Cooperative Path Planning for Heterogeneous Agents

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Abstract
Cooperation among vehicles is a promising concept for path-planning in transportation services. For instance, vehicle platooning on highways decreases fuel consumption because it reduces the air resistance, and this makes us construct paths sharing sub-paths in platooning. We study a model that permits heterogeneous cooperation and discuss a path-planning problem under the assumption that heterogeneous cooperation benefits the objective function. In this paper, we provide experimental evaluations and simple heuristic solvers to observe the behaviors of the optimization problem.

Introduction
We focus on path-planning problems for multiple vehicles, where vehicles cooperate with others by sharing sub-paths (i.e., sub-routes). The problem with one vehicle type, named vehicle platooning problems (VPPs), has been studied in the transportation domain (Larsson, Senntom, and Larson 2015). In previous work, the generalized problem of VPPs on heterogeneous vehicle types have been studied (Otaki et al. 2019b; 2019a) and named cooperative path planning problems (CPP). The heterogeneity can reflect different discount (or increment) effects. They reported theoretical and computational aspects of the problem using integer programming (IP) solvers. However, some metrics of experiments with IP solvers (e.g., gaps and computational times) were not precisely evaluated in the previous studies. Also, only small synthetic graphs were used in the experiments. We here experimentally evaluate the existing IP models using larger instances. To discuss the computational hardness of the problem, we also compare the results using an IP solver with those obtained by simple heuristic solvers.

The CPP Problem
We follow the notations used in (Otaki et al. 2019a). Let $\mathcal{T}$ be a set of vehicle types and $\mathcal{C} \subseteq \mathcal{T} \times \mathcal{T}$ be a set of binary cooperation relation. For $(T_1, T_2) \in \mathcal{C}$, we say that vehicles of type $T_1$ are parent and those of type $T_2$ are children of the cooperation. Parameters $\eta_{(T_1,T_2)}$ are given to represent the benefit obtained from $(T_1, T_2)$ cooperation for $(T_1, T_2) \in \mathcal{C}$. In addition, for an undirected weighted graph $G = (V, E, w)$, sets $\mathcal{R}(T) = \{a_i^{(T)}, d_i^{(T)}\} \subseteq V \times V$ of travel requests are given for type $T \in \mathcal{T}$, where $N_T$ is the number of type $T$ vehicles and $\{N_T\} = \{1, \ldots, N_T\}$. The CPP problem is to simultaneously compute a set $\mathcal{P}$ of paths from $a_i^{(T)}$ to $d_i^{(T)}$ for each vehicle $t \in [N_T]$ of type $T \in \mathcal{T}$ that minimizes the sum of travel cost $C(\mathcal{P}) = \sum_{T \in \mathcal{T}, e \in E} w(e)g^{(T)}(e)$, where

$$g^{(T)}(e) := g^0(T) + \sum_{T' \in \mathcal{T}} \eta_{(T,T')} \cdot g^{(T')}(e),$$

$$g^0(T)(e) := |\{\text{Type } T \text{ parent at } e\}|,$$

$$g^{(T')}'(e) := \eta_{(T,T')} \cdot |\text{Type } T' \text{ child of } (T, T') \text{ at } e|.$$  

The value $g^{(T)}(e)$ represents the discounted effect of vehicles traveling along with $e$ on $G$, where particularly the term $g^{(T')}_{(T',T)}$ reflects the effect by cooperation with $\eta_{(T,T')}$. If $\eta_{(T,T')} < 1$, the effect reduces to benefit the objective function (as the fuel consumption is reduced in VPPs). If $\eta_{(T,T')} = 1$, the cooperation can be interpreted as just following shortest paths. Cooperation-wise capacity constraints (the max. number of vehicles taking $(T, T')$ in Eq.(1)) also imposed (see Def. 3 at (Otaki et al. 2019a)). The IP formulation to solve the problem above is provided in Appendix A. at (Otaki et al. 2019a).

Numerical Experiments
We extensively evaluate the IP formulation and simple heuristics based on shortest paths and graph matching on synthetic and real graphs obtained from OpenStreetMap. Experiments are conducted on a workstation with an Intel Xeon W-2145 CPU at 3.70GHz with 64GB of memory and Gurobi 8.1. Graphs $K$-d represent graphs obtained from Kyoto, Japan and those of $R$-d means synthetic graphs generated by (van de Hoef, Johansson, and Dimarogonas 2015)1. We only report results using clustered requests, which are generated as traveling from left to right on $G$.

Evaluation of IP formulation
We evaluate CPP for single vehicle type, which is equivalent to capacitated VPP, in

1The center of map $K$-$d$ is (lat, long)=(35.026244, 135.780877) and the value $d$ is the distance to extract graphs. For synthetic graphs, $d$ is set to be the number of vertices in $G$. Copyright © 2020, Association for the Advancement of Artificial Intelligence (www.aaai.org). All rights reserved.
Table 1: The mean computational times on CPP with one vehicle type and \( \eta^{(LL)} = 0.7 \) on K-500.

<table>
<thead>
<tr>
<th>( N_T )</th>
<th>Capacity ( Q = 1 )</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12.2 (11.1)</td>
<td>7.9 (5.0)</td>
<td>3.8 (3.8)</td>
</tr>
<tr>
<td>15</td>
<td>103.3 (170.1)</td>
<td>71.6 (133.4)</td>
<td>63.1 (135.5)</td>
</tr>
</tbody>
</table>

Figure 1: Results on clustered requests against MIPGap \( \theta \).

Table 2: IP solvers and heuristics are compared with respect to times (T). For heuristics, gap (G) means the ratio of scores based on the IP solver.

<table>
<thead>
<tr>
<th>Label</th>
<th>IP solver</th>
<th>Heuristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T [s]</td>
<td>(G)</td>
</tr>
<tr>
<td>K-500</td>
<td>106</td>
<td>+1.38</td>
</tr>
<tr>
<td>K-750</td>
<td>489</td>
<td>+1.38</td>
</tr>
<tr>
<td>R-300</td>
<td>534</td>
<td>+1.47</td>
</tr>
</tbody>
</table>

Conclusions and Future work

We studied the cooperation among heterogeneous vehicle types in path-planning and experimentally evaluate the difficulty of the problem in various aspects. Although the CPP problem is an abstract problem class from the viewpoint of mobility-as-a-service (MaaS) applications, this experimental study opens a new door on models that support cooperating heterogeneous vehicles with the travel costs discounted.

Our future work will include the developments of sophisticated solvers (e.g., anytime algorithms, taking time-synchronization into account) and efficient solvers that can find optimal solutions in large-scale problems.

References


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2 Note that \( Q^{(T_1 T_2)} \) is the capacity of cooperation \((T_1, T_2) \in C\).

3 This parameter cannot be directly compared to the resulted gaps since MIPGap is the gap between the upper and lower bounds. However, the value \( \theta \) is often related to the obtained gap as we see in Fig. 1 and it is applicable to observe the problem.