Selecting optimal locations of public charging stations for electric vehicles using the big data of driving behaviors: A case study of Seoul, Korea

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RESEARCH BACKGROUND

▪ EV adoption in Korea

- The limited battery capacity is the one of the biggest factors interrupting EV adoption.

Short driving range

Long charging time

Low charging station accessibility

→ *Consumer preference* ↓

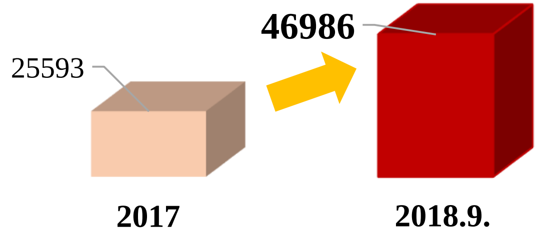
- Korean government has been implementing policies to improve charging infrastructure.

  - (e.g.) Installation of public charging stations, subsidy for home charging equipment

  - EV penetration rate in Korea is rapidly growing, although the market share of EV is still around 0.2%.

[Registration number increase of EV in Korea]

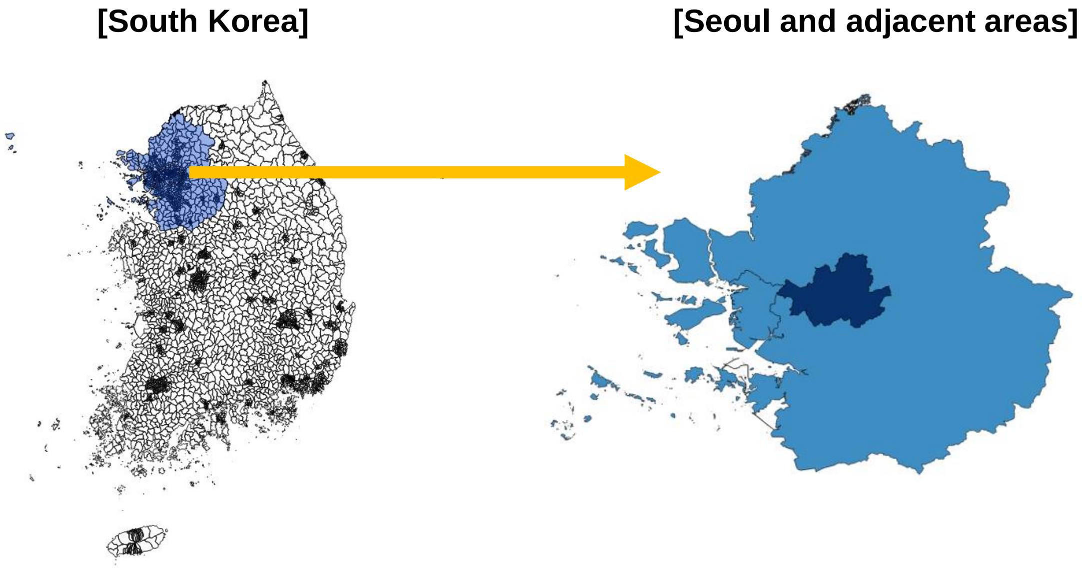
(Ministry of Environment, 2018)



RESEARCH BACKGROUND

▪ Importance of public charging stations in Seoul, Korea

- Seoul has ranked the 1st place in population density among the cities of OECD members.



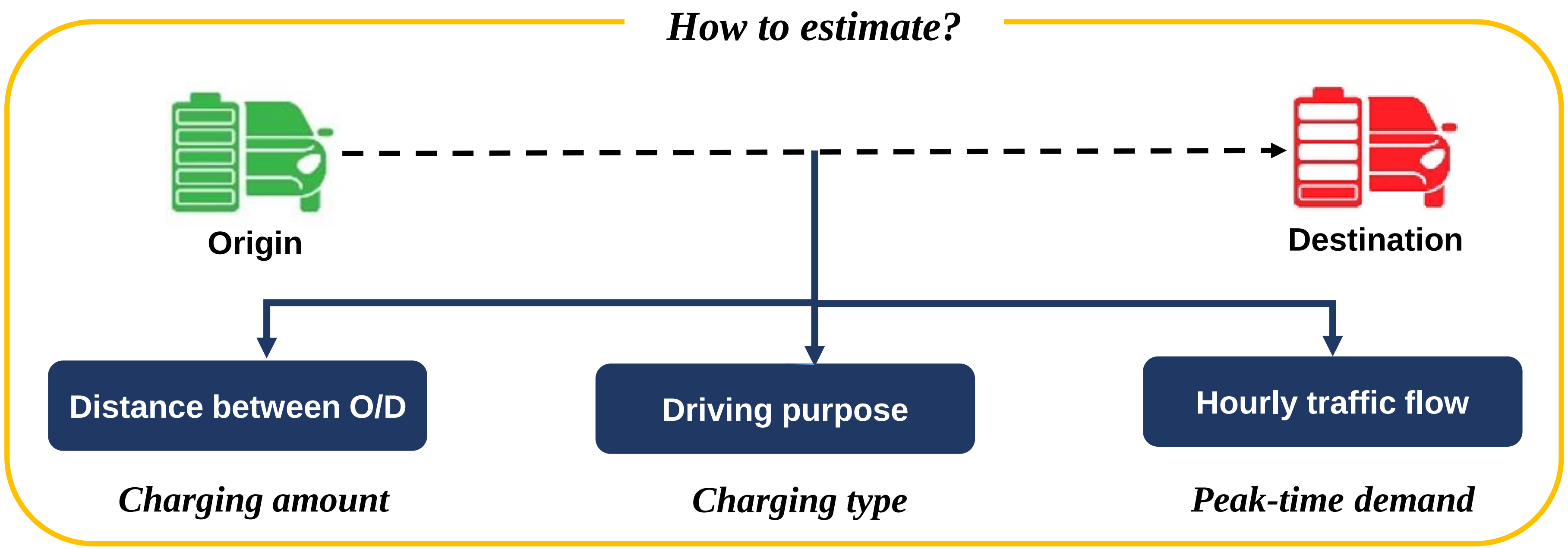
✓ Population of Seoul

- **9.77 million** people live in Seoul
- More than **25 million** people live in the adjacent areas of Seoul (half of Korean population)

- Citizens in Seoul have difficulty installing home chargers due to the lack of private space.
- Optimization research is necessary to install public charging stations efficiently.

RESEARCH BACKGROUND

- **Determining the location of charging stations**
  - Charging stations need to be systemically designed.
  - Demand for a specific type of charger in unit area should be estimated.
    - It is necessary to determine how many slow and fast chargers should be installed in the public charging point.



RESEARCH PURPOSE

[RESEARCH PURPOSE]

Develop an optimal location model of public chargers considering O/D data with drivers' travel purpose

Demand Estimation

Hourly demand estimation for slow and fast charger

Optimization

Installation cost minimization

Case Study

A case study of Seoul using actual data

LITERATURE REVIEW

▪ Previous research of EV charging demand estimation

- Demand estimation model can be divided into two types.

  1) Reflecting social, and demographic characteristics of a study area

  2) Using real-world data related to vehicle traffics

✓ The study reflects two types of demand estimation model

1) considering driving purpose (social characteristics)

2) considering O/D data (vehicle traffics)

	He et al. (2016)	Estimate the potential charging demand in a specific area through a weighted sum of six socio-demographic components, such as age, sex, income level, etc.
	Kleiner et al. (2018)	The average distance traveled in each area is calculated by the features of the area. (e.g., vehicle type ratio, commute distance)
Using vehicle traffic data	Xi et al. (2013)	Assigning tour direction to each EV randomly, based on real tour record data of conventional cars.
	Riemann et al. (2015)	Set each OD pair as a flow pattern, and generate EV charging demand, reflecting the routing choice behaviors of EV drivers
	Dong et al. (2014)	Make the daily driving route of EV by using the tour record of conventional cars
	Cai et al. (2014); Shahraki et al (2015)	estimate the traffic flow in the city through the driving data of taxis

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LITERATURE REVIEW

▪ Previous research of optimal locations

- Each model of optimal locations of EV charging stations has their own objective and constraints

✓ **The study develops a Mixed-Integer Programming model**

1) Variables: Number of slow / fast charger in each potential charging station

2) Objective: To minimize the total installation cost of chargers

3) Constraint: To cover the hourly potential demand fully

Riemann et al., (2015); He et al. (2018)	Network model	Capture the maximum flow	The number of charging stations is fixed.
He et al. (2016)	Mixed-integer program	1) Minimize the number of charging stations 2) Maximize demand coverage	1) Fully cover the potential demand 2) The number of charging stations is fixed.
Yang et al. (2017)	Mixed-integer program	Cost minimization	Ensure service quality above a certain level.

DEMAND ESTIMATION

Demand estimation procedure

- **EV charging demand in unit area** should be estimated to locate public charging stations.
- **Hourly demand** toward each type of charger (slow / fast) is estimated.

Estimation procedure

[Step 1] Calculating **the number of EVs** travelling a specific O/D in a day
- **Purpose type**
- **Transportation type**

[Step 2] Estimating **total hourly demand** in each demand point
- **O/D distance**
- **Home charger usage rate**

[Step 3] Separating demand with **each type of charger**
- **Purpose type**
- **Transportation type**

DEMAND ESTIMATION

Model assumptions

- Probabilities of a person's travel purpose, vehicle type, and travel time are independent.
- Travels occur in each time period and demand is generated at destination.
- The amount of demand is equal to travel distance.
- If an EV driver has home charger, he or she doesn't use public chargers.
- Propensity to each type of charger is determined by the vehicle type and travel purpose.

Notation of sets

Notation	Description
O	Set of all origins
D	Set of all destinations
P	Set of all travel purposes
V	Set of all travel transportations
T	24-hour time, $T = \{0, 1, 2, \cdots, 23\}$

DEMAND ESTIMATION

[Step 1] Calculating the number of EVs traveling a specific O/D in a day

The number of daily travels using electrified $v \in V$ with purpose $p \in P$ (from $i \in O$ to $j \in D$)

$$N_{ij}^{p,v} = E_v \times n_{ij} \times r_{ij}^{p,v}$$

- EV penetration rate of vehicle v
- The number of daily travels from i to j
- Prob. that a person travels with purpose p and vehicle v

[Step 2] Estimating total hourly demand in each demand point

Total charging demand of electrified $v \in V$ with purpose $p \in P$ (in demand point j at time $t \in T$)

$$D_{jt}^{p,v} = \sum_{i \in O} \left(N_{ij}^{p,v} \times d_{ij} \right) \times q_t^{p,v} \times (1 - H_v)$$

- Daily EV travels
- Distance between i and j
- Prob. That a travel with p and v occurs at t
- Home charger adoption rate

[Step 3] Separating demand with each type of charger

Demand for slow charger (in demand point j at time $t \in T$)

$$D_{jt}^{S} = \sum_{v \in V,\, p \in P} \left(\delta^{p,v} \times D_{jt}^{p,v} \right)$$

Demand for fast charger (in demand point j at time $t \in T$)

$$D_{jt}^{F} = \sum_{v \in V,\, p \in P} \left(\left(1 - \delta^{p,v}\right) \times D_{jt}^{p,v} \right)$$

- A person's preference for slow chargers when travelling with p and v
- Total charging demand

OPTIMAL LOCATION

▪ Optimization model outline

[Decision variables]

- The number of slow chargers
- The number of fast chargers

→

[Objective]

Minimize the installation cost of public chargers

[Constraints]

- Demand coverage
- Limitation of charging capacity
- Limitation of installable space for chargers

▪ Model assumptions

- Charging stations have their own limitations of installable spaces.
- There is a **maximum desirable distance**.

  - It means people will not drive further than maximum desirable distance for EV charging.

OPTIMAL LOCATION

Introduction

Model – 1
Demand estimation

Model – 2
Optimal location

Case study

Conclusion

▪ Notations

Notation	Description
Sets	
L	Set of potential charging stations
B_j	Set of potential charging stations whose distance is less than maximum desirable distance from demand point j
Parameters	
$COST_S$	Cost of a slow EV charger
$COST_F$	Cost of a fast EV charger
$CAPA_S$	Capacity of a slow EV charger per hour
$CAPA_F$	Capacity of a fast EV charger per hour
$SPACE_l$	Number of available installation spaces in potential EV charging station $l \in L$
Decision variables	
y_{jlt}^S	The amount of flow for a slow charger from demand point $j \in D$ to charging station $l \in L$ at time $t \in T$
y_{jlt}^F	The amount of flow for a fast charger from demand point $j \in D$ to charging station $l \in L$ at time $t \in T$
N_l^S	Optimal number of slow chargers in location $l \in L$
N_l^F	Optimal number of fast chargers in location $l \in L$

OPTIMAL LOCATION

- **Model**

$$\min \sum_{l \in L} \left(COST_S \times N_l^S + COST_F \times N_l^F \right)$$

Objective function:
Minimize the total installation cost of chargers

$s.t.$

$$\sum_{l \in B_j} y_{jlt}^S = D_{jt}^S \qquad \forall j \in J, t \in T$$

$$\sum_{l \in B_j} y_{jlt}^F = D_{jt}^F \qquad \forall j \in D, t \in T$$

Constraint 1:
Demand should be fully covered by public charging stations

$$\sum_{j \in D} y_{jlt}^S \le CAPA_S \times N_l^S \qquad \forall l \in L, t \in T$$

$$\sum_{j \in D} y_{jlt}^F \le CAPA_F \times N_l^F \qquad \forall l \in L, t \in T$$

Constraint 2:
There is a capacity limitation of each potential charging stations

$$N_l^S + N_l^F \le SPACE_l \qquad \forall l \in L$$

Constraint 3:
There is a limit of installation for chargers

$$N_l^S, N_l^F \in Z_+ \qquad \forall l \in L$$

$$y_{jlt}^S, y_{jlt}^F \ge 0 \qquad \forall j \in D, l \in L, t \in T$$

Constraint 4:
Variable domain

DATA DESCRIPTION

- **Data** (Source: Ministry of Land, Infrastructure and Transport of Korea, 2016)
  - Two types of O/D data, which represent the daily travel amount of people, are used.

(1) Purpose O/D (11 purposes)

Origin	Destination	Number of daily moves grouped by purpose			
		Going to work	Returning home	Shopping	…
A	B	20	40	10	…
B	C	80	15	20	…
…					

(2) Vehicle O/D (21 transportations)

Origin	Destination	Number of daily moves grouped by vehicles			
		Private car	Taxi	Bus	…
A	B	15	35	25	…
B	C	35	20	60	…
…					

  - For simplification, we grouped purpose and vehicles into 3 groups.

Purpose group	Transportation group
Purpose 1 (p1): Going to work Going to work, Going to school	***Vehicle 1 (v1): private car*** Private car (self-drive), Private car (drive by others)
Purpose 2 (p2): Returning home Returning home	***Vehicle 2 (v2): Taxi*** Taxi
Purpose 3 (p3): Others Send-off, Going to academy, etc.	***Vehicle 3 (v3): Others*** Bus, Rail, etc.

DATA DESCRIPTION

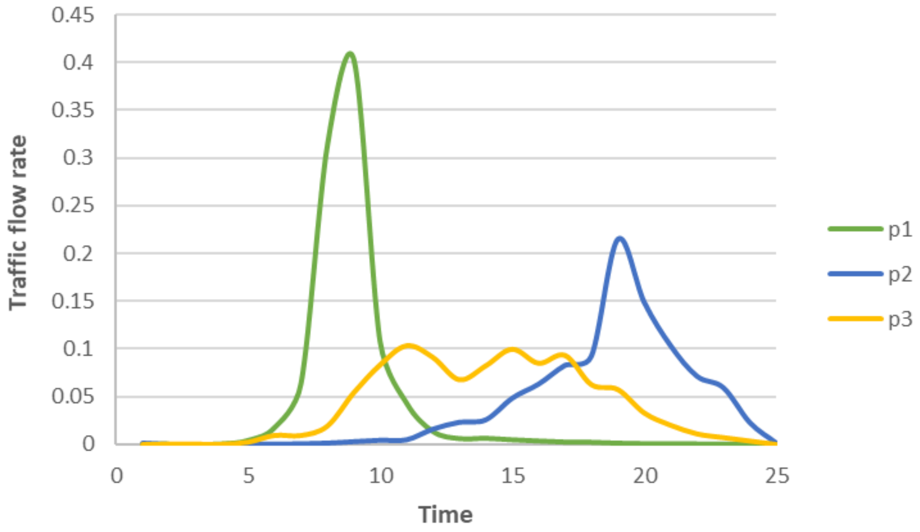
▪ Data (cont.)

- Hourly traffic flow of each travel purposes has significantly different characteristics.

  - *p1* (Going to work) has a quite high rate in the morning hours.

  - *p2* (Returning home) shows high rate in the evening time.

  - *p3* (Others) distribute relatively evenly in all time period except for late night hours.



[Hourly traffic flow ratio of each purpose]

STUDY AREA

Introduction

Model – 1
Demand estimation

Model – 2
Optimal location

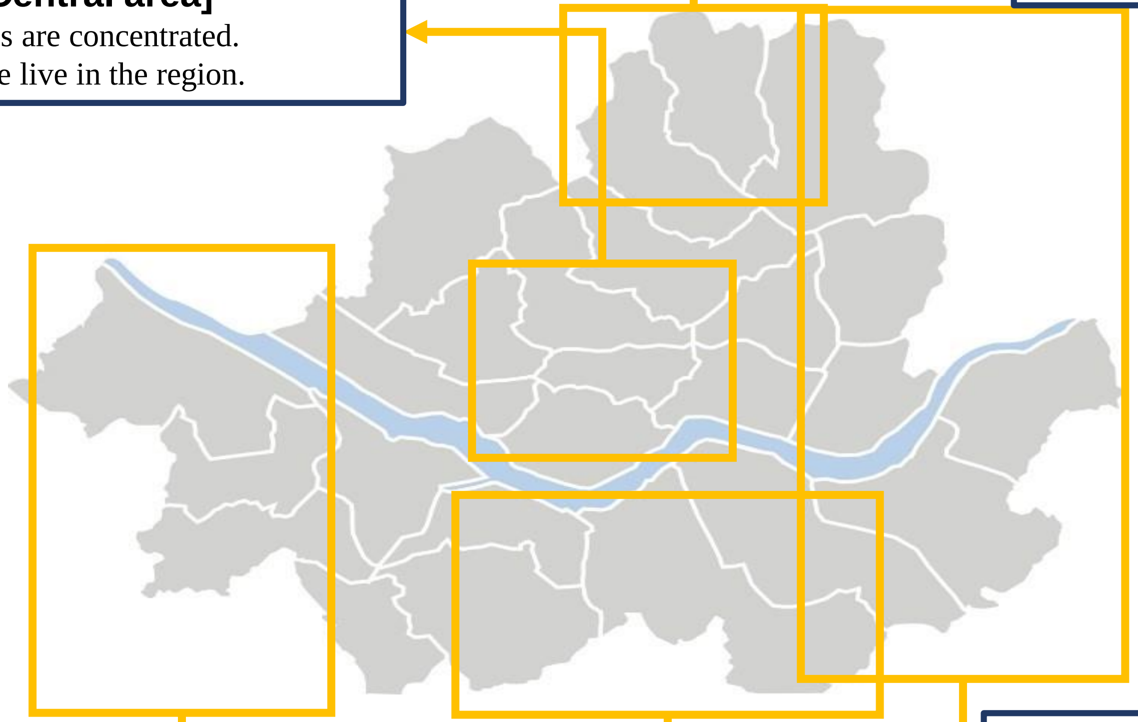
Case study

Conclusion

- **Characteristics of regions in Seoul, Korea**

[Northern area]
- Low-population
- A few workplaces & commercial places

[Central area]
- Workplaces are concentrated.
- Few people live in the region.



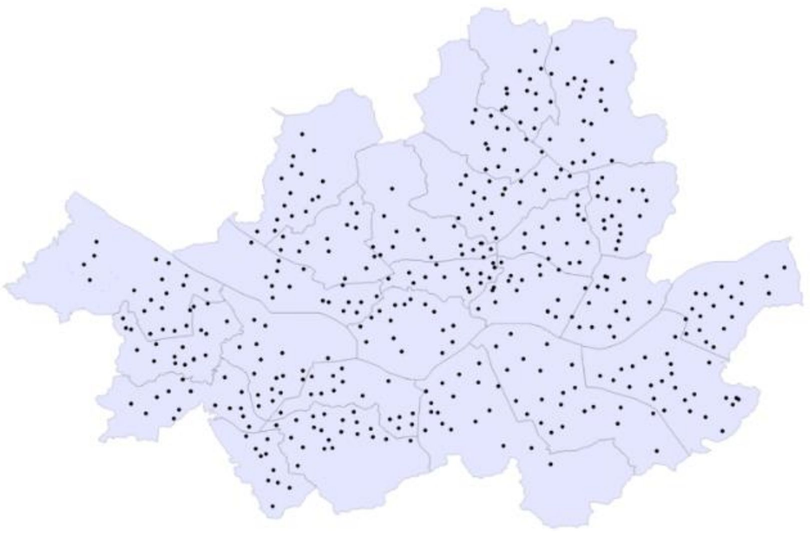
[Outer region]
- Mainly Residential areas

[Southern area]
- High-population
- Workplaces and residence coexist.
- Lots of commercial places

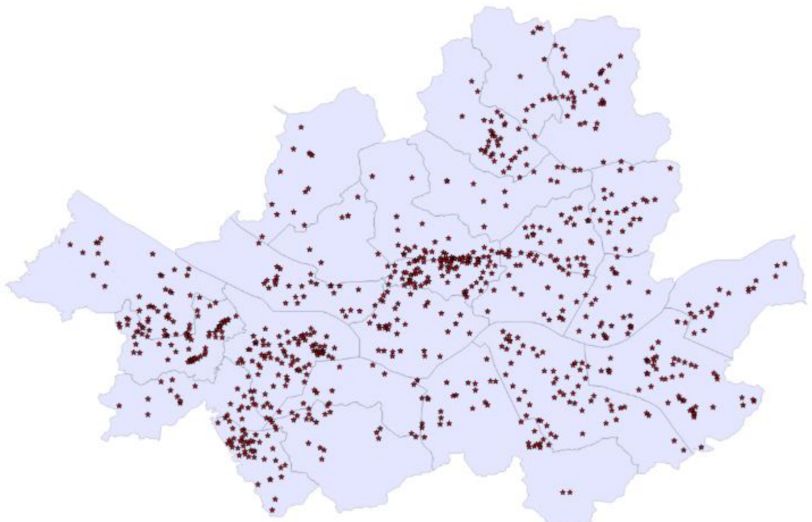
STUDY AREA

- **Location of demand points and charging stations**

[Demand points of Seoul]



[Potential EV charging stations]



✓ A total of 424 *Dong* (administrative districts of Korea) become demand points

✓ A total of 838 public car parks become potential EV charging stations
✓ 10% of parking lots are available to install chargers

DEMAND ESTIMATION RESULT

Parameter settings

- The origin and destination set: $O = \{\text{centers of Dong in Seoul, Incheon, and Gyeonggi-do}\}$ $\quad D = \{\text{centers of Dong in Seoul}\}$

- EV penetration rate: $E_v = \begin{cases} 0.01 & \text{if } v \in \{v_1, v_2\} \\ 0 & o.w. \end{cases}$

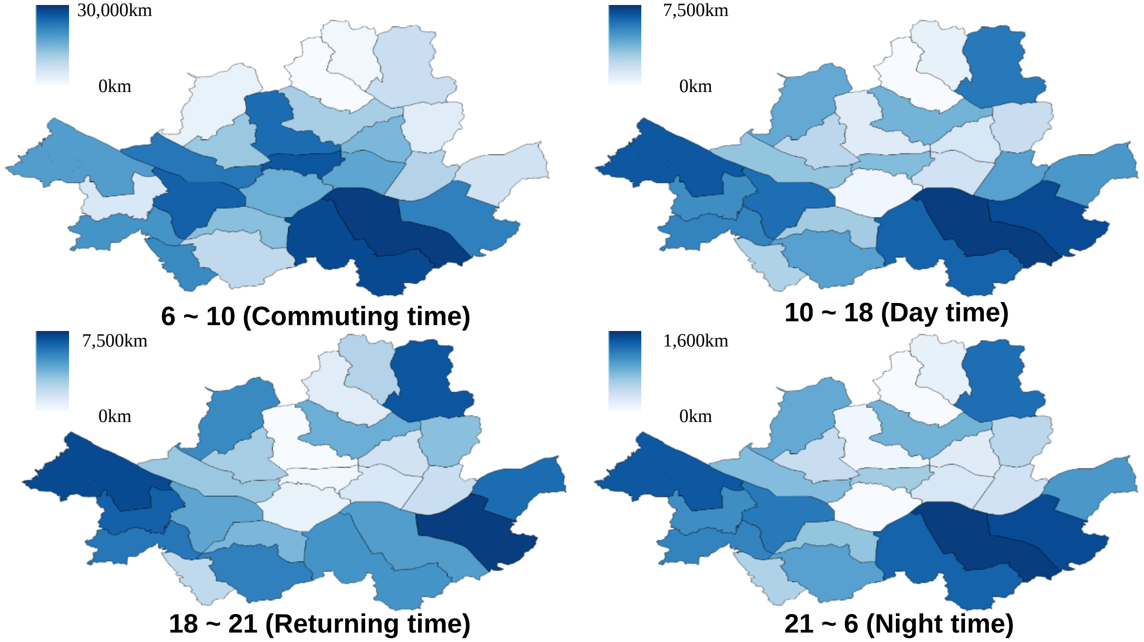
- Ratio of home charging users: $H_v = \begin{cases} 0.3 & \text{if } v = v_1 \\ 0 & o.w. \end{cases}$

- The propensity to each type of charger by purpose
  - When drivers use EV for commuting or returning home, they would like to prefer using slow chargers since they can park their car relatively long time.
  - When drivers use EV for other purposes, they would like to prefer using fast chargers.
  - Taxis always use fast chargers.

$$\delta^{p,v_1} = \begin{cases} 0.8 & p = p_1, p_2 \\ 0.2 & p = p_3 \end{cases} \qquad \delta^{p,v_2} = 0, \forall p \in P$$

DEMAND ESTIMATION RESULT

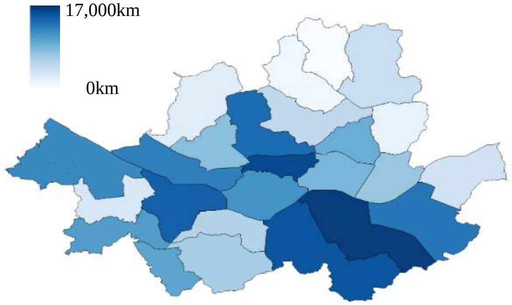
- **Demand for the slow chargers**



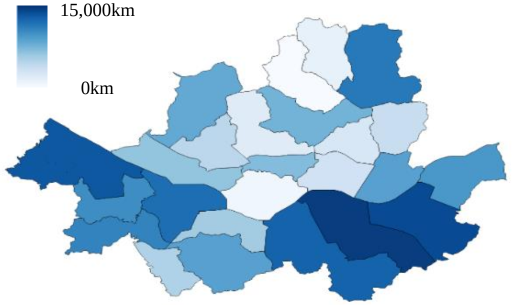
Results
• The southern and central areas, in which workplaces are concentrated, show higher demand in the morning. • Demand of outer areas rise sharply and that of central areas drop significantly in the evening time. • Southern parts show a high level of demand in all time period.

DEMAND ESTIMATION RESULT

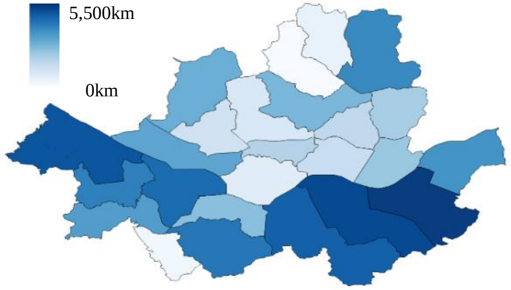
- **Demand for the fast chargers**



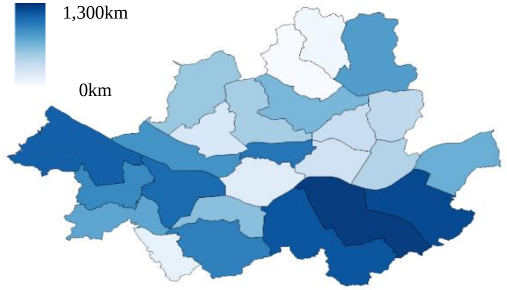
6 ~ 10 (Commuting time)



10 ~ 18 (Day time)



18 ~ 21 (Returning time)



21 ~ 6 (Night time)

Results

- It shows quite similar distribution regardless of time except for the central areas.
- The southern areas show a high level of demand in all time period.
- The northern areas show a low level of demand.

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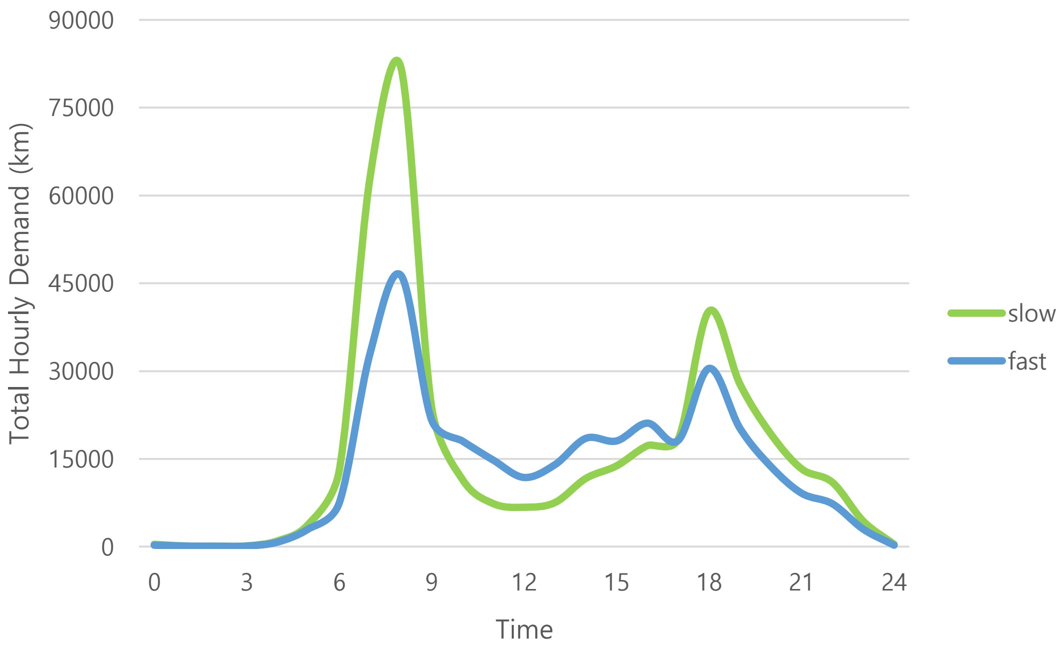
DEMAND ESTIMATION RESULT

- **Estimated total hourly demand**



✓ The peak time of both types of charging is 8 a.m. but demand for fast charging shows more flat shape.

✓ Commuting is the most influential in charging demand.

OPTIMAL LOCATION RESULT

Parameter settings

- Maximum desirable distance: 2km
- Capacity of slow and fast charger:

$$CAPA_S = \frac{200}{3}\text{km/hour}, \quad CAPA_F = 480\text{km/hour}$$

- Unit installation cost of slow and fast charger:

$$COST_S = \$3,000, \quad COST_F = \$40,000$$

- 10% of the total parking lot can be used to install chargers

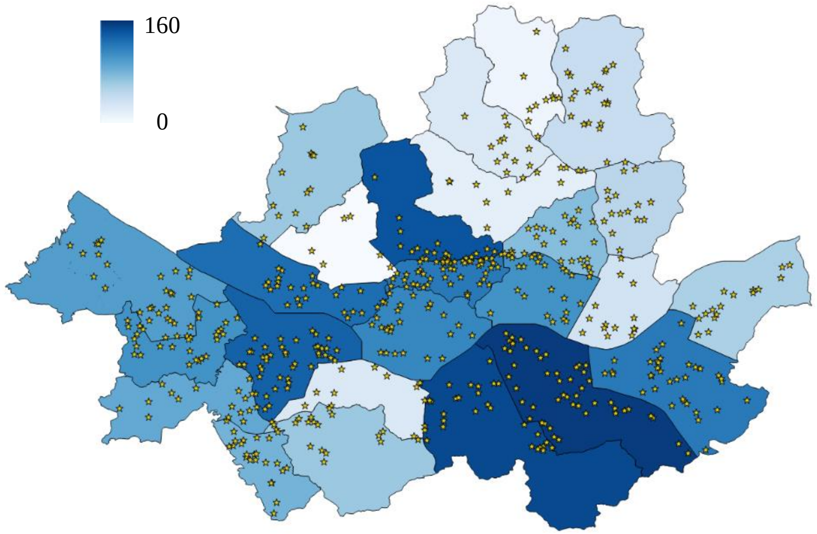
Experiment settings

- We used X-press of FICO® as a solver of our MIP model.
- We stopped the computation when the gap of LP bound and feasible IP solution goes below 5%.
- The model is performed on the PC with Intel® Core™ i7-6700 3.40GHz CPU and 16.0GB of RAM.

OPTIMAL LOCATION RESULT

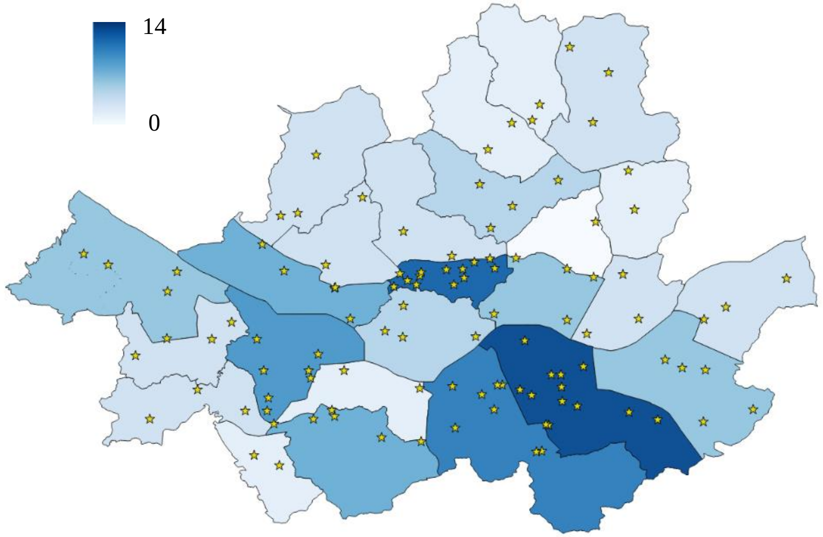
- **Optimal solution**

[Location of slow chargers]



Number of charging stations: 575
Average chargers in charging stations: 2.19

[Location of fast chargers]



Number of charging stations: 108
Average chargers in charging stations: 1.03

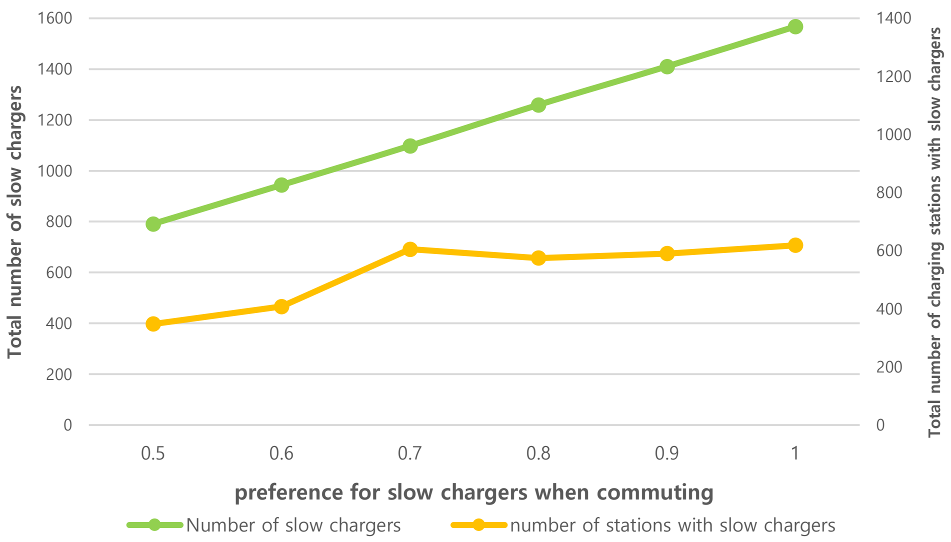
Results
• A total of 1259 slow chargers and 111 fast chargers are needed, and the minimized cost is $821,700.
• **Slow chargers**: highly distributed and many chargers in workplace areas ↔ highly distributed but a few chargers in residential areas
• **Fast chargers**: Evenly distributed due to taxi travels & almost of them are not installed in one place

SENSITIVITY ANALYSIS

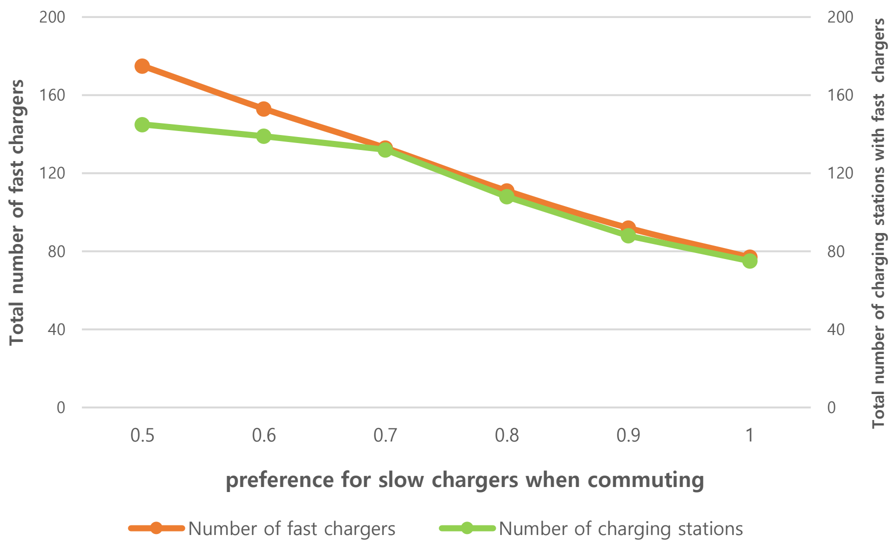
▪ Impact of the preference for each type of chargers

- The sensitivity of preference for each type of charger when people commutes ($\delta^{1,1}, \delta^{2,1}$) is analyzed.

[Change of slow chargers]



[Change of fast chargers]

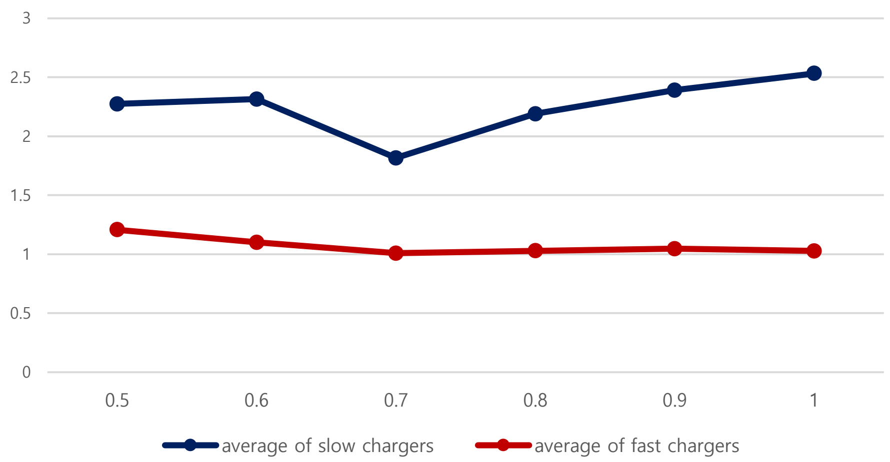


SENSITIVITY ANALYSIS

▪ Impact of the preference for each type of chargers

- The sensitivity of preference for each type of charger when people commutes ($\delta^{1,1}, \delta^{2,1}$) is analyzed.

[The average installed chargers in each charging stations]



Results

- As preference for slow charger increases, the number of slow chargers obviously increases.
- **However,** the number of charging stations does not increase as fast as the rate of increase of chargers (even decreases)
- The average installed chargers in charging stations does not change significantly.

  - If demand increases, it is better to install chargers in multiple locations rather than in concentrated location.

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CONCLUSION

We developed

- The model estimating potential demand for each type of EV chargers
- The model optimizing slow and fast chargers of public charging stations

We suggest

- Slow chargers should be installed in workplace, and residential areas
- Fast chargers should be distributed evenly around the metropolitan city.
- Charging stations should be more distributed rather than be concentrated in one place.

Further research

- Reflecting each driver’s travel route.
- More realistic model considering other cost, driver’s utility, etc.

THANK YOU

Q & A