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Optimal Placement of Electric Vehicle Charging Stations Using Mixed-Integer Linear Programming: A Case Study in Cambodia

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Abstract: *Electric vehicles produce zero tailpipe emissions, which can help to improve air quality and reduce greenhouse gas emissions in Cambodia. The Cambodian government has set a target of increasing the share of electric vehicles in the country's fleet to 20% by 2030. To support this goal, the government has introduced a number of incentives for EV owners, such as tax exemptions and reduced import duties. With this policy, the number of charging stations is expected raise to support the increased number of EV in circulation. This study introduces an optimization model that deals with the optimal placement of charging stations in terms of investment and convenience for EV owners. First, the candidate locations for charging stations are determined. With the help of the historical route of electric vehicles, a MILP problem is solved to find optimal placements. In this study, Cambodia is used as a case study to examine the challenges. The model can achieve the optimal solution regardless of the size of the data.*

Keywords: Electric Vehicle, Charging Station Placement, Optimization, MILP, Matlab

1. INTRODUCTION

Nowadays, global warming is the main problem in the world which is caused by carbon emissions from combustion engines that can affect climate change and natural disasters. The increasing fuel costs and environmental concerns have stimulated the recent take-off of (EVs) car market [1]. There are 3 types of Electric Vehicles including 1) battery-electric vehicles (BEVs), 2) hybrid electric vehicles (HEVs), and 3) plug-in hybrid electric vehicles (PHEV). EVs have the advantages of being environmentally friendly and cleaner compared to vehicles that use fossil fuels. They reduce greenhouse gas emissions depending on the technology used for electricity generation and some of them (battery electric vehicles (BEVs) emit no tailpipe pollutants (zero-emission vehicle). They also have the benefit of reducing dependence on foreign petroleum and contribute to the nation's energy independence. In addition, electric vehicles have other benefits such as having lower noise and better efficiency compared to conventional internal combustion engine vehicles which are relatively inefficient since the majority of energy is lost as heat during the conversion of fuel energy to propulsion. According to Tesla Company, drive efficiency of the Tesla Roadster is 88% which is almost three times more efficient than the conventional vehicle powered by internal combustion engine [2]. On the other hand, the limitation of the maximum range, a number of other factors also dissuade many consumers from purchasing an EV. In fact, while consumers rate the range as the most common reason for them to not purchase an EV [3].Based on the power and the range of voltages that are supported by EV chargers, they are classified into three levels A) lower than 3.7 kW are Level 1 chargers, B) between 3.7 and 22 kW are Level 2 chargers, and C) higher than 22 kW are Level 3 chargers [4].

Currently, Cambodia has installed five charging stations in provinces and cities such as Phnom Penh City, Siem Reap Province, Sihanoukville, Battambang Province, and Mondulkiri Province [5]. However, the problem in Cambodia nowadays is that we still don't have enough charging stations in urban and rural areas. Hence, the government wants to ensure that at all time the distance of the EV from the charging stations is always optimal.

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This paper studies the optimal placement of charge stations in Cambodia, to minimize investment costs, to minimize the distance to the stations / minimize charging time, analysis of the balance between investment cost and distance of the EV to the charging station. The scope of this paper focuses on how many charging stations should be open. The study is limited to all existing national roads and existing petrol stations for the candidate locations, ignoring traffic, and using all level-3 charging stations. The expected outputs are: 1) Find a solution of optimal placement for a selected number of stations, 2) Can provide analysis of the balance of cost and charging time based on the data of specific scenarios, 3) Provide a general optimal solution to actual scenario based on the actual data. This study can help providing consultation for investment in EV charging station.

In Section 2, literature reviews are conducted. In Section 3, methodologies are described for the optimization problem in the standard form of MILP such as a flowchart of procedure, input data indices, and set. A mixed integer linear programming (MILP) model is developed taking the number of vehicles and their routes as the input to find the optimal charging station locations. In Section 4, the demonstration of the results and the average result of the optimal charging station is discussed with that results. And finally, the conclusion is discussed in section 5.

2. LITERATURE REVIEWS

[6]developed an optimization model for detecting the best locations for charging stations. In the previous paper, Andrews's model is given first to clarify the contributions of the present study. Then the proposed model by including the missing parts of Andrews's work is discussed. Andrew's model consisted of a time period, a set of vehicles, and the set of candidate locations are as follows:
Equation(1) The objective is to minimize the total distance traveled by all vehicles to access the selected charging stations. Constraint equation(2) ensures that each vehicle is charged by selecting one charging option. Constraint equation(3) is a feasible cut introduced for computational purposes—it says vehicle v can charge at location j only if a charging station is opened there. Constraint equation (4) ensures that the number of vehicles assigned to a charging station at location j is not beyond the capacity of that location in any period. Constraint equation(5) makes sure that exactly P charging stations are opened. Where: v = vehicle, j = candidate locations, x = binary (0,1) vehicle being present in time t at the station j, yj = binary (0,1) decision variable that is 1 if a charging station is opened, Qj = number of vehicles that can charge there simultaneously, P = charging stations chosen from a set of candidate locations j.

$$min \quad \sum_{(v,t,j)} d_{v,t,j} x_{v,t,j} \qquad \text{(Eq. 1)}$$

$$s.t. \quad \sum_{(v,t,j)} x_{v,t,j} = 1 \qquad \forall v \in V \qquad \text{(Eq. 2)}$$

$$x_{v,t,j} \le y_j \qquad \forall (v,t,j) \qquad \text{(Eq. 3)}$$

$$\sum_{(v,t,j)} x_{v,t,j} \le Q_j y_j \qquad \forall j \in J \qquad \text{(Eq. 4)}$$

$$\sum_{(j \in J)} y_j = P \qquad \text{(Eq. 5)}$$

For minimizing the distance, the author used the shortest path algorithm. However, his model didn't include any charge of the state of any vehicle. Vehicles maximum and remaining range weren't indicated for charging situations. Moreover, the investment cost of charging stations in different locations within the city is not considered in the objective of the model [7].

Mixed-Integer Linear Programming (MILP) denotes optimization problems with continuous and integer variables, influencing a linear objective function and restricted by linear constraints. This methodology is detailed in [8]. MILP is the right model, when decisions to be optimized refer to indivisible entities and all quantitative relations can be expressed by linear equations and linear inequalities. For example, the navigation in a street network has to decide whether to turn right or to turn left – it is not possible that half a car goes to either side. The total travel time is the sum of all travel times between crossings. A famous example for the power of MILP is proven optimal solutions to very large instances of the Traveling Salesman Problem (TSP). In a TSP, a shortest closed tour visiting a given set of cities has to be planned. Trying out all possibilities for a 100-cities-TSP would mean to enumerate far more solutions than there are atoms in the universe. In contrast to this naive approach, MILP methods could solve TSPs with 25000 cities to proven optimality! The specialty of MILP compared to heuristic methods is the ability to generate not only better solutions but also so-called dual bounds during the solution process. Dual bounds provide a cost value that cannot be improved by any feasible solution. The solution process can be stopped as soon as one has found a solution whose optimality gap, i.e., the distance to the optimal value, is satisfactory.

A mixed-integer linear program (MILP) is a problem with 1)Linear objective function, fTx, where f is a column vector of constants, and x is the column vector of unknowns, 2)Bounds and linear constraints, but no nonlinear constraints (for definitions, see Write Constraints), 3) Restrictions on some components of x to have integer values. In mathematical terms, given vectors f, lb, and ub, matrices A and Aeq, corresponding vectors b and beq, and a set of indices intcon, find a vector x to solve

$$min\ f^T x\ \ subject\ to = \begin{cases} x\ (intcon)\ are\ intergers \\ A.\ x \le b \\ Aeq.x = beq \\ lb \le ub \end{cases}$$

3. METHODOLOGY

3.1 Flowchart of Procedure

In this paper, the optimal placement of electric vehicle charging stations using Mixed-Integer Linear programming is performed. The seven following steps will be addressed in this research; 1) Set the number of vehicles, 2) Set the possible charging locations, 3)Calulate the distances of the vehicles, 4) Formulate objective function equation, 5) Formulate constraints equations, 6) Develop the algorithm (MILP) using MATLAB and 7) Run the program. Fig.1 shows the flowchart for the various steps of the propose algorithm.

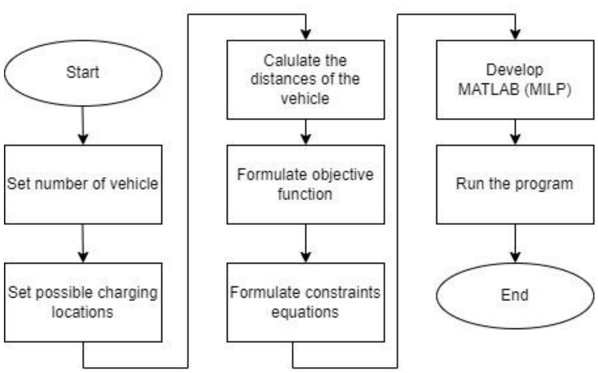

Fig.1. Flowchart of Procedure

3.1 Input data

The proposed input data are shown as followed:

- Distances of the vehicles to each location.
- Customs a number of the vehicle.
- Twenty-five possible charging locations:

The charging stations are supposed to locate at the center of each provinces of Cambodia. Table 1 details the names of the charging location.

3.3 Objective function and Constraints

To solve the above problem, we need to create the objective function and constraints of the following equation [6]:

Table.1. Possible charging locations

	Chosen charging locations
1	Phnom Penh (PP)
2	Kandal province (KD)
3	Kampong speu province (KPS)
4	Takeo province (TK)
5	Prey veng province (PV)
6	Kampong chhnang province (KPCH)
7	Svay Rieng province (SVR)
8	Kampong cham province (KPC)
9	Kampot province (KP)
10	Kampong thom province (KPTH)
11	Kep province (KEP)
12	Pursat province (PS)
13	Sihanoukville (SHV)
14	Koh Kong province (KK)
15	Battambang province (BTB)
16	Preah Vihear province (PVH)
17	Kratie province (KRT)
18	Siem Reap province (SR)
19	Banteay meanchey province (BMC)
20	Pailin province (PL)
21	Steung Treng province (STR)
22	Oddar meanchey province (ODM)
23	Mondulkiri province (MDK)
24	Ratanakiri province (RTK)
25	Tbong Khmum Province (TBK)

$$min \quad \sum_{(v,t,j)} d_{v,t,j} x_{v,t,j} \qquad (\text{Eq. }1)$$

$$s.t. \quad \sum_{(v,t,j)} x_{v,t,j} = 1 \qquad \forall v \in V \qquad (\text{Eq. }2)$$

$$x_{v,t,j} \le y_j \qquad \forall (v,t,j) \qquad (\text{Eq. }3)$$

$$\sum_{(v,t,j)} x_{v,t,j} \le Q_j y_j \qquad \forall j \in J \qquad (\text{Eq. }4)$$

$$\sum_{(j \epsilon J)} y_j = P \qquad (\text{Eq. }5)$$

Equation(1) The objective is to minimize the total distance traveled by all vehicles to access the selected charging stations. Constraint equation(2) ensures that each vehicle is charged by selecting one charging option. Constraint equation(3) is a feasible cut introduced for computational purposes—it says vehicle v can charge at location j only if a charging station is opened there. Constraint equation (4) ensures that the number of vehicles assigned to a charging station at location j is not beyond the capacity of that location in any period. Constraint equation(5) makes sure that exactly P charging stations are opened.

These are indicated by the index:

- v = vehicle.
- j = candidate locations.
- x = binary (0,1) vehicle being present in time t at the station j.
- yj = binary (0,1) decision variable that is 1 if a charging station is opened.
- Qj = number of vehicles that can charge there simultaneously.
- P = charging stations chosen from a set of candidate locations j.

3.4 Developing the algorithm in MATLAB

This is an algorithm of the procedure developed in MATLAB, the optimal placement of electric vehicle Charging Stations using Mixed-Integer Linear programming that we following steps: 1)Set the number of vehicles: for this paper, we use one vehicle to run each national road, 2)Set possible charging stations: we also set the potential locations all province and city as table1, 3)Set matrix of distance stations to stations are propose

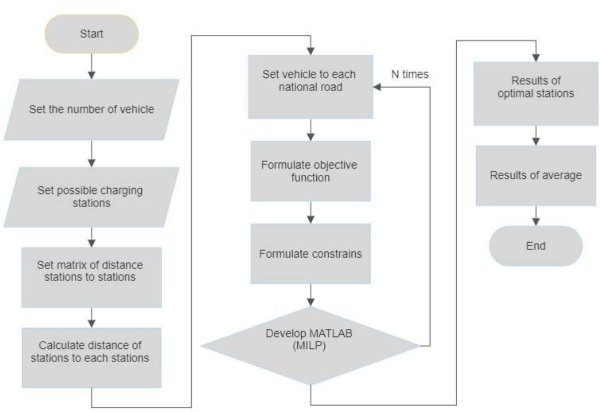

Fig.2. Flowchart of Procedure develop MATLAB

for calculation, 4)after we get the matrix of stations to stations we need to calculate the distance of stations to each station 5)Set vehicle run to each national road, 6)Formulate objective function based on equation(1), 7)Formulate constraints equation (2-5), 8)Develop MATLAB depending on the standard form of Mixed-Integer Linear Programming (MILP), 9)After that we obtain result of optimal stations, 10)Moreover the result of average will be found for this paper.

3.5 Case Study

A simple case study is adapted to clearly represent the effectiveness of the model and to provide a test trial for the interested audience. A simplistic map of Cambodia is shown in Fig.3 with potential twenty-five possible charging stations in table.1 and distance of stations to staions . In addition, the electric car in this case study is set to run their national routes.

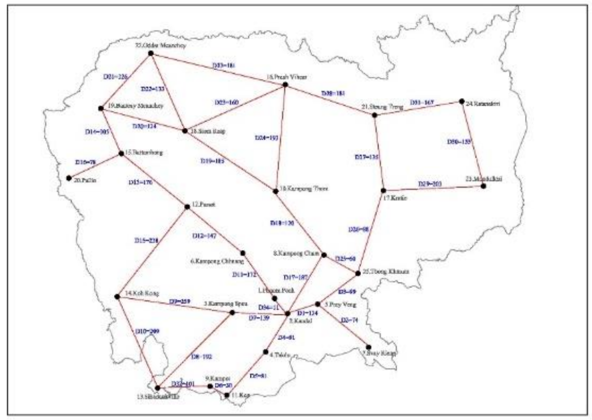

Fig.3. Map of Cambodia

4. RESULTS AND DISCUSSION

The optimization problem with the objective function of (Eq.1) subject to the constraints of (Eq.2-Eq.5) is develop in MATLAB. A case study consists of selecting Twenty-five possible charging stations and one electric car. The model solves the problem of optimally selecting the charging stations to be built while satisfying the constraints. Because of the data and restrictions entered, the model successfully showed the result of optimal charging stations that provide two options option one such as selecting five charging stations, and option two selects ten charging stations, the average distance of vehicles to the closest station for each case is found, and the finially optimal average distance of a vehicle to the closest for different also found.

4.1 Results of optimal charging stations

According to results of this study also define two options that, for option 1 the results of optimal charging stations at each charging location is define to five location. If a vehicle is being charged in a station, the solution of variable x indicates at each charging stations as shown in the results. Through the solution of variable yj, the optimal charging stations are shown in Table.2 and Fig. 4.

Table.2. Result of charging locations for option 1

Result for option 1 (Five selected) Possible charging locations		x	yj
1	Phnom Penh (PP)	0	0
2	Kandal province (KD)	1	1
3	Kampong speu province (KPS)	0	0
4	Takeo province (TK)	0	0
5	Prey veng province (PV)	0	0

6	Kampong chhnang province (KPCH)	0	0
7	Svay Rieng province (SVR)	0	0
8	Kampong cham province (KPC)	0	0
9	Kampot province (KP)	0	0
10	Kampong thom province (KPTH)	0	0
11	Kep province (KEP)	0	0
12	Pursat province (PS)	0	0
13	Sihanoukville (SHV)	0	0
14	Koh Kong province (KK)	0	0
15	Battambang province (BTB)	0	0
16	Preah Vihear province (PVH)	0	0
17	Kratie province (KRT)	0	0
18	Siem Reap province (SR)	0	0
19	Banteay meanchey province (BMC)	0	0
20	Pailin province (PL)	0	0
21	Steung Treng province (STR)	0	0
22	Oddar meanchey province (ODM)	0	1
23	Mondulkiri province (MDK)	0	1
24	Ratanakiri province (RTK)	0	1
25	Tbong Khmum Province (TBK)	0	1

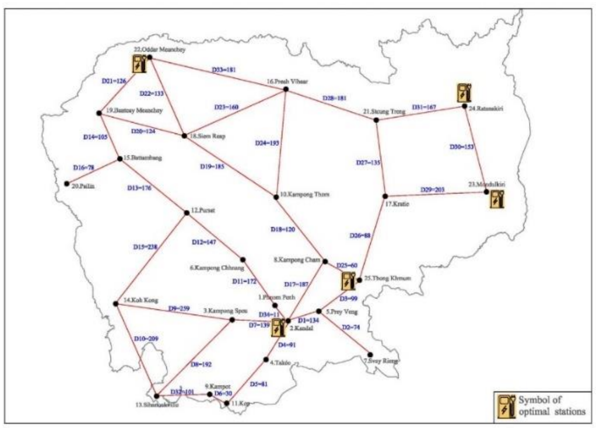

Fig.4. Result of charging locations for option 1

According to the results of this study also define two options that, for option 2 the results of optimal charging stations at each charging location is defined to ten locations. If a vehicle is being charged in a station, the solution of Variable x indicates at each charging stations as shown in the results. Through the solution of Variable yj, the optimal charging stations are shown in Table.3 and Fig. 5.

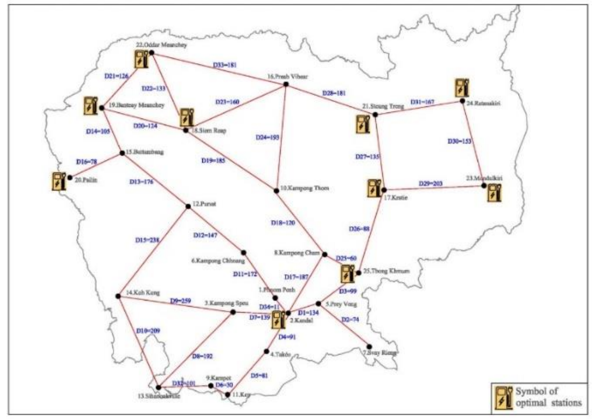

Fig.5. Result of charging locations for option 2

Table.3. Result of charging locations for option 2

Result for option 2 (Ten selected) Possible charging locations		x	yj
1	Phnom Penh (PP)	0	0
2	Kandal province (KD)	1	1
3	Kampong speu province (KPS)	0	0
4	Takeo province (TK)	0	0
5	Prey veng province (PV)	0	0
6	Kampong chhnang province (KPCH)	0	0
7	Svay Rieng province (SVR)	0	0
8	Kampong cham province (KPC)	0	0
9	Kampot province (KP)	0	0
10	Kampong thom province (KPTH)	0	0
11	Kep province (KEP)	0	0
12	Pursat province (PS)	0	0
13	Sihanoukville (SHV)	0	0
14	Koh Kong province (KK)	0	0
15	Battambang province (BTB)	0	0
16	Preah Vihear province (PVH)	0	0
17	Kratie province (KRT)	0	1
18	Siem Reap province (SR)	0	1
19	Banteay meanchey province (BMC)	0	1
20	Pailin province (PL)	0	1
21	Steung Treng province (STR)	0	1
22	Oddar meanchey province (ODM)	0	1
23	Mondulkiri province (MDK)	0	1
24	Ratanakiri province (RTK)	0	1
25	Tbong Khmum Province (TBK)	0	1

4.2 Average distance of vehicles to the closest station for each case

After obtaining the results of charging stations at each location, we assume ten charging stations. The result of the optimal locations are then compared with the set of ten random locations using average distance of vehicles to the closest station:

- Optimal locations: (KD), (KRT), (SR), (BMC), (PL), (STR), (ODM), (MDK), (RTK), and (TBK).
- Random set 1 (case 1): (KPS), (TK), (SVR), (KP), (KEP), (SHV), (KK), (BTB), (MDK), and (RTK).
- Random set 2 (case 2): (KEP), (PS), (SHV), (KK), (BTB), (PVH), (KRT), (SR), (BMC), and (PL).
- Random set 3 (case 3): (PVH), (KRT), (SR), (BMC), (PL), (STR), (ODM), (MDK), (RTK), and (TBK).
- Random set 4 (case 4): (KPTH), (PS), (KK), (PVH), (SR), (BMC), (PL), (STR), (ODM), and (MDK) as shown in Fig.6.

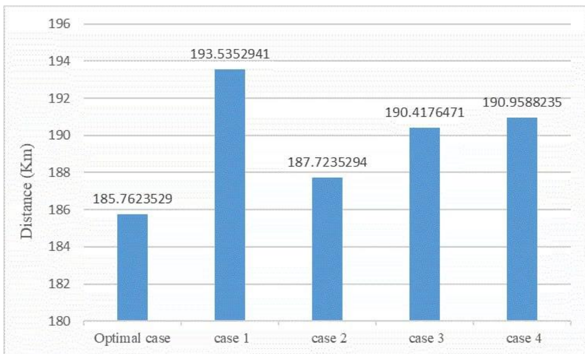

Fig.6. Average distance of vehicles to the closest station for each case

4.3 Optimal average distance of a vehicle to the closest for different (P)

To make it easier to analyze and select for investors in this work, we have made a comparison between the selection of the number of charging stations from one to twenty-five. The result is shown in Fig.7. P is the number of installed charging stations.

According to the graph, the more the number of stations, the lower the average distance from any one car to the charging station. But having more station cost more for investment. It is on the investors to analyse these data and decide on their investment in order to optimize the profit.

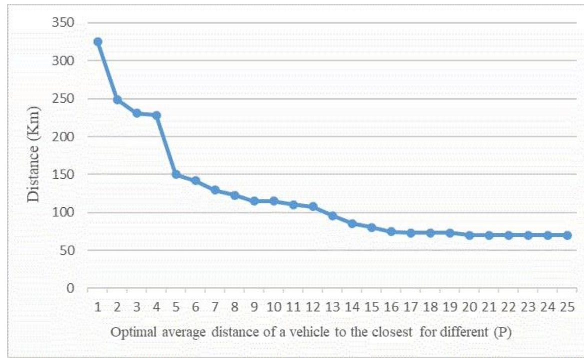

Fig.7. Optimal average distance of a vehicle to the closest for different (P)

5. CONCLUSIONS

In this paper, Mixed-integer linear programming (MILP) method has been presented for identifying patterns in potential locations activities to enable strategic deployment of new charging infrastructure. Cambodia is used as a case study to demonstrate the model, which incorporates national road data to test the proposed algorithm. The overall result and average results of this work are a methodology to be adapted for finding the optimal set of charging location in rural areas or urban areas. Future step, the model can integrate a more complex model of the EV availability, EV demand, and cost of electricity to model the optimization problem in order to gain more insights into the evolution of the actual EV market.

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