Approximate Dynamic Programming for Platoon Coordination under Hours-of-Service Regulations

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Platooning technology

Trucks driving in a platoon

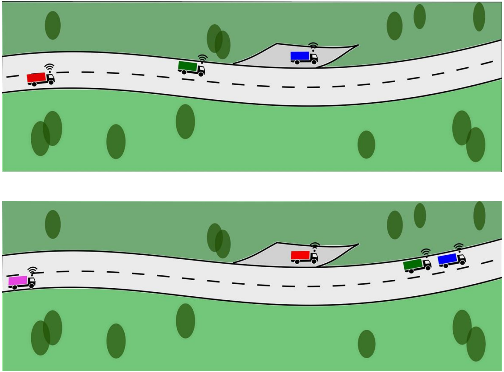
Platooning technology

Trucks driving in a platoon

Benefits:

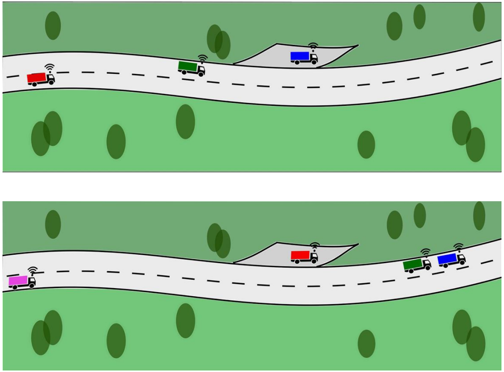
1) Increase road capacity
2) Save fuel
3) Reduce greenhouse gas emissions
4) Cut labor cost
5) Alleviate driver shortage
6) Enhance driving safety, etc

Platoon coordination



Hub-based platoon formation

Platoon coordination

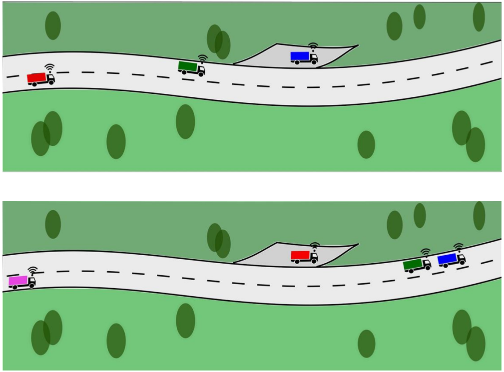


Hub-based platoon formation

	USA	EU	China
Continuous driving time (max.)	8 h	4.5 h	4 h
Mandatory rest time (min.)	30 min	45 min	20 min
Daily driving time (max.)	11 h	9 h	10 h

Hours-of-service (HoS) regulations

Platoon coordination



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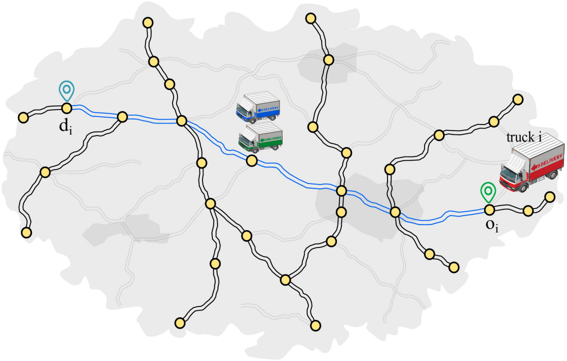
Hours-of-service (HoS) regulations

Our Problem: How to schedule trucks' waiting times at hubs to facilitate the formation of platoons while fulfilling the driving and rest time constraints?

System model



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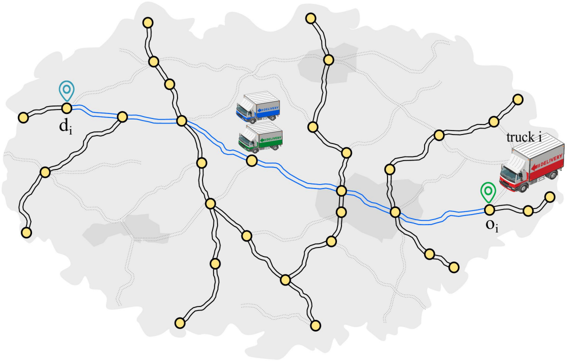

- Truck dynamics:

$$a_i(k+1) = a_i(k) + w_i(k) + \mathbf{1}_{\mathcal{H}_{i,r}}(k)t_r + \tau_i(k),$$

$a_i(k)$: arrival time at the k-th hub; $w_i(k)$: waiting time at the k-th hub;
t_r: the mandatory rest time; $\tau_i(k)$: travel time on the k-th road segment.

$$\mathbf{1}_{\mathcal{H}_{i,r}}(k) = \begin{cases} 1 & \text{if } k \in \mathcal{H}_{i,r}, \\ 0 & \text{if } k \notin \mathcal{H}_{i,r}. \end{cases}$$

Assumptions

- Maximum continuous driving time $\bar{t}_d$
- Maximum daily driving time T_d

- Example: EU's HoS regulations

driving	rest	driving
4.5 h	45 min	4 h

driving	rest	driving	rest	driving
3.5 h	45 min	4 h	45 min	1.5 h

Two feasible driving and rest time plans

$$\bar{t}_d = 4.5 \text{ h}, \; t_r = 45 \text{ min}, \; T_d = 9 \text{ h}$$

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1) Travel time on each road segment:
$\tau_i(k) \leq \bar{t}_d$

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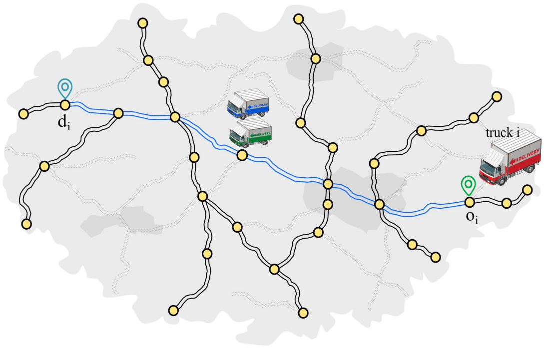
$\bar{t}_d = 4.5$ h, $t_r = 45$ min, $T_d = 9$ h

1) Travel time on each road segment: $\tau_i(k) \leq \bar{t}_d$

2) Travel time in the whole trip: $\sum_{k=1}^{N_i-1} \tau_i(k) \leq T_d$

Feasible rest hubs

- Given the travel times $\tau_i(k),\ k=1,\ldots,N_i-1$
  Determine offline the feasible rest hubs $\mathcal{H}^f_{i,r}$



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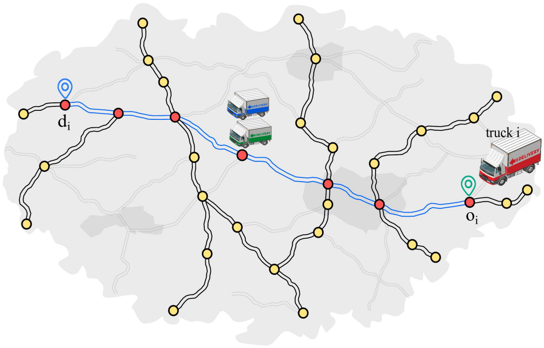

- **Zero rest time**: $\sum_{k=1}^{N_i-1} \tau_i(k) \leq \bar{t}_d \longrightarrow \mathcal{H}_{i,r}^f = \emptyset$

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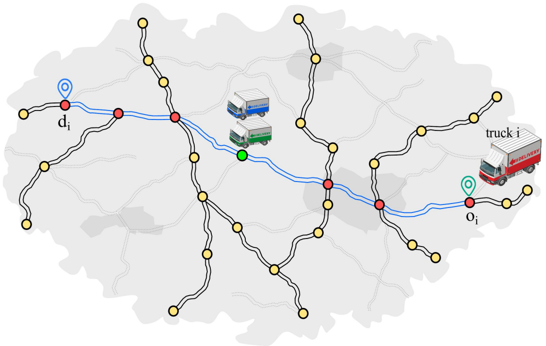

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- **One rest time**:

$$\sum_{k=1}^{\hat{k}-1}\tau_i(k)\le\bar{t}_d,\ \text{and}\ \sum_{k=\hat{k}}^{N_i-1}\tau_i(k)\le\bar{t}_d \longrightarrow \{\hat{k}\}\in\mathcal{H}^f_{i,r}$$

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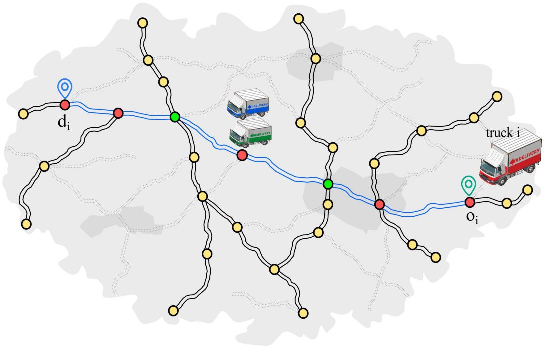

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- **Two rest times**:

$$\sum_{k=1}^{\tilde{k}-1}\tau_i(k)\le\bar{t}_d,\ \sum_{k=\tilde{k}}^{\hat{k}-1}\tau_i(k)\le\bar{t}_d,\ \text{and}\ \sum_{k=\hat{k}}^{N_i-1}\tau_i(k)\le\bar{t}_d \longrightarrow \{\tilde{k},\hat{k}\}\in\mathcal{H}^f_{i,r}$$

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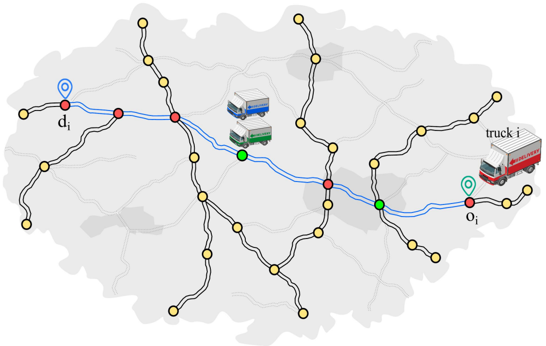

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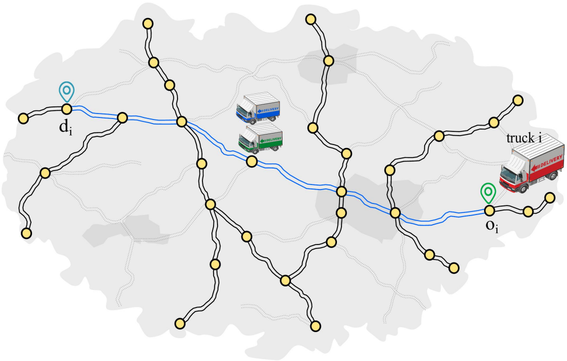
Distributed platoon coordination

- Target: $\mathbf{w}_i^*(k) = [w_i^*(k|k), \ldots, w_i^*(N_i-1|k)]$ and $\mathcal{H}_{i,r}^* \in \mathcal{H}_{i,r}^f$



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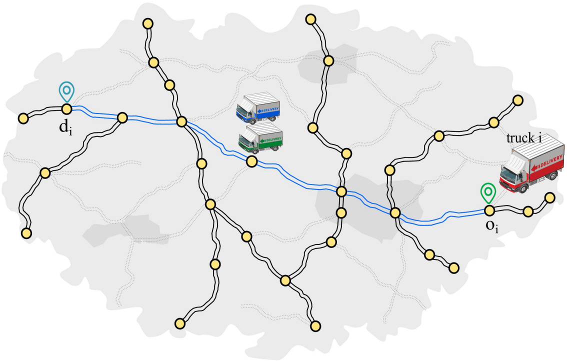
  $\rightarrow$ Predicted departure time of truck i: $a_i(k+h|k) + w_i(k+h|k) + \mathbf{1}_{\mathcal{H}_{i,r}(k)}(k+h)t_r$



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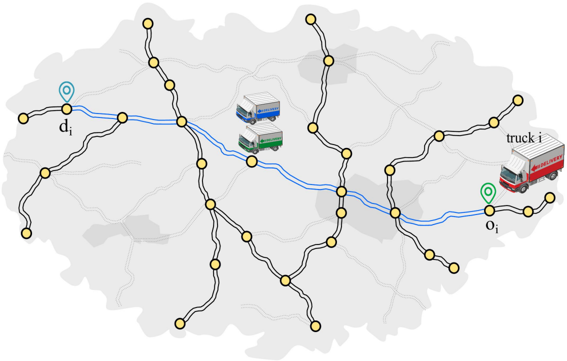

- Predicted platooning reward: $\quad R_i(k)=\sum_{h=0}^{N_i-1-k}\xi_i\tau_i(k+h)\frac{n_i(k+h|k)}{n_i(k+h|k)+1}$

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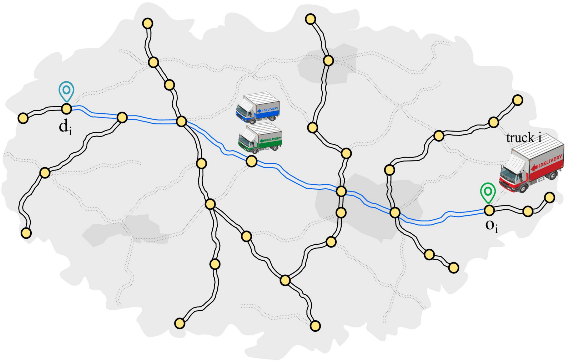
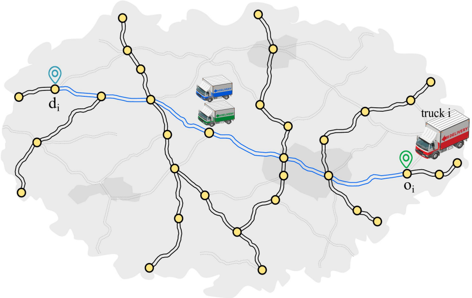


- Predicted platooning reward: $R_i(k) = \sum_{h=0}^{N_i-1-k} \xi_i \tau_i(k+h) \frac{n_i(k+h|k)}{n_i(k+h|k)+1}$
- Predicted waiting loss: $L_i(k) = \sum_{h=0}^{N_i-1-k} \epsilon_i w_i(k+h|k)$

Distributed platoon coordination

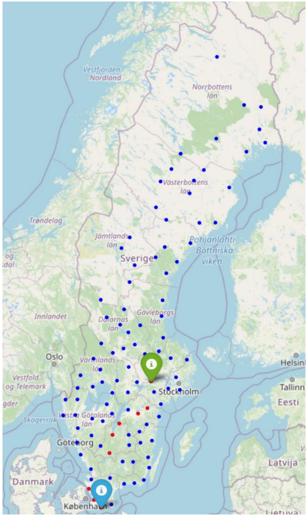


- Optimization problem (solved by *dynamic programming*):

$$\max_{\mathbf{w}_i(k),\mathcal{H}_{i,r}(k)\in\tilde{\mathcal{H}}^f_{i,r}(k)} \quad J_i(k) = R_i(k) - L_i(k)$$

$$\begin{aligned}
\text{s. t.} \quad & a_i(k|k) = t_{i,arr}(k)\\
& a_i(k+h+1|k) = a_i(k+h|k) + w_i(k+h|k) + \mathbf{1}_{\mathcal{H}_{i,r}(k)}(k+h)t_r + \tau_i(k+h),\\
& \qquad h = 0,\ldots,N_i-1-k\\
& a_i(N_i|k) \leq t_{i,end}
\end{aligned}$$

Simulation Study



The Swedish road network

- 105 hubs, 1000 trucks, EU's HoS regulations
- OD pair distribution from **SAMGODS**
- Routes from *OpenStreetMap*
- Trips start between 08:00-10:00
- Waiting budget is 5% of the total travel time
- Fuel consumption of follower trucks reduced by 10%
- Platooning benefit is 5.5€ per follower per hour
- Waiting loss is 25€ per hour

Simulation Study

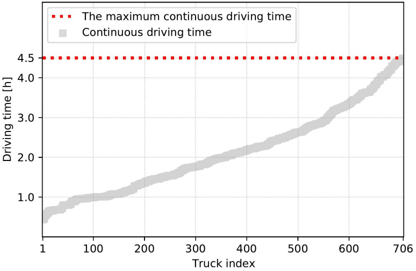
– Feasible rest hubs

	Zero rest time	**One rest time**		**Two rest times**	
Nr. of trucks	706	250		44	
Size of $\mathcal{H}_{i,r}^{f}$	0	$=1$	>1	$=1$	>1
Nr. of trucks	706	113	137	2	42

The number of rest times required for trucks

Simulation Study

– Continuous driving time of each truck



Zero rest time

Simulation Study

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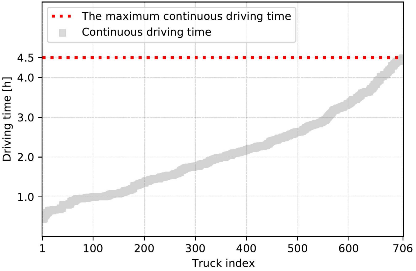

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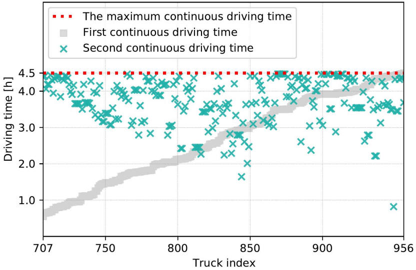

One rest time

Simulation Study

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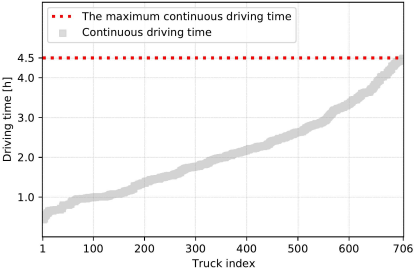
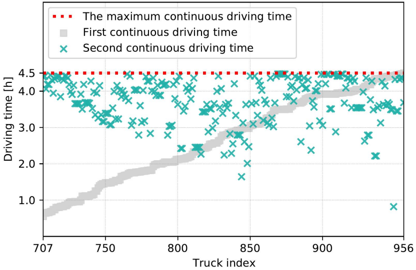
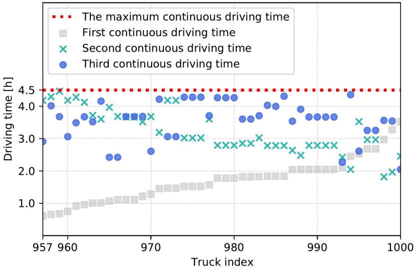


Zero rest time



One rest time

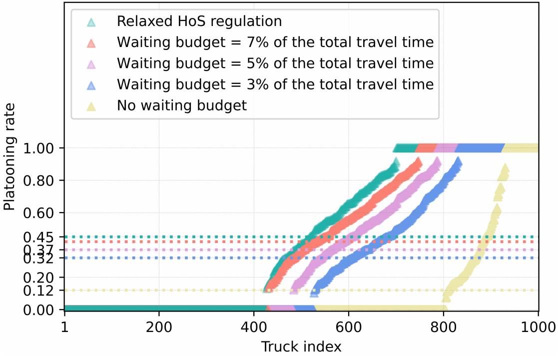


Two rest times

Simulation Study

– Platooning rate and utility

$$\text{Platooning rate of truck } i = \frac{\text{Truck } i\text{'s travel time } \textbf{in platoons}}{\text{Truck } i\text{'s travel in the road network}}$$



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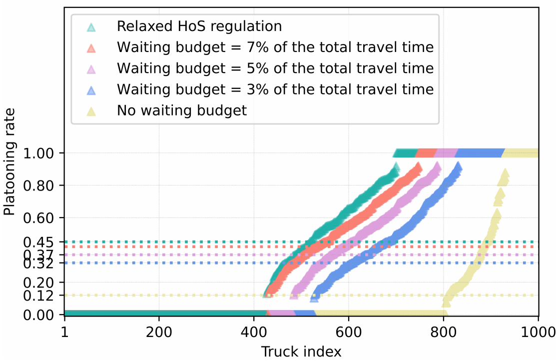

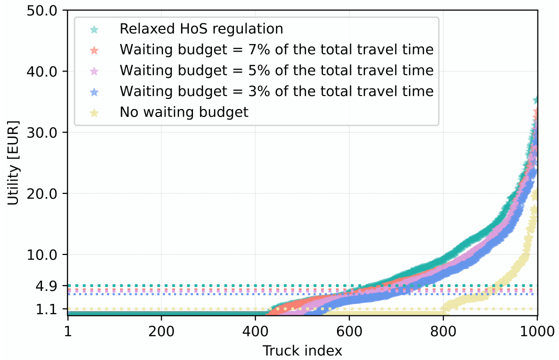

Conclusions

- A platoon coordination method is developed considering HoS regulations
- An approximate DP solution is presented where trucks' decision-makings are decoupled
- A large-scale simulation is conducted over the Swedish road network
  - Considerable platooning profits can be achieved under today's HoS regulations
  - Waiting budget plays an important role for achieving a high platooning profit

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Future work:

- Extend this work to capture less restrictive rest time constraints (30 min plus 15 min)
- Consider platoon coordination for electric trucks including HoS regulations