A Two-Stage Charging Station Allocation Model for EV Taxi Fleet Considering Interdependence Between the Networks of Transportation and Power Distribution

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Abstract

abstract-text

Nomenclature

Sets

I	Set of TN nodes
N	Set of PDN nodes
N^F	Set of PDN root nodes
E	Set of PDN lines
E^+	$E \cup \{0'0\}$ where $0'0$ is a dummy station
J	Set of opening locations of EVCS's
J^+	$J \cup \{0\}$ where 0 is a dummy station
K	Set of possible PDN lines to expand
Ω	Set of all scenarios

Parameters

A_j	Fixed cost of building a charging station at location j.
C_j	Cost of building a unity of capacity at location j
$\overline{D}$	Largest charging demand over all scenarios.
L	Cost of a unity substation expansion.
G_{mn}	Cost of each PDN line mn.
H_0	Unit penalty of an uncharged car.

H	Unit penalty of an unsatisfied car.
$U_{ij}(\omega)$	Utility of EV owners at region i choosing station j for charging at scenario ω.
$U^{min}(\omega)$	Threshold utility value below which EV owners do not make charging at scenario ω.
$D_i(\omega)$	Demand at TN node i at scenario at scenario ω.
$P_j(\omega)$	Price of charging unity at charging station j at scenario ω.
$T_{ij}(\omega)$	Travelling time from TN node i to charging station j at scenario at scenario ω.
$P_n^{load}(\omega)$	Real load at PDN node n at scenario ω if it is positive; otherwise real flow generated from electrical supplies.
$Q_n^{load}(\omega)$	Reactive load at PDN node n at scenario ω if it is positive; otherwise real flow generated from electrical supplies.
P_{mn}^{Max}	Capacity of allowed real power flow at PDN line mn.
Q_{mn}^{Max}	Capacity of allowed reactive power flow at PDN line mn.
V^{max}	Upper bound of voltage.
V^{min}	Lower bound of voltage.
V^{Max}	Square of the upper bound of voltage, $V^{Max} = (V^{max})^2$
V^{Min}	Square of the lower bound of voltage, $V^{Min} = (V^{min})^2$
R_{mn}	Resistance of PDN line mn.
X_{mn}	Reactance of PDN line mn.
W_n	Real power needed for each unit of charging load.

Decision Variables - First Stage

z_j	Fixed cost of building a charging station at location j.
x_j	Charging capacity at station j.
$u_{0'0}$	Exceed real power as substation expansion capacity.
u_{mn}^k	Binary variable indicating whether the k line should be added to PDN line mn.

Decision Variables - Second Stage

s_j	Unsatisfied demands at station j.
y_{ij}	Charging demand flow from traffic node i to station j.
p_{mn}	Real power flow passing PDN line mn.
q_{mn}	Reactive power flow passing PDN line mn.
V_m	Voltage at node m.

v_m Lineariaztion Variable, $v_m = V_m^2$

r_{mn}^k Lineariaztion Variable, $r_{mn}^k = u_{mn}^k(v_m - v_n)$.

Notations

ω Random variable with sample space Ω.

$\mathbf{z}$ Vector of all z_j.

$\mathbf{x}$ Vector of all x_j.

$\mathbf{u}$ Vector of all u_{mn}^k and $u_{0'0}$.

1 Introduction

With the advances of power electronics and battery technologies, Plug-in electric vehicles (PEVs) have made rapid development and become an attractive option in the transportation industry [8]. PEVs are regarded as a promising solution to relieve global environment issues for its low emission and high energy efficiency properties and are expected to increase in the next few years [12]. With the growing PEV penetration, more public charging stations (CS) are required to provide fast charging for PEVs on the road with more convenient charging services, which can further promote the adoption of PEVs.

The optimal CS placement is determined in [6] where PEVs are able to access a CS within its driving capacity anywhere in the city. The human factors rather than technological ones is the focus. However, the aggregated charging power from CS will have a great impact on distribution system operation, since it can change the load profile and result in overloading, low-quality voltage or increased losses in the system[2]. [7, 21] investigate the charging stations planning considering the operation of power distribution network (PDN). The optimal sites of PEV CS are identified with environmental factors and PEV CS service radius in the first step and the optimal size is determined with the minimization of total cost in the second step[7]. An optimal design of charging station and battery swap station based on life cycle cost is developed in [21] and a comparison of charging/swap stations is made. The joint planning of CS and PDN assets such as distribution lines, substation and other distributed energy resources with the aim of minimizing upgrading cost is discussed in [1, 9, 14].

Although a detailed formulation of PDN is considered in the above studies, the transportation network (TN) is ignored and leads to less efficient CS planning. The interdependency of TN and PDN brought by PEV behaviors indicates that it is necessary to consider TN and PDN simultaneously in PEV CS planning problem. Optimal planning of PEV CS in coupled TN and PDN has been widely discussed in literature [13, 4, 16, 17, 10, 19, 18, 5, 20]. The TN, PDN and PEV owner's driving behavior are taken into account in [13] with the objective of maximizing charging service ability and minimizing total power loss and voltage deviation. A user equilibrium based traffic assignment model is incorporated in [16] to capture the traffic flow pattern and the objective is to minimize overall annual investment cost and energy losses and maximize annual captured traffic flow at the same time. A capacitated-flow refueling location model is proposed in [19] which utilizes OD traffic flows to estimate PEV charging demand and queueing theory to model CS service abilities on TN. The mixed-integer linera programming (MILP) model is solved by deterministic branch-and-bound methods. A service performance metric for PEV CS is proposed in [18] which measures the probability that charging demands arriving in a given time interval can be directly fulfilled without extra waiting time. Dynamic OD traffic flow on TN is used to model time-varying

PEV charging demand and a stochastic mixed-integer SOCP is developed and is solved by the branch-and-cut method using an off-the-shelf solver.

The above literature address charging station planning in coupled TN and PDN, but system expansion is ignored. [15] proposes a comprehensive planning model which determines the optimal expansion strategies for both TN and PDN, including new CS sites and sizes, charging spots, TN lanes and PDN lines. An unconstrained traffic assignment model is used to capture the steady state distribution of traffic flows and linearized DistFlow is used to describe PDN operating conditions and an equivalent MILP is formulated. [3] presents an enhanced coordinated planning of multiple facilities in TN and PDN, including power lines, transportation roads, energy storage systems and fast CSs. To calculate the optimal solution, they introduce the applications of linear optimization theory including KKT conditions, the big M method, and a linear expression of power loss to transform the nonlinear planning problem into a mixed-integer quadratically constrained programming (MIQCP) formulation, which is solved by commercial solvers. However, both [15] and [3] focus on the planning stage without tackling the uncertain system operation stage.

To our understanding, there is no literature which deals with PEV CS planning problem in coupled TN and PDN with system expansion and uncertain system operation condition at the same time. Furthermore, the problem size is relatively small in the literature due to the computation complexity, which greatly limits the application of the planning model in real world. Consequently, this paper aims to propose a comprehensive PEV CS planning problem with consideration of PEV owners' utility, traffic flow in TN, as well as PDN expansion in a two-stage model, where the location and size of EVCS and PDN expansion strategies are determined in the first stage, the uncertain operation condition is considered in the second stage. The model is able to solve big-size planning problem in real world.

2 Problem Decription

Electrification is an important trend on rebuilding infrastructure. This trend will speed up due to the new U.S. infrastructure policy. Electrification of taxi fleet in big cities has been a long-term plan of government like New York City since last decade[], but it is far from completion. One of the most important challenges is due to the interdependence between TN and PDN because EV charging demand is generated and distributed in TN and need to be supported by PDN. Under this situation, it is hard to reach a strategy to satisify most of EV charging demand. However, as we consider taxi fleet, particularly, it has an recent trend of automation which we can take advantage of and possibly solve the issue.

The EV charging demand serves as a link between two networks, but in the meantime, it also leads to some conflicts between them. With EV charging demand, we need to consider all three possible restriction when we make decision including charging station related cost in TN, distribution network expansion cost in PDN, and the physical feasibility. These three factors are usually conflicted with each other. In the past, the PDN is constructed without consideration of the huge charging load of the emerging EV charging demand. To satisfy the large EV charging demand, it is inevitable to build charging stations and expand PDN correspondingly. However, since the current PDN is constructed without consideration of EV charging, the difficulty of PDN expansion for a desired station from only TN perspective could be extremely high. For example, some large residential area with large EV charging demand may be in the end of a long PDN branch, which is costly to make expansion to support a large station in that area. Furthermore, even though some station is both economically efficient, the PDN expansion might be physically difficult.

To solve this conflicts between TN and PDN caused by interdependence, we can consider possible solutions from both supply and demand side. From supply perspective, suppose the EV demand is fixed and we want to consider two interdependent networks as a whole system. In this system, we want to know if we are able to change the three factors, TN building cost, PDN expansion cost andphysical feasibility, how many cars are able to charge and how large the satisfaction of the demand or customers the system can achieve. From demand perspective, since the generated EV charging demand is always given, we want to know how to reallocate these given EV charging in order to best fit the existing structure of system formed by the current PDN and TN. This reallocation is possible when we deal with autonomous taxis because an individual taxi is flexible to choose the option which is not optimal individually but optimal systematically.

In our paper, we want to build a model which is able to explore solution from both supply and demand perspective. The model shoule be able to consider two network as a whole system and separate long-term planning stage and short-term operational stage, which enable us not only to make optimal long-term decision but also to operate and guide the charging route efficiently.

More specifically, we want to build a model to address the following four questions:

(a) How many EV fast charging stations should be built?

(b) Where and how large should each station be built?

(c) How is the existing PDN expanded to satisfy the potential charging loads?

(d) How are the constructed EVCS used to serve EV charging demands?

Questions (a)-(c) considers the long-term planning strategy of building EVCS and expanding PDN. On this basis, question (d) is to seek the optimal policy to operate the constructed charging stations to serve EV charging demand during a short-term period. This feature of the hierarchical structure motives us to specify a two-stage stochastic programming model, of which the first here-and-now stage is to study questions (a)-(c) and the second wait-and-see one is to answer question (d).

3 Mathematical Model and Solution Method

The factors we studied to reflect the results includes:

- Satisfied Cars(SAT#): the number of satisfied cars
- Unsatisifed Cars(UNSAT#): the number of unsatisfied cars
- Satisfaction Score(SATScore): the number quantifies satisfaction of charging
- TN Costs(TN$): all costs related to TN
- PDN Costs(PDN$): all costs related to PDN

3.1 The Two-Stage Model

The first stage of the model is to minimize long-term cost of three components: transportation network, power distribution network, and long-term charging satisfaction. For TN incurred cost, we decide whether we need to build a charging station at candidates (J) with capacity of the stations. Since we are considering large charging demand, we treat the charging demand as continuous variable, and thus the capacity of station is also reasonable to be considered as continuous number.

For PDN, there two different expansions, substation expansion and expansion lines. Substation expansion is considered as a continous

$$\min \sum_{j\in J} A_j z_j + \sum_{j\in J} C_j x_j + L u_{0'0} + \sum_{(m,n)\in E} G_{mn} \sum_{k\in K} k u_{mn}^k + \mathbb{E}[\Pi(\mathbf{z},\mathbf{x},\mathbf{u},\omega)] \tag{1}$$

$$\begin{aligned}
\text{s.t.} \quad & x_j \leq \overline{D} z_j, && j \in J \quad (2)\\
& z_j \in \{0,1\}, && j \in J\\
& x_j \geq 0, && j \in J\\
& u_{0'0} \geq 0
\end{aligned}$$

The objective of the first-stage minimizes the costs incurred from the selection of locations and sizes of EVCS's, the expansion of PDN, and the penalty $\Pi(x, r, u, \omega)$ for unsatisfied demand, on average, in the second-stage.

In the second stage, the PDN acts as a supplier which needs to best satisfy the charging demands of EV's in TN. The charging demands are generated at certain regions in TN and each EV is decentralized. Owners are able to makes charging decision to maximize its individual utility (see [27]). We characterize the preference as the following exponential utility function of charging cost and traffic time:

$$U_{ij}(\omega) = exp(-bp_j(\omega) - ct_{ij}(\omega))$$

where $U_{ij}(\omega)$ is the utility value of EV in region i charging at station j at scenario and the charging cost $p_j(\omega)$ and traffic time $t_{ij}(\omega)$ both varies in scenario. We set a dummy station ($j = 0$) for drivers decide not to charge their EV's, and let which is a given threshold.

The penalty term serves as the objective function of the second-stage model as follows:

$$\Pi(z, x, u, \omega) = \min \; H_0 s_0 + \sum_{j\in J} H s_j - \sum_{i\in I} \sum_{j\in J} G U_{ij}(\omega) y_{ij} \tag{3}$$

The three terms describe our different treatments on three types of EV charging demands:

- $H_0 s_0$: The negative utility of unsatisfied EV charging demands due to geographical limitation.
- $\sum_{j\in J} H s_j$: The penalty of unsatisfied EV charging demands due to EV charging station capacity limitation.
- $\sum_{i\in I} \sum_{j\in J} G U_{ij}(\omega) y_{ij}$: The utility of satisfied EV charging demands.

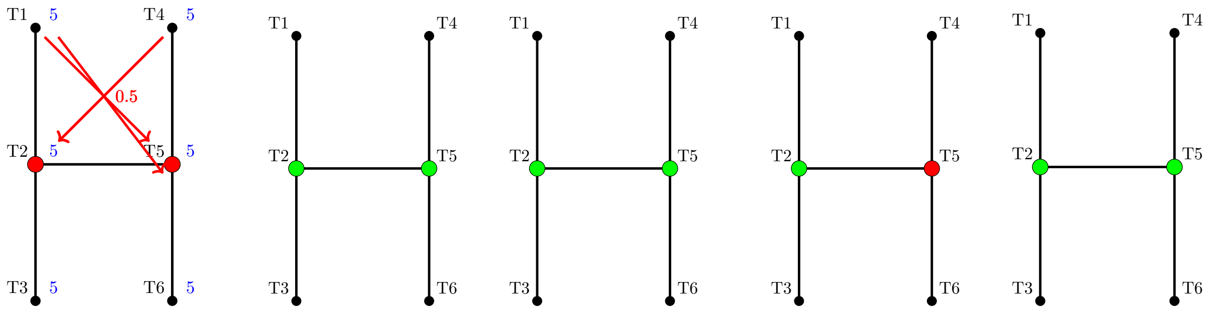
Now the largest utility value tells the station that an owner prefers to go. Hence, if we have decided the locations z_j and sizes x_j of charging stations, the user-choice assignment model [27] is formulated as follows:

$$\sum_{i\in I} y_{ij} - s_i \leq x_j, \qquad j \in J^+ \tag{4}$$

$$s_j \leq \overline{D} z_j, \qquad j \in J^+ \tag{5}$$

$$U_{ij} y_{ij} \geq y_{ij} max(U_{ik}(\omega) - \Delta U, U^{min}) - D_i(\omega)(1 - z_k), \qquad i \in I, j \in J^+, \; k \in J^+ \tag{6}$$

$$\sum_{j\in J^+} y_{ij} = D_i(\omega), \qquad i \in I(\omega) \tag{7}$$



(a) Example TN (b) Human Driving (c) Autonomous Driving (d) Human Driving (e) Autonomous Driving

Figure 1: Strong PDN (left), Weak PDN (Right)

$H = 2, H_0 = 1.5,$
We now integrate the EV charging demand into the PDN model as follows:

$$\sum_{m:(m,n)\in E^+} p_{mn} - \sum_{m:(n,m)\in E^+} p_{nm} = P_n^{load}(\omega) + W_n\left(\sum_{i\in I} y_{in} - s_n\right), \qquad n \in N \tag{8}$$

$$\sum_{m:(m,n)\in E^+} q_{mn} - \sum_{m:(n,m)\in E^+} q_{nm} = Q_n^{load}(\omega), \qquad n \in N \tag{9}$$

$$V_m^2 - V_n^2 \geq \frac{2R_{mn}p_{mn} + 2X_{mn}q_{mn}}{1 + \sum_{k\in K} k u_{mn}^k}, \qquad (m,n) \in E \tag{10}$$

$$V_n = 1 \ p.u. \qquad n \in N^F \tag{11}$$

$$V^{min} \leq V_n \leq V^{max}, \qquad n \in N \tag{12}$$

$$0 \leq p_{mn} \leq P_{mn}^{Max}\left(1 + \sum_{k\in K} k u_{mn}^k\right) \qquad (m,n) \in E \tag{13}$$

$$0 \leq p_{0'0} \leq P_{0'0}^{Max} + u_{0'0} \tag{14}$$

$$0 \leq q_{mn} \leq Q_{mn}^{Max}\left(1 + \sum_{k\in K} k u_{mn}^k\right) \qquad (m,n) \in E \tag{15}$$

$$0 \leq q_{0'0} \leq Q_{0'0}^{Max} + u_{0'0} \tag{16}$$

3.2 Reformulation and Solution Method

The aforementioned model aggregates TN and PDN. Either is a huge and complex system consisting of millions of subnetworks and individual agents. Moreover, the uncertainties of the renewable energy supplies and the EV charging loads bring a large number of scenarios into the model and further increase the complexity. We develop a fast algorithm based on the Bender decomposition method. Since the original problem is nonlinear and has high dimensional constraints, we perform linearization and reformulation to shrink the feasible region to speed up the solving process.

3.2.1 Reformulation - Linearization and Special Treatments on Integer Programming

The first stage problem is reformulated as:

$$\min \sum_{j \in J} A_j z_j + \sum_{j \in J} C_j x_j + L u_{0'0} + \sum_{(m,n) \in E} G_{mn} \sum_{k \in K} k u_{mn}^k + \mathbb{E}[\Pi(\mathbf{z}, \mathbf{x}, \mathbf{u}, \omega)] \tag{17}$$

s.t.

$$x_j \le \overline{D} z_j, \qquad j \in J \tag{18}$$

$$\sum_{k \in K} u_{mn}^k \le 1, \qquad (m,n) \in E, \; k \in K \tag{19}$$

$$u_{mn}^k \in \{0,1\}, \qquad (m,n) \in E, \; k \in K \tag{20}$$

$$z_j \in \{0,1\}, \qquad j \in J \tag{21}$$

$$x_j \ge 0, \qquad j \in J \tag{22}$$

$$u_{0'0} \ge 0 \tag{23}$$

The second stage problem is reformulated as:

$$\min H_0 s_0 + \sum_{j \in J} H s_j - \sum_{i \in I} \sum_{j \in J} G U_{ij}(\omega) y_{ij}$$

s.t.

$$\sum_{i \in I} y_{ij} - s_i \le x_j, \qquad j \in J^+ \tag{24}$$

$$s_j \le \overline{D} z_j, \qquad j \in J^+ \tag{25}$$

$$\mathbb{1}\{(U_{ij}(\omega) - max(U_{ik}(\omega) - \Delta U, U^{min})) < 0\} y_{ij} \le D_i(\omega)(1 - z_k), \qquad i \in I, j \in J^+, \; k \in J^+ \tag{26}$$

$$\sum_{j \in J^+} y_{ij} = D_i(\omega), \qquad i \in I \tag{27}$$

$$\sum_{m:(m,n) \in E^+} p_{mn} - \sum_{m:(n,m) \in E^+} p_{nm} = P_n^{load}(\omega) + W_n \left(\sum_{i \in I} y_{in} - s_n \right), \qquad n \in N \tag{28}$$

$$\sum_{m:(m,n) \in E^+} q_{mn} - \sum_{m:(n,m) \in E^+} q_{nm} = Q_n^{load}(\omega), \qquad n \in N \tag{29}$$

$$v_m - v_n + \sum_{k \in K} k r_{mn}^k \ge 2 R_{mn} p_{mn} + 2 X_{mn} q_{mn}, \qquad (m,n) \in E \tag{30}$$

$$0 \le r_{mn}^k \le V^{Max} u_{mn}^k, \qquad (m,n) \in E, \; k \in K \tag{31}$$

$$0 \le (v_m - v_n) - r_{mn}^k \le V^{Max}(1 - u_{mn}^k), \qquad (m,n) \in E, \; k \in K \tag{32}$$

$$v_n = 1 \; p.u. \qquad n \in N^F \tag{33}$$

$$V^{Min} \le v_n \le V^{Max}, \qquad n \in N \tag{34}$$

$$0 \leq p_{mn} \leq P_{mn}^{Max} \left(1 + \sum_{k \in K} k u_{mn}^k\right) \qquad (m,n) \in E \tag{35}$$

$$0 \leq p_{0'0} \leq P_{0'0}^{Max} + u_{0'0} \tag{36}$$

$$0 \leq q_{mn} \leq Q_{mn}^{Max} \left(1 + \sum_{k \in K} k u_{mn}^k\right) \qquad (m,n) \in E \tag{37}$$

$$0 \leq q_{0'0} \leq Q_{0'0}^{Max} + u_{0'0} \tag{38}$$

3.2.2 The Full Reformulated Model

The first stage problem is reformulated as:

$$\min \sum_{j \in J} A_j z_j + \sum_{j \in J} C_j x_j + L u_{0'0} + \sum_{(m,n) \in E} G_{mn} \sum_{k \in K} k u_{mn}^k + \mathbb{E}[\Pi(\mathbf{z}, \mathbf{x}, \mathbf{u}, \omega)] \tag{39}$$

s.t.

$$x_j \leq \overline{D} z_j, \qquad j \in J \tag{40}$$

$$\sum_{k \in K} u_{mn}^k \leq 1, \qquad (m,n) \in E \tag{41}$$

$$u_{mn}^k \in \{0,1\}, \qquad (m,n) \in E, \; k \in K \tag{42}$$

$$z_j \in \{0,1\}, \qquad j \in J \tag{43}$$

$$x_j \geq 0, \qquad j \in J \tag{44}$$

$$u_{0'0} \geq 0 \tag{45}$$

The second stage problem is reformulated as:

$$\min H_0 s_0 + \sum_{j \in J} H s_j - \sum_{i \in I} \sum_{j \in J} G U_{ij}(\omega) y_{ij}$$

s.t.

$$\sum_{i \in I} y_{ij} - s_i \leq x_j, \qquad j \in J^+ \tag{46}$$

$$s_j \leq \overline{D} z_j, \qquad j \in J^+ \tag{47}$$

$$\mathbb{1}\{(U_{ij}(\omega) - max(U_{ik}(\omega) - \Delta U, U^{min})) < 0\} y_{ij} \leq D_i(\omega)(1 - z_k), \qquad i \in I, j \in J^+, \; k \in J^+ \tag{48}$$

$$\sum_{j \in J^+} y_{ij} = D_i(\omega), \qquad i \in I \tag{49}$$

$$\sum_{m:(m,n) \in E^+} p_{mn} - \sum_{m:(n,m) \in E^+} p_{nm} = P_n^{load}(\omega) + W_n \left(\sum_{i \in I} y_{in} - s_n\right), \qquad n \in N \tag{50}$$

$$\sum_{m:(m,n) \in E^+} q_{mn} - \sum_{m:(n,m) \in E^+} q_{nm} = Q_n^{load}(\omega), \qquad n \in N \tag{51}$$

$$v_m - v_n + \sum_{k \in K} k r_{mn}^k \geq 2 R_{mn} p_{mn} + 2 X_{mn} q_{mn}, \qquad (m,n) \in E \tag{52}$$

$$0 \leq r_{mn}^{k} \leq V^{Max} u_{mn}^{k}, \qquad (m,n) \in E,\ k \in K \tag{53}$$

$$0 \leq (v_m - v_n) - r_{mn}^{k} \leq V^{Max}(1 - u_{mn}^{k}), \qquad (m,n) \in E,\ k \in K \tag{54}$$

$$v_n = 1\ p.u. \qquad n \in N^F \tag{55}$$

$$V^{Min} \leq v_n \leq V^{Max}, \qquad n \in N \tag{56}$$

$$0 \leq p_{mn} \leq P_{mn}^{Max} \left(1 + \sum_{k \in K} k u_{mn}^{k}\right) \qquad (m,n) \in E \tag{57}$$

$$0 \leq p_{0'0} \leq P_{0'0}^{Max} + u_{0'0} \tag{58}$$

$$0 \leq q_{mn} \leq Q_{mn}^{Max} \left(1 + \sum_{k \in K} k u_{mn}^{k}\right) \qquad (m,n) \in E \tag{59}$$

$$0 \leq q_{0'0} \leq Q_{0'0}^{Max} + u_{0'0} \tag{60}$$

4 Case Studies

4.1 Case Overview and Default Case Settings

General Background

- What Networks used
- Designed Structure of the network
- Properties of Structure of the network
- Why this structure has no problem in past but some problem now

Default Case

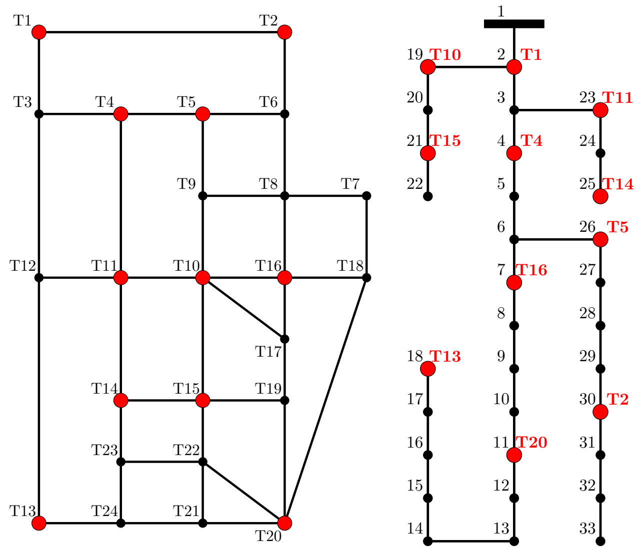
- Default Case Data from literature
- Default Case Data Generation
- Result and factors considered explaination
-

We test our model with two widely used benchmark networks in literatures, IEEE 33-node test feeder(PDN)[] coupled with Sioux Falls transportation network(TN)[]. In TN, we consider three classes: center, commercial and residential. We treat T10 as the center of the city with highest cost 3 times as residential nodes, and T4, T5, T11, T14, T15 as commercial node with middle cost 1.5 times as residential nodes. In PDN, we assume that the northern uptown has relatively small number of residents so it is relatively economically efficient to constructed the PDN root node at the northern uptown without considering EV charging demand in the past. Two short branches D2 - D22 and D3 - D25 are two lines specially support to downtown, and the longest branch D1-D18 is a line surrounding the entire city and the second longest line is the line surrounding north uptown. The PDN and TN work independently, and PDN is able to support the traditional electric demand. However, this structure could cause some problems when making PDN expansion for southern uptown. On one hand, from TN perspective, we tend to build some large stations in southern uptown area because there are large number of residents. On the other hand, from PDN perspective, the southern uptown are at the end of the longest PDN branch which is physically difficult to be expanded or costly to make expansion. Beside this principle probelm, there are also some detailed problem on trade off under this conflicted situation caused by interdependence. We want to first set up a default case in order to adjust parameters to see the interdependence and potential solution explicitly.

Table 1: TN and PDN nodes corresponding map

TN	1	2	4	5	10	11	13	14	15	16	20
PDN	2	30	4	26	19	23	18	24	21	7	11

In Fig.1 (a), the red colored nodes are the candidates for building EV charging stations in TN, which is marked correspondingly in Fig.1 (b). In our model, we want to analyze the marginal effects



(a) Sioux Falls transportation network

(b) IEEE 33-node

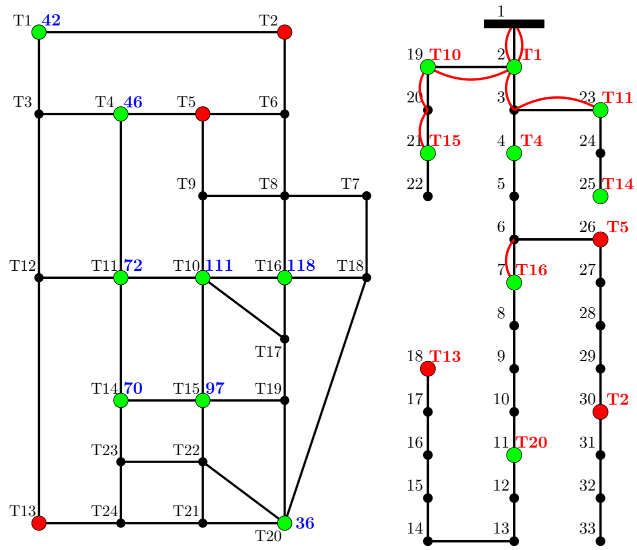
Figure 2: Test Networks

of changing factors in TN and PDN to study their interdependence and the impacts of autonomous vehicles. We first set up a default case with data following recent papers.

In our default case, we want to use data commonly used in literatures. The charging demand we take the original traffic flow data as bases for EV charging demand and the demand is higher closed to the center. In order to reflect the change of the demand during a regular day, we simulated 108 scenarios from 24 hours pattern for our EV charging demand. The default fixed cost of building a station in residential area is $A_i = \$1.63 \times 10^5$ and the capacity cost is $C_j = \$3,160$[]. The base cost per-unit cost of a distribution like is $G_{ij} = \$3 \times 10^5$, and the cost of substation capacity expansion cost is $L = \$5,000/kVA$[]. For each demand to power flow, $W_n = 7.7$[11]. In order to analyze the marginal effects, we use introduce two multipliers α and β on the cost of TN and PDN. The multiplier α is on both fixed cost of charging station and the capacity cost, and β is on unit cost of distribution lines. The default values are $\alpha = 1$ and $\beta = 1$. In our default case, we consider all vehicles are driven by human who always choose the closest station to charge. Lastly, we set the maximum number of line we are able to expand for each PDN line (K) as 2. We will stated the reason for this later in the analysis.

We solved our cases using iOptimize Solver based on Benders decomposition method via CPLEX 12.90. All simulation and solving processes are implemented on a computer with Intel i7-1065G7 CPU and 16-GB RAM. The default case result is as follows:

For example, in our default case, the number of satisfied cars is 384, which means over 108 scenarios, on average, 384 cars get charging services. The number of unsatisfied cars is 84, which means on average, 84 cars cannot get charging services,including the cars too far from the closest station to charge and the cars actually go to the stations but are not able to charge due to the limited capacity of the stations. The satisfaction score is 5015, which takes account of both positive effects of the cars able to charge and the negative effects of the cars not able to charge. The TN Cost is \$4977K including the fixed costs of the selected candidates and the capacity costs. The PDN Cost is \$4564K including substation costs and expanding line costs.



(a) Default TN (b) Default PDN

Figure 3: Default Decision Results: The green nodes in TN indicate we decide to build a charging station, and we also marked the corresponding PDN nodes as green; The red nodes are the candidate nodes we decide not to build stations; The blue numbers in the TN indicate the capacity of the charging stations.

4.2 Existing Conflicts Caused by the Interdependence

4.3 Case Overview and Default Case Settings

- FreeAll see potential demand
- FreeTN is from PDN perspective, avoid build at 13 and 16
- FreeTN is from PDN perspective, avoid build at 2 and 4
- PDN has larger effects than TN

We want to first see how constrained TN and PDN affects our decision. If building a charging station costs nothing, we called it FreeTN. If the capacity of current PDN is large enough to allow us to build large enough charging stations if needed, we call it FreePDN. If both of TN and PDN are free, we call it FreeAll. The results of both cases is as follows:

The result of FreeAll indicates the potential charging demand at each candidate station where the neighbor choose to charge. For example, charging demand generated at T7, T8, T16, T17, and T18 will always go to station at T16 to charge. The node T16 is also a special location as a transition node from commercial areas to residential areas. Under FreeTN, the building costs are all 0 at any location, so it is no longer a constraint to make a decision. We want to build stations as large as possible that the PDN can support. Comparing FreeTN with default case, we can see the impact of building cost. Building cost includes fixed cost and capacity cost. Fixed cost serves as a threshold whether to build a station and capacity costs determine the sizes of the stations. Furthermore, the building costs has structure in default case as TN has its structure. The first difference we can see from result is that at the location where we keep station open we want to build a larger station due to zero capacity cost. We also notice that we open two new stations

Table 2: TN Decision of Extreme Cases

TN	1	2	4	5	10	11	13	14	15	16	20
Default	42	0	46	0	110	72	0	70	97	118	37
FreeTN	50	45	90	74	194	113	0	92	150	0	80
FreePDN	35	0	0	84	134	76	106	0	162	148	76
FreeAll	30	44	62	92	168	58	108	104	162	182	92

Table 3: PDN Decision of Extreme Cases

PDN Line	1-2	2-3	3-4	6-7	10-11	2-19	19-20	20-21	3-23
Default	2	1	0	1	0	1	1	1	1
Free TN	2	1	0	0	0	2	2	2	0
Free PDN	-	-	-	-	-	-	-	-	-

Table 4: Factors of Extreme Cases

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
Default	384	84	7147	4977	4564
Free TN	419	49	8028	-	5015
Free PDN	459	9	9813	5821	-

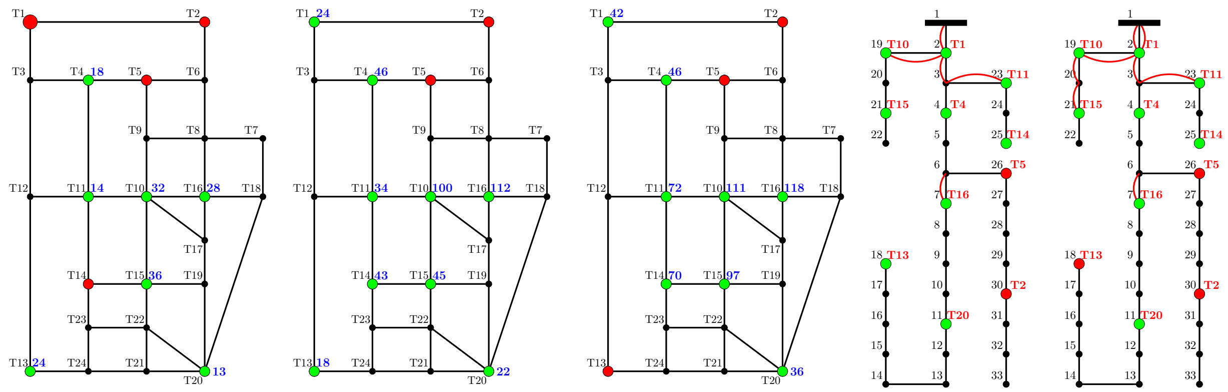
open at T2 and T5. We know in default case, we do not build them because of high TN cost. In FreePDN, we are able to build as large as needed stations. We also see there are large demand in the southern uptown T13 and T20, so the reason that we don't build large stations at the uptown is due to limitation of the existing PDN. We don't build station at T2 and T4 because in the northern area of the city, the total demand is not high, and building cost is relative high. Therefore, it is not economically efficient to build two small station just for a slightly more convenient for the potential chargers. Another fact from this result is that we close T14 and build a large station at T13. The reason is that T13 is located at the end of the deepest line of PDN, so it is difficult to make expansion to build a large station at T13. However, if this physical constraint is removed, it is better to build at T13 instead of T14 because the building cost at T14 as a commercial node is lower than T13 as a residential node.

4.4 Solution for Interdependence on Supply

Changing Maxmium number of Expansion line

- Without expansion we can only build very small station
- K =1 We want to build large station in downtown
- K =2 With large enough size station in downtown, we don't build small station at T13 in southern uptown.
- K =2 and K=3 has the same solution, physical effects removed, still have more than 15 percent unsatified demand. Next to consider economical effects.

From the extreme cases, we know the main constraint of TN is from economic perspective and constraint of PDN is from both economic and physical perspective. Therefore, we can change the maximum number of expansion lines(K). If we fix $K = 0$, we will not make any PDN expansion and use the current exisiting PDN for the EV charging demand. And we want to keep adding the K. If at some point, the optimal decision does not change, then it means we have remove all the physical constraint from PDN.



(a) TN K = 0 (b) TN K = 1 (c) TN K = 2 (d) PDN K = 1 (e) PDN K = 2

Figure 4: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

From the Figure 4, if we do not expand the PDN, our current PDN can only build some small stations. We have stations in all the areas, T4 and T 14at north and west commercial, T10 and T15 at east and south commercial, T13 at southwest residential, T20 at southeast residential, and T16 at east residential. If we increase K to 1, we notice we can have much larger stations than the station supported by the current PDN. We are able to build two more stations at T1 and T14. Finally, we find the solution for 2 or 3 expansion lines the same, which indicates we reach the best strategy under current economical condition.

Table 5: TN Decision of Changing K

TN	T1	T2	T4	T5	T10	T11	T13	T14	T15	T16	T20
K = 0	0	0	18	0	32	14	24	0	36	28	12
K = 1	24	0	46	0	100	34	18	43	45	112	22
K=2 (Default)	42	0	46	0	110	72	0	70	97	118	37
K = 3	42	0	46	0	110	72	0	70	97	118	37

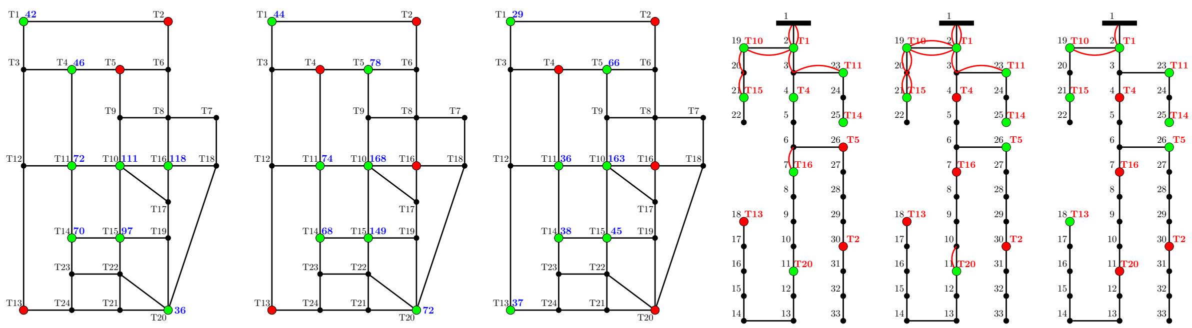
Table 6: Factors of Changeing K

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
K=0	119	349	-10950	2547	0
K = 1	306	162	741	4419	2787
K = 2 (Default)	384	84	5016	4977	4564
K = 3	384	84	5016	4977	4564

From Table 6, we notice the satisfied cars and satisfaction core siginficantly increase when we increase K to 1 and 2. However, the increment of the first expansion line are more than the second one. Therefore, the first expansion line is more economically efficient than the second one. As stated before, with the current PDN the best expansion strategy still cannot support most of demand especially the demand at the south down due to the structure of PDN. Since the best strategy also consider the economical factors. Therefore, we want to explore what if we can have lower or higher cost on PDN expansion. In the following results, we change β as the coefficient of PDN cost to see the effects.

Changing PDN Cost

- When expansion becomes easily, we want to first make expansion for east downtown.
- Increase or decrease PDN, we both close T16 but for different reason
- Competition between T16 and T13 when physical restrition is high T16 is auxiliary for T20, T13 is necessary if downtown station is small.
- Reduce PDN cost is useful but still not enough.



(a) $\beta = 1$ (b) $\beta = 0.5$ (c) $\beta = 3$ (d) $\beta = 1$ (e) $\beta = 0.5$ (f) $\beta = 3$

Figure 5: PDN Decision Result of Changing β

From the Figure 5 (b), we know if we cannot have less cost on PDN, we will change the expansion strategy and expand more lines. We want expand two lines for all upstream lines of D21 corresponding to T15. This branch is the special branch supporting the east commercial area where charging demand is highest in the TN. Notice when we can build large stations to support the east commercial area, we close the station at T16. Instead we build a larger station at T20. The reason is that T16 and T20 are corresponding to the same line in PDN, so they physicial competence relations. In the case that we can reduce cost on PDN, we can build large enough station at T10, which makes T16 station are less efficient and T20 becomes a winner on efficiency. In this case, we can support more demand from the south residential area. On the other hand, if we experience expansion difficulty and the expansion is more expensive, we only choose two line closed to root node in PDN and only expand one line. Similarly, the first priorty of expansion as the results showing is to support the east commercial when possible. Furthermore, we notice we build new station at T13 in the south uptown, because we have to build a station at each area.

In Table 8, we note that we can only satisfy slightly more demand with lower PDN cost. There are still more than 10 percents demand are unsatisfied. The satisfaction score only increases from 5016 to 5925. However, if the cost of PDN is higher, the satisfaction will significantly drop to negative number. Therefore, we still are not satisfied with result of the lower cost on PDN. Therefore, we want to explore if the TN cost can resolve the issue, and we change the TN cost coefficient α.

Table 7: TN Decision of Changing β

TN	T1	T2	T4	T5	T10	T11	T13	T14	T15	T16	T20
$\beta = 0.5$	44	0	0	78	168	74	0	68	149	0	72
$\beta = 1$ (Default)	42	0	46	0	110	72	0	70	97	118	37
$\beta = 3$	29	0	0	66	163	36	37	38	45	0	0

Table 8: Factors of Changeing β

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\beta = 0.5$	407	60	5924	5504	3824
$\beta = 1$ (Default)	384	84	5016	4977	4564
$\beta = 3$	287	180	-1269	4420	3315

Changing TN Cost

- Larger stations
- More expansion
- Increase or decrease TN, we both expansion two lines in the east down branches but for different reason
- Reduce TN cost is more useful than PDN cost.

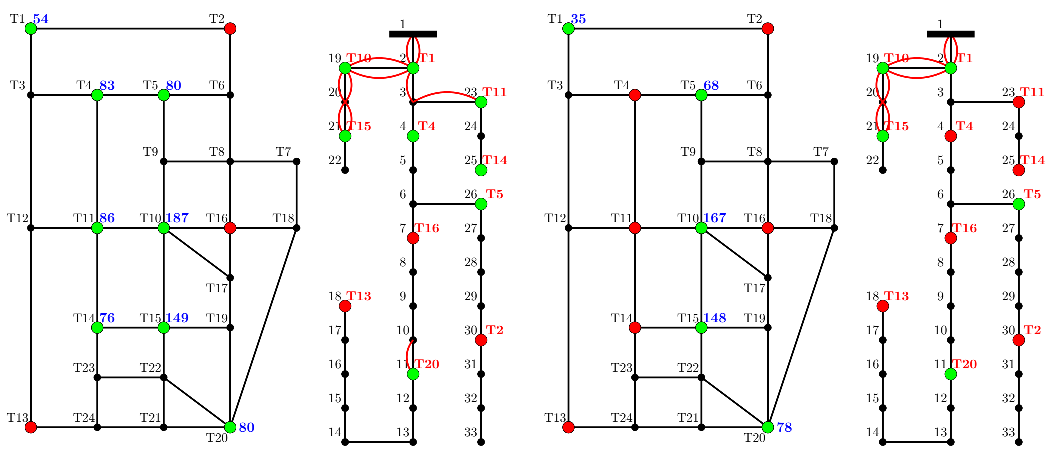


Figure 6: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

If we have smaller TN cost, we have smaller fixed cost and capacity cost, so we have more incentive to build more stations and larger station. From the Figure 6 (a) and (b), we notice we build a new station at T5, and all stations are larger. Especially for T10, we have large station so T16 becomes less economically efficient than T20, so we close T16. If we experience difficulty on TN build and it costs more, we want to build only stations are necessary. From the Figure 6 (c) and (d), we notice we only build one station at each row of TN, which mean we only want build a

Table 9: Building Capacity for TN

TN	T1	T2	T4	T5	T10	T11	T13	T14	T15	T16	T20
$\alpha = 0.5$	54	0	83	80	187	86	0	76	149	0	80
Default	42	0	46	0	110	72	0	70	97	118	37
$\alpha = 3$	35	0	0	68	167	0	0	0	148	0	78

Table 10: Expansion Strategy for PDN

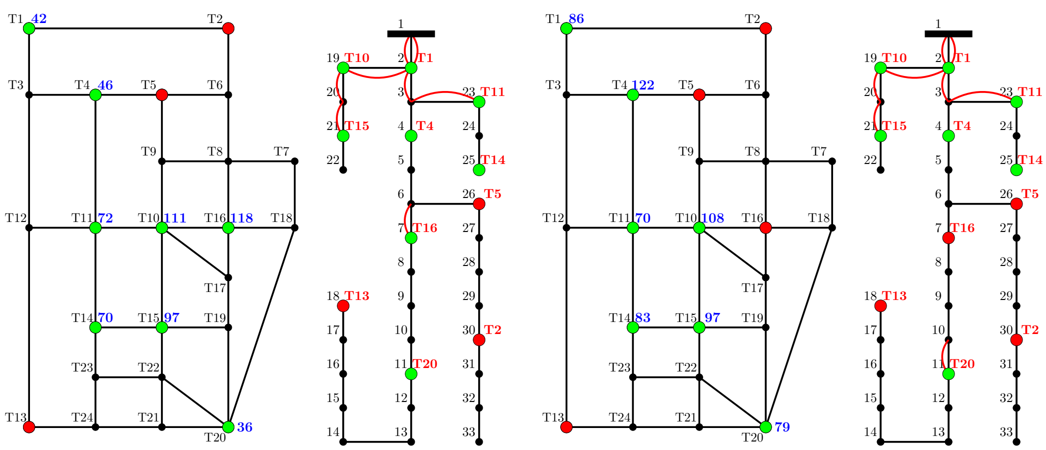
Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\alpha = 0.5$	419	49	6624	3241	4985
$\alpha = 1$(Default)	384	84	5016	4977	4564
$\alpha = 3$	349	119	1729	12826	3558

single station at each area. In the PDN, we only expand the branch for the east commercial area besides the root node expansion.

In Table 10, we can see the satisfied cars with lower cost still does not reach the a level with more than 90 percent and the satisfaction score are still increase slightly from 5016 to 6624 which is not significantly large. Therefore, we want to consider a different pattern of demand to whether the restriction is due to the demand pattern.

Changing Demand Pattern

- larger station in uptown
- Similar expansion strategy indicates we want to make expansion for downtown not only for the high demand, but the economical expansion efficiency is high itself.



(a) TN Default (b) PDN Default (c) TN Uniform (d) PDN Uniform

Figure 7: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

Table 11: Building Capacity for TN

TN	T1	T2	T4	T5	T10	T11	T13	T14	T15	T16	T20
Default	42	0	46	0	110	72	0	70	97	118	37
Uniform	86	0	122	0	108	70	0	83	97	0	79

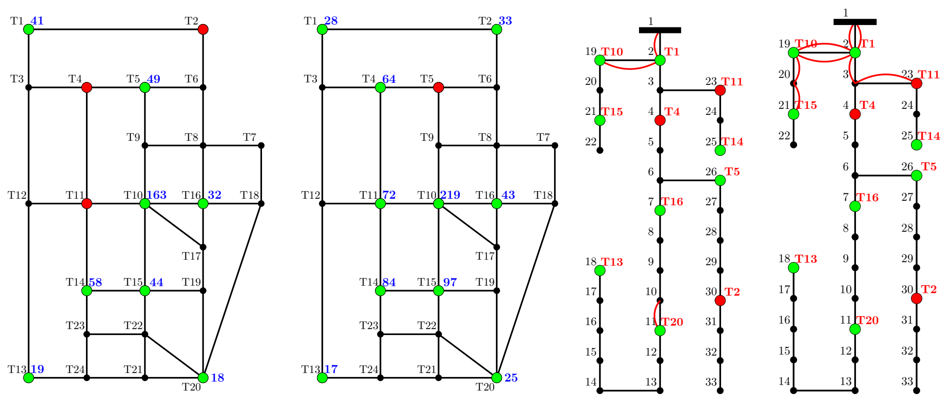
Table 12: Expansion Strategy for PDN

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
Default	384	84	5016	4977	4564
Uniform	385	83	3883	5103	4689

4.5 Solution for Interdependence on Demand

Changing K

- K=1 PDN expansion less but reach similar satisfaction
- K=2 Similar PDN expansion, reach much higher level satisfaction



(a) TN K = 1 (b) TN K = 2 (c) PDN K = 1 (d) PDN K = 2

Figure 8: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

Changing PDN cost

- $\beta = 1, 0.5$ Has the same $\beta = 0.2$ Very small improvement
- $\beta = 3$ Compared with Manual, it makes more PDN expansion.

Changing TN cost

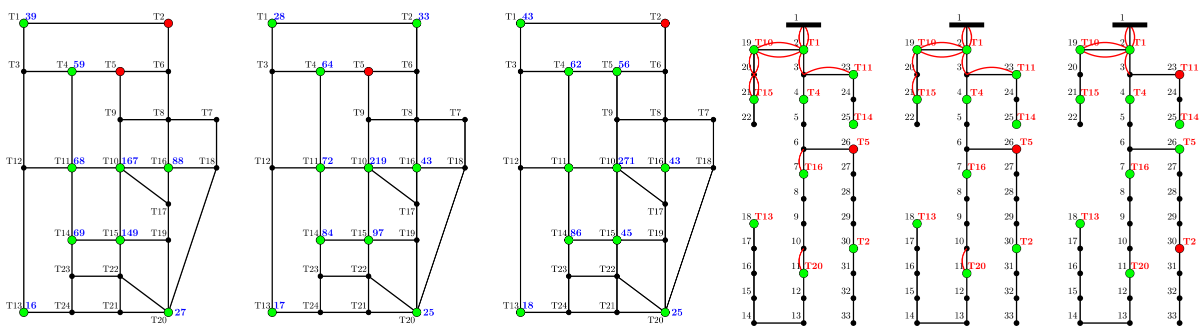
- $\alpha = 1, 0.5$ Has the Very small improvement.
- $\alpha = 3$ Compared with Manual, it makes more large station in TN.

Table 13: TN Decision of Changing K

TN	T1	T2	T4	T5	T10	T11	T13	T14	T15	T16	T20
K = 1	41	0	0	49	163	0	19	58	44	32	18
K=2	28	33	64	0	219	72	17	84	97	43	25
K = 3	28	33	64	0	219	72	17	84	97	43	25

Table 14: Factors of Changeing K

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
K=0	119	349	-10841	2592	0
K = 1	311	157	454	4485	2187
K = 2	447	21	8365	6317	4932



(a) $\beta = 0.2$ (b) $\beta = 0.5, 1$ (c) $\beta = 3$ (d) $\beta = 0.5$ (e) $\beta = 0.5, 1$ (f) $\beta = 3$

Figure 9: PDN Decision Result of Changing β

Table 15: Factors of Changeing β

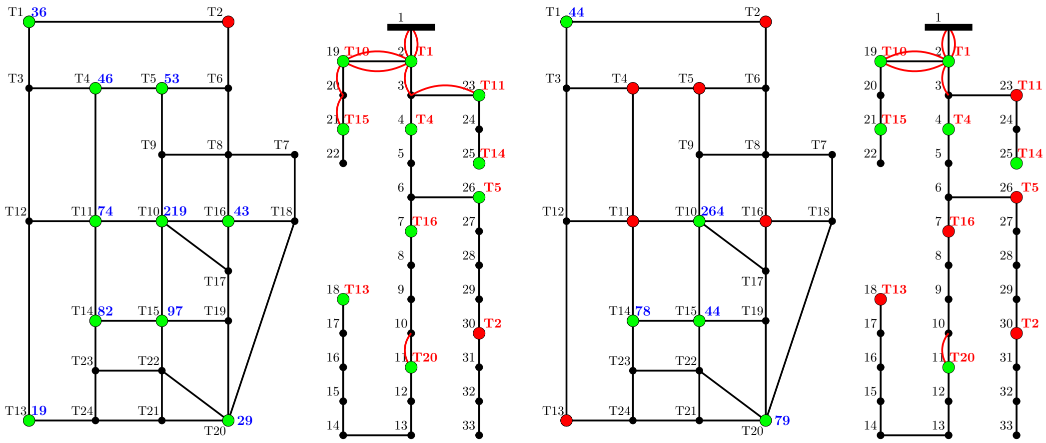
Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\alpha = 0.2$	448	20	8676	5875	3546
$\beta = 0.5$	447	21	8364	6317	4032
$\beta = 3$	428	40	6695	6275	5618

Table 16: Building Capacity for TN

TN	T1	T2	T4	T5	T10	T11	T13	T14	T15	T16	T20
$\alpha = 0.5$	36	0	46	53	219	74	19	82	97	43	29
$\alpha = 3$	44	0	80	0	264	0	0	79	44	0	79

Table 17: Expansion Strategy for PDN

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\alpha = 0.5$	449	19	8506	3255	4974
$\alpha = 3$	400	68	4836	16206	3822



(a) TN $\alpha = 0.5$ (b) $PDN \alpha = 0.5$ (c) TN $\alpha = 3$ (d) PDN $\alpha = 3$

Figure 10: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

4.6 Conclusion

- EV demand makes TN and PDN interdependent. Interdependence cause conflicts on struture of TN and PDN. Conflicts leads to physical difficulty and economical difficulty. Auto can reduce the conflicts.
- If the unsatisified demand is due to physical difficulty, we cannot solve the problem. However, with auto we can reach the physical potential with lower cost.
- If the unsatisified demand is due to economical difficulty, we cannot solve the problem with higher investment.

5 Conclusion

References

[1] Arias, N.B., Tabares, A., Franco, J.F., Lavorato, M., Romero, R., 2017. Robust joint expansion planning of electrical distribution systems and ev charging stations. IEEE Transactions on Sustainable Energy 9, 884–894.

[2] Clement-Nyns, K., Haesen, E., Driesen, J., 2009. The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Transactions on power systems 25, 371–380.

[3] Gan, W., Shahidehpour, M., Yan, M., Guo, J., Yao, W., Paaso, A., Zhang, L., Wen, J., 2020. Coordinated planning of transportation and electric power networks with the proliferation of electric vehicles. IEEE Transactions on Smart Grid .

[4] He, F., Wu, D., Yin, Y., Guan, Y., 2013. Optimal deployment of public charging stations for plug-in hybrid electric vehicles. Transportation Research Part B: Methodological 47, 87–101.

[5] Huang, X., Chen, J., Yang, H., Cao, Y., Guan, W., Huang, B., 2018. Economic planning approach for electric vehicle charging stations integrating traffic and power grid constraints. IET Generation, Transmission & Distribution 12, 3925–3934.

[6] Lam, A.Y., Leung, Y.W., Chu, X., 2014. Electric vehicle charging station placement: Formulation, complexity, and solutions. IEEE Transactions on Smart Grid 5, 2846–2856.

[7] Liu, Z., Wen, F., Ledwich, G., 2012. Optimal planning of electric-vehicle charging stations in distribution systems. IEEE Transactions on Power Delivery 28, 102–110.

[8] Martinez, C.M., Hu, X., Cao, D., Velenis, E., Gao, B., Wellers, M., 2016. Energy management in plug-in hybrid electric vehicles: Recent progress and a connected vehicles perspective. IEEE Transactions on Vehicular Technology 66, 4534–4549.

[9] de Quevedo, P.M., Munoz-Delgado, G., Contreras, J., 2017. Impact of electric vehicles on the expansion planning of distribution systems considering renewable energy, storage, and charging stations. IEEE Transactions on Smart Grid 10, 794–804.

[10] Shahraki, N., Cai, H., Turkay, M., Xu, M., 2015. Optimal locations of electric public charging stations using real world vehicle travel patterns. Transportation Research Part D: Transport and Environment 41, 165–176.

[11] Shareef, H., Islam, M.M., Mohamed, A., 2016. A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles. Renewable and Sustainable Energy Reviews 64, 403–420. URL: https://www.sciencedirect.com/science/article/pii/S1364032116302568, doi:https://doi.org/10.1016/j.rser.2016.06.033.

[12] Shaukat, N., Khan, B., Ali, S., Mehmood, C., Khan, J., Farid, U., Majid, M., Anwar, S., Jawad, M., Ullah, Z., 2018. A survey on electric vehicle transportation within smart grid system. Renewable and Sustainable Energy Reviews 81, 1329–1349.

[13] Wang, G., Xu, Z., Wen, F., Wong, K.P., 2013. Traffic-constrained multiobjective planning of electric-vehicle charging stations. IEEE Transactions on Power Delivery 28, 2363–2372.

[14] Wang, S., Dong, Z.Y., Chen, C., Fan, H., Luo, F., 2019. Expansion planning of active distribution networks with multiple distributed energy resources and ev sharing system. IEEE Transactions on Smart Grid 11, 602–611.

[15] Wang, X., Shahidehpour, M., Jiang, C., Li, Z., 2018. Coordinated planning strategy for electric vehicle charging stations and coupled traffic-electric networks. IEEE Transactions on Power Systems 34, 268–279.

[16] Yao, W., Zhao, J., Wen, F., Dong, Z., Xue, Y., Xu, Y., Meng, K., 2014. A multi-objective collaborative planning strategy for integrated power distribution and electric vehicle charging systems. IEEE Transactions on Power Systems 29, 1811–1821.

[17] Zhang, H., Hu, Z., Xu, Z., Song, Y., 2015. An integrated planning framework for different types of pev charging facilities in urban area. IEEE Transactions on Smart Grid 7, 2273–2284.

[18] Zhang, H., Moura, S.J., Hu, Z., Qi, W., Song, Y., 2017. A second-order cone programming model for planning pev fast-charging stations. IEEE Transactions on Power Systems 33, 2763–2777.

[19] Zhang, H., Moura, S.J., Hu, Z., Song, Y., 2016. Pev fast-charging station siting and sizing on coupled transportation and power networks. IEEE Transactions on Smart Grid 9, 2595–2605.

[20] Zhang, Y., Chen, J., Cai, L., Pan, J., 2019. Expanding ev charging networks considering transportation pattern and power supply limit. IEEE transactions on smart grid 10, 6332–6342.

[21] Zheng, Y., Dong, Z.Y., Xu, Y., Meng, K., Zhao, J.H., Qiu, J., 2013. Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning. IEEE Transactions on Power Systems 29, 221–229.