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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Background

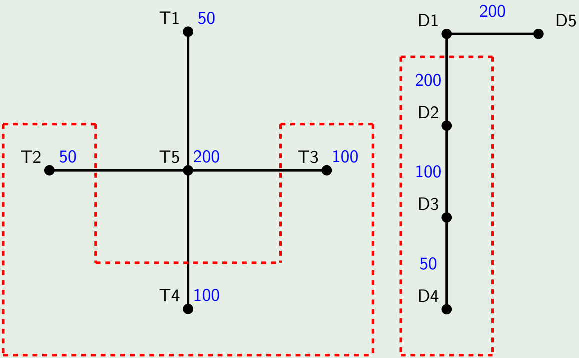
- Plug-in electric vehicles (PEVs) have made rapid development and become an attractive option in the transportation industry Martinez et al. [2016].
- The aggregated charging power from CS will have a great impact on distribution system operation, since it can change the load profile and result in overloading, low-quality voltage or increased losses in the systemClement-Nyns et al. [2009].

Problem Description

- The biggest impact brought by taxi fleet electrification is the interdependence of TN and PDN, which used to be operated separately
- The majority of the existing U.S. power grid was built in the early 1930s, making it more than 80 years old.
- The existing infrastructure of TN and PDN is built without such consideration and thus not ready for the integration of large amounts of EVs
- The mapping structure between TN and PDN which is determined long time back can be a main technical barrier when we try to enhance the TN and PDN system.

Problem Description

Example



(a) TN Example (b) PDN Example

Figure: 1. The number are corresponding, i.e. T_i maps to D_i. 2. Blue numbers in TN indicate the number of taxis in the area. 3. Blue numbers in PDN indicate upper limit of power load with expansion.

Problem Description - Summary

- On one hand, we want to build a station in TN where EVs can be all satisfied.
- On the other hand, we want to choose a location where we can expand PDN more easily with low cost and high extra load.
- The constraints for PDN expansion can be either physical limitation (voltage drop or substation limit) or high economic cost.
- The main problem is that these two objectives actually conflict with each other.
- We have to make trade off between satisfaction and expansion
- We want to know the key factors or restriction of loss of satisfaction since loss of satisfaction is inevitable.

Potential Solutions

- To expand system ability of holding more EV load, there are two perspectives: supply and demand.
- From supply perspective: increasing physical feasibility and decreasing cost.
- From demand perspective: allowing autonomous vehicle.

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First Stage Model

Objective Function

$$\min \quad \tau(\mathbf{z}, \mathbf{x}) + \phi(\mathbf{x}, \mathbf{u}) + \mathbb{E}[\Pi(\mathbf{z}, \mathbf{x}, \mathbf{u}, \omega)]$$

- Cost due to TN = Fixed Cost + Capacity Cost

$$\tau(\mathbf{z}, \mathbf{x}) = \sum_{j \in J} A_j z_j + \sum_{j \in J} C_j x_j$$

- Cost due to PDN = Substation Cost + Expansion Line Cost

$$\phi(\mathbf{x}, \mathbf{u}) = L u_{0'0} + \sum_{(m,n) \in E} G_{mn} u_{mn}$$

- Benefit/Loss due to construction of charging stations and expansion in PDN.

$$\mathbb{E}[\Pi(\mathbf{z}, \mathbf{x}, \mathbf{u}, \omega)]$$

First Stage Model

First Stage Model With Constraints

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

$$\begin{aligned}
\text{s.t.} \quad & x_j \le \overline{D} z_j, && j \in J \\
& z_j \in \{0, 1\}, && j \in J \\
& x_j \ge 0, && j \in J \\
& u_{0'0} \ge 0 && \\
& u_{mn} \in \mathbb{Z}^+ &&
\end{aligned}$$

Second Stage Model

Objective Function

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

- $H_0 s_0$: The negative utility of unsatisfied EV charging demands due to geographical limitation. In this case, the demand voluntarily quit charging. This term serves as the degree of encouragement of building stations for EV.
- $\sum_{j \in J} H s_j$: The penalty of unsatisfied EV charging demands due to EV charging station capacity limitation. In this case, the demand involuntarily fails to charge.
- $\sum_{i \in I} \sum_{j \in J} GU_{ij}(\omega) y_{ij}$: The utility of satisfied EV charging demands.
- $H > H_0$: The penalty for involuntarily unsatisfied demand is larger than the penalty for voluntarily unsatisfied demand.

Second Stage Model

TN related constraints

$$\sum_{i \in I} y_{ij} - s_i \leq x_j, \qquad j \in J^+ \qquad (1)$$

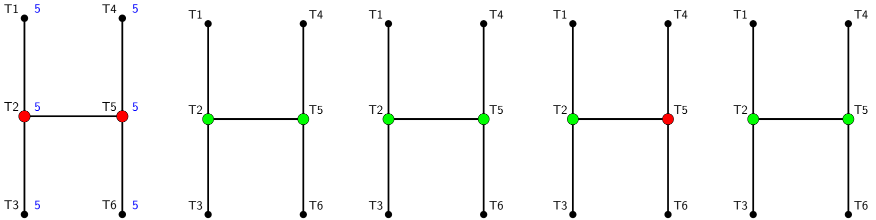
$$s_j \leq \overline{D} z_j, \qquad j \in J^+ \qquad (2)$$

$$U_{ij} y_{ij} \geq y_{ij} max(U_{ik}(\omega) - \Delta U, U^{min}) - D_i(\omega)(1 - z_k), \quad i \in I, j \in J^+, k \in J^+ \qquad (3)$$

$$\sum_{j \in J^+} y_{ij} = D_i(\omega), \qquad i \in I(\omega) \qquad (4)$$

- Constraint (1) depicts capacity requirement on each built EVCS.
- Constraint (2) indicates we do not allow unsatisfied demand at a location without charging station.
- Constraint (3) ensures EV owners select EVCS that they prefer
- Constraint (4) is for assigning charging demands to different EVCS's.

Illustration Example for (3)



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

Figure: Strong PDN (b, c), Weak PDN (d, e)

Second Stage Model

PDN related constraints - Power Flow

$$\sum_{m:(m,n)\in E^+} p_{mn} - \sum_{m:(n,m)\in E^+} p_{nm} = P_n^{load}(\omega) + W_n\left(\sum_{i\in I} y_{in} - s_n\right), \quad n \in N \tag{5}$$

$$\sum_{m:(m,n)\in E^+} q_{mn} - \sum_{m:(n,m)\in E^+} q_{nm} = Q_n^{load}(\omega), \quad n \in N \tag{6}$$

Second Stage Model

PDN related constraints - Voltage

$$V_m^2 - V_n^2 \geq \frac{2R_{mn}p_{mn} + 2X_{mn}q_{mn}}{1 + u_{mn}}, \qquad (m, n) \in E \qquad (7)$$

$$V_n = 1 \ p.u. \qquad n \in N^F \qquad (8)$$

$$V^{min} \leq V_n \leq V^{max}, \qquad n \in N \qquad (9)$$

Second Stage Model

PDN related constraints - Capacity

$$0 \leq p_{mn} \leq P_{mn}^{Max}(1 + u_{mn}) \qquad (m,n) \in E \qquad (10)$$

$$0 \leq p_{0'0} \leq P_{0'0}^{Max} + u_{0'0} \qquad (11)$$

$$0 \leq q_{mn} \leq Q_{mn}^{Max}(1 + u_{mn}) \qquad (m,n) \in E \qquad (12)$$

$$0 \leq q_{0'0} \leq Q_{0'0}^{Max} + u_{0'0} \qquad (13)$$

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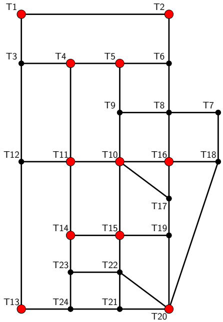
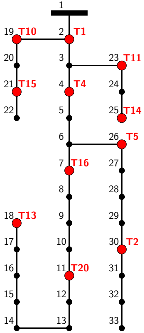
Networks and Assigned Structure

Table: 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



(a) Sioux Falls transportation network



(b) IEEE 33-node

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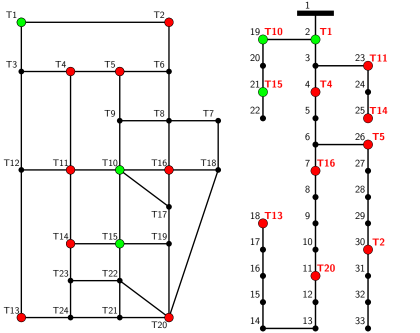

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Networks and Assigned Structure

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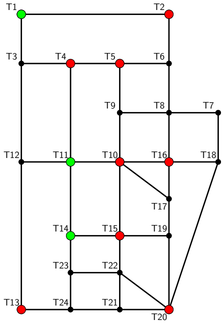
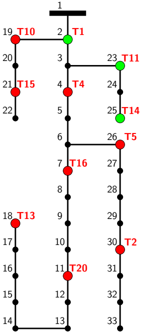


(a) Sioux Falls transportation network



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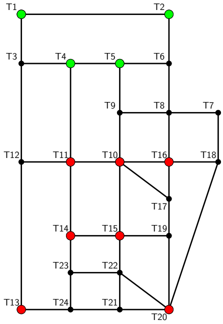

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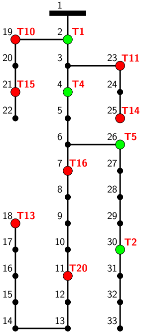

(b) IEEE 33-node

Networks and Assigned Structure

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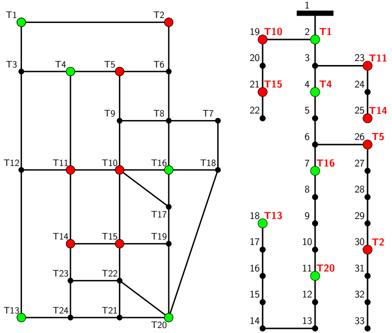


(a) Sioux Falls transportation network

(b) IEEE 33-node

Default Case Important Settings

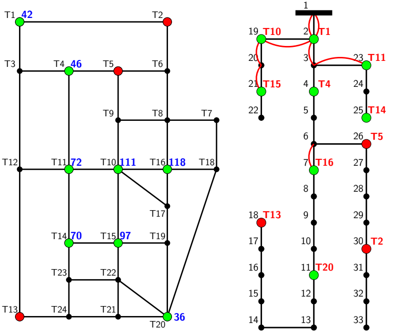
Demand Structure

- Downtown has more demand than uptown on average.
- East has more demand than West.
- South has more demand than North.

Parameters

- The maximum number of expansion line (K) is fixed to be 2.
- The autonomous level of taxis (ΔU) is fixed to be 0.

Default Case and Result



(a) Default TN (b) Default PDN

- Satisfied Cars(SAT#) = 384
- Unsatisifed Cars(UNSAT#) = 84
- Satisfaction Score(SATScore) = 5016
- TN Costs(TN$) = 4977
- PDN Costs(PDN$) = 4564

- The red nodes are the candidate nodes not to build stations;
- The green nodes is the selected charging stations to build;
- The blue numbers indicate the capacity of the charging stations.

Free TN and Free PDN

Table: 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

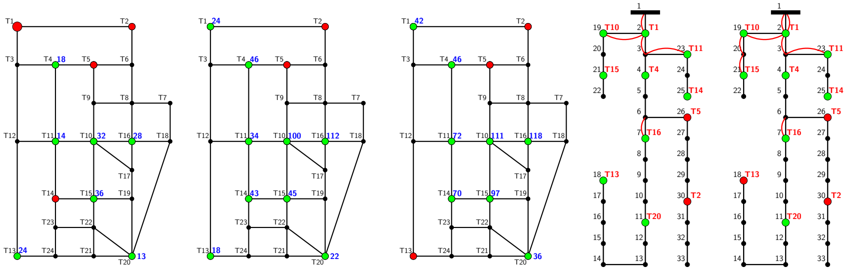
Table: PDN Decision of Extreme Cases

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	1	2	2	2	1
Free PDN	-	-	-	-	-	-	-	-	-

Table: Factors of Extreme Cases

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$

Changing Physical Restriction



(c) TN K = 0 (d) TN K = 1 (e) TN K = 2 (f) PDN K = 1 (g) PDN K = 2

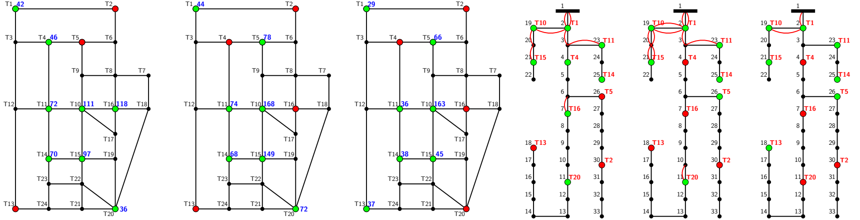
Figure: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

Changing Physical Restriction

Table: 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

Changing Cost of PDN



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

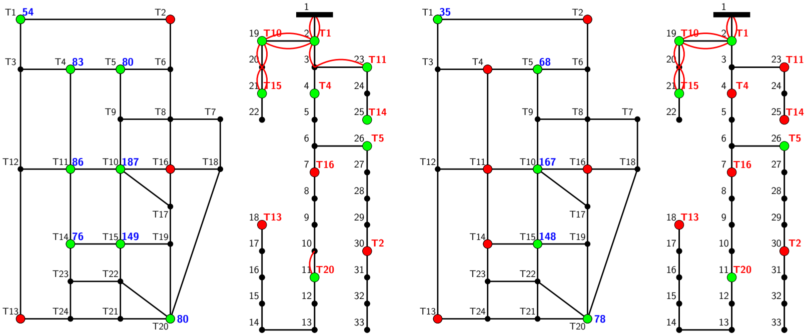
Figure: PDN Decision Result of Changing Coefficient of PDN line Cost(β)

Changing Cost of PDN

Table: Factors of Changeing β

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\beta = 0.5$	407	60	5924	5504	4424
$\beta = 1$ (Default)	384	84	5016	4977	4564
$\beta = 3$	287	180	-1269	4420	3315

Changing Cost of TN



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

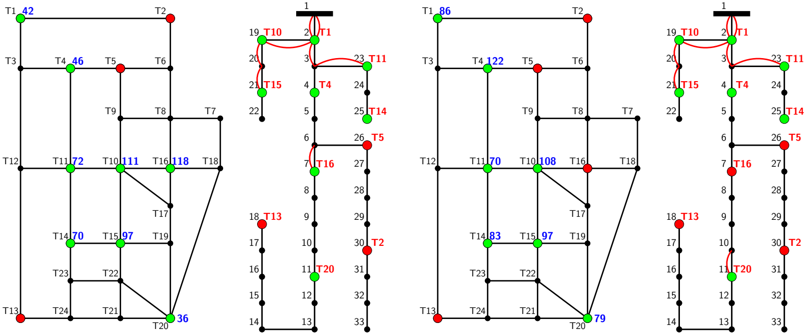
Figure: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

Changing Cost of TN

Table: Expansion Strategy for PDN

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\alpha = 0.5$	417	51	6624	3241	6185
$\alpha = 1$(Default)	384	84	5016	4977	4564
$\alpha = 3$	349	119	1729	12826	4758

Changing Demand Structure



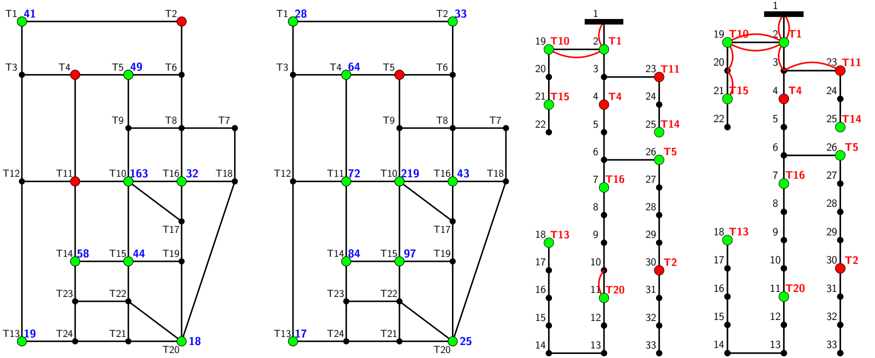
(a) TN Default (b) PDN Default (c) TN Uniform (d) PDN Uniform

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

Changing Demand Structure

Table: Expansion Strategy for PDN

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



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

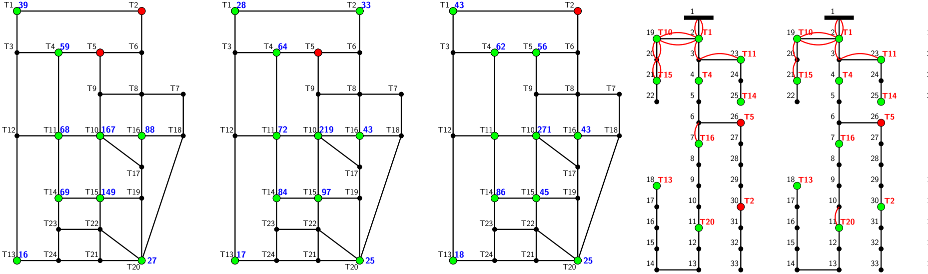
Figure: Decision Result of Changing K: The yellow node in (c) means the closed station compared with default case

Changing Physical Restriction

Table: 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	5532

Changing Cost of PDN



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

Figure: PDN Decision Result of Changing β

Changing Cost of PDN

Table: Factors of Changeing β

Factors	SAT#	UNSAT#	SATScore	TN$	PDN$
$\beta = 0.2$	448	20	8676	5875	3766
$\beta = 1$	447	21	8365	6317	5532
$\beta = 3$	428	40	6695	6275	5618

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Reference

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C. M. Martinez, X. Hu, D. Cao, E. Velenis, B. Gao, and M. Wellers. Energy management in plug-in hybrid electric vehicles: Recent progress and a connected vehicles perspective. *IEEE Transactions on Vehicular Technology*, 66(6):4534–4549, 2016.

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