Cooperative Routing with Heterogeneous Vehicles

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ABSTRACT
Cooperation among different vehicles is a promising application for Mobility as a Service (MaaS). A primary problem is optimizing the vehicle routes. In this paper, we propose a new concept, named delegation, where heterogeneous vehicles cooperate to reduce the total travel cost. Our study models a case in logistics, where a large truck for long-distance delivery carries small self-driving cargoes for the last mile delivery, and the travel cost of the small ones is discounted. We define an optimization problem enabling delegation, propose its integer programming (IP) instance, and discuss our concept through numerical experiments using a modern IP solver.

CCS CONCEPTS
• Computing methodologies → Planning and scheduling;

KEYWORDS
Cooperative routing; Heterogeneous vehicles; Integer programming

ACM Reference Format:

1 INTRODUCTION
To cope with transportation-related social problem (e.g., traffic jams), we need to optimize the way we use our transportation systems. Services provided by autonomous vehicles in MaaS (Mobility as a Service) have the potential to solve the problem, where we need to optimize both the routes that vehicles take and the locations that are used for cooperation (e.g., transfers between vehicles or cross-docking in logistics). In ride-sharing applications, the optimization is critical to reducing the total service costs [1, 2, 4, 7].

Sharing transportation has attracted considerable attention when optimizing vehicle routes [3, 6, 8, 9]. Let us begin our discussion using Fig. 1 that illustrates operation of trucks. Traveling accompanied by sharing transportation is an approach to planning the trucks’ routes, where operators can reduce travel costs. They move trucks as a platoon as shown in Fig. 1a, because forming platoons decreases the air resistance on the vehicles. The value of this discount has been validated both theoretically and experimentally [3, 6], where the problem is formalized as vehicle platooning problem (VPP).

2 PROPOSED CONCEPT
2.1 Notations
For a natural number \( n \in \mathbb{N}^+ \), \([n] = \{1, 2, \ldots, n\}\). Let \( G = (V, E, w) \) be an underlying weighted directed graph with the set \( V \) of vertices, the set \( E \subseteq V \times V \) of edges, where an edge \((u, v)\) corresponds to the move from \( u \) to \( v \), and the weight function \( w : E \rightarrow \mathbb{R} \), which indicates the travel costs on \( G \). For two vertices \( u, v \in V \), the set of all paths connecting \( u \) and \( v \) is denoted by \( \Pi(u, v) \) and a shortest path between them is represented by \( \pi(u, v) \in \Pi(u, v) \).

We introduce two vehicle types: large and small, assuming that both vehicles have the ability to move, and several small vehicles can be carried by the large vehicle as shown in Fig. 1b. To distinguish between vehicles, we often identify a large vehicle by \( l \) and a small vehicle by \( s \). We let \( N_l \) (or \( N_s \)) be the number of large (or small) vehicles. We assume that each vehicle has its transportation request. A request is a pair of vertices \( r = (o, d) \in V \times V \). A path \( p \) satisfies the request \( r = (o, d) \) if and only if \( p \in \Pi(o, d) \).

2.2 Cooperation among heterogeneous vehicles
Following the vehicle types defined in Section 2.1, we consider four types of possible cooperation among large and small vehicles, labeled \( SS, SL, LS, \) and \( LL \). We name the cooperation among heterogeneous vehicles delegation, which results in the travel cost reduction for heterogeneous vehicles. We explain the effects arisen from the heterogeneity using Fig. 2. Here we can optimize the route of \( s_1 \). We would select the \( LS \) reduction to carry \( s_1 \) in \( l \) with its good as in Fig. 2a for the request when the platoon \( SS \) with \( s_2 \) illustrated in Fig. 2b is less effective than the effect of \( LS \). Although
we have four possible combination, we here focus on the LS effect to model truck-UAV cooperation, which is named 2MP3.

Problem 1 (2MP3). Given sets $\mathcal{R}_S = \{r_1^{(S)}, \ldots, r_{N_S}^{(S)}\}$ and $\mathcal{R}_L = \{r_1^{(L)}, \ldots, r_{N_L}^{(L)}\}$ of requests for small and large vehicles, 2MP3 involves computing $P_T = \{P_i | i \in [N_T], P_i \in \Pi(o_i^{(T)}, d_i^{(T)})\}$ for $T \in [S, L]$, and $\mu = \{(s, l, u, v) | s \in [N_S], l \in [N_L], u, v \in V\}$ that minimizes

$$c^{\text{(del)}}(P) = \sum_{(u,v) \in E} w((u,v)) \sum_{T \in [S, L]} g^{\text{(del)}, T}_u(v),$$

where

$$g^{\text{(del)}, T}_u(v) = \#(\text{leading } T_l \text{ vehicle at } (u,v))$$

Note that Constraint (3) defines the evaluated flow on $(u,v)$ from Eq. (1). Constraint (4) represents a small vehicle $s$ traveling alone if and only if no assignments are given from $s$ to $l \in [N_L]$ at $(u,v) \in E$. Constraint (5) indicates that $\mu_{u,v}^{s,l}$ can be 1 if and only if both $l$ and $s$ travels $(u,v)$. Constraint (6) represents the exclusiveness for assignment and the capacity constraint. Constraint (7) means that all requests are satisfied. Constraint (8) defines variables.

### 3 COMPUTATIONAL EXPERIMENTS

We evaluated our IP instance on synthetic graphs. In the experiments, we used labels $(N_L Q_l^{(LS)})$; the label $(N_L Q_l^{(LS)}) = (2,3)$ means the number of large vehicles is two and the capacity of each large vehicle is three. For the label $(N_L Q_l^{(LS)})$, we always prepare $N_L Q_l^{(LS)}$ small vehicles and generate $N_L Q_l^{(LS)}$ requests.

Settings and Results. For a $10 \times 10$ grid graph with noisy coordinates, we generated random requests. We then compare the travel costs of optimized solutions obtained by (1) shortest paths (labeled ST), (2) routes optimized by the 2MP3 (labeled 2MP3), and (3) routes optimized by the VPP, where no travel costs are required if cooperate, and evaluated as routes by 2MP3 (labeled VPP(2MP3)). Note that (3) is prepared to validate the effect of introducing four cooperation combination and that of focusing on the LS effect in 2MP3. For both (2) and (3), we use Gurobi to optimize the problems [5].

Figure 3 shows the obtained travel costs for labels $(N_L Q_l^{(LS)}) \in [2] \times [4]$. They indicated that the PPP achieved smaller travel costs than shortest paths. We can interpret that the PPP could utilize the LS effect in optimization. In contrast, travel costs optimized by the VPP were worse than the routes by the shortest paths. This was because the VPP, which cannot distinguish vehicle types, tried to form the four cooperation combination.

### 4 CONCLUSION

We propose a new concept, named delegation, to model heterogeneous cooperation of vehicles. Our IP instance can deal with two types (large and small) of vehicles, where small vehicles could board in large vehicles and the travel costs get discounted. We validated our IP formulation through experiments. Delegation can be applied to MaaS applications for transportation and logistics.

Our future work include the development of more general framework that supports different types of cooperation among more than two vehicles. Further, developing distributed solvers is also an important problem for our researches.
REFERENCES


