The Capacitated Deviation-flow Fueling Location Model for Sitting Battery Charging Stations

Yunjian JIANG [1], Yong ZHANG[2*], Cong ZHANG[3], and Jiaqing FAN[3]

[1] School of transportation, Southeast University, Nanjing 210096; email: jyj402@163.com
[2*] Corresponding author, School of transportation, Southeast University, Nanjing 210096; email: zhang7678@126.com
[3] School of transportation, Southeast University, Nanjing 210096; email: xingzhexingzhe@yeah.net
[3] School of transportation, Southeast University, Nanjing 210096; email: willjill.coll@163.com

ABSTRACT:

The generalization of alternative fuel vehicles contributes to reducing the impact of energy crisis and environment pollution. However, the lack of refueling infrastructures is a main barrier. Several scholars have designed models to optimize the deployment of refueling infrastructures. Among them, the Flow Refueling Location model (FRLM) locates refueling stations to maximize the flow that can be fueled with a given number of stations. To relax the assumption of "all flows passing through a node can be served regardless of their volume" and "all flows follow the shortest path between pairs of nodes", a Capacitated Flow Refueling Location Model (CFRLM) and a Deviation-Flow Refueling Location Model (DFRLM) were proposed respectively. This paper relaxes both assumptions at the same time and constructs a mixed-integer linear programming model. At last, the model is applied to optimize a network of battery charging stations and the genetic algorithm is used to solve this problem.
Keywords: Battery charging station; Location; Mixed-integer linear programming model; Genetic algorithm

INTRODUCTION

Development background of alternative fuel vehicles (AFVs)

Nowadays, the structure of the global energy system is changing in a dramatic way. On the one hand, the growth of energy consumption and the shortage of energy require adequate response. On the other hand, people has emphasized on the environmental sustainability of energy production, transportation and storage (Michalski et al., 2011). In 2009, 28.99 billion tons of carbon dioxide was emitted globally, of which the transportation sector accounted for 22.6% (IEA, 2011). The reduction of transportation sector's carbon dioxide emission is essential to solve the energy crisis and environmental crisis.

In 2009, the Chinese government promised to reduce carbon dioxide emission per unit of GDP by between 40% and 45% by 2020 from the 2005 values. To fulfill that promise, the Chinese government actively promotes the use of AFVs. Many policies geared towards stimulating the purchase of AFVs have been implemented. In addition, China has used AFVs in the Beijing Olympic Games and the Shanghai World Expo.

However, the promotion of AFVs has encountered several problems. Melendez et al. (2006), who made a survey on the scientists of U.S. National Renewable Energy Laboratory, the coordinator of the U.S. Clean Energy Cities Alliance and the literatures of alternative fuels, found that the lack of refueling infrastructure is the biggest obstacle to the promotion of AFVs. This is recognized as the "chicken and egg" problem (Hodgson, 1990; Averbackh and Berman 1996).

For the facility operators, the operation of refueling facilities is not economical unless a sufficient number of AFVs is in operation. For the AFVs consumers, if the refueling facilities are not popular, consumers will not choose the AFVs (Lim and Kuby, 2010). Therefore, the layout of alternative energy refueling facilities plays a vital role in promoting AFVs.

Literature review

Optimization-based approaches for locating refueling stations are divided into two groups depending on the geometric representation of demand: models for point-based demands and flow-based demands (Kima and Kuby, 2011). P-median, location set cover, the maximum cover model and the fixed-charge models are the models for point-based demands. These models considered providing service to point-based demands.

However, Hodgson (1990) argued that only the traffic flow passed through the refueling facilities could be fueled and established the Flow Capture Location model (FCLM) to optimize the layout of a certain number of refueling facilities to capture the traffic flow most. The FCLM assumed once there is a refueling facilities on the path, all of the traffic flow could be captured and arrived the destination successfully. But this assumption ignored the maximum driving distance of the vehicles.

Based on the FCLM, Kuby and Lim (2005) considered the maximum travel distance of the vehicles and established the FRLM. The FRLM optimally locates a certain number of refueling stations on a network so as to maximize the total flow volume refueled (Kuby and Lim, 2005). However, the original incapacitated FRLM assumed that the presence of a refueling station is able to serve all flows passing through a node, regardless of their volume. Upchurch et al., (2009) introduced the Capacitated Flow Refueling Location model that limits the number of vehicles refueled at each station. Then, Kuby and Lim (2007) applied the greedy algorithms, alternative greedy algorithm and genetic algorithm to solve the FRLM, and concluded that all of the three algorithms were efficient. Later, Kuby et al. (2009) combined the GIS systems with the FRLM to obtain data, enter assumptions, analyze scenarios, evaluate tradeoffs and map results on authentic network in Florida. Kima and Kuby (2011) assumed that the drivers were likely to make the necessary deviations from their shortest paths refueling when the refueling station network is sparse and developed the DFRLM.

However, no prior study has considered both of the capacity of refueling stations and the necessary deviations drivers will make in a model. In fact, the relaxation of the assumptions of "all flows passing through a node can be served regardless of their volume" and "all flows follow the shortest path between pairs of nodes" is reasonable (Upchurch et al., 2009; Kima and Kuby, 2011). This paper relaxes both of the assumptions at the same time and constructs the Capacitated Deviation-Flow Refueling Location model.

Research objective and scope

Among all the AFVs, the electric vehicles (EVs) are the most mature in China. On the technical level, the technical performance of the EVs for test has been close to the gasoline fuel vehicles. On the environmental level, EVs are "zero emission" vehicles (Feng and Jun, 2009). Therefore, this paper chooses the EVs for study.

Based on the assumption that customers are willing to travel a certain distance of deviation from the shortest path (Kima and Kuby, 2011), this paper considers the capacity of battery charging stations and constructs the Capacitated Deviation-Flow Refueling Location model.

THE CAPACITATED DEVIATION-FLOW REFUELING LOCATION MODEL

Assumptions

The CDFRLM is an extension of the DFRLM, and it follows some assumptions of its precedent model (Kima and Kuby, 2011). The assumptions are presented as the followings:

1) Flow Refueling Location models are formulated to locate facilities that make round trips feasible.

2) Fuel consumption is strictly a function of distance.

3) Facility location is limited to network nodes.

4) Drivers would be willing to take a deviation path from the shortest path and the fraction of drivers who would be willing to take deviation path is decreasing with the increase of deviation. In this paper, we choose a linear function.

Besides, the CDFRLM adds some extra assumptions.

1) In this paper, the authors choose the EVs for study. As EVs can be charged at home or garage at night, the CDFRLM assumes the starting level of a vehicle is full power.

2) When the capacity of the shortest path is below zero, the drivers will choose the second shortest path, then the third shortest path and so on. And the driver is rational and gives the shorter path a priority.

3) The authors use i to represent a path's priority to an O-D pair. For two O-D pairs A and B, if $i_A < i_B$, then the facility operators satisfy demands on O-D pair A first.

Formulation of the capacitated deviation-flow refueling location model

This section presents a mixed-integer linear programming formulation of the Capacitated Deviation-Flow Refueling Location model (CDFRLM). This paper relaxes both of the assumptions of "all flows passing through a node can be served regardless of their volume" and "all flows follow the shortest path between pairs of nodes" at the same time and constructs a mixed-integer linear programming model.

Formulation of the CDFRLM

$$Maximize \sum_{q \in Q} \sum_{r | b_{qhr}=1} f_q y_{qr} \tag{1}$$

Subject to

$$y_{qr} \geq 0 \quad \forall q \in Q, r \in R \tag{2}$$

$$\sum_{r \in R_q} y_{qr} \leq 1 \ \forall q \in Q, r \in R \tag{3}$$

$$\sum_{q \in Q} \sum_{r | b_{qhr}=1} e_r g_{rhk} f_q y_{qr} \leq c x_k \qquad \forall k \in K \tag{4}$$

$$y_{qr} \leq g_{qr} \ \forall q \in Q, r \in R \tag{5}$$

$$\sum_{k \in K} x_k = P \tag{6}$$

$$x_k \in \{0,1\} \quad \forall k \in K \tag{7}$$

The objective function (1) maximizes the total flow that can be recharged actually. Constraint (2) ensures all the fractions of the flow between O-D pair q recharged by path r are not less than zero. Constraint (3) limits the sum of the flow between O-D pair q recharged by all the path r is not more than one. Constraint (4) ensures that the vehicles recharged by all the stations are less than their capacity. Constraint (5) ensures that the fraction of the flow between O-D pair q recharged by path r is no more than the fraction that customers would be willing to take the deviation path r. Constraint (6) ensures that the number of battery charging stations to sit is equal to P.

Where indices are:

q : a particular O-D pair,

r : index of deviation paths (include the shortest path),
k : a potential facility location, and
h : index of combinations of facilities; and

Sets are:

Q : set of all O-D pairs,

R : set of all deviation paths,

R_q : set of all deviation paths r for O-D pair q,

K : set of all potential facility locations,

K_h : set of all facilities k that are in combination h,

H : set of all potential facility combinations, and

H_{qr} : set of all facility combinations h that can refuel deviation path r that is originated from O-D pair q; and

Parameters are:

P : the number of facilities to locate,

f_q : flow between O-D pair q,

g_{qr} fraction of normal path q customers who would be willing to take deviation path r,

y_{qr} : fraction of the flow between O-D pair q recharged by path r,

e_r : the fraction of round trips, on average, that require refueling per time period on a path r, calculated as (Upchurch et al., 2009)

$$e_r = \frac{1}{\max(1, \mathrm{int}(\frac{range}{(roundtrip\ distance)}))}$$, and

g_{rhk} : the average number of times a vehicle traveling on path r and being refueled by combination h that stops at station k on each round trip that requires refueling (Upchurch et al., 2009).

It is a coefficient equal to:

- 2, if facility k is in combination h but not at the origin or destination, meaning the vehicle must stop at the station to refuel in both directions;
- 1, if facility k is in combination h and at the origin or destination of flow q;
- 0, if facility k is not in combination h that can refuel path q.

Decision Variables are:

x_k : 1 if there is a facility at location k, 0 otherwise

b_{qhr} : 1 if the path r for O-D pair q can be recharged by combination h and all facilities in combination h are open, 0 otherwise

CASE STUDIES AND SOLUTION PROCEDURE

Case description

In this paper, the authors construct a 20-node test network (Fig.1). Fig.1 shows the distribution of the 20 nodes and the distance between them. What's more, this paper assumes the flow between each O-D pair is 100 vehicles daily. Then, the case can be described as locating 5 facilities with the capacity of station being 2000 vehicles daily in the 20-node test network when the vehicle capacity is 400km.

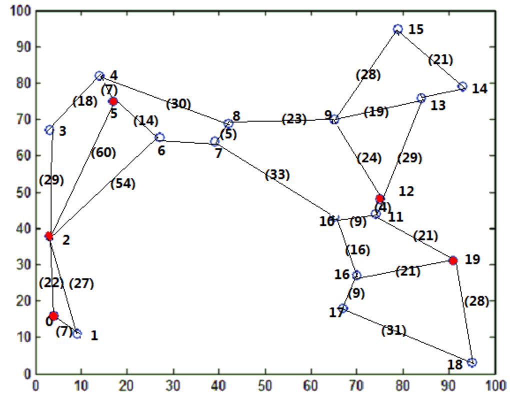

Fig.1 The 20-Node test network

Solution procedure

The CDFRLM was solved for the 20-Node test network using Microsoft visual C++ 6.0 software on a HP laptop with a 2.0GHz Pentium-R processor and 1280 MB RAM. The solution procedure is as follows:

Step 1: Data input

The data to input includes the capacity of vehicles and battery charging stations, the coordinate of nodes, the number of the stations to locate, the path between all O-D pairs, and the fractions of customers who would be willing to take deviation path with a certain deviation distance.

Step 2: Initializations

2.1Establish an empty master list of all nodes k.

2.2 Establish an empty master list of all O-D pair q.

2.3Establish an empty master list of all paths r.

2.4Establish an empty master list of all combination h.

Step 3: Calculate the shortest distance between each O-D pair and the length of each path r.

Step 4: Determine the combinations of nodes that can refuel a path and remove the combinations that are supersets of any other remaining combination. Record the facilities k in each viable combination h and the viable combinations

h for path q (Kuby and Lim, 2005).

Step 5: Sort all the paths r that can refuel an O-D pair q by the distance.

Step 6: Capacity allocation

6.1 Determine i which represents the priority of a path r to an O-D pair q. If the path is the shortest path to an O-D pair, then $i = 0$; If the path is the second shortest path to an O-D pair, then $i = 1, 2, 3......$

6.1.1 For a path, if it's the $i(i = 0, 1, 2......)$ shortest path to an O-D pair q, then allocate the station capacity to it.

6.1.1.1 Calculate the maximum capacity that can be supplied by the path, the maximum capacity is equal to the minimum capacity of the battery stations on the path.

6.1.1.2 Calculate the fractions of customers who are willing to take deviation path r.

6.1.1.3 Determine whether the fraction of customers who are willing to take deviation path r is larger than the maximum capacity that can be supplied by the path. If so, the fraction to recharge is equal to the maximum capacity that can be supplied by the path. If not, the fraction to be recharged is equal to the fraction of customers who would be willing to take deviation path r.

6.1.1.4 For all the stations on the path, the left capacity is equal to the prior capacity minus the fraction to be recharged.

6.1.2 Repeat step 6.1.1.1-6.1.1.4 for all paths q.

6.2 Repeat step 6.1.1.1-6.1.1.4 for all i.

Step 7: Generate the combinations of facilities nodes by the genetic algorithm and repeat step 6 for all combinations.

Results

In this paper, the genetic algorithm is set to operate 50 times and it takes almost 10 minutes to solve the case of the 20-Node test network, and the result is that the five stations to locate are on point 0, point 2, point 5, point 12 and point 19 (the red points in Fig.1). With the five stations, the flow that can be recharged is 11288 vehicles. It needs to point out that the flow that can be recharged (11288 vehicles) is actually lager than the capacity of the stations (10000 vehicles) in the CDFRLM. This is because the EVs are assumed to be capable of charging at home in this paper, so the flows between some O-D pairs can reach the destination without the recharge stations on the road.

CONCLUSIONS

This paper relaxes both of the assumptions of “all flows passing through a node can be served regardless of their volume” and “all flows follow the shortest path between pairs of nodes” at the same time and constructs a mixed-integer linear programming model. Then the authors apply the CDFRLM on a theoretical case.

However, the model has its limitations. First, the CDFRLM only takes the flow refueled into consideration, the environment impact and the construction cost was not considered. Second, the flow between O-D pair is static in the CDFRLM. However, the flow between O-D pair is always changing. Third, the CDFRLM regards the number of stations as an input which means other methods to determine the station amount is needed.

Therefore, the future studies should address a multi-objects problem, which considers a dynamic flow and the combination of the decision of the number of stations and the location of stations.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China (70902029) and Ph.D. Programs Foundation of Ministry of Education of China (20090092120045). We are grateful for valuable suggestions for improvements from these colleges.

REFERENCES

Averbakh, I., and Berman, O. (1996). "Theory and Methodology locating flow-capturing units on a network with multi-counting and diminishing returns to scale." *European Journal of Operational Research*, 91, 495-506.

Feng, Y., and Jun, F. (2009). "Economic comparison and analysis of the pure electric vehicles." *Wuhan University of Technology: Information and Management Engineering Edition*, 31.(In Chinese)

Hodgson M. J. (1990). "A flow capturing location-allocation model." *Geographical Analysis*, 22, 270–9.

Kima, J., and Kuby, M. (2011). "The deviation-flow refueling location model for optimizing a network of refueling stations." *Hydrogen energy*.

Kuby, M., and Lim, S. (2005). "The flow-refueling location problem for alternative-fuel vehicles." *Socio-Economic Planning Sciences*, 39, 125–145.

Kuby, M., and Lim, S. (2007). "Location of alternative-fuel stations using the flow-refueling location model and dispersion of candidate sites on arcs." *Networks and Spatial Economics*, 72, 129–152.

Kuby, M., Lines, L., Schultzc, R., Xiec, Z., Kima, J., and Limd, S. (2009). "Optimization of hydrogen stations in Florida using the Flow-Refueling Location Model." *Hydrogen energy*, 34, 6045–606.

Melendez, M. (2006). Transitioning to a hydrogen future: Learning from the alternative fuels experience. *National Renewable Energy Laboratory.* Technical Report No. NREL/TP-540-39423.

Lim, S., and Kuby, M. (2010). "Heuristic algorithms for siting alternative-fuel stations using the Flow-Refueling Location Model." *European Journal of Operational Research*, 204, 51–61.

Upchurch, C., Kuby, M., and Lim, S. (2009). A model for location of capacitated alternative-fuel stations. *Geographical Analysis* ISSN, 41, 85–106.