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Efficient Dynamic Programming Solution to a Platoon Coordination Merge Problem With Stochastic Travel Times ⋆

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Abstract: The problem of maximizing the probability of two trucks being coordinated to merge into a platoon on a highway is considered. Truck platooning is a promising technology that allows heavy vehicles to save fuel by driving with small automatically controlled inter-vehicle distances. In order to leverage the full potential of platooning, platoons can be formed dynamically en route by small adjustments to their speeds. However, in heavily used parts of the road network, travel times are subject to random disturbances originating from traffic, weather and other sources. We formulate this problem as a stochastic dynamic programming problem over a finite horizon, for which solutions can be computed using a backwards recursion. By exploiting the characteristics of the problem, we derive bounds on the set of states that have to be explored at every stage, which in turn reduces the complexity of computing the solution. Simulations suggest that the approach is applicable to realistic problem instances.

Keywords: Transportation, Platooning, Dynamic Programming, Uncertainty, Coordination

1. INTRODUCTION

Truck platooning is a promising technology that enables significant fuel savings for heavy vehicles. It leverages automatic control of inter-vehicle distances allowing for small longitudinal spacing between trucks without affecting safety. This reduces the air resistance of the trailing vehicles in the platoon effectively which translates into a reduction in fuel consumption. Other benefits include improved road utilization, increased safety, and decreased workload for the driver. Truck platooning has been successfully demonstrated by several vehicle manufacturers, e.g., (Besselink et al. (2016); Kunze et al. (2009); Tsugawa et al. (2001)).

The efficient management of platoon formation is a crucial ingredient for leveraging platooning (Janssen et al. (2015)). We propose to form platoons dynamically en route by slightly adjusting the speed of the vehicles. It has been shown that coordinating platooning centrally can improve the platooning rate and the system level reduction in fuel consumption significantly over spontaneous platooning where trucks form platoons if they happen to get into each others vicinity (van de Hoef et al. (2015)).

Platoon coordination has been approached on different levels of abstraction, including combination of platooning and routing (Larsson et al. (2015)), identification of promising platoon partners (Meisen et al. (2008)), as part of automated highway systems (Horowitz and Varaiya (2000)), and using local infrastructure based controllers (Larson et al. (2015)). Our previous work (van de Hoef et al. (2015)) proposes a framework in which pairwise plans are systematically composed into an overall coordination plan for all vehicles. The proposed planning assumes that the speed can be deterministically selected within a small range of feasible speeds. To this end, the upper bound on the speed on a road segment can be estimated by using historic data, traffic measurements and advanced prediction models (Wang and Papageorgiou (2005); Celikoglu (2014); Sun et al. (2003)). However, an accurate prediction of the travel times in a road network is a challenging task and even advanced prediction models leave some uncertainty. There is a wide scope of models that provide in addition to the expected travel time its distribution, typically with the goal of quantifying the reliability of road infrastructure, for instance, Kim and Mahmassani (2014); Hofleitner et al. (2012); Jenelius and Koutsopoulos (2013); Tu et al. (2007); Wang et al. (2016).

In this paper, we consider a scenario where two vehicles should merge at the intersection of their routes. One of the vehicles has a fixed reference speed while the reference speed of the other vehicle can be adjusted, fitting in the framework of van de Hoef et al. (2015). The objective is to control the second vehicle to maximize the probability of both vehicles arriving at the intersection with a time difference less than a given threshold. At the same time, this probability is to be computed as an input to the higher planning layer that combines pairwise plans into a plan for all vehicles that are coordinated by the platoon service provider at a given point in time. The considered distances to the merge point are larger than in settings like Koller

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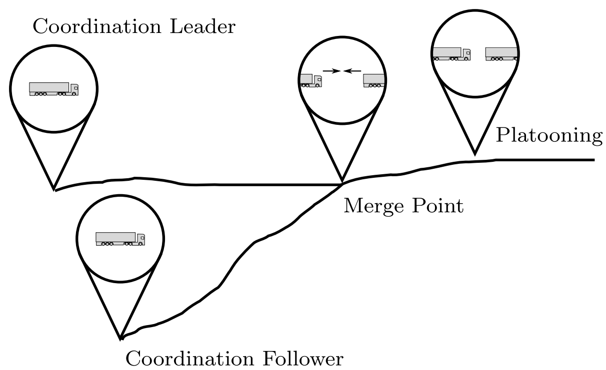

Fig. 1. In the considered scenario, two vehicles are to merge into a platoon at the intersection of their routes by adapting their speed on the way leading to that intersection.

et al. (2015); Rios-Torres and Malikopoulos (2016) and references therein, where vehicle dynamics and potentially all vehicles in the control zone can be explicitly considered. Liang et al. (2015) have employed traffic flow theory in a scenario where one vehicle catches up to the other on the same road. The main contribution of the paper is to formulate the platoon coordination merge problem in the framework of stochastic dynamic programming, which yields a controller that maximizes and explicitly computes the probability of a successful merge. Furthermore, we derive how to bound the subsets of states that need to be explored which is a prerequisite to computing solutions. By allowing for a freely selectable error tolerance these bounds are further improved. The method is demonstrated in a simulation example.

The outline of the remainder is as follows. The problem is formally modeled in Section 2. In Section 3, we formulate the dynamic programming solution and show how computing solutions can be made tractable. Section 4 discusses simulation examples demonstrating the effectiveness of the method. Section 5 concludes the paper and outlines future work.

2. PROBLEM FORMULATION

Consider the scenario depicted in Fig. 1 of two vehicles approaching an intersection at which they are supposed to merge into a platoon. One vehicle, the coordination leader, is controlled to arrive at the merge point at a specified point in time, and the other vehicle, the coordination follower, is controlled to maximize the benefit from platooning with the coordination leader. This is motivated by the framework introduced in van de Hoef et al. (2015), where several coordination followers are independently assigned to a coordination leader as the result of a discrete optimization problem.

First, we model the movement of a single vehicle until the merge point. We consider that the route is partitioned into a finite number of segments. We consider discrete time and represent it as integers where the measurement unit is such that one increment corresponds to a sufficiently small discretization interval. The traversal time T^i of the i-th segment is a random variable. Let $t^i \in \mathbb{Z}$ be the time the vehicle starts traversing the i-th route segment, in the following referred to as segment arrival time.

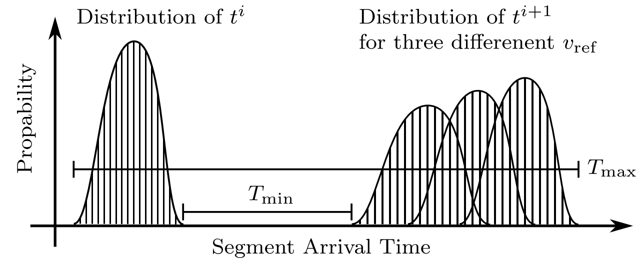

Fig. 2. Illustration of how the distribution of t^i and t^{i+1} are related for different reference speeds v_{ref}.

The arrival time at the next segment is the sum of the arrival time at the previous segment and the traversal time of the segment:

$$t^{i+1} = t^i + T^i. \tag{1}$$

The traversal time $T^i \in \mathbb{Z}$ is a random variable that is assumed only to be dependent on the reference speed at the i-th segment $v^i_{\mathrm{ref}} \in \mathbb{V}$, which is considered to be a control input. The domain of $\mathbb{V}$ is a finite set of reference speeds. It is assumed that $T^i_{\min} \le T^i \le T^i_{\max}$, see Fig. 2.

Since T^i is assumed to depend only on the control input v^i_{ref}, eq. (1) describes a Markov decision process where t^i denotes the value of its state at the i-th stage and $\mathbb{V}$ is the set of actions. Note that the stages in the decision process correspond to locations. Let $p_{T^i}(\tau|v^i_{\mathrm{ref}})$ denote the probability of $T^i = \tau$ conditioned on v^i_{ref}. The transition probability between state t^i to t^{i+1} is the probability that $T^i = t^{i+1} - t^i$, and thus the probability distribution of t^i can be recursively computed as

$$\begin{aligned} p_{t^{i+1}}(\mathtt{t}) &= \sum_{\tau=-\infty}^{\infty} p_{T^i}(\tau|v^i_{\mathrm{ref}}) p_{t^i}(\mathtt{t}-\tau) \\ &= \sum_{\tau=T^i_{\min}}^{T^i_{\max}} p_{T^i}(\tau|v^i_{\mathrm{ref}}) p_{t^i}(\mathtt{t}-\tau). \end{aligned} \tag{2}$$

Note that p_{T^i} can also be modeled conditioned on the segment arrival time t^i to reflect that travel time distributions are time dependent. Let t^i_ℓ denote the segment arrival time of the coordination leader at the i-th segment of its route. We consider that the reference speed of the coordination leader is given as v_ℓ and its start time t^{S}_ℓ is known meaning that $p_{t^1_\ell}(\mathtt{t}) = 1$ if $\mathtt{t} = t^{\mathrm{S}}_\ell$ and $p_{t^1_\ell}(\mathtt{t}) = 0$ otherwise. Let N_ℓ be the index in the coordination leader's route at which the coordination leader and the coordination follower are supposed to meet. The probability distributions of $t^{N_\ell}_\ell$ are recursively computed from (2).

We assume that a coordination leader and a coordination follower can platoon if they arrive at the merge point with an absolute time difference of at most Δt, which is chosen small enough so that they can establish vehicle-to-vehicle communication and initiate a merge maneuver.

The probability of platooning conditioned on that the arrival time of the coordination follower at the merge point $t^{N_{\mathrm{f}}}_{\mathrm{f}} = \mathtt{t}$ is