

Scheduling EV Battery Swap/Charge Operations

Jaeheon Kwak^{1*}, Seongtae Lee^{2*}, Kang G. Shin³, Jinkyu Lee²

*co-first authors

¹School of Computing, KAIST

²Department of Computer Science and Engineering, SKKU

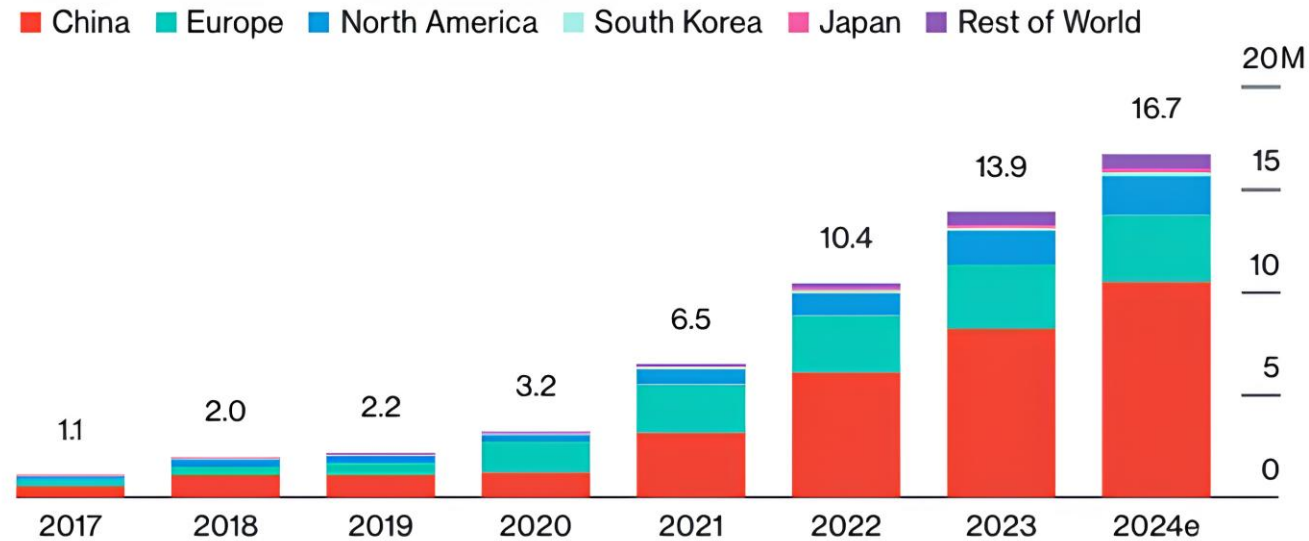
³ Department of Computer Science and Engineering, University of Michigan



Rapid EV growth

Electric Vehicle Sales Head For Another Record Year

Annual passenger EV sales by region



Source: BloombergNEF, MarkLines, Jato Dynamics
Note: Includes battery-electric and plug-in hybrid vehicles



Rapid EV growth is slowing down

Electric Vehicle Sales Growth is Slowing

Year-on-year change in passenger EV sales



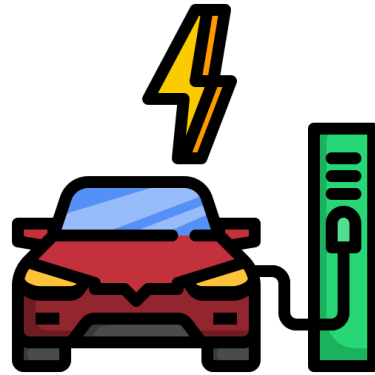
Source: BloombergNEF, MarkLines, Jato Dynamics

Note: Includes battery-electric and plug-in hybrids vehicles. Data as of September 2024.

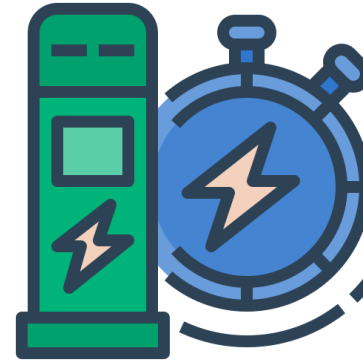
Reasons for the slowdown



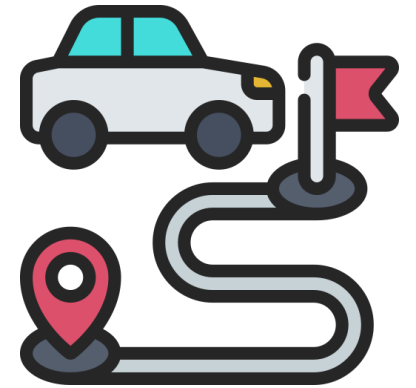
Relatively
high costs



Insufficient
charging infrastructure



Long charging
time



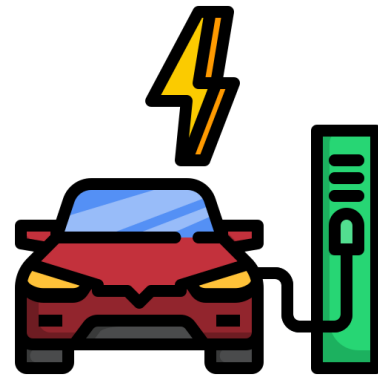
Limited
driving range

Reasons for the slowdown

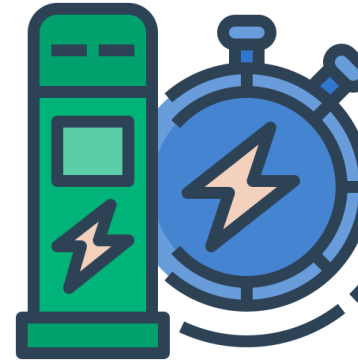
This talk's focus



Relatively
high costs



Insufficient
charging infrastructure



Long charging
time



Limited
driving range

Solution: battery swap station

Replace battery packs instead of charging them!

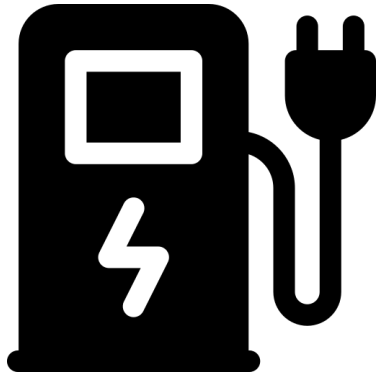
Advantages

- Rapid battery replacement takes 3-10 min
(Charging: 30-600 min to reach 80%)
- Better space utilization
(Charging: more space for longer service time)
- Better energy-efficiency
(Charging: high energy loss by fast charging)
- Longer battery life
(Charging: fast charging significantly degrades battery life)



Need of timing guarantees

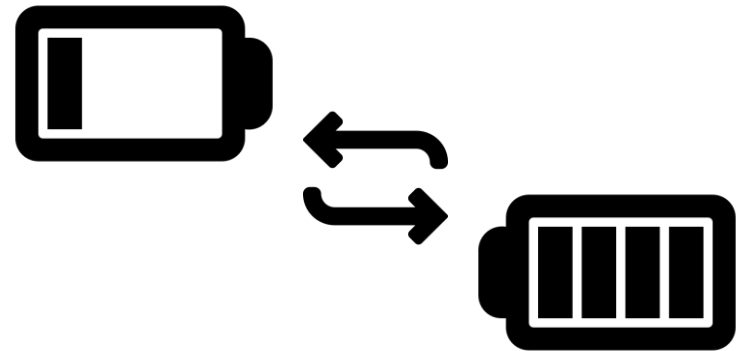
Battery charger



30-600 min

VS

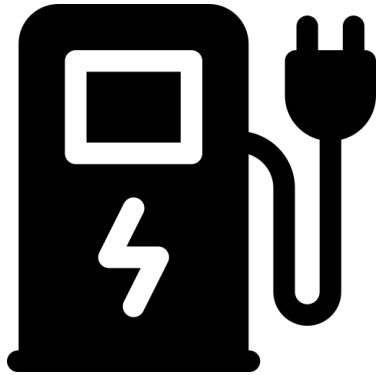
Battery swap station



3 min

Need of timing guarantees

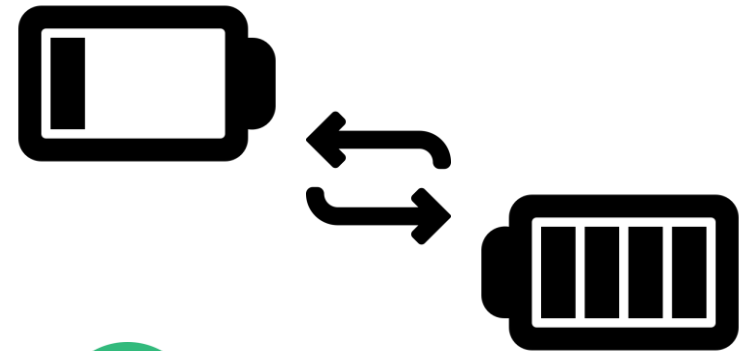
Battery charger



30-600 min

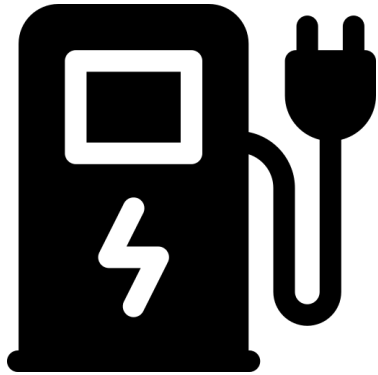
VS

Battery swap station



Need of timing guarantees

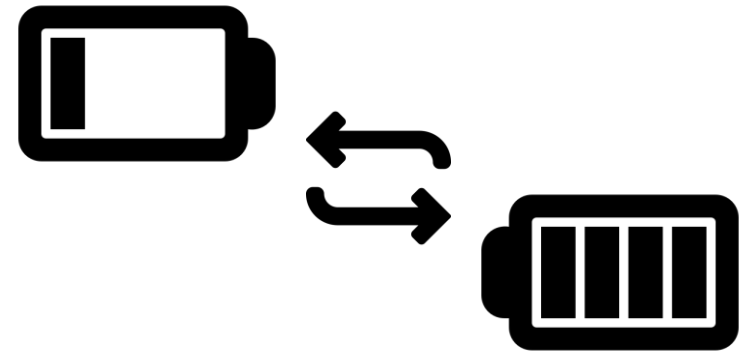
Battery charger



30-600 min

VS

Battery swap station



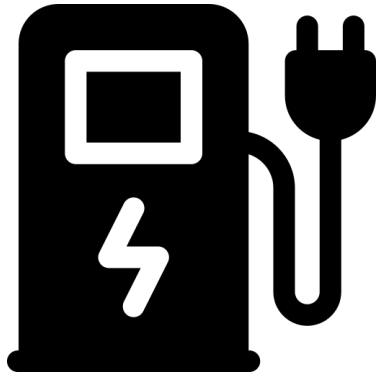
3 min



10 min

Need of timing guarantees

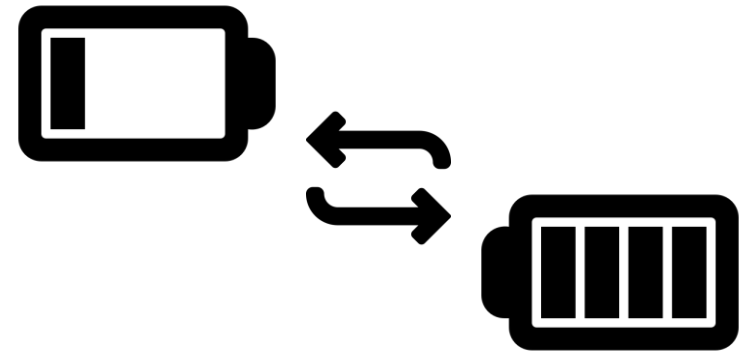
Battery charger



30-600 min

VS

Battery swap station



3 min

10 min

30 min



Need of timing guarantees

S&P Global

As for the concept of battery swapping, consumers in mainland China, India, and Brazil continue to be most interested in the concept - with more than 75% of global respondents willing to wait up to 30 minutes for a battery swap, at an average price point of \$16.

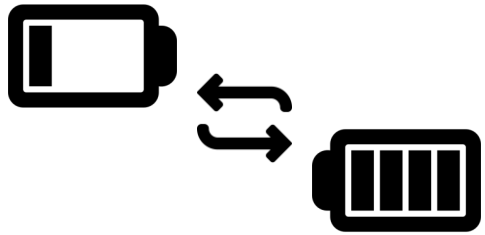
Battery swap stations need timing guarantees!

Understanding station



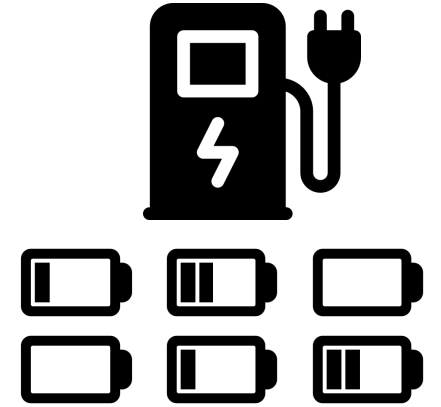
Battery swap station

Understanding station

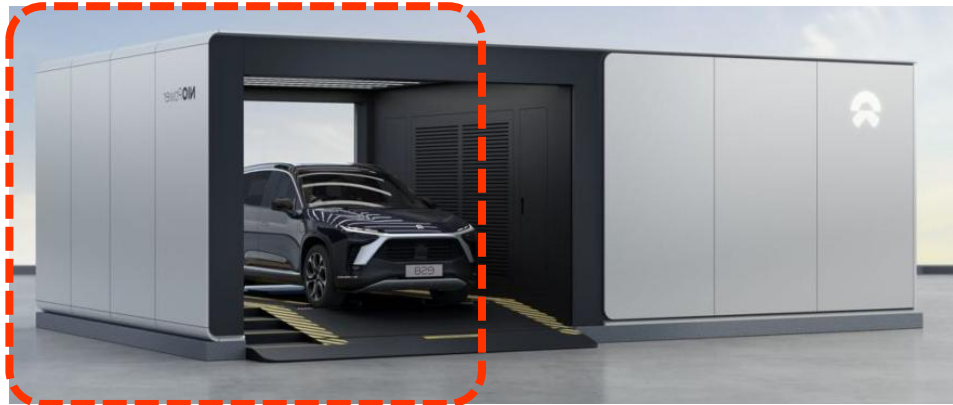
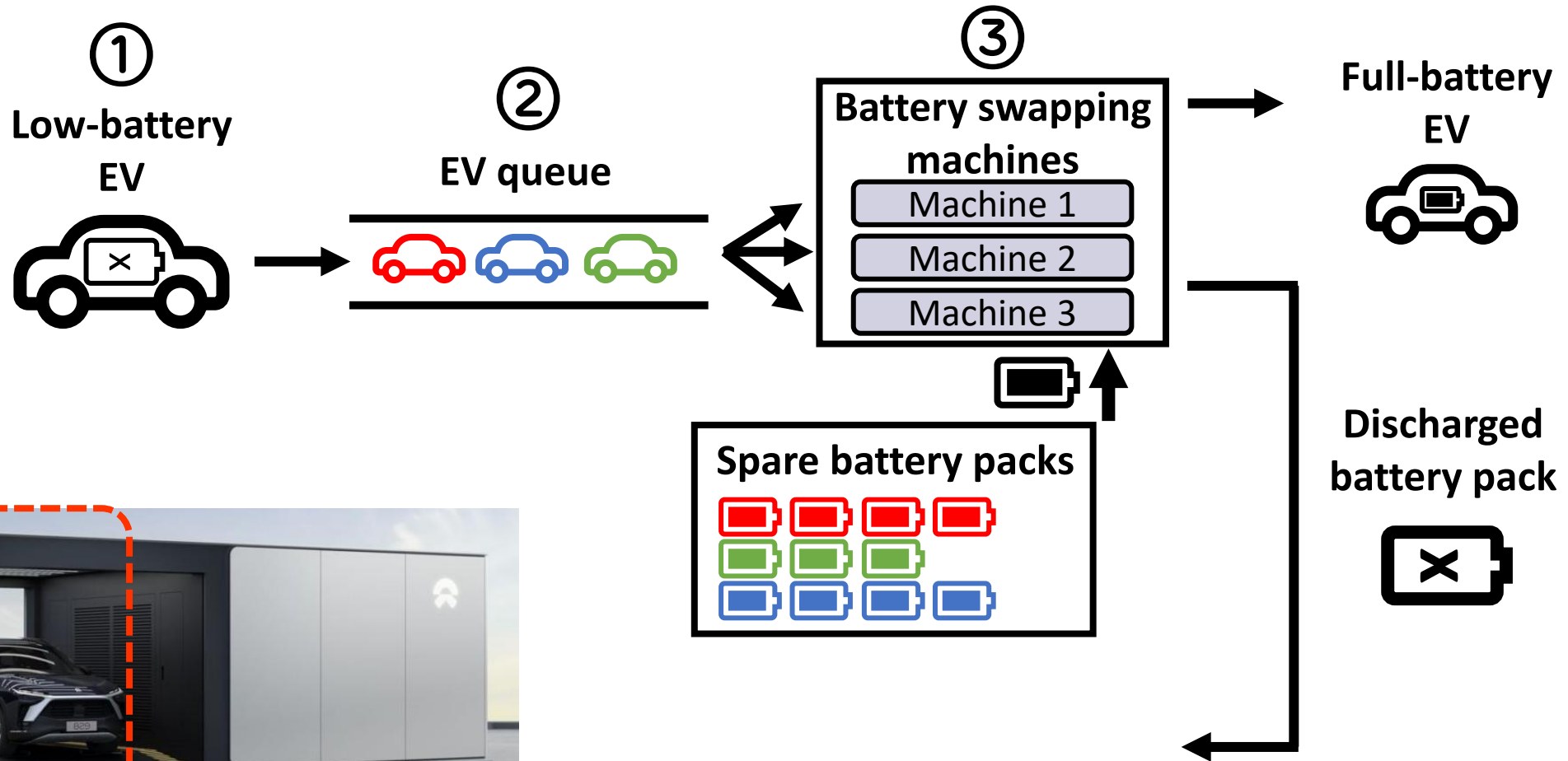


Swapping operation

Charging operation



Understanding station



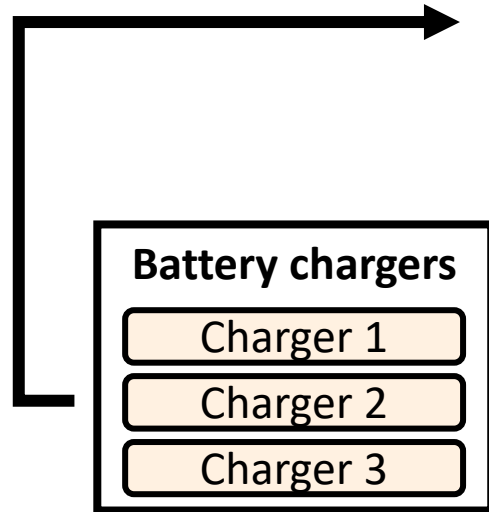
Swapping operation

Understanding station



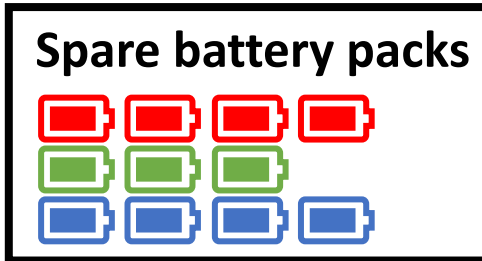
Charging operation

Fully charged
Battery pack



⑤

⑥ Swapping



Battery queue

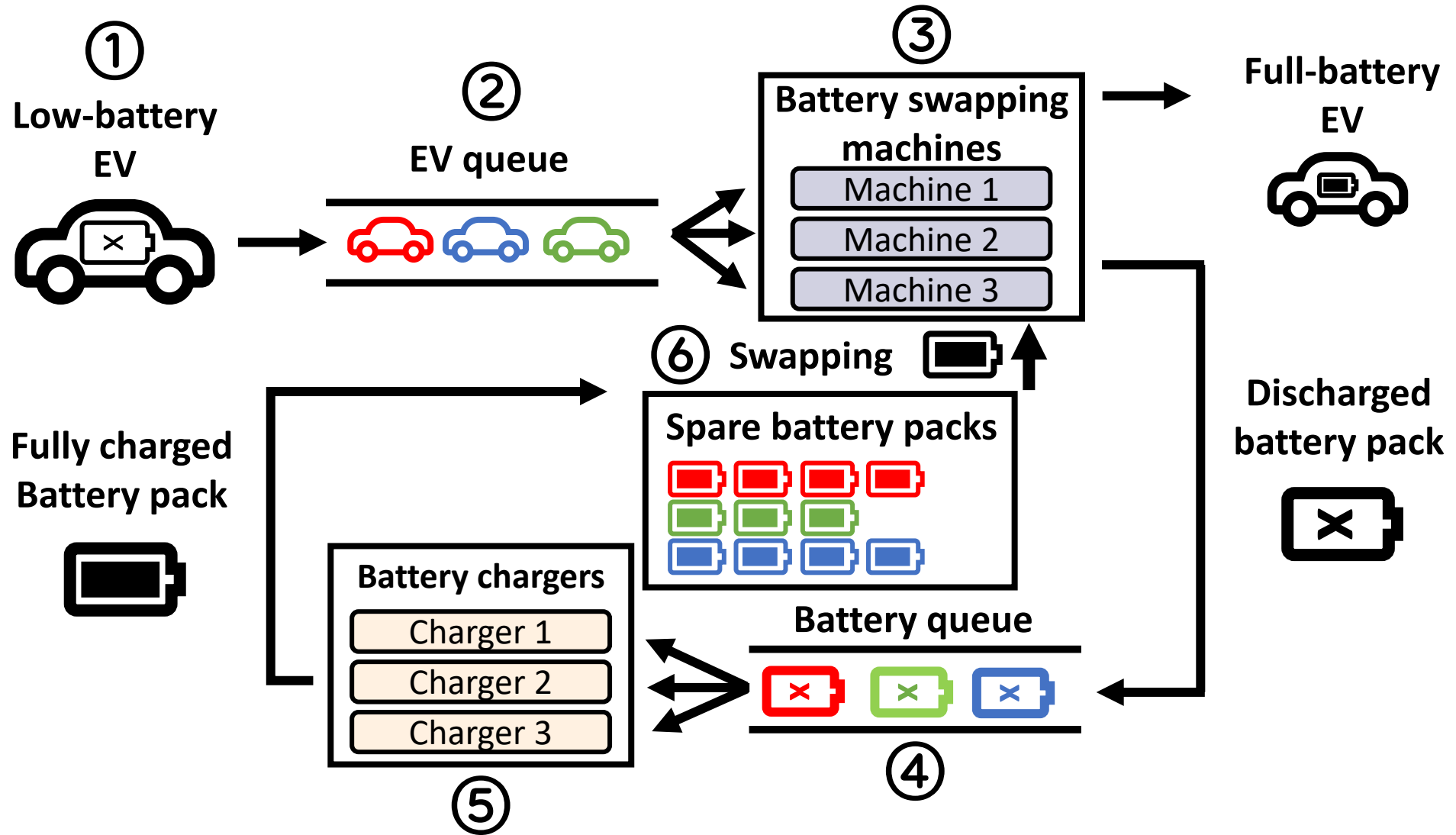


④

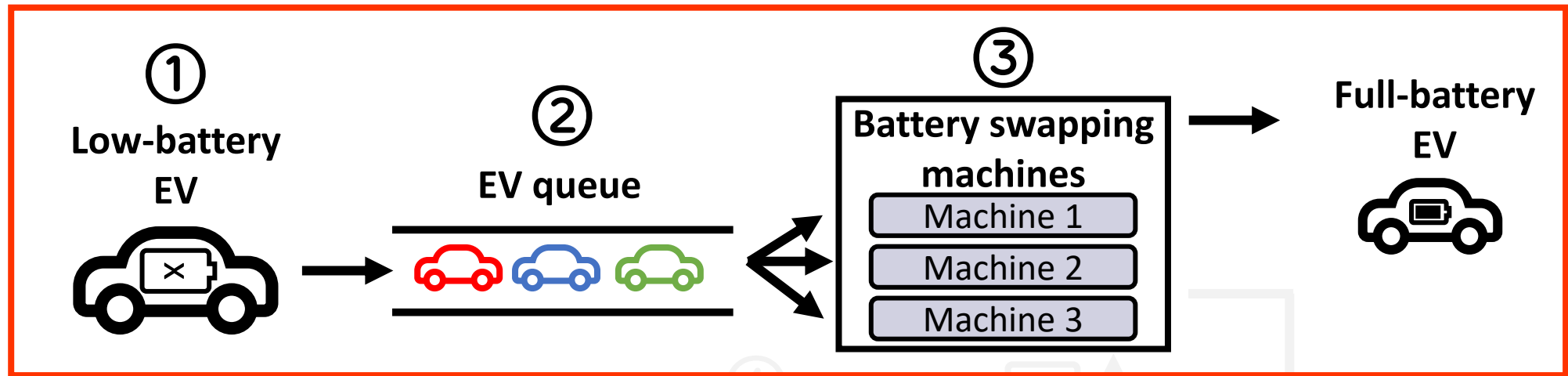
Discharged
battery pack



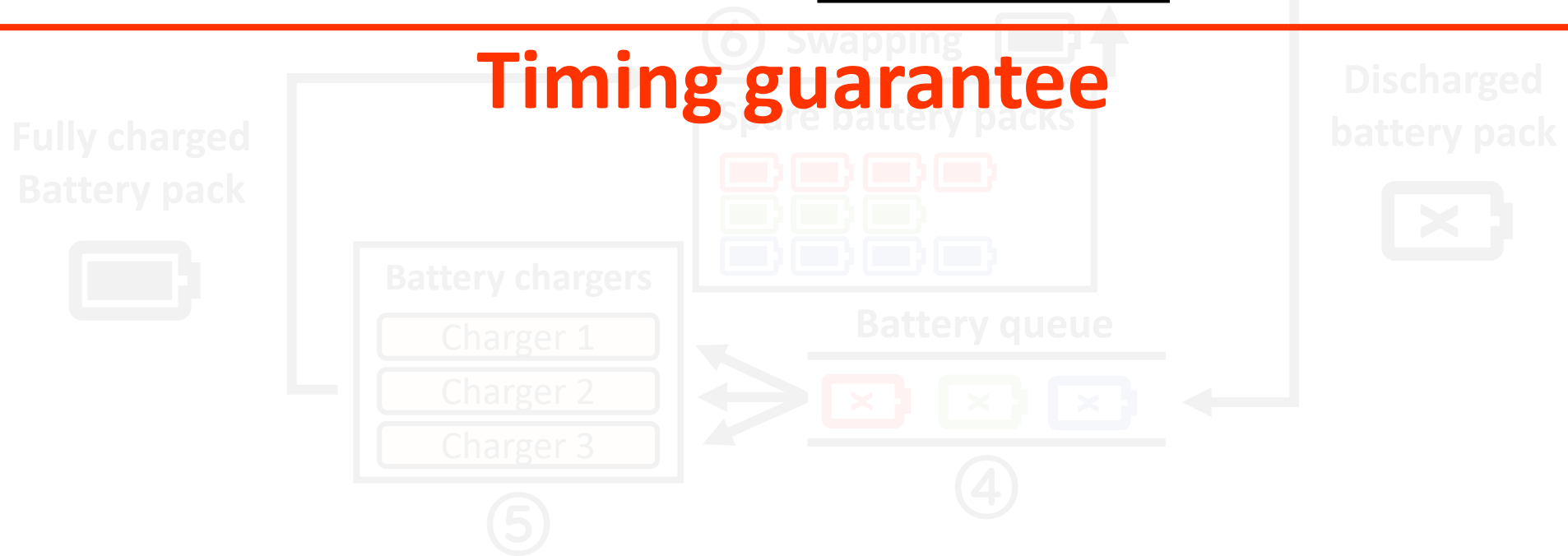
Understanding station



Problem statement



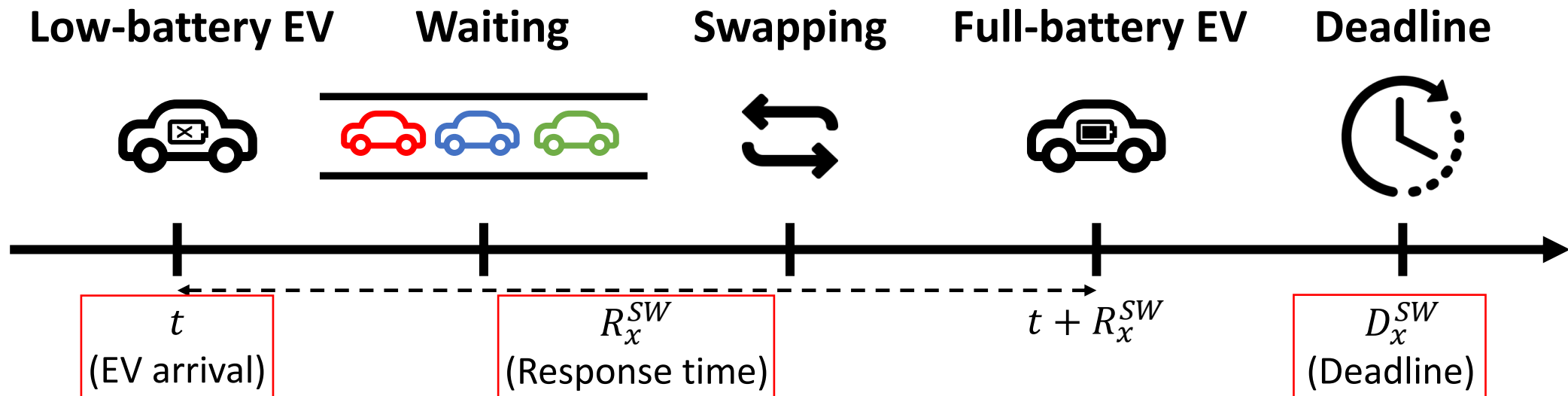
Timing guarantee



Problem statement

Naïve goal

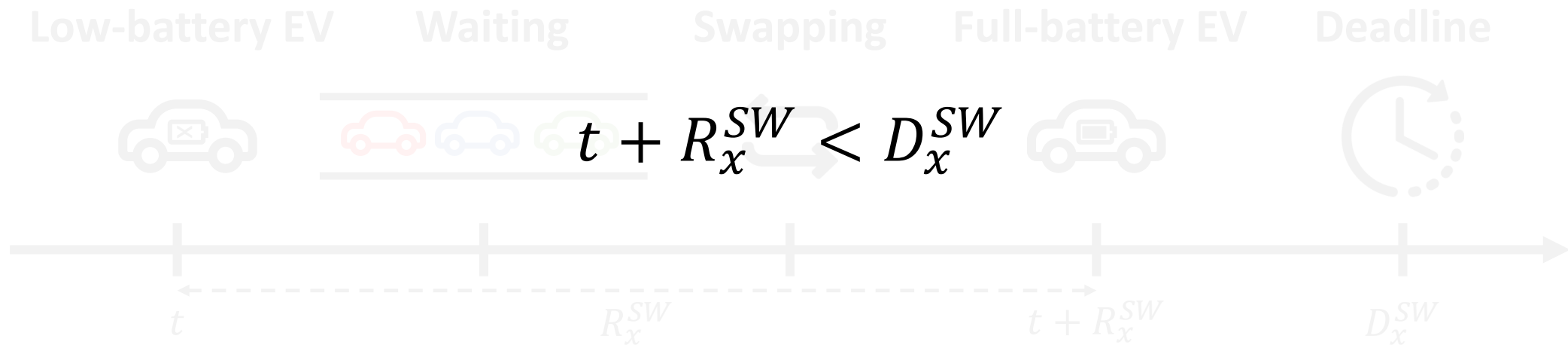
G1*. When EVs **sporadically** arrive at the station, we want to **guarantee** that all EVs complete their battery swapping operation within their deadlines.



Problem statement

Naïve goal

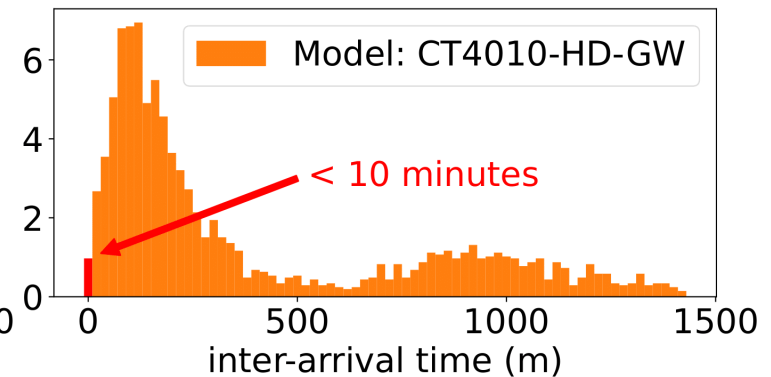
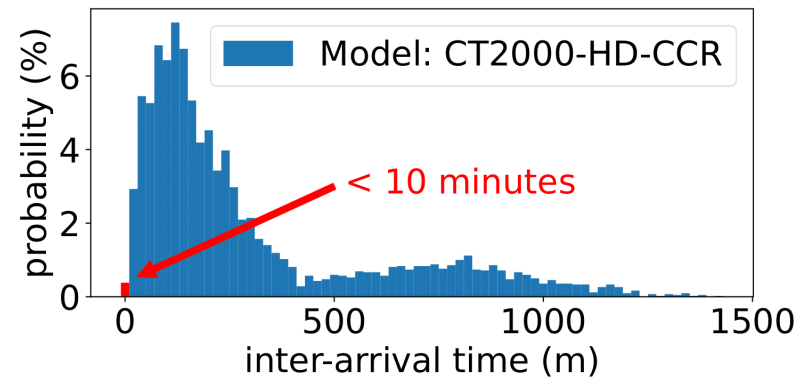
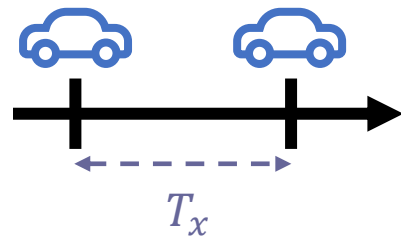
G1*. When EVs **sporadically** arrive at the station, we want to **guarantee** that all EVs complete their battery swapping operation within their deadlines.



Problem statement

Naïve goal

G1*. When EVs sporadically arrive at the station, we want to **guarantee** that all EVs complete their battery swapping operation within their deadlines.

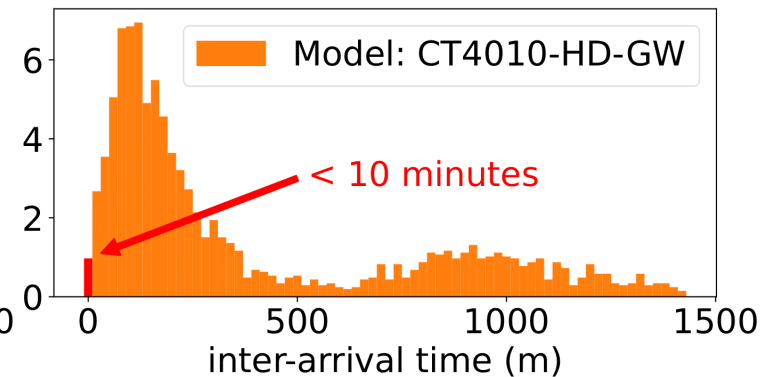
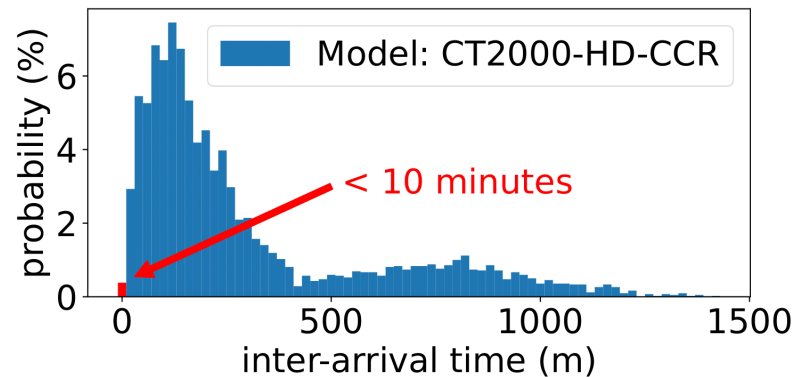
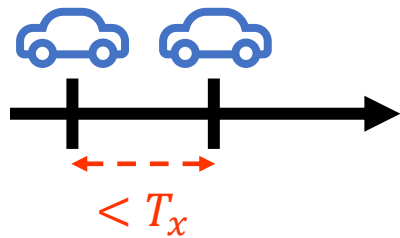


Modeling real-world arrivals as sporadic

Problem statement

Naïve goal

G1*. When EVs sporadically arrive at the station, we want to **guarantee** that all EVs complete their battery swapping operation within their deadlines.



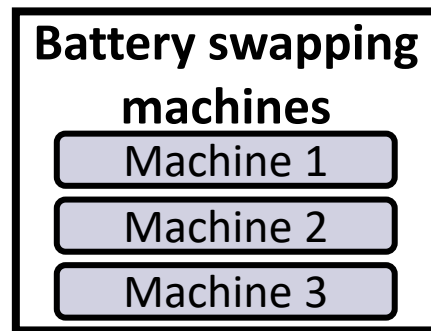
Managing real-world arrival patterns

Problem statement

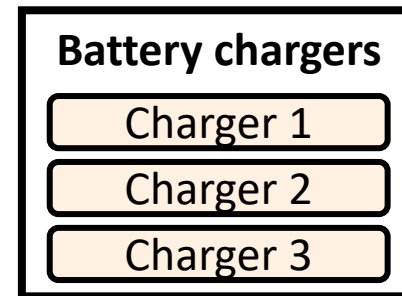
Suppose the following input parameters are given:
numbers N^{TY} , N^{SW} , N^{CG} , and n_x for every $1 \leq x \leq N^{TY}$, and
time durations T_x , C_x^{SW} , C_x^{CG} , and D_x^{SW} for every $1 \leq x \leq N^{TY}$.



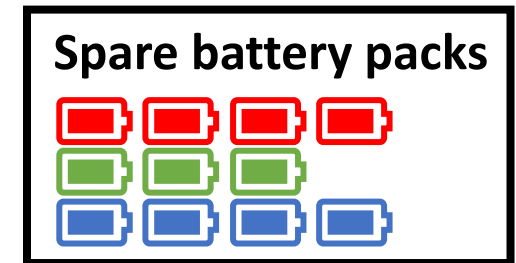
N^{TY} : number of
EV/battery types



N^{SW} : number of
swapping machines



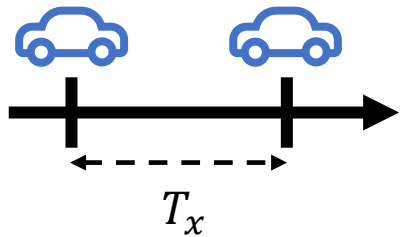
N^{CG} : number of
chargers



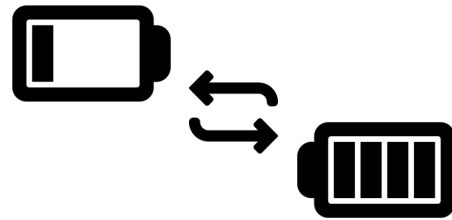
n_x : number of spare
battery of type- x
EV/battery

Problem statement

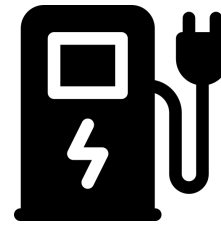
Suppose the following input parameters are given:
numbers N^{TY} , N^{SW} , N^{CG} , and n_x for every $1 \leq x \leq N^{TY}$, and
time durations T_x , C_x^{SW} , C_x^{CG} , and D_x^{SW} for every $1 \leq x \leq N^{TY}$.



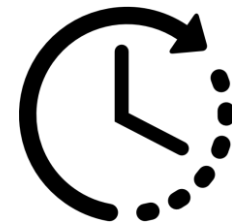
T_x : inter-arrival
time of type- x EVs



C_x^{SW} : swapping time
of a type- x EV



C_x^{CG} : worst-case
time to charge a
type- x battery



D_x^{SW} : relative deadline
of the swapping
operation of type- x EV

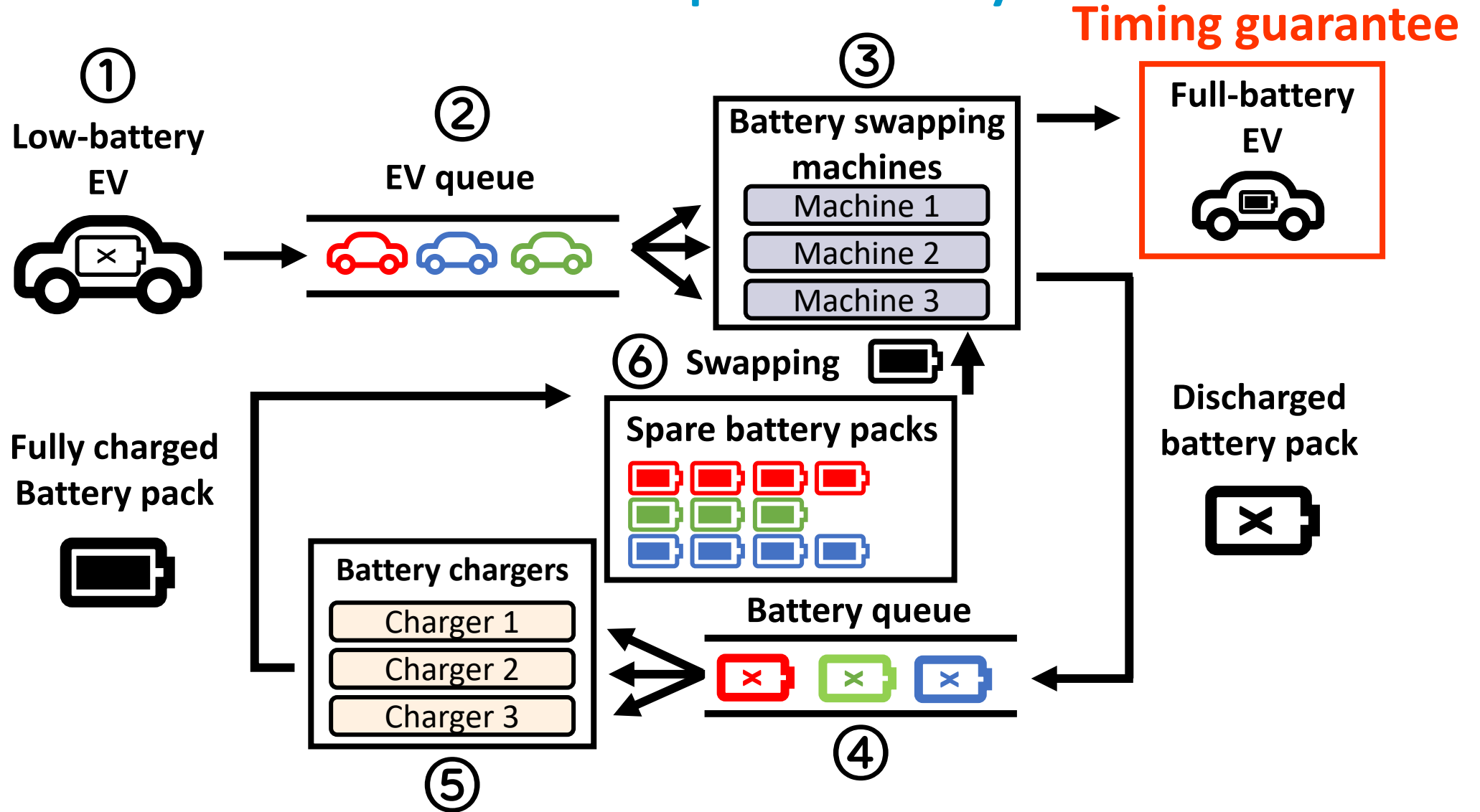
Problem statement

Suppose the following input parameters are given:
numbers N^{TY} , N^{SW} , N^{CG} , and n_x for every $1 \leq x \leq N^{TY}$, and
time durations T_x , C_x^{SW} , C_x^{CG} , and D_x^{SW} for every $1 \leq x \leq N^{TY}$.

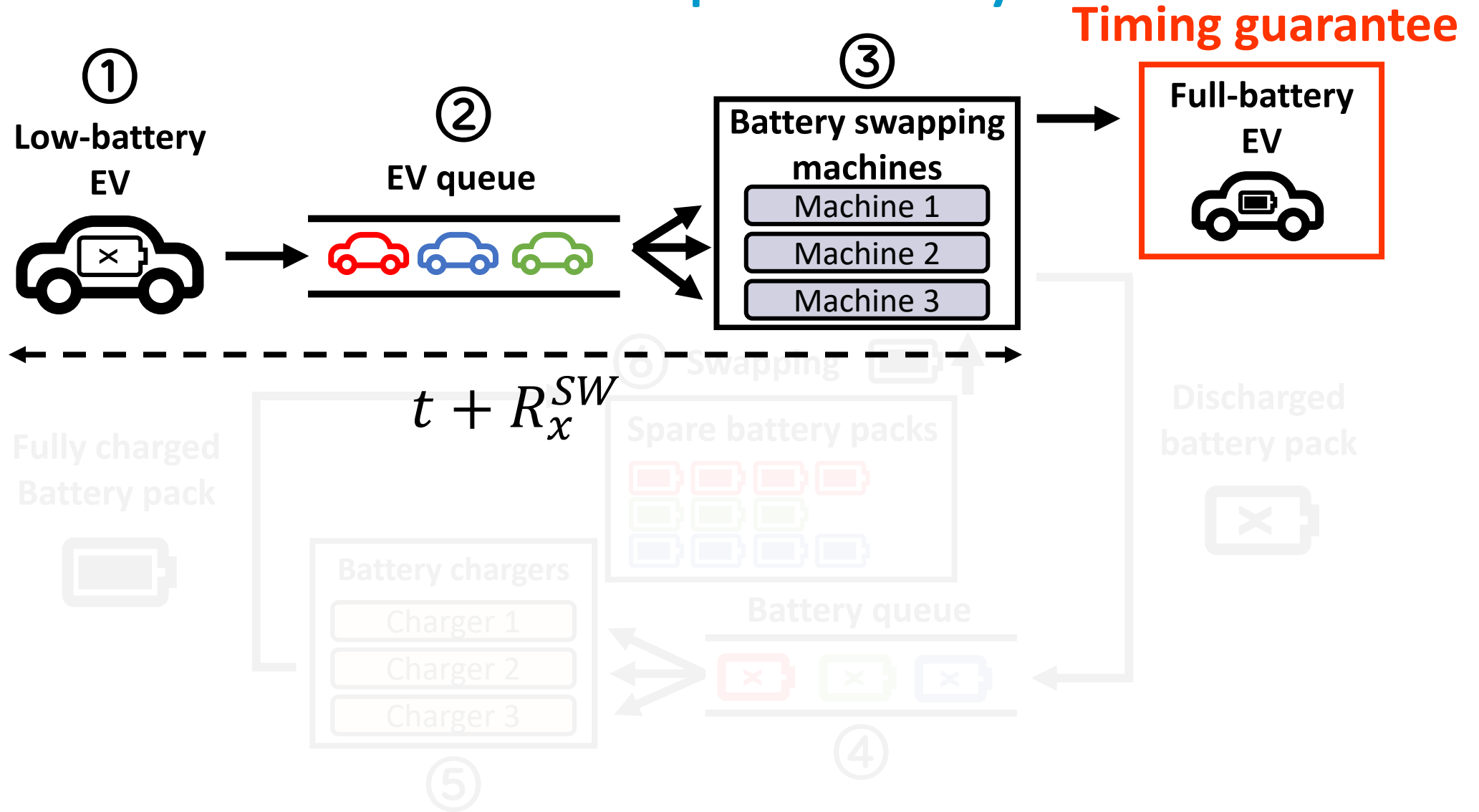
Strict goal

G1. For all $1 \leq x \leq N^{TY}$, we guarantee that the station completes the swapping operation of every type- x EV within D_x^{SW} time units since its arrival at the station, while type- x EVs arrive at the station sporadically with at least T_x inter-arrival time.

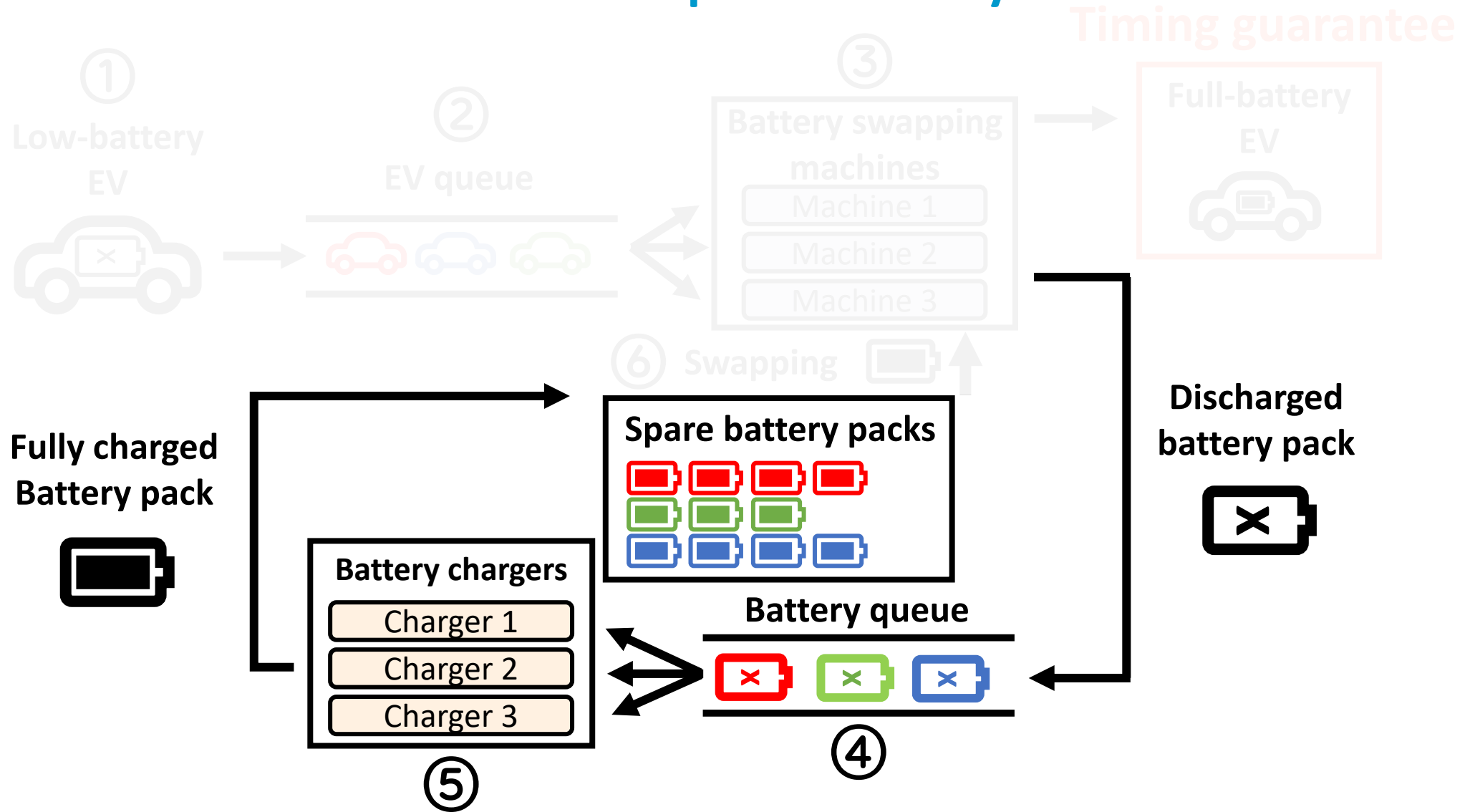
Circular dependency



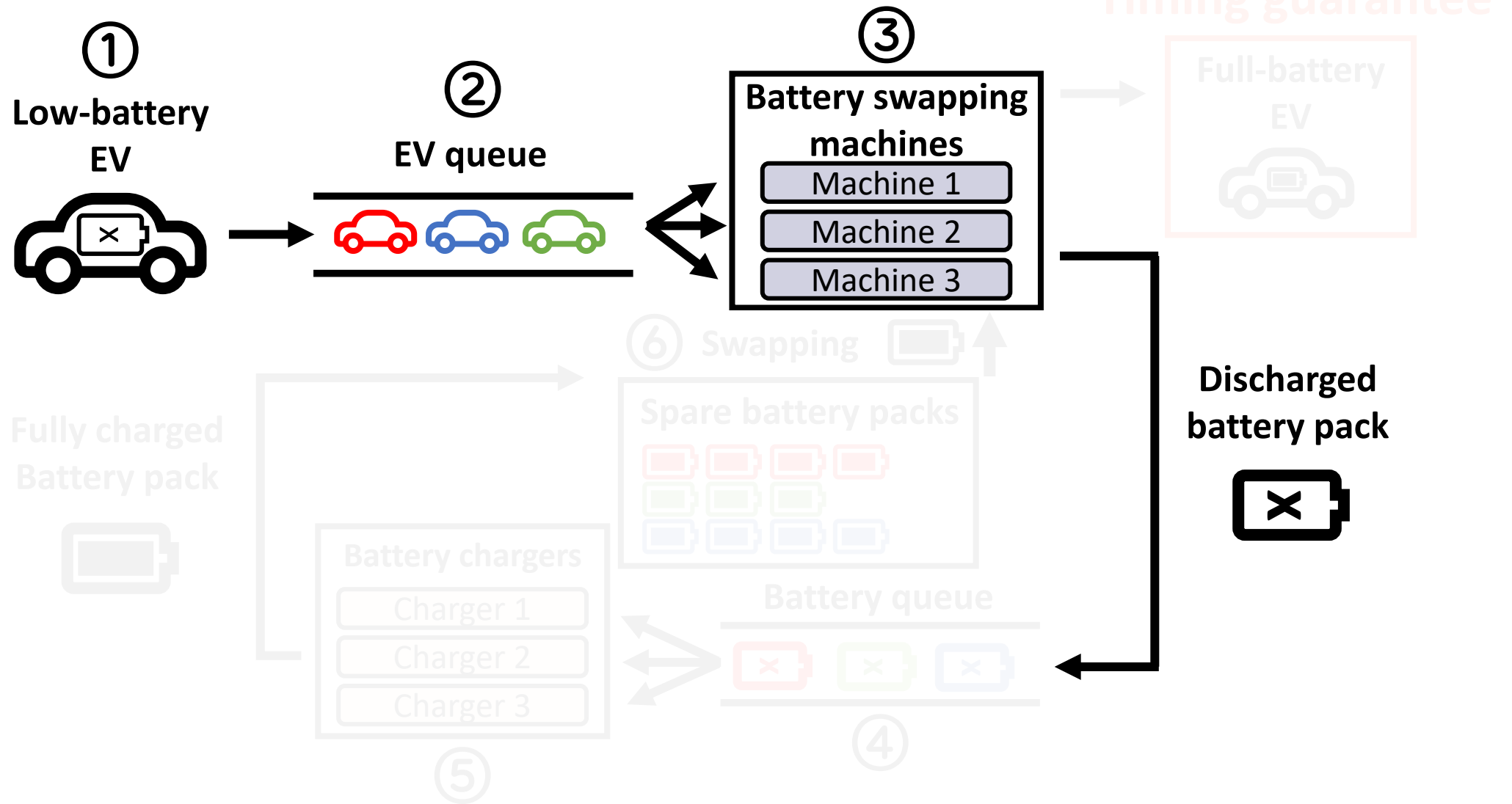
Circular dependency



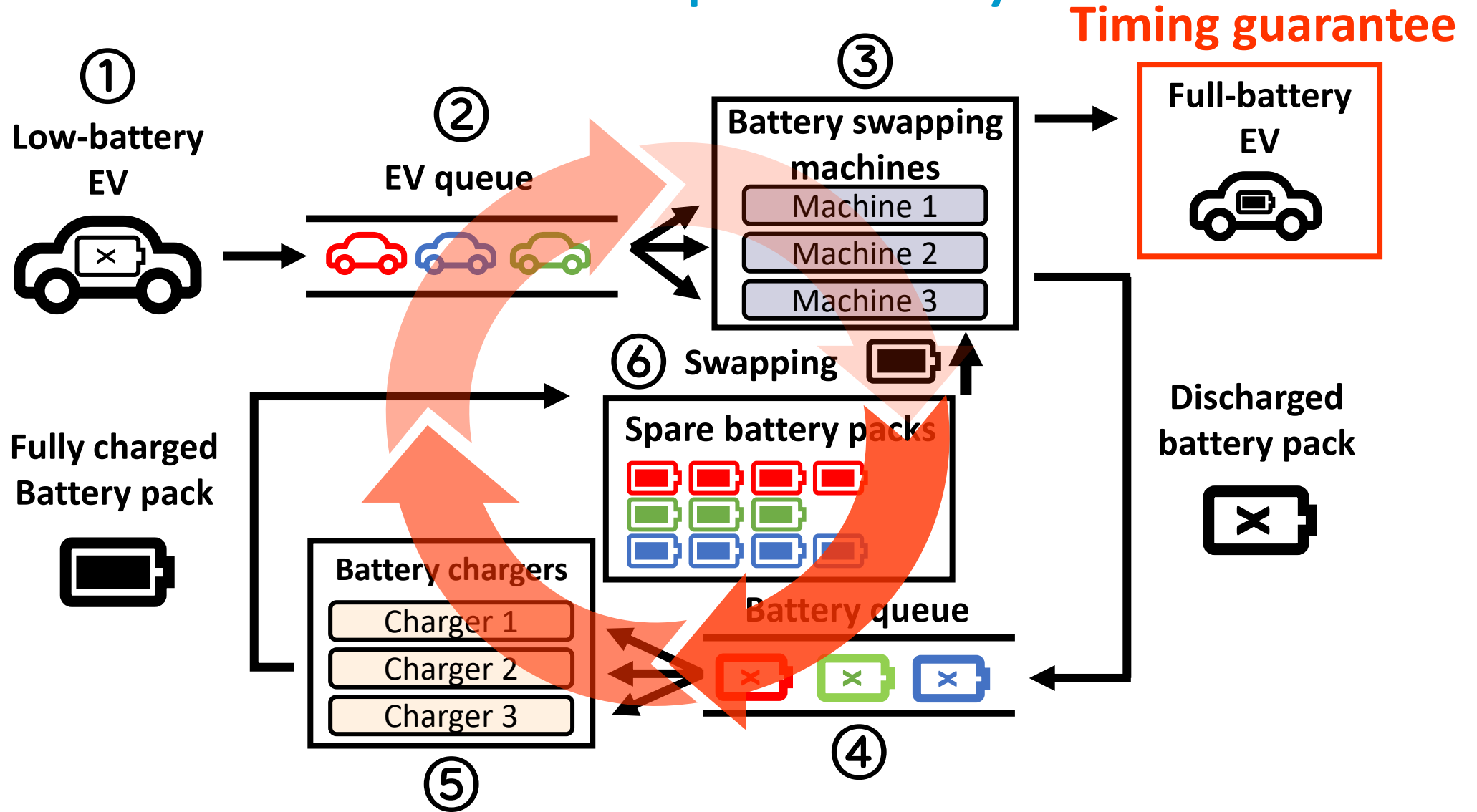
Circular dependency



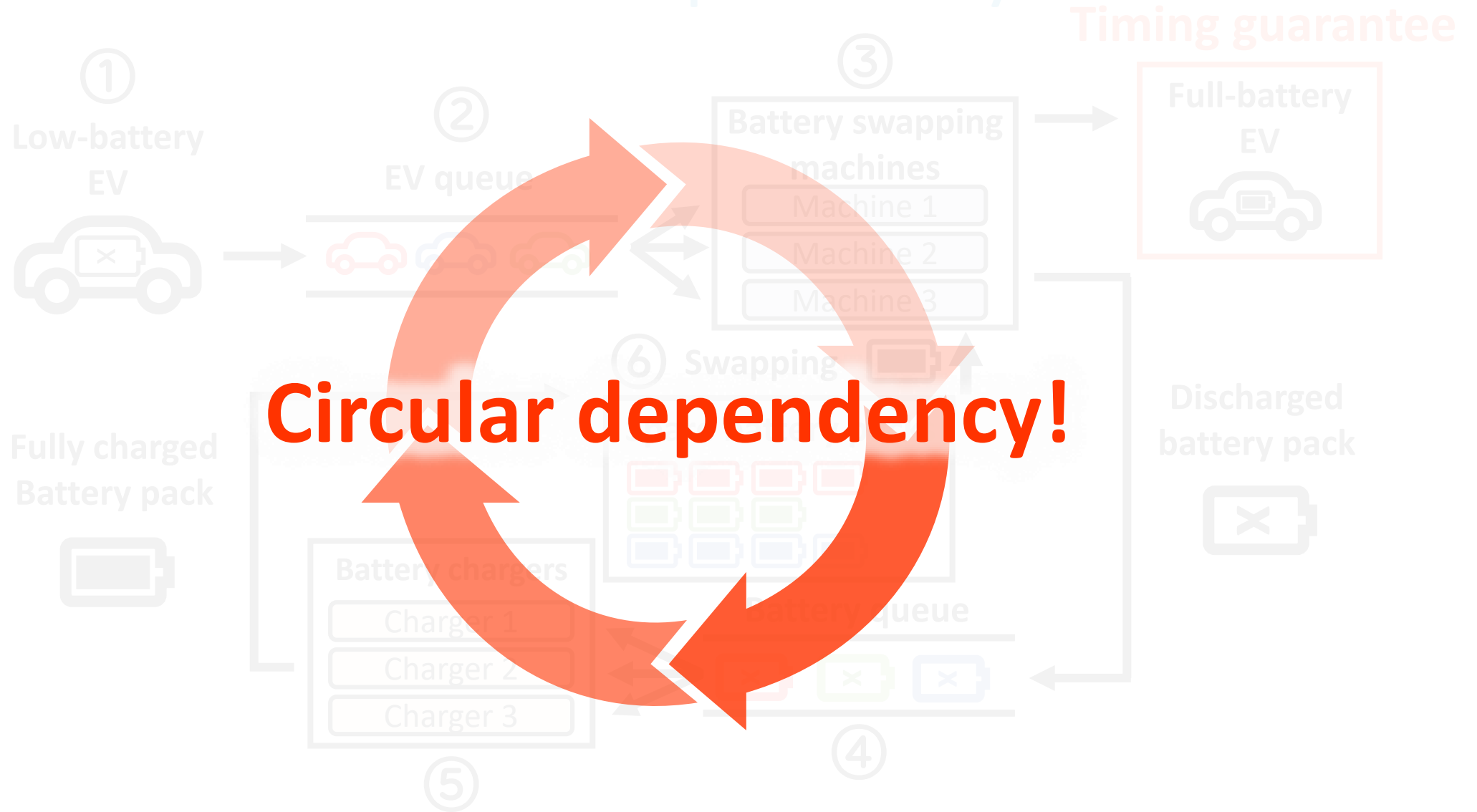
Circular dependency



Circular dependency



Circular dependency



Solution overview

We apply FIFO scheduling

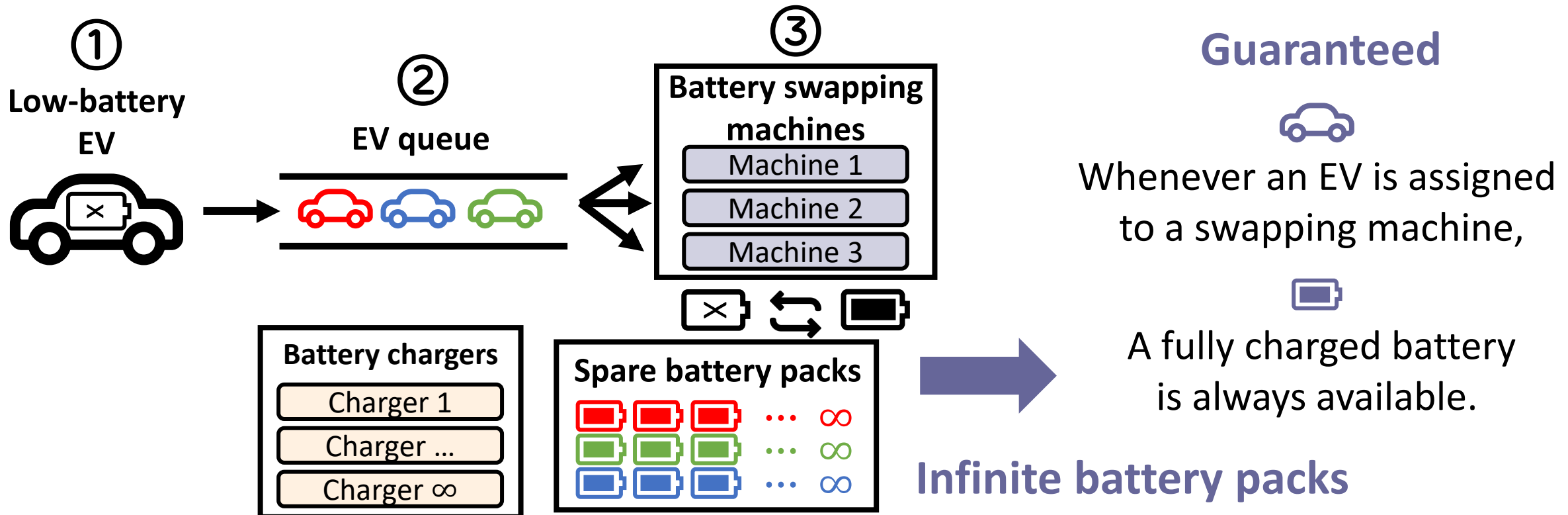
- The most practical policy for both stations and chargers
- Other policies should resolve physical overhead from order changes

Our solution consists of the following steps:

- **S1.** Analyze swapping response time under an *unrealistic situation* (Start with a simplified problem)
- **S2.** Identify a condition to *relax the unrealistic situation* from Step 1 (Decouple the circular dependency)
- **S3.** Analyze *charging response time* and improve the scheduling policy (Achieve timing guarantees and enhance charger efficiency)

S1. Swapping under an unrealistic situation

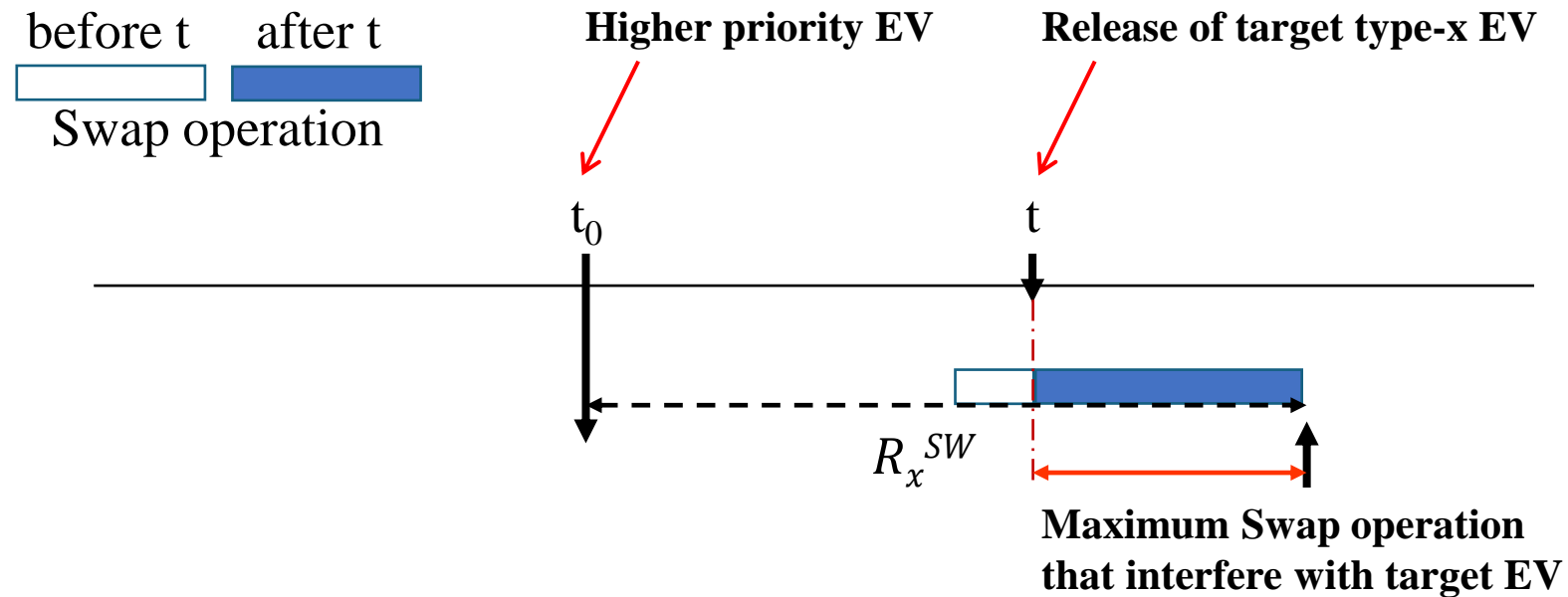
Situation 1: The number of chargers and the number of spare battery packs are infinitely many ($N^{CG}, \{n_x\}_{x=1}^{N^{TY}} = \infty, \infty$)



S1. Swapping under an unrealistic situation

The response time of swapping operation under the Situation 1.

- (FIFO) If a type-x EV arrives at time t , the only EVs that can interfere with its swap operation are those that arrived before t and have higher priority.

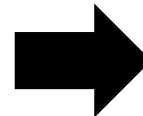
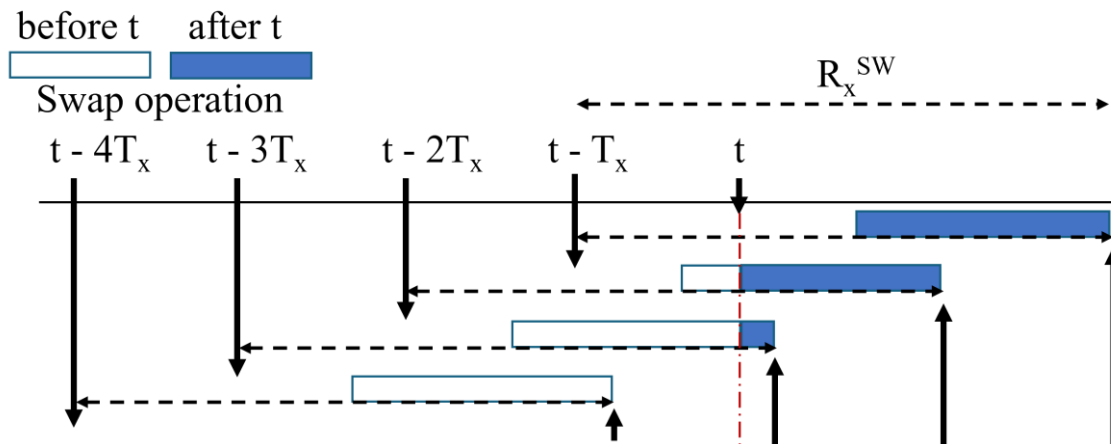


S1. Swapping under an unrealistic situation

The response time of swapping operation under the Situation 1.

- Interference is maximized when EVs arrive periodically.
- Backlogged swapping operation contribution by type-x EV

$$BL_x(R_x^{SW}) = \sum_{\alpha=1}^{\lfloor R_x^{SW}/T_x \rfloor} C_x^{SW}$$



$$BL_x^*(R_x^{SW}) = \sum_{\alpha=1}^{\lfloor R_x^{SW}/T_x \rfloor} \min(C_x^{SW}, R_x^{SW} - \alpha * T_x)$$

S1. Swapping under an unrealistic situation

The response time of swapping operation under the Situation 1.

- Update response time of each EV by traditional multiprocessor response time analysis techniques [1]

Lemma 1:

The swapping response time of the type-x EV is calculated by $R_x^{SW} = L$, where L satisfies following equation.

$$L = C_x^{SW} + \frac{BL_x^*(L) + \sum_{y \neq x}^{N^{TY}} C_y^{SW} + BL_y^*(R_y^{SW})}{N^{SW}}$$

➔ Only valid in Situation 1!

Type-x EV's operation

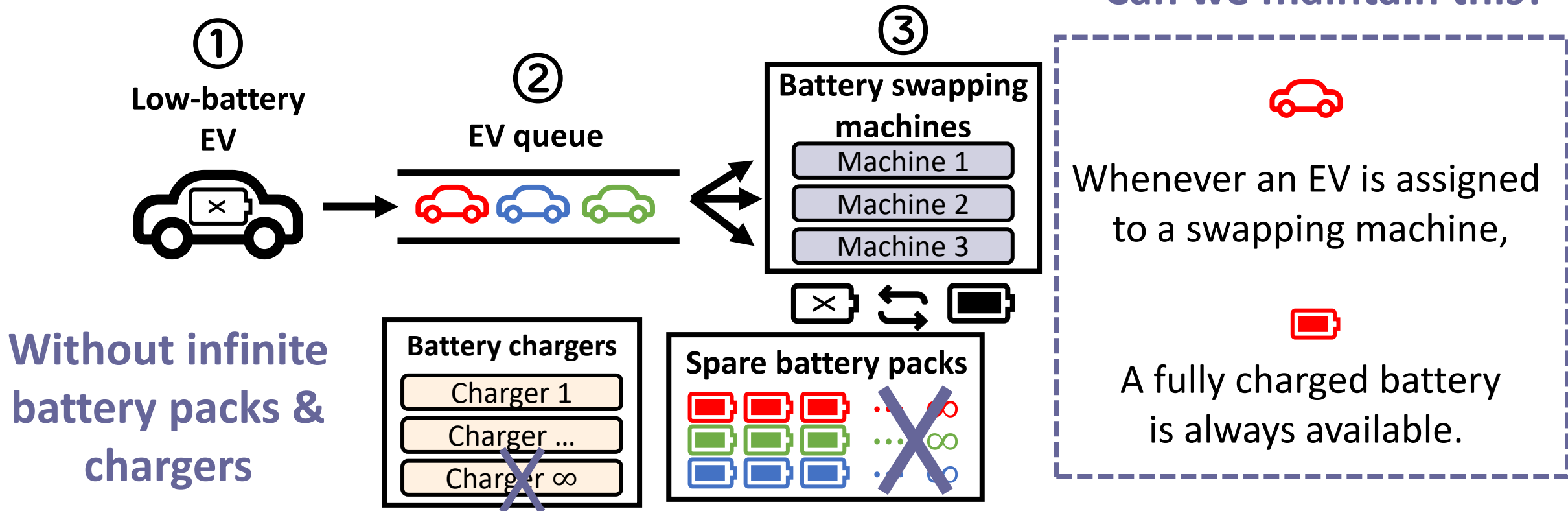
Type-x EV's back-logged operation

Type-y EV's tie-breaking operation

Type-y EV's back-logged operation

S2. Relaxing the unrealistic situation

Situation 2: A fully charged battery pack of any type is always available whenever a swapping operation needs it.



Without infinite battery packs & chargers

Can we maintain this?

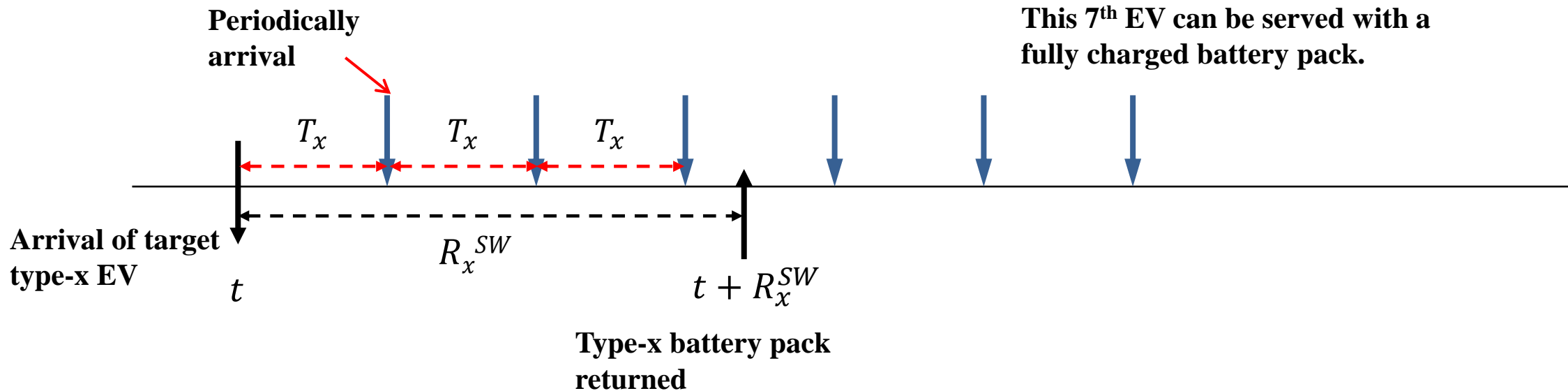
Whenever an EV is assigned to a swapping machine,

A fully charged battery is always available.

S2. Relaxing the unrealistic situation

A condition to guarantee Situation 2

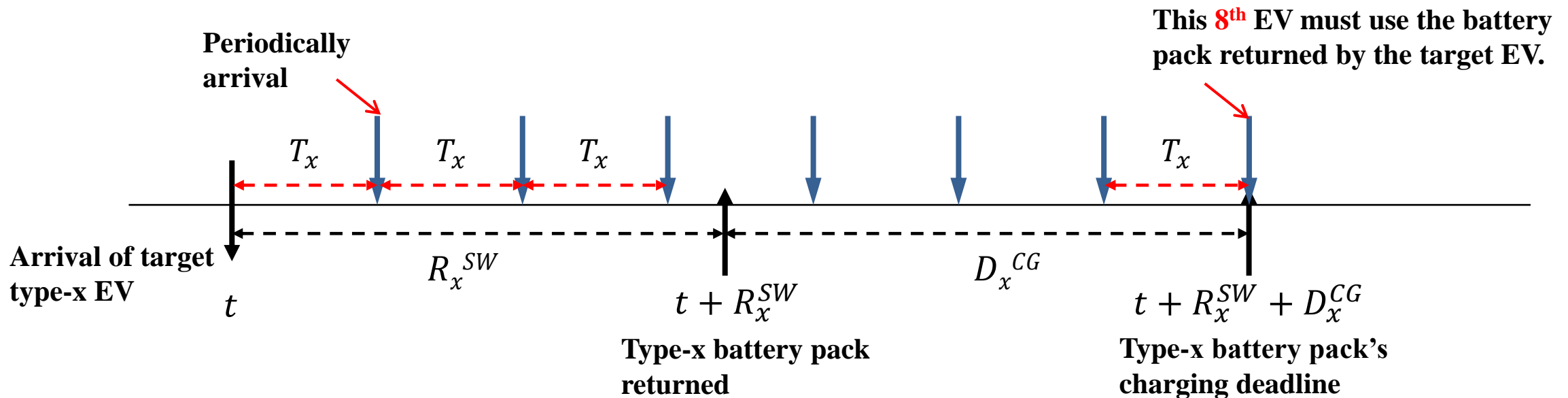
- Suppose that the total number of spare battery packs is 7



S2. Relaxing the unrealistic situation

A condition to guarantee Situation 2

- Suppose that the total number of spare battery packs is 7



$$\rightarrow D_x^{CG} = 7 \cdot T_x - R_x^{SW}$$

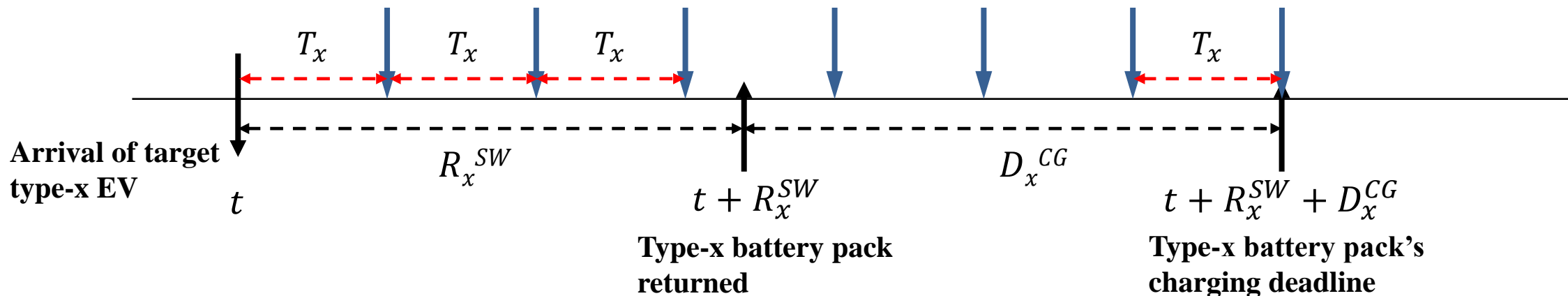
S2. Relaxing the unrealistic situation

A condition to guarantee Situation 2

Lemma 2:

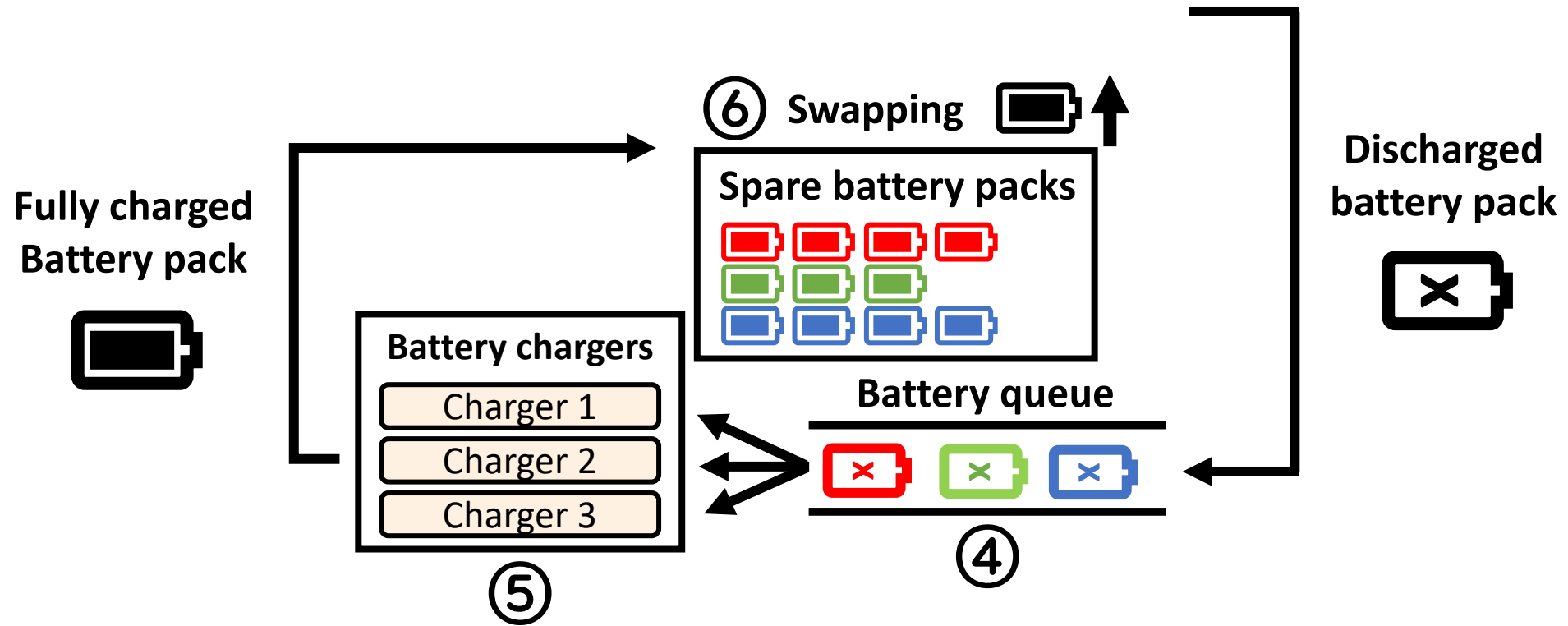
If following equation holds for all $1 \leq x \leq N^{TY}$, situation 2 holds, and therefore Lemma 1 and Theorem 1 hold without assuming unrealistic situation.

$$D_x^{CG} = n_x \cdot T_x - R_x^{SW}$$



S3. Charging under the relaxed situation

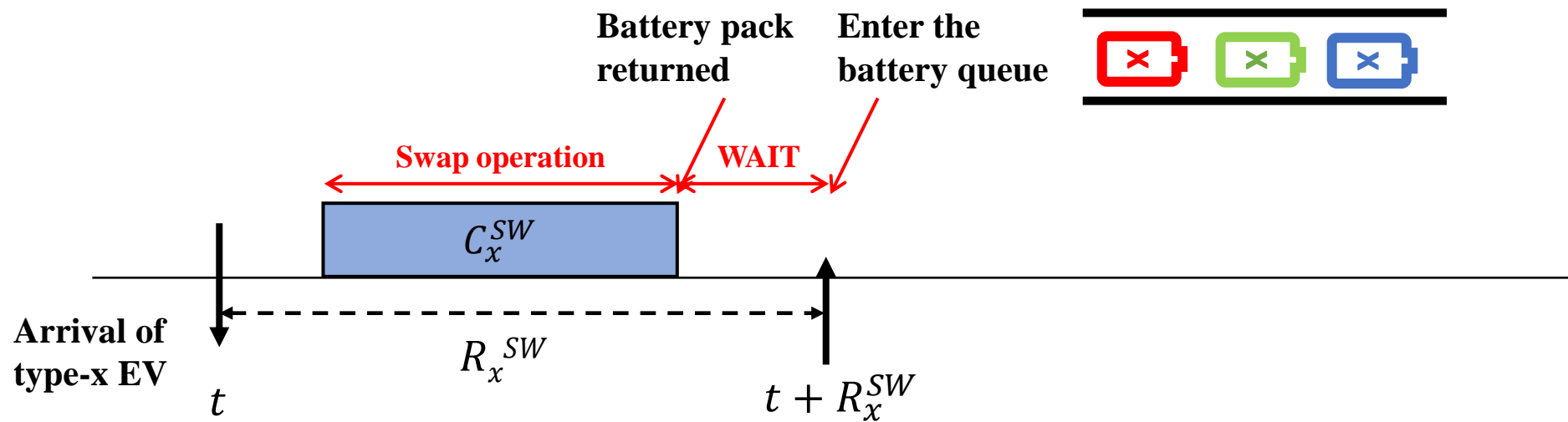
The response time of charging operation under the Situation 2.



S3. Charging under the relaxed situation

The response time of charging operation under the Situation 2.

- EVs arrive sporadically, yet battery pack returns are not sporadic.
(Swapping operations may finish before $t + R_x^{SW}$)
- However, we can enforce a sporadic pattern for battery pack returns.
(Making earlier returned battery pack wait to enter battery queue)



S3. Charging under the relaxed situation

The response time of charging operation under the Situation 2.

- Update response time of each EV by traditional multiprocessor response time analysis techniques [1]

Lemma 3 (following the same structure as Lemma 1) :

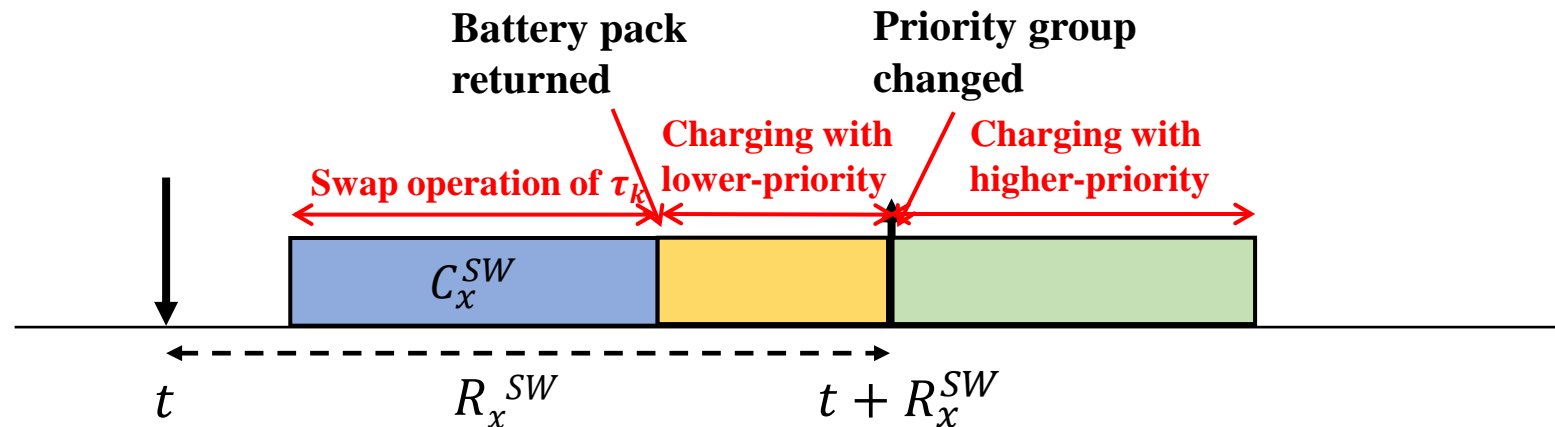
The charging response time of the type- x EV is calculated by $R_x^{CG} = L$, where L satisfies following equation.

$$L = C_x^{CG} + \frac{BL_x^*(L) + \sum_{y \neq x}^{N^{TY}} C_y^{CG} + BL_y^*(R_y^{CG})}{N^{CG}}$$

S3. Charging under the relaxed situation

Better scheduling policy: *quasi-non-preemptive dual-priority-FIFO*

- Eliminating waiting time while still satisfying Lemma 3.
(Better resource efficiency)
- Key Idea: Prioritize charging based on the threshold $t + R_x^{SW}$
(Please refer to our paper for the details)



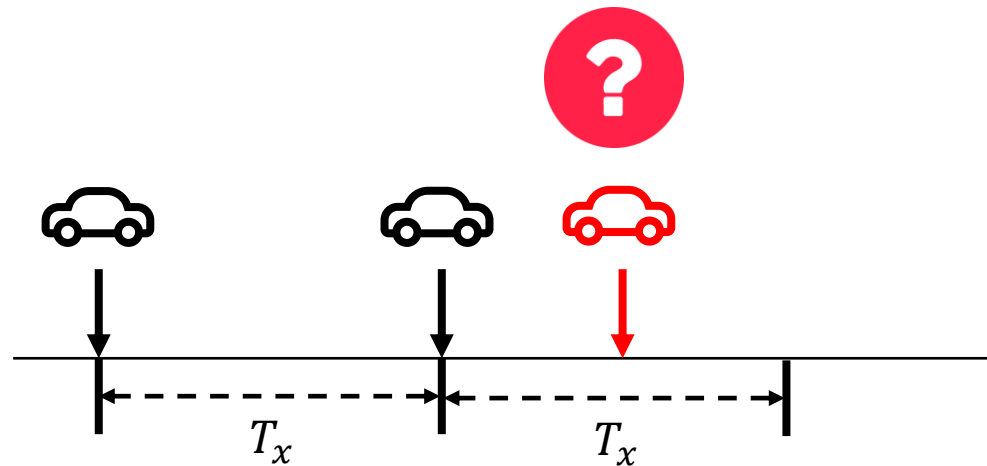
Managing real-world arrival patterns

Real-world EVs do not always arrive sporadically!

- Burst or successive arrivals can be happened

Battery Swap Station Management (BSSM)

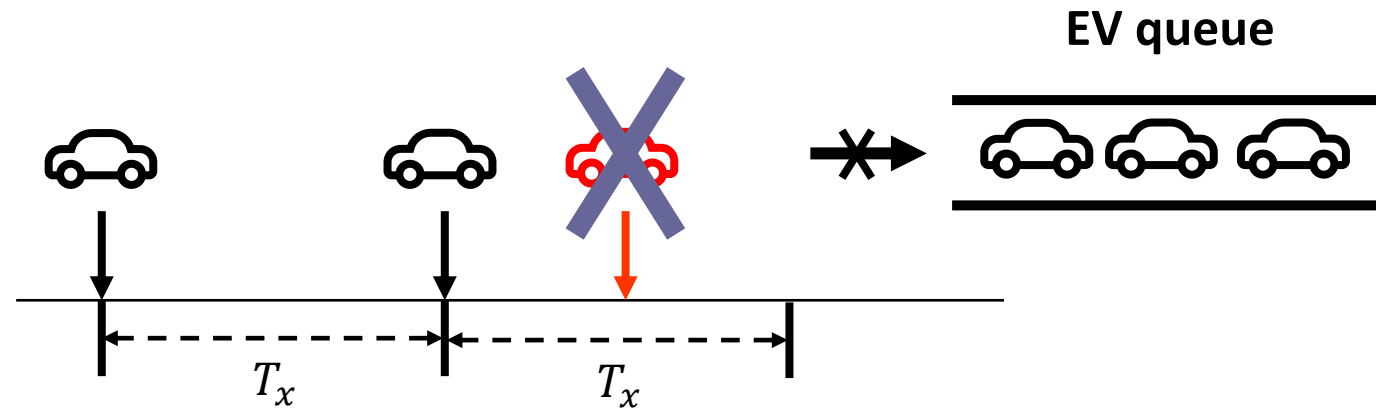
- Handles arrivals earlier than T_x



Managing real-world arrival patterns

BSSM-AC (Admission Control)

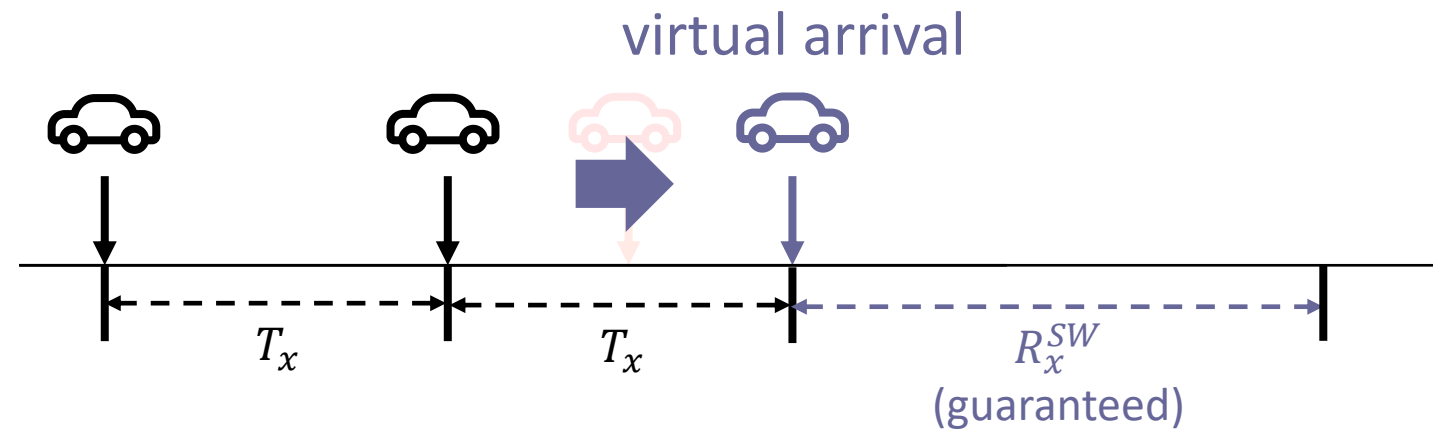
- Rejects all EV arrivals earlier than T_x
- Rejected EVs do not enter the EV queue



Managing real-world arrival patterns

BSSM-VA (Virtual Arrival)

- Accepts all EV arrivals and regards their arrivals as they arrive later
- Maintains timing guarantees from the virtual arrival time.



Evaluation

Parameter setting

- Swapping operation time (C_x^{SW}): 3-10 minutes [2-4]
- Charging operation time (C_x^{CG}): 60-600 minutes [5-6]
- Waiting deadline time (D_x^{SW}): 30 minutes [7]

- Number of swapping machines, chargers (N^{SW}, N^{CG}): 1-5, 12-48,
- Number of types, spare battery packs for each type (N^{TY}, n_x): 1-10, 3-27

- Utilization of swapping machines, chargers (U^{SW}, U^{CG}): 0.1-0.7, 0.3-0.9

Scheduling set generation

- 45 parameter combinations are selected
- 1,000 scheduling sets are generated (45,000 sets in total)

Evaluation

Q1. Does our proposed response time analysis improve schedulability?

Q2. Does our charger scheduling policy enhance resource efficiency?

Q3. What factors must be considered for managing real-world data?

Q4. How do BSSM approaches differ when applied to real-world data?

Evaluation

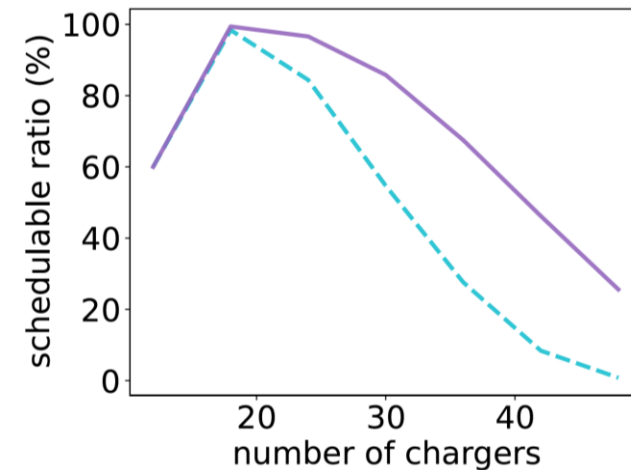
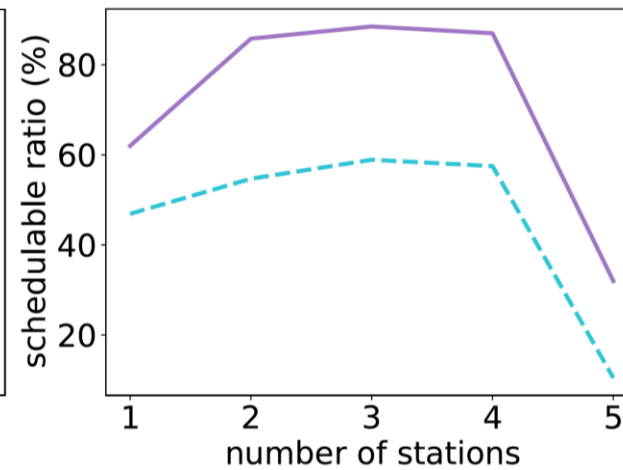
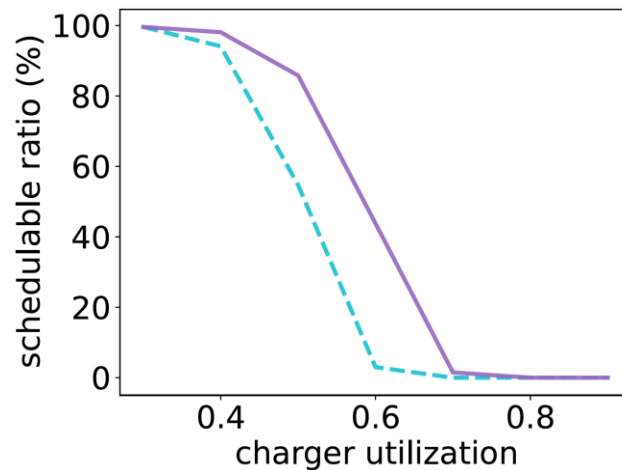
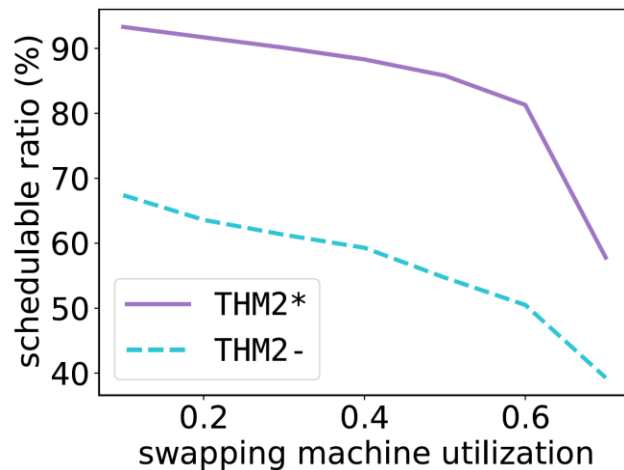
Q1. Does our proposed response time analysis improve schedulability?

Evaluation 1. Schedulable ratio by response time analysis

- Metric: scheduling ratio (# of passed sets / # of total sets)

- **THM2***: Our response time analysis $BL_x^*(R_x^{SW})$ → better

- **THM2-**: Naïve back-logged operation time analysis $BL_x(R_x^{SW})$



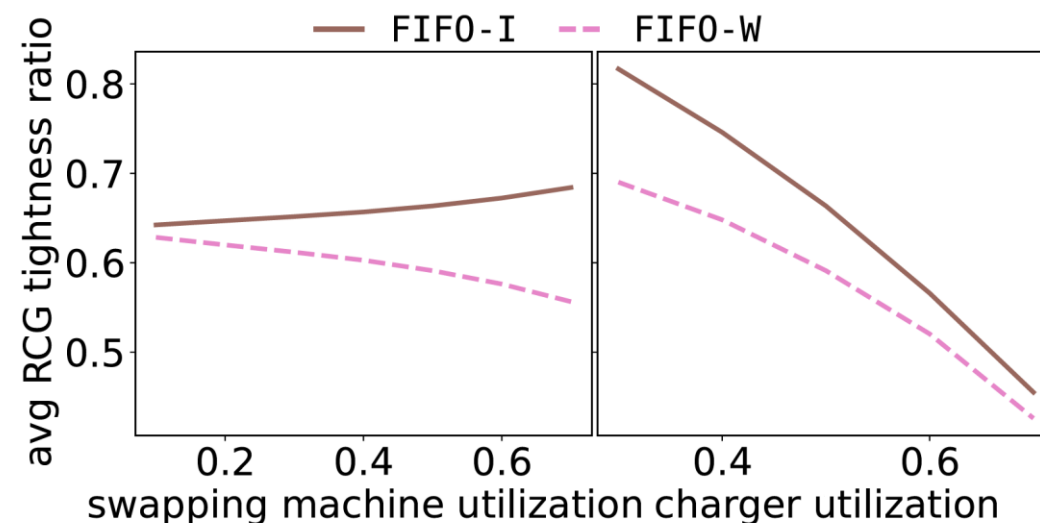
Evaluation

Q2. Does our charger scheduling policy enhance resource efficiency?

Evaluation 2. Resource efficiency by charger scheduling policy

- **FIFO-I**: Quasi-non-preemptive dual-priority-FIFO (ours) → better
- **FIFO-W**: Vanilla FIFO
- Metric: Average R^{CG} tightness ratio (higher = better charger efficiency)

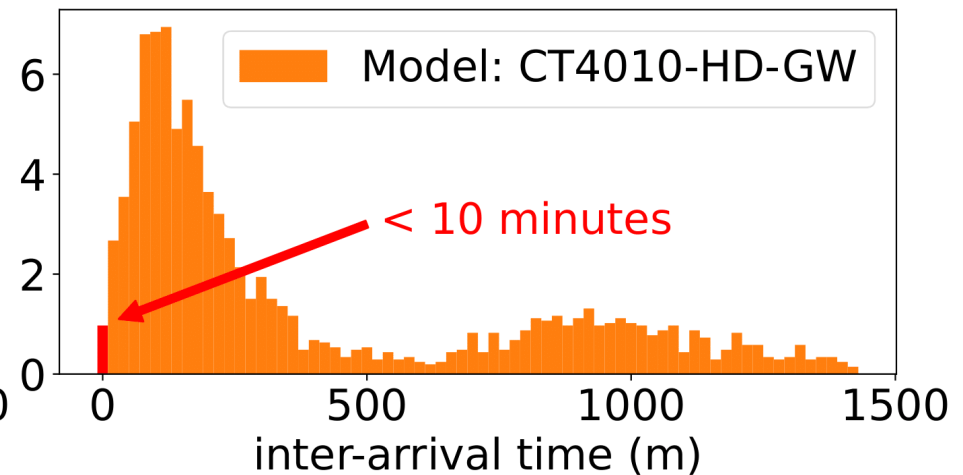
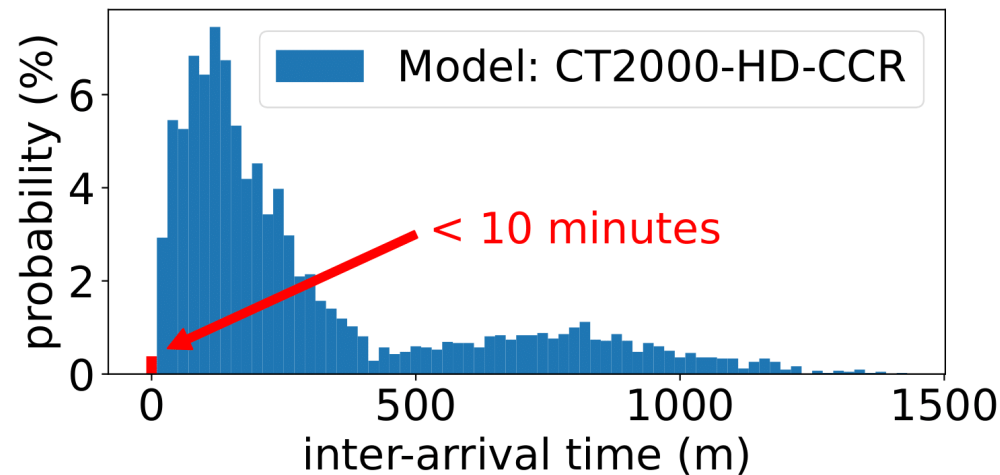
$$R^{CG} \text{ Tightness ratio} = \frac{\text{measured } R^{CG} \text{ (during run-time)}}{\text{calculated } R^{CG} \text{ (from lemma 2)}}$$



Evaluation

Case study: real-world arrival patterns

- Applying non-sporadic arrival patterns
- EVs visited at the charging station in the Palo Alto area in California, USA [8]

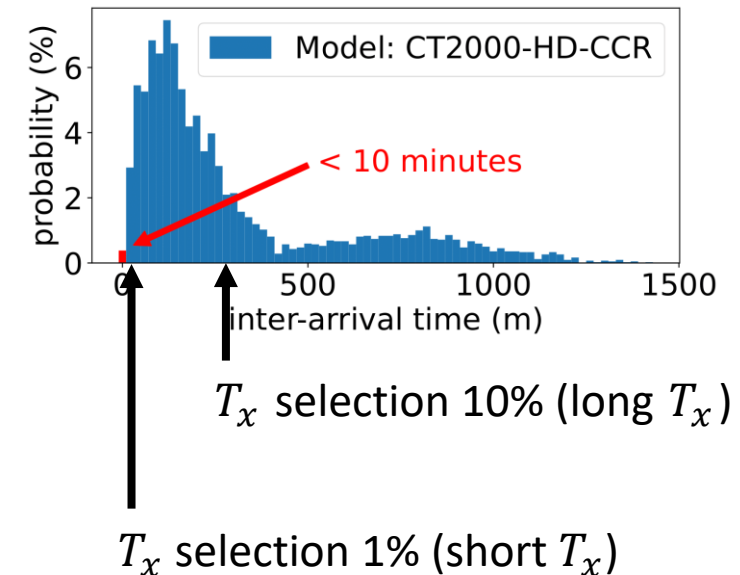
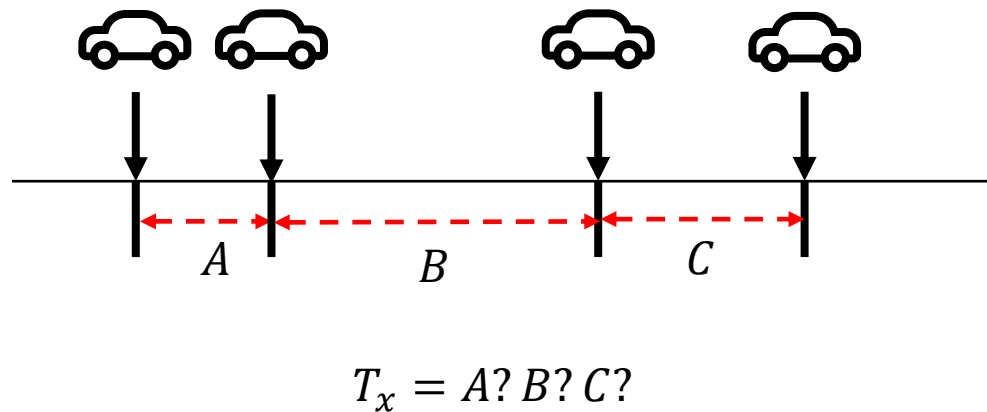


Evaluation

Q3. What factors must be considered for applying real-world data?

Applying real-world arrival patterns.

- We have to select representative T_x
- We selected T_x from the bottom 1%, 2%, 3%, ..., 10% of each actual inter-arrival pattern (lower percentiles mean shorter T_x)

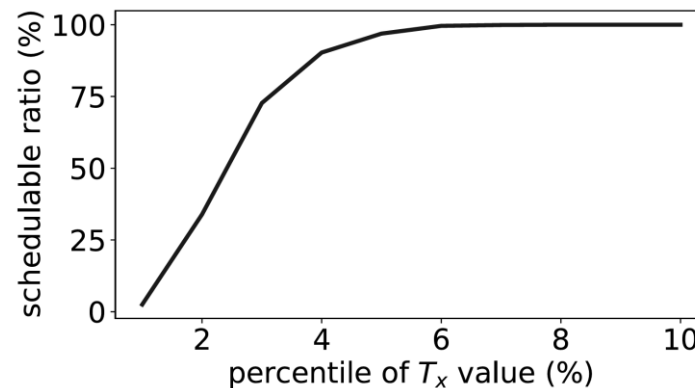


Evaluation

Q3. What factors must be considered for applying real-world data?

Applying real-world arrival patterns.

- We have to select representative T_x
- We selected T_x from the bottom 1%, 2%, 3%, . . . , 10% of each actual inter-arrival pattern (lower percentiles mean shorter T_x)
- We expanded generated scheduling sets while keeping all other parameters fixed

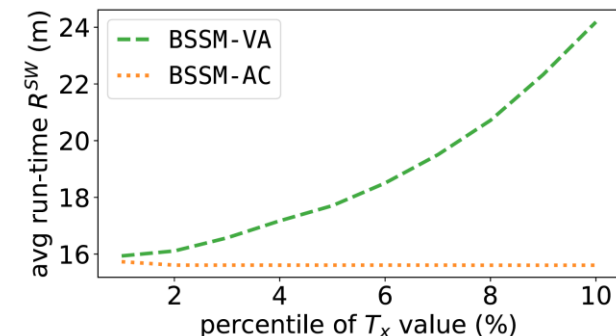
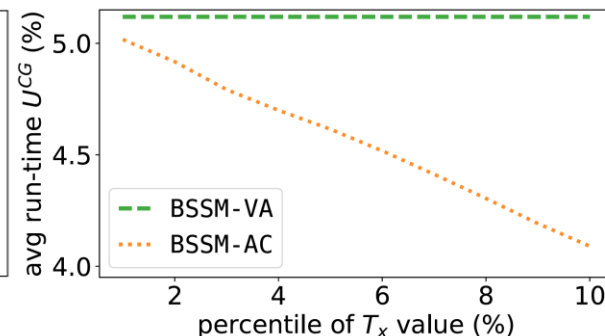
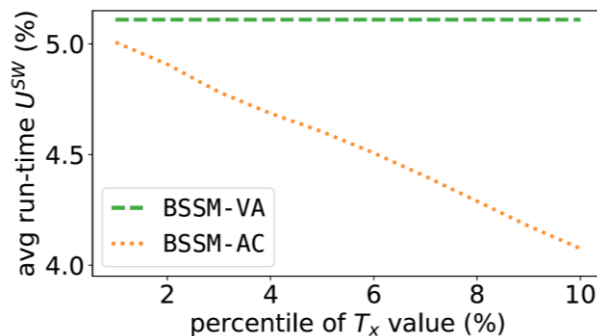


Evaluation

Q4. How do BSSM approaches differ when applied to real-world data?

Evaluation 3. Impact of T_x selection and BSSM policies

- Metric: schedulable ratio, run-time U^{SW} , U^{CG} , and R^{SW}
- **BSSM-AC**: Rejects EVs arriving earlier than T_x
- **BSSM-VA**: Accepts all EVs by virtual arrival
- Higher T_x selection \rightarrow higher schedulable ratio and lower resource utilization
- BSSM-VA \rightarrow Higher resource utilization, but delayed swapping completion



Evaluation

Q1. Does our proposed response time analysis improve schedulability?

→ Yes

Q2. Does our charger scheduling policy enhance resource efficiency?

→ Yes

Q3. What factors must be considered for managing real-world data?

→ T_x

Q4. How do BSSM approaches differ when applied to real-world data?

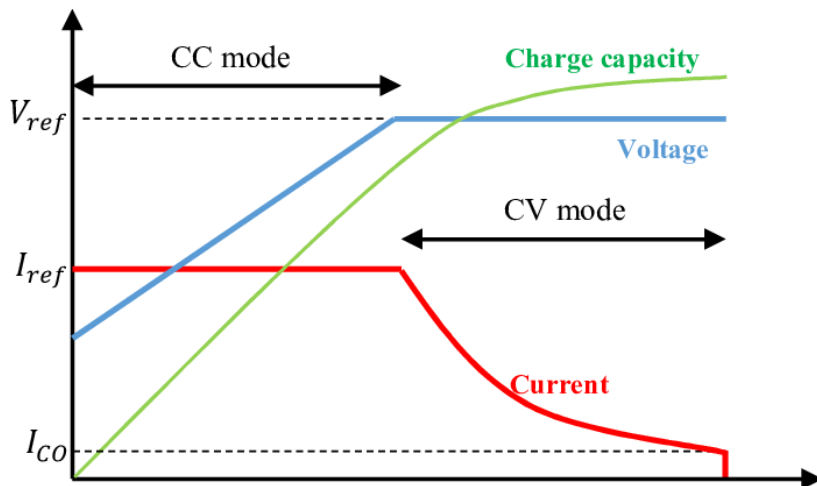
→ Differ in resource efficiency and delayed time

Conclusion

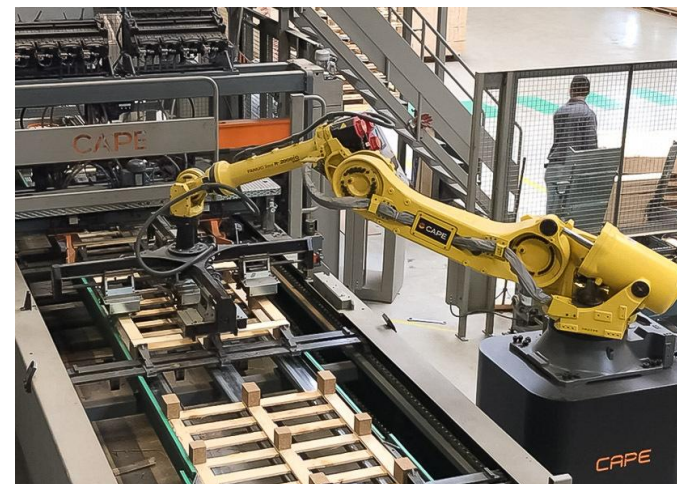
Contributions

- First formulated the real-time scheduling problem in EV battery swap stations
- Identified and resolved the issue of circular dependency
- Proposed a practical, timing-guaranteed FIFO-based scheduling solution
- Verified its effectiveness via extensive evaluations and real-world case studies

Future work



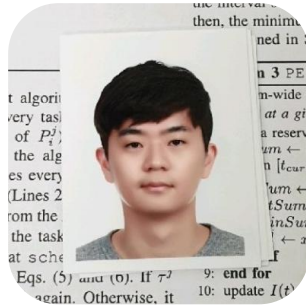
Further optimization
leveraging charging
characteristics



Extension to
other domains



Thank You!



Jaeheon Kwak

0jaehunny0@gmail.com

www.linkedin.com/in/jaehunny