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A HEURISTIC APPROACH TO THE LOCATION OF THE REFUELING STATIONS FOR THE ALTERNATIVE FUEL VEHICLES

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Abstract. *Growing interests in the global warming, greenhouse gas pollution, and high oil prices generate rapid interests to the alternative fuel vehicles (AFVs). One of the most difficult obstacles for massive AFV adoption is the dense infrastructure for refueling AFVs. In this paper, we introduce the refueling station location problem and its mathematical programming model. Although computational approaches such as column generation are desirable due to a large number of flow variables, we show that simple augmentation of arc sets to a feasible path segments and careful constraint formulation can be a feasible approach for this problem for small to medium sized instance.*
Keywords: Refueling station location, Alternative fuel vehicles, Mixed integer program, Expanded network

1. **Introduction.** Growing interests in the global warming, greenhouse gas pollution, and high oil prices generate rapid interests to the alternative fuel vehicles (AFVs). The alternative fuels include biodiesel, ethanol, hydrogen, electricity, and hydrogen. Among different AFVs, plug-in electric vehicles (EVs) are the most promising AFVs that reduce CO_2 emissions more than 50% at the current U.S. electric grid compared with internal combustion engine (ICE) vehicles. The cost of EVs is also decreased rapidly as production volume increases with the economies of scale cost reduction while end-user cost is estimated at 2-3 cents per mile while ICV's cost is 13 cents per mile [1]. However, the rapid adoption of AFV or EVs has several major obstacles to overcome. The most difficult barrier for AFV adoption is the massive infrastructure for refueling AFVs. For EVs, the major barrier for mass adoption of EVs is high battery cost that is higher than $10,000 on average and the so called range-anxiety that the batteries are running out middle of the road trip. In this paper, we consider procedures of economic construction of refueling stations for AFVs on the network to maximally cover the travel demand.

Earlier approach to the refueling station location problem includes set covering and p-median models. In the p-median model, each demand is located at the node and the objective is to minimize the total travel cost from the demand point to the nearest refueling station. Since refueling decisions are made by drivers during trips between origin and destination node and several refueling is possible, facility location models for capturing flow demand on the transportation network are developed [2]. In this model, each trip from the origin and destination is covered if there is at least one open refueling station on the shortest path. Flow capturing location model in [2] is generalized where multiple stops for refueling are allowed [3,4]. For this general model, the first stage constructs all possible feasible combinations of refueling stations for paths and the location of the refueling stations is determined using a mixed integer programming model in the second stage. Note that enumeration of all combinations of refueling station is a prohibitive task and recent research focuses on the column generation approaches to this problem [5-7]. This paper proposes a simpler heuristic approach for locating refueling stations for this general setting. Compared with the formulations in [6], the model proposed in this paper allows relaxation of the *half-full tank assumption* used in the previous research for more realistic solution through explicit constraints in the model formulation. For EVs, a robust programming approach for infrastructure construction of the battery charging and battery swapping station is proposed and social cost of battery charging capacity of the station and battery capacity is studied [8,9].

This paper is organized as follows. In Section 2, we describe refueling station location problem and its mathematical programming model. In Section 3, we show the computational results for 25-city problem on various input parameters. Section 4 concludes this paper.

2. **Refueling Station Location Problem.** Underlying transportation network is represented as a directed graph $G = (N, A_0)$, where N is the set of nodes representing intersections, A_0 the set of directed arcs, and $l(i,j)$ denotes the length of arc (i,j). On this network, origin-destination (OD) pair $q \in Q$ has its origin node $O(q)$ and the destination node $D(q)$. Travel demand for OD pair q is denoted as f_q. We assume that each vehicle has a driving range R when it is full tank. Because of long range travel, vehicles require refueling if the trip length exceeds R.

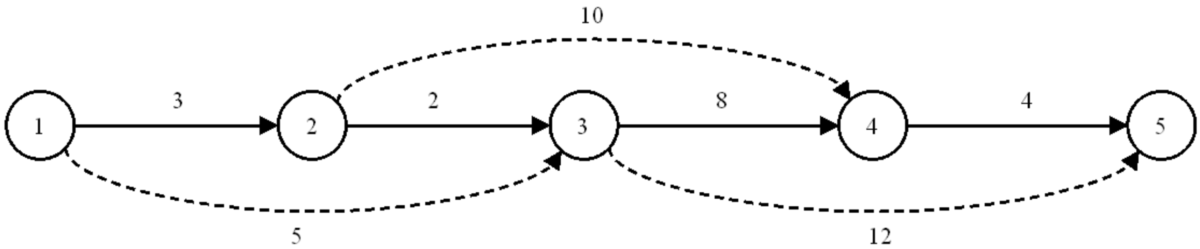

FIGURE 1. Refueling and expanded network when $R = 12$

Consider five nodes network in Figure 1. In Figure 1, original network links are four links $(i, i+1)$, $i = 1, \ldots, 4$ with link lengths 3, 2, 8, 4. Suppose the driving range of a full-tank vehicle is set as $R = 12$. Node 1 is the origin and node 5 is the destination node. Because the total trip length is 17, this vehicle needs refueling during its trip. We assume that refueling stations are located at the nodes between its origin and destination nodes. We require that at the origin node and at the destination node of its trip a vehicle is at least half-full tank. This requirement is common in the previous research and with this half-full tank assumption, the return trip using the same refueling scenario becomes a feasible plan. In Figure 1, additional arcs $(1,3)$, $(2,4)$, and $(3,5)$ denote path segments without refueling. A *path segment* $(i_1, i_2, \ldots, i_p)$ consists of arcs (i_k, i_{k+1}), $k = 1, \ldots, p-1$ and has length $\sum_{k=1}^{p-1} l(i_k, i_{k+1})$. We call a path segment with length at most the driving range R as a *feasible* path segment. In this paper, a path segment is always a shortest path between the starting node i_1 to the ending node i_p on the original network and its length is the shortest path length computed from the original arc lengths. Let A_1 denote the set of all the *feasible* path segments and $A = A_0 \cup A_1$. On the expanded graph $G = (N, A)$, the set of half driving range outgoing arcs from node i is defined as $\delta_1^+(i) = \{(i,j) \in A | l(i,j) \le R/2\}$, the set of half driving range incoming arcs is $\delta_1^-(i) = \{(j,i) \in A | l(j,i) \le R/2\}$, similarly $\delta_2^+(i) = \{(i,j) | R/2 < l(i,j) \le R\}$ and $\delta_2^-(i) = \{(j,i) | R/2 < l(j,i) \le R\}$ are defined. Also, $\delta^+(i) = \delta_1^+(i) \cup \delta_2^+(i)$ and $\delta^-(i)$ are similarly defined. For network in Figure 1, possible combinations of refueling station locations are {1, 2, 3, 4, 5}, {1, 2, 4}, {2, 4}, {3, 5}. Because of half-tank assumption on the origin and destination nodes, refueling at node 3 alone is not a feasible plan. If the only refueling station is located at node 3, trip $1 \rightarrow 3$ is feasible with half tank at the origin and trip $3 \rightarrow 5$ is also feasible with full tank at node 3, but when it arrives at node 5, it is less than half tank, the refueling at node 3 alone is not regarded as a feasible scenario in this paper. If refueling station is located at the destination node 5, trip $3 \rightarrow 5$ uses more than half-full tank, but return trip $5 \rightarrow 3 \rightarrow 1$ is also a feasible trip. In this paper, we relax the above half-full tank assumption so that if refueling station is located in origin or destination node, trip using more than half-full tank is allowed. We call this property as the *relaxed* half-full tank assumption. An OD q is *covered* if between $O(q)$ and $D(q)$ there is a feasible refueling scenario with the relaxed half tank requirements.

Refueling station location problem is to determine p refueling stations' location on the network to maximize the number of *covered trips*. Binary variables x_i, $i \in N$ indicate the opening of the refueling station at node i and y_q, $q \in Q$ the trip q is covered. The refueling station location problem with the relaxed half-full tank assumption is represented as the following mixed integer program.

$$
\begin{aligned}
\text{Max} \quad & \sum_q f_q y_q \\
\text{s.t.} \quad & \textstyle\sum_{a \in \delta^+(i)} x_a^q - \sum_{a \in \delta^-(i)} = \begin{cases} y_q, & i = O(q) \\ -y_q, & i = D(q) \\ 0, & \text{otherwise} \end{cases} \\
& \textstyle\sum_{a \in \delta_2^+(i)} x_a^q \le x_i, \ i = O(q), \ q \in Q \\
& \textstyle\sum_{a \in \delta_2^-(i)} x_a^q \le x_i, \ i = D(q), \ q \in Q \\
& \textstyle\sum_{a \in \delta^-(i)} x_a^q \le x_i, \ i \ne O(q), \ i \ne D(q), \ q \in Q \\
& \sum_{i \in R} x_i \le p \\
& x_i \in \{0, 1\} \\
& y_q \in \{0, 1\}, \ q \in Q \\
& x_a^q \ge 0, \ a \in A, \ q \in Q
\end{aligned}
\tag{1}
$$

In (1), the objective function is the total covered trip volumes and the first constraints are flow balance constraints on the expanded network. The second constraints allow that *if there is a refueling station located at the origin node*, half-tank requirement can be relaxed and if there is no refueling station at the origin node, feasible outgoing arc from the origin has length $l(i, j) \le R/2$. This assumption is different to the expanded network defined in [6] where outgoing arc from the origin has length $l(i, j) \le R/2$. The third constraints are for the destination nodes. The fourth constraints allow vehicles refueling in the intermediate node can travel up to the maximum range R. The next constraints limit the number of open refueling station at p.

Using formulation (1), capacity restriction on the refueling station can be formulated as

$$\sum_{q \in Q} \sum_{a \in \delta^-(i)} f_q x_a^q \le U_i x_i, \ i \in N \tag{2}$$

where U_i is the capacity limit on station i and different objective function minimizing total trip length can be modeled as follows

$$\text{Max} \sum_{q \in Q} f_q y_q - \sum_{q \in Q} \sum_{a \in A} c_a x_a^q \tag{3}$$

where c_a is the length or cost of segment a.

Also, the previous half full tank assumption can be incorporated into our model by changing flow balance equation using outgoing arcs in $\delta_1^+(O(q))$ and incoming arcs in $\delta_1^-(D(q))$.

3. **Computational Experiment.** In this study, we use 25-city example from [10] depicted in Figure 2 with node and arc weights. Each node in Figure 2 has node weight w_i that is 1,000 times the original node weight in [10]. For this example, for each OD pair (i, j), the shortest path length $d(i, j)$ is computed first and travel demand $f_q = w_i w_j / d(i, j)^{1.5}$, and the total number of OD pairs is $n(n-1)/2 = 300$. For this problem, $|N| = 25, |A_0| = 84$ and the number of x_a^q variables is 75,000. Table 1 shows objective value of model (1), 300 total OD pairs, and percentage of objective value with respect to $\sum_{q \in Q} f_q$ for number of covered OD pairs, i.e., $\sum_q y_q$, percentage of covered OD pairs with respect to $p = 1, \ldots, 25$. In half fuel restriction at OD nodes (columns 2-5) case, each origin and destination nodes use only arcs with length $l(i, j) \leq R/2$ even if there is a refueling station at the origin or destination nodes. Columns 6 to 9 show the result of the relaxed half-full tank restriction. In Figure 3, the optimal placement of refueling station is depicted (node with shaded color) when $p = 6$. The dotted line shows flows between OD pair (9,16) where both the origin and destination nodes do not have refueling station so that it uses arcs with $l(i, j) \leq R/2$. Notice that with strict half fuel restriction, fourth column in Table 1 shows that only 92% of the ODs are covered in the solution. This lack of total coverage is caused by the structure of the underlying graph. However, for the relaxed half full restriction, installing $p = 7$ refueling stations covers all OD trips. If we allow mid-arc location of refueling station, 15 refueling station covers all trips satisfying half-full tank restrictions.

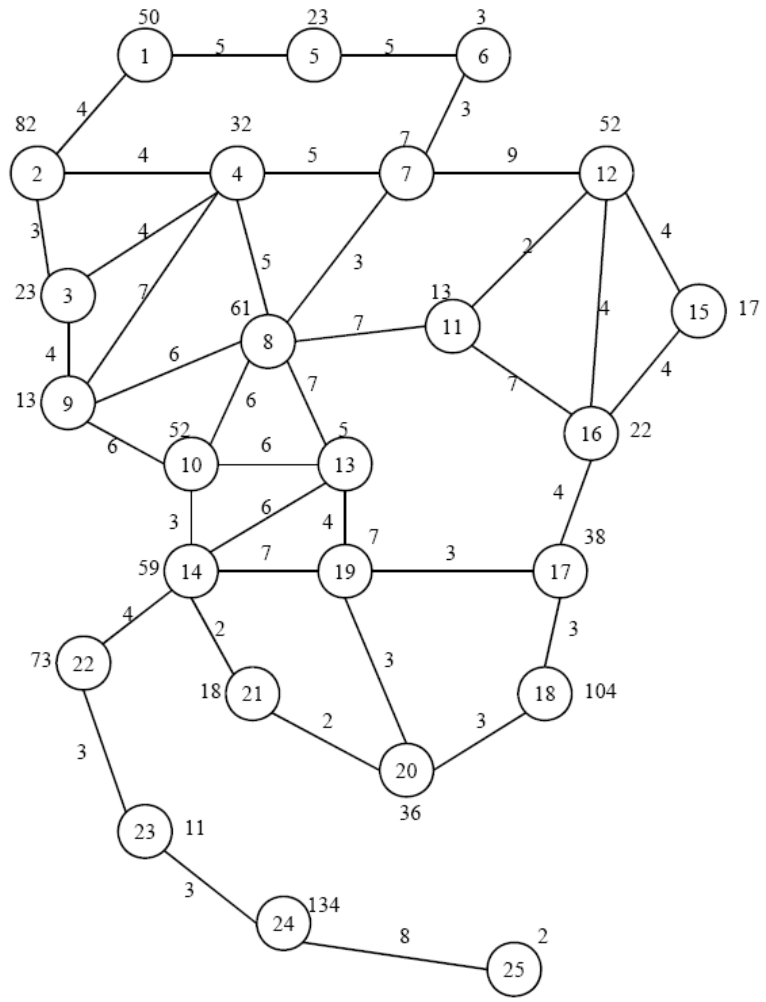

FIGURE 2. 25-city example with node and edge weights

Table 1. Result for 25 city case when $R = 12$

p	Half fuel restriction at OD nodes				Relaxed half fuel restriction at OD nodes			
	Objective value	#covered OD	Percentage of covered OD	Percentage of obj. value	Objective value	#covered OD	Percentage of covered OD	Percentage of obj. value
1	8813.02	44	0.15	0.5458	8813.02	44	0.150	0.546
2	10082.18	58	0.19	0.6244	10397.68	64	0.210	0.644
3	11869.25	106	0.35	0.7351	12554.56	140	0.470	0.778
4	13743.19	144	0.48	0.8511	15078.09	201	0.670	0.934
5	14526.06	173	0.58	0.8996	15732.65	257	0.860	0.974
6	15093.39	219	0.73	0.9348	16119.79	276	0.920	0.998
7	15611.87	238	0.79	0.9669	16146.62	300	1.000	1.000
8	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
9	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
10	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
11	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
12	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
13	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
14	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
15	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
16	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
17	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
18	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
19	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
20	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
21	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
22	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
23	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
24	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000
25	16119.79	276	0.92	0.9983	16146.62	300	1.000	1.000

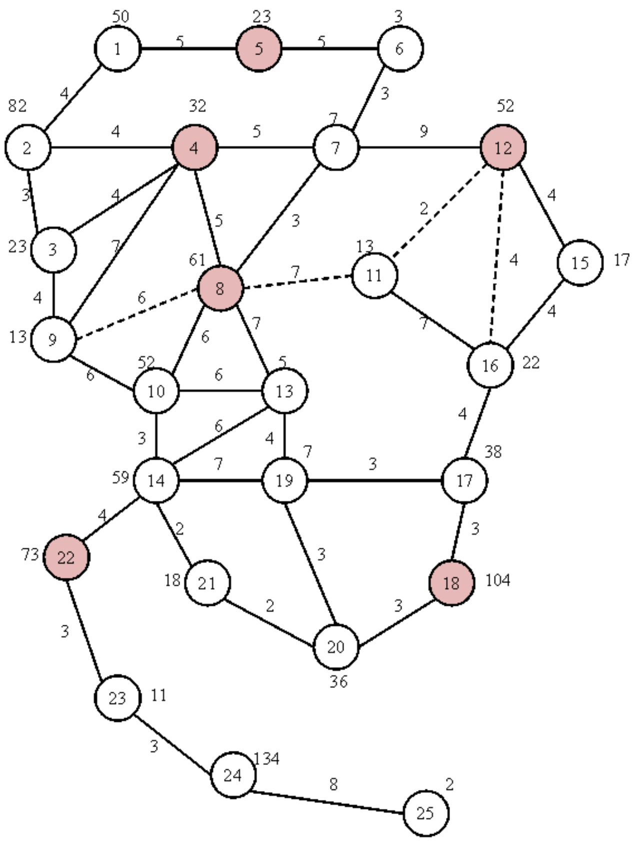

Figure 3. $p = 6$, $R = 12$ optimal solution with trip $9 \rightarrow 16$

4. **Conclusions.** In this paper, refueling station location problem for the AFVs is introduced and a mixed integer program on an expanded network is formulated. The expanded network consists of original arc added with the feasible path segments that can be used during a feasible refueling scenario during OD trip. This formulation allows when refuel station is located at the origin/destination node, half-tank assumption is relaxed and expanded network is defined simpler than one in previous research. Using relaxed half-full tank assumption, the number of required refueling station computed through the proposed method is less than the strict assumption employed in [6]. The reason behind the development of the proposed model is that for small to medium sized problem, pre-generation of simple feasible path segments is a fast solution approach compared with full column generation approach.

Future research topics include design of the efficient column generation schemes as well as a branch and price procedure for this problem.

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