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A feedforward and feedback integrated lateral and longitudinal driver model for personalized advanced driver assistance systems

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ABSTRACT

Advanced driver assistance systems (ADAS) are a subject of increasing interest as they are being implemented on production vehicles and also continue to be developed and researched. These systems need to work cooperatively with human drivers to increase vehicle driving safety and performance. Such cooperation requires the ADAS to work with the specific driver with some knowledge of the human driver's driving behavior. To aid such cooperation between human drivers and ADAS, driver models are necessary to replicate and predict human driving behaviors and distinguish among different drivers. This paper presents a combined lateral and longitudinal driver model developed based on human subject driving simulator experiments that is able to identify different driver behaviors through driver model parameter identification. The lateral driver model consists of a compensatory transfer function and an anticipatory component and is integrated with the design of the individual driver's desired path. The longitudinal driver model works with the lateral driver model by using the same desired path parameters to model the driver's velocity control based on the relative velocity and relative distance to the preceding vehicle. A feedforward component is added to the feedback longitudinal driver model by considering the driver's ability to regulate his/her velocity based on the curvature of his/her desired path. This interconnection between the longitudinal and lateral driver models allows for fewer driver model parameters and an increased modeling accuracy. It has been shown that the proposed driver model can replicate individual driver's steering wheel angle and velocity for a variety of highway maneuvers.

1. Introduction

Vehicle performance and safety are directly related to the control actions taken by the driver who acts as an adaptive, optimal decision-making controller for the vehicle. This human controller plays a significant role in terms of vehicle motion control, stability, driving safety, as well as energy consumption and emissions. Recent advances in vehicle active control and driver-assistance systems, e.g., electronic stability control (ESC), adaptive cruise control (ACC), lane departure warning (LDW), forward emergency braking (FEB), active lane change assist, and emergency steering assist [1] etc., have aimed to improve upon the control limitations of a human driver. The advanced driver assistance system (ADAS) success depends on the system's ability to work with each individual driver and share control with the driver in a way that complements the driver's driving style. Driver models offer a mathematical approach to define a driver's driving style/behavior and can interact with the ADAS.

Driver modeling is a broad research topic that spans many fields and disciplines. Automotive driver modeling can be split into two broad categories: longitudinal and lateral control modeling. This paper studies both driver's lateral and longitudinal motion controls and looks at their interconnection. For lateral driver steering behavior, research has been done in regards to modeling physical human characteristics such as sensory delays, limb movement, eye tracking, etc. [2–7]. Models for perception and behavioral aspects have been developed to supplement the basic physical driver models. Many of these steering models use compensatory transfer functions based on heading/lateral errors at a preview distance/time and some models include a feedforward, anticipatory term that is common in human drivers. There are other methods used to model driver steering behavior besides these physical models [8–20]. For a complete review of lateral driver models see [21]. The methods used to model the driver's lateral control of a vehicle are similar to the methods used to model the longitudinal control of a vehicle. Many models have been developed to describe not only traffic flow, which is not of a particular interest for the present research, but also car-following and collision-avoidance (CA) maneuvers, which are relevant for the present research. Physical based longitudinal driver models are one method researchers have employed to describe the

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speed control of a driver [22–30]. These models use physics based models with meaningful driver parameters such as acceleration limits, time delays, and following speeds/distances. Other methods including AutoRegressive with Exogeneous (ARX) models under the hybrid dynamical system (HDS) structure [32–36], rule-based decision field theory (RDFT) [37], action point theory [38–41] etc., are used to describe human driver longitudinal control of a vehicle. More recent driver models for ADAS applications include an improvement to the Intelligent Driver Model (IDM) called the Foresighted Driver Model [42] that balances driver risk and trip time, models that learn driver behavior and adjust to fit an individual vehicle/driver response [43,44] along with an Autogressive Input-Ouput HMM used to anticipate driving maneuvers a few seconds before they happen [45]. For a complete review of car-following methods, see [31].

Most of the aforementioned driver models have been designed and evaluated for standard, non-emergency lane-changing (LC) maneuvers. These maneuvers are beneficial to obtain a set of baseline parameters for the driver model; however, the major benefit of ADAS is to provide support during high-speed, dynamic, and challenging maneuvers where the driver is unable to provide the necessary control inputs to maintain a safe vehicle trajectory. In order for ADAS to seamlessly integrate control intervention with the driver during these emergency maneuvers, an accurate model of the driver is needed. Some research has been done in modelling driver steering behavior during CA maneuvers [46–52] and on modelling driver's vehicle speed control [53–55] to assist with automatic braking system for forward collision avoidance. However, in collision-imminent scenarios it has been shown that the distance required to make a lane change is shorter than that required to stop. Prynne and Martin [56] observed that in many cases only moderate steering input would be required to avoid the collision versus heavy braking and that drivers who steer to avoid collisions have a lower incidence of hitting an obstacle than drivers who brake. Drivers who brake and steer had the highest success rate of avoiding collisions. Lechner and Malaterre [57] stated that 45% of accidents in a case study could have been avoided with proper driver intervention. For 50% of these cases the correct intervention was steering input. This had led to the desire to develop active steering collision avoidance systems that incorporate steering intervention that could be autonomously steering the vehicle or by supplementing driver steering inputs. Choi and Yu [58] use a steering assist system that aids the driver by applying additional steer torque. This method is more readily accepted by drivers since there is less indication of system intervention than that in system where there is autonomous steering.

For these reasons the proposed driver model is able to model and predict not only the driver's steering wheel angle and velocity for standard, everyday maneuvers but also during emergency, collision-avoidance maneuvers. It does so using a longitudinal car-following model that takes into account the driver's safe following distance, desired relative velocity to the preceding vehicle, and their desired velocity along their individual path, along with a lateral driver model based on a compensatory transfer function along with a feedforward anticipatory subsystem. It also uses a method for determining each individual driver's desired target path in parallel with determining the driver model parameters, which is also missing in the previous driver model research. This variance in driver's desired path and trajectory generation has been observed in research [59–63]; however, none of these studies take into account each driver's desired path as part of the driver model. This feature allows the model to accurately depict how each individual driver steers and brakes/accelerates based on their perception of their own desired paths.

The rest of the paper is organized as follows. Section 2 introduces the structure of the combined driver model and desired path generation. In Section 3, the driving simulator and experimental procedure are introduced. Section 4 provides driving simulator human subject test results and driver steering and velocity control model to observed maneuvers. Section 5 concludes this paper.

2. Combined driver model

The combined lateral and longitudinal driver model proposed in this paper was selected because of its ability to accurately model the driver's steering wheel angle and vehicle velocity, with its relatively small set of meaningful parameters. The desired path parameters are shared amongst the lateral and longitudinal models. When the lateral model was used in previous research, it was necessary to assume a constant velocity or that the driver's speed was known in order to model the driver's anticipatory steering input [2,3]. With the addition of the longitudinal driver model, this assumption is no longer necessary.

2.1. Desired path

A baseline path for each type of maneuver can be constructed geometrically. The paths for the LC and CA maneuvers were generated using a second-degree polynomial fit. From this baseline centerline, each driver may interpret the maneuver differently based on their driving preference, i.e. driving in the center of the lane or left/right of center, entering into the maneuver sooner/later, changing lanes faster/slower, to generate his or her own desired centerline. The driver's desired path can be custom fit to their vehicle trajectory with 4 parameters for the LC/CA maneuvers as seen in Fig. 1.

The first parameter, Y_1, can be fit to the driver's first horizontal section of the maneuvers in the **Y** direction. The location of the start of

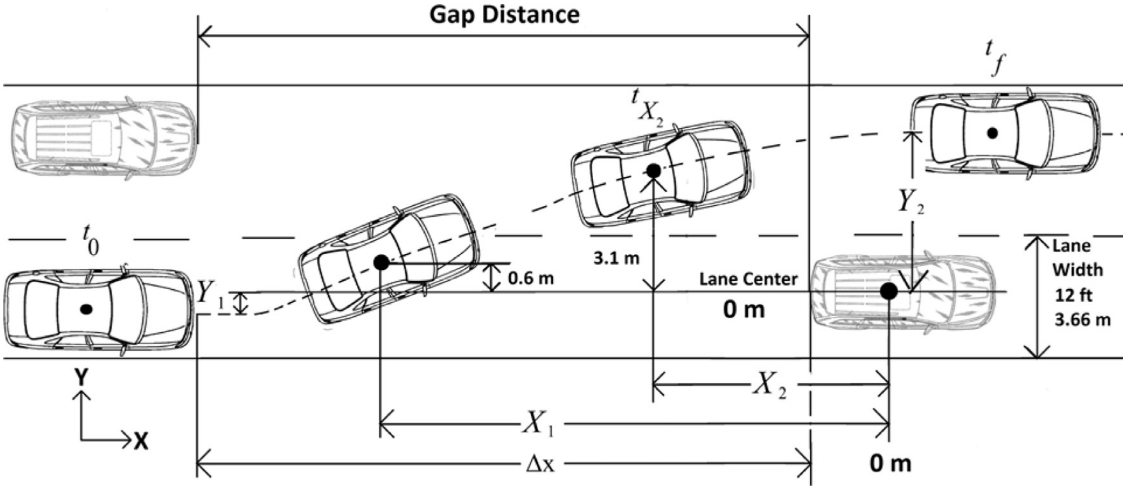

Fig. 1. Driver desired vehicle path.