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The Optimal Site Selection of Electric Vehicle Charging Facilities Using Location Theory Model

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Abstract

Ecosystems are changing due to the effects of global warming, and efforts are being made to reduce greenhouse gases globally in response. As a result, the demand for environmentally friendly electric vehicles (EVs) is increasing due to changes in domestic and external conditions, global environmental regulation, strengthening and reduction of energy costs. In addition, the market demand for electric cars and environmentally friendly cars is increasing along with the government's policy will. However, there are still many difficulties in meeting the market demand due to the high cost of building basic infrastructure such as the installation cost of battery charger. Therefore, this study calculates the optimum capacity to cover electric vehicle charging demand in the analysis area. The effect of T-cad was analyzed by applying the number of charging facilities to each model of Location Theory. The purpose of this paper is to select the optimal location based on the travel cost and travel time for the different infrastructures in each model.

Keywords: *battery charger, ecosystem, electric vehicles, location theory, t-cad*

1. Introduction

1.1. Overview

Ecological system has been changed due to global warming and there are strong efforts to reduce greenhouse gases worldwide. Korean government set the goal to reduce greenhouse gases emissions in Korea by 30% compared to Business as Usual (BAU) by 2020. For the purpose, the government introduced the Greenhouse Gases and Energy Goal Management System which has managed energy and green gases by setting each objective by part, since 2010. In specific, to minimize short-term burden in the industrial area, the green gas reduction will be performed focusing on non-industrial sectors such as building and transportation. Currently, it is demanded to promote vitalization of environment-friendly powerless and free carbon dioxide transportation means through legislation of "Framework Act on Low Carbon, Green Growth" and "Sustainable Transportation Logistics Development Act". Overseas countries have set the upper limit of CO2 emissions for the registered cars in EU since 2012, which was set to 130g/km on average and aims to be 95g/km in 2020. In case of breach of the upper limit, they plan to levy a penalty on the breaching automobile manufacturers.

Along with changes in domestic and international circumstances, worldwide trend to intensify environmental regulations and reduce energy costs, there are increasing demands for environment-friendly electric vehicles (EVs). To reduce greenhouse gases and promote low-carbon green growth, research projects are being promoted worldwide including, providing vitalization plan for next-generation green cars and developing instant charging technology for commercialization of EVs. According to Bloomberg reports, EVs are

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expected to take up 3% of the worldwide annual sales of automobile in 2020, and 11% in 2025, which will take up more than 10% for the first time in history.

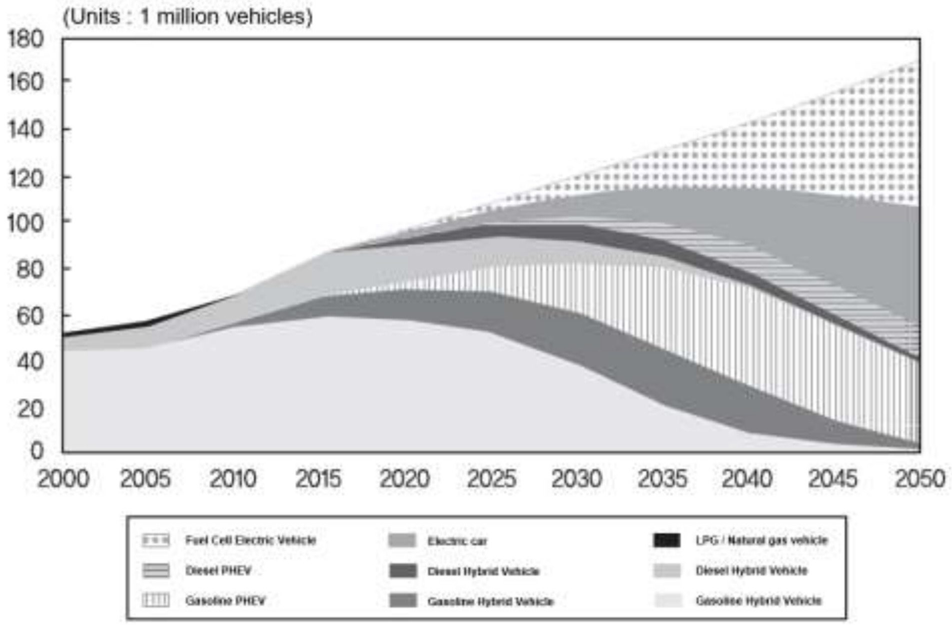

Figure 1. Market Demand by Environment-Friendly Car Power Source

In order to fulfill such increasing demands in the market, charging infrastructure for EVs should be built. They will eventually resolve the anxiety of EV users and secure the convenience for their use. However, due to high price of installation cost of the chargers and huge financial burden to install the charger in every gas station, it is important to select optimal location and capacity with minimal investment cost.

For the purpose, this study aims to calculate optimal capacity to cover demands for EV chargers in the analysis area. Applying the number of charging facilities to each model of Location Theory, it analyzed the effect by using Trans-CAD. As for the charging infrastructure located differently in each model, this study intends to select optimal location based on travel expenses and travel time.

1.2. Research Procedures and Methods

This study selected capacity of service facility to meet the EV-charging demand in the analysis area and optical locations based on travel time and cost.

First of all, in order to select proper number of charging stations suitable for the charging demands in Gangnam-gu area, it used a queueing model which is widely used in analyzing network traffic and call center problems. In order to determine the number of servers, it used Poisson distribution on arrival rate and service rate, and employed an M/M/s model that can calculate the necessary number of servers when the length of queues are not restricted with consistent service time.

Next, this study calculated the number of the optimal service facilities and connected them with selecting the locations. It reviewed previous Location Theories and application cases and investigated the methods to select the optimal candidate locations. Then it provided the criteria to review the candidates. Due to different objective functions and restrictions, the locations of the EV charging service were different case by case. This study decided the fitness of the model based on maximum travel time and average travel time calculated in each scenario.

2. Reviews of Previous Studies

2.1. Calculation of Optical Capacity for Charging Station

In order to determine optimal capacity of an EV charging station, queueing model was applied. To apply the model, following hypotheses were used.

Number of EVs to use the charging station is infinite.

① EV arrives in accordance with Poisson distribution and the average arrival rate is λ (number of EV/time)
② The average charging time is $1/\mu$ (hour) and it follows exponential distribution.
③ EVs are independent to each other.
④ EV chargers in each charging station have same capacity.

Optimal capacity of the charging station was analyzed through comparison of M/M/n/n type having no queues with M/M/n/K having limited (K-n) number of queues, based on Erlang Loss System. As for charging traffic imposed on the charging station, this study decided the required number of chargers that satisfied charging hindrance rate on the traffic, and then multiplied each charger capacity to that number in order to calculate the charging capacity of a charging station. Number of chargers equals to the number of EVs that a charging station can cover, and it means the scale (area) of the charging station. Therefore, M/M/n/n type can be applied to the model for the charging station having no area restriction while M/M/n/K type is proper for the charging station having area restriction of which number of EVs that it can cover is K.

2.2. Selection of Optimal Location for a Service Facility

2.2.1. Minisum Location Problem

Based on the optimization criteria of each model, Facility Location Problem Model can be classified into Minisum Location Problem, Minimax Location Problem, and Covering Location Problem which can be subdivided into Set Covering Location Problem and Maximum Covering Location Problem. Facility Location Problem Model can reflect EV demands in selecting a location and minimize the average travel time. However, it had short of constraint conditions on maximum travel time, which resulted in setting maximum travel time a little longer by the location selection. The number of required facilities should be decided in advance. The equation of the model for the P number of facilities is as follows.

Objective function : $\sum_{i=1}^{n} h_i(t_{ij}X_{ij})$ (1)
Constraints : $\sum_{j=1}^{n} X_{jj} = P$ (2)
Min: $\sum_{j=1}^{n} X_{ij} = 1(X_{ij} \le X_{jj}, X_{ij} = 0\ or\ 1)$ (3)

h_j *: Demands in Point i*
t_{ii} *: Distance between Point i and Point j(or travel time)*
$X_{jj} = 1$ *: In case Facility j provides service to Point i*
$X_{jj} = 0$: In case Facility j does not provide service to Point i

2.2.2. Minimax Location Problem

In general, Minimax Location Problem minimizes maximum distance or time, optimizing possible actions in the worst case. However, this model does not consider demands, which is a shortcoming of this model.

Objective function : $Min\ Q$ (4)
Constraints : $\sum_{i=1}^{n} t_{jj}X_{jj} \le Q$ (5)

$$\sum_{j=1}^{n} X_{ij} = m \quad (6)$$

$$\sum_{j=1}^{n} X_{ij} = 1(X_{ij} \le X_{jj}, X_{ij} = 0 \ or \ 1) \quad (7)$$

h_j: Demands in Point i

t_{ij}: Distance between Point i and Point j(or travel time)

2.2.3. Set Covering Location Problem (SCLM)

It calculates minimal number of facilities that can cover all demand points. It should decide maximum distance(λ) that can cover facilities in advance, and the model is as follows. It can reflect distance and time at marginal costs, and cover all demand points. However, due to the constraints that should cover all demand points, it might calculate excessive number of facilities.

Objective function : Min $\sum_{i=1}^{n} X_i$ (8)

Constraint : : $\sum_{i=1}^{n} a_{ij} X_i \ge 1(X_i = 0 \ or \ 1)$ (9)

$a_{ii} = 1$ In case distance between Point i and Point j is same or below.

$a_{ii} = 0$ ：In case distance between Point i and Point j is bigger than.

$X_i = 1$ ： In case Facility j provides service to Point i

$X_i = 0$ ： In case Facility j does not provide service to Point i

2.2.4. Maximum Covering Location Problem (MCLM)

When the charging service is provided by restrictive number of facilities in a certain area, it considers maximum distance(λ) between each demand and a facility, and decides the optimal location of the facility so that the maximum number of demand points can use the facility. The equation of the model when P facilities are required is as follows.

Objective function : Min $\sum_{i=1}^{n} h_j Z_j$ (10)

Constraint : : $\sum_{i \in N_j}^{n} X_i \ge Z_j$ (11)

$\sum_{i \in N_j}^{n} X_i = P(X_i = 0 \ or \ 1, Z_j = 0 \text{ or} 1)$ (12)

h_j: Demand in Point j

N_j: Set of Location i of the facility of which distance between Point i and Point J is equal or less than λ

$X_i = 1$ ： In case the facility is installed on Point i.

$X_i = 0$ ： In case the facility is not installed on Point j.

$Z_i = 1$ ： In case the demanding point j is covered by a certain facility

$Z_i = 0$ ： In case the demanding point j is not covered

3. Research Subjects and Research Methods

As for the geographical scope for effect analysis resulted from optimal capacity and selection of optimal location, this study selected Gangnam-gu where most number of cars are registered among 25 municipal districts (Gu) in Seoul and includes Samsung-dong that currently has EV chargers. Candidate locations were selected from existing 49 gas stations which installed EV chargers in Gangnam-gu. Quick chargers were selected for installation among chargers. This study aims to determine the capacity meeting the demands for EV charging stations and select their optimal location. For the purpose, it built a model for optimal capacity and selection of location. To determine the capacity of a charging station, M/M/s model was used. Under the hypothesis that all charging stations have same capacity, this study applied Minisum Location Problem, Minimax Location Problem, Set Covering

Problem, and Maximum Covering Problem and compared them one another for the selection of optimal location.

3.1. Candidate Location2 and Demand Location*

The subjects of this study were quick chargers and existing gas stations were selected as candidate locations according to the plan to build EV charging infrastructure. 49 gas stations in Gangnam-gu were selected as candidates. Gas stations of which size was smaller than 810.0 m^2 , which was the minimum area required for a gas station with EV chargers in Seoul, was excluded from candidates. Among the candidate gas stations, the selected gas stations were regarded as supply locations and the remaining candidates were regarded as demand locations. Gas stations having sufficient area for quick chargers were selected as candidate locations. This study set 30 gas stations as candidate locations that satisfied the condition of a certain area.

3.2. Calculating Travel Cost

Travel cost of a link that connects each node was calculated based on travel time. In calculating travel time of each link, length of the link and speed limit, which had been applied in existing network, were reflected. The free speed was set as 80kph for national roads and 50 kph for municipal roads, in consideration of speed limit on the roads in Seoul. Average travel time was obtained by using BPR equation of T-Cad.

3.3. Calculating the Demands for Electric Vehicles

As for gas stations, number of registered cars are turned out to be an absolute factor for profit. It was found that traffic volume, which is a traffic factor, is a demand variable that takes crucial role in deciding a location. Since there are difficulties in estimating substantial demands for EVs under the circumstances where EVs have not been commercialized yet, this study calculated demands for EVs based on the number of registered cars and traffic volume, which are the most influential factors for selecting locations of gas stations. As for the EV demands in Gangnam-gu, we extracted number of registered passenger cars except for taxi among the number of whole registered cars by administrative district (Dong), and calculated estimated supply of EVs, assuming that the expected market share will be 2%. This study also surveyed incoming and outgoing traffic volume in Gangnam-gu, based on which prospect supply was calculated. In the study of Kim and An (2009) on the choice probability for gas stations, that assuming if the gas price is same throughout the regions, cars that took up 80% of traffic volume filled the fuel within the region probabilistically, while cars that took up 20% of traffic volume filled the fuel outside the region. Based on the result, 0.8 and 0.2 was given as weight value to the number of registered cars and traffic volume, respectively, and utilized the sums as supply data (Kim, 2011).

3.4. Number of Arrived Cars Per Hour (λ)

To apply M/M/s model for calculating optimal capacity, number of arrived cars per hour should be calculated. Since EVs have not been specifically commercialized yet, it is hard to get time series data and sensitivity analysis. Number of arrived cars per hour was obtained through additional literature survey.

$$\lambda = \text{Demand} \times (\text{Average daily mileage Mileage / one-time charging}) / 24 \text{ hours} \quad (13)$$

* Candidate location : It refers to a gas station located in Gangnam-gu and has certain scale of area so that EV chargers can be installed.
Demand location: It refers gas stations except for 11 candidates which were calculated through Capacity Decision Model.

In the equation above, average daily mileage was 32.28 km/car/day(Korea Transportation Safety Authority, 2009), which was the mean value of the average daily mileage of municipal passenger cars of Seoul and the average daily mileage of common passenger cars in Seoul. As for one-time charging mileage, this study set 155.33km, which was the average of high-speed EVs (reported by Ministry of Environment, 2010) of automobile manufacturers in Korea (Hyundai, Renault Samsung, and GM Daewoo).

3.5. Maximum Coverage Distance and Service Time

Although the covering capacity of EV charging service facilities could be the distance to travel by one-time charging, it is not an obvious ground due to different charging facilities and their capacity. In the EV Infrastructure Planning Report released by Ministry of Knowledge and Economy in 2001, maximum coverage distance of a charging station was set to 4km according to Quick Charger Installation Plan of which coverage distance for quick chargers was 4km per car.

When M/M/s is applied for setting capacity of a service facility, average service time should be calculated. This study analyzed quick chargers as service facility but the quick charging time was set through previous theses. In the previous studies, charging time was 4 minutes (Hong *et al.*, 2009), 10 minutes(Go, 2009), 15 minutes(Ha, 1998), 15～30 minutes(Son, 2010), 20 minutes(Jung and Lee, 2010), and 30 minutes(Sim and Lim, 2010). The mean value of their charging time was set 20 minutes.

4. Models

4.1. Calculating Optimal Capacity (M/M/s applied)

M/Ms was used to determine number of chargers by locational characteristics in Gangnam-gu. Arrival distribution formed a Poisson distribution and service time followed exponential distribution. The model has more than two servers. Number of arrived cars per hour according to the demands in Gangnam-gu was calculated as about 26.2 cars/time and number of cars to charge per hour was 3 cars/hour.

System availability $$\rho = \frac{\lambda}{s\mu} \tag{14}$$

In case there is no customer in the system:

$$\mathrm{P}(0) = \frac{1}{[\sum_{n=0}^{s-1}\frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n] + \frac{1}{s!}\left(\frac{\lambda}{\mu}\right)^s\left(\frac{1}{1-\rho}\right)} \tag{15}$$

Probability that there is n number of customers in the system:

$$\mathrm{P(n)} = \begin{cases} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n P_0 & (0 \le n \le s) \\ \frac{1}{s!s^{n-s}}\left(\frac{\lambda}{\mu}\right)^n P_0 & (n \ge s) \end{cases} \tag{16}$$

Average number of customers in the queue

$$L_q = \frac{P_0(\lambda/\mu)^s\rho}{s!(1-\rho)^2}$$

Average number of customers in the system

$$\mathrm{L} = L_q + \frac{\lambda}{\mu} \tag{17}$$

Average time spent in the queue

$$W_q = \frac{L_q}{\lambda}$$

Average time spent in the system

$$\mathrm{W} = W_q + \frac{1}{\mu}$$

Table 1. Results of M/M/s Application

Each scenario was based on average waiting time (minutes)				
Scenario	Sc.1	Sc.2	Sc.3	Sc.4
Number of arrived cars per hour(λ)	26.2	26.2	26.2	26.2
Number of charging cars per hour (μ)	3	3	3	3
Number of servers supplied (s)	9	10	11	12
System availability (ρ)	0.97	0.87	0.79	0.73
Average number of customers in the queue (L_q)	32.7	6.9	3.8	2.7
Average number of customers in the system (L)	33	7	4	3
Average time spent in the queue (W_q)	1.25	0.26	0.15	0.10
Average time spent in the queue (Minutes)	74.9	15.8	8.8	6.1
Average time spent in the system (W)	1.58	0.59	0.48	0.44

Note: Each scenario was set to calculate number of servers required for calculating targeted average spent time.

In Scenario 1, the number of servers was 9 according to number of servers supplied and average time spent in the queue (minutes) was 75 minutes. In Scenario 2, Scenario 3, Scenario 4, the average time spent in the queue (minutes) was 16 minutes, 8.8 minutes, and 6 minutes, respectively. In consideration of average waiting time in gas stations in Seoul, proper average time spent for EV charging service was set to 5~10 minutes. This study applied Scenario 3 where average time spent in the queue was 8.8 minutes with 11 servers supplied as the optimal scenario. That is, 11 EV charging stations were required to maintain average waiting time in the queue similar to general gas stations while meeting the demands for EV in Gangnam-gu.

4.2. Selection of Optimal Location

The representative optimal location selection models based on Location Theory include Minisum Location Prolbem, Minimax Location Problem, SetCovering Problem(SCLM), and Maximum Covering Problem(MCLM). This study excluded Minimax location Problem, as the model cannot reflect the demands of Gangnam-gu, though it can minimize maximal travel time. Location selection models consist of different objective functions and constraints, which resulted in different location selections on the 11 candidates. Evaluation on the locations, which varied depending on model characteristics, were done based on average travel time and maximum travel time of 38 demand locations and 11 supply locations.

Comparing the results through average travel time and maximum travel time, optimal location selection by MCLM turned out to be most appropriate. As for Minisum Location Problem, average travel time was short but the maximum travel time was longer than other locations. In SCLM, average travel time was long. In MCLM, the demands covered by limited number of facilities could be maximum, but some demand points could not be covered by this model. Since it calculated gas stations in existing road network as candidate, demand or supply locations, it produced errors that selected most gas stations on major main roads.

SetCovering Problem		**Minisum Location Problem**		**Maximum Covering Problem**	
					
average travel time	maximum travel time	average travel time	maximum travel time	average travel time	maximum travel time
7.1 min	16.4 min	5.8 min	19.8 min	5.8 min	19.1 min

Figure 2. The Result of Location Selection

5. Conclusions and Further Research Tasks

This study set the geographical scope to Gangnam-gu where charging station are currently installed, and converted demands for EV that are not commercialized yet based on number of registered passenger cars and traffic volume. This study applied M/M/s, a queueing model to calculate optimal capacity for EV demands in Gangnam-gu. It calculated the number of optimal facilities that can cover the demands through Location Theory Model(SCLM) and Minisum Location Problem(MCLM) and suggested optimized locations for facilities in terms of demands and travel time with arrivals in the shortest distance. This study set the maximum distance that could cover charging stations and suggested a model that connects decision process of the capacity and optimal location of EV charging facilities sequentially by sharing demand data. This study selected optimal location by evaluating average travel time of users, through which it suggested the establishment plan for substantial charging stations. On the assumption that the kind and functions of chargers located in many places are same, this study set the capacity (the number of chargers) that meets the demands in Gangnam-gu.

In terms of demands, this study distributed demands of Gangnam-gu to each demand point equally. Due to the assumption, there was no proper distribution in consideration of the areas with high demands and low demands in Gangnam-gu. Also, candidate locations, supply locations and demand locations were selected through the locations of existing gas stations, supply location on the link with high travel speed was analyzed with advantages. Therefore, researches in the future should consider the methods to have charging facilities be located meeting the demands in the area. It also required comparative analysis in consideration of demand locations.

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