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Freight transport platoon coordination and departure time scheduling under travel time uncertainty

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ABSTRACT

The paper formulates and analyzes a freight transport platoon coordination and departure time scheduling problem under travel time uncertainty. The expected cost minimization framework accounts for travel time cost, schedule miss penalties and fuel cost. It is shown that platooning is beneficial only when scheduled arrival times differ less than a certain threshold. Travel time uncertainty typically reduces the threshold schedule difference for platooning to be beneficial. Platooning in networks is less beneficial on converging routes than diverging routes, due to delay at the merging point. The model provides valuable insights regarding platooning benefits for freight transport planning.

1. Introduction

A platoon is an array of vehicles that drive together with short inter-vehicle distances in the same lane. The concept of platooning was originally proposed by California Partners for Advanced Transportation TecHnology (PATH) (Varaiya, 1993). Since then, the topic has attracted interest from researchers in automatic control, wireless communication and other areas, mostly devoted to maneuvering vehicles efficiently and safely when driving closely to each other. Ideally (i.e., when communication latency is neglected and the entire system functions properly), the vehicles in the platoon act almost simultaneously if equipped with adaptive cruise control (ACC) or cooperative adaptive cruise control (CACC) systems.

The benefits of platooning have been asserted in a number of studies. Hucho (2013) reported a reduction in air drag coefficient by about 22% for the second vehicle in a platoon with 50 m inter-vehicle distance, and about 32% reduction with 20 m distance. This slipstreaming effect occurs because of a reduction in the dynamic pressure at the tail. Even the leading vehicle obtains an air drag reduction of about 4% with 10 m distance. Regarding fuel consumption, experiments show that the following truck may save about 21% fuel with 10 m distance and constant speed 80 km/h, and the leading truck experiences about 7% reduced fuel consumption (Bonnet and Fritz, 2000). Given that vehicle CO_2 emissions are directly proportional to fuel consumption, simulations have showed that a 40% penetration rate of platooning among heavy-duty vehicles on highways can achieve a 2.1% reduction in total vehicle CO_2 emissions with 10 m distance (Tsugawa et al., 2011). The reduction is even greater with shorter distances.

Although there is no uniform legislation world-wide regarding safe driving distances between trucks, with the help of autonomous driving technology the safe distance can be very short. For example, Alam et al. (2014) have reported that when driving at the speed 90 km/h, a 1.2 m inter-vehicle distance can be maintained for two identical heavy-duty vehicles without any risk of collision. Under a worst-case scenario (considering system uncertainties), a 2 m distance will suffice.

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To make use of the advantages of platooning, a coordination strategy is needed. By coordination, vehicles may have to adjust their scheduled departure times to form a platoon so that the fuel consumption can be reduced. If the time constraints are soft (with penalties), changing departure times may give rise to other kinds of costs. The scheduling of vehicle departure times so that the vehicles involved can form platoons and reduce fuel consumption without inducing too much extra cost is therefore an important problem, in particular when travel times are uncertain.

The objective of this study is to formulate and analyze the platoon coordination and departure time scheduling problem under travel time uncertainty. No assumptions are made regarding the travel time distribution other than that it is continuous with support on the positive real axis. The paper considers the setting where platooning is planned in advance by a transport carrier in control of all involved vehicles. The transporter is assumed to minimize an expected transport cost function involving fuel cost, cost related to travel time (drivers' wages, opportunity cost, etc.), and schedule miss penalties in relation to a fixed scheduled arrival time. The decision variables considered are the departure times of the vehicles and the binary choice whether they should platoon or drive independently; no constraints in terms of pick-up time windows are assumed. It is assumed here that all vehicles involved are driven manually but are equipped with technology such as cooperative adaptive cruise control (CACC) systems, which facilitates driving with the short inter-vehicle distances required for fuel savings.

Platooning reduces fuel consumption, but may increase schedule miss penalties in cases where scheduled arrival times differ among vehicles. The trade-off between the two cost components determines whether it is more profitable to form a platoon and thus save fuel at the risk of incurring lateness or earliness penalty. The components of the transport cost are not independent of each other, which adds a level of complexity to the scheduling problem. In particular, travel time uncertainty influences both fuel consumption and schedule miss penalties. The paper demonstrates that travel time uncertainty has significant impacts on the benefits of platooning compared to independent driving, which have not been previously acknowledged in the literature.

The schedule miss cost component in the platoon scheduling problem builds on the model for a single trip originally formulated by Vickrey (1969). The model assumes that late or early arrival in relation to a scheduled arrival time are associated with costs that are proportional to the schedule miss, with typically a higher unit cost for late arrivals. Fosgerau and Karlström (2010) derive the optimal departure time in order to minimize expected schedule miss cost. The model is extended to chains of trips in Jenelius (2012), and to commuting for meetings in Fosgerau et al. (2014). The latter study assumes that each traveler seeks to minimize her own cost function in a non-cooperative game setting.

The paper first formulates the platoon scheduling problem for two vehicles with different scheduled arrival times on a common route and shows that the problem of minimizing total cost (schedule penalties, travel time cost and fuel cost) is convex. The impacts of the schedule difference and the travel time uncertainty on the optimal departure time and minimum expected transport cost are analyzed. It is shown that there exists a threshold schedule difference below which platooning is beneficial. The impact of travel time uncertainty on the threshold schedule difference is studied in a numerical example. The problem is then extended to network configurations of diverging and converging routes, respectively. It is shown that platooning on converging routes, where vehicles must coordinate at the merging point, leads to higher schedule miss and driving costs than on diverging routes, where vehicles split after platooning. This distinction is an effect of travel time uncertainty.

The remainder of the paper is organized as follows. Section 2 discusses relevant studies in the literature. Section 3 introduces the transport cost function and describes the modeling of driving cost, schedule miss cost and fuel cost. In Section 4, the scheduling problem for independent and platooning vehicles on a common route is formulated, and the impacts of different parameters are analyzed. A numerical example highlighting the trade-off between fuel savings and schedule miss penalties is given in Section 5. In Section 6, the problem is extended to networks of diverging and converging routes. Section 7 discusses extensions of the model to more vehicles. Section 8 concludes the paper.

2. Literature review

Research on vehicle platooning has so far been mainly driven by the technical requirements for safe and efficient autonomous driving. Some studies have considered vehicle sorting, merging and splitting at network nodes or at highway on-ramps and off-ramps. Hall and Chin (2005) focus on the formation and characteristics of platoons on ramps. They define a set of platoon formation strategies and develop analytical models for calculating performance measures. In the study, vehicles are allowed to form groups by lanes at highways on-ramps. Contet et al. (2006) present an approach for decentralized platoon control. The introduction of a multi-agent system provides both longitudinal and lateral control as well as merge and split capabilities. By simulation with the MaDKit (the Multi-agent Development Kit) platform, the control strategy shows flexibility with respect to obstacle avoidance and reliability. Similarly, Zhou et al. (2012) propose a higher-level longitudinal decentralized control algorithm targeting safety, highway capacity and energy efficiency improvement.

The introduction of heavy-duty vehicle platooning adds new possibilities for transport carriers to reduce fuel costs and emissions, but also increases the complexity of the transport scheduling and routing problem. Still, there is relatively little research on freight transport planning with platooning as a decision variable. A few studies have considered platoon routing and coordination in networks. In general, there are two types of platoon coordination modes based on the number of vehicles that participate in the system, referred to as off-road coordination and on-road coordination. In off-road mode, vehicles are