Electric vehicle charging schedule for a car sharing system considering real traffic condition

Tianyuan Xu, Bongju Jeong

xu.tianyuan@yonsei.ac.kr, bongju@yonsei.ac.kr

2022년 한국SCM학회 춘계컨퍼런스

Intelligent Manufacturing Systems Lab.

Yonsei Univ.

이 논문은 2019년도 정부(과학기술정보통신부)의 재원으로 한국연구재단 기초연구사업의 지원을 받아 수행된 연구임 (NRF-2019R1F1A1061349)

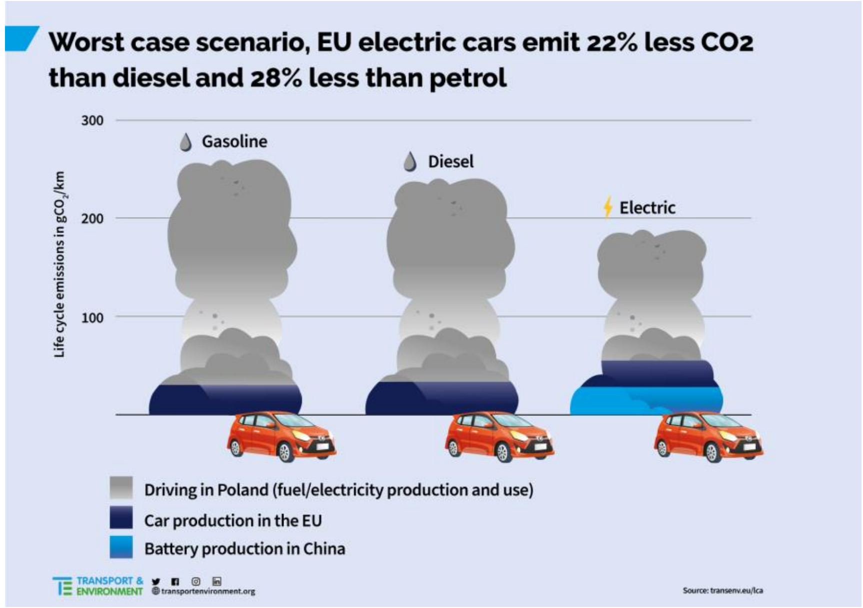
Contents

1.Introduction

1.1 Research background

- Green house gases emission causing severe pollution problem -> **sustainable development**
- **Urban transportation sector**: electric vehicle (EV) replacing internal combustion vehicle

➢ **Impact of urban transportation sector on EVs is in need of study and research**



<Fig. 1 Emission comparison of EV, gasoline car and diesel car>

Reference: https://m.gettyimagesbank.com/view/eco-friendly-electric-cars-and-gasoline-car-comparison-electric-auto-environment-protection-advantage-vector-illustration-set-gasoline-electro-car-comparison-infographic/1343361954
https://www.cittimagazine.co.uk/news/electric-vehicles-charging/te-busts-ev-co2-myth.html

1.Introduction

1.2 Research objective

This research studies

- Impact of **urban traffic condition** on **EV charging power demand**
- **EV charging schedule** at charging stations operate by a car sharing system

❖ **Research objective**

1) Charging power demand estimation

2) EV charging schedule formulation

<Fig. 2 Car sharing system charging station>

<Fig. 3 Car sharing system charging station>

Reference: https://www.youtube.com/watch?v=BL99dIYDq6Y
https://www.autoevolution.com/news/wattmobile-new-ev-car-sharing-program-starting-in-france-81997.html

2. Literature review

Literature	Energy management	Charging infrastructure	Car sharing system	Traffic network
Sundström and Binding, (2010)	o	x	o	x
Wang and Xu, (2013)	x	o	x	o
Honarmand et al., (2014)	o	x	x	x
Wu and Sioshansi, (2017)	o	o	o	x
Wang and Thompson, (2019)	o	o	x	x
Wang and Shahidehpour, (2019)	o	o	x	o
Chen, Wu and Zhang, (2020)	o	x	x	o
Xia and Chen, (2021)	x	o	x	o
This research	o	o	o	o

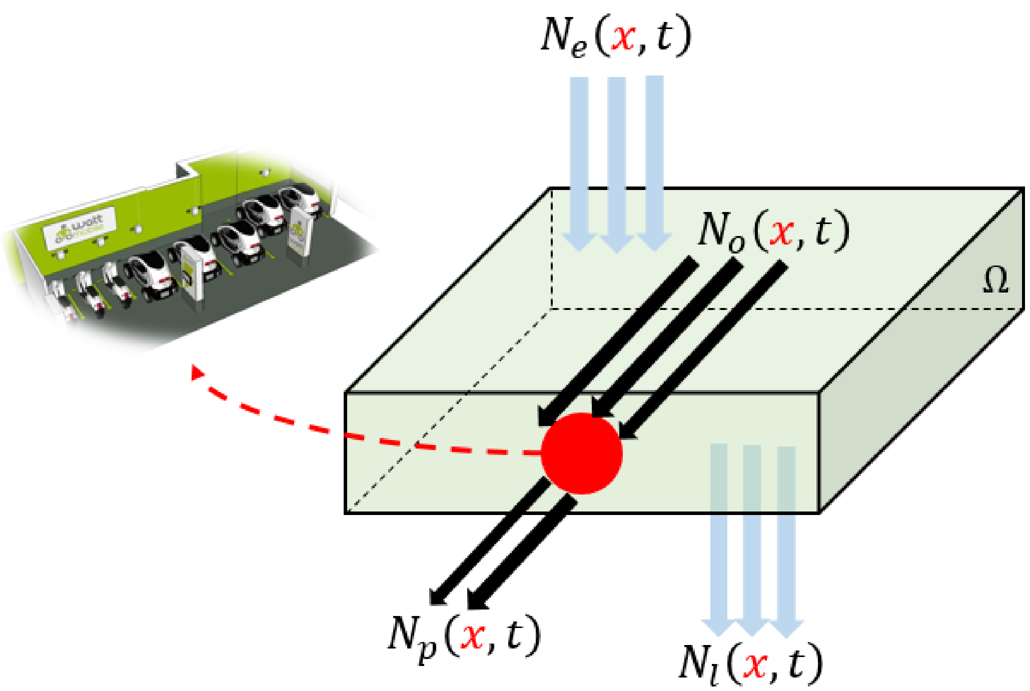
2. Literature review

Contribution

- ➢ Connection of **<u>individual EV charging</u>** schedule with **<u>traffic network</u>**
- ➢ Impact of **<u>urban traffic condition</u>** on **<u>EV sharing system</u>** operation
- ➢ Implementation of **<u>charging power demand estimation</u>** in charging station operation

3. Charging power demand estimation model

3.1 Traffic fluid model



<Fig. 4 Traffic fluid model schematic diagram>

$N_e(x,t)$: Number of discharged EVs entering area *Ω* during time *t*

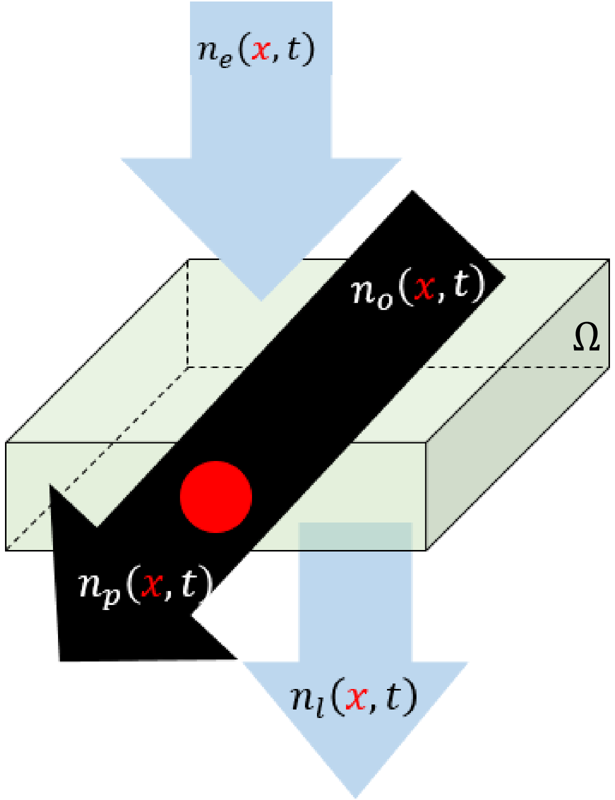
$N_l(x,t)$: Number of discharged EVs leaving area *Ω* during time *t*

$N_o(x,t)$: Number of discharged EVs from spatial origin to charging station at time *t*

$N_p(x,t)$: Number of discharged EVs that have already passed through charging station before time *t*

3. Charging power demand estimation model

3.1 Traffic fluid model



<Fig. 5 Traffic density and flow diagram>

$n_e(x,t) = \frac{\partial^2 N_e(x,t)}{\partial x \partial t}$: **density** of discharged EVs entering area Ω at time t

$n_l(x,t) = \frac{\partial^2 N_l(x,t)}{\partial x \partial t}$: **density** of discharged EVs leaving area Ω at time t

$n_o(x,t) = \frac{\partial N_o(x,t)}{\partial x}$: **density** of discharged EVs at charging station at t

$n_p(x,t) = \frac{\partial N_p(x,t)}{\partial t}$: **traffic flow** of discharged EVs at charging station at t

3. Charging power demand estimation model

3.2 Fluid conservation equation

➢ Fluid conservation equation:

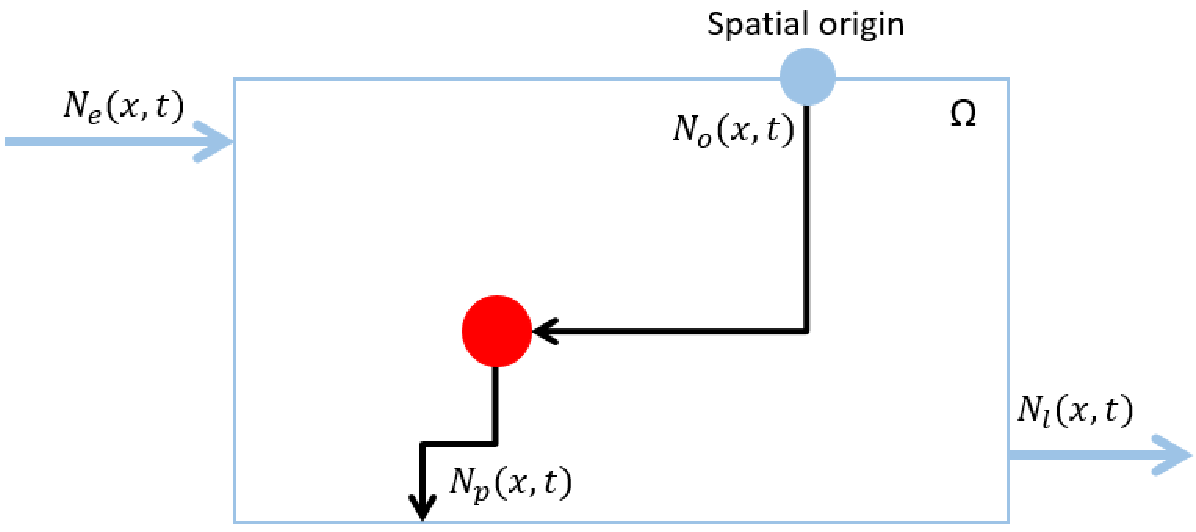
$$\boldsymbol{N_e(x,t) - N_l(x,t) = N_o(x,t) + N_p(x,t)}$$

$$\boldsymbol{n_e(x,t) - n_l(x,t) = n_o(x,t) + n_p(x,t)}$$

flow = density * velocity: $n_p(x,t) = n_o(x,t) \times v(x,t)$

$$n_e(x,t) - n_l(x,t) = \frac{dn_o(x,t)}{dt} + \frac{\partial v(x,t)}{\partial x} n_o(x,t)$$

➢ $\frac{dn_o(x,t)}{dt} = n_e(x,t) - n_l(x,t) - \frac{\partial v(x,t)}{\partial x} n_o(x,t)$

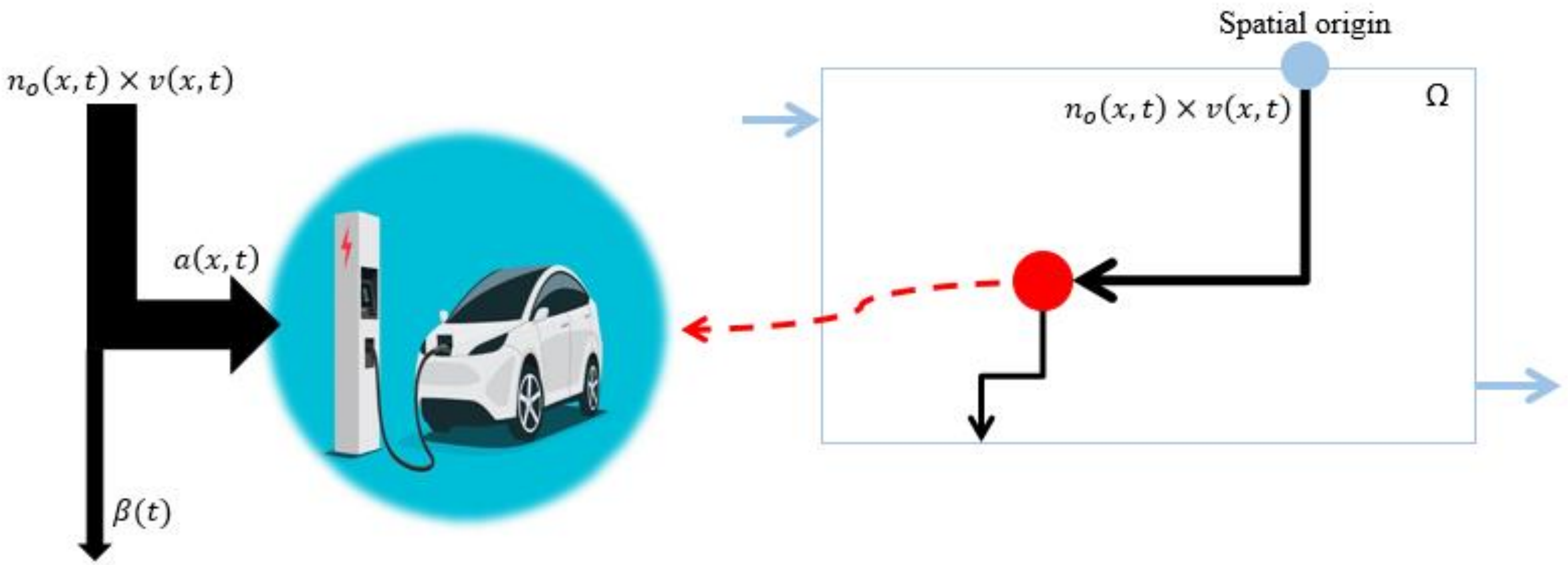


<Fig. 6 Representation of fluid conservation equation>

3. Charging power demand estimation model

➢ **Arrival rate:**

$\boldsymbol{a(x,t) = n_o(x,t) \times v(x,t) - \beta(t)}$ --> $\beta(t)$: arrival rate of discharged EVs will be charged at other charging station



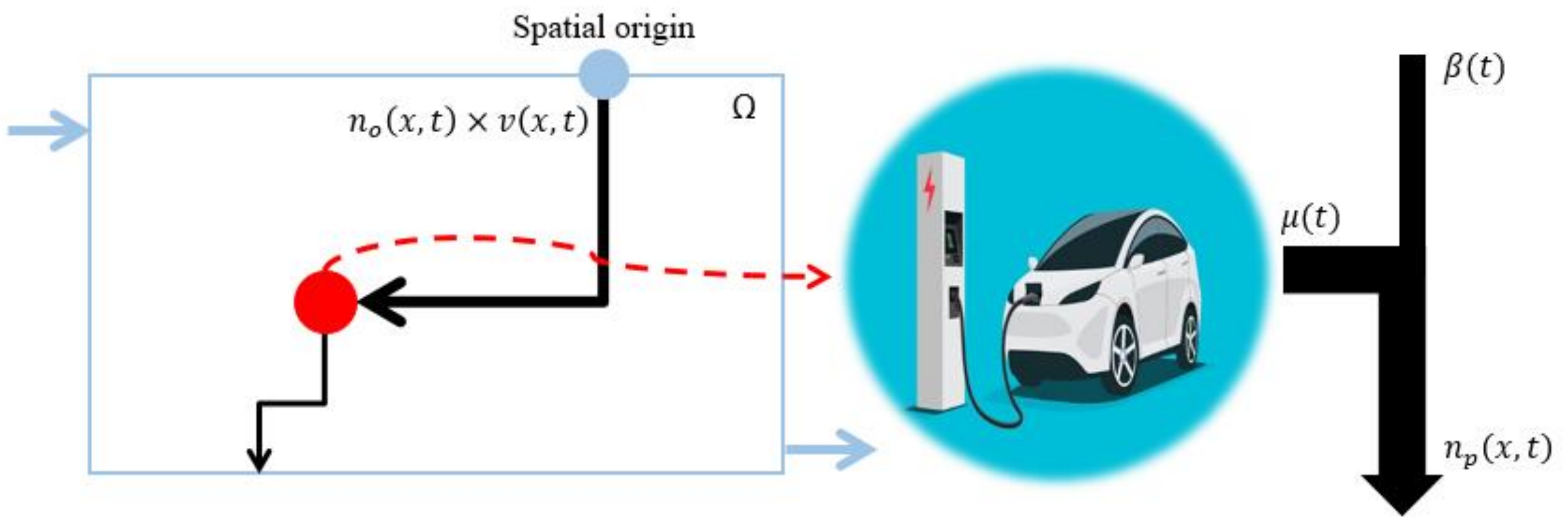
<Fig. 7 Arrival rate diagrammatic drawing>

Reference: https://www.lboro.ac.uk/media-centre/press-releases/2019/november/loughborough-joins-vpach-team/

3. Charging power demand estimation model

➢ **Minimum number of charging piles:**

$\boldsymbol{s_{min}} = \frac{\boldsymbol{a(x,t)}}{\boldsymbol{\mu(t)}}$ --> $\mu(t)$: service completion rate

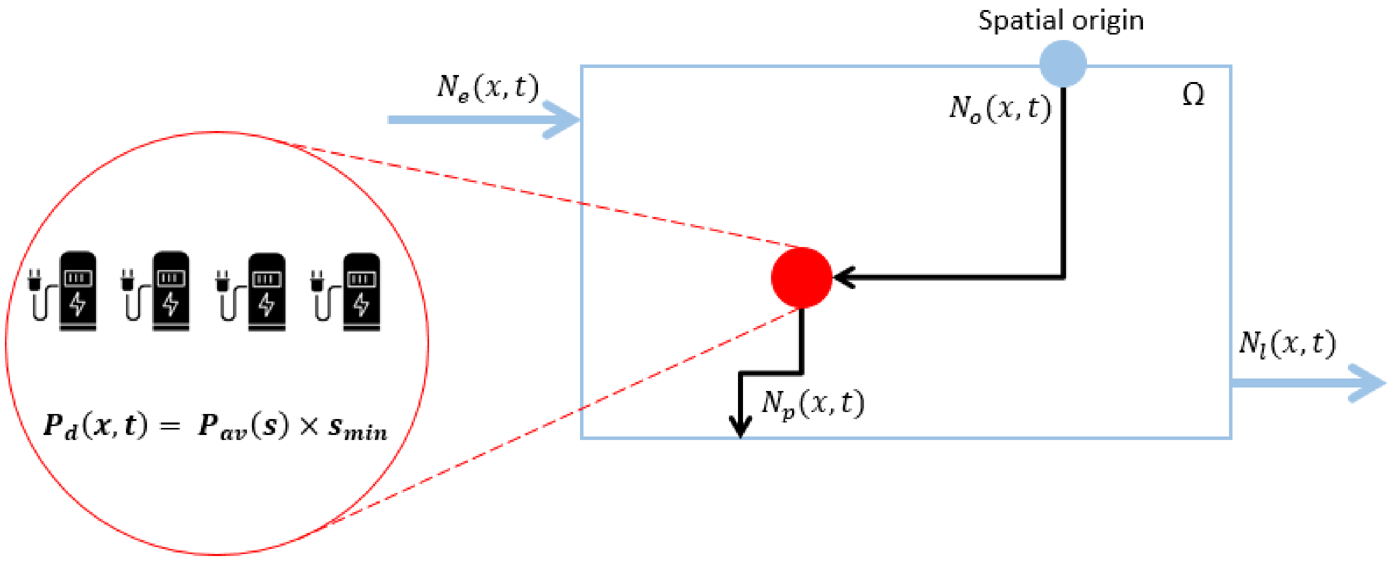


<Fig. 8 Service completion rate>

3. Charging power demand estimation model

➢ **Charging power demand:**

$\boldsymbol{P_d(x,t) = P_{av}(s) \times s_{min}}$ --> $P_{av}(s)$: average charging power per charging pile



<Fig. 9 Charging power demand diagram>

4. EV charging schedule model

4.1 Notations

Indices

t time index, $t \in T$

i EV index, $i \in I$

s charging pile index, $s \in S$

Parameters

$N_e(x,t)$ number of discharged EVs entering area Ω at t

$N_l(x,t)$ number of discharged EVs leaving area Ω at t

$N_o(x,t)$ number of discharged EVs from spatial origin to charging station at t

$N_p(x,t)$ number of discharged EVs that have already passed through charging station before t

$n_o(x,t)$ traffic density at charging station at t

$n_p(x,t)$ traffic flow at charging station at t

$v(x,t)$ velocity of EV at charging station at t [km/h]

$\beta(t)$ rate of discharged EVs charging at other charging station at t

$a(x,t)$ arrival rate of EVs at charging station at t

$\mu(t)$ service completion rate at charging station at t

e unit electricity price [$/kWh]

$SOC_{arr}(i)$ arrival battery state-of-charge of ith EV [%]

$SOC_{req}(i)$ required battery state-of-charge of ith EV [%]

$t_{arr}(i)$ arrival time of ith EV

$t_{dep}(i)$ departure time of ith EV

$P_{max}(i)$ max charging power of ith EV [kW]

$P_{max}(s)$ max charging power of sth charging pile [kW]

$P_{max}(sys)$ system capacity [kW]

$P_{av}(s)$ average charging power of sth charging pile [kW]

$P_d(x,t)$ estimated charging power demand for charging station at time t

$p(s,t)$ power provided by sth charging pile at t

cp_1 penalty cost occurs when $SOC_{dep}(i) \leq SOC_{req}(i)$ [$/kWh]

cp_2 penalty cost occurs when charging power exceeds $P_d(x,t)$ [$/kWh]

Decision variables

$SOC_{dep}(i)$ departure battery state-of-charge of ith EV [%]

$z(x,t)$ = 1, sth charging pile is occupied at t

= 0, sth charging pile is unoccupied at t

$y(i,s,t)$ =1, ith EV is charging at sth charging pile at t

=0, ith EV is not charging at sth charging pile at t

4. EV charging schedule model

4.2 EV charging scheduling problem description

Assumptions:

(1) EVs arrive following arrival rate $a(x, t)$

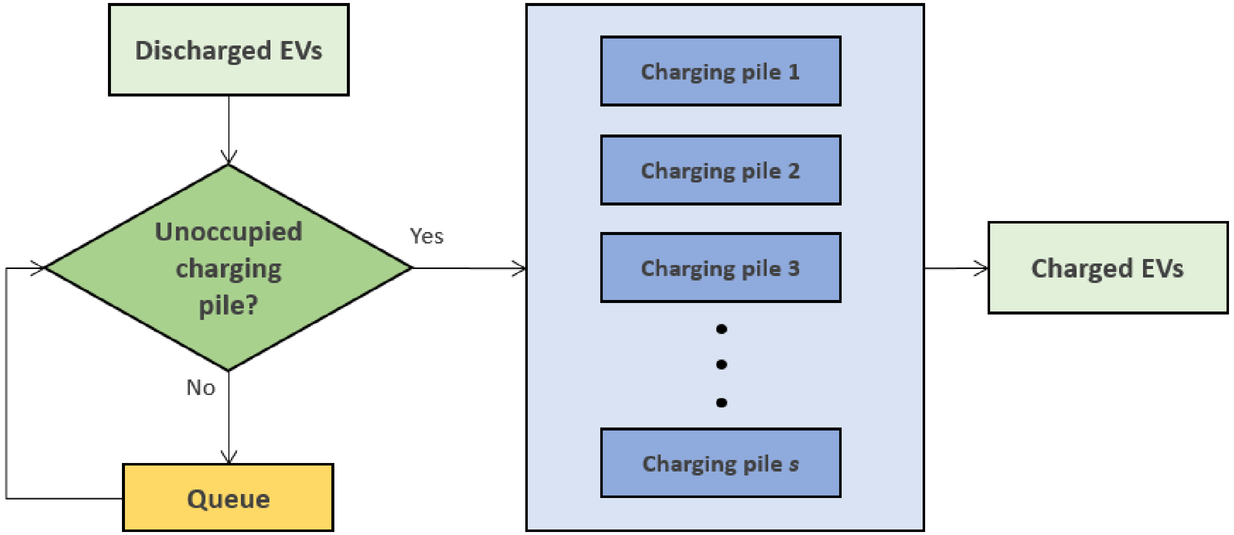
(2) First-come-first-serve

(3) Earliest idle charging pile selection

(4) Charging EVs stop charging when:

-->Battery state-of-charge requirements are satisfied

-->Departure time is reached



<Fig. 10 Charging station operation>

4. EV charging schedule model

4.2 Solution approach

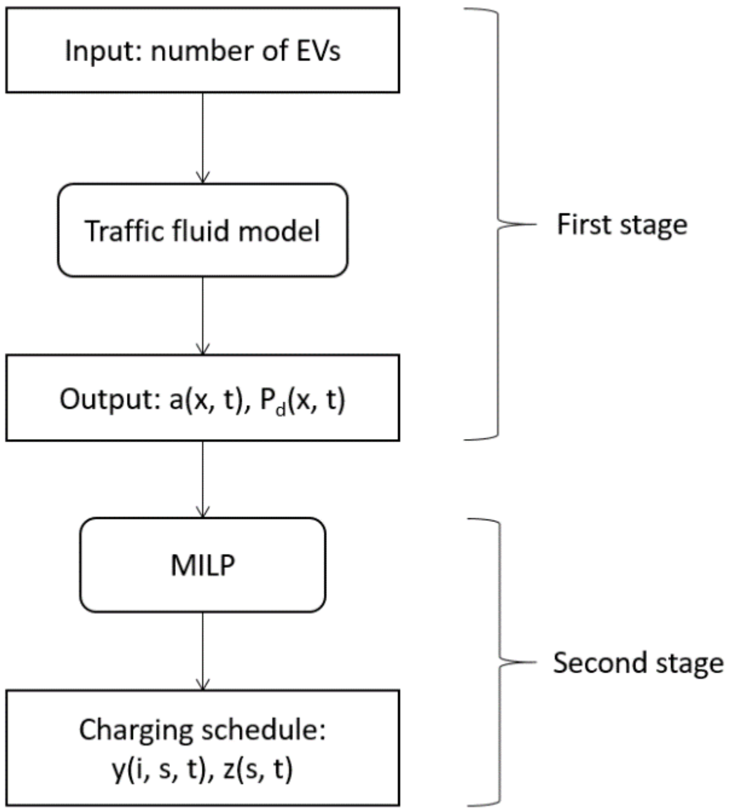
Two-stage mechanism proposed to solve the problem formulated:

1) First stage: charging power demand estimation

Arrival rate, charging power demand computation

2) Second stage: EV charging schedule

Mixed-integer linear programming



<Fig. 10 Solution approach>

4. EV charging schedule model

Objective: total cost minimization = (electricity consumption cost + penalty cost 1 + penalty cost 2)

min

$$TC = \underbrace{\sum_t^T e(t) \times \sum_s^S p(s,t) \times z(s,t)}_{\text{Electricity consumption cost}} + \overbrace{\sum_i^I \left(SOC_{req}(i) - SOC_{dep}(i)\right) \times c_{p1}}^{\text{Penalty cost1: } SOC_{dep}(i) \le SOC_{req}(i)} + \underbrace{\left(\sum_s^S p(s,t) \times z(s,t) - P_d(x,t)\right) \times c_{p2}}_{\text{Penalty cost2: charging power} \ge \text{estimated charging power demand}}$$

4. EV charging schedule model

Constraint 1: individual capacity

For charging pile: $p(s,t) \times z(s,t) \le P_{max}(s) \quad \forall s,t$ (1)

For EV: $p(s,t) \times y(i,s,t) \le P_{max}(i) \quad \forall i,\mathrm{t}$ (2)

Constraint 2: charging pile and EV consistency

$\sum_t^T \sum_i^I y(i,s,t) = \sum_t^T z(s,t) \ \ \forall s$ (3)

Constraint 3: EV departure battery state-of-charge

$SOC_{dep}(i) = \left(\sum_{t_{arr}(i)}^{t_{dep}(i)} p(s,t) \times z(s,t)) \times y(i,s,t) \right) / P_{max}(i) + SOC_{arr} \quad \forall i,t$ (4)

4. EV charging schedule model

Constraint 4: penalty cost non-negative

$$\sum_{s}^{S} p(s,t) \times z(s,t) - P_d(x,t) = max\left(0, \sum_{s}^{S} p(s,t) \times z(s,t) - P_d(x,t)\right) \ \forall t \qquad (5)$$

$$SOC_{req}(i) - SOC_{dep}(i) = max\left(0,\ SOC_{req}(i) - SOC_{dep}(i)\right) \ \forall i \qquad (6)$$

Constraint 5: system capacity

$$\sum_{s}^{S} \sum_{t}^{T} p(s,t) \times z(s,t) \leq P_{max}(sys) \ \ \forall t \qquad (7)$$

Constraint 6: binary variable

$$y(i,s,t) \begin{cases} = 1 \ ith\ EV\ charging\ at\ charging\ pile\ s\ at\ t \\ = 0 \ ith\ EV\ discharging\ at\ charging\ pile\ s\ at\ t \end{cases} \qquad z(s,t) \begin{cases} = 1 \ sth\ charging\ pile\ occupied\ at\ t \\ = 0 \ sth\ charging\ pile\ unoccupied\ at\ t \end{cases}$$

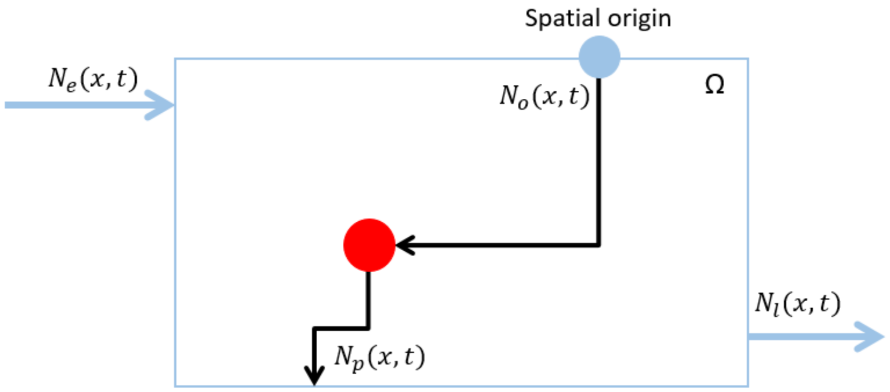
5. Experimental analysis and result

5.1 Case study

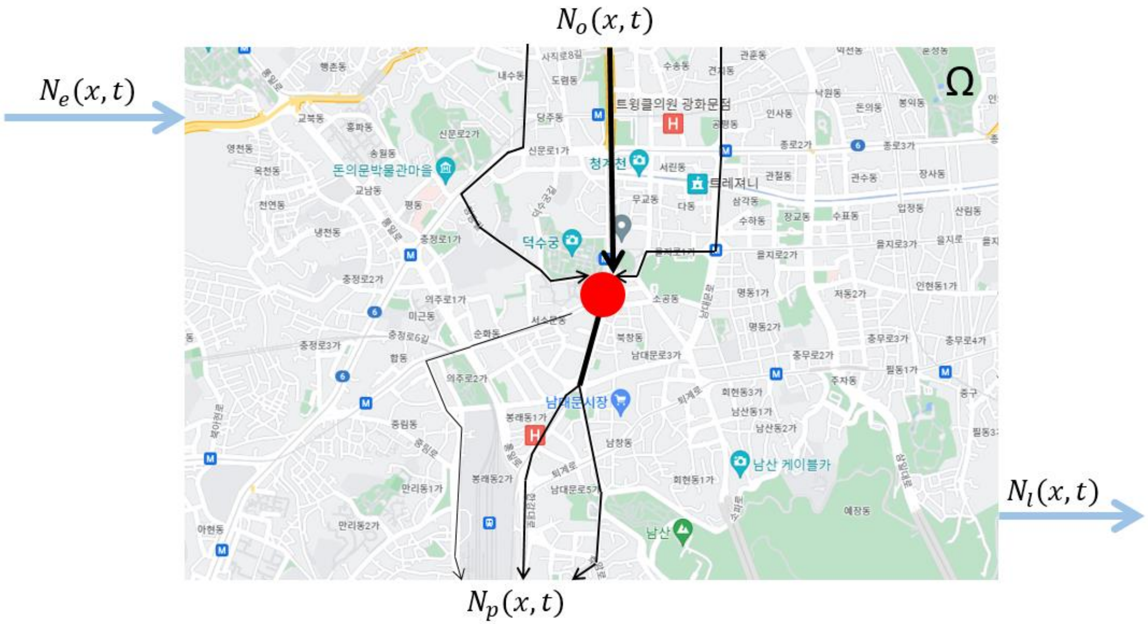
Numerical example to illustrate proposed problem

➢ Real geographical information in Seoul, South Korea is applied

- Operation objective --> area Ω
- Road segments --> black arrows
- Charging station location --> red node



<Fig. 11 Representation of traffic fluid model>



<Fig. 12 Implementation in real map>

5. Experimental analysis and result

5.1 Case study

	Time-interval	Number of vehicles	Number of discharged EVs	Traffic density	Velocity
00:00am - 01:00am	1	14	0.3	0.1	50.0
	2	12	0.2	0.0	50.0
	3	22	0.4	0.1	50.0
	4	21	0.4	0.1	50.0
	5	26	0.5	0.1	50.0
	6	41	0.8	0.2	50.0
01:00am-02:00am	7	36	0.7	0.1	50.0
	8	29	0.6	0.1	50.0
	9	14	0.3	0.1	50.0
	10	14	0.3	0.1	50.0
	11	23	0.5	0.1	50.0
	12	25	0.5	0.1	50.0
02:00am-03:00am	13	22	0.4	0.1	50.0
	14	31	0.6	0.1	50.0
	15	47	0.9	0.2	50.0
	16	35	0.7	0.1	50.0
	17	21	0.4	0.1	50.0
	18	11	0.2	0.0	50.0
03:00am-04:00am	19	17	0.3	0.1	47.0
	20	13	0.3	0.1	47.0
	21	12	0.2	0.0	47.0
	22	16	0.3	0.1	47.0
	23	18	0.4	0.1	47.0
	24	23	0.5	0.1	47.0

<Table. 1. Data collection (partial)>

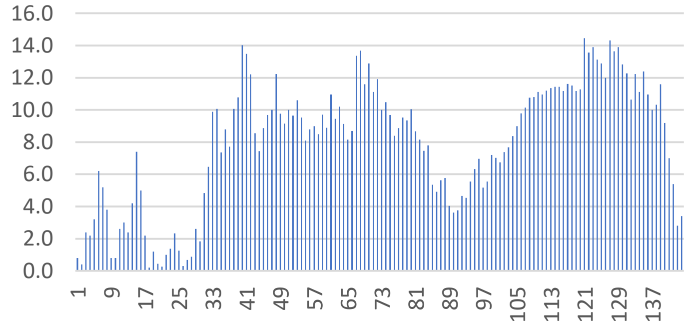
Reference: https://topis.seoul.go.kr/?tr_code=rsite

5. Experimental analysis and result

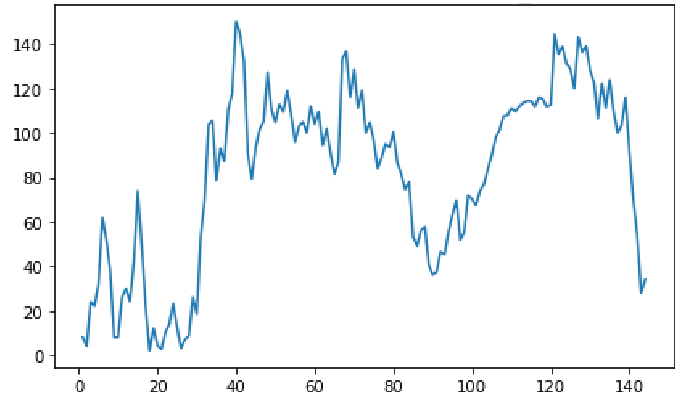
5.1 Case study

Arrival rate and charging power demand are shown:

- **Maximum arrival rate** of EVs is **14.5** and **minimum** is **0.2**
- **Maximum charging power demand** is **144.6kW** and **minimum** is **2.0kW**
- **Five** charging piles are needed



<Fig. 13 Arrival rate of EVs>



<Fig. 14 Charging power demand for charging station>

5. Experimental analysis and result

5.1 Case study

Parameter setting is illustrated according to previous research (Yang et al., 2019) :

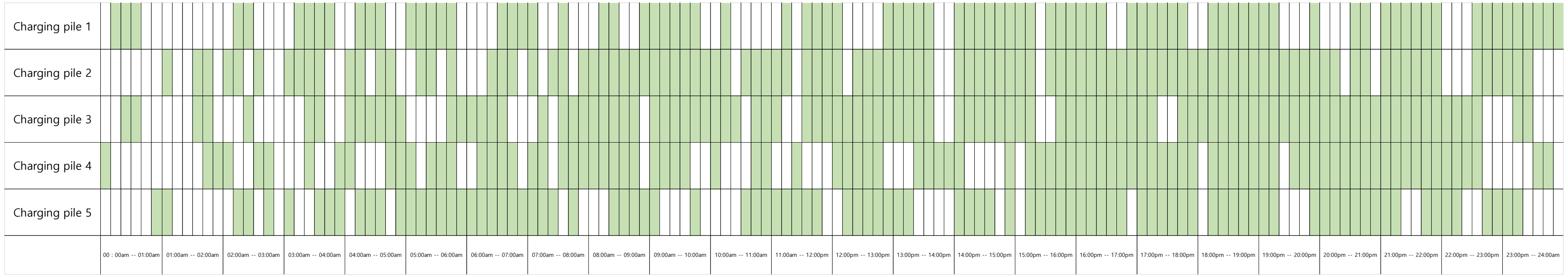
Parameter		Value
$P_{max}(sys)$	System capacity	500 [kW]
$P_{max}(s)$	Max charging power of sth charging pile	20 [kW]
$P_{max}(i)$	Max charging power of ith EV	100 [kW]
$SOC_{req}(i)$	Required battery state-of-charge of ith EV	80 [%]
$SOC_{arr}(i)$	Arrival battery state-of-charge of ith EV	N(0, 50) [%]
$p(s,t)$	Power provided by sth charging pile at t	20 [kWh]
cp_1	Penalty cost occurs when $SOC_{dep}(i) \leq SOC_{req}(i)$	0.5 [$/kWh]
cp_2	Penalty cost occurs when charging power exceeds $P_d(x,t)$	0.5 [$/kWh]
e	unit electricity price	N(2, 10) [$/kWh]
T	time index	144
S	charging pile index	5

<Table. 2 Parameter setting>

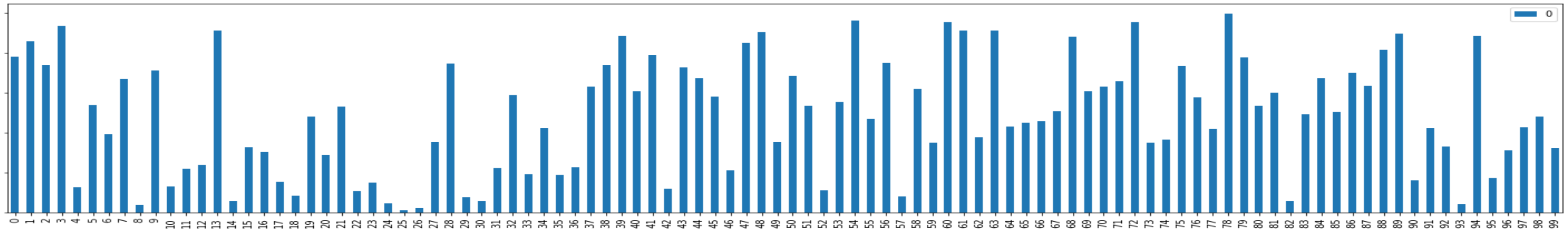
5. Experimental analysis and result

5.1 Case study

➤ Result of case study is achieved by gurobi in python



<Fig. 15 Charging schedule>



<Fig. 16 Departure battery state-of-charge (partial)>

5. Experimental analysis and result

5.2 Experimental analysis

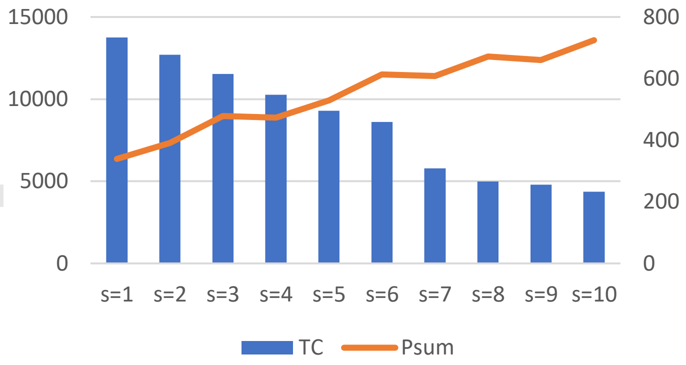
5.2.1 Sensitivity analysis

1. Number of charging piles (Fig. 17)
2. Estimated charging power demand (Fig. 18)
3. Departure battery state-of-charge (Fig. 19)

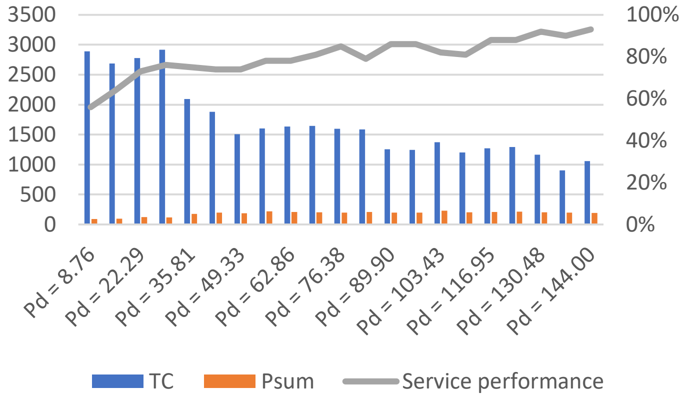
➢ Number of charging piles increase --> total cost decrease & total energy consumption increase (system idleness)

➢ Estimated charging power demand $P_d \geq 49.33$ (= system is acceptable)

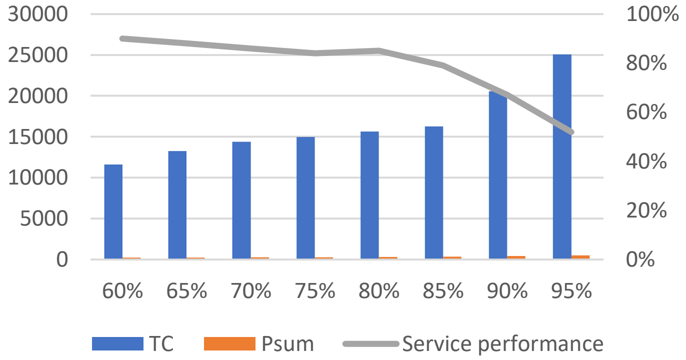
➢ Required battery state-of-charge $SOC_{req} \geq 85\%$ (= system breakdown)



<Fig. 17 Number of charging piles>



<Fig. 18 Estimated charging power demand>



<Fig. 19 Departure battery state-of-charge>

5. Experimental analysis and result

5.2 Experimental analysis

5.2.2 Interaction between penalty costs

- c_{p1} penalty cost occurs when $SOC_{dep}(i) \leq SOC_{req}(i)$ [$/kWh]
- c_{p2} penalty cost occurs when charging power exceeds $P_d(x,t)$ [$/kWh]

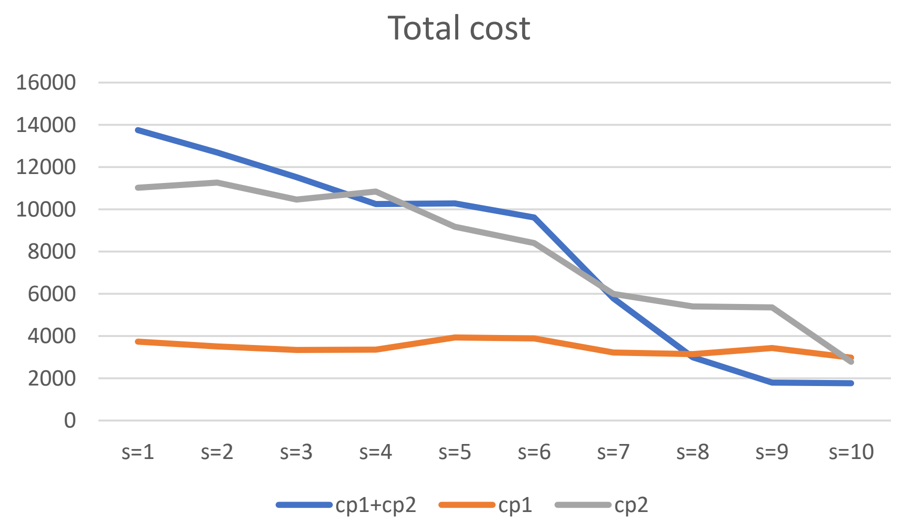
Scenario		Objective function
1	$c_{p1}+c_{p2}$	$TC = \sum_t^T e(t) \times \sum_s^S p(s,t) \times z(s,t) + \sum_i^I \left(SOC_{req}(i) - SOC_{dep}(i)\right) \times c_{p1} + \left(\sum_s^S p(s,t) \times z(s,t) - P_d(x,t)\right) \times c_{p2}$
2	c_{p1}	$TC = \sum_t^T e(t) \times \sum_s^S p(s,t) \times z(s,t) + \sum_i^I \left(SOC_{req}(i) - SOC_{dep}(i)\right) \times c_{p1}$
3	c_{p2}	$TC = \sum_t^T e(t) \times \sum_s^S p(s,t) \times z(s,t) + \left(\sum_s^S p(s,t) \times z(s,t) - P_d(x,t)\right) \times c_{p2}$

<Table. 3 Scenarios for cost interaction experiment>

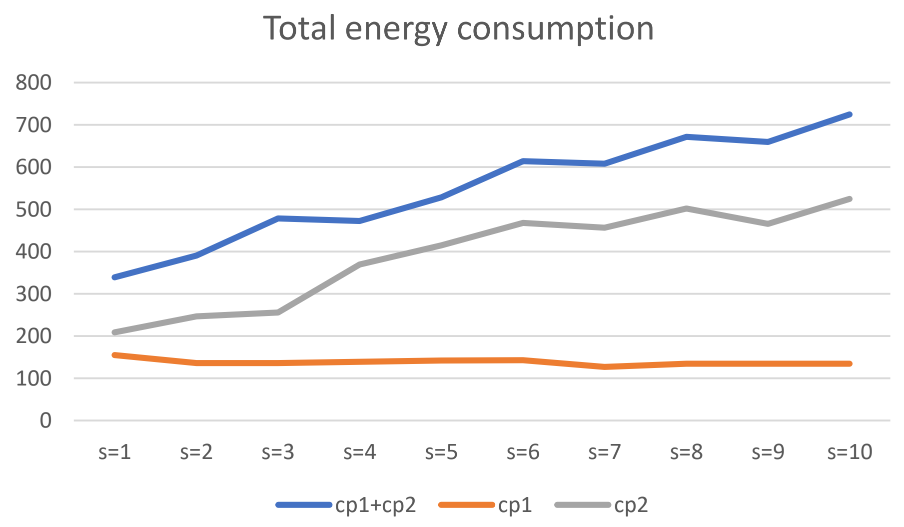
5. Experimental analysis and result

5.2 Experimental analysis

5.2.2 Interaction between penalty costs (cont.)



<Fig. 20 Penalty cost interaction experiment result (a)>



<Fig. 21 Penalty cost interaction experiment result (b)>

- c_{p2} is more effective and critical to the system compare with c_{p1}

5. Experimental analysis and result

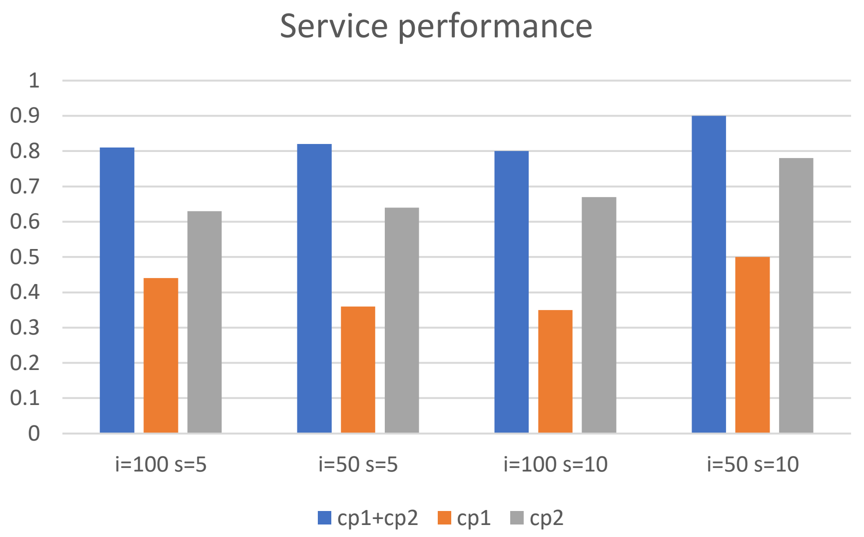
5.2 Experimental analysis

5.2.2 Interaction between penalty costs (cont.)

Service performance is investigated using four scenarios

Scenario	Number of EVs	Number of charging piles
1	100	5
2	50	5
3	100	10
4	50	10

<Table. 3 Simulation scenario>



<Fig. 22 Service performance experiment result>

➢ In all four scenarios, proposed model presented the best service performance level

5. Experimental analysis and result

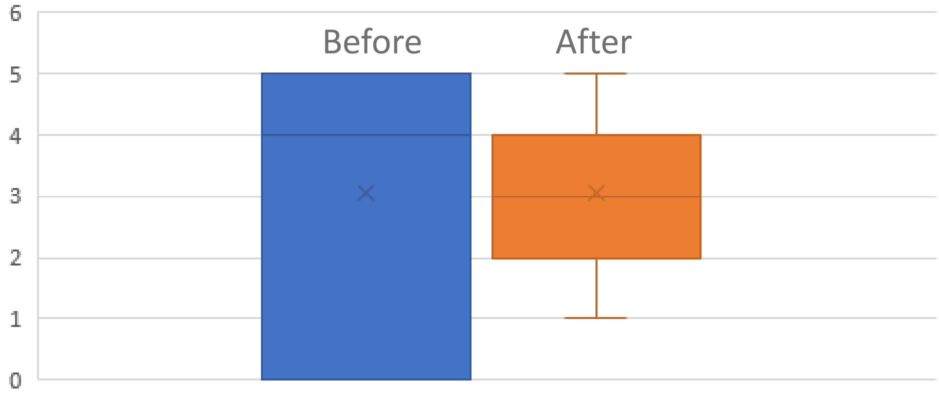
5.2 Experimental analysis

5.2.3 Instantaneity electricity consumption

instantaneity electricity consumption before and after optimization is tested:

- Instantaneity electricity consumption altered to:

1) Less peak power output
2) Better stability in energy transmission



<Fig. 23 Instantaneity electricity consumption comparison>

➢ **Through charging power demand consideration:**

1) Balancing energy transmission and consumption

2) Maintaining energy system capability

6. Conclusions and future study

6.1 Conclusions

- This research combined 1) **charging power demand estimation** & 2) **EV charging scheduling problem**

Solution approach:	**First stage:** dynamic traffic fluid model computation **Second stage**: MILP
System performance:	**Total cost** & **total energy consumption** & **service performance**
Experimental analysis:	**Sensitivity analysis**: number of charging piles, charging power estimation, required battery state-of-charge **Cost interaction**: penalty cost effectiveness **Instantaneity electricity consumption**: maintain energy consumption system capability

6. Conclusions and future study

6.2 Research schedule

- Charging power demand estimation model evaluation --> performance index development
- Expanding data diversity and quantity --> data acquisition
- Enhancing the efficiency of problem solving

THANK YOU