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Platoon coordination with time windows: an operational perspective

Wei Zhang*, Marcus Sundberg, Anders Karlström

Department of Transportation Science, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden

Abstract

It has been reported that platooning has the potential of saving fuel and increasing traffic throughput. We formulate a platoon coordination problem with soft time windows as a mixed-integer linear programming problem and solve it with exact solutions. The objective function consists of operation costs, schedule miss penalties and fuel costs. In the numerical example, a Swedish highway network model is used and the computation result shows that, for 21 vehicles, the total cost can be reduced by 3.5% when the optimal preferred arrival times are chosen. A random disturbance is then added to the optimal time windows and the optimal result shows great sensitivity with respect to the disturbance. When the mean of the disturbance becomes larger than 10 minutes, more than half of the platooning benefits will be lost. The study also analyzes the change of different cost compositions as disturbance increases.

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Keywords: Heavy-duty vehicle platooning; operational cost; time window; freight transportation.

1. Introduction

Platooning is to group multiple vehicles such that they drive closely in the same lane. It has been reported that platooning has the potential of saving fuel and increasing traffic throughput due to the reduced inter-vehicle distance and air drag (Bonnet and Fritz, 2000; Hucho, 2013; Hall and Chin, 2005). For the purpose of safe driving, vehicles should be equipped with adaptive cruise control (ACC) or cooperative adaptive cruise control (CACC) systems to enable autonomous driving. With the help of automatic control and wireless communication technology, coordinated heavy-duty vehicle (HDV) platoon formation becomes possible to be applied in reality.

Due to the fact that freight transportation by HDVs consumes a large proportion of the total fuel consumption, platooning of HDVs becomes a promising strategy to reduce fuel consumption and thus to relief the emission problem. Liang et al. (2014) investigate the spontaneous platooning rate of 1,800 HDVs by sparse vehicle position data and the result is 1.2%, whereas with coordination schemes, the platooning rate can be prompted to 6.97% by catch-up coordination and 10.76% by departure coordination, given that the coordination horizon is 20 km. In view of the

* Corresponding author.
E-mail address: wzh@kth.se (W. Zhang), marcus.sundberg@abe.kth.se (M. Sundberg), anders.karlstrom@abe.kth.se (A. Karlström)

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comparison between the spontaneous and coordinated scenarios, there should be necessity in exploring the strategy of platoon coordination so that the most fuel saving can be achieved.

Based on the time when the coordination plan is made, the platoon coordination strategies can be roughly divided into two categories, namely on-road coordination and off-road coordination. On-road coordination is the scheme where vehicles are grouped in real time, whereas off-road coordination strategy assigns the platooning plan to each vehicle before departure. On-road coordination can be responsive to the real-time traffic condition and this strategy is preferably to be carried out when there is a relatively high penetration of the targeted vehicles. In comparison, the off-road coordination decides the departure time, speed profile, waiting time or route ahead of time, which is suitable for the situation where the penetration is comparatively low. This study falls into the latter category.

There are a bunch of off-road platoon coordination strategies, using different models and decision variables. Larsson et al. (2015) propose integer-linear programming models to solve the platoon routing problems, without considering preferred arrival time. Kammer (2013) studies the platoon routing problem with deadlines, where vehicles are required to arrive no later than deadlines and waiting is not allowed for all departed vehicles. Van De Hoef et al. (2015) investigate the speed-dependent coordination problem with deadlines where the routes are predefined and vehicles form platoons by adjusting speed levels. It is worth mentioning that the objectives of all these models are to minimize the fuel consumption. Being aware of the NP-hardness of the platoon coordination problem, various algorithms are developed to solve large-scale problems (Larsson et al., 2015). A genetic algorithm (GA) is presented in Nourmohammadzadeh and Hartmann (2016) to solve the fuel optimization problem with hard deadlines. The exact solutions by the LINDO solver and the results obtained by GA are compared, where the latter shows high computation efficiency especially when the problem size increases. Global and local search heuristics can also be found in Larsson et al. (2015).

Although fuel cost has often been mentioned in previous studies, the operational cost has not been sufficiently examined. In practice, there will be trade-offs between driving time, arrival time and fuel consumption for individual vehicles, and at the aggregated level, the freight transportation companies will try to minimize the total operational cost instead of the fuel cost. Therefore, we propose an optimization model where the total cost is minimized, including operation cost, fuel cost and schedule miss penalty. In addition, soft time windows are used in this study instead of hard constraints, which makes the model more general than the models presented in previous studies. The model used in our research is essentially a vehicle routing problem with soft time windows, of which the comprehensive reviews can be found in Desrosiers et al. (1995). The aim of this study is to investigate the cost and benefits for companies of implementing platooning. The major concern is under what circumstances and to what extent the benefits will be offset by extra costs.

The paper is organized as follows. In Section 2 we formulate the problem as a mixed-integer linear programming (MILP) problem. The numerical example is presented in Section 3, and the problem is solved with exact solutions. The impacts of the disturbance are studied to reflect the sensitivity of the optimization result. Finally, Section 4 concludes the paper.

2. Problem formulation

2.1. Objective and cost composition

We consider the problem in the setting that a set of homogeneous vehicles $\{1, 2, ..., N\}$ are assigned with transportation tasks, one for each vehicle. Each vehicle is required to drive from origin *ori* to the corresponding destination *des* and the preferred arrival time window is given, denoted by $[t^{\mathrm{a}}, t^{\mathrm{b}}]$. The total cost consists of three ingredients: operation cost, fuel cost and schedule miss penalty, i.e.,

$$C_{\mathrm{total}} = C_{\mathrm{o}} + C_{\mathrm{f}} + C_{\mathrm{p}}. \tag{1}$$

We assume there is only one speed level, that is, any vehicle which traverses a specific link will have the same link travel time. Besides, all three kinds of costs are modeled as linear or pairwise-linear functions of time or time interval.

The operation cost can be denoted by

$$C_{\mathrm{o}} = w_{\mathrm{o}}(t^{\mathrm{des}} - t^{\mathrm{ori}}), \tag{2}$$