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Preliminary Steps in Understanding a Target & Control Based Driver Steering Model

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Abstract—**This paper presents the preliminary steps in understanding a target & control based (T&C) driver steering model. This driver steering model was developed and verified based on vehicle test data of Double Lane Change (DLC) maneuvers. According to the data, drivers use target points located at the centerline of the lane to be changed to as references for control and determine steering rate based on a target angle error with respect to the current target point. The T&C driver model was shown to effectively capture driver's steering behavior. This paper examines the extendibility of this T&C driver steering model to other common maneuvers, such as left/right turns in intersections; the initial simulations show that this T&C model is capable of performing other maneuvers with ease, indicating its potential to be a generic driver model. Moreover, the preliminary control synthesis shows that this model exhibits plenty of stability margins for drivers to increase their control gain when necessary.**

I. INTRODUCTION

A driver model is designed to simulate driver's actions according to his perception of the environment, driving experience, and preferences over a wide range of traffic situations. Driver models have been developed to characterize many aspects of the driving task. Human factor engineers usually focused on the higher-level driver behavior of cognitive processing and decision-making [1]. With the development of vehicle control systems, such as antilock brake systems, electronic stability systems and x-by-wire systems which could significantly alter vehicle dynamics, there is a need to understand how drivers will interact with the transitional and changed vehicle dynamics when those systems are engaged. It is therefore necessary to develop a driver model from a control's perspective that can capture and represent driver's driving behavior.

As reviewed in [2-4], a large number of articles with driver models have been published. Among them, some driver steering models focus specifically on a steering control law that determines the steering angle with an assumed control input. For example, the steering model in [5] uses the lateral deviation from the centerline of the road as the input and specifically maps the steering angle (the output) to this assumed input. Such a model may be directly applied to lane keeping or lane following maneuvers, but not to maneuvers such as lane changes and DLC. Other driver steering models [6] take a broader scope where the steering model determines the steering control based on the maneuver a driver wishes to execute.

In driver steering models that adopt this broader scope, trajectory planning is commonly assumed. The desired trajectory for driver models is often regarded as an optimized path; either the total maneuver can be optimized or, from the driver point of view, towards an optimization horizon at some previewed seconds in advance ([6-8]). Naturally, different trajectories are designed for different maneuvers; for example, the trajectories for left turns are different from those for right turns and the trajectories for turns are different from those for lane changes. With these trajectories, the maneuver execution then becomes a trajectory tracking problem for the steering control.

However, analysis with vehicle test data of DLC maneuvers show strong evidence that drivers do not plan a trajectory to go through the DLC course. Rather, drivers simply use target points located at the centerline of the lane to be changed to as references for control [9]. Furthermore, drivers perceive a target angle error based on a straight-forward geometric relationship and determine steering rate based on the target angle error. In fact, drivers can intuitively sense small target angle errors by observing whether the vehicle is inching toward left or right. Accordingly, a target and control based (T&C) driver steering model is developed and verified with vehicle data of 80 DLC runs [9]. This model can effectively capture driver's driving behavior in the steering angle and the steering rate.

This T&C driver steering model seems to offer a generic framework that can be readily extended to other maneuvers such as lane change, lane keeping, and left/right turns. One objective of this paper is to investigate the performance of this driver model in those maneuvers. Such investigation is to evaluate whether this driver steering model developed and verified using DLC test data can indeed be a generic model that have the potential to be a universal driver model across different maneuvers. Note that this investigate is not yet on whether the driver model captures or represents driver's actual driving behavior in those maneuvers (future work).

A second purpose of this paper is to understanding this T&C driver steering model from the control's perspective. The control synthesis of this T&C driver steering model in

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lane keeping maneuvers is conducted and the corresponding control model is provided. The control model show interesting characteristics such as inherent linear time varying property and the invariant damping at 0.707 in its open-loop zeros, which provide stability margin to allow the driver to increase his or her control gain when needed.

This paper is organized as follows. Section II describes the driver steering model developed based on the DLC vehicle test data. Section III examines the performance of the driver steering model in different types of maneuvers. Section IV presents the control synthesis of the driver steering model in lane keeping maneuvers and Section V provides discussions and future research directions. Section IV concludes the paper.

II. Driver Steering Model based on DLC Test Data

As a prerequisite, this section describes the driver steering model developed based on the vehicle data of DLC maneuvers at a proving ground [9]. The model development starts with examining the commonly assumed or accepted elements in a driver steering model, including trajectory planning, preview/prediction, and steering controller. Subsequently, new hypotheses are made and verified with the 80 sets of DLC vehicle data [9]. Figure 1 shows the proposed target & control (T&C) driver steering model.

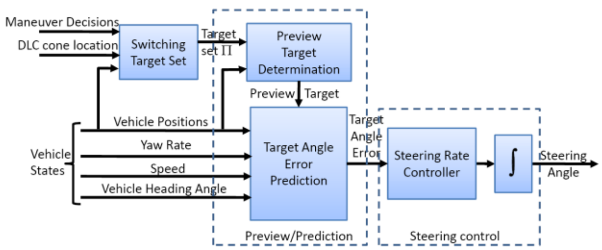


Fig. 1 The T&C driver steering model based on the DLC

Compared to typical driver models, this T&C driver model has the following unique and simple key concepts:

- Instead of planning a trajectory, drivers use target points along the centerline of the lane they are changing to or following as references for control.
- The preview target is the target at a look-ahead distance from the vehicle position.
- Drivers perceive target angle errors, which are angle errors based on a straight-forward geometric relationship with respect to the preview target.
- Contrary to the typical steering angle control in most driver models, drivers employ a linear rate control and the control gain is mostly constant (proportional to the ratio of speed over look-ahead distance) with a few steps of gain increases when the angle error exceeds some thresholds.

Although it is outside of the scope of this paper, the driver maneuver decision simply becomes when to start switching to a new set of target points. The trajectory is the result of the T&C based on individual driver characteristics (such as timings, control gain and scheduling). The remaining of this section will review these unique concepts of this T&C driver steering model [9], and it will serve as the starting point for exploring the T&C scheme to other maneuvers.

A. Switching Target Set

As verified in [9], drivers simply use target points located along the centerline of the lane they are change to as references for control. For the DLC maneuver, the target points are illustrated in Fig. 2.

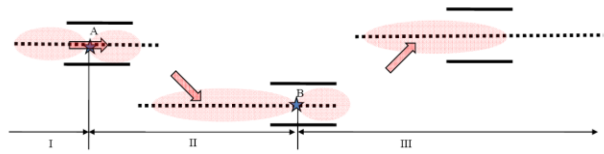


Fig. 2 Target sets (dotted line along the lane centerline)

As shown in Fig. 2, the DLC course can be divided into three segments separated at the transition points A and B, the locations where a driver starts changing to the next lane. Depending on the segment the current vehicle position is in, the corresponding moving target point is described below:

- Segment I (before Point A): the targets lie on the centerline of the lane defined by the first cone set;
- Segment II (between Point A and Point B): the targets lie on the centerline defined by the second cone set;
- Segment III (beyond Point B): the targets lie on the centerline defined by the third cone set.

The maneuver in Segment I is the lane keeping maneuver, and the targets are the future road. The maneuvers in Segment II and III are lane changes (with different initial conditions[1]); the targets represent the lane the vehicle is changing to and there is no explicit trajectory planning.

B. Preview Target Determination

In the target & control scheme, the target points replace the desired or planned trajectory in traditional driver steering models; however, the traditional concept of preview/preview still applies, but in a different fashion. At any specific time, the target point is a look-ahead distance (i.e., preview distance, possible varying) away from the vehicle position; therefore, it is also referred to as the preview target. Thus, given the maneuver execution locations A and B and a look-ahead distance $d(t)$, the preview target T ($x_T(t)$, $y_T(t)$).can be determined based on the current vehicle position ($x(t)$, $y(t)$):

$$\left\| \begin{bmatrix} x_T(t) - x(t) \\ y_T(t) - y(t) \end{bmatrix} \right\| = d(t) \text{ and } \begin{bmatrix} x_T(t) \\ y_T(t) \end{bmatrix} \in \Pi, \qquad (1)$$

Where Π is the centerline of the lane which the vehicle is changing to. In this DLC maneuver, Π is a function of the vehicle current position ($x(t)$, $y(t)$) and the transition locations A and B.

C. Prediction of the Target Angle Error

In this T&C driver steering model, the prediction errors are based on target heading angles as described below.

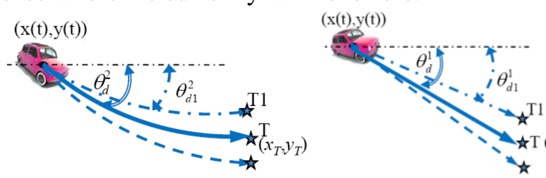
Definition: Target heading angle:

Given vehicle current position ($x(t)$, $y(t)$), yaw rate $\omega(t)$, speed $v(t)$, and a target T($x_T(t)$, $y_T(t)$), and assuming the

[1] Since the second lane change typically starts before the first one settles.

vehicle maintains its current yaw rate $\omega(t)$ and speed $v(t)$ (that is, the vehicle travels along a curve with a fixed radius $R(t) = v(t)/\omega(t)$), the target heading angle θ_d is the heading angle that ensures the vehicle to reach the target T.

Figure 3 illustrates the target heading angles, θ_d and θ_{d1}, corresponding to two targets T and T1, respectively. In Fig. 3(a), the vehicle maintains its current yaw rate $\omega(t)$ and speed $v(t)$ while traveling toward the target point. Thus, the blue curvy lines are curves with the same fixed radius: $R(t) = v(t)/\omega(t)$. Figure 3(b) shows the special case where the current yaw rate is zero.



(a) (b)

Fig. 3 First-order and second-order target heading angles

Therefore, the target heading angle is the desired heading angle and the goal of the steering controller is to reduce the difference between the actual vehicle heading angle and the target heading angle. Accordingly, the target angle error is introduced as the predicted error to be regulated by the steering controller:

$$\theta_e(t) = \theta_d(t) - \theta_v(t) \tag{2}$$

D. The Steering Rate Controller

The steering controller aims to regulate the target angle error to zero; it is a function of the target angle error:

$$\delta(t) = f(\theta_e(t)) \tag{3}$$

The open-loop analysis based on the DLC vehicle test data consistently shows that the control is approximately a linear steering rate controller [9]:

$$\dot{\delta}(t) = k(t)\theta_e(t) \tag{4}$$

Moreover, the linear gain *k(t)* is typically proportional to the ratio of speed over look-ahead distance and the proportional factor is approximately a constant (which does vary from driver to driver) except at the beginning of the lane change, where the gain increases continuously to avoid a sharp jump in the steering rate. This controller law implies that drivers do not have a desired steering angle as a control command to turn the steering wheel to. Instead, drivers determine how fast the changes in the steering angle are needed based on the target angle error and move the steering wheel to increase or reduce the steering angle accordingly.

The actual control law can also include the time delay as well as the driver's actuating "servo" characteristics. That is:

$$\dot{\delta}(t) = g\left(\dot{\delta}_{cmd}(t)\right) = g\left(k(t)\theta_e(t-\tau)\right) \tag{5}$$

III. Maneuver Handling of the T&C Model

The T&C model, although developed for DLC, does have a generic structure that seems to be readily applicable to other maneuvers. This section examines the model's capability in handling different common maneuvers. Due to the page limitation, the DLC maneuver is not included; readers can find the detailed model verification in [9], where the model-generated steering matched the actual driver's steering in both steering angle and steering rate.

A. The LC Maneuver

Applying the driver steering model to the single LC maneuver is rather straight-forward. Once the driver decides to execute the LC maneuver, the target points are switched from the centerline of the current lane to the centerline of the lane to be changed to. The specific preview target at any time instance is the target point at a look-ahead distance away. One significant difference between the DLC and the LC lies in the choice of the look-ahead distance. For the DLC, the look-ahead distance is constrained by the DLC course except for very low speeds, while for the LC the look-ahead distance reflects more of the driver's preference.

Figure 4 shows the performance of the driver steering model at 60 kmh with the look-ahead distances (*d*) ranging from 20 m to 45 m. The control gain is a simple ramp up from 0 at the start of the LC to a constant gain equivalent to the ratio of speed over look-ahead distance: *v*/*d*.

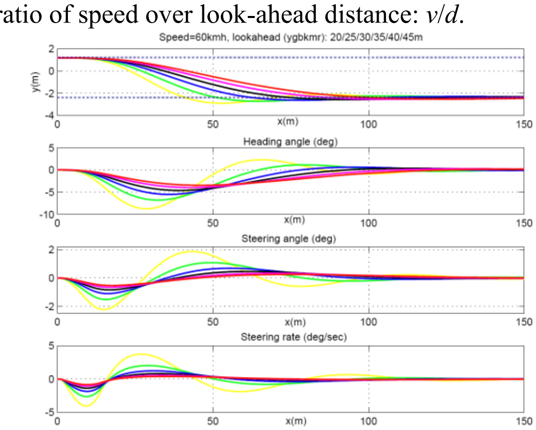


Fig. 4 The LC performance of the driver steering model

As shown in Fig. 4, the driver steering model with such a simple gain performs the LC smoothly and successfully, without an explicit desired trajectory (see the top subplot for the actual trajectory). Furthermore, the longitudinal distance to reach the centerline of the next lane is approximately twice the look-ahead distance. In addition, with the constant control gain defined at (*v*/*d*), the shorter the look-ahead distance is, the larger the overshoot. This result suggests that the look-ahead distances is preferred to be larger than the distance travelled in 1 second. The driver could also increase the control gain to reduce the overshoot when he/she chooses a relatively short look-ahead distance.

B. The Lane Keeping Maneuver

When performing the lane keeping (LK) maneuver, the target points are simply the centerline of the lane the vehicle is in. The latter part of the lane change shown in Fig. 4 can be regarded as the lane keeping on a straight lane. To evaluate the LK performance on curves, a road consisting of a straight segment and a curve with radius of 100m is used. The speed is chosen to be 60 kmh (i.e., 16.7 m/s), which results in a 0.28g lateral acceleration on the curve. Five look-ahead distances ranging from 17.5 m to 30 m are used in the simulation. The control gain is set to be constantly at 1.5 times the ratio of speed over look-ahead distance[2].

Figure 5 shows the vehicle trajectories and Fig. 6 show the lateral deviation, heading angle, steering angle (at tire), as well as the steering rate. As shown in Fig. 5, the vehicle follows the road (red dots) consistently and the maximum deviation occurs when the vehicle is transitioning from the straight segment to the curve. As shown in Fig. 6, with the given range of the look-ahead distance and with the control gain fixed at 1.5**v*/*d*, the longer the look-ahead distance is, the larger the maximum deviation. This is consistent with the real-life experience that we often need to shorten our look-ahead distance when driving on curves.

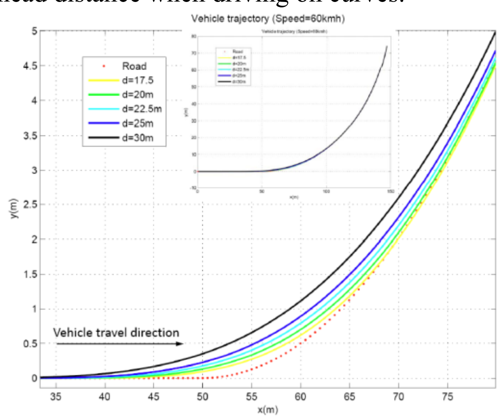


Fig. 5 LK performance of the driver steering model: vehicle trajectory (details with insert of the complete trajectory)

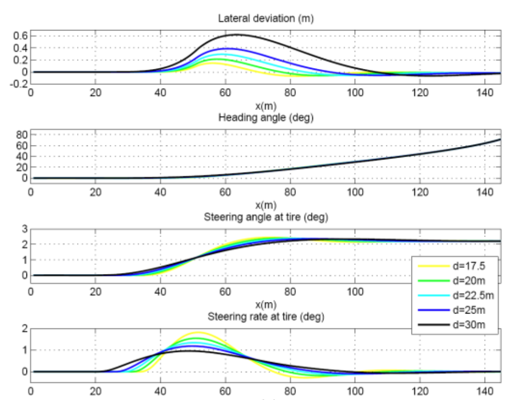


Fig. 6 LK performance of the driver steering model

While a relatively shorter look-ahead distance results in a better tracking performance, it also demands a higher steering rate thus a faster change in steering angle (Fig. 6). Note that the driver only adjusts the steering left or right based on the target angle error he perceives. He adjusts faster when the target angle error is larger. The authors are surprised to observe that the model can tolerate a large range of gains while still stable. Such capability allows drivers to exhibit various driving characteristics such as those described as conservative, and aggressive.

[2] The control gain is higher than that used in the lane change simulations. The reason is that the look-ahead distances are shorter (needed for the 100m-radius curve) than those used in the lane changes.

C. The Left/Right Turn Maneuver

For left and right turns, the driver steering model uses the current lane center as the target points before the turn and the center of the lane to the vehicle is turning to as the target points during and after the turn. The red dots in Fig. 7 show the center of the two lanes for the simulation of a 90 degree left turn maneuver. For typical intersections, the turn starts 1.5 times the lane width before the lane the vehicle is turning to and ends about 1.5 times the lane width away from the vehicle is turning from. In this simulation, the lane width is set to be 3.7 m (standard US highway lane width); therefore, the turn starts 5.55 m before the perpendicular lane and should be completed 5.55 m above the horizontal lane[3].

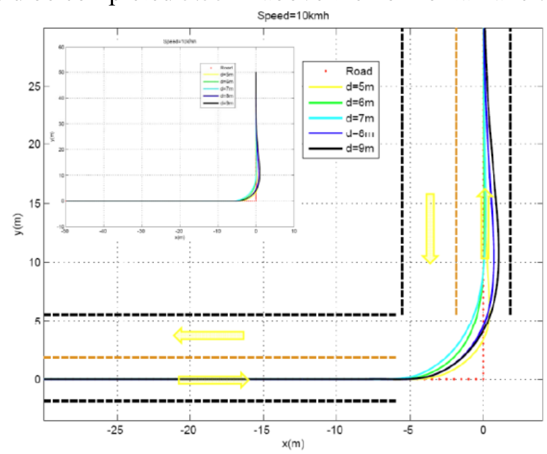


Fig. 7 Left turn performance of the driver steering model: vehicle trajectory

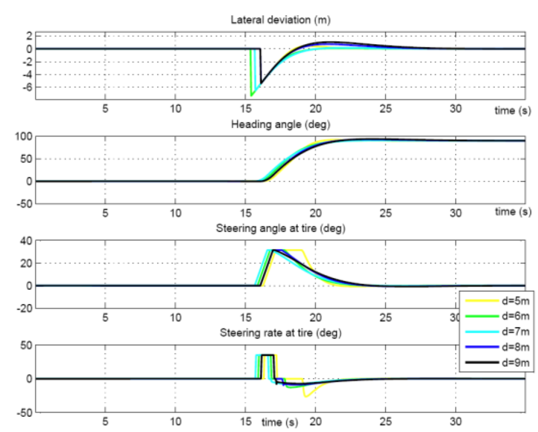


Fig. 8 Left turn performance of the driver steering model[4]

Figures 7 and 8 show the simulation results with the look-ahead distances from 5 m to 9 m. The driver steering model performs the left turn successfully without any pre-planned trajectory. The lateral error when entering the new lane is about 0 to 2 ft, similar to the errors most drivers have.

[3] The simulations indicates that for look-ahead distances smaller than 7 m, the turn needs to start a little earlier and end a little late to reduce the lateral deviation.

[4] The lateral deviation is with respect to the horizontal lane before the turn and with respect to the perpendicular lane during and after the turn. Therefore, the lateral deviation during the turn (approximately between time 15 to 20 s) is the distance to the perpendicular lane.

In summary, these initial simulations with the T&C driver steering model show that this T&C model is capable of performing other maneuvers with the simple setup of fixed look-ahead distances and fixed control gains. The resulting closed-loop system is surprisingly robust with plenty of room for simulating different driver characteristics. These results indicate that this straight-forward driver steering model originally developed based on DLC test data has the potential to be a generic driver model.

IV. Control Synthesis of The Driver Steering Model

To further understand this T&C driver steering model from the perspective of control theory, we formulate the model into a standard state feedback control in this section. Since the lane keeping (LK) scenario is the most basic driving scenario and the LK capability reveals the basic regulation capability of the driver steering model, we start the formulation with the LK scenario.

In the LK scenario, the target set is the centerline of the lane the vehicle is in. Figure 9 shows a vehicle traveling on a curved road. The points in the figure are:

- Point V (x, y): the current vehicle position;
- Point T (T_x, T_y): preview target at look-ahead distance d;
- Point A (A_x, A_y): the location the vehicle will be if it travels the distance d while keeping its current heading angle, θ_v;
- Point B (B_x, B_y): the location the vehicle will be if it travels the look-ahead distance d while keeping its current yaw rate and speed;
- Point O: the center of the curve corresponding to the vehicle trajectory if it keeps its current yaw rate and speed. And R is the radius of the curve.

The coordinates are set to be the road coordinates with the origin at the lane center corresponding to the vehicle position. Thus, y is the lateral deviation of the vehicle from the lane center.

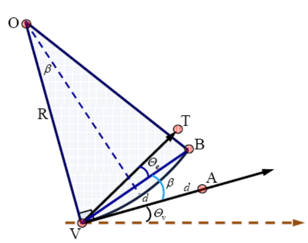


Fig. 9 Illustration of target angle error computation

Assuming the radius R is much larger than the look-ahead distance d (which is typically true for LK since the road curvature is relatively small), the travel distance from V to Point B is approximately the distance between V and B. Therefore, by rotating the curve between V and B an angle of θ_e, Point B will be at the location of Point T. Thus, the angle θ_e is the target angle error. The positions of Point T can then be calculated as:

$$\begin{cases} T_x = x + d\cos(\theta_v + \beta + \theta_e) \\ T_y = y + d\sin(\theta_v + \beta + \theta_e) \end{cases} \tag{6}$$

Assumption #1: assuming vehicle heading angle θ_v is small, we have $\cos(\theta_v) \approx 1$ and $\sin(\theta_v) \approx \theta_v$.
Assumption #2: assuming the radius is much larger than the look-ahead distance: $R \gg d$, thus, β is a small angle and $\sin\beta = d/(2R)$.
Assumption #3: assuming the target angle error θ_e is also small, we then have $\cos(\theta_e) \approx 1$ and $\sin(\theta_e) \approx \theta_e$. Thus,

$$\begin{cases} T_x = x + d\left(1 - \frac{d}{2R}\theta_e - \frac{d}{2R}\theta_v - \theta_e\theta_v\right) \\ T_y = y + d\left(\theta_v - \frac{d}{2R}\theta_e\theta_v + \frac{d}{2R} + \theta_e\right) \end{cases} \tag{7}$$

Further ignoring the higher order component $\theta_e\theta_v$, and replace R with $R = v/\omega$, we have

$$\begin{cases} T_x = x + d\left(1 - \frac{d\omega}{2v}\theta_e - \frac{d\omega}{2v}\theta_v\right) \\ T_y = y + d\left(\frac{d\omega}{2v} + \theta_e + \theta_v\right) \end{cases} \tag{8}$$

Note that $T_x \approx x + d$ since $R \gg d$ and both θ_e and θ_v are small.

On the other hand, assuming a constant road curvature $\rho_{road} = 1/R_{road}$ and $R_{road} \gg d$, the preview target should satisfy the following:

$$\begin{cases} T_x = x + d\cos\beta_{road} \approx x + d \\ T_y = d\sin\beta_{road} = d\left(\frac{d}{2R_{road}}\right) = \frac{d^2\rho_{road}}{2} \end{cases} \tag{9}$$

Combining Eq. (8) and (9), we have:

$$\theta_e = \frac{d}{2}\rho_{road} - \left(\frac{1}{d}y + \frac{d}{2v}\omega + \theta_v\right) \tag{10}$$

Correspondingly, we have the controller law as the follows:

$$\dot{\delta} = k\theta_e = \frac{kd}{2}\rho_{road} - k\left(\frac{1}{d}y + \frac{d}{2v}\omega + \theta_v\right) \tag{11}$$

In other words, the steering rate control is a feedback control based on the lateral deviation y, the yaw rate ω, and the heading angle θ_v. Figure 10 shows the configuration of the steering controller equivalent to the driver steering model.

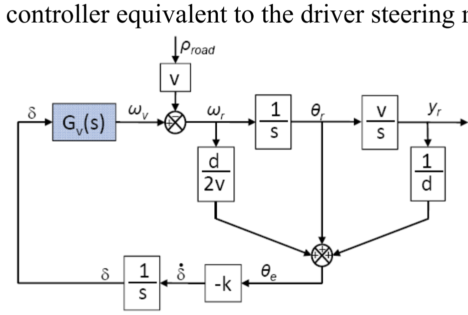


Fig. 10 The closed-loop configuration with driver steering model

Thus, the overall controller of the driver steering model in lane-keeping maneuvers can be derived as:

$$C(s) = \frac{k}{s}\frac{d\left(s^2 + 2\frac{v}{d}s + 2\left(\frac{v}{d}\right)^2\right)}{2vs^2} \tag{12}$$

Accordingly, the overall closed loop with the driver steering model is shown in Fig. 11.

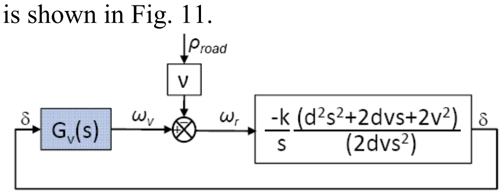


Fig. 11 The closed loop with the driver steering model

V. Preliminary Discussion and Future Research

In this paper, a T&C driver steering model developed and verified based on DLC maneuvers has been shown to be capable of performing various other maneuvers, including LC, LK, and left/right turns. Compared to most driver steering models in literature, this model is unique in three key aspects corresponding to three key discoveries in driver's driving behavior.

First, the driver model does not involve trajectory planning and the steering control is not to follow a designed trajectory. Instead, the model uses targets located at the lane center as references. This target-based control is verified by the vehicle DLC data, and the simulations in this paper demonstrate that this straight-forward driver steering model can perform various types of maneuvers with ease.

Second, the steering control is based on the target angle error, which drivers can perceive intuitively according to a simple geometric relationship. The target angle error is based on the preview target, the vehicle yaw rate, speed, and heading angle; therefore, the driver model does not need an internal dynamic model of the vehicle. In fact, drivers can easily detect such error by observing how fast the vehicle travelling direction is deviating from the desired target point.

Third, contrary to the steering angle controller assumed by most driver models, the steering control of this driver steering model is a steering rate controller. This indicates that the driver determines how much more or less steering he/she needs and increases or reduces the steering angle accordingly. As a comparison, under the traditional steering angle control, the driver needs to know the desired steering angle and steers the handwheel to the desired steering angle. The DLC vehicle test data strongly supports the steering rate control and the real-life experience of most drivers seems to be more consistent with the steering rate control as well.

The control synthesis of the driver steering model reveals several advantages of this driver steering model. First, the controller has two zeros at $(-\frac{v}{d} \pm \frac{v}{d} i)$. These two zeros have a constant damping at 0.707. As the control gain gets larger, two of the closed-loop poles will be approaching these two open-loop zeros that have favorable damping. That is, the controller is likely to be able to sustain higher gains without sacrificing the stability. Thus, it provides a nice reservoir of stability margin that allows the driver to increase his or her gain when a higher gain is needed.

Furthermore, the controller is inherently a linear time varying controller, which is necessary for the driver to drive the vehicle at a relatively wide range of speeds.

Further researches are needed in several directions. One is to verify that the driver model can indeed capture driver's steering behavior across other maneuvers. Such research shall examine how drivers choose look-ahead distances and control gains for different maneuvers, as well as the decision points and factors contributing to the variety of driver's driving style and preference.

In parallel, we need to further our understanding of this driver steering model from the perspective of control theory. On-going work includes analyzing the model's sensitivity and robustness to disturbances, as well as its advantages and limitations as compared to popular automated steering controllers such as the look-ahead controller. The implications of this driver steering model on our existing knowledge of human control behavior beyond driving may also be a potential area worth exploring.

VI. Conclusion

This paper presents the preliminary steps in understanding a target & control based (T&C) driver steering model, which was developed and verified based on DLC vehicle test data. To evaluate whether the model has the potential to be a generic driver model, the paper examines the capability of this T&C driver steering model in handling common maneuvers such as lane changes, lane keeping, and left/right turns. The initial simulations show that this T&C model is capable of performing other maneuvers with the simple setup of fixed look-ahead distances and fixed control gains. The resulting closed-loop system is surprisingly robust with plenty of room for simulating different driver characteristics. The results indicate that this straight-forward driver steering model has the potential to be a generic driver model.

To understand this T&C driver steering model from the control's perspective, the preliminary control synthesis is then conducted with the model performing lane keeping maneuvers. The control synthesis reveals several advantages of this driver steering model, including open-loop zeros with a constant damping at 0.707, which provides stability margin for drivers to increase their control gain when needed.

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