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A dynamic lane-changing trajectory planning model for automated vehicles

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ABSTRACT

This paper focuses on the lane-changing trajectory planning (LTP) process in the automatic driving technologies. Existing studies on the LTP algorithms are primarily the static planning method in which the states of the surrounding vehicles of a lane-changing vehicle are assumed to keep unchanged in the whole lane-changing process. However, in real-world traffic, the velocities of the surrounding vehicles change dynamically, and the lane-changing vehicle needs to adjust its velocity and positions correspondingly in real-time to maintain safety. To address such limitations, the dynamic lane-changing trajectory planning (DLTP) model is proposed in the limited literature. This paper proposes a novel DLTP model consisting of the lane-changing starting-point determination module, trajectory decision module and trajectory generation module. The model adopts a time-independent polynomial trajectory curve to avoid the unrealistic assumptions on lane-changing velocities and accelerations in the existing DLTP model. Moreover, a rollover-avoidance algorithm and a collision-avoidance algorithm containing a reaction time are presented to guarantee the lane-changing safety of automated vehicles, even in an emergent braking situation. The field lane-changing data from NGSIM data are used to construct a real traffic environment for lane-changing vehicles and verify the effectiveness of the proposed model, and CarSim is applied to investigate the traceability of the planned lane-changing trajectories using the proposed model. The results indicate that an automated vehicle can complete the lane-changing process smoothly, efficiently and safely following the trajectory planned by the proposed model, and the planned velocity and trajectory can be well-tracked by automated vehicles.

1. Introduction

Automated vehicle technologies can significantly improve traffic safety and reduce traffic congestion, and have attracted much attention in recent years (Bevly et al., 2016; Wang et al., 2015; Bonnefon et al., 2016; Wadud et al., 2016; Petit and Shladover, 2015; González et al., 2016; Bansal et al., 2016; Levin and Boyles, 2016; Krueger et al., 2016; Tideman et al., 2010; Fraedrich and Lenz, 2014; Ammoun and Nashashibi, 2010; Glaser et al., 2010; Roncoli et al., 2015; Girault, 2004; Le Vine et al., 2015; Carbaugh et al., 1998; Roncoli et al., 2015; Katrakazas et al., 2015; Roncoli et al., 2016; Zhu and Ukkusuri, 2015). Some automated vehicles are already testing on highways, such as Google Car, nuTonomy, and Apple Car. However, the existing testing automated vehicles met some safety problems in driving in a real traffic environment due to the complexity of the traffic system. A series of traffic accidents

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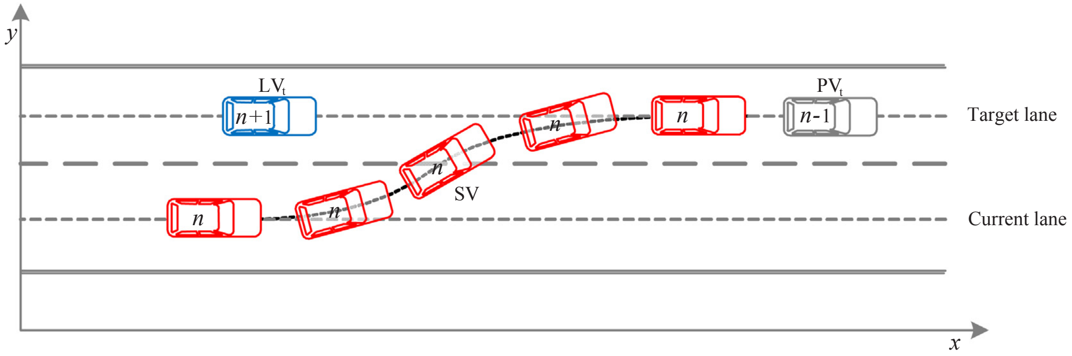

Fig. 1. Schematic diagram of a lane-changing process.

happened for the testing automated vehicles recently, and one important reason for these accidents was that the control algorithms embedded in automated vehicles failed, facing the real-time dynamic change of real traffic environment.

This paper focuses on the lane-changing trajectory planning (LTP) algorithm of automated vehicles, which is one of the key algorithms in automatic driving systems. Fig. 1 displays the schematic diagram of a lane-changing process for an automated vehicle. In Fig. 1, the automated lane-changing vehicle n (the subject vehicle, SV) will move gradually from the centerline of the current lane to the centerline of the target lane in lane-changing. The SV will eventually position in the gap between the vehicle $n-1$ (the preceding vehicle on the target lane, PV$_t$) and the vehicle $n+1$ (the lag vehicle on the target lane, LV$_t$). In a lane-changing process, the states of the PV$_t$ and LV$_t$ have significant impacts on the trajectory planning results. Existing studies on LTP assumed that the PV$_t$ and LV$_t$ maintained the constant velocities in the whole lane-changing process, and only one trajectory corresponding to the initial states of the PV$_t$ and LV$_t$ was planned. Those existing models are referred to as the static lane-changing trajectory planning (SLTP) models in the paper. However, in real-world traffic, the velocities of the surrounding vehicles, PV$_t$ and LV$_t$, change in real-time. The SV needs to dynamically adjust its velocity and position to maintain safe distances to the PV$_t$ and LV$_t$ in the lane-changing process. Therefore a new trajectory should be planned for each time step, that is, a dynamic lane-changing trajectory planning (DLTP) process. Furthermore, the DLTP is feasible due to the fast development of sensor technologies. The real-time information of the surrounding vehicles can be captured easily and accurately by the sensors and communication units installed on automated vehicles, such as cameras, radars (Luo et al., 2016; Li et al., 2012) and V2V devices (Yang and Jin, 2014).

The studies on the DLTP models are few. So far, only Luo et al. (2016) proposed a DLTP model in which an automated vehicle can capture the real-time information variations of the surrounding vehicles through the connected vehicle technology and made a dynamic response to the state changes of the surrounding vehicles. However, the model still has some disadvantages. First, the model did not consider the reaction time of the system, while the reaction time was a critical factor in automatic driving system and had a significant influence on driving safety (Young and Stanton, 2007). Second, the model used the time-dependent polynomial trajectory equation to represent the lane-changing trajectory curve, in which it was assumed that the initial acceleration of the SV was zero, which was not consistent with the reality. Third, the model assumed that the final target velocity of the lane-changing process was known (taken as the average velocity of vehicles on the target lane), which was also not consistent with the reality. Fourth, the collision-avoidance algorithm adopted in the proposed model did not consider the emergent braking situations, which may result in crashes.

To address the limitations in existing DLTP and SLTP models, this paper proposes a novel DLTP model based on real-time information of neighboring vehicles. The model includes the three modules, the lane-changing starting-point determination module, trajectory decision module and trajectory generation module. A time-independent cubic polynomial equation is adopted in the model to characterize the lane-changing trajectory curve, which can loosen the unreal assumptions on the velocity and acceleration of Luo et al.'s model (Luo et al., 2016). The study also introduced a rollover-avoidance algorithm and a collision-avoidance algorithm containing the reaction time to ensure automated vehicles can change lanes safely, even in an emergent braking situation. In the proposed model, the SV will dynamically adjust its velocity and distances to the surrounding vehicles according to the real-time lane-changing environment. The proposed model is evaluated based on several typical lane-changing scenarios constructed based on real-world lane-changing data. Furthermore, CarSim is used to verify the traceability of the trajectories planned by the proposed model.

The rest of the paper is organized as follows. Section 2 is the literature review. Section 3 presents the proposed dynamic lane-changing trajectory planning model in detail. Section 4 is the model verification part, using both the real-world lane-changing data and the CarSim simulation tool. Section 5 concludes this paper and discusses the future work.

2. Literature review

The prevailing method of the LTP is the geometric curve method, in which the vehicle is assumed to follow a specific geometric curve to finish a lane-changing process. The information of the starting and ending states of a lane-changing process was used to acquire the parameters in the curve function. The commonly-used geometric curves include the polynomial curve, circle curve, sine (cosine) curve, spiral curve, B-spline curve, trapezoidal curve, etc.