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Electric Vehicle Charging Stations Allocation Model

Fouad Baouche, Romain Billot, Rochdi Trigui, Nour Eddin El Faouzi.

1. Introduction

The goal of this paper is to present a methodology for the optimal location of charging stations. The background of the proposed methodology is an adaptation of the Fixed Charge Location problem (1) with the p-Dispersion (2) constraint. More specifically, we adapt a linear model based on these two classical location models. Instead of fixing the charging stations in the demand points, our model focuses on minimizing the total travel cost from the demand point to the charging station location together with the server investment cost. The energy demand was derived from a vehicle consumption model developed as part of the VEHLIB model library (3) (4). The energy consumption was assessed by VEHLIB from realistic trips generated from routing tools and enriched with elevation profile. This effort enables to accurately approximate the actual energy needs taking into account the travel demand derived from the Origin-Destination (OD) household travel survey of the Rhône region. For the validation purposes, a case study was constructed as part of the metropolitan area of Lyon and the associated problem was solved based on various configurations of Electric Vehicles (EV) market penetration rate.

2. Modeling Approach

Many studies focused on the trip range to estimate the consumption needed for the charging station location models. However, other factors need to be considered. In our model, we defined a methodology to deal with all impacting factors. First, we use an OD matrix to determine the travel demand and then the energy demand. This OD matrix was derived from the largest household travel survey conducted in the metropolitan area of Lyon, France (5). Demand clusters have been built based on the OD demand trips centralized on the destinations. From each OD couple a trip was constructed according to routing API where the optimum travel time was selected as the traveller choice criteria. Next, we enriched these trips with elevation information provided by the IGN Alti-Maps Database. Finally, we applied a dynamic consumption model from the VEHLIB library to provide realistic consumption estimation.

Our optimization model determines the charging stations to place from the candidate location sites list, with the objective of minimizing the charging station fixed charge and the electric vehicle travel cost. Our model includes three sets of constraints. First, each demand cluster is associated to one charging station. Second, the capacity restriction constraint requires that the total energy provided to vehicles does not exceed the capacity of the selected charging station. Last the non-proximity constraint, forces the model to locate the charging stations with a minimum radius R . In the following, we introduce the models parameters with more details:

J : set of candidates charging stations sites.

I : set of travel demand zone.

f_j : cost of locating a charging station at candidate site i .

D_i : energy demand at cluster i .

d_{ij} : energy needed for a vehicle to travel from demand cluster i to charging station j .

r : minimal distance between located charging station.

$dist_{ij}$: distance between charging station i and charging station j .

c_j : capacity of charging station j .

α : kilowatt cost.

nbV_i : number of EVs in cluster i .

Decision variables:

$$x_j = \begin{cases} 1 & \text{if a charging station is located at candidate site } j \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if the demand zone } i \text{ is covered by the charging station } j \\ 0 & \text{otherwise} \end{cases}$$

$$\text{FCLDM} \left\{ \begin{array}{l} \text{Min } \sum_{j \in J} f_j x_j + \alpha \sum_{j \in J} \sum_{i \in I} nbV_{ij} d_{ij} y_{ij} \quad (1) \\ \sum_{j \in J} y_{ij} = 1 \quad \forall i \in I \quad (2) \\ y_{ij} - x_j \leq 0 \quad \forall i \in I \quad \forall j \in J \quad (3) \\ \sum_{i \in I} nbV_i (D_i + d_{ij}) y_{ij} \leq c_j x_j \quad \forall j \in J \quad (4) \\ r + (M - \text{dist}_{ij}) x_i + (M - \text{dist}_{ij}) x_j \leq 2M - \text{dist}_{ij} \quad \forall i, j \in I, i < j \quad (5) \\ x_j \in \{0,1\}, \quad j \in J, \quad r \geq 0 \quad (6) \\ y_{ij} \in \{0,1\}, \quad \forall i \in I \quad \forall j \in J \quad (7) \end{array} \right.$$

The first equation represents the optimization function. The objective is to minimize the total cost and the total distance traveled by all vehicles to access to a charging station. Equation (2) and (3) assume that each demand zone is covered by one charging station. The constraint (4) ensures that the demand assigned at location j is not beyond the capacity c_j of the charging station under consideration. Indeed, since the demand D_i for a zone i is the sum of all the downstream trips derived from the OD matrix, this implies that the total energy to be covered by a charging station j must include the travel energy cost from this zone to the located charging station. The last constraint is derived from the p -dispersion problem (2). This non-linear constraint forces each server to be separated with a minimum radius r . M is a large number (fixed to $\text{Max}(\text{dist}_{ij})$). Finally, constraints (6) and (7) define y_{ij} and x_j as 0 or 1 integrals and $r > 0$.

3. VEHLIB Library

The VEHLIB is a modular library that combines different vehicle models. The approach used for the vehicle modeling is divided into different sub-systems, each sub-system representing a component of the studied vehicle. The parameters of the component are either identified by experimentation or directly given by the manufacturer. Two validations phases are used: the first one studies the components independently and the second one is a complete validation of the entire system where all the sub-systems are connected. The resulting models are validated by measures on engine, electric motor and battery test benches as well as on chassis dynamometer for the entire vehicle.

The VEHLIB library is based on the reproduction of the forces acting on the vehicle according to the desired acceleration (a) and speed (v) to define the necessary drive train torque output T_{drive} . From the Newton's second law:

$$T_{\text{drive}} = J_{\text{veh}} \cdot a / R_{\text{tire}} + F_{\text{res}}(v) R_{\text{tire}}$$

where J_{veh} is the equivalent vehicle inertia, R_{tire} is the tire radius and the resistance forces F_{res} depend on the vehicle speed. It can be computed as a sum of rolling resistance, aerodynamic drag and road grade on the chassis.

$$F_{\text{Roll}} = C_r M_{\text{veh}} g \cos(\alpha)$$

with C_r the coefficient of rolling resistance, which depends on the vehicle load and wheel radius, g is the gravitational constant and M_{veh} the vehicle's total mass (chassis, drive train, engine and passenger).

$$F_{aero} = \frac{1}{2} \rho_{air} S_f C_x(\alpha_R) V_R^2$$

where ρ_{air} the volumic mass of the air, S_f is the front surface of the vehicle, C_x the shape coefficient, α_R is the relative angle of the wind and V_R is the relative vehicle velocity according to the wind velocity.

$$F_{grade} = M_{veh} g \sin(\alpha)$$

and M_{veh} is the vehicle mass, g the gravity acceleration and α the angle representing the road segment slope.

This model library brings more modularity, allowing the reproduction of the behavior of each separate component and models the vehicle as a whole system. Moreover, it can be used to propose new solutions to layout and manage energy for the most complex vehicles.

4. Data and results

The resolution of the Fixed Charge Dispersion Location Model (FCDLM) is proposed for the city of Lyon. This city is composed of 9 districts with an estimated population of 492 578 inhabitants (6) and a proportion of 470 vehicles for 1000 inhabitants (5). The OD matrix used for this simulation is derived from the household travel survey of the Rhone Region, France. Initially, this OD matrix was composed of 843*843 OD pairs, the dimension being reduced to 42x42 for the 9 districts of Lyon.

The EV mobility demand was modeled as energy clusters: these clusters were constructed from all the OD couples. Between an origin and a destination, shortest paths were computed and transformed into speed profile and enhanced with elevation profiles collected from the IGN Alti-database. The resulted speed/elevation profile were computed with the VEHLIB library to evaluate the energy consumption on each OD pair. The studied vehicle is an urban model characterized by a 20 KWh battery. We chose this configuration to be close to the vehicles fleet currently available on the market. This enabled us to construct the demand D_i (42x42 matrix) and supply cost d_{ij} parameters (42x72 matrix). The distance matrix $dist_{ij}$ (72x72) can be computed by an Euclidean distance (or by shortest path distance) between all the potential sites. The potential charging sites were selected from the existing petrol stations and public parking facilities. We assume that the petrol station will be equipped with fast chargers (43KW AC/50 KW DC) and the parking lots with semi-fast chargers (22 KW). We also define two proportion parameters, one for the number of slow chargers depending on the size of the parking (e.g. 2 % of the total capacity) and the other for the electric vehicles penetration rate. The minimal radius r was fixed to 1 km. The modeling approach was validated on a real case study. The resolution of the integer linear programming was achieved by the Matlab® extension of ILOG CPLEX Solver. The studied model is composed of 1 869 constraints and 1 796 binary variables. It should be noted that the classic fixed charge location model belongs to the NP-hard problem class (7) and that the resolution depends on the problem instances even with powerful solvers. We studied instances where the time resolution is consistent (limited to up to 24 hours per instance). We simulated different configurations of charging station locations with different parameters. The first simulation consisted of varying the number of vehicles that require simultaneously to be recharged. We will name these vehicles "recharge-needed vehicles". The electric vehicle penetration rate was fixed to 20 %. This rate has been chosen based on the electric vehicles European penetration scenario for 2020 (see (8)).

The second simulation optimizes the location configuration by varying the penetration rate and total satisfaction of all this demand simultaneously (see Table 1 for the model output). We assume here that all the vehicles need to be recharged.

Simultaneous recharge-needed vehicles	1%	2%	3%	4%	5%	6%	7%	8%	9%
Semi-fast charging station	2	3	2	3	4	4	5	4	4
Fast Charging Station	0	0	0	0	0	0	0	0	0
Number of chargers	22	34	51	68	84	101	118	134	151
Kwh charged	12,4	22,3	41,92	38,8	45,4	46,4	68,9	69,4	79
Location cost (k€)	1 144	1 768	2 652	3 536	4 368	5 252	6 136	6 968	7 852

Table 1: Demand satisfaction for 20 % EVs' penetration rate

Table 2 shows the results of the first simulation, for all these instances no fast charging station was selected. This is due to the high cost of the fast charging stations (550 k€) and the limited number of chargers (6 chargers max by fast charging stations) compared to the semi-fast charger (5,2 k€-7 k€). Moreover the number of chargers depends on the size of the park site. The total location cost and the amount of energy supplied are also provided. These results highlight consistent results. Charging stations are located at attractor areas from travel perspective such as shopping centers, business district or other points of interest (PIs). The model is robust and shows a relevant evolution according to the evolution of simultaneous recharge needs .

The second part of the simulation provides the deployment of the charging stations according to a given travel demand (note that the goal here is to satisfy the need of all vehicles) with a variable penetration rate. The results show the located charging stations and the chargers needed to satisfy 100 % of the demand for 1 %, 2 % ,3% and 4 % of EVs' penetration rate based on the actual travel demand patterns in the metropolitan area of Lyon during afternoon peak hour (17:00).

Electric Vehicle penetration rate	1 %	2 %	3 %	4 %
Semi-fast charging station	3	4	5	3
Fast charging station	0	0	0	0
Number of chargers	84	168	252	335
Kwh charged	12,4	22,3	41,9	689,4
Location cost (k€)	4 368	8 736	13 104	1 742

Table 2: Variation in the EVs' penetration rate

In contrast with the first simulation that was prospective in terms of penetration rate (20 % predicted at horizon 2020), the second simulation is very close to current penetration rates figures in Lyon. For both simulations, we can see that charging stations are well separated thanks to the dispersion constraints. The proposed model exhibits a robust behavior and able to adapt to the demand changes.

5. Conclusion

We have presented a study about the location of EV charging stations for the metropolitan area of Lyon. Results show that the EVs will mainly have to be recharged at public-parking sites with semi-fast type stations (22 Kw) and in private service station for the fast charging (50KV ~ 43KW).

The methodology used in this work brings many innovative contributions as it relies on accurate estimates of both travel demand based on a comprehensive OD Matrix and the energy demand i computed by a dynamic consumption model from the VEHLIB library. This model is applied on real trips constructed with routing tools enhanced with an elevation profile to reflect the real vehicle consumption. This refined approach allows obtaining relevant energy-demand profiles. Next, locations of charging stations are modeled by a modified Fixed Charge Location Model mixed with a p-dispersion constraint. This model minimizes the trip energy and total location cost and satisfies all the mobility energy demand. A sensitivity analysis has been carried out in order to validate our model according to the electric vehicle penetration rate and the total simultaneously refueled vehicles.

Based on these results, some conclusions can be stressed. First, a dynamic consumption model derived from the VEHLIB library provides high accurate energy consumption evaluation. This model takes into account all the parameters that influence the vehicle consumption estimation (speed, acceleration and road geometry). It also shows that this model can easily be adapted to the electric charging station location problem as long as OD matrix data and OD trip are available. Simulations have shown that increasing the number of semi-fast chargers enables a demand satisfaction and a cost-effective investment in rapid charging station.

6. Reference

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