OPTIMIZING ELECTRIC VEHICLE (EV) CHARGING STATION LOCATIONS IN AN INTER-CITY NETWORK UNDER USER EQUILIBRIUM CONSTRAINTS

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Electric vehicles are becoming an increasingly popular eco-friendly option for urban transportation. Their adoption is led by developed nations, while developing countries like Bhutan also aim for 100% EVs by 2050. Despite the rising popularity, there are still challenges to their widespread adoption. Range anxiety arising from limited range and inadequate charging stations is one of them. The American Automobile Association survey shows that 58% of respondents have range anxiety, fearing that the charge will deplete before reaching their destination. One way to alleviate range anxiety is the establishment of strategic placement of charging infrastructure. However, establishing such infrastructure is costly and necessitates optimization to minimize the total network cost.

EVs exhibit distinctive path selection behaviors when it comes to long-distance travel stemming from their specific charging requirements, including the presence and characteristics of charging infrastructure along the route. Therefore, this research proposes a method to optimize charging station locations in a road network. The method is formulated as the total cost minimization problem under user equilibrium constraints.

Key Words : *electric vehicle, charging infrastructure, user equilibrium*

1. INTRODUCTION

In the evolving context of the automotive industry, Electric Vehicles (EVs) stand out as a key part, offering numerous benefits compared to conventional fuel-based vehicles. In terms of comfort, EVs are recognized for their contribution to diminishing noise pollution owing to their quieter performance. Moreover, they typically demand lower operating costs as they avoid the consistent maintenance associated with internal combustion engines in traditional vehicles. Perhaps the most distinguished advantage of EVs is their ability to minimize greenhouse gas emissions, thus playing a vital role in mitigating the effects of climate change by promoting a cleaner and more sustainable environment. For these reasons, numerous countries, such as China, Japan, South Korea, Singapore, and Taiwan, among many others are promoting EV adoption through various subsidies[Note 1)]. Through the report on Data Collection Survey for Electric Vehicles Promotion in Bhutan compiled out by Japan International Cooperation Agency (JICA) in 2016, it could be learnt that even Bhutan, a smaller and less developed nation, is also encouraging EV usage by offering substantial tax exemptions on the import of EVs which for fuel-based vehicles goes upto 110% of the original cost [Note 2)]. Futher, from the United Nations Development Programme (UNDP) Bhutan's website, initiatives on installing charging infrasture in Bhutan can also be seen whose long term goal is to achieve 100% EV utilization within its borders by 2050 [Note 3 and Note 4)].

Despite the substantial advantages of Electric Vehicles (EVs) and governmental endorsements, their widespread adoption continues to come across significant obstacles. Initial high costs, a restricted selection of models, and limited battery capacities are few of the critical barriers. The limited driving range

of EVs induces 'range anxiety' among drivers. A survey conducted by the American Automobile Association reveals that 58% of participants express concerns about EV batteries running out before reaching their destinations[Note 5)]. Alleviating such range anxiety can be realized through two strategies: enhancement of battery technology and the adequate establishment of charging stations in the network. Installation of EV charging insfrastructure is a financially intensive endeavor[1)]. Thus, this research concentrates on developing a strategy in selecting optimal locations for charging infrastruture installation within a network under a limited budget so that it can be a guide to countries like Bhutan in deciding locations for EV charging infratsucture which helps in achieveing the lowest long term cost.

BEV drivers' route and charging preferences are dependent on the route attributes, vehicle-related variables, charging characteristics, and socio-economic factors[2)]. Hence, EVs in general exhibit unique path selection behaviors during long distance journeys, which are mainly dictated by their charging necessities. The positioning and characteristics of charging infrastructures in a network thus become pivotal and influences the route choice of drivers. Research has been developing in this field. Bao and Xie[3)] developed a novel model to solve for optimal locations for installing EV charging station in an intercity network. The governing objective in their study was to minimize the total travel cost in the network and this was carried out under the consideration of the limited range of EVs and associated routing behaviour as well as the limited budget for installation of the charging stations. A similar study was carried out by Li, Xie and Bao[4)]. In their study, a metanetwork approach of solving the locating charging station in the network was presented. However, these two studies have not accounted for the time taken by the EV during charging and waiting in line for charging which for an EV is a part of their travel time.

Hence, this paper offers a method that optimizes the location of charging stations in an intercity network through a total network cost minimization problem under user equilibrium constraints. The total network cost includes cost associated with travelling, charging and waiting in line at charging stations as well as the cost associated with installation of EV charging stations.

3. ASSUMPTIONS

In this research the following assumptions have been made:

1) All vehicles in the network are electric vehicles.
2) All vehicles start the journey from the origin at full battery.
3) The cost of charging is excluded in this study.
4) The battery consumption of EVs depends only on the trip length.
5) The cost to install a charging station is the same for all potential nodes for the same design of charging stations.
6) A vehicle is fully charged at a charging station.

4. PROBLEM FORMULATION

In this study, a network comprised of set of nodes, N and set of links, A is taken as the scope of the study. The set of nodes is comprised of set nodes, N_c, which represent candidates of charging stations and the set of nodes, N_n, which are normal nodes where charging is not possible, i.e., $N = N_c \cup N_n$. Note that, both origin and destination nodes are included in N_n. The problem selects node(s) from N_c which are served as charging station(s). The selection of charging station node(s) is carried out such that the overall costs associated with the network is minimized. The flows in the network are calculated based on user equilibrium principle. For expressing charging station choice behavior, dummy links and charging links are introduced. These links are not physical links on the ground. The charging link is used for expressing the charging time and waiting time in line at charging station. After passing through the charging link, EV's battery level becomes 100%. As for the dummy link, it is just a link that represents the EV's choice to not charge at the node with charging station. EVs can pass through the dummy link by consuming neither time nor electricity. Here are the notations used for the problem formulation:

(1) Notations

Following are the notations used.

N	Set of nodes in the network
N_c	Set of candidates of charging station nodes
N_n	Set of normal nodes
$N_{i,j}$	Set of nodes on path *j* between o-d pair i
A	Set of links in the network
A_p	Set of actual physical links in the network
A_c	Set of charging links in the modified network
I	Set of o-d pairs in the network
J_i	Set of paths serving o-d pair $i \in I$ in the network

$F_{i,j}$ Flow on path $j \in J_i$
f_a Flow on link $a \in A$
$c_{i,j}$ Cost associated with path $j \in J_i$
t_{0a} Free flow travel time on link a
cp_a Capacity on link a
α, β BPR parameters
$t_a(f_a)$ Time required for passing through link $a \in A$ (when $a \in A_c$, t_a represents waiting and charging time)
tc_0 Average charging time for each EV
γ, ζ Parameters associated with waiting and charging time
$t_{i,j}$ Average time on path j serving o-d pair $i \in I$
$e_{a,i,j}$ Variable which equals one when $j \in J_i$ path passes through link $a \in A$, and zero otherwise
VOT Value of time
P_n Price of setting up EV Charging station at node n
$BL_{i,j,n}$ Battery Level of an EV on node n during its journey for o-d i through path j where $n \in N_{i,j}$
θ Battery level of an EV below which EV will cease to stop unless charged at a charging station
$BC_{j,a}$ Battery Consumption of link $a \in A$ on path j
B Budget limit in monetary value
x_n Charging station indicator on node n which equals 0 when node n is not a charging station and 1 when node n is a charging station
q_i Demand for o-d pair $i \in I$
$Y_{i,j}$ Path useability indicator

(2) Formulation

The main objective function in solving for optimal location of EV charging station is taken as minimizing the total cost in the network that includes the cost that arises from the total time spent on the network (travel, charging and waiting time) and the cost of setting up the charging station/s.

$$min \sum_{i \in I} \sum_{j \in J_i} F_{i,j} \cdot c_{i,j} + \sum_{n \in N_c} P_n \cdot x_n \qquad (1)$$

with respect to

$$x_n = \{0,1\} \quad \forall n \in N_c \qquad (2)$$

subject to

$$\sum_{n \in N_c} P_n \cdot x_n \leq B \qquad (3)$$

This constraint ensures that the solution is limited to the available budget. When P_n is 1, B is the maximum number of charging stations that can be installed.

And to the Beckmann transformation which ensures that the route choice behavior and traffic distribution in the network happen under user equilibrium condition

$$f_a \in argmin \sum_{a \in A} \int_0^{f_a} t_a(w)\, dw \qquad (4)$$

which is further subjected to non-negativity constraints and flow conservation constraints.

$$f_a \geq 0 \quad \forall a \in A \qquad (5)$$

$$F_{i,j} \geq 0 \quad \forall i \in I, \forall j \in J_i \qquad (6)$$

$$\sum_{j \in J_i} F_{i,j} . Y_{i,j} = q_i \quad \forall i \in I \qquad (7)$$

The definition of $Y_{i,j}$ is explained later. The relation between link flow and path flow is represented as

$$f_a = \sum_{i \in I} \sum_{j \in J_i} e_{a,i,j} \cdot F_{i,j} \quad \forall a \in A \qquad (8)$$

The travel times on actual links are governed by the popular BPR function.

$$t_a(f_a) = t_{oa} \cdot \left\{1 + \alpha \left(\frac{f_a}{cp_a}\right)^{\beta}\right\} \forall a \in A_p \qquad (9)$$

The time spent on charging and waiting in queue to get charged is also represented by a BPR type function and is allocated to the charging links in the modified network.

$$t_a(f_a) = tc_o \cdot \{1 + \gamma \left(\frac{f_a}{cp_n}\right)^{\zeta}\} \quad \forall a \in A_c \qquad (10)$$

The path travel time is inclusive of the travel times on the actual links as well as charging and waiting time incurred on the charging links

$$t_{i,j} = \sum_{a \in A_p} e_{a,i,j} \cdot t_a(f_a) \quad \forall i \in I, \forall j \in J_i \qquad (11)$$

And this can be converted into monetary value by the using value of time.

$$c_{i,j} = VOT \cdot t_{i,j} \quad \forall i \in I, \forall j \in J_i \tag{12}$$

Due to the limited range of an electric vehicle, every path for an o-d pair in a network may not be useable to an EV. Non useable paths occur when an EV cannot complete the trip without its battery getting drained. A non-useable path can be converted into a useable one by installing charging stations at proper location on the path. As users will only choose to travel on useable paths, the traffic allocation for the network will be distributed among the useable paths. Thus, a path useability indicator $Y_{i,j}$ which takes on values 1 when the path *j* for od *i* is useable and 0 when it is not useable is introduced.

$$Y_{i,j} = \begin{cases} 1, & \text{if } BL_{i,j,n} \geq \theta \ \forall n \in N_{i,j} \\ 0, & \text{Otherwise} \end{cases} \quad \forall i \in I, j \in J_i \tag{13}$$

The path useability indicator is based on the battery level (BL) of an EV at every node of path. When an EV starts its journey from the origin, it starts at 100% BL and as it crosses links, the battery level will decrease until the next node. Hence, if BL of an EV does not drop below θ, a minimum BL till which and EV can continue its journey, at every node on the path including the destination node, it means the battery has not been drained totally, throughout the journey on the path thereby deeming the path useable. However, in a path, at any node if the calculated BL drops below θ into negative values, it indicates that the EV could not reach that node and got stuck on the previous link due to its battery getting exhausted. Hence, the EV cannot complete its journey on that path. Thus, in such case the path is deemed not-useable. This is indicated in equation (13).

As for computing the BL at each node on a path it can be calculated from the BL of the previous node on the path by subtracting the battery consumption on the link between the two nodes belonging to the path. Hence the BL of an EV on o-d *i* travelling through path *j* at node *s(a)* can be calculated from BL at the previous node *r(a)* by subtracting the battery consumption on link *a*, the link directed from node $r(a)$ to node $s(a)$ on path *j*. Note that $r(a)$ and $s(a)$ are the mappings to return the tail node and head node of link *a*.

$$BL_{i,j,s(a)} = BL_{i,j,r(a)} - BC_{j,a} \quad \forall i \in I, j \in I_i, a \in A \tag{14}$$

This equation can be applied to find the $BL_{i,j,n}$ and can be applied for all the nodes present in modified network which includes actual links, charging links and dummy links. However, for the typical unmodified network, the battery level at each node shall be worked out including an additional check point as these typical nodes does not have charging links and charging behavior is only depicted through charging nodes. The additional check point is:

$$BL_{i,j,n} = \begin{cases} BL_{i,j,n} & \text{if } x_n = 0 \\ 100\% & \text{if } x_n = 1 \text{ and } BL_{i,j,n} \geq \theta \\ BL_{i,j,n} & \text{if } x_n = 1 \text{ and } BL_{i,j,n} < \theta \end{cases} \quad \forall i \in I, j \in J_i, n \in N_{i,j} \tag{15}$$

This equation for the unmodified shows that battery level at node *n* on path *j* of o-d pair *i* can be calculated by equation (14) if node *n* is not designated as a charging station. However, if node *n* is designated as a charging station, the battery level shall depend on the value of $BL_{i,j,n}$ calculated from equation (14). If the value of $BL_{i,j,n}$ is more than θ, it signifies that the EV is able to reach to node *n* on path *j* of o-d *i*. As, there is a charging station on node *n*, the EV's battery level will be charged back to 100%. However, if the $BL_{i,j,n}$ calculated from equation (14) is lesser than θ, it signifies that the EV couldn't reach till node *n*, and will get stuck on the previous link itself. Hence, the calculated $BL_{i,j,n}$ remains the same and it becomes a case of non-useable path.

3. SOLUTION METHODOLOGY

(1) Initial Network Study

The main aim of this study is to select a node or a combination of number of nodes to be set up as

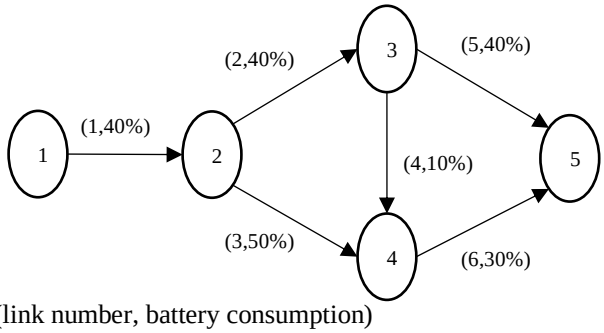


Fig. 1 Simple Network

charging stations. Setting up node or combination of nodes in a network as charging station changes the whole travel dynamic of the network by making several paths useable. As each node or combination of nodes induces specific travel behavior and generates unique solution, this is a very tough combinatorial optimization problem.[5] Thus, solving this problem requires firstly, studying the network and enumerating all possible combinations. If we take the example of the network displayed in Fig. 1, It can be noticed that this is a simple network of 5 nodes and 6 links where there is only 1 o-d pair originating at node 1 and going towards the destination node 5. In between, nodes 2, 3 and 4 are the intermediate nodes where charging stations can be set up. In this typical network, three physical paths from the origin to destination, namely, path 1 (1-2-3-5), path 2 (1-2-3-4-5) and path 3 (1-2-4-5) can be noticed.

(2) Combinations and Useable Paths

Even though there are three physical paths, without assigning any intermediate nodes as a charging station, none of these three physical paths are useable as the BL of EV by the time they reach the destination depletes below θ and becomes negative. However, installing charging station(s) on them makes certain paths useable. For instance, having a charging station on node 2 makes all 3 physical paths useable while having the charging station on node 3 makes physical paths 1 and 2 useable and having charging station at node 4 makes path 2 and 3 useable. Similarly, by installing charging stations at these nodes in different combinations will bring about different set of useable paths. Hence it is important to enumerate the possible combinations.

In the simple network, there are eight combinations in which charging station can be set up. The combinations in [x_2 x_3 x_4] format are [1 1 1], [0 1 1], [1 0 1], [1 1 0], [1 0 0], [0 1 0], [0 0 1] and [0 0 0]. Each combination makes a set of paths useable. For instance [1 1 1], [0 1 1], [1 0 1], [1 1 0] and [1 0 0] combinations allow for all physical paths to be useable whereas combinations [0 1 0] and [0 0 1] allows for only 2 useable physical paths. The combination [0 0 0] doesn't have any useable paths symbolizing the requirement of at least one charging station in the network.

(3) Ranking Combinations

The next step will be ranking the combinations into different level based of their likelihood of being the combination that brings out the optimal objective solution. This is to implement a strategy inspired from 'iterative deepening strategy'. This strategy is to reduce the computational demand as even within a small network as the one presented in Fig. 1, there are eight possible combinations to be analyzed. The analysis involves traffic assignment under user equilibrium, hence, for larger network having numerous combinations, this task could prove to be computationally demanding requiring larger memory space.

Iterative deepening is a search algorithm which is said to combine the advantages of Breadth-First Search (BFS) and Depth-First Search (DFS). The basic idea is to explore all nodes up to a certain finite distance from the source node before exploring any node at a greater distance. Thus, each iteration has a distance bound beyond which no node will be explored in that iteration, and all nodes within that distance must be visited. The bound for the next iteration may be decided during the course of an iteration[5)].

Adopting from this strategy, all the potential solution combinations shall be categorized into different depth or levels to be explored. This level shall be developed based on the likelihood of the combination of bringing about the optimal solution. Securing an optimal solution is contingent upon minimizing time within the network, and it is hypothesized that having a greater number of paths and charging stations potentially provides more options for traffic to flow efficiently through the network, which theoretically minimizes congestion and reduces the overall time spent within the network. Therefore, the levels can be established based on the decreasing total number of charging stations and useable paths available in each combination. This provides an avenue for the combinations to be explored in levels with the most likely option explored initially and jumping to the levels with lesser likely combinations strategically.

For the aforementioned network, the development of levels is established as shown in Table 1. The combination having the highest value of number useable paths and charging stations has been allocated level 0 and subsequently other combinations follow in subsequent levels. After that, the combinations are systematically evaluated, starting from level 0 (root level). Initially, the optimal objective value is determined at level 0 and set as a temporary benchmark.

Table. 1 Ranking solution combinations based on likelihood of being optimal solution based on number of useable paths and number of charging stations

Combinations	Useable Paths	Charging Stations	Total	Level
[1 1 1]	3	3	6	0
[0 1 1] [1 0 1] [1 1 0]	3	2	5	1
[1 0 0]	3	1	4	2
[0 1 0] [0 0 1]	2	1	3	3
[0 0 0]	0	0	0	4

Then, the process iteratively progresses to the next level where the optimal objective value is evaluated for the level. If the optimal objective value obtained at the next level proves to be better than the initial temporary optimal objective value, then the optimal objective value used for the benchmark will be replaced by the one from the newer level and the iteration will continue by jumping to the subsequent level. When a level fails to provide a better objective value than the previous one, the iteration will stop, declaring the current temporary optimum as the final optimal value. This heuristic based approach offers a smart way to solve charging station location combination problem by not only accessing the more likely solutions initially but also not failing in looking for other likely solutions while also reducing computer memory usage.

(3) Traffic assignment

Evaluating a combination for objective value necessitates conducting a traffic assignment exercise since the objective function is influenced by the travel cost, which is a function of travel time, hinging largely on the network's traffic distribution. These assignments are executed under user equilibrium conditions utilizing the Method of Successive Averages (MSA) algorithm. However, deploying the algorithm directly to the network presents challenges because conventional networks and paths don't account for charging behaviors. Therefore, adaptations to the existing network can be initiated by modifying the existing network by introducing charging links and dummy links. Charging links are subjected to charging time and waiting time while dummy links neither impacts charge nor time signifying that the vehicle doesn't charge at that node.

Passing through the charging link on the modified network depicts the user behavior to charge at the node while passing through the dummy link depicts user behavior of not opting to charge at that node. The resultant modified network for the aforementioned network is shown Fig. 2 whereby new charging links namely link 8, 10 and 12 and dummy link namely links 7,9 and 11 are added to show the charging decision behavior on each node.

Accounting in charging station choice behavior, seven unique paths are observed which is an increase to the three observed previously. The new paths as per their link notation are as given in Table 2.

With this modified network, application of method of successive averages (MSA) algorithm becomes simple and the traffic can be distributed based on path availability for every combination of charging station availability.

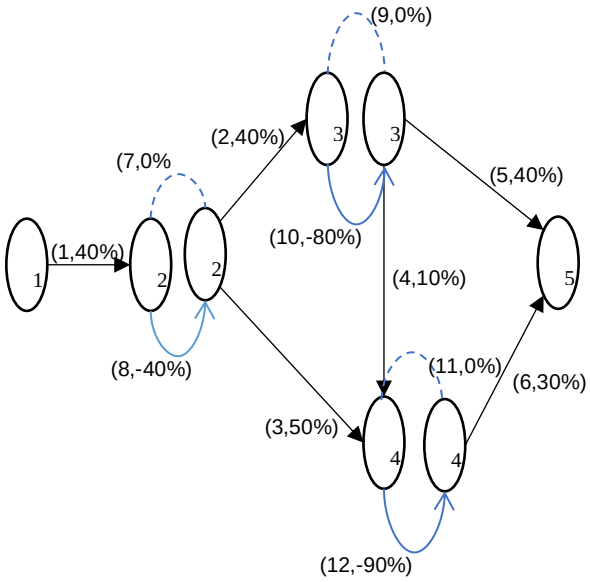


Fig. 2 Modified Network

Table. 2 Link Wise Paths in the modified network showing charging station choice behavior

Path No	Links	Charging Location
1	1-8-2-9-5	Node 2
2	1-8-2-9-4-11-6	Node 2
3	1-8-3-11-6	Node 2
4	1-7-2-10-5	Node 3
5	1-7-2-10-4-11-6	Node 3
6	1-7-2-9-4-12-6	Node 4
7	1-7-3-12-6	Node 4

4. ANALYSIS AND RESULTS

The above-mentioned network with additional information given in Table 3 has been analyzed for optimal location of setting up charging station as per the methodology explained above. In the analysis, BPR parameter $\alpha = 0.15$ and $\beta = 4$ and link capacity, cp_a=100 was assumed for the BPR function. Similarly, for waiting and charging time, parameters $\gamma = 0.015$ and $\zeta = 1.349$ was used. A total of 120 o-d daily demand was also assumed. Additionally, the VOT was taken as 30yen/min while the cost of charging station installation P_n was taken as 90 million yen, 135 million yen and 180 million yen for charging station design with 4 charging ports, 6 charging ports and 8 charging ports respectively. Additionally, θ was assumed as 5% as users don't usually make journey until 0% battery level.

Table 3. Additional Network information

Link	Length (km)	Free Flow travel time
1	80	80 min
2	80	80 min
3	100	100 min
4	20	20 min
5	80	80 min
6	60	60 min

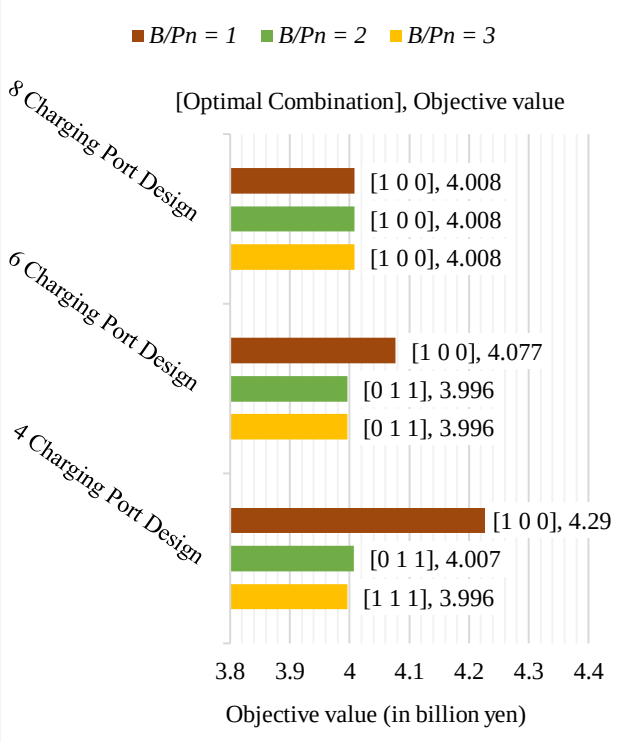


Fig. 3 Optimal Solutions for various cases under different charging station design and under different budget constraint

With that the analysis was done under various cases of budget limit which allowed for installation of 3, 2 and 1 charging stations. This was done for three charging station designs which have 8, 6 and 4 charging port. The objective function was calculated for a time period of 10 years and the result is shown in Fig 3.

5. DISCUSSIONS AND CONCLUSIONS

In the comparing the three results for charging station with 4 charging ports design, it was observed that increasing the number of charging stations in the network minimized the total network cost. Thus, it can be concluded that the physical availability of charging stations, even with limited ports, can enhance network efficiency by providing more path options.

From the outcomes of cases where the total number of charging stations in the network was limited to 1 due to the budget (B/P_n=1), it can be noticed that increasing the number of charging ports reduced the total overall cost. This suggests that concentrating charging ports at fewer but more accessible charging station locations can also alleviate congestion effect thereby bringing the total network cost down. So, in networks with lesser candidates for charging nodes, adopting a charging station design with a greater number of charging ports and installing them at a strategic location can bring down the total network cost.

All the results are the solution combinations which allowed for a greater number of useable paths under their budget constraint. This validated that opting for a combination that maximizes usable paths renders an optimal solution, as it effectively dilutes congestion effects. By providing multiple viable routes for travel, traffic is disseminated across the network, alleviating pressure on individual paths and thus ensuring smoother flow and potentially reducing overall travel times.

Holistically, this approach which initially preliminarily assesses the network, then ranks the solution combinations into level and then carry out traffic assignment for the combinations in search of the optimal solution by means of modified network and in a level-by-level assessment method demonstrates substantial merit for identifying optimal locations for charging stations in an intercity network.

6. CHALLENGES AND FUTURE DIRECTIONS

The initial limitation of the approach lies in its application to a relatively simplistic problem. Thus far, the method has been simulated only on a smaller and less complex network. For its viability and effectiveness to be substantively validated, it's imperative that it be applied and tested on a larger, more intricate network. This would help in ensuring that the method can stand up to the complicated challenges that larger networks, with their increased complexity and varied traffic patterns, may present.

Secondly, while costs associated with waiting time and charging time have been accounted for, the actual cost of charging the electric vehicles (EVs) has not been incorporated into the calculations. Implementing a scenario where the charging cost is also factored into the objective function could enhance the result, providing a more comprehensive understanding of the financial implications and potentially facilitating more economically sound solutions.

Thirdly, the model operates under the assumption that all EVs embark from the origin with a fully charged battery. It is also assumed that all vehicles will be charged fully at the charging station. These

may not reflect real-world conditions accurately. Vehicles might commence their journeys with varying battery level based on individual user's behavior and circumstances. Similarly, users may not opt to charge fully at the charging stations during their journey. Integrating such cases will be close to real life scenario.

Each of these aspects presents an avenue for further exploration and refinement of the model, underscoring potential areas for enhancement and adjustment in future research and application endeavors.

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