Charging Facility Planning for Electric Vehicles

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Abstract—With the fast development and growth of Electric Vehicles (EV) in use, finding optimal locations for charging facilities became a critical issue since growth of EVs heavily depends on the availability of public charging facilities. Several researches have been done related to this topic considering optimal locations of charging stations on road networks. In this paper, we extend the problem by also taking into account optimal locations of charging pads which uses inductive charging technology. Flow Refueling Location Model (FRLM) was proposed to maximize the refueled traffic flow by allocating a fixed number of facilities, e.g., gas stations. This paper extends FRLM to consider both charging station and charging pad allocation to maximize the recharged EV flow. Evaluation on a sample network shows that deploying charging pads on road network enables us to capture more traffic flow than locating charging stations only. Charging pad deployment also significantly shortens the charging time spent by EV drivers.

I. INTRODUCTION

Energy consumption and air pollution have become major concerns which lead to the development of electricity powered vehicles. Pure Electric Vehicle (EV) and Plugin Hybrid Electric Vehicle (PHEV) are two main types of vehicles being promoted to replace conventional fossil consuming vehicles [3]. It is forecasted that their market penetration will experience a significant increase in the following years [2], [9], [16], [18]. However, due to the limitation of driving range of a charged vehicle, the accessibility of public charging facilities is one key issue that restricts the widespread adoption of EVs [6].

Charging station is one type of charging facilities that is available on road network. However, the risks of charging stations such as electrocution and charger points become frozen on vehicles in extreme weathers advance the development of an inductive charging technique which is applied by charging pad [22]. The feature of charging pad is that it charges an EV wirelessly while an EV is driving above it, which overcomes the drawbacks of wired charging applied by charging stations. It is shown in [22] that charging pads provide a way to overcome the battery limitation.

In this paper, we focus on studying finding optimal locations both for charging stations and charging pads. The main difference between locating these two charging facilities is that charging stations are similar to conventional refueling stations, such as gas stations, and are assigned to intersections or points of interests of a road network. These locations are denoted by nodes in a graph. However, charging pads charge vehicles while they are in motion, meaning an EV is required to travel on a charging pad for a certain distance to get charged. This specific feature requires charging pads to be assigned to segments of roads instead of nodes.

The Flow Refueling Location Model (FRLM) [5], [12], [13] is a flow-based location-allocation model aims at finding optimal locations for refueling stations. FRLM is categorized as a flow-based model because it treats serving demands as traffic flows between various origins and destinations with the goal of maximizing the amount of flows being refueled. One critical feature of this models is that it assumes vehicles stop at refueling stations on their preplanned trips instead of making a single purpose trip to refueling stations. Another feature is that the FRLM takes vehicle’s driving range into consideration which is one crucial factor of EVs.

So far, several researches have concentrated on locating charging stations on road network [8], [11], [14], [19], [21]. To our best knowledge, this is the first paper studies locating charging pads on road network. In this paper, our main contributions are: 1) we extend FLRM in order to choose optimal locations for both charging station and charging pad on road network, 2) we compare the performances of locating charging pads and charging stations in terms of captured flow volume, and 3) we discuss trade-offs of deploying charging pads compared to building charging stations.

This paper is structured as follows: in Section III we review the FRLM; in Section IV we introduce our extended FRLM to locate both charging stations and charging pads; in Section V we evaluate the extended FRLM on a 9-node network and compare its performance with the original FRLM that is capable of allocating only charging stations; and in Section VI we conclude the paper with a discussion on trade-offs between charging station and charging pad.

II. RELATED WORK

In [19], authors made decision on locations for new charging infrastructure by developing an agent-based decision support system which identifies patterns in residential EV ownership and driving activities. In [21], authors formulated a multi-objective optimization problem which considered EV owner’s driving behavior to choose optimal locations for charging stations. The objective of the optimization problem consists of three sub-optimization problems with 3 goals: (i) minimizing

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the power losses; (ii) minimizing the node voltage deviations in the distribution network; and (iii) maximizing the utilization of charging stations. In [11], authors focused on finding optimal charging station locations for EVs in urbanized areas by developing a two-step model. The first step was transferring road information into data points and then clustering the data points into demand clusters. The second step was building an optimization problem given the clusters. In [8], researchers applied the flow capturing model to find optimal locations for charging stations. Two optimization problems were formulated separately. The first optimization problem followed the flow capturing approach to maximize the amount of flow that would be captured by the charging stations. The goal of the second optimization problem was to minimize the setup cost of charging stations while ensuring capture a minimum amount of flow. In [14], the authors formulated a mixed-integer linear programming problem to minimize the construction cost incurred when building stations. The constraints of the optimization problem ensured a minimum amount of flow being served.

III. REVIEW OF FRLM

In this section, we review the original Flow Refueling Location Model (FRLM). Before introducing the details, basic terminologies of road network are discussed first.

A road network can be abstracted as a network of nodes and links, where nodes represent intersections or hot spots, and links represent road segments that connecting adjacent nodes. Traffic flow is defined as the traffic flow volume passing a reference point during a given time period, typically in the unit of vehicles per hour. An Origin Destination (OD) pair is a pair of origin and destination nodes in the network. An OD matrix $O$ summarizes the traffic flow of each OD pair, i.e., $O_{i,j}$ is the traffic flow from origin node $i$ to destination node $j$. Note that OD matrices are often published as symmetric matrices, and the flows between OD pairs $(a,b)$ and $(b,a)$ are regarded as the same for any OD pair $(a,b)$ in the network [4].

The FRLM is a flow-based model which treats serving demands of road networks as traffic flows with various OD pairs. FRLM applies a critical concept, combination, which is first introduced in [12]. A candidate combination is defined as a set of candidate locations to locate refueling facilities. The refueling facilities discussed in [12] are hydrogen stations and they are assigned to nodes. We use Figure 1 to illustrate some examples of combination. Number two and four indicate the length of corresponding links.

Given the short path in Figure 1, if we only allocate stations to nodes, then the following subsets of nodes constitute all candidate combinations: $\{A\}$, $\{B\}$, $\{C\}$, $\{A,B\}$, $\{A,C\}$, $\{B,C\}$, $\{A,B,C\}$. Candidate combination $\{A\}$ means a station is assigned to node A only. Candidate combination $\{A,B,C\}$ indicates that all nodes on the path are assigned with stations.

Each candidate combination is either eligible or ineligible in terms of a specified OD pair. An eligible combination refers to a combination that can refuel vehicles driving a round trip between the origin and the destination without running out of fuel [12]. Otherwise, the candidate combination is ineligible. We make the following assumptions about EV battery status before or after charging:

- Assume the vehicle’s driving range is five units when fully refueled. In other words, the full fuel range is five.
- A vehicle gets fully refueled after passing a refueling station.
- A vehicle’s starting fuel range is full fuel range if a refueling station is located at the origin of its trip. Otherwise, its starting fuel range is half the full fuel range.

In order to test if a candidate combination is eligible, we need to consider the vehicle’s driving range. For example, in Figure 1, if we assume the EV’s full battery range is 5, i.e., an EV with full battery can move a distance of 5 units without charging, then candidate combination $\{B\}$ cannot refuel the OD pair $(A,C)$, because the distance for a vehicle to drive from node B to node C then back to B is (2*4=)8, which is longer than the EV’s full battery range of 5.

Now we move on to the details of the FRLM. The FRLM consists of two major steps:

1) Generate and record all eligible combinations for all OD pairs on road network.
2) Given the combinations generated by the first step, build an optimization problem to select combination(s) to achieve a prefixed goal.

Detailed description of the first step can be found in [12] where an algorithm was developed. Since we will describe its extension in detail in Section IV, so we do not repeat it here. In concise, the first step outputs two matrices $\{a_{hp}\}$ and $\{b_{gh}\}$ which are explained as follows:

- Matrix $\{a_{hp}\}$ is used to store configuration of each combination. Each row of matrix $\{a_{hp}\}$ indicates a distinct combination and each column represents a candidate location for assigning refueling facilities. Matrix entry $a_{hp} = 1$ when a refueling facility is located at location $p$, otherwise 0.
- Matrix $\{b_{gh}\}$ is used to keep track of eligibility of each combination in terms of each OD pair. Each row of matrix $\{b_{gh}\}$ represents an OD pair on the network and each column represents a combination whose configuration is stored in matrix $\{a_{hp}\}$. Matrix entry $b_{gh} = 1$ if combination $h$ is able to refuel OD pair $g$, otherwise 0.

After getting matrices $\{a_{hp}\}$ and $\{b_{gh}\}$ from the first step, an optimization problem is built in the second step which is
formulated as follows:

\[
\text{maximize } Z = \sum_{q} f_q^T x_q \\
\text{s.t. } \sum_{h \in H} b_{qh} v_h \geq x_q, \forall q \in Q \\
a_{hp} y_p \geq v_h, \forall h \in H, \forall p \in P \\
\sum_{p \in P} y_p = c, \\
x_q, y_p, v_h \in \{0, 1\}, \forall q, \forall h, \forall p
\]  

where:

- \( q \) = index of OD pairs.
- \( Q \) = a set of all OD pairs.
- \( f_q \) = traffic flow, in veh/hr, on the shortest path between OD pair \( q \).
- \( x_q = 1 \) if flow \( f_q \) is refueled, otherwise 0.
- \( b_{qh} = 1 \) if combination \( h \) could refuel flow \( f_q \), otherwise 0.
- \( h \) = index of combination.
- \( H \) = a set of all combinations.
- \( v_h = 1 \) if all facilities in combination \( h \) are selected to get assigned, otherwise 0.
- \( p \) = index of candidate location.
- \( p_n \) = index of of candidate location which is a node.
- \( p_r \) = index of candidate location which is a candidate path.
- \( P \) = a set of all candidate locations.
- \( a_{hp} = 1 \) if a refueling facility is assigned to candidate location \( p \) in combination \( h \), otherwise 0.
- \( y_p = 1 \) if a refueling facility is assigned to candidate location \( p \).
- \( c \) = fixed number of refueling facilities to locate on the network.

The objective of this optimization problem is to maximize the refueled flow volume as described by Equation (1). Constraint (2) specifies that a flow \( f_q \) is considered refueled only when at least one of its eligible combination is selected. Constraint (3) specifies that an eligible combination is considered selected only when all of the facilities required by the combination are actually being assigned with refueling facilities. Constraint (4) fixes the total number of refueling facilities to locate on the network. Constraint (5) specifies that \( x_q, y_p \) and \( v_h \) are all binary variables. By restricting \( x_q \) to be either zero or one, it makes sure each refueled flow is counted at maximum one time.

IV. EXTENDED FRLM

As discussed in [3], charging stations share the same feature as traditional refueling stations, such as gas stations, that they can be treated as facilities assigning to nodes of road network. However, the charging pads charge EVs while EVs are driving above them [22]. This implies that the charging capability of a charging pad depends on its length. Therefore, we assign charging stations to nodes (points of interest) and charging pads to links (roads).

In contrast to the combinations discussed in Section III, we in addition consider candidate combinations including links for the purpose of locating charging pads. To better illustrate the differences, we revisit the short path example in Figure 1.

All candidate combinations including both nodes and links are listed under the following three situations:

- If we only locate charging stations, then the candidate combinations are the same with the combinations discussed in Section III.

- If we only locate charging pads, then the following subset of links constitute all candidate combinations \{AB\}, \{BC\}, \{AB,BC\}. Candidate combination \{AB\} means that a charging pad is assigned to link AB.

- If we locate both charging stations and charging pads, then candidate combinations are all possible combinations of two candidate combinations, each from the above two separate lists. Note that we exclude the combinations where we assign both charging pads to a link and charging station to one of its end-point. For example, combination \{A,AB\} is not considered a candidate combination since node A is assigned with a charging station and is on link AB where has a charging pad. In contrast, combination \{A,BC\} is a valid candidate combination. The reason of setting this criteria is to decrease the size of the set of candidate combinations. The intuition behind this is the maximum flow refueling objective will not be achieved by having overlapping charging facilities since spreading them would have a higher chance of serving more flows. Thus we suspect that, even though all candidate combinations including those with overlapping facilities were fed into the optimization solver, they should be eliminated eventually. Therefore, we are pre-excluding these combinations to reduce the burden of optimization solver.

As we have discussed in Section III, to test eligibility of candidate combinations, we need to consider the driving range of EVs. Since an EV can be charged while moving above charging pads, we assume that the State-of-Charge (SoC) of EV’s battery remains the same while moving on links with charging pads. 

\( ^1 \)This is in fact a conservative assumption since driving above charging pads actually increases remaining energy of an EV. For example, the energy consumption rate of Nissan Leaf 2011 model is 34kW [20]. As discussed in [1], [7], [15], charging pads are capable of achieving 37kW to 51kW energy transfer. It proves that driving above charging pad increases SOC level.

We pick one candidate combination from each situation discussed above to test their eligibility as an illustration.

- Candidate combination \{A\} from the first situation is not an eligible combination. This is proved in Section III.

- Candidate combination \{AB\} from the second situation is not an eligible combination since the starting remaining
fuel range of EV is 2.5 and the EV cannot make round trip from node B to C with remaining fuel range of 2.5.

- Candidate combination \{A,BC\} from the third situation is an eligible combination since EV gets fully charged at node A and it can make a round trip from node A to node B along with the fact that no energy consumption on the round trip from node B to C.

The extended FRLM shares the same two steps as introduced in Section III: 1) generate eligible combinations for all OD pairs; and 2) formulate an optimization problem to find optimal solutions. These two steps are discussed in detail in the following sections.

A. Eligible combination generation

An algorithm is developed in [12] which considers combinations only consists of nodes. In this section, we extend the algorithm so that it takes both nodes and links into consideration in order to model charging station and charging pad allocation.

Due to the effect that considering all possible combinations of links and nodes, the number of candidate combinations explodes which results in a large decision space for the optimization problem formulated in the second step. Instead of treating each single link as a candidate site to assign charging pads, we treat each OD pair as an entity to assign charging pads. To be more specific, in Figure 1, we do not consider assigning charging pads to either link AB or link AC but to assign charging pads to the entire AC path. As long as the OD pair AC is chosen to assign charging pads, link AB and link AC both get assigned.

Inputs of the algorithm are the network topology and driving range of EV, and outputs are two matrices \{a_{hp}\} and \{b_{qh}\} which have the same meaning as in Section III, yet a slight difference on the number of columns of matrix \{a_{hp}\}.

Revisit the short path example in Figure 1. According to Section III, matrix \{a_{hp}\} has 3 columns. However, in our case, assuming we select 2 candidate OD pairs to assign charging pads, the number of columns of matrix \{a_{hp}\} is then 5.

Now we introduce the algorithm as follows:

Step 1: initialization. Generate shortest paths for all OD pairs and store their corresponding nodes and links. Keep a list of all OD pairs \(Q\).

Step 2: select OD pairs as candidate paths to assign charging pads. Given a network with more than one OD pair, select a subset of OD pairs, \(R\), to be candidate paths.

Step 3: initialize matrix \{a_{hp}\} as an empty matrix with number of \(n\) columns where \(n\) is the summation of the number of candidate nodes and the number of candidate paths.

Step 4: generate candidate combinations for all OD pairs.

1) Begin with the first OD pair \(q\) on the list of \(Q\).
2) List all candidate combinations when assigning charging stations only.
3) If \(q\) is in list \(R\), list the combinations of \(q\) assigned with charging pads only and the combinations of assigning both charging pads and charging stations. Else, skip this step.
4) Repeat the above two steps until candidate combinations are generated for all OD pairs in \(Q\).
5) Record all combinations in matrix \(a_{hp}\).

Step 5: check eligibility for all combinations by discussing if EV could complete trips with limitation of its driving range.

1) Initialize matrix \(b_{qh}\) with entries all zero.
2) Begin with the first candidate combination \(h\) and the first OD pair \(q\). Generate a round trip \(q_h\) for OD pair \(q\).
3) If any links of path \(q_h\) in combination \(h\) is assigned with charging pad, update the energy cost of corresponding links to zero. This is based on the assumption that SOC of EV remains the same while driving above charging pads.
4) If a charging station is located at the origin of path \(q_h\), set the starting fuel range as full fuel range. Otherwise, set it as half of the full fuel range.
5) Check if combination \(h\) is an eligible combination for OD pair \(q\).
   - Start from origin node and move to the next node on the round trip path \(q_h\). Update the remaining fuel range by subtracting the fuel cost from the remaining fuel range at previous node.
   - If the remaining fuel range is negative. We reached the conclusion that the combination \(h\) is not able to refuel path \(q\). Leave \(b_{qh} = 0\) as initialized. Go check the next combination for path \(q\).
   - If the remaining fuel range is nonnegative, check the followings:
     If the current node is destination node of path \(q\) and there is a charging station at the destination node, then combination \(h\) can refuel OD pair \(q\). Set \(b_{qh} = 1\) and go check the next combination.
     If the current node is the origin node, then the EV is able to make a round trip without running out of energy. This is an eligible combination. Set \(b_{qh} = 1\) and go check the next combination.
8) Move to the next node and repeat the same procedures until the round trip is checked.
6) Repeat the above steps until the eligibility of all combinations have been evaluated for all OD pairs.

Step 6: remove combinations which are supersets of any other remaining combination. For example, in Figure 1, if combinations \{A,B,C\} and \{A,C\} are both eligible, we remove combination \{A,B,C\} since it is a superset of combination \{A,C\}.
B. Optimization problem

After generating matrices \( \{a_{hp}\} \) and \( \{b_{qh}\} \), we formulate the problem into an optimization problem described below:

\[
\text{maximize} \quad Z = \sum_q f_q^T x_q \\
\text{s.t.} \quad \sum_{h \in H} b_{qh} v_h \geq x_q, \quad \forall q \in Q \\
\quad \quad \quad \quad \quad a_{hp} y_p \geq v_h, \quad \forall h \in H, \forall p \in P \\
\quad \quad \quad \quad \quad \sum_{p \in P} y_p = c, \\
\quad \quad \quad \quad \quad y_{p_n} + y_{p_r} \leq 1, \quad \forall p_n \in p_r, \forall p_n \in P, \forall p_r \in P \\
\quad \quad \quad \quad \quad x_q, y_p, v_h \in \{0, 1\}, \quad \forall q, \forall h, \forall p
\]

where notation \( q, Q, f_q, x_q, b_{qh}, h, H, v_h, p, P, a_{hp}, y_p, c \) have the same meaning as in the optimization problem from Section III except for the following two:

\( p_n \) = index of of candidate location which is a node.
\( p_r \) = index of candidate location which is a candidate path.

The objective function and all constraints share the same meaning with the optimization problem discussed in Section III except for Constraint (10). Constraint (10) means that no overlapping of charging station and charging pad is allowed. This is achieved by restricting the number of facilities a node could be assigned is at maximum one. In other words, when charging pad is assigned to one candidate path, none of the nodes on this path could get assigned with charging station anymore.

In this paper we validate the allocation optimization problem on a small network with 9 nodes in Section V. Future study on approximation algorithm could alleviate the scale issue with large networks.

V. EVALUATION

In this section, we evaluate the extended FRLM on a network, shown in Figure 2. We use A:B in which A represents the index of corresponding link or node and B denotes the weight of the node or length of the link.

We assign each node with a weight and each link with a length. The length of links describes the distance between two points on the road network. The weight of each point describes the popularity of each node: high weight means high popularity. High popularity of a location could resulted from, for example, high number of residents or having a business center.

The feature of this network is that node four is the center node which has the highest weight while rest of the nodes share similar weights and the weights are apparently lower than node four. According to explanations before, node four attracts most of the traffic flows traveling to the center.

One real life example of this type of network is the city Berlin of Germany. Berlin is typically grouped into six districts with district Mitte in the center and the other five surrounding it. The center district Mitte attracts and generates large volumes of traffic flows into the center. Therefore, studying the network in Figure 2 helps us to have a better understanding on how the charging facilities should be located for such center-formed networks and later apply the model to similar cities.

This network has 36 flows, i.e., OD pairs, with the top five flows listed in Table I as examples. As we can see from Table I, flows traveling from the center node four to other surrounding nodes have the top flow volumes which corresponds to the fact that center node four attracts and generates most of the flows.

When testing the extended FRLM model, we set the two variables as follows:

- Number of facilities equals 3.
- Number of candidate paths equals 5.

The reason of picking the above values for these two variables is to generate a sufficient amount of distinct combinations. We will later compare the affect of different numbers of charging facilities may have on the network. Also, we assume the full fuel range of EV is 5 unit.

We pick candidate paths based on flow volumes in decreasing order. Therefore, Flow 25, Flow 22, Flow 10, Flow 24, and Flow 34 are candidate paths to assign charging pads which are listed in Table I.

The optimal solution is to locate charging pads and charging pads only on the network. The configuration is assigning charg-
ing pads to Flow 10, Flow 22, and Flow 24. The corresponding links are Link 4, Link 5, and Link 10. The total amount of flow being refueled is 3515.1 (veh/hr). Details of refueled flows by this combination are listed in Table II.

Since we are locating 3 charging facilities on the network, the possible situations of charging pads and charging stations are:

- locate 3 charging pads,
- locate 2 charging pads and 1 charging station,
- locate 1 charging pad and 2 charging stations,
- locate 3 charging stations.

Next, we compare the performance of the optimal solutions each from the above situations in Table III:

As we can see from Table III, locating 3 charging pads on the network is doubling the amount of flows being refueled by locating charging stations only.

Next, we compare the charging time, i.e. contact time, when placing charging stations and charging pads. Suppose we study EV model of Nissan Leaf driving between OD pair node two and node seven. The battery capacity of Nissan Leaf is 24 kWh and its driving range is about 70 miles [10] which corresponds to the 5 unit of full fuel range we assumed previously. Scale the distance accordingly, then the distance of the round trip between this OD pair is 252 miles. Therefore, driving from this OD pair 2, 7 requires at least four times of charging. Also, assume the speed limit is 70 mile/hr meaning without stops, it takes 3.6 hours to complete the trip.

Given the fact that on-board charger on the Nissan Leaf is around 3 kW [10], [17], so the time it takes to fully charge Nissan Leaf is about 8 hours. Further more, to complete the round trip between OD pair 2, 7, it requires 32 hours of charging. Comparing with its pure driving time, 3.6 hours, this is a significant amount of time.

However, if locating charging pads between OD pair 2, 7 as discussed in Section IV, as long as the vehicle drives on the path it does not need to stop for charging. This results in a huge saving in terms of time. Therefore, assigning charging pads to roads could be considered for those who have high traffic volumes or those who are required to have shorter travel time and higher efficiency.

Next, we show the effect of locating different number of facilities on the refueled traffic flow volumes.

As shown in Figure 3, the total amount of traffic flows being refueled increased with the number of charging facilities to locate. This meets our expectation since increasing accessibility of charging facilities by EVs enables EVs to travel longer distances. However, increasing the number of facilities on a network raises the building and management cost which is normally a limitation.

Given the fact that discussions on comparison between the costs on building and managing charging stations and charging pads are not available. For now, the constraint which sets a fixed number of facilities to locate only helps us to roughly control the total cost but it is not precise. As long as these numbers are available, we could modify the optimization problem so that it suits better in practice.

VI. Conclusion

In this paper, we proposed an extended FRLM to find optimal location for both charging pads and charging stations. The goal is to find optimal locations for charging facilities to maximize the traffic flows (veh/hr) being served. Our evaluation on a sample 9-node network suggests that allocating charging pads helps to charge significantly more EV traffic flows compared to allocating charging stations only. Also, by comparing the charging time required by charging stations and charging pads, it showed that charging pads performs better in terms of saving travel time. In summary, optimal planning of charging stations and charging pads could benefit the road network by serving more traffic flows (veh/hr) as well.
as benefiting individual drivers with dramatically decreased charging time.

There are several extensions to be studied in future work: 1) we only discussed charging facility allocation for EV, it would be a nice extension to consider PHEV. 2) approximation algorithm for the optimization problem could be studied to handle large scale network.

REFERENCES


