this study, each EV is assumed to travel along various routes, with no particular shortest path, but its routes is assumed to be exogenously determined. That is, the EV shall not change its route to pass where the WPTS is located. Meanwhile, acceleration/deceleration and speed changes due to traffic signals and traffic conditions are explicitly considered. In particular, the road network is divided into small segments, and the various behavior sof the EVs on each segment are represented as “motion”. The motion is given by a probability distribution.

All notations for the model is defined below.

Indices:

q Index of flow demands

i Index of link segments

m Index of motions

Sets:

Q Set of flow demands

I Set of link segments in the entire network

M Set of motions

Parameters:

f_q Flow volume of flow demand q

d_i Length of the segment i [m]

c_i^m Required electric power to pass through segment i by the motion m [kWh]

r_i^m Electric power transfer from WPTS at segment i by the motion m [kWh]

$p(m)_i^q$ Probability of the motion m for the demand q at the segment i

R_q Expected power consumptions for the demand q

Decision Variables:

x_i 1 if the WPTS is installed on i, 0 otherwise

2.2. Optimal Location Problem for In-motion WPTS

We formulated a flow-capturing location problem for in-motion WPTSs. A flow demand is captured when an EV with a certain battery capacity can reach its destination using its battery capacity and energy transferred via WPTS.

$$\text{Min.} \quad \sum_{i\in I} d_i x_i \tag{1}$$

subject to:

$$R_q = \sum_{i\in I} \sum_{m\in M} p(m)_i^q \times (c_i^m - r_i^m x_i) \qquad \forall q \in Q \tag{2}$$

$$\sum_{q\in Q} f_q R_q \leq 0 \tag{3}$$

$$x_i \in \{0,1\} \qquad \forall i \in I \tag{4}$$

3. NUMERICAL EXAMPLES

3.1. Networks and Flow Volumes

Using the methods presented in Section 2, we applied our model to Japanese typical middle-sized city. First, as for the network data. we extracted detailed road information from OpenStreetMap. Then, based on the actual building data and road network data, its travel demand and routes were estimated, and motion data was created. The flow demand data is shown in Fig. 1.

Fig. 1 Flow demand data

3.2. Parameter settings

We summarize the parameter settings for the energy consumption. In this study, we used Equation (5) to calculate the motor power [kW], based on the studies by Tanaka et al. (2008), Wu et al. (2015), and Fiori et al. (2016).

$$P(v,a,\theta) = \frac{1}{\eta} v \left(ma + mg\cos\theta\, f_{rl} + \frac{1}{2}\rho A_f C_D v^2 + mg\sin\theta \right) \tag{5}$$

Equation (5) expresses the motor power P when the EV has a velocity v [m/s], acceleration a [m/s2], and road gradient θ [°]. The parameters used in this study, based on Tanaka et al. (10), Wu et al. (11), Fiori et al. (12), and The Engineering ToolBox (13), are summarized in Table 1. In these parameters, we assumed a Nissan Leaf as the EV.

Next, we assumed the transfer power of the WPTS. Although there is no global standard amount of power to be transferred by an in-motion WPTS, existing studies assumed a power output of 20–25 kW (2). In addition, when a vehicle is stationary, a wireless power transfer, such as that of WPT4, has been proposed (14). In this study, the transfer capacity was set to 22 kW with a transfer efficiency of 85%, resulting in a power output of 18.7 kW.

Table 1 Parameters for calculating the motor power

Parameters	**Values**
Efficiency of the electric motor η [%]	90
Vehicle weight (including the driver) m [kg]	1640
Gravitational acceleration g [m/s^2]	9.8066
Rolling resistance coefficient f_{rl}	0.015
Air mass density ρ [kg/m^3]	1.2256
Frontal area of the vehicle A_f [m^2]	2.34
Aerodynamic drag coefficient C_D	0.32

3.3. Optimal locations

Fig. 2 shows the optimal WPTS locations that achieved the zero power consumptions in the entire region. Note that the flow demand here is based on the direction, and Japan is a left-hand drive traffic area. As can be seen, it is mathematically optimal to be located at the intersection. Specifically, the result is that the WPTS should be placed at major intersections, approximately 30 [m].

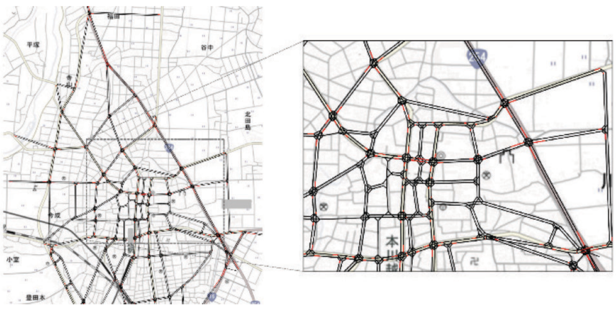

Fig. 2 Result of the optimal WPTS locations

4. CONCLUSIONS

In this study, we proposed a new mixed integer programming (MIP) model to determine the optimal locations of WPTSs in urban-scale area. Specifically, we calculated the amount and locations of WPTS necessary and sufficient to achieve substantially zero consumption of energy in urban areas. We also presented an numerical example by real data of a typical medium-sized city in Japan.

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