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Coordinated platooning with multiple speeds☆

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A B S T R A C T

In a platoon, vehicles travel one after another with small intervehicle distances; trailing vehicles in a platoon save fuel because they experience less aerodynamic drag. This work presents a coordinated platooning model with multiple speed options that integrates scheduling, routing, speed selection, and platoon formation/dissolution in a mixed-integer linear program that minimizes the total fuel consumed by a set of vehicles while traveling between their respective origins and destinations. The performance of this model is numerically tested on a grid network and the Chicago-area highway network. We find that the fuel-savings factor of a multivehicle system significantly depends on the time each vehicle is allowed to stay in the network; this time affects vehicles' available speed choices, possible routes, and the amount of time for coordinating platoon formation. For problem instances with a large number of vehicles, we propose and test a heuristic decomposed approach that applies a clustering algorithm to partition the set of vehicles and then routes each group separately. When the set of vehicles is large and the available computational time is small, the decomposed approach finds significantly better solutions than does the full model.

1. Introduction

Improving the fuel efficiency of vehicles is essential to increasing energy independence and decreasing greenhouse gas emissions. To help reduce fuel consumption, the U.S. government sets higher fuel efficiency standards for passenger cars and heavy-duty vehicles (Harrington and Krupnick, 2012). In response to these regulations, automakers incorporate various engine technologies, including direct fuel-injection, turbocharging, and deceleration fuel shut-off (Navigant, 2014); they have also developed hybrid, fuel-cell, and pure-electric vehicles (Chan, 2007; Pollet et al., 2012). Fuel-efficiency technologies have a large potential market because they help consumers save money when fuel prices are high and they help meet efficiency standards. Most important, improving fuel efficiency is a necessary step toward environmental sustainability.

Vehicle platooning is another such promising fuel-efficient technology that involves coordinating multiple vehicles to form a trainlike grouping of vehicles on the highway. Vehicles in the platoon drive the same speed with small intervehicle distances. For safety and convenience, it is common to consider a maximum platoon length so that, for example, platoons will not block freeway exits.

Vehicles driving in a platoon can save fuel because they experience less aerodynamic drag than when driving individually, especially for the trailing vehicles. The fuel-savings rate for a vehicle in a platoon depends on many factors including the accuracy of the navigation system, the cruising speed, the intervehicle distance, the vehicle weight, and the traffic condition. Different rates of

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fuel reduction for a platooned vehicle have been reported from field experiments. Specifically, Browned et al. (2004) investigated a two-truck system and reported that fuel savings of 10–12% and 5–10%, respectively, for the trailing truck and leading truck when the intervehicle spacing was 3–10 m. Lu and Shladover (2011) reported that when a dedicated short-range communications system was used to accurately coordinate the platoon of three class-8 tractor-trailer trucks, the fuel saving for the lead truck and trailing trucks were, respectively, 4–5% and 10–14% when the intervehicle gap was 6 m. Lammert et al. (2014) reported experiments of platooning class-8 trucks over a range of speeds, intervehicle gaps, and mass. They showed that the trailing trucks achieved fuel reduction in the range of 2.8–9.7% with speeds between 55 and 70 mph, gross vehicle weight 65–80 T, and intervehicle gap 20–75 ft. Roberts et al. (2016) conducted a comprehensive investigation on two-truck platooning, in the presence of traffic on the highway and various terrain conditions. They found that the real-world fuel saving of two-truck platooning is likely to be 4% on average across the two trucks. Early field experiments with a more ideal setting showed that the fuel reduction rate for trailing vehicles was approximately 21% and 16% at a speed of 80 km/h with an intervehicle gap of 10 m and 16 m, respectively, while the fuel reduction rate was 16% and 10% with respect to the above intervehicle gaps at a speed of 60 km/h (Bonnet and Fritz, 2000). To maintain a constant speed and a constant intervehicle gap during cruise, researchers have studied the implementation of wireless communication and navigation systems, including dedicated short-range communication, adaptive cruise control, and GPS, have been (Lu and Shladover, 2011; Nowakowski et al., 2011). Research in developing control systems to help forming stable platoons for safety and fuel-saving purposes has also been performed (Li et al., 2013; Ghasemi et al., 2015; Liang, 2016; Liang et al., 2013; Wang et al., 2012) along with studies of platoon-formation strategies under various road conditions and related communication protocols (Hobert, 2012).

In contrast to most of existing research on vehicle platooning that concerns intervehicle communication (Jia et al., 2014; Jia and Ngoduy, 2016), adaptive cruise control (Milanés and Shladover, 2014; Tuchner and Haddad, 2017), and platoon-forming heuristics (Saeednia and Menendez, 2016; Bang and Ahn, 2017; Tuchner and Haddad, 2017), our research focuses on modeling the route, speed, and schedule selection problem for a set of vehicles with different origins and destinations in order to minimize the total fuel consumed by the group. These optimal routes, speeds, and schedules can then be sent to each vehicle, for example via GPS instructions in an intelligent transportation system integrated with a central office and other necessary infrastructures (Liang, 2016). Such coordinated routing has occasionally been studied. Liang et al. (2013) applied mechanical principles to model and simulate fuel consumption of an individual truck in the process of catching up to a platoon. Liang et al. (2014) investigated an 1,800 heavy-duty vehicle system spreading over a regional road network and developed map-matching and path-inference algorithms to identify platooning opportunities; see Liang (2016) for more details about platooning modeling and simulation. Baskar et al. (2013) proposed a mixed-integer linear programming that minimizes the total travel time of a set of platoons. Larson et al. (2015) sought to minimize the total fuel consumption of concerned vehicles distributed in a transport network by routing and scheduling them to form or leave platoons. Larsson et al. (2015) showed that finding an optimal routing and schedule for an arbitrary set of vehicles is NP-complete, but modeling techniques that exploit constraints common to many platooning networks have been shown to greatly decrease the time to solve such problems (Larson et al., 2016). Rather than centralized control, other researchers consider a distributed network of controllers that collect information from nearby vehicles and identify opportunities for these vehicles to share some subset of edges (i.e., road segments) in order to save fuel (Kammer, 2013; Liang, 2014).

Maiti et al. (2017) develop a conceptual scheme of vehicle platooning operations and logical building blocks that can be used to standardize complex platooning behaviors, but do not address optimization of platoon operations. Zhong et al. (2017) develop a multiobjective optimization framework that accounts the mobility, safety, driver comfort, and fuel consumption of a single platoon. A stochastic model of the formation and deformation of a single platoon is studied in Li (2017a,b). The closest related research is that of Boysen et al. (2018) which investigates an identical-path truck platooning problem, in which all trucks have the same origin and destination but with different departure windows, and the goal is to minimize the total fuel consumption. They show that if the fuel cost of a platoon as a function of the number of trucks in the platoon has certain properties such as linearity or concavity, the problem can be solved in polynomial time complexity when departure time windows meet some regularization conditions. (Note that this problem setting is a special case of previous research (Larson et al., 2016).) The literature review of Bhoopalam et al. (2018) provides a comprehensive literature review and possible future research directions, especially highlighting the need for optimization in platoon routing and scheduling.

The previous work on optimal platoon routing and coordination that we are aware of assumes that all vehicles traverse a given edge at the same speed. In this paper, we extend the model from Larson et al. (2016) to investigate a coordinated platooning model with multiple speed options (CPMS) for each vehicle. This model is presented in Section 2, and a range of experiments are described in Section 3. Since the fuel consumption of traveling a unit distance varies at different speeds, this modification provides vehicles more opportunities to save fuel and more flexibility in satisfying their arrival time requirements. In Section 4, we describe numerical experiments of our CPMS model when the fuel-savings rates are assumed to be more conservative and vehicles are not allowed to wait at intermediate nodes. In all numerical tests, we disregard the additional fuel costs of vehicles adjusting speeds. We also assume that all vehicles are able to traverse any road at any allowed speed. The CPMS model applies equally to any set of vehicles, trucks or cars or a mix of vehicle types, provided that any vehicle can platoon with another. (Naturally, different vehicle types will require different fuel-savings rates to be specified. Although CPMS considers cars and trucks are equally in terms of their coordinated routes, there are various technical challenges that must be addressed to ensure the safety of mixed-vehicle platoons.) Vehicle order within platoons can be taken into account if necessary. We assume no congestion is present in the network. In Section 5, we develop a heuristic decomposed method to find approximate solutions to centralized platooning problems with 1,000 vehicles by dividing the vehicles into groups. The grouping criterion is to minimize differences in the origins/destinations and starting/destination times among vehicles in the same subgroup; this is achieved by applying a clustering algorithm on a metric space of vehicles.