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Synthesis of a behavior-guided controller for lead vehicles in automated vehicle convoys[☆]

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ABSTRACT

Reliable cooperative adaptive cruise control on highways requires the lead vehicle of a vehicle convoy to be capable of resisting disturbances outside the convoy. This paper proposes a controller synthesis approach adopting behavior classification to improve the lead vehicle's ability to deal with outer disturbances. First, a behavior classifier is developed based on hidden Markov models to detect dangerous driver behaviors of surrounding traffic participants. The classification results with corresponding predicted trajectories are then imported to a model predictive controller for the lead vehicle. A behavior-guided cost function of the controller is carefully designed to react to behavior differences and to contribute to convoy string stability. The impact of the lead vehicle's state deviation on the convoy is studied based on leader-to-formation stability properties. Furthermore, a nonlinear bound is also given to state the performance of the proposed controller. Simulations of a cut-in scenario are conducted using the CarSim simulation environment to show the effectiveness of the proposed controller.

1. Introduction

Cooperative adaptive cruise control (CACC) plays an important role in building automated highway systems. By specifying proper inter-vehicle spacing and traveling velocities, CACC has the potential of increasing highway traffic capacity and improving vehicle fuel economy [1,2] that has been widely investigated from other ground traffic management systems (see, e.g., [3–5]). To ensure the performance of a vehicle convoy comprising a string of vehicles, CACC schemes are required to be capable of attenuating spacing errors uniformly down the vehicle string, which is also known as string stability. Typically, this property is achieved by designing controllers of convoy followers to meet desired criteria, e.g. bounding the H_∞ norm of the closed-loop transfer function [6]. With the development of reliable sensors and wireless communication technologies, string stable controllers have been proposed using various control approaches [7–9] and different spacing strategies [10]. For a vehicle convoy traveling on the highway, CACC performance is affected not only by error attenuation capability of convoy followers but also by state deviation magnitude of the lead vehicle. Large state deviations of the lead vehicle can cause non-negligible fluctuations of the overall convoy, which could degrade performance of the convoy even if it is string stable. Moreover, complicated maneuvers of vehicles around the lead vehicle make inevitable disturbances to the lead vehicle. Therefore, it is undesirable to regulate such disturbances using control schemes with conservative spacing-based strategies since the impact of state deviation of the lead vehicle on followers is not considered. A control scheme for the lead vehicle is required that can improve convoy performance by properly dealing with the exogenous disturbances.

To optimize CACC performance, the controller for the lead vehicle must be able to effectively minimize state deviations and spacing fluctuations while guaranteeing a safe headway. Out of this arise two problems that need to be addressed, i.e. i) accurate trajectory prediction and ii) driver intention detection of surrounding vehicles. For the first portion, accurate trajectory prediction makes it possible to reduce state deviations by controlling the lead vehicle in a predictive way. Several approaches to trajectory prediction have been proposed using model-based methods [11,12]. In addition to vehicle models, differences between driver intentions and behaviors have also been considered to improve prediction performance [13–15]. Sorstedt et al. [15] showed that improved prediction ability was obtained by taking into account the estimation of driver input. For the second portion, understanding intentions of surrounding traffic participants is essential for the controller to intervene proactively and to determine proper reference state, e.g. set a larger headway for the lead vehicle when detecting a dangerous cut-in maneuver of the preceding vehicle. Many approaches based on probabilistic models have been developed to detect and

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predict driver intentions [14,16]. Among these models, the Hidden Markov Model (HMM) is widely used since it concisely expresses the unobservable driver states as a hidden Markov chain [16]. Gadepally et al. [17] applied HMM to driver intention prediction at intersections. Their results showed advantages of HMM classifiers compared to a common K nearest neighbors (KNN) algorithm. In addition to intention recognition and maneuver-level prediction, classifying different driver behaviors of a predicted maneuver for convoy CACC is also critical since the behavior difference is coupled with trajectory prediction. As more naturalistic driving data sets are collected and analyzed, it becomes possible to train classifiers that are able to detect dangerous driver behaviors. Aoude et al. [18] proposed an HMM-based classifier to classify compliant and violating behaviors at an intersection. Validation of their approach on naturalistic driving data showed consistent improvements compared to threshold-based approaches.

This work proposes a controller synthesis approach for the lead vehicle that adopts behavior classification of vehicles out of a convoy to improve convoy CACC performance. The main idea is to minimize the state deviation of the lead vehicle when surrounding vehicles behave normally, and to implement a conservative control law if a vehicle behaves dangerously. The binary classification over all possible driver behaviors alleviates the computational load while still making it possible to separately control dangerous scenarios that have a higher likelihood causing traffic crashes. Specifically, the driver behavior of a surrounding vehicle is classified using an HMM-based classifier by analyzing the estimations of vehicle dynamics. The trajectory of this vehicle is predicted considering the classification result, and imported to a model predictive control (MPC) scheme for the lead vehicle. MPC-based vehicle controller synthesis can achieve effective inter-vehicle spacing regulation due to its receding horizon optimization property [19]. Approaches based on MPC in vehicle convoy control can be found in, e.g., [19–21].

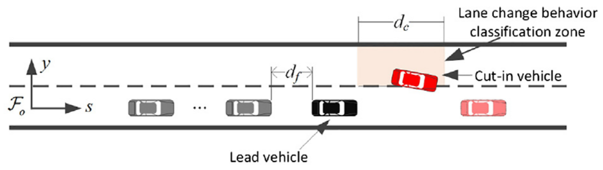
As an extension of MPC for string stable following vehicles, the control scheme proposed in this work takes into account behavior classification results by adaptively adjusting a behavior-guided cost function and by selecting reference states of the lead vehicle according to classification results. Minimization of state deviations of the lead vehicle is achieved by reducing conservatism of the control law regulating exogenous disturbances from vehicles that have normal behaviors. To analyze performance of control schemes for the lead vehicle in attenuating propagation of exogenous disturbances through the overall convoy, a nonlinear bound based on leader-to-formation stability (LFS) [22] is proposed for vehicle convoys that implement constant car-following strategies. The proposed controller is tested in a cut-in scenario where a preceding vehicle cuts in front of the lead vehicle, and compared with a typical MPC controller without behavior classification. Simulations of the proposed controller are conducted in the CarSim simulation environment.

The rest of the paper is outlined as follows. Section 2 models the homogeneous convoy on highways and describes the HMM-based behavior classifier and the trajectory prediction model considering behavior differences. Section 3 gives the behavior-guided MPC controller synthesis process. Section 4 discusses the nonlinear bound of state deviations for a vehicle convoy based on LFS theories. Simulation results and the controller performance are shown in Section 5. A conclusion of the work is given in Section 6.

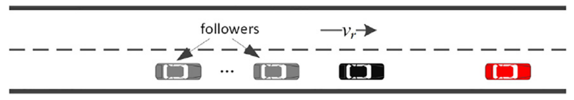
2. Driver behavior classification

2.1. Vehicle convoy modeling

In the context of this paper, the vehicle convoy consists of one lead vehicle and m followers. All the followers try to maintain a desired cruising speed while keeping fixed spacing d_f to the vehicle ahead, as described in [23]. In addition to maintaining the desired velocity and headway, the lead vehicle also needs to deal with disturbances caused by surrounding vehicles outside the convoy. While different maneuvers of surrounding vehicles could cause different kinds of disturbances to the lead vehicle, the maneuvers can be treated in a similar behavior classification and controller synthesis scheme. Here we focus on the scenario where a lane changing vehicle cuts in front of the lead vehicle abruptly, as shown in Fig. 1. In this scenario, special emphasis is placed on vehicles in the *lane change behavior classification zone* in the adjacent lane. Vehicles in the lane change behavior classification zone are treated as *target* vehicles. To achieve behavior-guided predictive control of the lead vehicle, vehicle states of a target vehicle are estimated in the behavior classification zone. The future maneuver of the target vehicle is predicted periodically using the estimated vehicle states. The target vehicle is labeled as a *cut-in* vehicle if its future maneuver is predicted to be *lane change*. The driver behavior of the cut-in vehicle is classified using the same vehicle states. The future trajectory of the cut-in vehicle is predicted according to the detected lane change behavior. Details of behavior classification and trajectory prediction are given in sections 2.2 and 2.4. Since the disturbance to follower i can be transformed into the disturbance to a new convoy with the i^{th} follower being the lead vehicle of the new formed convoy, we specifically focus on the disturbance to the lead vehicle.



(a) vehicle convoy encounters a preceding cut-in vehicle



(b) the convoy regulates the cut-in disturbance and maintains a safe headway to the cut-in vehicle

Fig. 1. Vehicle convoy formation with a preceding cut-in vehicle, here we assume convoy members have required V2V communication connection.

Before further modeling the CACC convoy, several assumptions are made and listed as follows

i. the convoy is homogeneous, i.e. vehicles in the convoy have identical longitudinal dynamics
ii. the lead vehicle has access to basic dynamic states of target vehicles, e.g. position, velocity, acceleration, etc.
iii. the lead vehicle cannot directly get the driver behavior of a target vehicle

Remark 1. Assumption ii could be satisfied via on-board ACC sensors and emerging V2V communication technologies. Note that accurate state estimation is also important to driver behavior prediction and classification even if V2V connection to the target vehicle is available. For details on vehicle state estimation, please refer to, e.g., [24–27] and references therein. Since the behaviors of the target vehicles reflect impacts from their surrounding traffic participants, only vehicles adjacent to the lead vehicle are considered in the classification framework to reduce system complexity.

The reference position for follower i, $1 \le i \le m$, in the convoy is defined as

$$s_i^r = s_{i-1} - d_f \tag{1}$$