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# Trade-offs between WPT Infrastructure Investment and EV Investment towards Infinite Driving

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**ABSTRACT**: In-motion Wireless Power Transfer Systems (WPTS) are increasingly seen as critical infrastructure to support electric vehicle (EV) mobility, especially in achieving the concept of "Infinite Driving." This study examines the trade-offs between WPTS infrastructure investment and EV battery capacity requirements by analyzing optimal WPTS locations in urban areas. By simulating EV charging and discharging patterns with considerations for acceleration, deceleration, and traffic signals, this research assesses the required battery capacity for urban EV travel. Findings highlight that strategically located WPTS can significantly reduce battery capacity requirements, demonstrating the potential of WPTS to complement EV investments and support sustainable urban mobility.

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

## 1. INTRODUCTION

In recent years, expectations for low-carbon alternative fuel vehicles, particularly electric vehicles (EVs), have risen rapidly. For the widespread adoption of these alternative vehicles, infrastructure development is essential to improve their convenience; in the case of EVs, this requires an extensive and efficient charging infrastructure network. [(1)] However, EVs face inherent challenges, such as limited driving range due to battery capacity constraints and long charging times. As a new power supply solution to address these issues, in-motion Wireless Power Transfer Systems (WPTS) have gained attention. [(2)] WPTS can charge EVs on the move by transferring power through coils embedded under the road, allowing EVs to recharge without waiting at charging stations and enabling continuous driving.

In addition to extending EV range, WPTS also has the advantage of potentially reducing the required battery capacity in vehicles, especially in urban areas. A promising scenario is the installation of WPTS near major intersections, where vehicles slow down, enabling more frequent charging opportunities and thus reducing the necessary onboard battery capacity.

The effectiveness of support infrastructure such as charging stations and WPTS greatly depends on their location. Optimal facility location, particularly in urban settings, is widely studied using discrete optimization methods, especially within geography and operations research fields. [(3)] Numerous studies have examined optimal location strategies for charging stations; [(4,5)] however, few have focused on WPTS, particularly on highways and in cities. Therefore, the authors have also conducted research examining the optimal location of WPTS for use on highways and in urban areas. [(6,7)]

In this study, we investigate how optimally located WPTS in urban environments could minimize the necessary battery capacity for EVs. First, we introduce an optimal location model based on discrete optimization, designed to meet urban EV travel demand while minimizing the total length of WPTS required. We then verify the feasibility of various battery capacities using a traffic simulation model conducted in Kawagoe City, Saitama Prefecture.

This research offers two primary innovations. First, it demonstrates that the feasibility of EV travel demand is highly dependent on WPTS location. Optimal location results in a significantly reduced total WPTS length compared to uniform intersection placement. Second, assuming optimal WPTS location, EVs may require only around 5 kWh of battery capacity—significantly lower than current standard capacities, demonstrating WPTS's potential to support "Infinite Driving" with reduced EV investment.

## 2. OPTIMAL LOCATION MODEL

### 2.1. Frameworks

In this section, we focus on everyday urban mobility and introduce a mathematical model for deriving the optimal location of WPTS to meet EV travel demand.

The urban mobility model in this section assumes that each EV follows various routes, with routes being determined exogenously; EVs do not intentionally alter their routes to pass through locations with WPTS. We explicitly consider EV acceleration and deceleration, as urban mobility frequently involves speed changes due to traffic signals and traffic conditions. To represent these factors in a mathematical model, we divide the road network into small segments of 7 meters each and express various EV behaviors as motions within each segment. The probability distribution for each EV motion is also exogenously determined and calculated separately.

The notations used in this urban mobility model are listed 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 $q$
- $\alpha$ Safety Coefficient

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:

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

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

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

## 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 Example of OD Flow in Kawagoe-city

### 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).

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

Equation (5) expresses the motor power $P$ when the EV has a velocity $v$ [m/s], acceleration $a$ [m/s2], and road gradient $\theta$ [°]. 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.

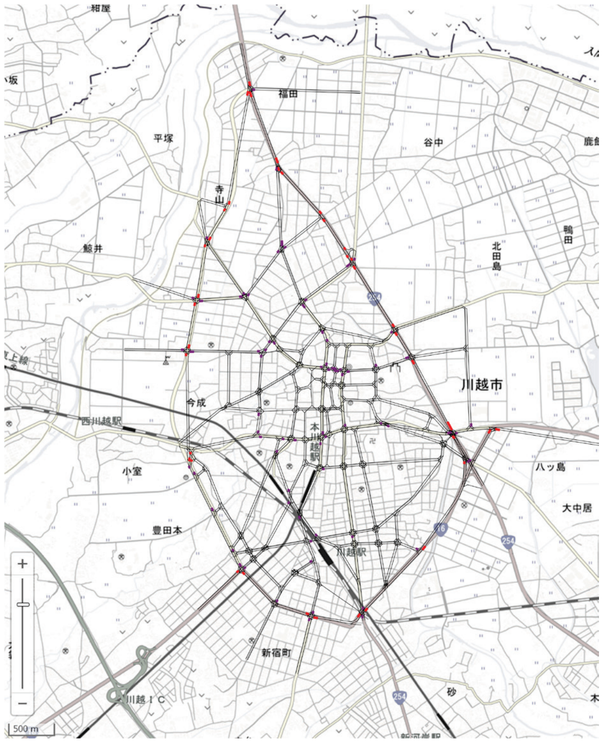
Next, we assumed the transfer power of the WPTS. Although there is no global standard amount of power to be transferred by an in-motion WPTS, existing studies assumed a power output of 20–25 kW [(2)]. In addition, when a vehicle is stationary, a wireless power transfer, such as that of WPT4, has been 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 Motor Power

| Parameters | Values |
|---|---|
| Efficiency of the electric motor $\eta$ [%] | 90 |
| Vehicle weight (with drivers), $m$ [kg] | 1640 |
| Gravitational acceleration $g$ [m/s$^2$] | 9.8066 |
| Rolling resistance coefficient $f_{rl}$ | 0.015 |
| Air mass density $\rho$ [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

Figure 2 shows the optimal location results for WPTS with a safety factor of 1.1. While it is intuitively clear that intersections are favorable locations, the analysis confirms that this is indeed the mathematically optimal strategy. The total road length in the target area is approximately 150 km, with 127 intersections; however, the total length of WPTS installation required is 2,359 meters, covering 56 intersections. The average WPTS installation length per location is 14.77 meters.




(a) Overall figure


(b) Enlarged figure

Fig. 2 WPTS Optimal Location

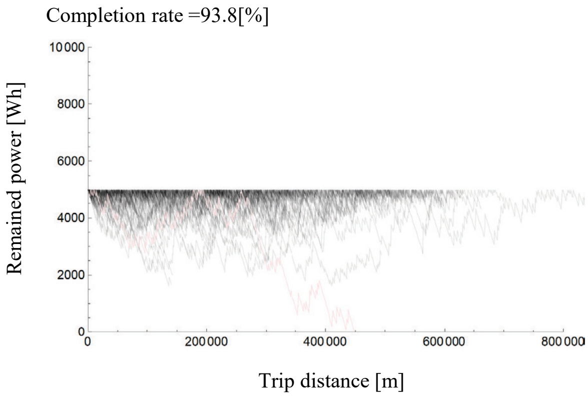
## 4. REQUIRED BATTERY CAPACITY

### 4.1. Assumptions

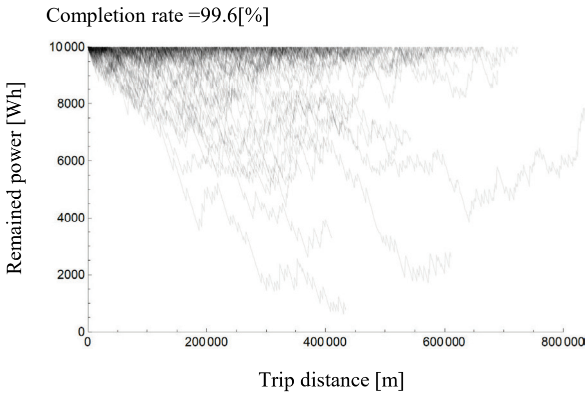
This study outlines the assumptions made regarding the required battery capacity. First, we focus on a specific departure point and consider round-trip travel to various destinations. Each trip is configured to randomly select not only the destination but also the time of travel. For each departure point, we conduct 100 round-trip simulations, and a total of 1,000 simulations are carried out by changing the departure point itself. This allows us to verify whether each trip can be completed without a single instance of battery depletion.

### 4.2. Simulation results

Figure 3 shows the results of the simulation based on the optimal location of WPTS, with battery capacities set at 5 kWh

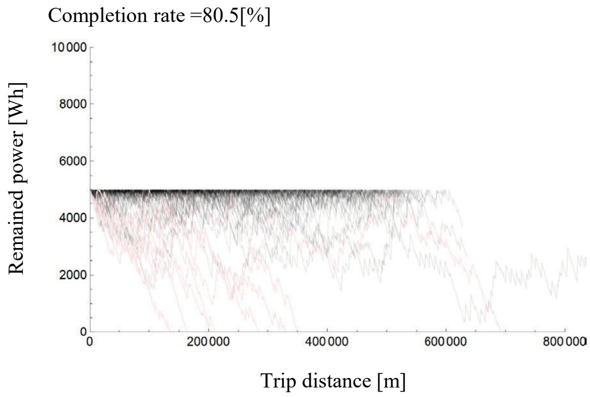



(a) Battery Capacity = 5[kWh]

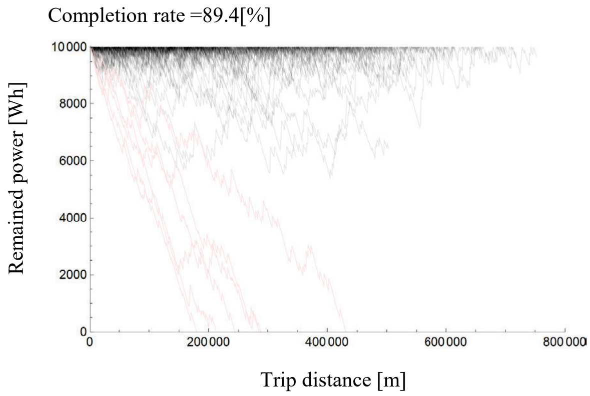



(b) Battery Capacity = 10[kWh]

Fig. 3 Simulation with optimal location




(a) Battery Capacity = 5[kWh]




(b) Battery Capacity = 10[kWh]

Fig. 4 Simulation with uniform location

and 10 kWh. For comparison, Figure 4 presents results from a similar simulation where each intersection was uniformly equipped with one slot (7 meters) of WPTS. Instances of battery depletion are indicated in red, and the completion rate is also calculated.

In terms of total WPTS installation length, the optimal configuration requires 2,359 meters, while the uniform configuration requires 3,584 meters, indicating that the optimal location strategy uses less infrastructure. Despite this, with a battery capacity of 10 kWh, the completion rate is 99.6% for the optimal configuration compared to only 89.4% for the uniform configuration. This demonstrates that the feasibility of meeting EV travel demand is highly dependent on the WPTS location, highlighting the effectiveness of the optimal configuration approach.

## 5. CONCLUSIONS

This study discusses the required battery capacity for urban mobility under the assumption of an optimally located WPTS. The findings reveal that even with a relatively small battery capacity, urban travel can be successfully completed, highlighting the promising potential of WPTS as a supportive EV infrastructure toward achieving "Infinite Driving."

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