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Locating passenger vehicle refueling stations

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ABSTRACT

The study follows the concept of set cover and vehicle refueling logics to propose a hybrid model with dual objectives, using a mixed integer programming method, to economically site refueling stations to simultaneously serve intercity and intra-city travel. The model can be applied to plan a network of refueling stations for the emerging and/or monopolistic automotive market of alternative fuel vehicles. From a real-life case study, the factors of vehicle range and coverage distance are identified as playing important roles in any solution. Based on the non-inferior solutions, decision makers can thus better formulate viable station-deployment plans.

1. Introduction

Today, 65% of global CO_2 emissions come from energy use, with 21% from transportation due to its dependence on fossil fuels (WRI, 2006). Moreover, the emissions from transportation are expected to rise in the coming years, particularly in developing countries (Bento, 2008). Policies to raise the use of renewable energy are thus being initiated as part of the global response to climate change. A key element in achieving such goals is to use renewable energy in the transportation sector (Lund and Clark, 2008). Alternative fuel vehicles can play an important role in addressing the challenges of climate change, energy security, urban air pollution and the continued growth in demand for transportation services (Melaina and Bremson, 2008). Nevertheless, the lack of refueling (or recharging) stations is one of the major barriers to the adoption of alternative fuel vehicles (AFV), especially dedicated AFV that operate on a single fuel (Melaina and Bremson, 2008; Romm, 2006; Kuby and Lim, 2005; Melaina, 2003). One problems is that a sufficient number of refueling stations is required before AFV can be widely adopted (Bento, 2008). AFV thus face a chicken-and-egg infrastructure dilemma: consumers will be reluctant to purchase vehicles until a sufficient number of refueling stations has been installed, while vehicle manufactures will not produce vehicles that consumers will not buy, and fuel providers will not invest in a new energy infrastructure until there is sufficient demand for it (Melaina, 2007, 2003; Kuby and Lim, 2005; Melaina and Ross, 2000; Leiby and Rubin, 2004; Sperling, 1988). Therefore, it is likely that governments will need to play a significant role in promoting any change to alternative fuels, although public support alone will not ensure the success of this transformation.

Melaina (2003) suggested some general criteria for identifying effective locations for early hydrogen stations, such as close to areas with high traffic volume, in places to provide fuel during long distance trips, at high profile locations to increase public awareness, and in places that are accessible to individuals who are buying their first fuel-cell vehicle. Two

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types of initial hydrogen stations can fulfill these criteria: stations in metropolitan areas (named "prime" stations), which can serve a high volume of customers undertaking urban short-distance trips, and stations located along interstate highways (named "placeholder" stations) for less frequent refueling events, such as those that occur during long distance trips. Both prime and placeholder stations are necessary to ensure consumer confidence in the reliability of the refueling network. For example, in the HyWays project, the early hydrogen user centers (analogous to metropolitan areas) and corridors (similar to interstate highways) were selected to form the part of European hydrogen energy roadmap (Stiller et al., 2008). Moreover, prime and placeholder stations can play a critical role in the gradual build-up of the refueling infrastructure. Melaina also proposed some simplified analysis methods to estimate the necessary numbers of refueling stations for two stages within the initial process, first for fuel-cell vehicle enthusiasts, and second for new vehicle buyers in metropolitan areas. Due to the large capital costs involved in infrastructure investment, economic factors are very important in determining the number and location of stations. Therefore, studies must work to provide a theoretical basis for station deployment, such as with a facility location model, to economically serve long- and short-distance trips with AFV.

A few previous studies have simultaneously considered the two types of demand in facility-location modeling, but none of them have provided completely satisfactory solutions to this problem. The first combined model was proposed by Goodchild and Noronha (1987) to site a finite number of gasoline outlets to maximize the refueling market share of a firm (the sum of residential and traffic demand), and it can be transferred to a p-median problem (minimizing the sum of demand-weighted distances from residential units and link points to the sited stations). This model assumes that residential demand with single-purpose (for refueling) trips, and traffic demand (centered at each link) form the basis for impulse purchases. However, because the model uses link flow data, not the origin–destination (O–D) flows, it suffers from the problems of double-counting and cannibalization of flows that pass over many links, and thus is unable to assess whether the entire path of a vehicle could be refueled (Kuby and Lim, 2005).

Hodgson and Rosing (1992) extended the flow capturing location–allocation model (FCLM) (Hodgson, 1990) to propose a hybrid model (flow capturing plus p-median) with two conflicting objectives for siting a finite number of refueling stations, namely maximum flows and minimum demand-weighted distance. This model supposed that a flow was captured by only one station along the shortest path (i.e., one-stop refueling to satisfy the demands of long-distance travel). Later, the FCLM model was extended by Kuby and Lim (2005) by considering the range limitation with an AFV to formulate the flow-refueling location model (FRLM) for maximizing the coverage of multi-stop refueling flows on long-distance tours along their shortest paths. However, these models require the O–D flow data, which is not easy to obtain in practical applications (Lin et al., 2008; Averbakh and Berman, 1996).

Current et al. (1985) formulated the Maximum Covering/Shortest Path Problem (MCSPP) with multiple objectives of maximum population coverage and minimum shortest path (cost) from a predetermined point of origin to the destination for network design and routing. Later, Bapna et al. (2002) extended the MCSPP to the Maximum Covering/Shortest Spanning Subgraph Problem (MC3SP) for siting unleaded gas stations to serve short-distance journeys within cities and make long-distance travel possible among large, populated cities. The model that was presented for this facility location problem had two conflicting objectives, minimum cost (the fixed costs associated with the enabling arc, plus the variable cost of traffic along that arc) and maximum coverage (populations on or near the enabling arc). However, two factors limit the applicability of this model. One is the roundabout paths obtained from the spanning subgraph due to the weights on the objectives. The other is the maximum-cover objective maximizes the population along the enabling arcs, not the volume of O–D flows that can refuel along their shortest path (Kuby and Lim, 2005).

Different from the location of non-competing or public-service facilities in earlier stage of AFV development (when there is low market demand) and/or when such services are operated in natural monopoly situations, some competitive facility location models have been proposed that consider two types of service demand (special-purpose trips and by-passing traffic), such as the flow intercepting spatial interaction model (Berman and Krass, 1998) and its variants (Berman and Krass, 2002; Aboolian et al., 2007). These models assume that there are some investors or competitors in the retail market (for example, gas stations, convenience stores, and so on) and thereby the determination of optimal facility locations for a (new) company is dependent on the set of existing competitor locations. Obviously, competition is the norm in a rapidly growing retail market, if the market has been liberalized. In contrast, in the period of low market demand, there are few companies interested in pursuing such investments at a national level due to the high initial cost and large uncertainties in demand uptake (Bento, 2008). Therefore, the government plays an important role in establishing a basic or demonstration network of non-competing or public-service facilities in order to foster the use of AFV. In addition, the flow interception based models are based on the integration of flow interception and spatial interaction models (i.e., gravity models). The flow interception models focus on situations where a significant portion of the demand for a service results from intercepting pre-existing customer flows (by at least one facility) (Berman and Krass, 1998). Assuming one-stop refueling can satisfy the refueling demand (in spite of special-purpose trips or by-passing traffic) explicitly indicates that the range limitation of an AFV is not necessarily considered in model formulation, or that vehicle performance, especially the range, has been accepted by the users (i.e., it approaches the range of gas-fueled vehicles) for their daily activities in that development stage. That is, in the stage of full commercialization or practical application, a considerable number of AFV (such as hydrogen-powered vehicles) should be in use, along with the infrastructure necessary to produce and distribute the alternative fuels (Bersani et al., 2009).

Obviously, demand in a such network is often of two types, and can be expressed by passing flows and by consumers centered in residential areas, aggregated as nodes (Hodgson and Rosing, 1992; Berman et al., 1992; Hodgson, 1990; Goodchild and Noronha, 1987). In this study, demand related to traffic flows from multiple origins on a multiple-stop tour to destinations represents intercity (long-distance) travel along national or provincial highways, while the demand at nodes represents intra-city (short-distance) travel along city roads from the users' home or place of work on a one-stop tour to a service facility, then a return journey by AFV. Ideally, an appropriate model should be able to fulfill both kinds of refueling demand. To consider the service of demand nodes in modeling, the notion of set coverage is used. The set covering problem is to find a minimum cost set of facilities from among a finite set of candidates, so that every demand node is covered by at least one facility (Toregas et al., 1971; Daskin, 1995). The demand nodes are said to be covered if the shortest path distance between a demand node and a facility is less than or equal to the coverage distance. The constraints (i.e., each node being covered by at least one facility) in the set covering model (Toregas et al., 1971) are modified slightly and employed to ensure that most of the nodal demands are covered. In addition, to consider the service of traffic flows, the notion of vehicle refueling logics (Wang and Lin, 2009) is utilized. These refueling logics or constraints (which can ensure the completion of long-distance travel along the actual shortest or reasonable paths of interest) in the refueling-station location model (Wang and Lin, 2009), which is a flow-based set covering one, are introduced to ensure adequate service of the traffic flows (intercity trips). Since both models are based on the concept of set cover (node- or flow-based), the (modified) constraints can be easily integrated to consider the service of both types of demand.

Based on this integration, this paper develops a new hybrid model with the duel objectives of minimum locating cost and maximum population coverage, using data on the distance matrix of O–D pairs, and extends Wang and Lin's model to also consider the population coverage at fixed points or locations. Instead of siting a finite number of facilities to have the maximum coverage of demand at fixed points and/or on the shortest paths, the model, following the objectives of MCSPP and MC3SP, focuses on refueling-station siting in order to serve intercity travel along the shortest paths of interest (among major populated cities) and cover most of intra-city travel at specific locations (within cities).

The present study next introduces the formulation of the facility location problem for the placement of refueling-stations at various nodes to serve the two types of demand. A practical case study based on the island of Taiwan is used to test the model and identify the important inputs and parameters. The final section provides a discussion of the results and the conclusions that can be drawn from them.

2. Model formulation

The formulation of the model focuses on the placement of refueling stations to serve intercity (long-distance) travel among the large cities and simultaneously cover intra-city (short-distance) trips. To avoid the problem of double-counting and cannibalization resulting from the introduction of link flows, the flows on the intercity tours along the shortest O–D paths among cities are considered, and it is assumed that the service capacity of each station is unlimited. That is, for a long-distance (AFV) flow on a network from an origin node i to a destination node j along the shortest path, the trip can be completed by extending the range via refueling at each node that is passed. We also assume that the travel demand within a city is concentrated on the center of the city (a node), and a predetermined coverage distance (s) is used to decide whether a station could serve the nodal demand. That is, it is assumed that there exists a known demand, a_i, at a node i on the network, and the demand at this node is satisfied if the path enters it directly, or if it enters some other node, say j, such that node j is within the coverage distance of s. In addition, as in the study of Wang and Lin (2009), a lot of other assumptions are made to establish the model, including a single type of AFV with a uniform range, a linear relationship between the fuel consumption (or refuel) and driving (or extending) distance, and each AFV having the same amount of fuel at the point of origin.

In order to model the refueling-station location problem, the following indexes, sets, parameters, and decision variables are used:

Indices

i, j	nodes or locations ($i = 0$ is the point of origin)
m	AFV

Sets

N	set of all nodes or locations
M	set of AFV traveling along paths

Parameters

W	weights totaling 1 (assigned to the separate objectives)
c_i	the cost of locating a station at node i
p_i	the population at node i
k	a large positive integer
s	the coverage distance
a_{ij}	1, if candidate site j can cover demand at node i within the coverage distance s, and 0, otherwise
d_{ijm}	traveling distance between nodes i and j using AFV m on a path
e	a conversion coefficient (fuel consumption per unit distance traveling)
β	refueling capacity

Decision variables

X_i	1, if we locate a station at node i, and 0, otherwise
H_i	1, if demand at node i can be served, and 0, otherwise
Y_{im}	1, if an AFV m is refueled at node i on a path and 0, otherwise
U_{im}	amount of fuel adjusting at node i for an AFV m on a path
B_{im}	amount of fuel remaining at site i for an AFV m on a path
R_{im}	amount of fuel replenishing at site i for an AFV m on a path

The location problem is formulated as a two objective mixed-integer program, as follows:

$$\text{Minimize} \quad Z = WZ_1 + (1-W)Z_2 \tag{1}$$

$$\text{Subject to} \quad \sum_{j\in N} a_{ij}X_j \geqslant H_i \quad \forall i \in N; \tag{2}$$

$$B_{jm} = (B_{im} + R_{im}) - d_{ijm} \times e \quad \forall i,j \in N, \ \forall m \in M, \tag{3}$$

$$R_{im} \leqslant \beta - B_{im} \quad \forall i \in N, \ \forall m \in M, \tag{4}$$

$$R_{im} = Y_{im} \times \beta - U_{im} \quad \forall i \in N, \ \forall m \in M, \tag{5}$$

$$\sum_{m\in M} Y_{im} \leqslant k \times X_i \quad \forall i \in N, \tag{6}$$

$$Y_{im} \in \{0,1\} \quad \forall i \in N, \ \forall m \in M, \tag{7}$$

$$X_i \in \{0,1\} \quad \forall i \in N, \tag{8}$$

$$H_i \in \{0,1\} \quad \forall i \in N, \tag{9}$$

$$B_{im} \geqslant 0, U_{im} \geqslant 0, R_{im} \geqslant 0 \quad \forall i \in N, \ \forall m \in M, \tag{10}$$

where Z_1 is $\sum_{i\in N} c_i X_i$; Z_2 is $-\sum_{i\in N} p_i H_i$; $B_{0m} = \beta$; $R_{0m} = 0$.

Constraint (1) represents the function with weighted dual objectives of minimum cost and maximum population coverage. Constraint (2) ensures that if a demand node i is covered, there must be at least one station sited within its coverage distance. To minimize the second objective (Z_2) (maximum population coverage), H_i tends to be 1, but this depends on the weights assigned to the objective. That is, the constraints can not ensure that all demand nodes can be served by station locations. In contrast, if H_i is equal to 1, the constraint can ensure that all the demand nodes can be covered. The formulation will be discussed later. Constraint (3) is derived from the vehicle refueling logic (b) (Wang and Lin, 2009), and means that the remaining fuel at node j is equal to the remaining fuel plus refueling at the prior node i, minus the fuel consumption during the link travel. Constraints (4), (5) are derived from the vehicle refueling logic (c) (Wang and Lin, 2009). Constraint (4) means that the amount of refueling at node i must be less than or equal to the refueling capacity (β), minus the amount of fuel remaining at the node. Constraint (5) means that the amount of refueling at node i is equal to the refueling capacity minus the amount of fuel adjusting at that node. The parameter U_{im} is used to calibrate the fuel replenished at a site to prevent refueling in excess of the vacant space in the fuel tank ($\beta - B_{im}$), such that the inequality of $Y_{im} \times \beta - U_{im} \leqslant \beta - B_{im}$ (R_{im} in Constraint (4) replaced by $Y_{im} \times \beta - U_{im}$ in Constraint (5)) can be ensured. Nevertheless, the perfect formula should be in the form of $Y_{im} \times \beta \times L \leqslant \beta - B_{im}$, where L is a refueling coefficient (in the range of 0–1) based on the vacant space in the fuel tank at each stop, and this is nonlinear, which at present it is difficult to resolve. Consequently, a linear formula with an adjustment variable (U_{im}) is introduced (Wang and Lin, 2009). Constraint (6) ensures that all the vehicles arriving at node i can be served if a station is located at the node, i.e., the capacity of the station is unlimited. Constraints (7)–(9) require that the variables of Y_{im}, X_i, and H_i all equal either zero or one. Constraint (10) requires that the variables of B_{im}, U_{im}, and R_{im} are not less than zero. Where the inequality of $B_{im} \geqslant 0$ can ensure an AFV m has some remaining fuel when arriving at node i (i.e., that it does not run out of fuel before reaching the node). In addition, if i is equal to 0, B_{0m} represents the amount of fuel remaining (carry-on fuel) at the point of origin for vehicle m on a path. Its value can be set to any positive integer less than β. In this study, the traveling AFV are assumed to be full of fuel (β assigned) at the original points on the paths.

Constraint (2) is derived from the set covering problem (Toregas et al., 1971), while Constraints (3)–(6) are directly from the refueling-station location problem (Wang and Lin, 2009). Therefore, the proposed model extends the refueling-station location model (Wang and Lin, 2009) by adding the constraints of nodal demand coverage, with the dual objectives of minimum cost and maximum coverage, to provide a range of alternatives for planners or decision makers in determining fast-refueling-station deployment.

There are several methods for generating an approximation of the multiple objective trade-off curve. The weighting method (Zadeh, 1963) is recommended for the refueling-station location problem, because this does not alter the structure of the constraints set (Current et al., 1985; ReVelle, 1989). By means of an appropriate scale weight, W, the multiple objectives function can be combined into a single-objective one, which can be minimized (or maximized) to obtain an approximation of non-inferior solutions. At $W = 0.0$, the model is entirely dedicated to maximal coverage of the demand nodes, and thus the value of variable H_i in Constraint (2) will tend to be 1. In this situation, all the demand nodes will be served by at least one facility. Furthermore, if all demand nodes can be covered by station locations, we can know intuitively that the overall flow-type demands can also be satisfied. Thus, the model reduces to the set covering model (Toregas et al., 1971).

In contrast, at $W = 1$, the model is entirely devoted to the objective of minimal locating cost. To minimize the cost, the model will tend to economically site the stations to cover the flow-type demand, neglecting the nodal demand so that it will reduce to the refueling-station location model (Wang and Lin, 2009). In theory, the trade-off curve (an infinite number of non-inferior solutions) can be obtained. Because of the computational burden associated with generating the entire non-inferior set, it is usually satisfactory to generate an approximation of the non-inferior solution set (Current et al., 1985). However, due to the 0–1 integer constraint of the decision variables, such as X_i, with regard to the location problem, the trade-off curve will tend to be discrete (with a finite number of non-inferior solutions) and thereby all the non-inferior solutions can be reasonably generated.

Planning situations certainly exist where it is possible to satisfy the entire demand (passing flows and nodal points) because of sufficient resources or budgets. Therefore, how to economically determine the number and location of refueling stations to serve both types of demand is the problem addressed in this work. The dual objective problem can be further reduced to a single-objective one with minimum cost. It can be formulated by using the constraints in the set covering model (Toregas et al., 1971; Daskin, 1995) to replace Constraint (2), and the two objectives can be replaced by the single one of the minimum locating cost, as follows:

$$\text{Minimize} \quad \sum_{i \in N} c_i X_i \tag{11}$$

$$\text{Subject to} \quad \sum_{j \in N} a_{ij} X_j \geqslant 1 \quad \forall i \in N; \tag{12}$$

Constraints (3)–(10).

Intuitively, the model is similar to the proposed dual-objective model where the weights assigned are close to zero, and thus the total population will be covered with the minimum costs. In such conditions, the solutions from the dual-objective model are identical to those derived from the single-objective model. In other words, the planning situations for serving the entire demand with the minimum cost can be satisfied by using the proposed dual-objective model.

3. Case study

Since the new model was extended from the flow-based set covering model, the case of Taiwan's refueling-station planning was used again to test it and contrast the solutions thus derived with the previous ones. The purpose of facility planning in this case is to site the fast-refueling stations or battery (or fuel cell) exchange stations to serve the refueling demand of intercity and intra-city travel using AFV, with the trade-off objectives of minimum facility cost and maximum population coverage.

3.1. Data acquisition

A discrete representation of Taiwan's road network is shown in Fig. 1 (Wang and Lin, 2009). In this figure, there are 51 demand nodes composed of 22 city or county centers, which are the points of origin and destination of the intercity trips, and the 29 local centers (to form the entire network with consideration of the range of AFV, such as 50–350 km), and the distances between two adjacent nodes are shown on the arcs. The population at the nodes is represented by the circles with different sizes (in Fig. 1), and the actual numbers are shown in Table 1. It is assumed that the intercity return trips would utilize the shortest paths (to the number of $1100(22 * (51 - 1))$) between two nodes (centers) of origin and destination. That is, the intercity travel from one city or county center to another follows the shortest path and returns to the origin along the same route. In addition, since few studies have explored the problem of station cost, the cost data (about US$37,000–44,000 (NT$ 1,125,000–1,338,000) per station) from a pilot project of electric vehicle charging stations in China (Fong, 2008) is used to demonstrate the effect of the cost-population objective trade-off.

3.2. Solutions

Assuming that the AFV with an onboard refueler could refuel at home, it is not necessarily to site stations at the points of origin in order to undertake intercity travel (Wang and Lin, 2009). On the assumption that the locating cost at each site is equal (NT$1,125,000 per station) and the parameters were the links' distances and populations of each site (as shown in Fig. 1 and Table 1), a coverage distance S (10 km), the weight W (0, 0.01, 0.2, 1), a vehicle range or refueling capacity (250 km), and full refueling at the points of origin, solutions can be obtained (Fig. 2) using LINGO's branch and bound algorithm (Thornburg and Hummel, 2003). In Fig. 2, at a weight of 0 (maximum coverage for the total short-distance travel), the number of refueling stations sited is 40, which can achieve a high ratio of 78.43% (40/51), and the whole population (22,798,144) is covered. In contrast, at a weight of 1 (the minimum locating cost to serve the total long-distance travel), the number of stations being sited reduces significantly to eight, accounting for just 15.69% (8/51), with 36.44% of the population (8,306,548/22,798,144) being covered. That is, when the weight gradually increases from 0 up to 1 ($0 \to 0.01 \to 0.2 \to 1$), the number of refueling stations sited decreases dramatically from 40 down to eight ($40 \to 30 \to 20 \to 8$), and the ratio of population being covered also reduces, slightly at the beginning, from 100% to

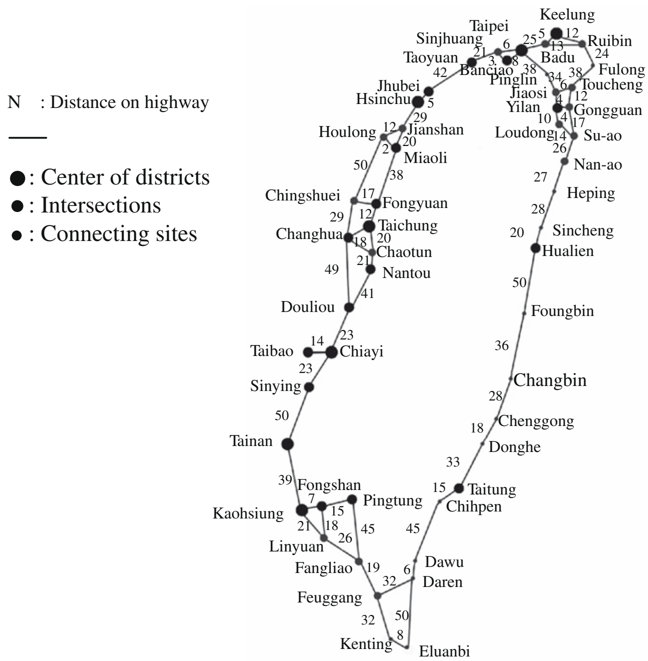

Fig. 1. Possible locations to site the fast-refueling stations (Wang and Lin, 2009).

Table 1
Population at each site.

No.	Node i	P_i	No.	Node i	P_i	No.	Node i	P_i
1	Keelung	351,308	18	Douliou	725,491	35	Jiaosi	35,891
2	Badu	38,422	19	Chiayi	273,486	36	Yilan	244,940
3	Taipei	26,30,966	20	Taibao	549,828	37	Gongguan	25,146
4	Sinjhuang	396,751	21	Sinying	11,04,906	38	Loudong	74,118
5	Banciao	33,45,697	22	Tainan	766,292	39	Su-ao	43,553
6	Taoyuan	19,41,878	23	Kaohsiung	15,22,343	40	Nan-ao	5827
7	Jhubei	489,786	24	Fongshan	11,72,121	41	Heping	14,975
8	Hsinchu	401,108	25	Pingtung	823,151	42	Sincheng	20,326
9	Jianshan	8189	26	Linyuan	71,342	43	Hualien	302,295
10	Houlong	40,371	27	Fangliao	27,312	44	Foungbin	5302
11	Miaoli	519,549	28	Feuggang	6221	45	Changbin	8803
12	Chingshuei	85,925	29	Kenting	15,629	46	Chenggong	16,308
13	Fongyuan	14,66,786	30	Eluanbi	15,628	47	Donghe	9654
14	Taichung	10,59,821	31	Ruibin	43,376	48	Taitung	169,254
15	Changhua	13,13,669	32	Fulong	13,993	49	Chihpen	18,381
16	Chaotun	100,008	33	Pinglin	6563	50	Dawu	7048
17	Nantou	433,162	34	Toucheng	31,517	51	Daren	3728

96.40%, and then rapidly downward to 36.44% (100% → 99.73% → 96.40% → 36.44%) due to the decrease in relative weighting ($(1 - w)/w$: a person equivalent to a cost) and the higher contribution from the locating cost to the objectives in contrast to the population at each site.

Fig. 3 shows all the non-inferior solutions along the weight continuum to the combined weighted objective functions, with ranges of (250, 150 km) and coverage distances of (10, 20 km). The trade-off relationship of the locating cost to the population coverage is quite significant as the weight increases from 0 to 1. Specifically, the fewer stations sited (which satisfies the objective of minimizing locating cost), the less population covered (which contradicts the objective of maximizing the population coverage). For example, with a range of 150 km and coverage distance of 10 km, the number of refueling stations required falls significantly, from 40 to 25, while the population covered only decreases slightly to 22,497,849 (99.68%), as the weight increases from 0 up to about 0.07. However, when the weight increases from 0.07 to 1, the number of refueling stations decreases gradually, from 25 to 14, while and the population covered also falls significantly, down to only 10,943,692 (48.00%). A similar relationship between the number of stations sited and the population covered with the increase of the weight still exists, with combinations of vehicle range and coverage distance of (250, 10 km), (250, 20 km) and

Fig. 2. Distributions of locations (with names shown) and numbers of fast-refueling stations, at weights of (0, 0.012, 0.257, 1), with range of 250 km and coverage distance of 10 km.

(150, 20 km). On the whole, when the range increases, such as from 150 to 250 km, the minimum number of stations and the corresponding population coverage will decrease, at the specific weight assigned. However, when the coverage distance increases, such as from 10 to 20 km, the minimum number of stations will also decrease, while the population coverage will increase at the specific weight assigned. For example, with combinations of (150, 10 km) and (150, 20 km), at a weight of 0.3, the number of stations and population covered is (21, 21,283,314) and (19, 21,804,264), respectively. In addition, at a weight of 1, the minimum number of stations sited to cover the total long-distance travel depends mainly on the vehicle range. For example, with combinations of (250, 10 km), (250, 20 km), (150, 10 km) and (150, 20 km), the required number of stations is 8, 8, 14 and 14, respectively. In contrast, at a weight of 0, the minimum number of stations required to cover the total population depends mainly on the coverage distance. For example, with combinations of (250, 10 km), (150, 10 km), (250, 20 km) and (150, 20 km), the required number of stations to cover the total population is 40, 40, 29, and 32, respectively.

In effect, as the weight increases from 0 to 1, the number of stations necessary decreases stepwise, as shown in Fig. 4. This indicates that there is a range of weights determining the specific number of stations at the locations with a constant coverage of population. For example, in Fig. 4, with a range of 250 km and coverage distance of 10 km, the solutions remain unchanged along the weight continuum of (0.6332, 0.7255). That is, ten stations need to be sited and a population of 14,845,274 can be covered. However, at a weight of 1 (the duel-objective model reduced to the minimum-cost model),

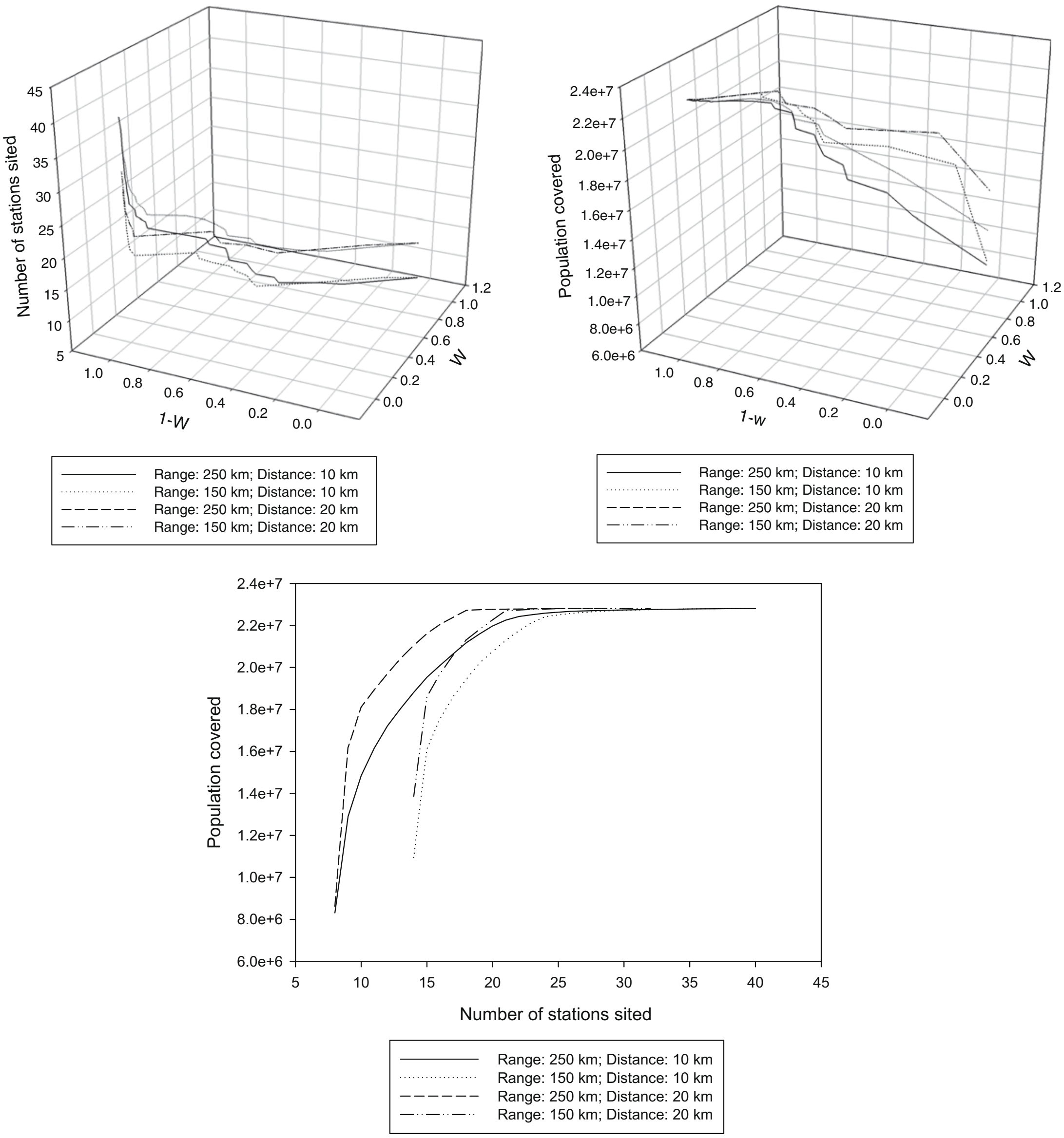

Fig. 3. Entire non-inferior solutions along weight continuum (1 → 0) when ranges = (250, 150 km) and coverage distances = (10, 20 km).

the minimum number of stations sited can possibly have different combinations of locations which can satisfy the long-distance travel demand (Wang and Lin, 2009), and thus can serve the different sizes of population. For example, with a range of 250 km and coverage distance of 10 km, eight stations can have many choices of siting locations to satisfy total intercity travel, and their population coverage is in the range of [8,306,548, 9,930,550]. In effect, the station locations with the maximal coverage of population are not easy to ascertain using the single-objective (minimum cost) model proposed by Wang and Lin (2009). However, the locations can be obtained easily using the dual-objective model. For example, with a range of 250 km and coverage distance of 10 km, at weights in the range of (0.725, 1), eight stations are sited, namely at Taipei, Jhubei, Fongyuan, Sinying, Fangliao, Su-ao, Foungbin, and Chihpen (in Fig. 2), and a maximal population coverage of 9,930,550 can be obtained directly. In addition, if the weight scale of 0 is assigned, the dual-objective model will reduce to a single-objective one (maximizing the population covered) and thus the locating cost is not a critical issue to be considered. Therefore, the number of stations obtained from the model solutions to cover the total population may not be the best from the viewpoint of either locating costs or the number of stations sited. For example, with a range of 250 km and coverage distance of 20 km, at a weight of 0, the minimum number of stations to cover the total population is 29. However, 25 stations is actually the best solution, at a weight of 0.005, to cover the total population. That is, planners or decision makers should not only choose the appropriate pairs of weights to consider the trade-off between station costs and population coverage, but should also

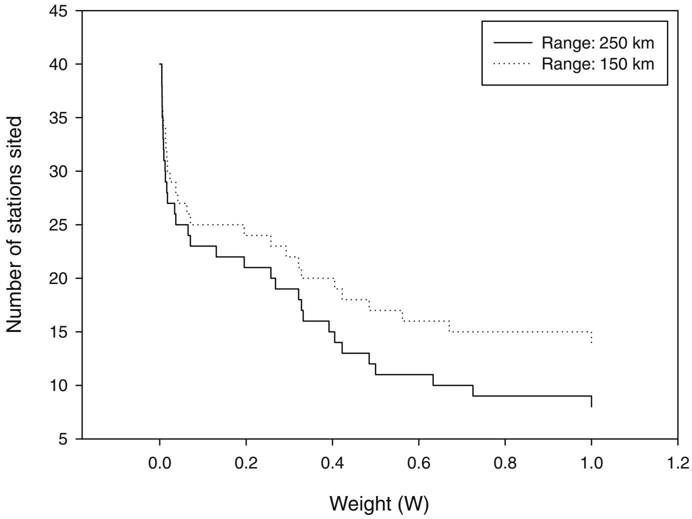

Fig. 4. Required number of stations sited corresponding to the increase of weight from 0 to 1.

choose locations with more population in order to deploy a specific number of stations while considering only a single objective (either minimal locating cost or maximal population coverage).

In addition, if the locating cost is different at various locations, the model solution will also look for locations with the minimal total costs and maximal coverage of population based on a trade-off relationship between cost and population covered, on the premise that long-distance travel via range-limited AFV can be satisfied. For example, with a range of 250 km and coverage distance of 10 km, at a weight of 0.7, nine stations will need to be sited at Taipei, Hsinchu, Fongyuan, Sinying, Kaohsiung, Su-ao, Hualien, Chenggong, and Dawu, and a population of 12,903,396 will be covered, if the locating cost at each location is equal (NT$1,125,000/per station). If the locating cost at three locations (Taipei, Hsinchu, and Fongyuan) is doubled, the optimal solution still requires nine stations to be sited at Sinjhuang, Jhubei, Taichung, Sinying, Kaohsiung, Su-ao, Hualien, Chenggong, and Dawu. The results show three locations (Taipei, Hsinchu, and Fongyuan) in the original solution are transferred to the lower-cost sites (Sinjhuang, Jhubei, and Taichung), and the total population covered is reduced from 12,903,396 to 12,496,431. Some locations are necessary, and are difficult or virtually impossible to replace, or can only be replaced by several locations in order to cover the total long-distance travel. For example, with a vehicle range of 250 km, one of three of the locations (Taipei, Sinjhuang, and Banciao) is necessary to meet the demands of long-distance travel. Thus, if the locating cost at these three sites is different, the lower cost one will be selected to reduce the total cost. For example, for

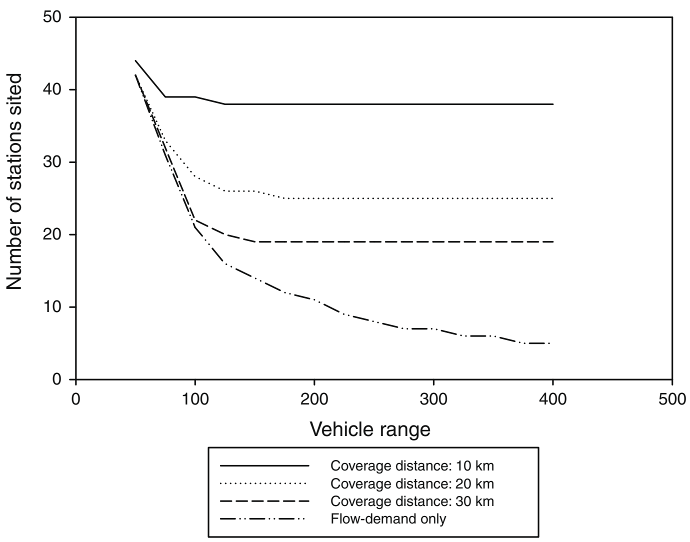

Fig. 5. Required number of stations sited to serve the overall travel or long-distance travel only, with coverage distances of 10, 20 and 30 km, when vehicle range increases from 100 to 400 km.

the case just mentioned, if the locating cost at these three locations is doubled, then the total number of stations required and the population covered remain almost unchanged, with only the station at Hsinchu being replaced by one at Jhubei.

Furthermore, if the objective of the planner or decision maker is to economically serve the total long- and short-distance travel, the required number of stations is as shown in Fig. 5. For example, if the coverage distance is 20 km, the number of stations sited will decrease gradually from 42 to 25, when the vehicle range increases stepwise (25 km) from 50 to 400 km. Where for ranges equal to or over 125 km, the number of stations remains unchanged at 25, which is the minimum required to cover all the short-distance travel. In other words, when the vehicle range is equal to or greater than 125 km, all the long-distance travel can be satisfied by the stations' located to cover the total population (short-distance travel). In addition, the solutions from the minimum-cost model are identical to those from the proposed dual-objective model with the weights assigned close to zero. For example, with a range of 250 km and coverage distance of 20 km, at a weight of 0.005, the required number of stations sited is also 25 to cover the total long- and short-distance travel. In Fig. 5, we also see that with a specific vehicle range, as the coverage distance increases, so the required number of stations decreases. For example, with a range of 100 km and coverage distances of 10 km, 20 km, and 30 km, the number of stations is 39, 28 and 22, respectively. In addition, the required number of stations to satisfy long- and short-distance travel is quite different from the number needed to satisfy long-distance travel alone. That is, far fewer are needed for long-distance alone than for both the long- and short-distance travel. For example, with a vehicle range of 400 km, the number of stations required to serve long-distance travel is only five, in contrast to the 38 stations required to cover long- and short-distance travel if a coverage distance of 10 km is used.

From the above discussion, the following observations can be made.

(a) The dual-objective model can be used to determine the appropriate station locations to serve all long-distance travel and cover most of the short-distance travel. In general, the greater the vehicle range or coverage distance, the fewer refueling stations that will be needed to cover a specific (constant) population. In addition, when the model is reduced to a single-objective one, (at weights of 1 or 0), of either the minimal cost or maximal coverage, the optimal stations' deployment can also be obtained directly by using the weights close to the boundary values. The planner or decision maker can thus easily select the required (or minimum) number of stations to cover a suitable proportion of the population based on the best solutions along the weight continuum in order to formulate a viable station-deployment plan. Obviously, the dual-objective model is much more useful in practice than a single-objective one (like Wang and Lin's model) from the viewpoint of facility planning.
(b) Due to the constraint of discrete locations, the entire non-inferior solutions to the combined weighted functions can be obtained easily based on the trade-off relationship between locating cost and population coverage ($(1 - w)/w$). Furthermore, as the weight increases from 0 to 1, the required number of stations and the population coverage decrease dramatically, given a specific range and the coverage distance of a station. In effect, the number of stations required decreases in a stepwise fashion, and this indicates that there is a weight range determining the specific number of stations with the constant coverage of the population.
(c) If the locating cost is different at various locations, and it is necessary to meet the demand for all long-distance journeys, the stations will possibly be moved to lower-cost sites, but the maximum population coverage will still be maintained.
(d) If the single minimum-cost objective is used to determine the station locations for serving total long- and short-distance travel, the number of stations required is far more than that needed to serve only all the long-distance travel. On the whole, the number of stations required to serve all travel mainly depends on the short-distance travel, and it will decrease when the coverage distance increases. In addition, the model solutions are identical to the ones from the dual-objective model when the weights assigned are close to zero.

4. Conclusions

The study proposed a new location model with dual objectives of minimum cost and maximum coverage, based on the concept of set covering and vehicle refueling logics, using a mixed integer programming method to economically determine the number of fast-refueling-stations and their locations for serving long- and short-distance travel with range-limited AFV. The model was successfully applied to the case of fast-refueling-station planning on Taiwan's road network, and the results show that a number of parameters, such as vehicle range and the predetermined coverage distance, have an important role in the outcome. In general, the greater the vehicle range or coverage distance, the fewer the refueling stations that will be needed to cover a specific (constant) population. Moreover, with a specific range and coverage distance, as the weight increases from 0 to 1, the required number of stations and population coverage decrease dramatically. With the model solutions along the weight continuum, the planner or decision maker can easily choose appropriate alternatives (i.e., compromise solutions) by selecting different pairs of weights depending on their utility function to formulate the optimal station-deployment plan.

The contributions of the paper to the literature are to extend the refueling-station location problem (Wang and Lin, 2009) by adding the constraints of nodal demand coverage derived from the set covering model (Toregas et al., 1971) to consider the service of long- and short-distance travel. Although the present model follows the objectives of MCSPP and MC3SP, with maximum coverage and minimum locating cost (similar to the shortest path or shortest spanning subgraph), the actual shortest paths among O–D pairs (obtained from the use of easily obtained O–D distance matrix data) were used as the inputs to the solutions, and thereby the problem of roundabout routes derived from the weighted objective and population coverage along the enabling arcs (not the volume of O–D flows) in Bapna et al.'s model can be avoided. Since long-distance travel along the shortest paths is covered by multi-stop refueling, the assumption of one-stop refueling to achieve the long-distance journeys in Hodgson and Rosing's model can be relaxed. In addition, because the model has dual objectives, the solution for optimal station deployment to cover the most population can be easily obtained, which is a difficult task with the Wang and Lin's model.

Based on the concept of set covering, no matter which weight is assigned or selected, the solutions of the model necessarily fulfill the service of all intercity travel and the maximum coverage of intra-city travel. Although the major city pairs to be covered can be selected or evaluated by the planner before the analysis or planning to reduce the demand for resources or capital investment, the assumption of sufficient resources is often not practical in real-world applications. Indeed, resources are generally limited or constrained, which is why maximum-coverage-based models (like Hodgson and Rosing's model) are developed. However, we must emphasize again that a sufficient number of refueling stations is critical to ensure consumer confidence in the overall system, especially in the early stages of AFV development (Melaina, 2003; Melaina and Bremson, 2008). In addition, because the model was based on refueling logics, a real-world large-scale problem will include many constraints, and the mixed-integer program is not easy to resolve by using an exact algorithm, such as the branch and bound method. In effect, in Wang and Lin's model, uncapacitated stations were considered to greatly reduce the number of constraints and make the exact algorithm workable, and thus some refueling behaviors were changed, although they are still reasonable. However, reformulating the refueling-station location problem to reduce the number of constraints or developing a meta-heuristic method to effectively solve the large-scale set covering problem are still important tasks in future research.

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