

Characterization of Driver Steering Control of Articulated Freight Vehicles Based on a Two-Stage Preview Strategy

Siavash Taheri, Subhash Rakheja, and Henry Hong
Concordia University Montreal

ABSTRACT

A two-stage preview strategy is proposed to characterize steering control properties of commercial vehicle drivers. The strategy includes a near and a far preview points to describe the driver control of lateral path deviation and vehicle orientation. A human driver model comprising path error compensation and dynamic motions of the limb is subsequently formulated and integrated to a yaw-plane model of an articulated vehicle. The coupled driver-vehicle model is analyzed under an evasive steering maneuver to identify limiting values of the driver control parameters through minimization of a generalized performance index comprising driver's steering effort, path deviations and selected vehicle states. The performance index is further analyzed to identify relative contributions of different sensory feedbacks, which may provide important guidance for designs of driver-assist systems (DAS). The results show that the proposed model structure could serve as an effective tool to identify human control limits and to determine the most effective motion feedback cues. The results further imply that lateral position and heading angle of the lead unit are the most essential sensory cues to achieve satisfactory guidance and control of the vehicle, while the lateral acceleration and yaw rate of the vehicle can serve as secondary cues to enhance path tracking performance of the vehicle in emergency driving situations.

CITATION: Taheri, S., Rakheja, S., and Hong, H., "Characterization of Driver Steering Control of Articulated Freight Vehicles Based on a Two-Stage Preview Strategy," *SAE Int. J. Commer. Veh.* 6(2):2013, doi:10.4271/2013-01-2388.

INTRODUCTION

The directional control performance of road vehicles and thus the road safety is strongly influenced by control actions of the human driver that mostly arise from vehicle-road-environment interactions. The human drivers may exhibit limited control performance, particularly during emergency situations that generally impose greater demand on the drivers' decisions and control abilities [1]. The reported highway accidents data suggest that more than 90% of the road accidents are attributable to errors associated with drivers' perception of the situation, decision making process and control actions [2,3]. Considerable efforts have thus been made to characterize cognitive behavior of human drivers in the context of vehicle control [4, 5, 6, 7]. These have evolved into a number of mathematical models that describe the driver as a controller considering the human perception, prediction, preview and compensation abilities. It has been suggested that formulations of mathematical models that emulate human driving behavior can help to identify performance limits of the driver and contribute to enhanced control performance of the driver through developments in

effective driver-assist systems (DAS) and driver-adaptive vehicle designs [7,8]. The reported human driver models generally consider the driver as an ideal controller that can readily adjust its driving strategy to adapt to a desired vehicle path with little or no considerations of control limits of the human driver [9]. The vast majority of the reported studies on driver-vehicle interactions focus on automobile drivers. The human driver's control performance is perhaps of greater concern for articulated vehicle combinations, which exhibit significantly lower control limits and may pose relatively greater highway safety risks compared to automobiles [10]. The directional dynamic analyses of such vehicles have been limited either to open-loop steering and braking inputs or simplified path-following driver models [7,9].

In the context of interactions between the human driver and articulated vehicles, only a few studies have investigated the coupled driver-vehicle system responses [9,11,12]. These generally focus on characterization of driving control requirements through minimization of lateral position error between center of mass (cg) of the tractor and the desired path using a single-point preview strategy. A single point preview strategy, however, may lead to unsatisfactory path

tracking performance and instability, particularly under high speed directional maneuvers coupled with a relatively short preview distance [13,14]. A human driver would exhibit superior control performance when a preview of the entire roadway is available. A few studies have proposed multi-point preview strategy for enhanced directional control performance of the driver. A multi-point preview strategy involves simultaneous preview of a number of equally spaced target points for mapping of the required path information [14,15]. Measurements performed under restricted visual situations have shown that human drivers observing only two segments of the roadway achieve improved path tracking performance that is similar to that could be realized with entire roadway visible [16]. A two-point strategy, has thus considered adequate for describe driver preview opposed to more complex multi-point approach. A few studies have employed two-point preview strategy to develop coupled single-unit vehicle-driver models [17, 18, 19, 20]. These studies have also suggested that the vehicle driver needs only two target points ahead of the vehicle to obtain the required roadway coordinates.

In this study, a two-point preview driver model is used to develop a coupled driver-articulated vehicle model. The proposed model involves essential elements of the human driver, such as perception, prediction, path preview, error estimation, decision making and hand-arm dynamics in conjunction with a yaw-plane articulated vehicle model. The path preview is realized using near and far preview points, where the near preview helps maintain central lane position and the far preview helps control vehicle orientation. The driver model parameters are identified by minimizing a composite performance index subject to constraints imposed by the human driver's control and compensation limits. Subsequently, the control demands on the driver are evaluated through enhanced perception of different vehicle states so as to identify secondary cues that could facilitate vehicle path tracking while limiting the control demands. The vehicle states that help reduce path deviation could be utilized as additional sensory feedbacks in a DAS for enhanced path tracking performance of the coupled driver-vehicle system.

YAW-PLANE VEHICLE MODEL

A three-degrees-of-freedom (DOF) linear yaw plane model of an articulated vehicle is used for developing the coupled driver-vehicle model. The model incorporates two-DOF of the three-axle tractor (lateral velocity, v_{y1} , and yaw velocity, r_1) and one-DOF of the two-axle semi-trailer unit (yaw velocity, r_2), as shown in Fig. 1. The model is formulated assuming small side-slip and steering angles, negligible contributions due to vehicle roll and pitch motions, and free relative yaw motions of the two units at the articulation joint, as described in many earlier studies [9,12,21]. The equations of motion for the yaw-plane model of the articulated vehicle are presented in Appendix A. The

well-known Magic Formula is used to derive longitudinal and cornering forces, and aligning moment due to tire-road interactions as nonlinear functions of the side-slip, longitudinal slip and vertical load [22]. The validity of the vehicle model was examined by comparing its directional responses with the reported measured responses of a five-axle tractor-semitrailer combination subject to a constant speed lane change maneuver [23], as shown in Fig. 2. From the comparison, it was deduced that the three-DOF used in this study can provide reasonably good prediction of yaw directional responses to steering inputs. The observed deviations between the measured and model responses were mostly attributed to lack of parameters of the vehicle used in the field-measurements study. In Fig. 2, a_{y1} and a_{y2} are lateral accelerations of the tractor and trailer units, respectively, and δ_{fw} and γ are the front wheel steer angle and articulation angle, respectively.

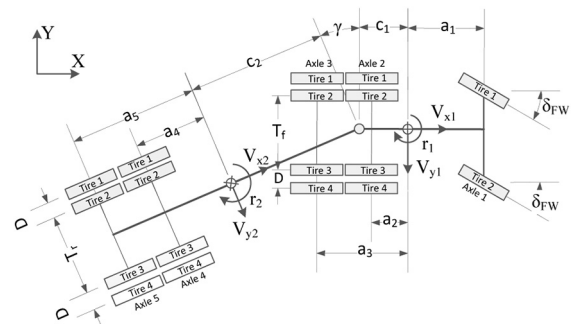


Figure 1. Three-degrees-of-freedom yaw-plane model of the articulated freight vehicle.

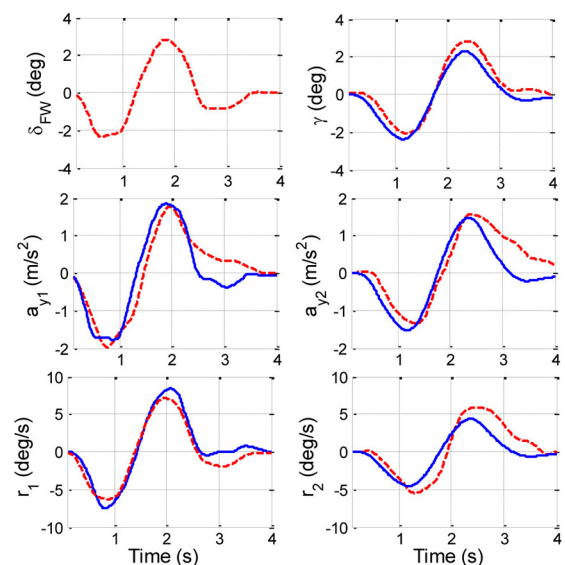


Figure 2. Comparisons of directional responses of the yaw plane vehicle model (solid line) with the measured data (dashed line), to a lane change maneuver at a constant speed of 68.8 km/h [23].

TWO-POINT PREVIEW DRIVER MODEL

The human driver serves as both the sensor and the controller, so as to satisfy the control and guidance requirements of the driving task [4,24]. Generally, these would include maintaining the vehicle on a specified path, reducing of the path tracking error to a permissible threshold level, and rejection of the environmental and road disturbances [9]. The driver steering process can be described by four essential elements, namely: (i) perception/prediction; (ii) preview; (iii) decision making process; and (iv) limb motion (Fig. 3). Drivers' perception of the instantaneous states of the vehicle help predicting future vehicle trajectory in a qualitative sense, while the roadway coordinates are previewed through the visual field, which is described as the preview process. Using the previewed path coordinates and predicted vehicle trajectory, the driver estimates lateral position and orientation errors of the vehicle with respect to the desired roadway. The driver subsequently imparts required compensatory control to minimize the tracking error subject to control performance limits, processing time delay, muscular dynamic and the vehicle steering system dynamics.

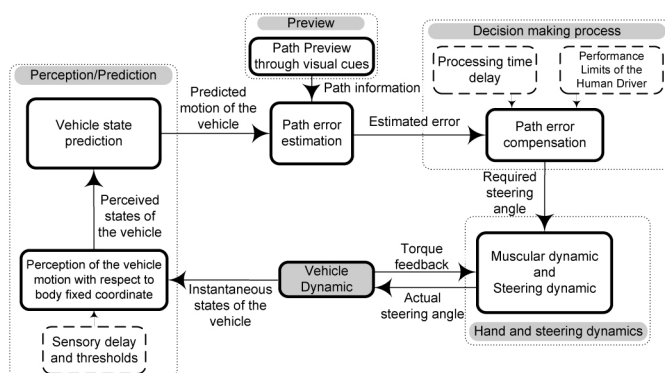


Figure 3. Overall structure of the coupled driver/vehicle system.

Perception/Prediction Process

It is established that the vehicle driver can sense instantaneous vehicle motion states through its visual, vestibular and kinesthetic cues [24]. Considerable efforts have been made to define these sensory cues and their mathematical descriptions, which invariably consider that the instantaneous coordinates and orientation of the vehicle relative to its surroundings is perceived by the driver through visual sensory cues [24,25]. For commercial articulated vehicles, it has been suggested that drivers also perceive linear and rotational accelerations as well as rotational velocities of the tractor unit in a qualitative manner through vestibular and body-distributed kinesthetic cues [9,25]. In addition, it has been suggested that the human driver may indirectly perceive motion states of the trailing unit through in-vehicle sensors [7,9]. The reported models mostly focus on

single unit vehicles and employ lateral coordinate and heading angle of the vehicle as the two primary cues, which can be more precisely perceived by the human driver. In case of articulated vehicles, drivers' perception of secondary cues related to additional motion states of the vehicle could assist the driver to undertake the required steering control actions more effectively. These may include articulation rate, lateral acceleration and yaw velocity of both the tractor and semi-trailer units. The human perception of these states could be described considering two essential characteristics: (i) perception delay time [24]; and (ii) a perception threshold that relates to minimum value of a state that can be sensed by the human driver [25]. The delay time to perceive vehicle states can be mathematically expressed as:

$$D(s) = e^{-s\tau_d} \quad (1)$$

where τ_d is the driver's perception delay time, which could vary depending upon the driver's sensory channels and environmental factors, and ranges from 0.1 to 0.2 s [1,9,24]. The magnitude of a vehicle state, however, must exceed its threshold value to be detected by the human driver. The threshold values vary for different sensory channels. For instance, it has been reported that human can detect linear acceleration exceeding 0.06 m/s^2 through the vestibular system [25]. The perception threshold of the human driver can be mathematically expressed by a dead-zone operator (Fig. 4), such that [24]:

$$S_j(I_j, T_j) = \begin{cases} \max\{I_j - T_j, 0\} & ; T_j > 0 \\ I_j & ; T_j = 0 \\ \min\{I_j - T_j, 0\} & ; T_j < 0 \end{cases} \quad (2)$$

where I_j and S_j are instantaneous and perceived motion states, and T_j is the perceptive threshold of vehicle state j ($j=1, \dots, n$); n being the number of motion states to be perceived. The transfer function, $G_1(s)$, shown in Fig. 5, describing drivers' perception of vehicle states is formulated as a combination of perception time delay and perception threshold, such that:

$$G_1(s) = S_j(I_j, T_j) D(s) \quad (3)$$

The human driver continually predicts vehicle coordinates at a future instant in a qualitative sense on the basis of perceived information related to primary and secondary cues such as heading angle, forward speed, lateral acceleration and lateral coordinates of the vehicle. The driver undertakes a control or corrective or preventive action on the basis of anticipated deviations between the predicted and previewed paths [8,26,27]. Considerable attempts have been made to characterize the driver prediction capability using first and second-order prediction models [8,28]. In this study, a second-order prediction model is used considering constant

lateral acceleration of the vehicle within the preview interval, T_P [27]:

$$\begin{aligned} Y(t + T_P) &= Y(t) + T_P \dot{Y}(t) + \frac{T_P^2}{2} \ddot{Y}(t) \\ X(t + T_P) &= X(t) + T_P V_x(t) - \frac{T_P^2}{2} r_1(t) V_{y1}(t) \end{aligned} \quad (4)$$

where $\dot{Y}(t)$ and $\ddot{Y}(t)$ are the instantaneous lateral velocity and lateral acceleration of the vehicle in the global XY frame, respectively, as shown in Fig. 6. Referring to Fig. 5, the prediction function, $G_2(s)$ of the driver is obtained as:

$$G_2(s) = \frac{Y(t+T_P)}{Y(t)} = \frac{T_P^2}{2} S^2 + T_P S + 1 \quad (5)$$

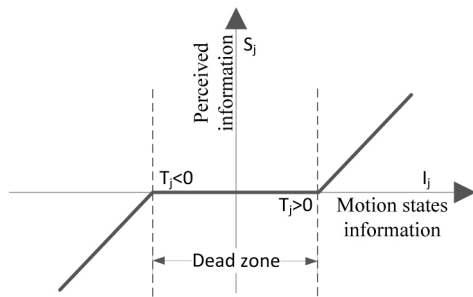


Figure 4. The dead-zone model used to describe perception threshold of the human body sensory feedbacks.

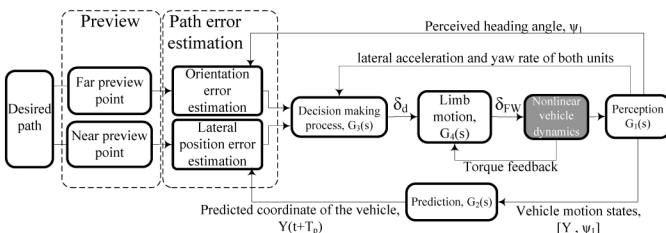


Figure 5. The structure of the proposed two-stage preview strategy driver model.

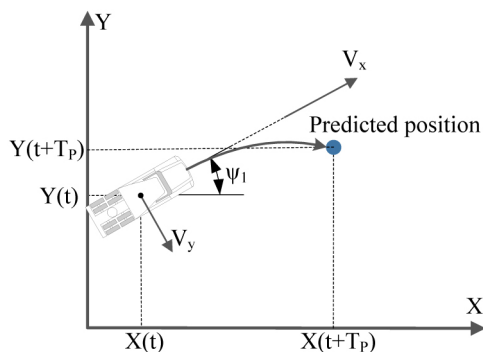


Figure 6. Prediction of vehicle motion at a future instant using the second-order prediction model.

Preview Process and Error Estimation

Many theoretical and empirical studies have shown that human driver tends to compensate for its perception/response delays through preview of future path information [4,16]. This path preview process involves assessment of the lateral coordinate, orientation and curvature of the desired roadway at a preset sight point, denoted as the preview point [5,17,26,27]. The preview distance D_P , the distance from the preview point to the driver's position, is strongly influenced by the vehicle forward speed, maneuver severity, path curvature and driver's path preview strategy [8,9,24]. The preview distance is generally expressed in terms of preview time T_P , which can account for the speed effect assuming constant driving speed within the preview interval, which could range from 0.5 to 9 s, where $T_P = D_P / V_x$ [9,26]. Further, it has been suggested that during a curve negotiation the drivers tend to rely on a so-called tangent point on the inside edge of the previewed path for estimating the future curvature of the path and thereby undertake required control action [18,29].

A two-point preview strategy is used in this study to describe human drivers' path preview process. The human driver aims to minimize the lateral position error between the vehicle trajectory and the desired roadway using the previewed path coordinates in the near visual field. The far preview process is described as minimization of the orientation error between the direction of motion of the vehicle and the far preview point on the roadway. The locations of the near and far preview points are determined in three sequential steps involving: (i) identifications of near and far visual fields; (ii) locating near preview point with respect to driver's position; and (iii) locating the point of tangency and far preview point with respect to driver's position. These are described below considering the path geometry.

The majority of the reported studies have defined path coordinates with respect to vehicle cg, assuming that the driver is located at or near vehicle cg. This, however, may lead to some errors for the articulated vehicles. The coordinates of the driver's seat (point D in Fig. 7) can be determined from the lateral (W_D) and longitudinal (L_D) position of the seat with respect to the tractor cg:

$$\begin{aligned} X_D &= X_g + L_D \cos \psi_1 - W_D \sin \psi_1 \\ Y_D &= Y_g + L_D \sin \psi_1 + W_D \cos \psi_1 \end{aligned} \quad (6)$$

where ψ_1 is the tractor heading angle, and (X_g, Y_g) and (X_D, Y_D) are, respectively, the coordinates of the vehicle cg and the driver's seat in the global axis system. Referring to Fig. 7(a), the driver's overall visual field is described as a circular sector centered at the driver's seat position. The overall visual field is defined by the field angle Φ and its radius, which is determined through minimization of a performance index, as described in the following sections. In the two-preview points strategy, it is hypothesized that driver determines the coordinates of the roadway at two target points within the