Transportation Research Part E 58 (2013) 76–87

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Locating multiple types of recharging stations for battery-powered electric vehicle transport

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ARTICLE INFO

Article history:
Received 30 August 2012
Received in revised form 3 May 2013
Accepted 29 June 2013

Keywords:
Recharging stations
Electric vehicle
Set coverage
Maximum coverage
Mixed integer programming
Location

ABSTRACT

This study used the concepts of set- and maximum-coverage to formulate capacitated multiple-recharging-station-location models, using a mixed integer programming method, based on a vehicle-refueling logic. The results of the case study demonstrate that the use of mixed stations can achieve the optimal deployment for the planning area, with results that are better than those achieved with a single type of recharging stations. While in some paths the use of slow-recharging stations means that tours are not feasible, the deployment of mixed stations can provide an economical approach which ensures the completion of overall tours on each path.

1. Introduction

As a result of concerns over climate change, energy security, urban air pollution and the continued growth in demand for transportation services, the adoption of alternative fuel vehicles is becoming ever more important (Melaina and Bremson, 2008; Kley et al., 2011). Electric vehicles (EV) powered by batteries can be charged by regular power outlets and offer lower operating costs than combustion engine cars. They are also efficient, emit no pollution, and are almost noiseless (Eggers and Eggers, 2011), and thus are expected to become more popular over the next decade (San Román et al., 2011), a trend that seems to be confirmed by the fact that several manufacturers are currently, or soon will be, offering their own EVs for customers, such as BMW, Mercedes, Honda and Toyota (Khan and Kockelman, 2012). However, the successful penetration of EVs still depends on the support of government policies, such as tax exemptions, and an environment where consumers do not need to worry over the range of such vehicles (Schroeder and Traber, 2012). Therefore, the establishment of a convenient recharging system is one of the most important factors to encourage the widespread use of EVs. However, due to the high capital cost involved in doing this, developing a recharging station location model to achieve this economically is a pressing concern for both researchers and government bodies.

Advances in technology mean that battery recharging times have now been cut to within 20–30 min using Direct-Current fast charging (Schroeder and Traber, 2012; Svoboda, 2009). However, in practice, due to considerations of battery life and the limited power supply at each site, slow recharging stations are still the predominant ones, as seen with the Park & Charge system used in Europe (Park and Charge, 2012). However, in the near future, we can expect that EV recharging systems will operate with multiple types of recharging stations, including both slow- and fast-recharging ones, such as currently seen on the West Coast Electric Highway in America (West Cost Electric Highway, 2012). In these systems, multiple types of recharg-

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http://dx.doi.org/10.1016/j.tre.2013.07.003

ing stations will be used to meet the varied demands or preferences of EV road users, while staying within the limits of the power supply in each area. Therefore, there is an urgent need to develop a location model for mixed recharging station deployment.

In previous research, various location models were proposed to optimally site refueling facilities. The proposed models can be classified as node-based, arc-based, and flow-based, based on their assumptions of refueling demand type (Upchurch and Kuby, 2010).

In this study, we mainly review the literature related to flow-based models of refueling facility location, since the refueling demand for vehicles is generally in the form of traffic flows that pass by the refueling facilities (Hodgson, 1990).

To consider many types of service demand that can be thought of as traffic flows, such as that seen for convenience stores, automated teller machines (ATM), and gasoline stations, Hodgson (1990) proposed a flow-capturing location model (FCLM) based on the concept of maximum coverage, which locates p facilities to maximize the capture of the passing flows. This is different from conventional facility location theory (Daskin, 1995), which is based on the assumption of fixed-node demand, such as from homes to service stations. Two years after Hodgson, Berman et al. (1992) proposed a flow interception facility location model, which is based on the same flow-demand that is used in the FCLM.

Hodgson (1990) provided a basic theoretical framework for dealing with the problem of locating alternative fuel refueling stations. However, this approach depends on the assumption that if one facility is sited on a node of a path, then all the related traffic flows will be captured, and this cannot be applied to alternative fuel vehicles, since these have a limited range and need a multi-stop refueling system to extend their driving distance and carry out long-distance journeys.

In order to achieve the multi-stop refueling needed for long-distance travel, Kuby and Lim (2005) proposed a flow refueling location model (FRLM) on the basis of FCLM. Similar to the FCLM, the objective of FRLM is also to maximize the capture of the traffic flows on each path if a combination of stations sited on the paths can be successfully used to refuel vehicles so that they can complete their trips. This model needs to be solved in two stages. The first stage is to find feasible combinations of candidate locations or stations to refuel the flows on each path, and the second stage is when these combinations are used as inputs to the model to determine the station locations (Kuby and Lim, 2005). Due to the time-consuming process of generating combinations in first stage, Lim and Kuby (2010) provided some heuristic algorithms to solve larger scale problems, including greedy substitution and genetic algorithms.

Later, Capar and Kuby (2012) developed a new approach to solve the flow refueling location problem in one stage. Three locating logics were used to check whether a path could be refueled by the sited refueling stations. The first one is if there is no station built at the origin then there should be at least one station built within half the vehicle range to the origin node, so that it can be reachable by half a tank of fuel or half a battery charge. The second one is if there is a station built at a location, then the next built facility should be within the vehicle range, otherwise the vehicle cannot reach to the next station. The third one is if the vehicle range is greater than or equal to two times the path length, then a single station at any point can refuel the entire path. However, these logics are available only when the vehicle has regained its full fuel or charge level (for maximum range) after each period of refueling/recharging at the stations, for example via fuel-tank or battery exchange, which makes the newer approach difficult to apply with regard to multiple types of stations with different refueling or recharging efficiencies. In addition, this approach cannot solve the capacitated location problem. Basically, such models do not consider the factors of refueling or recharging efficiency and time, and are limited to the location of a single type of station for performing the battery or fuel-tank exchange (or very fast refueling) to refill the vehicles.

Different from the maximum-coverage type models, Wang and Lin (2009) proposed a flow-based set covering model for economically siting fast-refueling stations, such as battery exchange or hydrogen refilling stations. The model was formulated based on vehicle refueling logics which can ensure the alternative fuel vehicle has sufficient fuel to move between the nodes, and a feasible path can then be achieved. The model can also be solved in one stage, i.e. it does not need to predetermine the feasible combination of stations, like the original FRLM does. In addition, this approach does not need the fuel or charge level after each refueling or recharging to be full, and thus has more flexibility with regard to different situations. Wang and Wang (2010) extended Wang and Lin's model and proposed a bi-objective one by combining the flow-based set covering model and classic set covering model to simultaneously consider intercity (path flow demands) and intra-city travel (the nodal demands). Later, the flow-based set covering model was extended to consider battery recharging efficiency and time to locate sufficient slow-recharging stations for electric scooters traveling in a destination area (Wang, 2011). However, these models still adopt a set coverage approach for locating a single type of refueling stations.

This study extends the slow-recharging station location model (Wang, 2011) based on the flow-based set covering model (Wang and Lin, 2009) by considering facility budget constraints, multiple types of recharging stations, and vehicle routing behavior, and then proposes more generalized models with the characteristics of maximum-coverage and set-coverage to locate multiple types of refueling stations for the (maximal) coverage of battery (or non-battery) powered EV journeys on each path. At each site along paths, multiple types of charging stations, for example, including slow-recharging, fast-recharging, and battery exchange stations, would be candidates to locate based on consideration of the station locating cost, recharging efficiency and time (i.e. the specific extended range), and vehicle routing behavior. In addition, the available refueling time (also the length of stay) at each site can be divided into three categories, including the sight-seeing or recreational time at attractions, the battery switching time at convenience stores, and the normal refueling time at common sites (similar to the refueling time at gasoline stations). An EV can be refueled by using the refueling time and refueling rate at a specific type of station to increase its range for the movement between sites, and different vehicle ranges are also considered in the models.

Each path will consist of a sequence of visiting points to emphasize that the vehicles depart from the origin point and visit specific points, such as tourist attractions, and then return to designated points, but not necessarily the original one. In this way, the set of routes can include the shortest paths of the single origin–destination round trips, but need not be limited to them, and can also include tours of various kinds.

This study next introduces the formulation of the facility location problem for the placement of multiple types of recharging-stations at various nodes. Section 3 of this paper then applies this model to a case study of Penghu Island in Taiwan, and the solutions produced by the new model are compared with that produced for siting a single type of recharging station. The final section provides a discussion of the results and the conclusions of this work.

2. Model formulation

Wang (2011) proposed the slow-recharging station location model based on the flow-based set covering model proposed by Wang and Lin (2009) to determine the station locations for serving tourism transport using battery-powered electric scooters (ES). The model already considers the parameters of battery recharging efficiency and time. The specific recharging efficiency (from the single type of recharging station) and time were used to determine the replenished energy and the number of station locations. To clarify the relationship between the fuel consumption or refueling and riding distance, an ES field-test was undertaken (Yu and Lu, 2013). The experimental data showed that the relationship between residual charge and riding range is almost linear, and thus the charge consumed per unit riding distance is nearly constant. The experimental results also showed that after riding 5 km the original state of charge can be recovered by 10 min recharging in the situations of 40%, 50%, and 60% residual charge. Similarly, after riding 15 km it can be recovered by 30 min recharging. Therefore, the extended riding distance per minute charged is almost constant, at around 0.5 km, and so a linear recharging rate over time is assumed. To locate multiple types of recharging stations, multiple recharging rates should also be considered in the model.

In addition, some planning situations exist where it is impossible to satisfy the entire refueling demand, due to resource or budget constraints, and thereby the maximum coverage models will probably be a more appropriate choice for station location plans (Wang, 2011). Wang's set-coverage model is based on the assumption that there is sufficient budget to cover the overall flow demand on paths, and it is necessary to further consider budget constraints when developing a new maximum-coverage one. Moreover, almost all the proposed models assume that the traveling path is a round trip on a single path (Berman et al., 1992; Capar and Kuby, 2012; Hodgson, 1990; Kuby and Lim, 2005; Lim and Kuby, 2010; Wang and Lin, 2009; Wang and Wang, 2010). That is, a node or point will be revisited again in the return trip. However, in practice a node or point may not necessarily be revisited again in a journey, such as those that occur in tourism and delivery travel, and this behavior should be considered in the model. To solve these problems, new location models are thus proposed based on the relaxation of certain assumptions, including multiple recharging stations (i.e. multiple recharging rates), budget constraints, and the consideration of practical vehicle routing behavior. The key notations used in the model are as follows.

Indexes	
p	Paths
i, j	Nodes or locations
k	Type of recharging stations
Sets	
P	Set of all paths
N	Set of all nodes (potential locations)
K	Set of all types of recharging stations
Parameters	
c_i^k	Cost of locating a type k recharging station at node i
d_{ij}	Distance (km) between node i and node j
β^k	Recharging rate of type k station; the increased driving distance per min recharge (km/min)
γ	Battery's maximal state of charge, which is equivalent to the EV range (km) using the full charge (energy)
u_i^k	The locating capacity at node i (the maximum number of type k stations that can be located at this node)
w^p	EV flows on path p
t_i^p	Length of stay (also possible recharge time (min)) at node i on path p
ℓ	Budget for siting recharging stations
s^k	Vehicle sharing of a type k recharging station
Decision variables	
F^p	If the path p is covered (EV flows on a path can be served by the sited stations), $F^p = 1$, otherwise $F^p = 0$
X_i^k	If there are type k stations located at node i, $X_i^k \geqslant 0$, otherwise $X_i^k = 0$
Y_{ik}^p	If an EV is recharged using a type k station at node i on path p, $Y_{ik}^p = 1$, otherwise, $Y_{ik}^p = 0$
B_i^p	The available range (km) using the remaining charge (energy) in the battery at node i on path p
R_i^p	The increased range (km) using the energy being recharged in the battery at node i on path p

With these notations, the problem of siting multiple types of recharging stations can be formulated as follows:

$$\text{Maximize} \sum_{p \in P} F^p w^p \tag{1}$$

Subject to

$$B_j^p = (B_i^p + R_i^p) - F^p d_{ij} \quad \forall i, j \in N, \forall p \in P, \tag{2}$$

$$R_i^p \leqslant \gamma - B_i^p \quad \forall i \in N, \forall p \in P, \tag{3}$$

$$R_i^p \leqslant \sum_{k \in K} (Y_{ik}^p t_i^p \beta^k) \quad \forall i \in N, \forall p \in P, \tag{4}$$

$$R_i^p \leqslant F^p \gamma \quad \forall i \in N, \forall p \in P, \tag{5}$$

$$\sum_{k \in K} Y_{ik}^p \leqslant 1 \quad \forall i \in N, \forall p \in P, \tag{6}$$

$$s^k X_i^k \leqslant \sum_{p \in P} (Y_{ik}^p w^p) \quad \forall k \in K, \forall i \in N, \tag{7}$$

$$X_i^k \leqslant u_i^k \quad \forall k \in K, \forall i \in N, \tag{8}$$

$$\sum_{k \in K} \sum_{i \in N} c_i^k X_i^k \leqslant \ell \tag{9}$$

$$F^p, Y_{ik}^p \in \{0, 1\} \quad \forall k \in K, \forall i \in N, \forall p \in P, \tag{10}$$

$$X_i^k, B_i^p, R_i^p \geqslant 0 \quad \forall k \in K, \forall i \in N, \forall p \in P, \tag{11}$$

The objective function (1) is to maximize the coverage of EV flows on paths by the siting of multiple types of stations. Constraint (2), derived from the vehicle refueling logic (b) (Wang and Lin, 2009), states that when an EV travels from node i to node j on a path (if $F^p = 1$), the available range using the remaining energy at node j is equal to the available range using the remaining energy at node i, plus the increased range using the energy via the recharge (if any) at node i, minus the traveling distance (the energy consumed) between them. In contrast, if $F^p = 0$, EV did not move from node i to node j on a path. That is, the path will not be covered. F^p is the critical variable to determine whether or not a path is covered, and the formula is derived from the previous one, $B_j^p = (B_i^p + R_i^p) - d_{ij}$ (Wang and Lin, 2009). Constraint (3), derived from the vehicle refueling logic (c) (Wang and Lin, 2009), represents the increased range using the energy replenished at a node, which must be less than or equal to the consumed energy (i.e. the range with full battery energy, minus the available range using the remaining energy at a node). Constraint (4) means that the increased range using the actual energy recharged at a node on a path is less than or equal to the increased range using the whole replenished energy at a specific recharging rate during the length of the visit. For example, if an EV (with a range of 40 km) with enough remaining energy to travel 10 km is recharged for 30 min at a recharging rate of 2 (km/min) at a station, its increased range is only 30 km before leaving. In this case, constraint (3) will force the replenished energy (R_i^p) to be less than or equal to 30 km (40–10 km). Therefore, the practical refueling time and energy replenished are 15 min and 30 km instead of 30 min and 60 km, respectively. Constraint (5) states that if a path cannot be covered (if $F^p = 0$), the increased range at each node on the path must be zero. Since $F_p = 0$, the right hand side of constraint (5) will be zero, and thus force R_i^p to be zero. If $F^p = 1$, the increased range is less than or equal to the EV range (γ). Constraint (6) indicates that an EV on a path can only use one type of station to refuel at a node. Constraint (7) states that the number of each type of station sited at node i is equal to the number of EV being recharged using that type station at the node. The sharing of a type k station can be considered via the s^k parameter. Constraint (8) means that the number of each type of recharging station located at a site must less than or equal to the locating capacity (i.e. maximum number of type k stations being sited) for each type of station. The limitations of local power and land use can be considered via the parameter of u_i^k. Constraint (9) is the resources or budget constraints used to limit the number of all types of recharging stations being sited. Constraint (10) indicates that F^p and Y_{ik}^p are 0 or 1 integers. Constraint (11) requires that the variables of X_i^k, B_i^p, and R_i^p are not less than zero.

In the present model, constraints (2) to (4) ensure that if $F^p = 1$, an EV can move between nodes with sufficient energy from the original point to the destination. The model can thus be applied to any type of traveling path, not only to the shortest path of specific original-destination round trips assumed in previous models, such as FRLM. In addition, since the model considers the battery recharging rate and time, it can simulate the battery's state of charge (energy) at each site to further determine the locations of multiple types of stations. Moreover, when the recharging rate is high enough, such as 10 km/min, the battery recharging time is significantly shortened, and can be neglected ($t \to 0$). In this situation, the battery recharging behavior is quite similar to the battery-exchange or DC fast recharging one. Constraint (4) can be reduced to $R_i^p \leqslant \sum (Y_{ik}^p \beta^k)$ (where β^k is the range of EV instead of the rate of recharging), as used in Wang and Lin's model (2009). In fact, no matter whether battery recharging (slow and fast) or exchange is used, the refilling time is still a critical factor in the practical use of EVs. Including the recharging time in the model formulation is also a simple way to represent the characteristics of battery replenishment for different types of recharging station, such as battery recharging and exchange ones. Therefore, the model can be used to locate multiple types of recharging stations. In addition, the battery's state of charge (energy) at the original point can be set to any positive integer (via B_0^p) which is less than or equal to the range of the EV. This means that the planner can determine the parameters based on the actual situations of EV energy at each starting point.

In facility location planning, there may be sufficient budget to meet the entire demand on all paths. Therefore, how to economically determine the number and location of multiple refueling stations to serve the flow demands on each path is the problem addressed in this work. The formulas used to achieve this are as follows.

$$\text{Minimize} \sum_{i \in N} \sum_{k \in K} c_i^k X_i^k \tag{12}$$

$$B_j^p = (B_i^p + R_i^p) - d_{ij} \quad \forall i, j \in N, \forall p \in P, \tag{13}$$

Constraints (3–4), (6–7), (10) and (11).

The objective function (12) is to minimize the total cost of locating multiple recharging stations. Since the total path demand will be covered, the F^p will be equal to one. Formula (2) can be reduced to formula (13). The other constraints are as described above.

3. Case study

Since the new model is extended from the slow-recharging station location model (Wang, 2011), the case of Penghu Island's recharging station planning is used again to test it and contrast the solutions thus derived with those from the previous work.

3.1. Data acquisition

Penghu Island, located off the coast of Taiwan, has abundant natural resources, such as a good windfield, and was selected as an example of a low-carbon island by the Taiwanese government in its low-carbon island plan, which began in 2010. Due to the significant emissions from the transportation sector, green transport is a critical part of this plan. At present, there are about 1600 ES on the island, some of which are used for vehicle rental, and thus the rental firms need to deploy sufficient battery exchange or recharging stations on the popular routes to enable the ES to complete their journeys. In addition, the rental firms have undertaken strategic alliances with local convenience stores (7-Elevens) to site the battery recharging and exchange stations.

Fig. 1 shows a network representation of the popular scenic touring routes on Penghu Island. This network extends the original one described in Wang (2007, 2008) to include the eastern and southern central traveling routes. In the network, there are three types of possible locations or nodes, including the attractions (nodes D1, D2 ... D12) marked with triangles, intersections (nodes A, B, C, D and E) marked with circles, and convenience stores (nodes S1, S2 ... S8) marked with rectangles. Basically, at the attractions only slow-recharging stations (SRS) can be sited, while the intersections are for the fast recharging ones (FRS). The convenience stores can have battery exchange stations (BES), SRS, and FRS. The distribution of recreational trips along the popular routes is shown in Table 1, with 12 popular paths. The lengths of the paths are all over the range of the ES (approximately 40 km when fully charged), and thus the vehicles need to be recharged to complete these journeys. The maximal flows per hour for each path are between two to four electric scooters, according to one survey in Wang et al. (2002). Also from the same survey, tourists' average stays (and also possible recharging times) at Citou (D1),

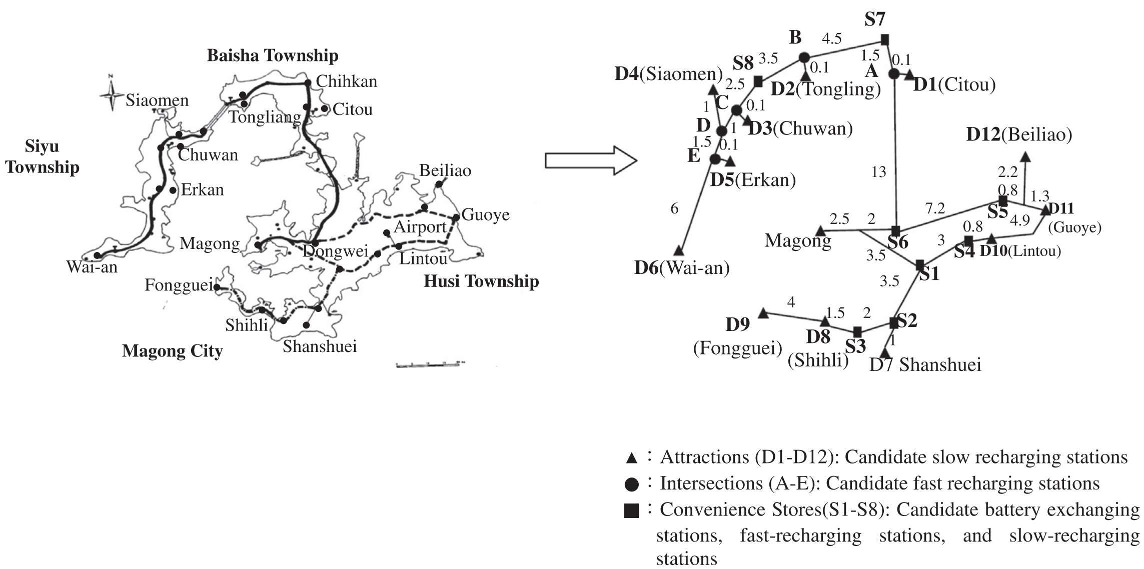

Fig. 1. Candidate sites. (a) Locations on the map, and (b) a network representation.

Table 1
Trip distributions along popular routes.

No.	Type of routes	Distance (km)	Maximum flow (scooters/h)
1	Magong → Citou → A → Tongling → B → Chuwan → C → Siaomen → D → Erkan → E → Wai-An → S8 → S7 → S6 → Magong	78.8	3
2	Magong → Citou → A → Tongling → B → Chuwan → C → Siaomen → D → E → Erkan → S8 → S7 → S6 → Magong	66.8	3
3	Magong → Citou → A → Tongling → B → C → Chuwan → S8 → S7 → S6 → Magong	59.6	3
4	Magong → A → Tongling → B → C → Siaomen → D → E → Erkan → S8 → S7 → S6 → Magong	66.4	3
5	Magong → A → B → Chuwan → C → Siaomen → D → E → Wai-An → S8 → S7 → S6 → Magong	78.2	3
6	Magong → A → B → C → Siaomen → D → E → Wai-An → S8 → S7 → S6 → Magong	78	4
7	Magong → Citou → A → B → C → D → Siaomen → S8 → S7 → S6 → Magong	63.2	2
8	Magong → A → Tongling → B → C → Chuwan → S8 → S7 → S6 → Magong	59.4	2
9	Magong → A → Citou → B → C → D → E → Wai-An → S8 → S7 → S6 → Magong	76.2	2
10	Magong → Citou → A → Tongling → B → C → D → E → Wai-An → S8 → S7 → S6 → Magong	76.4	2
11	Magong → S6 → S5 → Beiliao → Guoye → Linto → S4 → Fonggeui → S3 → S2 → S1 → Magong	54.9	2
12	Magong → Shanshuei → Shihli → Fonggeui → S3 → S2 → S1 → S4 → Lintou → Guoye → Beiliao → S5 → S6 → Magong	56.9	2

Tongliang (D2), Chuwan (D3), Siaomen (D4), Erkan (D5), Wai-an (D6), Shanshuei (D7), Shihli (D8), Fonggeui (D9), Lintou (D10), Guoye (D11), and Beiliao (D12) are 56, 19, 22, 28, 33, 30, 30, 25, 20, 32, 28, and 28 min, respectively. The average times spent at the nodes of the intersection points and convenience stores are around 20 and 10 min, respectively.

In addition, the cost of each station location mainly depends on the cost of land use, charging equipment, and battery backup and delivery (for exchange stations). In general, the cost of a slow-recharging station is far less than that of a fast-recharging one, while the cost of battery exchange station is linearly related to the number of the batteries needed to meet demand. However, the actual cost of each type of recharging station still needs more exact calculations. In this study, suppose that the locating cost of slow-recharging, fast-recharging, and battery exchange stations are NT$4000, 50,000, and 20,000, respectively. In addition, the estimation of the recharging rate for each type of station is based on the recharging time of the battery, from empty to full charge. The rates (km/min) for slow-recharging, fast-recharging, and battery exchange stations are thus 0.133, 2, and 4, respectively. These data are used as the inputs for the model.

Given that the location model was established using a mixed integer program, LINGO's BRANCH and BOUND method (Thornburg and Hummel, 2003) is used to obtain the solutions, running on a computer with Windows XP 32-Bit OS, Intel (R) Core (TM) 2 CPU at 3.4 GHz with 3 GB of RAM.

3.2. Solutions for the set-coverage based model

On the assumption that the budget was sufficient to meet the entire demand on the paths, the solutions listed in Table 2 were obtained using the following parameters: the range of the ES (40 km), the battery's state of charge at the original point (fully charged: 40 km), recharging rates for the slow-recharging, fast-recharging, and battery exchange stations (0.133, 2, 4), vehicle sharing of a type k station is set at 1, the capacity of locating each type of station at each site (5, 6, 7, 8, 9, and 10), the locating cost for slow-recharging, fast-recharging, and battery exchange stations (as mentioned above), and the length of stay at the sites (as mentioned above)). The locations of multiple types of stations, in the cases of the ranges of 40 and 50 km together with capacities of 5 and 10, are shown in Fig. 2.

In Table 2, the optimal station location plans have the multiple recharging stations sited to cover the overall path refueling demand with the minimum cost, and the stations sited at the locations of convenience stores currently exist, for example, in the case of a capacity of 5, with 15 stations sited at location S8, including 5 slow-recharging stations, 5 fast-recharging ones, and 5 battery exchange ones.

In addition, when the capacity of each site increases from 5 to 10, the number of stations being sited increases from 49 to 57 for SRS, decreases from 17 to 7 for FRS, and increases from 10 to 20 for BES. Because of the higher locating cost for fast-recharging stations, the present set-coverage based model with the objective of minimizing the locating cost will tend to select the location of slow-recharging and battery-exchange stations. With regard to the changes (from 76 to 84) in the total number of stations, the locating cost falls from NT$1,246,000 to NT$978,000. A higher station capacity will lead to greater reductions in the locating cost.

As seen in Fig. 3, when the recharging rate falls from 2 to 0.6 (km/min), the total number of multiple stations increases from 84 (57, 7, and 20) to 116 (85, 11, and 20), although the increase in the number of slow-recharging stations, from 57 to 85, is more significant. Due to the decrease in the recharging rate when using fast-recharging stations at intersections, more slow-recharging stations need to be located at the attractions to recharge the ES.

In Fig. 4, when the unit cost of a battery exchange station increases from NT$10,000 to NT$60,000, the number of multiple stations increases from 72 (41, 7, and 24) to 110 (89, 21, and 0), and the reduction in the number of battery-exchange stations and increase in the number of slow-recharging stations are more significant. With regard to the station cost of NT$

Table 2
The number and locations of recharging stations for different capacities with a vehicle range of 40 km.

Location capacity	Location (number of SRS)	Location (number of FRS)	Location (number of BES)	Total number of stations (SRS, FRS, BES)	Total location cost (NT$)
5	D1(5), D2(4), D3(3), D5(3), D6(4), D7(2), D10(4), D11(4), D12(4), S4(2), S6(5), S7(4), S8(5)	S8(5), C(3), D(4), E(5)	S7(5), S8(5)	76(49, 17, 10)	1,246,000
6	D1(5), D2(5), D3(5), D4(6), D5(6), D6(6), D7(2), D10(4), D11(4), D12(4), S4(2), S6(6), S7(6), S8(6)	S8(4), D(6) E(3)	S6(3), S7(5), S8(6)	94(67, 13, 14)	1,198,000
7	D1(6), D2(5), D3(2), D6(6), D7(2), D10(4), D11(4), D12(4), S1(2), S6(3), S7(6), S8(7)	D(7), E(6)	S7(7)S7(7), S8(8), S8(7)	78(51, 13, 14)	1,134,000
8	D1(8), D2(5), D3(3), D4(5), D5(6), D6(8), D7(2), D10(4), D11(4), D12(4), S1(2), S6(7), S7(8), S8(8)	D(2), E(7)	S7(7), S8(8)	98(74, 9, 15)	1,046,000
9	D1(7), D2(5), D3(3), D4(9), D5(9), D6(9), D7(2), D10(4), D11(4), D12(4), S4(2), S6(6), S7(6), S8(9)	E(7)	S7(8), S8(9)	103(79, 7, 17)	1,006,000
10	D1(9), D2(2), D3(3), D4(3), D5(6), D6(6), D7(2), D10(4), D11(4), D12(4), S2(2), S6(4), S7(3), S8(5)	D(4), E(3)	S7(10), S8(10)	84(57, 7, 20)	978,000

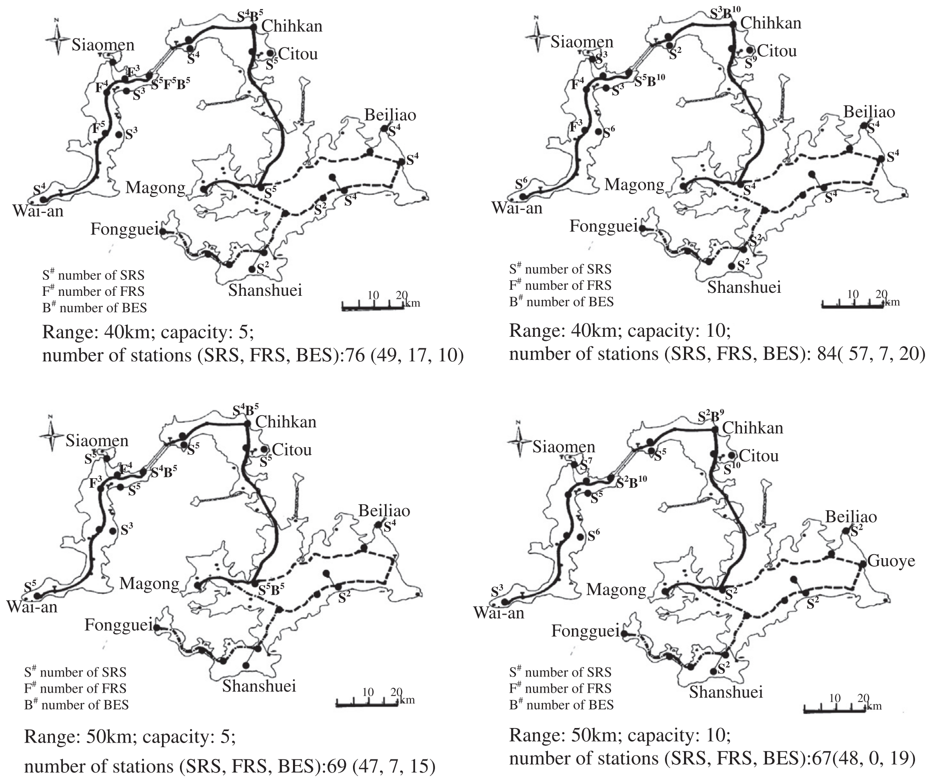

Fig. 2. The maps of station locations in the cases of ranges of 40 and 50 km, with capacities of 5 and 10.

50,000, 10 more fast-recharging stations need to be deployed to replace the 10 less battery exchange stations to recharge the ES. When the station cost is up to NT$60,000, no battery-exchanging stations are used, as they are all replaced by the fast-recharging ones.

Fig. 5 shows that as the vehicle range increases, the locating cost decreases for different deployment methods. For example, with respect to the locations of multiple stations (convenience store mixed, i.e. mixed stations located only at convenience stores), the locating cost decreases from NT$978,000 to 296,000 when the range increases from 40 to 60 km. Since the number of recharging stations required to service all routes mainly depends on the vehicle range, the greater this range, the fewer recharging stations that are needed to accomplish all journeys. The vehicle range is thus crucial for determining the optimal number and locations of stations, regardless of whether single or multiple types of stations are used. Slow-recharging stations have the lowest unit cost, while fast-recharging ones have the highest. Ideally, the locations of slow-recharging stations will have lowest locating cost. However, since the completion of a journey is mostly affected by the practical recharging rate, recharging time and vehicle range, siting slow-recharging stations probably cannot meet the

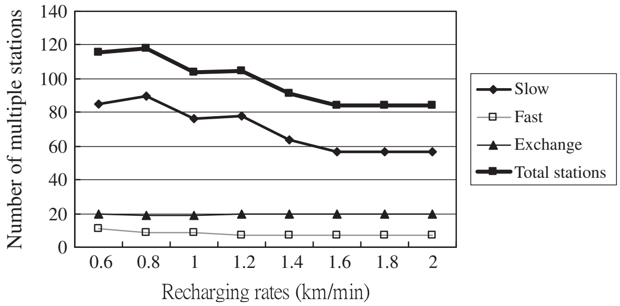

Fig. 3. The number of multiple stations for fast-recharging stations with different recharging rates.

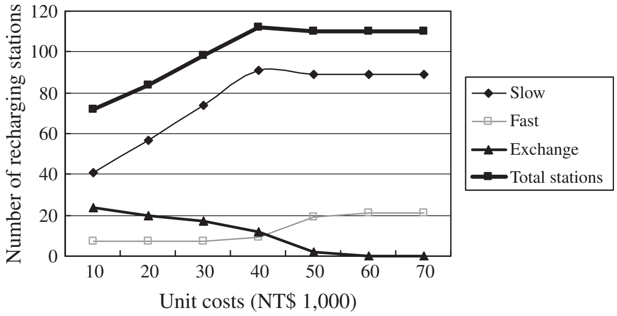

Fig. 4. The number of multiple stations for different unit cost of battery exchange station, with unit costs of slow- and fast recharging stations set at NT$4000 and NT$50,000.

overall recharging demand on the paths. For example, with the lower recharging rate of 0.133 at slow-recharging stations, in some vehicle ranges, such as 40 to 55 km, the station locations cannot ensure the completion of entire ES journeys, as shown in Fig. 6. That is, there are no solutions to the model when the range is below 60 km, as shown in Fig. 5. In contrast, the use of multiple stations or fast-recharging or battery exchange ones can guarantee the completion of all journeys.

Fig. 5 shows that the use of multiple types of stations will lead to the lowest locating cost. The figure also shows that the locating cost when using the partially mixed stations (i.e. convenience store mixed) is higher than the cost of using battery exchange stations alone when the vehicle range is below 55 km. However, if the mixed stations are located at the overall candidate sites, the locating cost will be the lowest. For example, with respect to the range of 40 km, the costs for a network of mixed stations and battery exchange ones are NT$652,000 and 740,000, respectively. In addition, the locations of multiple stations will enable ES users to choose which type of station to visit based on their recharging demand or preferences.

3.3. Solutions for the maximum-coverage based model

On the assumption that the budget is insufficient to meet the entire demand on all paths, the solutions listed in Table 3 were obtained using the following parameters: the range of the ES (40 km), the battery's state of charge at the original point

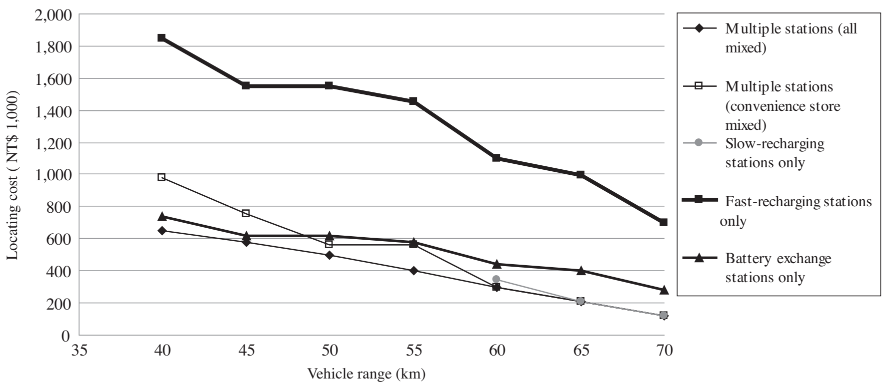

Fig. 5. The relationship between the vehicle range and the locating cost for different deployment methods, with the capacity of 10 for each type of station.

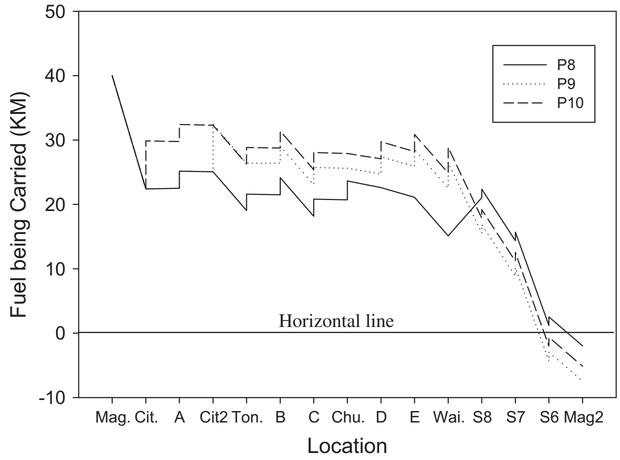

Fig. 6. Some paths uncovered (below horizontal line) with a range of 40 km.

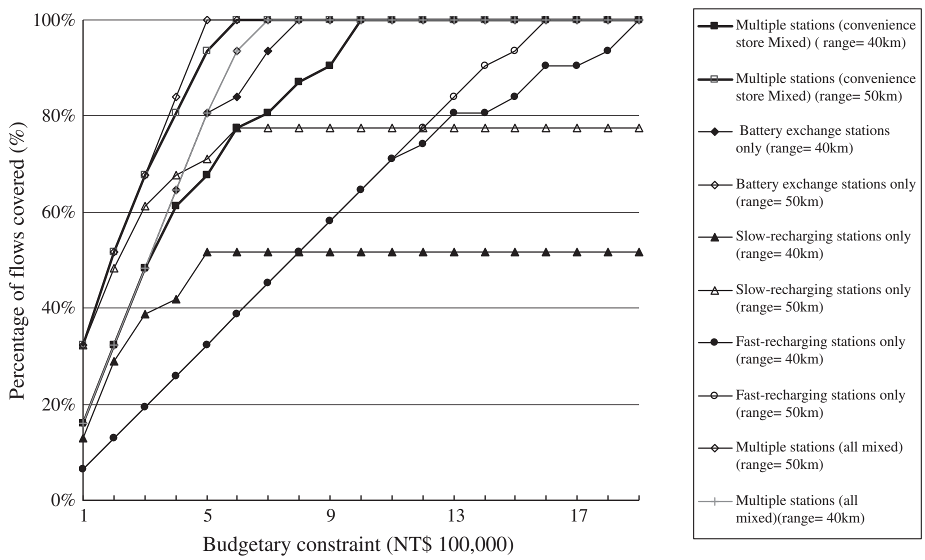

Fig. 7. The tradeoff between the budget and percentage of flows covered for different vehicle ranges and deployment methods.

(fully charged: 40 km), recharging rates for the slow recharging, fast recharging, and battery exchange stations (0.133, 2, and 4), vehicle sharing of a type k station is set at 1, the capacity for locating each type of station at each site (10), locating cost for slow-recharging, fast-recharging, and battery exchange stations (as mentioned above), and the length of stay at sites (as mentioned above), and budgetary constraints (from NT$100,000 to 978,000). Table 3 shows that when the budget increases from NT$100,000 to 978,000, the percentage of path flows being served increases from 5% to 100%. In addition, the mixed location of different types of recharging stations is still carried out, no matter what budget constraint is used. For example, with respect to the budget of NT$300,000, to cover 48.8% of the flows three SRS and eight BES need to be sited at the S8 convenience store. In theory, the budget needed to cover 100% of the flows when using the maximum-coverage based model is same as the locating cost when using the set-coverage based one, and in this case this is NT$978,000. Although the cost is the same, the number and location of stations using the set-coverage based model are different from those with the maximum-coverage one. For example, some station locations, such as D3(3), D6(6), S2(2), S7(3), S8(5), D(4), and E(3), as shown in Table 2, can be changed to D6(5), S4(2), S7(4), S8(8) and E(7), as shown in Table 3. That is, there are alternate optimal solutions to this problem (Wang and Lin, 2009).

Fig. 7 shows the tradeoff between the budget and the percentage of path flows served for different vehicle ranges and deployment methods. The higher the percentage of path flows that are covered, the higher the cost. In Fig. 7, if only a single type of slow-recharging stations is deployed, the maximal percentage of flows covered just can reach 51.6% and 77.4% for the ranges of 40 and 50 km, respectively, due to the lack of coverage of some path flows, such as paths 5, 6,

Table 3
The number and location of recharging stations, and the percentage of path flows covered for different budgets, with a vehicle range of 40 km, and the station capacity of 10.

Budgetary constraint (NT$)	Location (number of SRS)	Location (number of FRS)	Location (number of BES)	Total number of stations (SRS, FRS, BES)	Path covered	Number of flows covered (percent)
100,000	–	–	S8(5)	5(0, 0, 5)	P3, P7	5 (16.1%)
200,000	D10(2), D11(2), D12(4), S3(2)	–	S8(8)	18(10, 0, 8)	P2,P3,P7,P11	10 (32.3%)
300,000	D1(3), D2(3), D3(3), D7(2), D10(4), D11(4), D12(4), S3(2), S6(3)S7(3), S8(3)	–	S8(8)	42(34, 0, 8)	P2,P3,P4,P8,P11,P12	15 (48.4%)
400,000	D1(7), D6(2), D7(2), D10(4), D11(4), D12(4), S3(2)	–	S7(5), S8(10)	40(25, 0, 15)	P2, P3, P4, P7, P8, P10, P11, P12	19 (61.3%)
500,000	D1(6), D3(3), D5(3), D6(4), D7(2), D9(2), D10(4), D11(4), D12(4), S8(6)	–	S7(8), S8(9)	55(38, 0, 17)	P2, P3, P4, P7, P8, P9, P10, P11, P12	21 (67.7%)
600,000	D1(9), D2(5), D4(3), D5(6), D6(2), D7(2), D9(2), D10(4), D11(2), D12(2), S1(2), S3(2), S5(2), S6(2), S7(3), S8(2)	–	S7(10), S8(10)	70(50, 0, 20)	P1, P2, P3, P4, P7, P8, P9, P10, P11, P12	24 (77.4%)
700,000	D1(10), D4(3), D5(6), D6(7), D7(2), D10(4), D11(4), D12(4), S1(2), S8(5)	E(3)	S7(8), S8(10)	68(47, 3, 18)	P1, P2, P3, P4, P5, P8, P9, P10, P11, P12	25 (80.6%)
800,000	D1(9), D2(5), D3(6), D5(6), D6(8), D7(2), D10(4), D11(2), D12(4), S3(2), S5(2), S6(2), S7(3), S8(5)	E(3)	S7(10), S8(10)	83(60, 3, 20)	P1, P2, P3, P4, P5, P7, P8, P9, P10, P11, P12	27 (87.1%)
900,000	D1(7), D2(5), D3(3), D4(3), D5(3), D6(8), D7(2), D10(4), D11(2), D12(4), S1(2), S3(2), S5(2), S6(6), S7(10), S8(3)	E(7)	S7(5),S8(9)	87(66, 7, 14)	P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12	28 (90.3%)
974,000	D1(5), D4(3), D5(6), D6(6), D10(2), D11(2), D12(2), S3(2), S7(10), S8(8)	D(4), E(3)	S2(2), S4(2), S7(8), S8(10)	75(46, 7, 22)	P1, P2, P3, P4, P5, P6, P7, P8, P9, P11, P12	29 (93.5%)
978,000	D1(9), D2(2), D4(3), D5(6), D6(5), D7(2), D10(4), D11(4), D12(4), S4(2), S6(4), S7(4), S8(8)	E(7)	S7(10), S8(10)	84(57, 7, 20)	P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12	31 (100%)

7, 8, 9, and 10 for a range of 40 km, and paths 5 and 6 for a range of 50 km. Therefore, to cover the overall vehicle flows, the location of multiple stations (partially or all mixed) or battery-exchange or fast-recharging stations are needed. However, due to the higher station cost, reaching the same coverage ratio with fast-recharging stations is more expensive than with multiple stations (for either partially or all mixed stations). In addition, with respect to a specific budget, vehicles with a higher range will have a higher percentage of flows covered. For example, with the deployment of multiple stations and a budget of NT$50,000, the percentage of flows covered is 94% for vehicles with the range of 50 km, which is significantly more than the ratio of 67.5% for those with a range of 40 km. From the viewpoint of cost effectiveness (the percentage of flow covered with respect to a budget), the location of multiple stations (i.e. mixed stations sited at all candidate locations) is significantly better than the location of a single type of stations, no matter whether they are slow-recharging, fast-charging or battery-exchange ones. For example, with respect to the range of 50 km and the budget of NT$500,000, the percentage of flows covered is 100%, 93.54%, 80.64%, 70.96%, and 32.25% for the location of all mixed stations, partially mixed stations, battery-exchange stations, slow-recharging stations, and fast-recharging stations, respectively.

4. Conclusions

Due to the limited range of electric vehicles, the establishment of a refueling infrastructure is necessary to ensure that travelers can achieve their journeys. In practice, to increase the convenience and choice of road users, the siting of sufficient, multiple types of recharging stations is the main task of facility planning. This study extended the slow-recharge station location model presented in Wang (2011), and used the concepts of set coverage and maximum coverage to formulate capacitated multiple-recharging-station-location models using a mixed integer programming method, based on a vehicle-refueling logic (Wang and Lin, 2009). The results of the case study demonstrate that the approach presented in this work can achieve the optimal deployment for a specific area, regardless of whether the minimum locating cost or maximum traffic flows are considered, and further that a mixed stations location plan is the optimal one, when compared to the location of a single type of recharging station, from the viewpoint of system cost or cost effectiveness.

The contributions of the paper to the literature are that it relaxes the constraints of using a single type of recharging station and sufficient budget in Wang's model (2011) in order to offer greater convenience and choice to travelers, as well as cost effective facility planning based on a limited budget. To the best of our knowledge, previous studies assume that a single type of refueling station will be used (Hodgson, 1990; Berman et al., 1992; Kuby and Lim, 2005; Wang and Lin, 2009; Wang and Wang, 2010; Wang, 2011), while this work presents a location model for multiple types of recharging stations. Moreover, the proposed models can be applied to any type of routing behavior, and can relax the assumption of the shortest path of single origin–destination round trips used in most of previous studies, such as those that employed the FCLM and FRLM models. The new maximum-coverage based model, which considers the battery's recharging rate and time, as well as vehicle range, can simulate the changes in an EV's stored energy at each site to determine the combination of recharging stations and their locations needed to cover the maximal flows of such vehicles, which is not easy to achieve with conventional models, such as FCLM and FRLM.

The results of the sensitivity analysis show that the greater the vehicle's range, the fewer the number of stations that need to be sited, although the recharging efficiency and capacity are also factors that influence this number and the sites' locations. In addition, since the objective is the minimum locating cost or the maximal flows covered with a specific budget, the station cost is a critical factor when it comes to selecting the type of recharging stations used. Therefore, how to increase the range of an EV and decrease the station cost are critical to achieving an effective reduction in the costs of the recharging infrastructure, and important for the future development of this technology (Wang and Lin, 2009).

Although the proposed models with a single objective, such as minimum cost or maximum flow, can achieve cost effectiveness from the viewpoint of the supplier, the vehicle users may be concerned as to whether the infrastructure is easy to access and the recharging time is short enough. In future work, the single objective used in this study can be extended to multiple ones, such as also minimizing the total recharging cost or time from the viewpoint of users to determine the optimal composition of station locations. In addition, the pricing of charging services still needs to be explored in order to assess the effects of charging cost or time on the location of stations. Furthermore, the impacts of the refueling system on the existing grid or electrical power systems also need to be identified. Finally, although the case of Penghu Island is a small-scale problem and the solution time in most of cases is less than 2 min, in some cases the time can be up to 60 min for the set coverage based model, due to the consideration of recharging rate and time, mixed stations, and also the refueling logics (Wang and Lin, 2009). The performance of the proposed models when used with a large-scale network still needs to be examined, and mostly likely also needs to be improved.

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