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Large-Scale Multi-Fleet Platoon Coordination: A Dynamic Programming Approach

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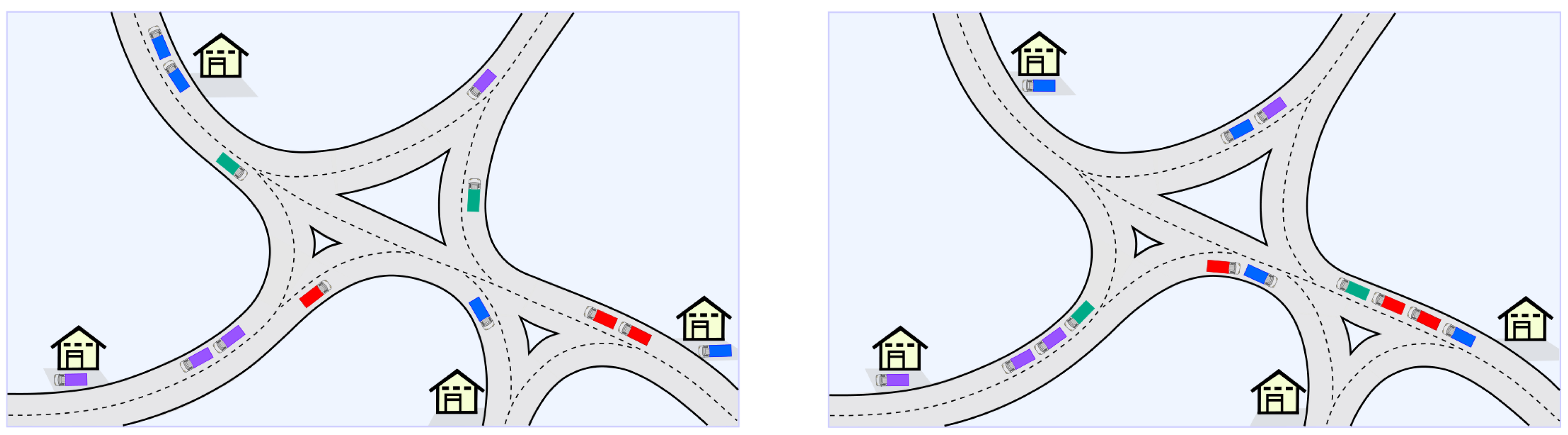
Problem Formulation

Problem: We study multi-fleet platoon coordination in large transportation networks, where each truck has a fixed route and aims to maximize its own fleet's platooning profit by scheduling its waiting times at hubs [1].



(a) Single-fleet platooning (b) Multi-fleet platooning

Figure 1: *Platoon coordination schemes.*

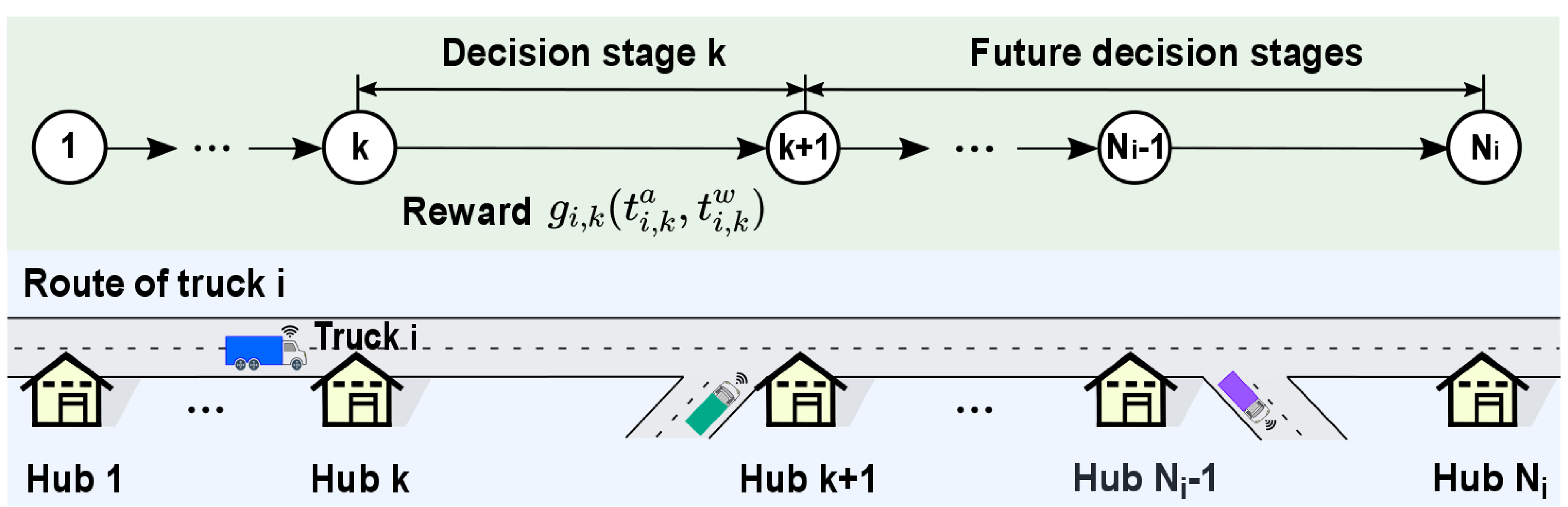


Figure 2: *Decision-making stages of truck i.*

- The dynamics of truck $i \in \mathcal{F}_s$:

$$f_{i,k}(t^a_{i,k}, t^w_{i,k}) = t^a_{i,k} + t^w_{i,k} + \tau(\boldsymbol{e}_{i,k}), \quad k = 1, \dots, N_i - 1,$$

where the waiting time at each hub $m = k, \dots, N_i - 1$ is restricted by

$$t^w_{i,m} \in \Gamma_{i,m}(t^a_{i,m}) = \left\{ t^w_{i,m} \,\middle|\, 0 \le t^w_{i,m} \le t^{dd}_i - t^a_{i,m} - \sum_{m=k}^{N_i-1} \tau(\boldsymbol{e}_{i,m}) \right\}.$$

- Platoon coordination problem solved by truck i at its hub k:

$$J^*_{i,k}(t^a_{i,k}) = \max_{\substack{t^w_{i,m} \in \Gamma_{i,m}(t^a_{i,m}), \\ t^a_{i,m+1} = f_{i,m}(t^a_{i,m}, t^w_{i,m}), \\ m = k, \dots, N_i - 1}} g_{i,N_i}(t^a_{i,N_i}) + \sum_{m=k}^{N_i-1} g_{i,m}(t^a_{i,m}, t^w_{i,m}), \tag{1}$$

where the <u>stage reward function</u> is modeled by

$$g_{i,m}(t^a_{i,m}, t^w_{i,m}) = \begin{cases} \xi\tau(\boldsymbol{e}_{i,m}) - \dfrac{\xi\tau(\boldsymbol{e}_{i,m}) p^{-s}_{i,m}}{\left(p^s_{i,m} + p^{-s}_{i,m} + 1\right)\left(p^s_{i,m} + p^{-s}_{i,m}\right)}, & \text{if } \mathcal{R}_{i,m}(t^a_{i,m}, t^w_{i,m}) \neq \emptyset \\ 0, & \text{otherwise,} \end{cases}$$

which captures the increased platooning reward of the fleet $\mathcal{F}_s$ contributed by truck i's waiting time decision at its hub m. The waiting loss that truck i causes to its fleet is captured by the <u>terminal reward function</u>

$$g_{i,N_i}(t^a_{i,N_i}) = -\epsilon_i \left(t^a_{i,N_i} - t^a_{i,k} - \sum_{m=k}^{N_i-1} \tau(\boldsymbol{e}_{i,m}) \right).$$

Methods

Challenge: The problem (1) is hard to address by gradient methods (as $g_{i,m}(t^a_{i,m}, t^w_{i,m})$ is non-differentiable) and by dynamic programming (DP) with uniform discretization (as $\Gamma_{i,m}(t^a_{i,m})$ is continuous and infinite).

(Optimality) The optimal value of $J^*_{i,m}(t^a_{i,m})$ can be achieved by solving the following Bellman Optimality Equation:

$$J^*_{i,m}(t^a_{i,m}) = \max_{t^w_{i,m} \in \Gamma^D_{i,m}(t^a_{i,m})} g_{i,m}(t^a_{i,m}, t^w_{i,m}) + J^*_{i,m+1}\big(f_{i,m}(t^a_{i,m}, t^w_{i,m})\big),$$

where

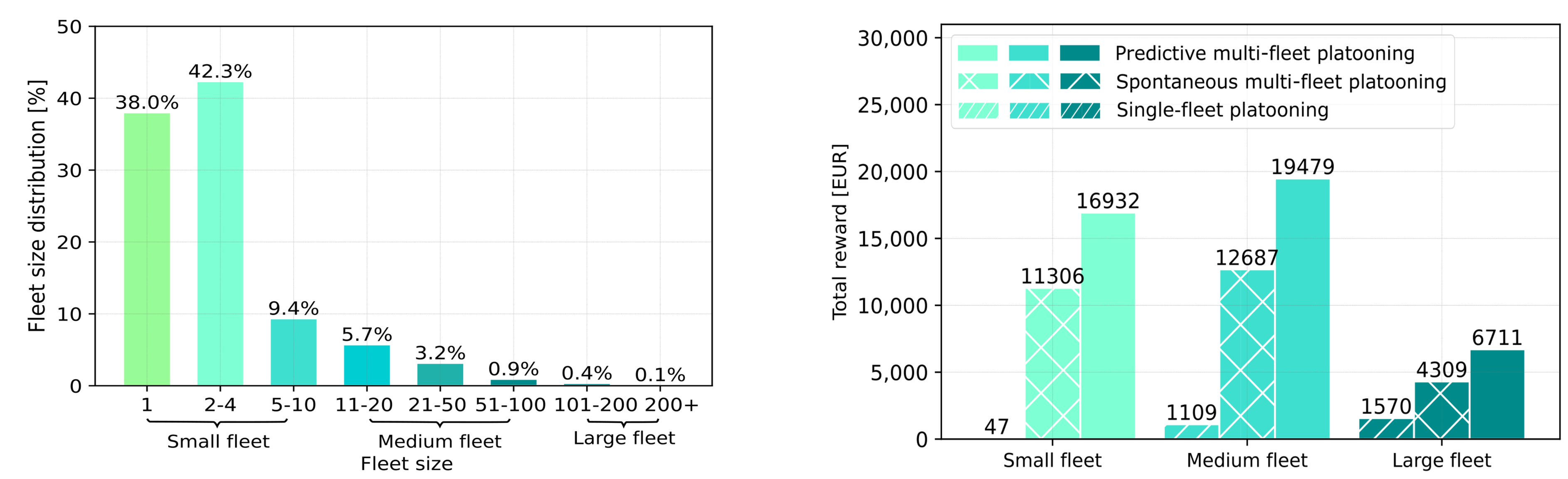
$$\Gamma^D_{i,m}(t^a_{i,m}) = \left\{ t^{d,j}_{i,m} - t^a_{i,m} \in \Gamma_{i,m}(t^a_{i,m}) \,\middle|\, j \in \mathcal{P}_{i,m} \right\} \cup \{0\},$$

and $t^{d,j}_{i,m}$ denotes the predicted departure time of other truck $j \in \mathcal{P}_{i,m}$.

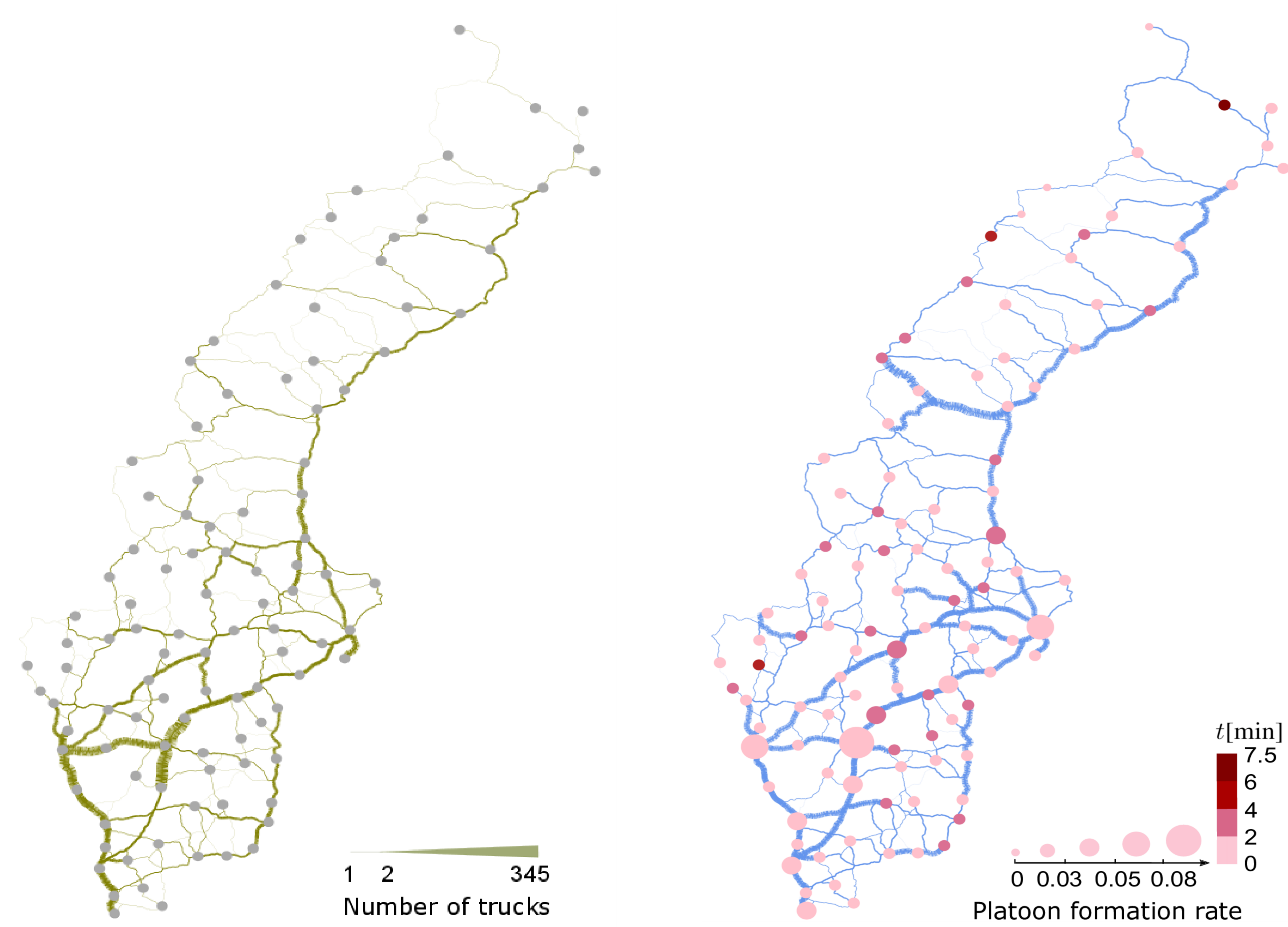
Complexity: Solving (1) by DP at the first hub has the computational complexity of $O(\tilde{n}N_i)$, where $\tilde{n}$ is no worse than $\max_{m \in \{1,\dots,N_i\}} |\Gamma^S_{i,m}|^2$.

Simulation Studies

- Setup: Truck flow from the SAMGODS model is used to obtain a realistic distribution of transport missions for 5,000 trucks from 855 fleets. Routes are attained via *OpenStreetMap*, and fuel saved from platooning is 10%.



(a) The fleet size distribution (b) Total rewards of fleets



(c) Road transport flow (d) Platoon formation rate

Figure 3: *Selected simulation results.*

- Computation efficiency: Over 96% of the decision-making instances take less than 5 seconds to compute the optimal waiting times.

References

[1] T. Bai, A. Johansson, K. H. Johansson, and J. Mårtensson, "Large-scale multi-fleet platoon coordination: A dynamic programming approach," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 12, pp. 14427-14442, 2023.