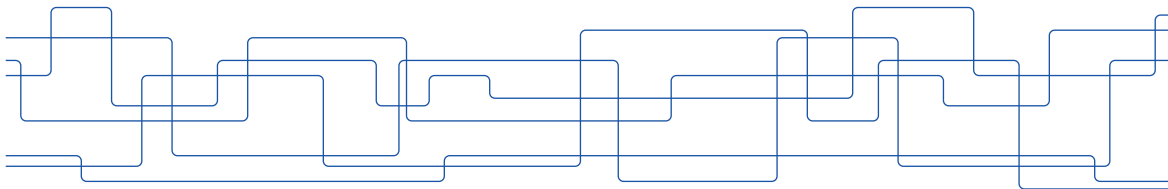


Distributed Charging Coordination of Electric Trucks with Limited Charging Resources

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Road Freight Electrification

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- Insufficient battery capacity – Range anxiety



Limited driving range (200-600 km)

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- ▶ Limited charging resources – Long queuing time



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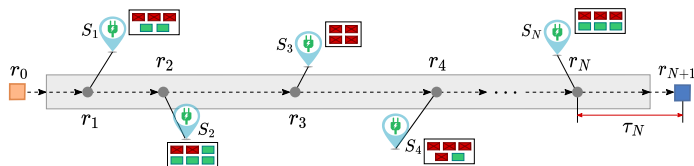
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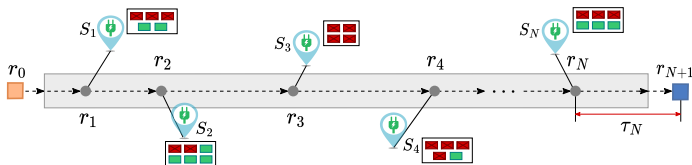
Problem: How to design reliable and efficient **charging strategy** for electric trucks so that trucks can **complete delivery task** while **minimizing charging costs**, subject to limited charging resources?

Charging Problem: Route Model and Decision Variables



T. Bai, Y. Li, K. H. Johansson, and J. Mårtensson, "Rollout-based charging strategy for electric trucks with hours-of-service regulations". *IEEE Control Systems Letters*, 7, 2167-2172, 2023.

Charging Problem: Route Model and Decision Variables



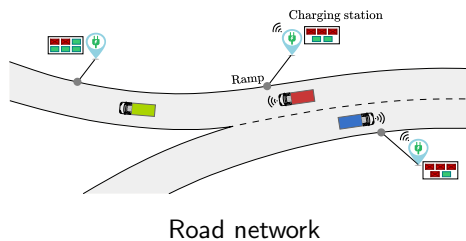
- The decision variables are:

$$b_k \in \{0, 1\}, \quad t_k \in \mathbb{R}_+, \quad k = 1, \dots, N$$

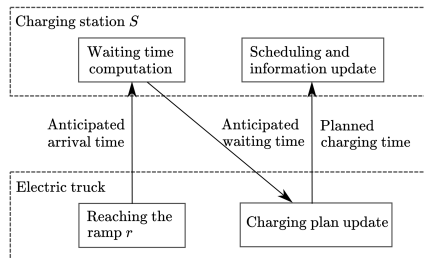
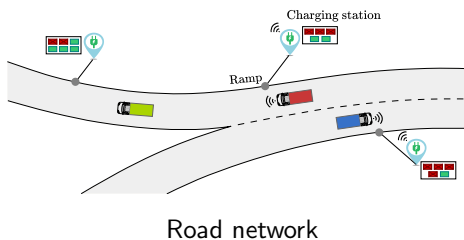
b_k : whether to charge at the station S_k

t_k : the planned charging time of the truck at S_k if $b_k = 1$

Two-Layer Charging Coordination Framework

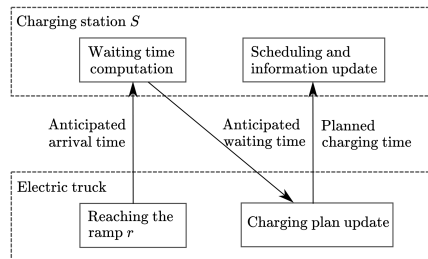
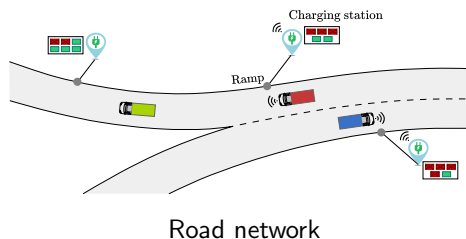


Two-Layer Charging Coordination Framework



Station-truck coordination framework

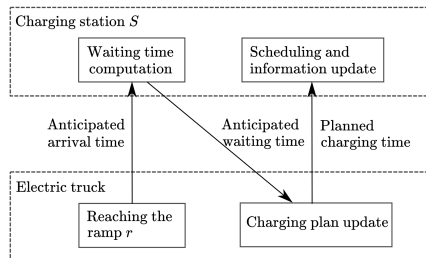
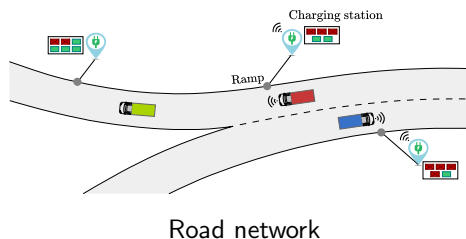
Two-Layer Charging Coordination Framework



Station-truck coordination framework

- ▶ Our framework highlights the following properties:
 - It is fully distributed and applies to cases where all parties do not belong to the same fleet

Two-Layer Charging Coordination Framework

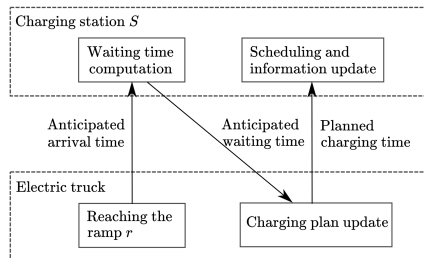
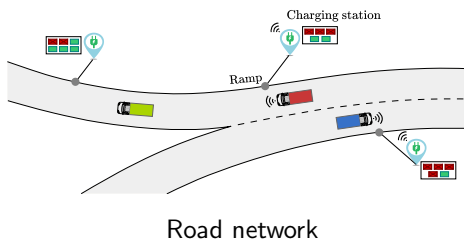


Station-truck coordination framework

► Our framework highlights the following properties:

- It is fully distributed and applies to cases where all parties do not belong to the same fleet
- It is light-weight, involving only simple information exchange between trucks and stations

Two-Layer Charging Coordination Framework

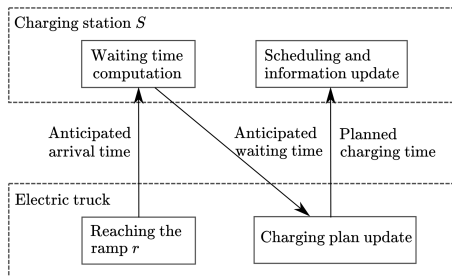


Station-truck coordination framework

► Our framework highlights the following properties:

- It is fully distributed and applies to cases where all parties do not belong to the same fleet
- It is light-weight, involving only simple information exchange between trucks and stations
- It is adaptive, enabling changes in charging plans when needed via real-time computation

Waiting Time Computation



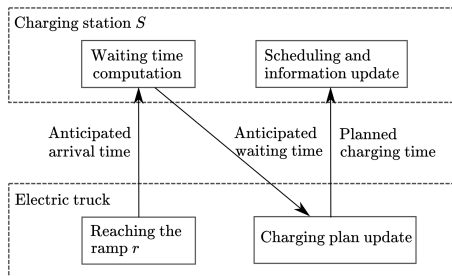
- The station computes the anticipated waiting time \tilde{w} as

$$\tilde{w} = \max \left\{ \min_{c \in C} (a_c - \tilde{t}_a), 0 \right\}$$

a_c : the earliest time from when the port $c \in C$ becomes available onward

\tilde{t}_a : the anticipated arrival time of a truck

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- The station assigns the port c^* to the truck and update its information via

$$c^* \in \arg \min_{c \in C} a_c, \quad a_{c^*} = \tilde{t}_a + \tilde{w} + t$$

Computing Charging Plan: Delivery Deadline

- Reaching the destination before the deadline is described by a soft constraint:

$$\Delta T_k = b_k(2d_k + t_k + \tilde{w}_k) + \sum_{\ell=k+1}^N b_\ell(2d_\ell + t_\ell + \hat{w}_\ell) + \sum_{\ell=k}^N \tau_\ell - T_k,$$

\tilde{w}_k : the anticipated waiting time received from S_k when arriving r_k

\hat{w}_ℓ : the certain waiting time assumed at the subsequent station S_ℓ , $\ell = k+1, \dots, N$

T_k : the remaining travel time for charging planning when arriving at r_k

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→ $\Delta T_k > 0$: indicates the **violation** of the delivery deadline

Computing Charging Plan: Optimization Problem

- The charging problem upon reaching r_k is cast as:

$$\min_{\{(b_\ell, t_\ell)\}_{\ell=k}^N} \kappa \left(b_k(2d_k + t_k + \tilde{w}_k) + \sum_{\ell=k+1}^N b_\ell(2d_\ell + t_\ell + \hat{w}_\ell) \right) + \sum_{\ell=k}^N \epsilon_\ell b_\ell t_\ell + \max\{\rho \Delta T_k, 0\}$$

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$$\text{s. t. } b_k \in \{0, 1\}, \quad t_k \in \mathbb{R}_+, \quad k=1, \dots, N, \quad (1)$$

$$e_1 = e_{\text{ini}} - \bar{P}\tau_0, \quad (2)$$

$$e_{k+1} = e_k + b_k \Delta e_k - \bar{P}(2b_k d_k + \tau_k), \quad k=1, \dots, N, \quad (3)$$

$$e_k \geq e_s + \bar{P}d_k, \quad k=1, \dots, N, \quad (4)$$

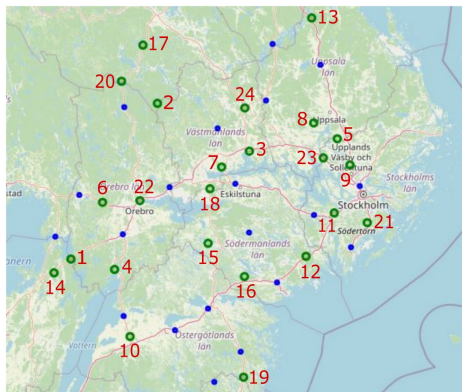
$$e_{N+1} \geq e_s, \quad (5)$$

$$\Delta e_k = t_k \min\{P_k, P_{\max}\}, \quad k=1, \dots, N, \quad (6)$$

$$0 \leq \Delta e_k \leq e_f - (e_k - \bar{P}d_k), \quad k=1, \dots, N, \quad (7)$$

$$\Delta T_k = b_k(2d_k + t_k + \tilde{w}_k) + \sum_{\ell=k+1}^N b_\ell(2d_\ell + t_\ell + \hat{w}_\ell) + \sum_{\ell=k}^N \tau_k - T_k \quad (8)$$

Simulation – Parameter settings

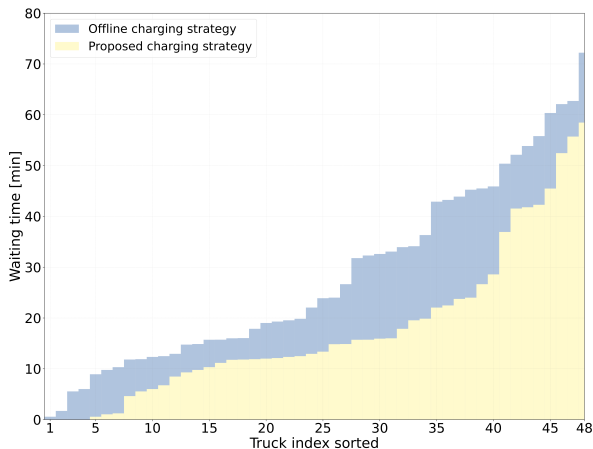


The road network and charging stations

- 150 trucks, 24 charging stations, 3 charging ports per station
- Start times are randomly determined between 08:00-10:00 a.m.
- Random initial battery with feasibility guarantee
- Routes are pre-planned using data from *OpenStreetMap*
- Parameters related to trucks are set using the data latest published by Scania

Simulation – Evaluation Results (1)

► Real waiting times of individual trucks



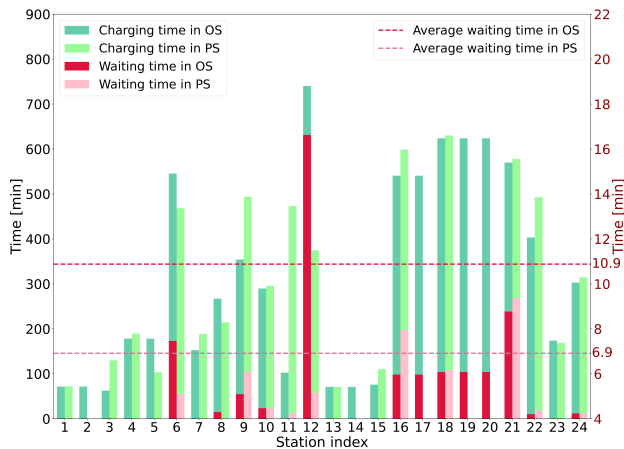
Total waiting time:

— Offline strategy: 22.67 hours

— Proposed strategy: 14.30 hours

Simulation – Evaluation Results (2)

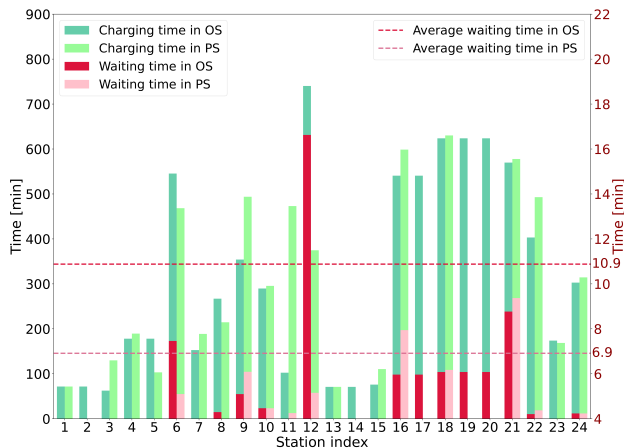
► Charging and waiting times at each station



- Alleviate charging congestion by reducing average waiting time from 10.9 to 6.9 minutes

Simulation – Evaluation Results (2)

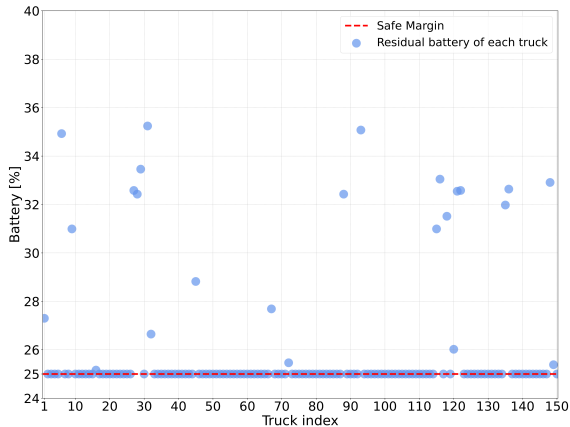
► Charging and waiting times at each station



- Alleviate charging congestion by reducing average waiting time from 10.9 to 6.9 minutes
- Our method may result in longer waiting times for some trucks due to characteristic diversity

Simulation – Evaluation Results (3)

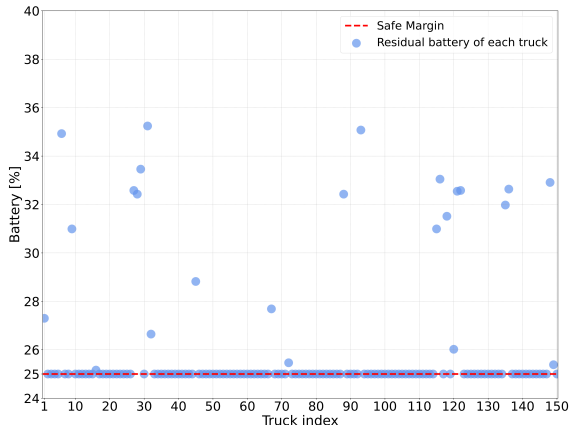
- ▶ Trucks' residual batteries upon reaching destinations



- Most trucks complete their delivery missions while consuming all the usable batteries

Simulation – Evaluation Results (3)

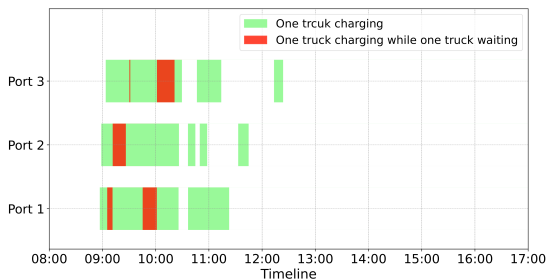
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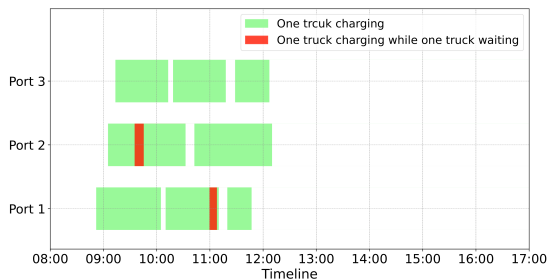
- Most trucks complete their delivery missions while consuming all the usable batteries
- Note: our method can be easily modified to meet higher battery requirements at destinations

Simulation – Evaluation Results (4)

- ▶ Charging ports assignment at two stations (“first-arrive, first-served” rule)



Charging time scheduling at Station 12



Charging time scheduling at Station 22

Conclusions and Future Work

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 - It requires **simple** information exchange
 - It allows **fully distributed** computations
 - It enables **re-planning** by trucks
- ▶ Simulation studies show our approach outperforms the offline strategy by large margins.
- ▶ Future research will focus on developing data-driven schemes for waiting time estimations at future stations, as well as single-carrier charging planning.

