Distributed Charging Coordination of Electric Trucks with Limited Charging Resources

Ting Bai[†], *Yuchao Li*[‡], *Karl H. Johansson*[†], *Jonas Mårtensson*[†]

[†]Division of Decision and Control Systems, KTH Royal Institute of Technology, Stockholm, Sweden
[‡]School of Computing and Augmented Intelligence, Arizona State University, Tempe, AZ, USA

Road Freight Electrification

Road Freight Electrification

- Insufficient battery capacity – Range anxiety

Limited driving range (200-600 km)

Road Freight Electrification

- Insufficient battery capacity – Range anxiety
- Limited charging resources – Long queuing time

Limited driving range (200-600 km)

Limited number of charging ports

Road Freight Electrification

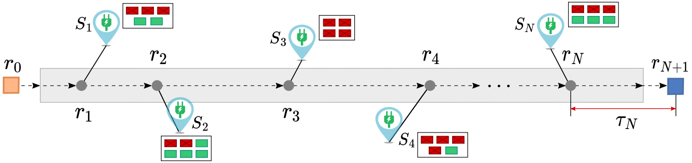
- Insufficient battery capacity – Range anxiety
- Limited charging resources – Long queuing time

Limited driving range (200-600 km)

Limited number of charging ports

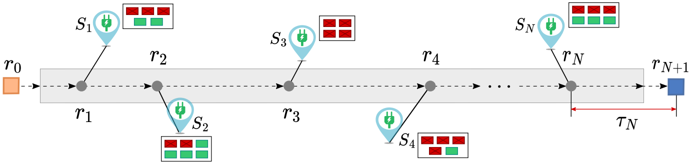
Problem: How to design reliable and efficient **charging strategy** for electric trucks so that trucks can complete delivery task while minimizing charging costs, subject to limited charging resources?

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



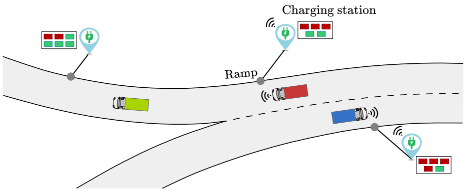
- The decision variables are:

$$b_k \in \{0, 1\}, \;\; t_k \in \Re_+, \qquad k = 1, \ldots, N$$

b_k: whether to charge at the station S_k
t_k: the planned charging time of the truck at S_k if $b_k = 1$

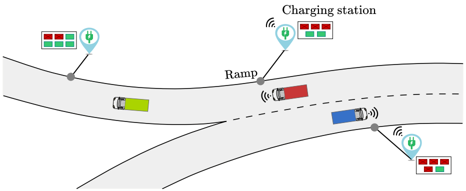
T. Bai, Y. Li, K. H. Johansson, and J. Mårtensson, "Rollout-based charging strategy for electric trucks with hours-of-service regulations". *IEEE Control Systems Letters*, 7, 2167-2172, 2023.

Two-Layer Charging Coordination Framework

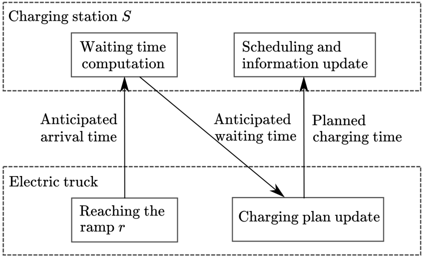


Road network

Two-Layer Charging Coordination Framework

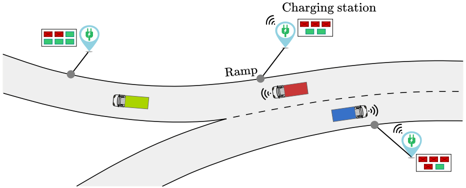


Road network

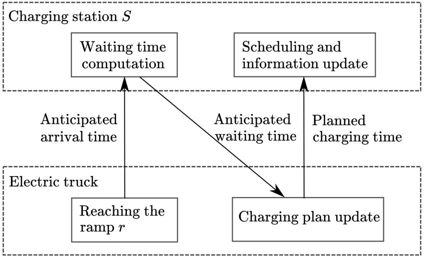


Station-truck coordination framework

Two-Layer Charging Coordination Framework



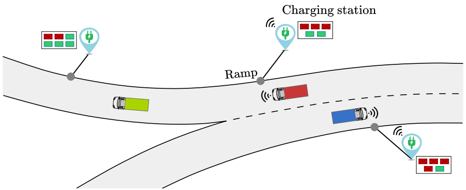
Road network



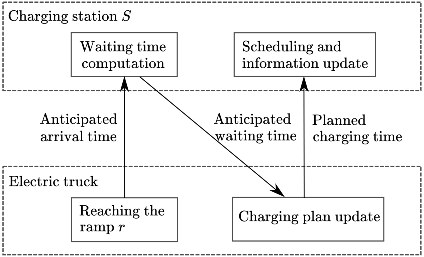
Station-truck coordination framework

- 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



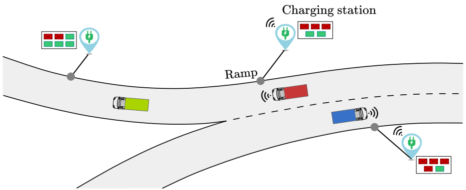
Road network



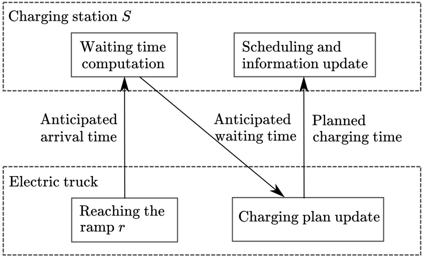
Station-truck coordination framework

- 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



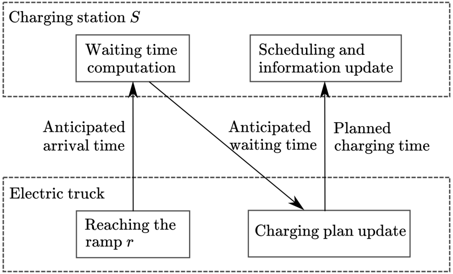
Road network



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

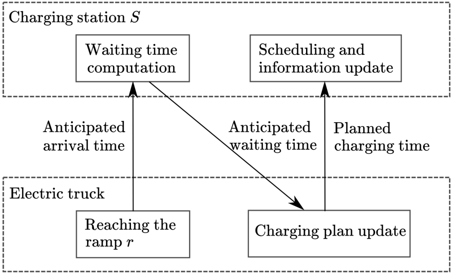


- The station computes the anticipated waiting time $\tilde{w}$ as

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

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

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

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

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

Computing Charging Plan: Delivery Deadline

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

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

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

Computing Charging Plan: Delivery Deadline

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

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

$\tilde{w}_k$: the anticipated waiting time received from S_k when arriving r_k
$\hat{w}_\ell$: the certain waiting time assumed at the subsequent station S_ℓ, $\ell = k+1, \ldots, N$
T_k: the remaining travel time for charging planning when arriving at r_k

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

Computing Charging Plan: Optimization Problem

- The charging problem upon reaching r_k is cast as:

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

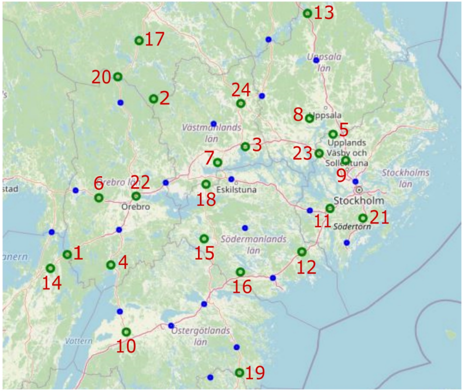
Computing Charging Plan: Optimization Problem

- The charging problem upon reaching r_k is cast as:

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

$$\begin{aligned}
\text{s.t.}\quad & b_k\in\{0,1\},\ t_k\in\Re_+,\quad k=1,\ldots,N, && (1)\\
& e_1=e_{\text{ini}}-\bar{P}\tau_0, && (2)\\
& e_{k+1}=e_k+b_k\Delta e_k-\bar{P}(2b_kd_k+\tau_k),\quad k=1,\ldots,N, && (3)\\
& e_k\ge e_s+\bar{P}d_k,\quad k=1,\ldots,N, && (4)\\
& e_{N+1}\ge e_s, && (5)\\
& \Delta e_k=t_k\min\left\{P_k,P_{\max}\right\},\quad k=1,\ldots,N, && (6)\\
& 0\le\Delta e_k\le e_f-\left(e_k-\bar{P}d_k\right),\quad k=1,\ldots,N, && (7)\\
& \Delta T_k=b_k(2d_k+t_k+\tilde{w}_k)+\sum_{\ell=k+1}^{N} b_\ell\left(2d_\ell+t_\ell+\hat{w}_\ell\right)+\sum_{\ell=k}^{N}\tau_k-T_k && (8)
\end{aligned}$$

Simulation – Parameter settings

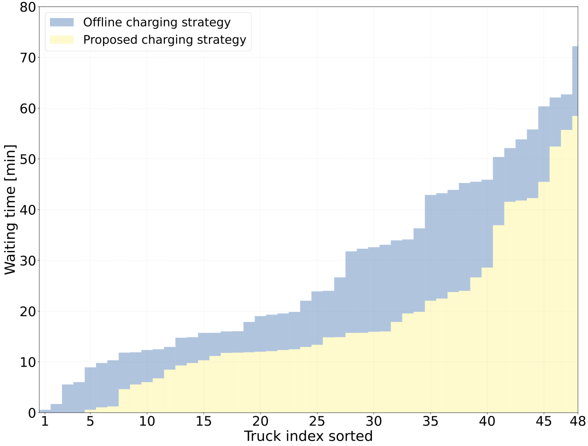


The road network and charging stations

- 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



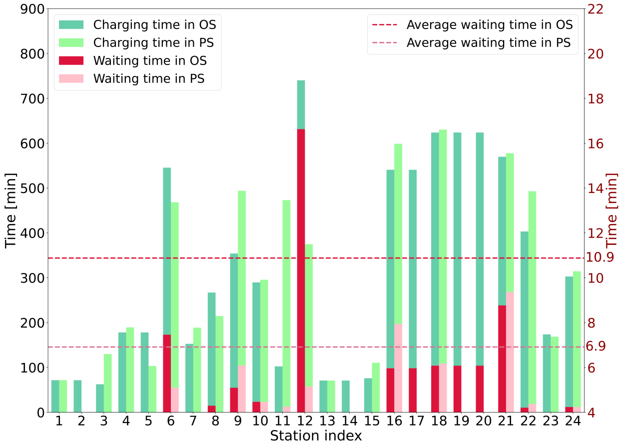
Total waiting time:

– Offline strategy: 22.67 hours

– Proposed strategy: 14.30 hours

Simulation – Evaluation Results (2)

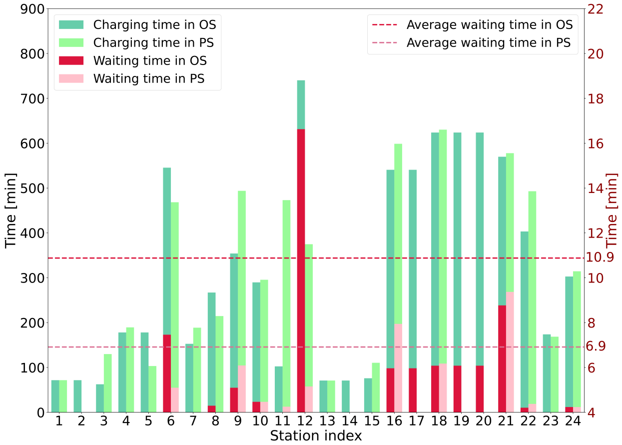
- Charging and waiting times at each station



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

Simulation – Evaluation Results (2)

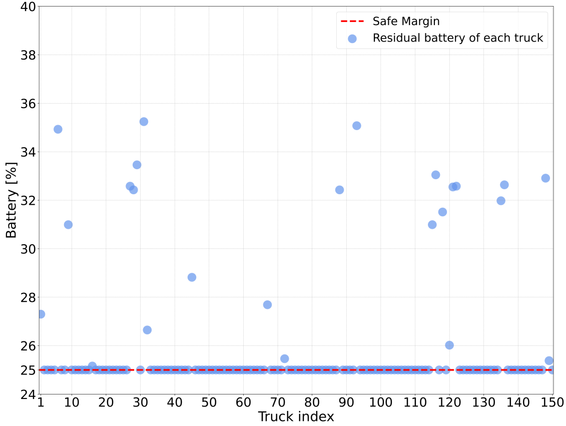
- Charging and waiting times at each station



- 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)

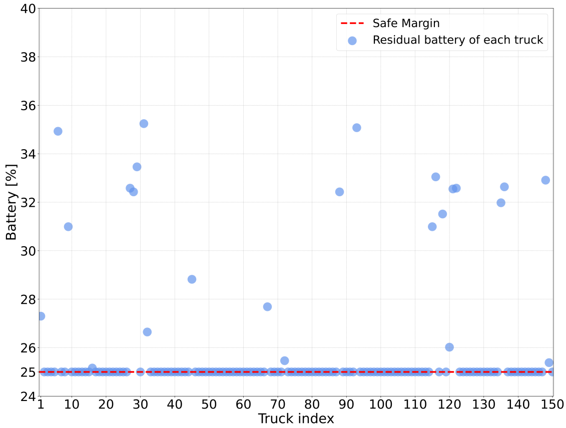
- Trucks' residual batteries upon reaching destinations



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

Simulation – Evaluation Results (3)

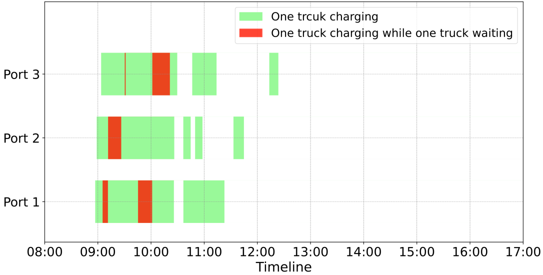
- Trucks' residual batteries upon reaching destinations



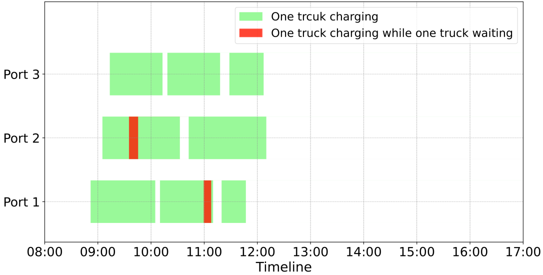
- Most trucks complete their delivery missions while consuming all the usable batteries
- Note: our method can be easily modified to meet higher battery requirements at destinations

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

- We have proposed a two-layer coordination framework to mitigate charging congestion.

Conclusions and Future Work

- We have proposed a two-layer coordination framework to mitigate charging congestion.
  - It requires simple information exchange

Conclusions and Future Work

- We have proposed a two-layer coordination framework to mitigate charging congestion.
  - It requires simple information exchange
  - It allows fully distributed computations

Conclusions and Future Work

- We have proposed a two-layer coordination framework to mitigate charging congestion.
  - It requires simple information exchange
  - It allows fully distributed computations
  - It enables re-planning by trucks

Conclusions and Future Work

- We have proposed a two-layer coordination framework to mitigate charging congestion.
  - 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.

Conclusions and Future Work

- We have proposed a two-layer coordination framework to mitigate charging congestion.
  - 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.