A Study of the Analytical Method for the Location Planning of Charging Stations for Electric Vehicles

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Abstract. This study describes an analytical method for the location planning of charging stations for electric vehicles (EVs). EVs are expected to help CO_2 reduction and to improve road environment such as noise level. In this paper, the theoretical framework of the optimum location of charging stations is explained. We assume that the number of charging stations to install and the basic performance are given. This framework has the base of the traffic assignment technique with Stochastic User Equilibrium (SUE) and its optimization will be achieved with the idea of the entropy maximization.

Keywords: Electric Vehicle, Charging Station, Stochastic User Equilibrium Assignment, Entropy Maximization

1 Introduction

The purpose of this study is to develop an analytical method for the location planning of charging stations for electric vehicle (EV)s. This method optimizes the locations of charging stations considering the route choice behavior of EV drivers and the spatial distribution of the electric demand from EVs. The optimization here is aiming that the travel cost of each EV including its charging time is to be minimized and that the electric demand for each charging station is to be equalized.

In recent years, the performance of EV has been suitable for practical use such as battery capacity. EV is needed electronic power and used electric motors to drive. Thus it is said that the CO_2 emission by driving can be zero because EV is not used gasoline engine. In addition to this, the noise level of electronic motors of EV is lower than the engine of gasoline-powered vehicle. Therefore EV is expected to help CO_2 reduction and to improve road environment such as noise level. Generally, the maximum driving range of EV is limited comparing to gasoline-powered vehicles. And it is also said that the way and the location to refill the energy of EV (electricity) can be different from the way of gasoline-powered vehicle (gasoline). Furthermore, the charging time of EV is longer than that of gasoline-powered vehicle. Therefore, the behavior of the EV driver will be affected by the location of charging stations.

The location planning of charging stations will be a serious issue as the market of EV growing in the future. Many existing studies concerned with the charging station planning focused only on the minimization of EV users' cost [1] [2] [3] [4]. For example, Koyanagi *et al*. the analytical location planning method to optimize the accessibility to the public transport station, main road, parking lot and shopping center [1]. However, it is rarely discussed about the location optimization from the viewpoint of the power supply side. We need to aware of the possibility that if the balance of the power supply is unstable, some charging station is not able to supply enough and the re-planning of the electric infrastructure is needed.

. In this study, we try to harmonize those two objectives, i.e. the equilibrium of users' costs and the equalization of the electric demand for each charging station in the location planning. In section 2, we discuss about the formulation of the location planning of charging station using examples from some past studies. In section 3, the assumption of the driving behavior of EV is discussed for the formulation, and we show the framework of the optimum location method of charging station in section 4. In section 5, the case study applied the method. Finally, we conclude this paper through the result of the case study and show the future works in section 6.

2 Development principles for the optimum location method

Before the development of the optimum method of charging station, we review the past studies and consider the principle of the formulation.

There are many studies about optimum location method. These studies applied the approach from mathematical programming. To develop the optimizing model, a variety of optimization method is applied including Meta-heuristic Methods such as Genetic Algorithms and Neural Networks [5]. Other some are coming from the field of physics such as perturbation theory [6]. According to some studies developed the optimum location methods, these methods are considered the factors to impact the facilities such as demand of customers, population, distances from the facilities. For example, Furuta et. al. [7] describes the optimum location method of commerce facility considering the behavior of customer. They assumed the relationship between the purchasing power of customer and the facilities which compete in sales. Berman [8] describes a solution for the flow-demand facility location problem based on the situation that customers travel (go shopping etc.) with several purpose who can be changed the original trip. Basically, the optimum location method for charging station can also be applied to same analytical steps. And most of these methods are considered to minimize the distance to destination or the cost such as money, travel time and waiting time.

In this study, we focused on the factor associated with the location planning which is assumed from the characteristics of EV and formulate the optimum location planning for charging station considering the following issues.

1) The size of the target area issued in this method will cover a city-scale network which covers the trips in daily activities.

2) The number of charging stations to install and their charging performance (number of charger and charging rate) are given as inputs.
3) The demand of EVs to each charging station can be calculated using the traffic assignment algorithm assuming the route choice behavior of EVs from origin to destination we assumed.
4) The route cost from origin to destination consists of the travel time and the waiting time at the charging station. The location of charging station is decided such that the route cost of each EV is minimized and each charging station is maintained a certain distance.

3 Route choice behavior of EV and charging station

In this section, let us summarize the feature of EV and the charging station for the formulation.

An EV consumes electricity stored in the battery in proportion to its travel distance. EV users can charge their EVs at their home, any charging stations, their offices, shopping centers and so on. EV is needed to charge the battery before when State of Charge (SOC) reaches to zero. SOC can be regarded as a fuel gauge for the battery. If EV is needed to charge on the way to the destination, the route might be changed to charging station. Therefore, we assume that there are three behaviors of EV to the destination. Fig.1 shows the behavior of EV to the destination.

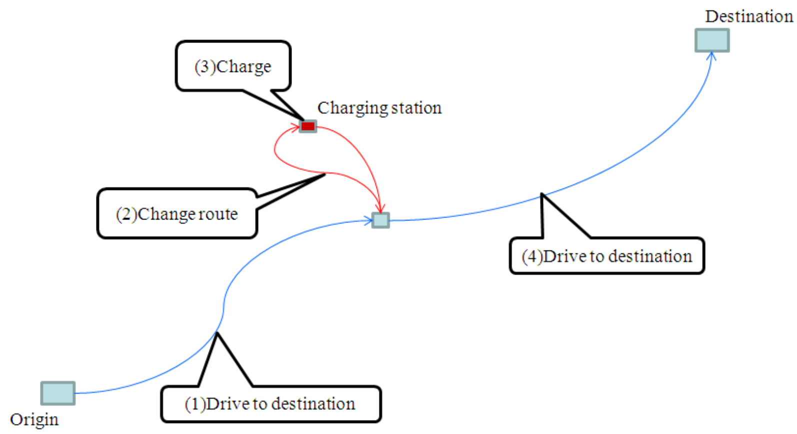

Fig.1. Behavior of EV to the destination

The issue we should focus on is the waiting time at charging station. The waiting time can be formulated as the M/M/1 queueing theory from the relationship between the electric capacity of charging station and the electric demand of EV for charging. Let e_g^x denote the supply rate of the charger g in the charging station x. The electric capacity rate of the charging station E_x^{sh} per unit time h is formulated the following equation:

$$E_x^{sh} = \sum_{g \in G_x} e_g^{xh} \qquad (1)$$

Where Let G_x the set of charger of the charging station *x*. On the other hand, the electric demand can also be formulated from the characteristic of EV (in Fig.1). It is assumed that EV is charged the energy to the destination or the next charging station. Let $d_k^{x^{next}h}$ denote the distance to the destination or the next charging station x^{next} along the route *k*. Let f_k^{xh} denote the number of EV via the charging station *x* along the route *k*. And let *S* the fuel efficiency (electric energy consumption for unit distance) of EV. The electric demand rate of EV for the charging station x E_x^{dh} per unit time *h* is formulated the following equation:

$$E_x^{dh} = \sum_{k \in \hat{K}_x} \frac{d_k^{x^{next}h} f_k^{xh}}{S} \qquad (2)$$

From the equations (1) and (2), the average waiting time for *h* can be formulated as the cost of EV. Let λ_x denote the arrival rate for the electric demand of E_x^{dh}. Let μ_x is the service rate for the electric capacity of E_x^{sh}. The utilization ratio ρ_x is the following equation:

$$\rho_x = \frac{\lambda_x}{\mu_x} = \frac{E_x^{dh}}{E_x^{sh}} \qquad (3)$$

Therefore, the waiting time at the charging station *x* can be found using the equation (3). We assumed that the waiting time is added the penalty time in the situation when $\rho_x \geq 1$ or the calculated waiting time is larger than or equal to the unit time *h*. The equation of the waiting time T_w^x per unit time *h* is formulated changing the interpretation of M/M/1 theory as:

$$T_w^x = \begin{cases} \frac{\rho_x}{(1-\rho_x)}\mu_x & \rho_x < 1, \frac{\rho_x}{(1-\rho_x)}\mu_x < h \\ \rho h & otherwise \end{cases} \qquad (4)$$

Finally, the average cost for the waiting time at the charging station *x* t_x^{wait} including the charging time is calculated as:

$$t_x^{wait} = T_w^x + 1/\mu_x \qquad (5)$$

4 Optimum location method for charging station

In this section, we explain the optimum location method for the location planning of charging station. Basically, it is said that EV driver has 3 behaviors showed in Fig.1. From the view point of EV driver, it is important that the cost to the destination such as travel time should be minimized. On the other hand, from the view point of the administrator, it may say that the electric demand from the infrastructures for EV should be controlled not to have demand bias for each region. Therefore, it is possible to build up two hypotheses. We assume the objectives of the optimum location method as follows:

1) The cost for one trip (from Origin to Destination) which is included the waiting time of the battery charging at charging station should be minimized (Objective 1).
2) The bias of the electric demand for each charging station should be minimized (Objective 2).

The objective 1 depends on the route from origin to destination and the waiting time of the battery charging. Especially, the time of battery charging is the unfavorable condition than the waiting time for gasoline charging. Thus it is said that the minimizing of the waiting time of charging is an important factor for the solution. The object of calculation is the EVs that are needed to charge at charging station.

In the objective 2, a possibility of the bias of EV users is indicated. For example, if many charging stations are located in an area, the electric demand of each charging station might be low. However, the charging stations in other areas are needed to handle the high demand. From this viewpoint, the location of charging station should be considered to give equal charging opportunities for EV users and to equalize the electric demand of the battery charging. In this study, it can be discussed that the design problem is defined the optimum location problem consists of two stages. The formulation is explained in subsection 4.1 and 4.2.

4.1 Method for the objective 1

Here, let c_k^{rs} denote the route cost of the route *k* in the set of route for the OD pair *rs* (K_{rs}). And let f_k^{rs} denote the path flow of the route *k* in the set of route K_{rs}. The solution for the objective 1 is formulated using the total cost of EVs *Z* as follows:

$$\text{Minimize} \quad Z = \sum_{k \in K_{rs}} c_k^{rs} f_k^{rs}$$

$$\text{Subject to} \quad x_a = \sum_{rs} \sum_{k} \delta_{a,k}^{rs} f_k^{rs} \qquad a \in A \tag{6}$$

$$\sum_{k} f_k^{rs} - Q_{rs} = 0 \qquad rs \in \Omega$$

$$f_k^{rs} \geq 0 \qquad k \in K_{rs}, rs \in \Omega$$

Where x_a is the traffic flow of the link *a*, $\delta_{a,k}^{rs}$ is the variable with a condition that if the link *a* on the route *k* of the OD pair *rs* is included, $\delta_{a,k}^{rs}$ is 1 and the otherwise is 0. Q_{rs} is the OD flow of OD pair *rs*. Using this equation, the traffic assignment to minimize the total cost of EV is examined. Here a total cost of a charging station *x* c_x is calculated as:

$$c_x = \sum_{k \in \hat{K}_x^{rs}} c_k^{rs} f_k^{rs} \tag{7}$$

Where $\hat{K}_x^{rs}$ is the subset of route of the OD pair *rs* via the charging station *x*. Next c_k^{rs} is assumed the situation that some charging stations are located at some nodes. Therefore c_k^{rs} is included the link costs and the waiting times at the charging stations. Let t_a denote the link cost of the link *a* on the route *k* of OD pair *rs*. And let t_x^{wait} denote the waiting time of battery charging at the charging station *x* on the route *k* of OD pair *rs*. Then c_k^{rs} can be formulated as:

$$c_k^{rs} = \sum_{a \in \hat{A}_k^{rs}} t_a + \sum_{x \in \hat{X}_k^{rs}} t_x^{wait} \tag{8}$$

Fig.2 shows the image of the definition of EV cost from origin to destination.

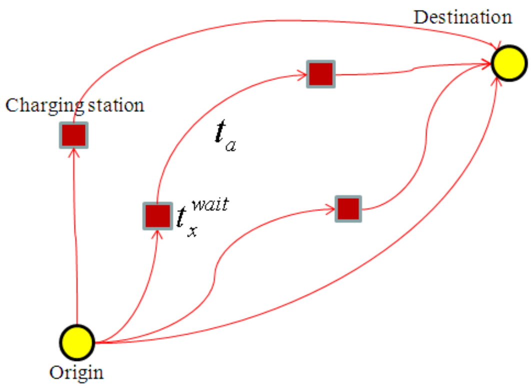

Fig.2. Cost to the destination of EV

Finally, the link cost t_a is considered the penalty cost in when the cruising distance of EV is over the available (or maximum) cruising distance. The link cost t_a is defined as the following equation:

$$t_a = \frac{\sum_{rs}\sum_{k}\sum_{v\in V_k^{rs}} \delta_{a,k}^{rs}(c_a + t_a^{penalty}(v))}{f_{k,a}^{rs}}$$
$$t_a^{penalty}(v) = \begin{cases} 0 & d_v^{soc} - \sum_{a_k \in \hat{A}_{kav}^{rs}} l_{a_k} \geq 0 \\ t_a & otherwise \end{cases} \quad (9)$$

Where c_a is the link travel time of the link a, $t_a^{penalty}(v)$ is the penalty cost of the passing EV *v* in link *a*, and $f_{k,a}^{rs}$ is the count of the passing EVs for link *a*. d_v^{soc} is the accumulated distance from the origin for the EV *v*. l_{a_k} is the link length of the link *a* on the route *k* in the link subset $\hat{A}_{kav}^{rs}$ that the EV *v* selected until the link *a*. This equation using d_v^{soc} is the condition to check whether the accumulated distance is over the available distance or not.

To find the solution for equation (6), the traffic assignment listing the paths for all OD pairs should be done. In this study, we apply the Dial's algorithm [9]. The Dial's algorithm is a traffic assignment technique with SUE not to list the paths from origins to destinations. The following is the calculation step of the Dial's algorithm. As the first step, the minimum cost $c(i)$ to each node (destination) *i* from the origin *r* is calculated.

$$c(i) \leftarrow C\min[r \rightarrow i] \quad (10)$$

Then, the link likelihood $L[i \rightarrow j]$ from the node *i* to the node *j* is calculated for all links.

$$L[i \rightarrow j] = \begin{cases} \exp[\theta\{c(j) - c(i) - t_{ij}\}] & c(i) < c(j) \\ 0 & otherwise \end{cases} \quad (11)$$

Where θ is the logit parameter and t_{ij} is the link cost which is equal to t_a. As the second step, we consider the node in ascending order of the cost $c(i)$ from (near) the origin *r*. The link weight $W[i \rightarrow j]$ is calculated as:

$$W[i \rightarrow j] = \begin{cases} L[i \rightarrow j] & for \quad i = r \\ L[i \rightarrow j]\sum_{m\in I_i}[m \rightarrow i] & otherwise \end{cases} \quad (12)$$

Where I_i is the set of node which inflow to the node *i*. As the third step, we consider the node in descending order of the cost $c(i)$ from (far from) the origin *r*. the link flow (traffic count) from the node *i* to the node *j* x_{ij} is calculated by the following equation.

$$x_{ij} = (q_{rj} + \sum_{m \in O_j} x_{jm}) \frac{W[i \to j]}{\sum_{m \in I_j} W[m \to j]} \qquad \textbf{(13)}$$

Where q_{rj} is the OD flow from the origin *r* to the destination *j* and O_j is the set of node which outflow from the node *j*. Each route of EV is determined from the third step. At the same time, the route cost without the waiting time for battery charging can be also calculated. Basically, the traffic assignment including the Dial's Algorithm have iteration process. In this method, the first assignment process is calculated by the default link cost and is not considered the waiting time for battery charging. From the second assignment process, the waiting time is calculated and is considered with the previous result of link cost.

4.2 Method for the objective 2

In this subsection, we set up the equation for the objective 2. To set up the formulation, we apply the idea of Principle of Maximum Entropy. First, the total electric demand of all of charging station E_d can be formulated as:

$$E_d = \sum_{x \in X} E_x^d \qquad \textbf{(14)}$$

Secondary, the percentage of the electric demand of charging station x of the total electric demand $P_e(x)$ is the following:

$$P_e(x) = \frac{E_d^x}{E_d} \qquad \textbf{(15)}$$

Then it is clear that we have the following equation.

$$\sum_{x \in X} P_e(x) = 1 \qquad \textbf{(16)}$$

Finally, the entropy of the combination of the location of charging station H_p can be calculated when we assume that $P_e(x)$ is the probabilistic distribution satisfied the condition of equation (16).

$$\begin{aligned} &\text{Maximize} \quad H_p = -\sum_{x \in X} P_e(x) \log P_e(x) \\ &\text{Subject to} \quad \sum_{x \in X} P_e(x) = 1 \end{aligned} \qquad \textbf{(17)}$$

From the viewpoint of principle of maximum entropy, it is said that the entropy have a trend to be increased if the distribution of the electric demand is closed to the equal probability. Therefore, if the entropy is maximized, we can find the optimum location of charging station satisfied the objective 2.

5 Implementation of the optimum location method

This section is discussed the implementation of the optimum location method in section 4. Fig.3 shows the flow chart for the implementation. This process consists of three steps. In the first step, the locations of charging stations are decided. To decide the location, the suitable search algorithm is needed to feedback the result of entropy. In the second step and the third step, we apply the Dial's algorithm and the optimum method we suggest.

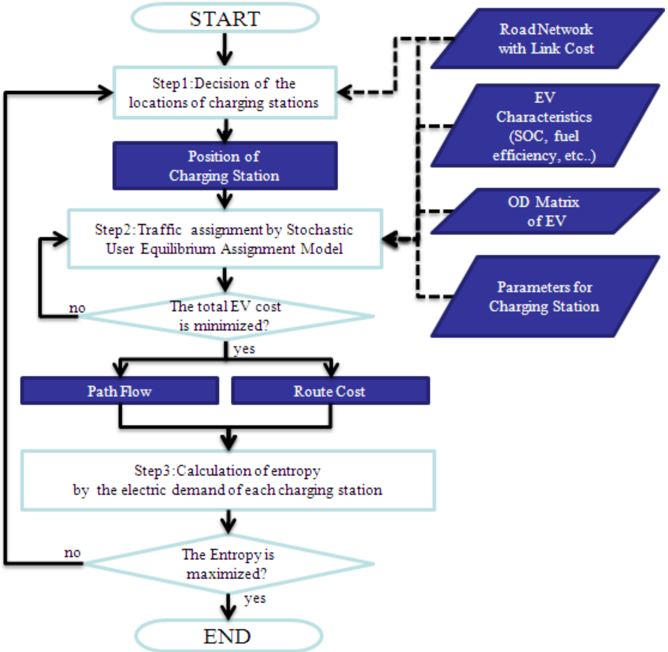

Fig.3. Flow chart for implementation

6 Future Works

In this paper, we explained a method for the design problem of EV charging station. As the future works, we will apply the virtual road network such as grid network first for the verification. After the verification, a case study using this method will be examined for the real road network. Fig.4 shows the target area of the case study.

The issues to be tackled for the implementation are the decision methodology of the initial location of charging station and to find the search algorithm for the method with the validation of the calculation time.

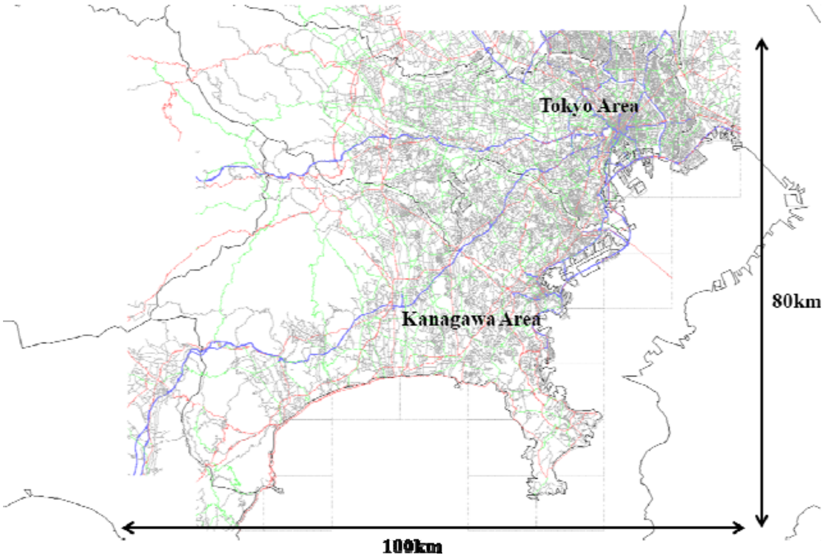

Fig.4. Target area for case study

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