Event-Triggered Distributed Model Predictive Control for Platoon Coordination at Hubs in a Transport System

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What is Truck Platooning?

Trucks drive one after another on the road with small inter-truck distances.

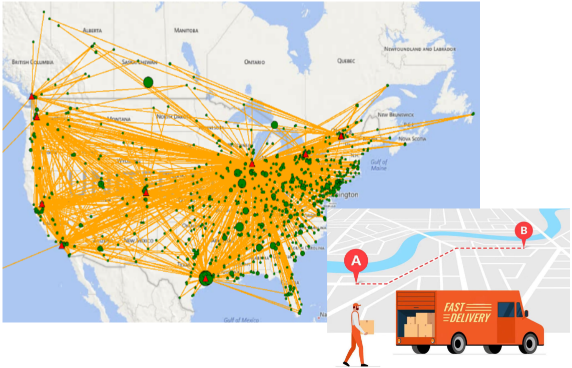
Benefits of Truck Platooning:

1) Save fuel
2) Reduce greenhouse gas exhaust
3) Cut human labor cost
   (follower trucks can be autonomous)
4) Positive for safety

Trucks need **coordination** *to form platoons*

→ High-level platoon coordination

Large-Scale Platoon Coordination

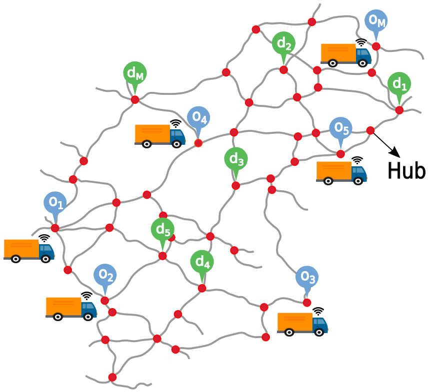


Centralized platoon coordination methods are inapplicable

1. Endure a heavy computational burden;
2. Suffer from a multi-fleet nature of the problem;
3. Fail to handle external changes efficiently, such as delivery mission changes.

Problem Formulation

Can we set up a distributed framework for solving the platoon coordination problem?



Given:

the delivery task of every truck (including the origin, destination, route, travel time)

Problem:

when and where they should wait in order to maximize their own benefits from joining platoons.

Our solution:

→ *Distributed Model Predictive Control (DMPC)*

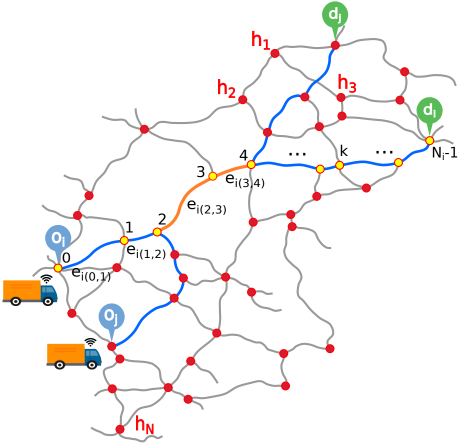
Network Description

The transport system is associated with $\mathcal{D}(\mathcal{H},\mathcal{E})$:

$$\mathcal{H}=\{h_1,h_2,\ldots,h_N\},\quad \mathcal{E}=\cup_{i=1}^{M}\mathbf{e}_{(o_i,d_i)}.$$

The **route** of truck i:

$$\mathbf{e}_{(o_i,d_i)}=\{e_{i(0,1)},e_{i(1,2)},\ldots,e_{i(N_i-2,N_i-1)}\}.$$



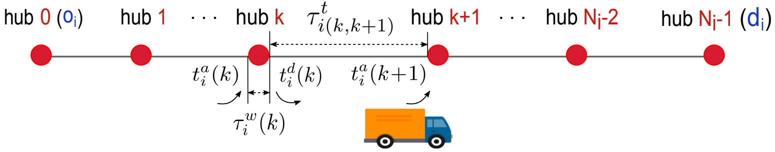
Common route segment:

$$e_{i(k,k+1)}=e_{j(k',k'+1)}$$

If $H_i(k)=H_j(k')$ and $H_i(k+1)=H_j(k'+1)$

Event-Triggered DMPC for Platoon Coordination

- Dynamical model:



For any truck i, its dynamics is of the form

$$t^a_i(k+1) = t^a_i(k) + \tau^w_i(k) + \tau^t_{i(k,k+1)}$$

$t^a_i(k)$: the arrival time of truck i at its k-th hub;
$\tau^w_i(k)$: the waiting time of truck i at its k-th hub;
$\tau^t_{i(k,k+1)}$: the travel time on $e_{i(k,k+1)}$.

$$x_i(k+1) = x_i(k) + u_i(k) + c_{i(k,k+1)}$$

where $u_i \in \mathcal{U}_i = \{u_i : \underline{\tau}^w_i \leq u_i \leq \bar{\tau}^w_i\}$.

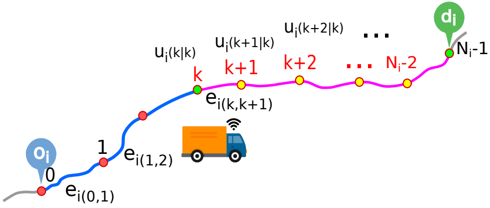
Event-Triggered DMPC for Platoon Coordination

- Utility function:

– *The predicted loss function*

$$L_i(k) := \sum_{h=0}^{N_i-2-k} \epsilon_i u_i(k+h|k)$$

where ϵ_i is the monetary loss per time for waiting.



– *The predicted reward function*

Definition 1: (*Potential partner set*) → *determined OFFLINE*

$$\mathcal{P}_i(k) = \{j : j \text{ have a common route segment with } i\}.$$

Definition 2: (*Predicted partner set*) → *optimized ONLINE*

$$\begin{aligned}\mathcal{R}_i(k+h|k) &= \{j : j \text{ is predicted to departure from the } (k+h)\text{-th hub together with } i\} \\ &= \{j : j \in \mathcal{P}_i(k+h) \wedge x_i(k+h|k) + u_i(k+h|k) = \hat{x}_j(H_i(k+h)) + \hat{u}_j(H_i(k+h))\}.\end{aligned}$$

Event-Triggered DMPC for Platoon Coordination

The predicted reward function of truck i at its k-th hub is

$$R_i(k) := \sum_{h=0}^{N_i-2-k} \xi_i c_{i(k+h,k+h+1)} \frac{|\mathcal{R}_i(k+h|k)|}{|\mathcal{R}_i(k+h|k)|+1}$$

where ξ_i is the monetary platooning benefit per follower truck and travel time unit.The utility function of truck i at its k-th hub is

$$J_i(k) = R_i(k) - L_i(k).$$

- The **DMPC problem** for platoon coordination:

$$\begin{aligned} \max_{\mathbf{u}_i(k)} \quad & J_i(k) \\ \text{s. t.} \quad & x_i(k) = t_i^a(k) \\ & x_i(k+1|k) = x_i(k) + u_i(k) + c_{i(k,k+1)} \\ & u_i(k+h|k) \in \mathcal{U}_i, \quad h \in [0:N_i-2-k] \\ & x_i(N_i-1|k) - t_i^{end} \leq 0 \end{aligned}$$

Event-Triggered DMPC for Platoon Coordination

- Event-triggered control scheme:

The event-triggering condition

$$t_{sys} = x_i(k) \quad \text{and} \quad k \neq N_i - 1$$

The optimization variable

$$\mathbf{u}_i^*(k) = [u_i^*(k), u_i^*(k+1|k), \ldots, u_i^*(N_i-2|k)]$$

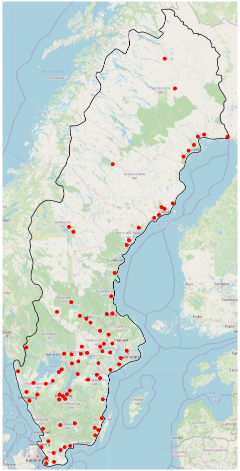
Algorithm 1: Event-triggered Distributed MPC for Platoon Coordination at Hubs

Input : $\mathcal{D}(\mathcal{H}, \mathcal{E})$, t_i^{start}, t_i^{end}, $\tau^t_{i(k,k+1)}$, $\underline{\tau}_i^w$, $\bar{\tau}_i^w$

Output: $\boldsymbol{u}_i^*(k)$, $\{\mathcal{R}_i^*(k+h|k)\}$

Initialization: $\boldsymbol{u}_i^*(0) \leftarrow \boldsymbol{0}$, obtain $x_i(k)$, $\hat{\boldsymbol{x}}_{-i}(H_i(k))$, $\hat{\boldsymbol{u}}_{-i}(H_i(k))$, $\mathcal{P}_i(k)$;
$\mathcal{S}_d \leftarrow \emptyset$;
$t_{sys} \leftarrow 0$;
while $t_{sys} \neq \max_{i \in \mathcal{M}} \{t_i^{end}\}$ **do**
  $t_{sys} \leftarrow t_{sys} + 1$;
  $\mathcal{S}_d \leftarrow \{i \in \mathcal{M} : t_{sys} = x_i(k) \wedge k \neq N_i - 1\}$;
  for $i \in \mathcal{S}_d$ **do**
    solve truck i's distributed MPC problem (16);
    update $x_i^*(k+h|k), u_i^*(k+h|k)$ at future hubs;
    return $\boldsymbol{u}_i^*(k)$, $\{\mathcal{R}_i^*(k+h|k)\}$.
  end
end

Simulation over Swedish Road Network

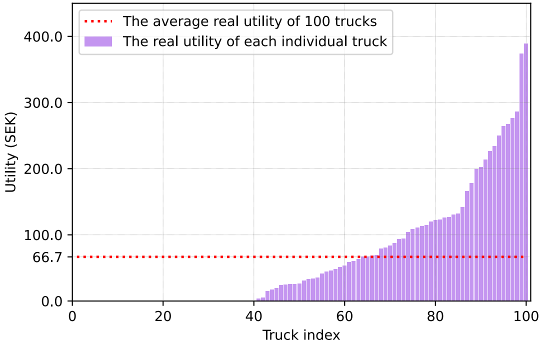


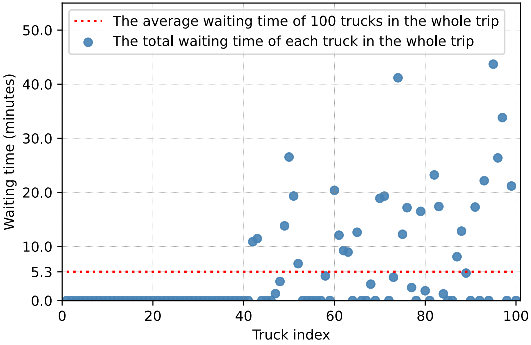
Parameter Settings:

- Consider 84 major hubs
- The OD pairs of trucks are randomly drawn from the hub-set
- The routes are obtained from *OpenStreetMap*
- Each truck starts its trip at a random time during 8:00-9:00
- The total maximal waiting time in the entire trip is 1 hour
- The maximal waiting time at a local hub is 30 minutes
- The fuel consumption of follower trucks is reduced by 10%
- The platooning benefit is $\xi_i = 57.6$ SEK per follower per hour
- The cost of waiting is $\epsilon_i = 45$ SEK per hour.

Simulation Results

– The utilities and waiting times of individual trucks

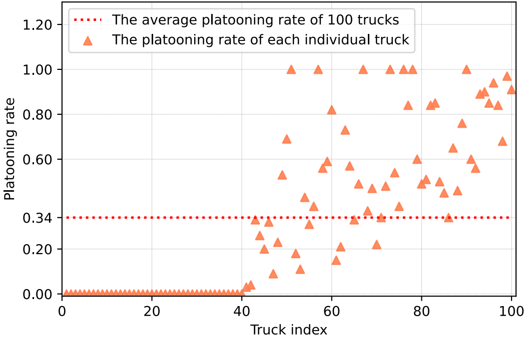


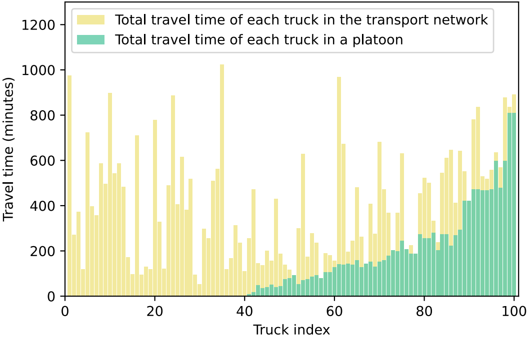


Simulation Results

– The platooning rate

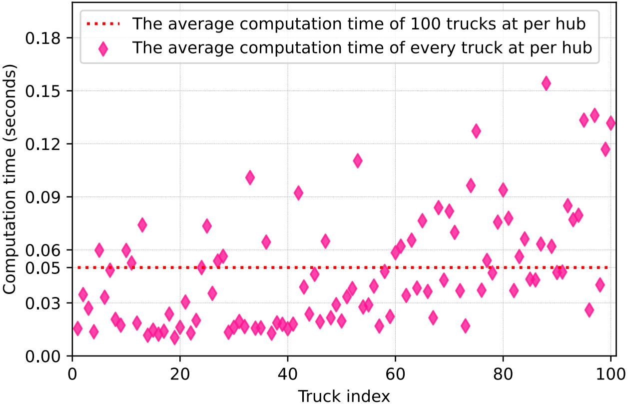
$$\mathbf{r}_i = \frac{\text{Total travel time of truck } i \text{ in a platoon}}{\text{Total travel time of truck } i \text{ in the network}}$$





Simulation Results

– Computational efficiency



Conclusions and Future Work

In this paper:

- An event-triggered DMPC approach was developed to address the hub-based platoon coordination in large-scale transport systems;
- A utility of individual trucks that captures the predicted reward from platooning and the predicted loss caused by waiting at hubs was presented;
- The performance of the proposed method was evaluated through a numerical example of one hundred trucks traveling in Swedish transport system.

Future work:

- Taking into account *stochastic travel times* in the platoon coordination

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