

Numerical Simulation and Analysis of Closed-Loop Driver/Articulated Vehicle Dynamic Systems

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ABSTRACT

This paper presents a preliminary investigation of the closed-loop driver/articulated vehicle directional dynamics using numerical simulation. To date, a lot of attention has been focused on investigating the closed-loop directional dynamics of driver/single-unit vehicle systems. Little effort has been paid to examining the closed-loop directional dynamics of driver/articulated vehicle systems. Compared with single-unit passenger cars, multi-unit articulated vehicles have unique directional dynamic characteristics. Generally, a driver's behavior for an articulated vehicle is different from that for a passenger car. To investigate the impact of driver behavior on articulated vehicle directional dynamics, three driver models based on dynamic responses of tractor, trailer and combined tractor/trailer, respectively, have been developed. The three driver models are tested and compared through the numerical simulations of a low-speed path-following and a high-speed lateral stability test maneuvers for a driver/articulated vehicle system. The numerical studies are conducted in a Simulink-TruckSim simulation environment in such a way that the driver model is designed using Simulink from Matlab software, and the articulated vehicle model is constructed in TruckSim multibody dynamic package, then, the computer simulation can be implemented by combining the driver and vehicle models. With the benchmark comparisons, the distinguished features of different driver models are revealed and their applicability is demonstrated.

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INTRODUCTION

Articulated vehicles with a tractor and trailer(s) play an important role in road transportation. The requirements on good fuel economy, less greenhouse gas emissions, and high directional performance have made the development of articulated heavy vehicles (AHVs) challenging tasks for researchers and design engineers [1, 2]. Last two decades has witnessed many studies and control technologies developed for these commercial vehicles, including anti-lock brakes (ABS), trailer steering systems, traction control, drive by wire, etc. [3, 4]. AHV directional performance strongly depends on vehicle/driver interactions. Under an operating condition, an AHV may be required to follow a desired trajectory. In this case, the driver should monitor and control the vehicle quickly and accurately to follow the designated trajectory by turning the steering wheel [5]. This driving process is considered as a closed-loop dynamic problem, in which the following key components are involved: 1) the human driver; 2) the vehicle; and/or 3) an active control system. A driver model-based closed-loop dynamic simulation method may be used to evaluate the directional performance of AHVs. In the dynamic modeling, the human

driver, the vehicle and the relevant controller are represented by a driver model, a virtual vehicle prototype and a control algorithm, respectively. With the integration of these models in specified software package(s), the numerical simulations can be conducted. The driving action simulated by the driver model is crucial, as the driver's driving skills may greatly affect the vehicle performance during the vehicle-driver interactive process. Dynamic responses of the AHV are determined not only by the vehicle and operation conditions, but also the interactions between the vehicle and driver. In North America, professional AHV drivers are aware of the complexity of the AHVs and are trained to effectively handle the steering wheel and improve the overall vehicle directional performance.

A lot of investigations have been focused on developing driver models for single-unit vehicles, such as passenger cars or trucks. Few reports on investigations of AHV driver models can be found in the literature. This paper will evaluate AHV directional performance through the investigation of the three driver models developed in the current research. Due to AHV's large size and complicated configuration, they have unique dynamic behaviors, such as jackknifing and trailer

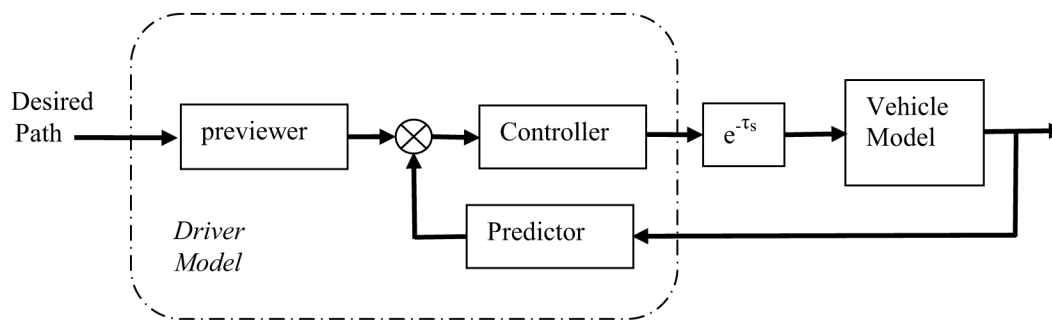


Figure 1. Basic preview predictor concept of the driver model

swing. It is usually difficult for an AHV driver to sense the trailer motions, as the driver's perception is based mainly on the tractor response rather than the trailer(s). The AHVs have poor maneuverability at low speeds and low stability at high speeds [6, 7, 8, 9]. To examine the driver/vehicle interactions, a linear yaw plane model for an AHV with a tractor and a semi-trailer is generated; this vehicle model is integrated with the corresponding driver model; closed-loop dynamic simulations are conducted. The main objective of this work is to examine the impact of different driver models on directional performance of the AHV. The directional performance measures of the AHV are evaluated through the simulation of the single lane change maneuver specified by SAE J2179 test procedure.

The rest of this paper is organized as follows. In Section 2, the driver model concept is introduced. An integration of the AHV model constructed in TruckSim and the driver model designed in Matlab/Simulink is presented in Section 3. The simulation results of the AHV driver model for single (tractor or trailer) and multi vehicle units are given in Section 4 and 5, the different performances of their lateral displacement are compared and analyzed. Finally, conclusions are given in Section 6.

DRIVER MODEL CONCEPT

To evaluate road vehicle directional performance, two types of tests, namely, open-loop and closed-loop, are frequently conducted [10]. In open-loop tests, specific steering inputs are predefined and they are not dependent on the response of the vehicle. These tests can be conducted with high repeatability and they are used for the purpose of characterizing only vehicle responses. In the closed-loop tests, a desired vehicle motion or trajectory is achieved by continuously monitoring vehicle response and adjusting steering actions accordingly. Because of the cost and safety concerns, it may not be practical to perform field testing during the concept design phase. Simulation assessment thus may be more practical in certain situations. In past studies on AHV directional performance, numerical simulation methods based the open-loop tests were frequently used [11]. Numerical experiments demonstrate that the open-loop dynamic simulation is difficult to accurately simulate the well-defined single lane change test maneuver defined by

SAE J2179 [12]. In order to evaluate AHV directional performance measures, a closed-loop dynamic simulation method was recently proposed for the design synthesis of AHVs with active trailer steering systems [13]. In the simulated test maneuvers, the driver model 'drives' the vehicle model to follow a prescribed route at a given speed. However, the driver model was mainly based on conventional preview driver models developed for single-unit vehicles. In the current research, the driver model reported in Ref. [13] is extended and the features of the updated model are investigated.

Driving is essentially a control process of the vehicle dynamic system, because the driver adaptively adjusts the steering wheel angle to align the current vehicle heading to the desired direction. A preview-predictor driver model is frequently introduced to represent the driver in closed-loop vehicle dynamic simulations [14, 15, 16, 17, 18, 19]. As illustrated in Figure 1, this driver model has three fundamental functions, including previewer, predictor and compensator, to make the vehicle model follow the desired path. The previewer assumes that the driver can sample a target point on the path at a regular time interval T to preview the vehicle position. The predictor evaluates the current vehicle motions and previewed information to predict in advance where the vehicle will be. The predicted location is then compared with the desired path, the lateral difference between the predicted position and the desired path is defined as the lateral displacement error. This error is identified and transferred to the compensator, which is equalized to a compensatory gain in the control loop to correct the corresponding vehicle position by adjusting the front steering wheel angle.

When applying the above driver model to the AHV path following control, the time delay rising from the human driver's action and physiological lag is considered in the control loop. Due to this effect, there always exist a few time delays between the driver model controller output and the driver reaction. Thus, the steering wheel angle exported to the AHV is not the one derived from the instant vehicle outputs and the current road conditions. Depending on a driver's experience and a variety of individual physical conditions, a typical time delay of 0.1-0.2 second is recommended [6, 15, 16, 20].

Figure 1 also shows the vehicle model working with the driver model. In order to calculate the preview-predictor lateral displacement error, it is necessary to transform the path preview information from a global coordinate system to fit with the vehicle body-fixed coordinate system. Then the preview point in front of the vehicle body is used to take into account the current vehicle position output from the vehicle model and feedback to the driver model. The driver model is functional in previewing and predicting the future vehicle position, and comparing the current vehicle position with the desired target point on the path. Finally, the lateral displacement error in the vehicle body-fixed coordinate system can be determined. The error is transferred via the controller to evaluate the required front steering wheel angle and to reduce the driver reaction time delay effect. The value of the error is positive if the predicted vehicle position is located on the left of the desired path. This means that a right turning of the steering wheel is needed to correct the current vehicle heading. By tuning the controller parameters, the driver model can collaborate with the vehicle model to follow the specified path well.

DRIVER AND VEHICLE MODELING

In order to derive the driver model to minimize the lateral displacement error of the vehicle, a yaw plane vehicle model is generated to represent the AHV with a tractor/semi-trailer configuration. Figure 2 shows the schematic diagram of the AHV in top view. The vehicle forward speed is assumed to be constant and three motions are considered, which include the lateral velocity of the tractor, the yaw rate of the tractor and the articulation angle between the tractor and trailer.

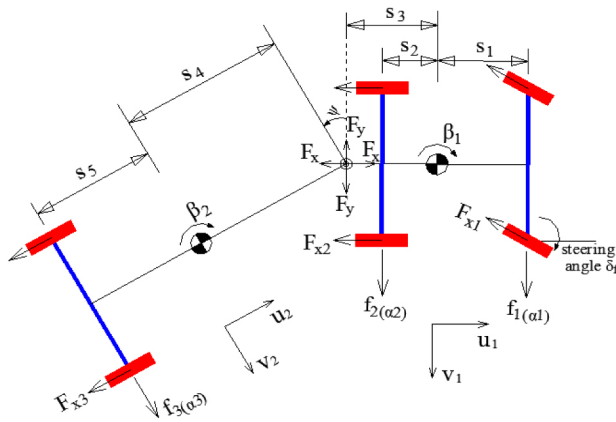


Figure 2. Top view of the AHV model

The driver model is derived based on a path following control strategy. The driver model is to adjust the front wheel steering angle to make the vehicle follow the desired path. Figure 3 shows the preview-predictor follow strategy.

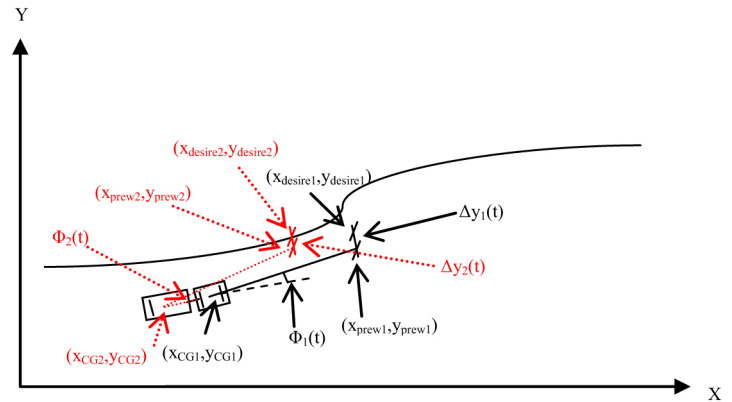


Figure 3. Single point preview-predictor follow strategy

The path follow strategy is used to evaluate the lateral displacement error between the predicted vehicle position and the desired target point on the path. It synthesizes the desired path over the preview time T and calculates the necessary front wheel steering angle to minimize the error. The lateral displacement error of the tractor CG is evaluated as

$$\Delta y_1(t) = (x_{prew1} - x_{desire1}) \cdot \sin \phi_1(t) - (y_{prew1} - y_{desire1}) \cdot \cos \phi_1(t) \quad (1)$$

$$x_{prew1} = x_{CG1} + l_{fwd1} \cdot \cos \phi_1(t) \quad (2)$$

$$y_{prew1} = y_{CG1} + l_{fwd1} \cdot \sin \phi_1(t) \quad (3)$$

The lateral displacement error of the trailer CG is determined as

$$\Delta y_2(t) = (x_{prew2} - x_{desire2}) \cdot \sin \phi_2(t) - (y_{prew2} - y_{desire2}) \cdot \cos \phi_2(t) \quad (4)$$

$$x_{prew2} = x_{CG2} + l_{fwd2} \cdot \cos \phi_2(t) \quad (5)$$

$$y_{prew2} = y_{CG2} + l_{fwd2} \cdot \sin \phi_2(t) \quad (6)$$

The lateral displacement error is used to feed to a PD controller, where the derivative gain is adopted to reduce the transport time delay between the vehicle dynamics and the driver reaction response. The PD controller is carefully tuned to minimize the lateral displacement error in a rapid and smooth manner. The path following task performed by the PD controller is to evaluate a new set of steering angles for the front wheels of the tractor. The solution for the steering angle is repetitive and adaptive. Each time the controller is called, and the updated front wheel steering angle is provided