Development of a longitudinal and lateral driver model for autonomous vehicle control

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Abstract: Since the autonomous vehicle is intended to simulate a human driver's behaviour, it is very helpful to introduce a driver model to the design of the autonomous vehicle controller. The intention of this paper is to exhibit the approaches of building a longitudinally and laterally integrated driver model and the methods of applying the model in autonomous vehicle control. A series of simulations is undertaken in typical driving conditions such as double lane change, speed or position following in straight line, braking-in-turn, high-speed U turn, etc. During the entire course of the simulations, the driver model has demonstrated the great accuracy in terms of following both the path and the vehicle speeds. It can be concluded that this particular type of driver model is highly applicable in autonomous vehicle control.

Keywords: autonomous vehicle control; driver model; preview-follower theory.

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Biographical notes: Konghui Guo, born in 1935, is a Professor at Jilin University of China, and the Director of the State Key Laboratory of Automotive Dynamic Simulation. From 1958 to 1993, he worked in Changchun Automotive Research Institute. In 1994, he was honoured as the Academician of the Chinese Academy of Engineering. From 1993 to 2000, he was the Vice President of Jilin University of Technology.

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1 Introduction

Aiming at replacing the human driver with the electronic control system partially or completely, Autonomous Vehicle Control demonstrates its bright prospects in the automotive industry in terms of providing drivers with comfortable and safe environments. Considering that an autonomous vehicle simulates the human driver's driving behaviour, the development of an autonomous vehicle tends to benefit from the researchers' in-depth understanding of driver behaviour as well as its subsequent applications to autonomous vehicle control. In general, the process of autonomous vehicle control consists of two stages. During the first stage, the desired path and vehicle speeds are to be determined on the basis of the driving environment. For the second stage, the vehicle is operated with the aim of realising the anticipated path and vehicle speeds. In this sense, the driver model takes two roles: one is to decide the path and speed (Driver Decision Model, see Figure 1), the other is to follow the driver's decision (Driver Following Model, see Figure 1). For this reason, the driver decision model needs to determine the desired path and speed through the interactions with the factors such as the traffic conditions, driver's driving habits and current vehicle states. With the ground co-ordinate XOY (Figure 2) and the desired path and vehicle speeds as the outputs of the driver decision model, the desired path can be described as $Y = F(X)$ and the desired speed as $V_x^{(ref)} = G(S)$ where S is the distance along the path $Y = F(X)$. Accordingly, within the vehicle co-ordinate xoy (Figure 2), the desired path is $y = f_y(t)$ while the desired speed is $V_x^{(ref)} = g(t)$ where t is the time.

Figure 1 Overview of the autonomous vehicle control using driver model

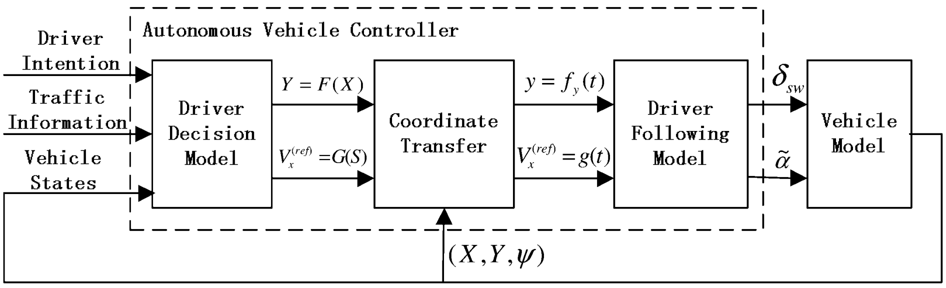
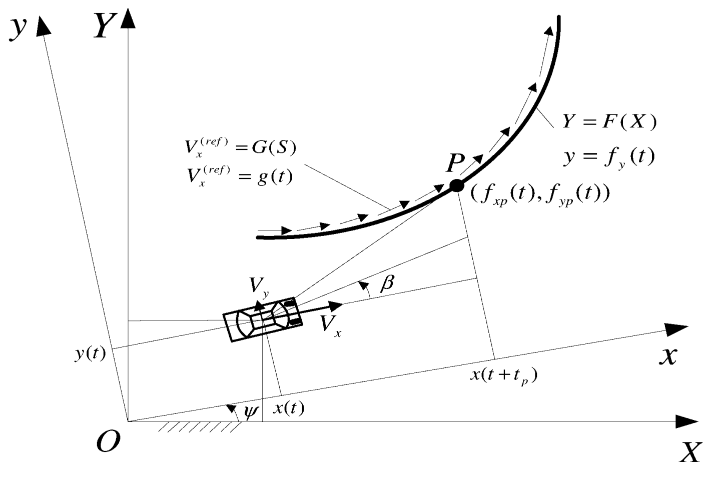


Figure 2 Description of the driver's decision



As Figure 2 illustrates, the ground co-ordinate XOY is an absolute system while the vehicle coordinate xoy rotates with the vehicle's heading direction but shares the same fixed origin with the ground co-ordinate. Figure 1 portrays the overview of the autonomous vehicle control by using driver model. Basically, the autonomous vehicle controller is composed of three modules: driver decision model, co-ordinate transfer and driver following model. As discussed above, the outputs of the driver decision model $Y = F(X)$ and $V_x^{(ref)} = G(S)$ are described in the space domain (XOY). For simplicity in driver modelling, it is desirable for the driver's decisions to be described in the time domain in the vehicle co-ordinate rather than the space domain in the ground co-ordinate. Following the co-ordinate transfer module, the inputs of the driver following model are described as $y = f_y(t)$ and $V_x^{(ref)} = g(t)$ while the outputs of the driver following model are steering wheel angle δ_{sw} and unified throttle $\tilde{\alpha}$. As shown in Figure 1, the autonomous vehicle tends to deliver good performance as long as the driver model is capable of reflecting the skilful human driver's behaviour. Though the driver decision model tends to vary with the driving conditions, it is not covered by the discussion in this paper. Assuming that the desired path and vehicle speed have been determined, this paper is going to focus on the approaches of achieving the desired elements. For reasons of simplicity, the driver following model is also called the driver model below.

2 Vehicle model and longitudinal acceleration map

A vehicle model with engine, driving system (powertrain), braking system and steering system should be established for autonomous vehicle control simulation. In order to simplify the drive line, the vehicle is assumed to be equipped with an ideal Continuously Variable Transmission (CVT), which allows the driving performance to be exclusively controlled by a throttle pedal while the clutch and gear box are managed by the ideal CVT logic.

2.1 Overview of the vehicle model

Figure 3 demonstrates a 4-DOF vehicle model in the dimensions of longitudinal displacement, lateral displacement, yaw movement and roll movement for the purpose of autonomous vehicle control simulation. In the context of the vehicle body dynamics, axle load transfer is taken into account. Meanwhile, rolling steer and suspension compliance steer are also included in the model in the form of the wheel alignment correction. For the vehicle lateral dynamics, the simplified steer system model is introduced. δ_i ($i = 1, \ldots, 4$: where i stands for wheel number) is the steer angle of each wheel. For the vehicle longitudinal dynamics, an engine model, powertrain model, brake model and aerodynamics model are introduced. Among these models, the engine model is an experimental data-fitted model, and can be of the following description.

$$T_{ed}(s) = T_{es} \cdot \frac{\exp(-t_{ed}\, s)}{1 + t_{eh}\, s}, \tag{1}$$

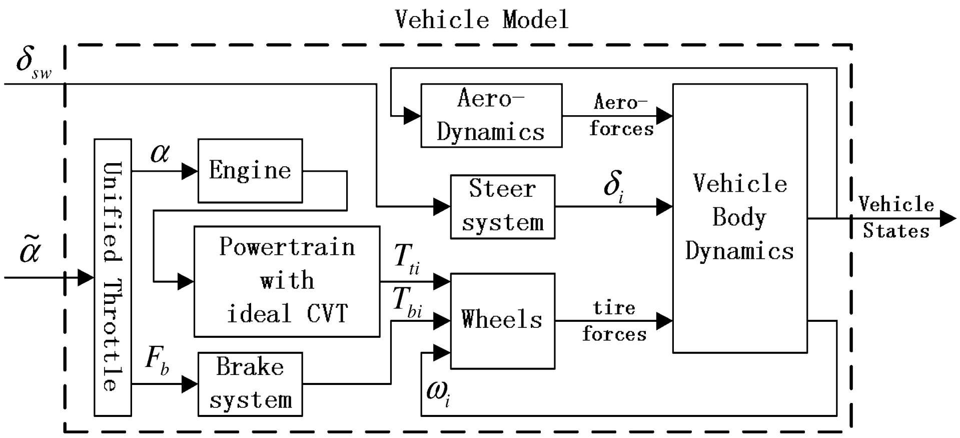
where T_{ed} and T_{es} are the dynamic engine output torque and the steady state engine output torque accordingly while t_{ed} and t_{eh} are the time delay constant. The steady state output torque of the engine T_{es} is determined by the engine throttle α and engine speed n_c.

$$T_{es} = fun(\alpha, n_e). \tag{2}$$

The powertrain model provides the wheel model with the traction torques $T_{ti}\,(i = 1, \ldots, 4)$ while the brake system model provides the braking torques $T_{bi}\,(i = 1, \ldots, 4)$. The wheel model consists of the wheel dynamics model and the tyre model, where inputs to the wheel model are traction torque, brake torque and wheel speed $\omega_i\,(i = 1, \ldots, 4)$ while outputs are tyre forces. Being relatively more complex than other models, the tyre model demonstrates a series of properties that tend to influence vehicle behaviour significantly. In this paper, UniTire which is proposed by Professor Guo (Guo and Ren, 1999; Guo et al., 2001) is applied to the tyre model.

In order to simplify the interface between the driver model and the vehicle model, engine throttle α and the brake pedal force F_b are integrated into one control parameter $\tilde{\alpha}$ called unified throttle, which will be defined in Section 2.3.

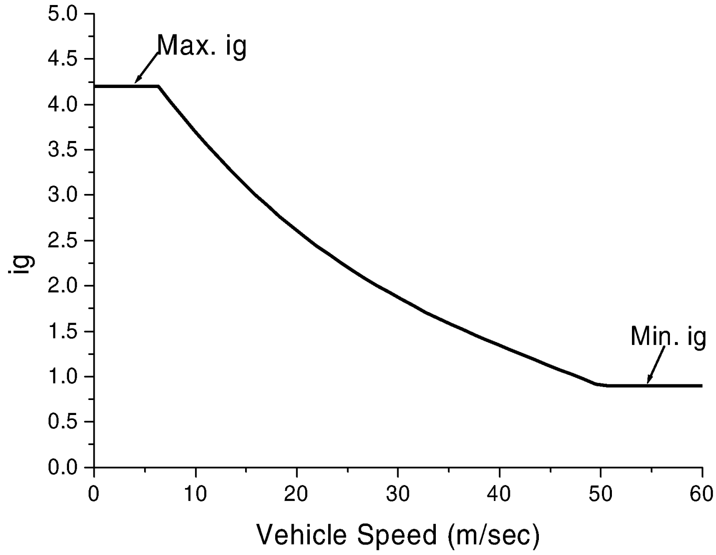
Figure 3 Vehicle model for autonomous vehicle control simulation



2.2 Powertrain with ideal CVT

Based on the optimal vehicle driving performance, an ideal CVT model is introduced in order to simplify the driver operation interface. As exhibited by Figure 4, the transmission ratio of the gear box i_g is the function of vehicle speed.

Figure 4 Transmission ratio of the gear box vs. vehicle speed for the ideal CVT



2.3 Vehicle longitudinal acceleration map

For a vehicle with CVT, its longitudinal acceleration is determined by throttle α and brake pedal force F_b. By defining α_b as,

$$\alpha_b = -\frac{F_b}{F_{b\max}}, \tag{3}$$

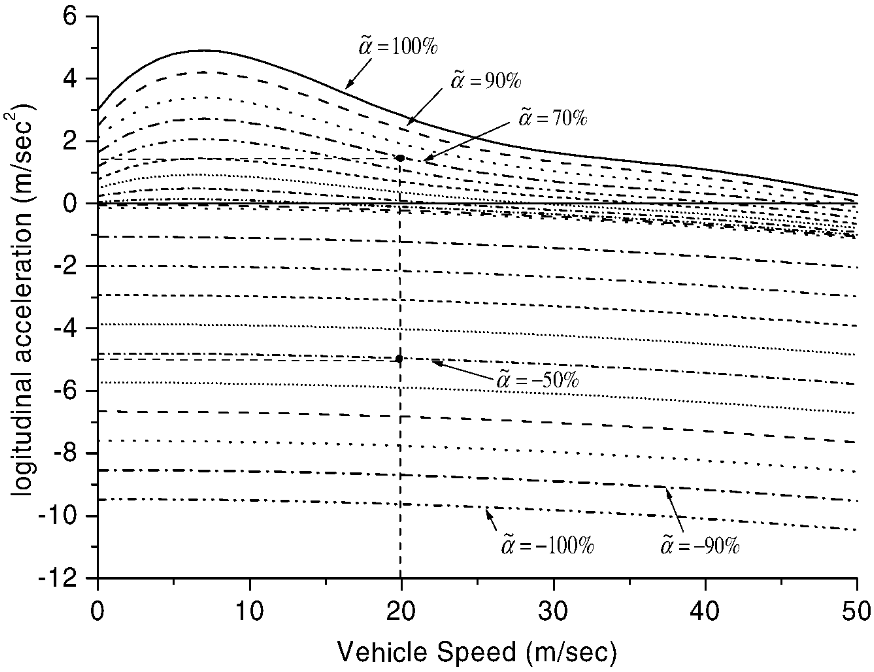
where $F_{b\max}$ is the maximal force exerted to the brake pedal, unified throttle $\tilde{\alpha}$ can be given as,

$$\tilde{\alpha} = \begin{cases} \alpha & \tilde{\alpha} \geq 0 \\ \alpha_b & \tilde{\alpha} < 0 \end{cases}. \tag{4}$$

Subsequently, the relationship between the longitudinal acceleration and unified throttle $\tilde{\alpha}$ in the vehicle with the ideal CVT can be approximated as shown in Figure 5.

The vehicle longitudinal acceleration map describes the steady state relationship between the unified throttle and the vehicle's acceleration at different vehicle speeds. For example, when the vehicle speed is 20 m/s and $\tilde{\alpha}$ is 70%, the vehicle's steady state longitudinal acceleration is about 1.5 m/s^2. In another word, if the driver intends to have a 1.5 m/s^2 longitudinal acceleration at 20 m/s, he/she is supposed to depress the throttle pedal to 70%. It implies that in the case of $\tilde{\alpha} < 0$, unless the brake is applied, the release of the throttle pedal is unable to provide sufficient deceleration. For example, with the vehicle speed as 20 m/s, the full release of throttle must be supplemented by 50% of brake pedal depress in the pursuit of a -5 m/s^2 longitudinal acceleration, which means $\tilde{\alpha} = -50\%$. To summarise, given the current vehicle speed and the desired longitudinal acceleration, the desired unified throttle $\tilde{\alpha}$ can be identified by referring to the vehicle longitudinal acceleration map.

Figure 5 The vehicle longitudinal acceleration map



3 Preview-follower theory for driver modelling

The preview-follower theory discussed herein is initially derived from a research investigation undertaken by Professor Guo in early 1980s (Guo et al., 1983). The preview-follower theory describes the driver's behaviour on the basis of the hypothesis that the driver's operation is always aimed at minimising the errors between the desired trajectory of the vehicle while following the desired vehicle speed. In the context, the transfer function of the driver/vehicle closed-loop system is considered as a multiplication of two parts. One is the previewer transfer function which describes the driver's preview effect. By contrast, the other is the follower transfer function which reflects the driver's following process. Given that the driver's operation to vehicle is a low frequency process, the transfer function of the whole system should always be '1' at low frequency range.

$$\frac{y}{f}(s) = P(s) \cdot F(s) = 1, \tag{5}$$

where $P(s)$ is the transfer function of the previewer, which has a Taylor's expansion as

$$P(s) = P_0 + P_1 \cdot s + P_2 \cdot s^2 + P_3 \cdot s^3 + \cdots, \tag{6}$$

and $F(s)$ is the transfer function of the follower, the inverse of which has a Taylor's expansion as

$$F(s)^{-1} = a_0P_0 + a_1P_1 \cdot s + a_2P_2 \cdot s^2 + a_3P_3 \cdot s^3 + \cdots, \tag{7}$$

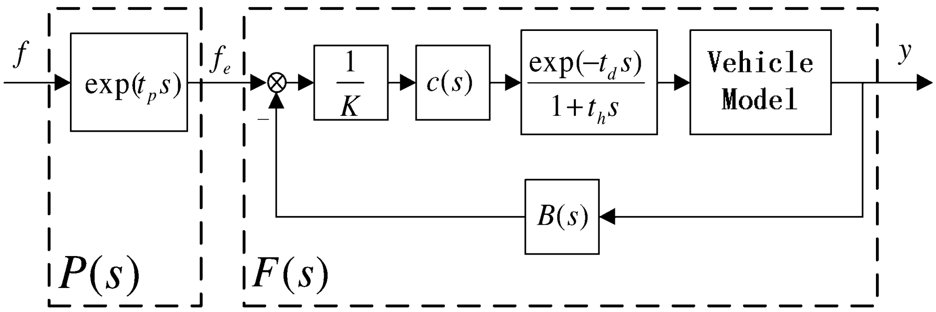
where a_0, a_1, a_2, ... are constants depending on the dynamics of the vehicle and the parameters of the driver. If the transfer function of the whole system can be described by Equations (5)–(7), and

$$a_i = \begin{cases} 1 & \text{for} \quad i = 0, 1, 2, \ldots, n \\ 0 & \text{for} \quad i > n \end{cases} \tag{8}$$

then the system is called the n^{th} order preview-follower system. For a preview-follower system, if the parameters of the driver model can meet Equation (5) at the low frequency range, the driver model will have good following precision.

Figure 6 demonstrates an example of a driver model based on the preview-follower theory. f describes the driver's following target, y is the corresponding vehicle output, $\exp(t_p s)$ is the previewer transfer function based on single-point preview assumption, $\exp(-t_d s)/(1 + t_h s)$ stands for the driver's action delay, $B(s)$ refers to the feedback transfer function of the vehicle output, $c(s)$ represents the driver's correction transfer function. Also, the follower transfer function $F(s)$ is shown in Figure 6. If the whole driver/vehicle closed-loop system meets Equation (8), the output of vehicle y will follow the desired input f at low frequency range. For in-depth understanding of preview-follower theory, please refer to Guo et al. (1983) and Guo and Guan (1993).

Figure 6 An instance of preview-follower theory



4 Pure lateral driver model

4.1 Pure lateral driver model based on the preview-follower theory

The vehicle co-ordinate, incorporates a few elements e.g. the desired vehicle lateral position $f_y(t)$, the vehicle's current lateral position $y(t)$ and the driver's preview time t_{yp}. If the vehicle operates at constant acceleration, the predicted vehicle lateral position at the time $t + t_{yp}$ is,

$$y(t + t_{yp}) = y(t) + t_{yp} \cdot \dot{y}(t) + \frac{t_{yp}^2}{2} \cdot \ddot{y}(t). \tag{9}$$

The driver's goal is to follow the desired path, that is, at the time $t + t_p$, the predicted lateral position is equal to the previewed lateral position. In this sense, the optimal lateral acceleration is,

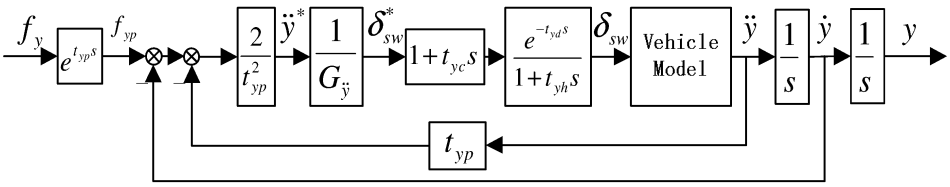
$$\ddot{y}^*(t) = \frac{2}{t_{yp}^2}\left[f(t + t_{yp}) - y(t) - t_{yp} \cdot \dot{y}(t)\right]. \tag{10}$$

The steady state gain derived from the combination of $\ddot{y}$ and steering wheel angle δ_{sw} is $G_{\ddot{y}}$. Therefore,

$$\delta_{sw}^* = \frac{\ddot{y}^*(t)}{G_{\ddot{y}}}. \tag{11}$$

There are two kinds of driver delays, driver neural response delay $\exp(-t_{yd}s)$ and driver muscle action delay $1/(1 + t_{yh}s)$. In order to compensate the delays, a leading correction $1 + t_{yc}s$ is introduced. The overview of pure lateral driver model is shown in Figure 7.

Figure 7 Pure lateral driver model based on preview-follower theory



According to the preview-follower theory, the previewer transfer function is,

$$P(s) = \frac{f_{ye}(s)}{f_y(s)} = e^{t_{yp}s} = 1 + t_{yp}s + \tfrac{1}{2}(t_{yp}s)^2 + \tfrac{1}{6}(t_{yp}s)^3 + \cdots. \tag{12}$$

The follower transfer function is,

$$F(s) = \frac{y(s)}{f_{ye}(s)}. \tag{13}$$

Since the driver's target is to follow the desired path, at the low frequency range it is assumed that

$$P(s) \cdot F(s) = 1. \tag{14}$$

The lateral vehicle property between δ_{sw} and $\ddot{y}$ can be described as,

$$\frac{\ddot{y}}{\delta_{sw}}(s) = G_{\ddot{y}} \cdot \frac{1 + T_{y1}s + T_{y2}s^2 + \cdots}{1 + T_1 s + T_2 s^2 + \cdots}. \tag{15}$$

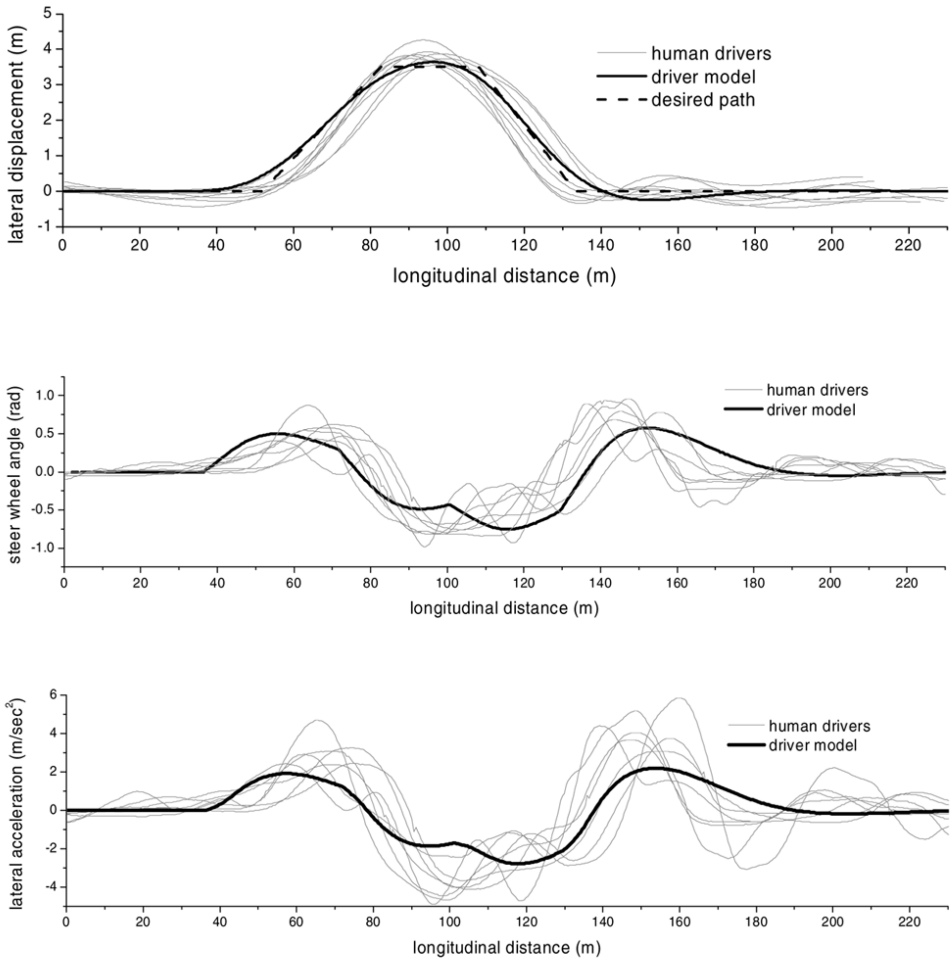
Considering Equation (14), the leading correction time t_{yc} can be determined by,

$$t_{yc} = t_{yd} + t_{yh} + T_1 - T_{y1}. \tag{16}$$

4.2 Simulation and verification

Suppose that the driver's delay time constant $t_{yd} = 0.4$, $t_{yh} = 0.2$ and preview time $t_{yp} = 1.4$, comparisons between experiment and simulation through lateral driver model at double lane change are illustrated in Figure 8. The experiments are taken on the driving simulator (Guo et al., 1999) at Jilin University by skilful human drivers at 80 km/h. For the simulation with the driver model, cruise control logic is introduced to maintain the constant vehicle speed in the double lane change. As illustrated in Figure 8, the pure lateral driver model reflects the skilful human driver's steering behaviour and demonstrates a great level of accuracy in respect of tracking the vehicle lateral positions.

Figure 8 Comparison between experiment and lateral driver model simulation at double lane change at vehicle speed 80 km/h



5 Pure longitudinal driver model

5.1 Position following and velocity following longitudinal driver models based on the preview-follower theory

Similar to the lateral driver model, the longitudinal driver model based on the preview-follower theory consists of two components: position following longitudinal driver model (Figure 9) and velocity following longitudinal driver model (Figure 10).

Figure 9 Position following longitudinal driver model

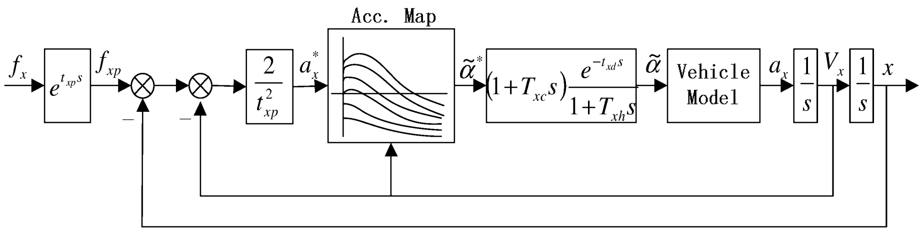
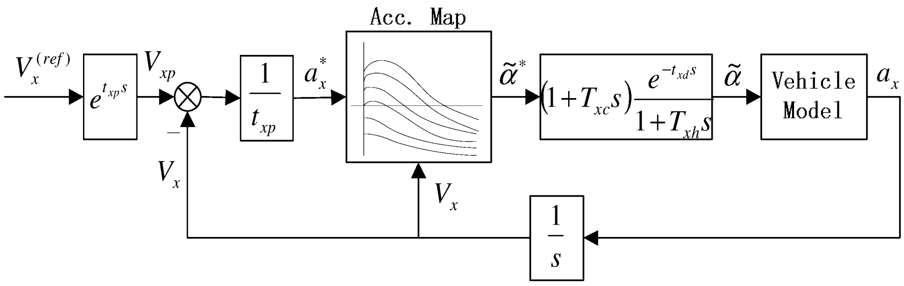


Figure 10 Velocity following longitudinal driver model



For the longitudinal position following driver model, variables include the desired longitudinal position f_x, the previewed longitudinal position f_{xp}, the longitudinal preview time t_{xp}, the desired longitudinal acceleration a_x^*, the desired unified throttle $\tilde{\alpha}^*$ and the unified throttle longitudinal driver model outputs $\tilde{\alpha}$. For the longitudinal velocity following driver model, $V_x^{(ref)}$ is the desired vehicle speed along the path while V_{xp} is the previewed vehicle speed.

In the lateral driver model, the steady state gain $G_{\ddot{y}}$ as a constant, is derived from the interactions between $\ddot{y}$, steering wheel angle δ_{sw} and a certain vehicle speed. Moreover, the $1/G_{\ddot{y}}$ in the pure lateral driver model (Figure 7) and the $G_{\ddot{y}}$ in the vehicle model (Equation 15) are supposed to be counteracted, which is essential to design the driver model by using the preview-follower theory. Unlike the lateral driver model, the steady state gain between longitudinal acceleration and unified throttle is much more complex in the longitudinal driver model. It depends not only on the vehicle speed but also the unified throttle. For this reason, the longitudinal acceleration map is introduced to the driver model to express the relationship between longitudinal acceleration a_x and the desired unified throttle $\tilde{\alpha}$.

$$a_x = fun(\tilde{\alpha}, V_x). \tag{17}$$

By referring to the acceleration map, the desired unified throttle $\tilde{\alpha}^*$ can be determined by the desired longitudinal acceleration a_x^* and current vehicle speed V_x.

$$\tilde{\alpha}^* = fun^{-1}(a_x^*, V_x). \tag{18}$$

Given the longitudinal vehicle model as,

$$a_x = fun\,(\tilde{\alpha}, V_x) \cdot \frac{\exp(-t_{ed}s)}{1 + t_{eh}s}. \tag{19}$$

Equation (19) indicates that on one hand, the steady state response between a_x and $\tilde{\alpha}$ complies with the description of the longitudinal acceleration map; on the other hand, the dynamic response is the outcome of the engine and powertrain delays. Suppose that in the longitudinal driver model, $fun^{-1}(a_x^*, V_x)$ and $fun(\tilde{\alpha}, V_x)$ can be counteracted, similar to lateral driver model in the light of the preview-follower theory, parameters of the longitudinal driver model are determined as follows.

$$t_{xc} = t_{xd} + t_{xh} + t_{eh}. \tag{20}$$

Likewise, similar to the position following model, the velocity following the longitudinal driver model allows the leading correction time to be expressed by Equation 20.

5.2 Simulation and verification

Figure 11 is the simulation result of the position following longitudinal driver model on the straight line. The desired path is derived from the integration of the desire vehicle speed shown in Figure 11. With the comparison between the desired longitudinal displacement f_x and the vehicle's real longitudinal displacement x, it can be implied that the longitudinal acceleration map describes the basic vehicle longitudinal dynamics properties while the longitudinal driver model has good precision in following the desired vehicle longitudinal position. However, in terms of the longitudinal velocity and acceleration, there are still discrepancies between the simulation data and the desired data. It is likely that the inconsistencies arise from the mismatches between the descriptions of the longitudinal acceleration map and the real longitudinal properties of the vehicle. With the vehicle longitudinal position as the main feedback, the position following driver model is thus able to directly maintain the following precision of the vehicle longitudinal displacement. It explains why the longitudinal velocity following precision is not as good as the position following precision. In the scenario where driver is more concerned about the vehicle position than the vehicle speed, the position following longitudinal driver model is applied. By contrast, if the driver focuses more on vehicle speed, the velocity following longitudinal driver model is introduced (see Figure 10). Figure 12 is the simulation of the velocity following longitudinal driver model. From the simulation, it can be concluded that the vehicle speed following precision improves greatly compared with the position following the longitudinal driver model. However, the unified throttle of velocity following the longitudinal driver model varies to a greater degree than the position following the longitudinal driver model. Building on this, in pursuit of higher velocity following precision, the velocity following the longitudinal driver model needs to adjust the throttle more frequently than the position following the longitudinal driver model. In the scenario where the driver is more concerned with vehicle speed manipulation, the velocity following the longitudinal driver model appears to be a better choice.

Figure 11 Position following longitudinal driver model simulation

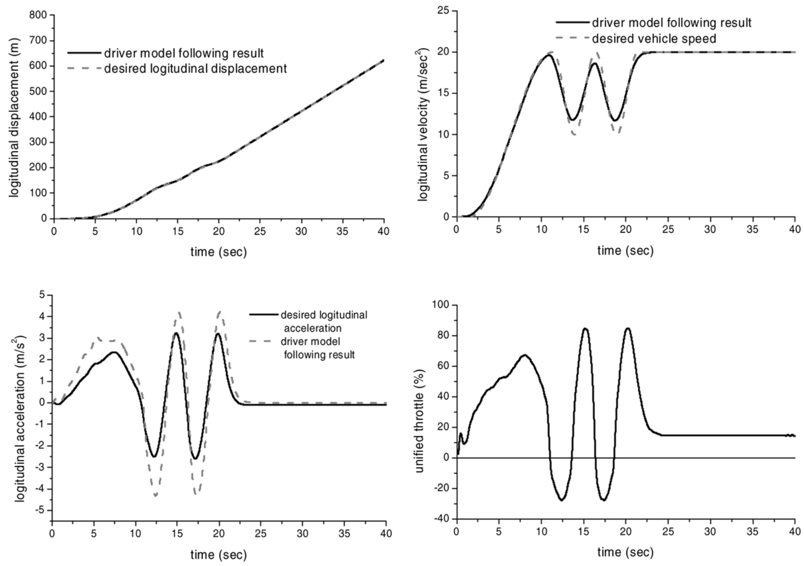
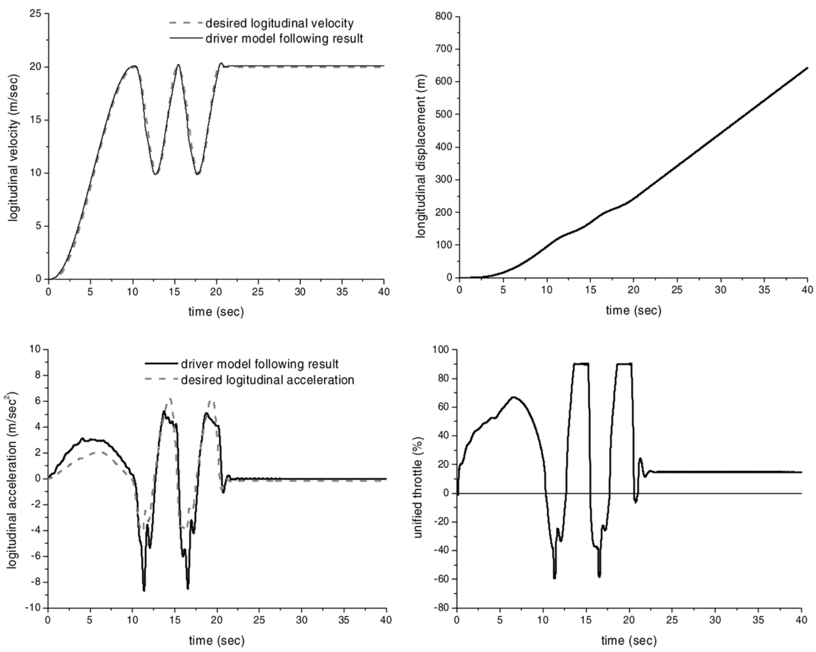


Figure 12 Velocity following longitudinal driver model simulation



6 Longitudinal and lateral combined driver model for autonomous vehicle control

6.1 Longitudinal and lateral combined driver model

Assuming that the interactions between the vehicle longitudinal and lateral properties can be ignored, the longitudinally and laterally integrated driver model can be developed (Figure 13) by combining pure lateral and longitudinal driver models. In the combined driver model, the steady state gain $G_{\ddot{y}}$ is the function of vehicle speed and in need of repeated updating during the simulation. Since the pure lateral driver model and the pure longitudinal driver model are expressed by the time domain in the vehicle co-ordinate, all the vehicle states, desired path and desired vehicle speed in the combined driver model need to be transferred from ground co-ordinate in the space domain to the vehicle co-ordinate in the time domain, without exception.

Figure 13 Longitudinal and lateral combined driver model

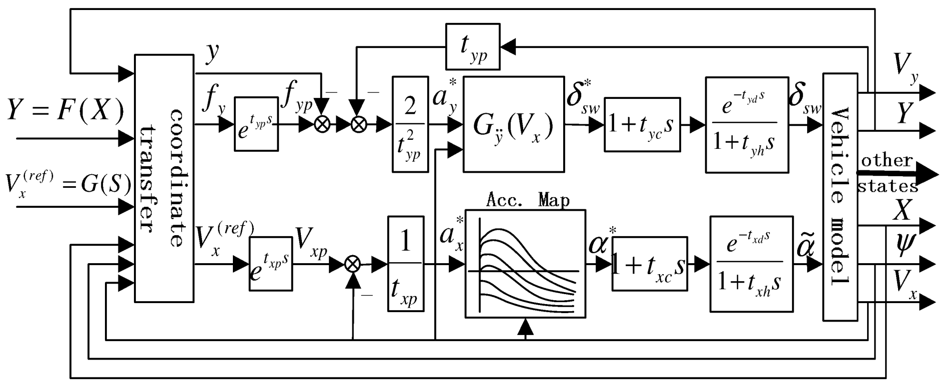


Figure 14 shows the scenario when the driver intends to drive the vehicle to avoid two obstacles. The scenario supposes that the desired path to be followed has been determined as shown in Figure 14 and that the driver attempts to slow down the vehicle speed from 30 to 15 m/s. Consequently, Figure 15 bears the simulation result through using the longitudinal and lateral combined driver model, which demonstrates that the proposed driver model is able to follow the driver's decision within the desired path and speed.

Figure 14 Obstacle avoidance using the combined driver model

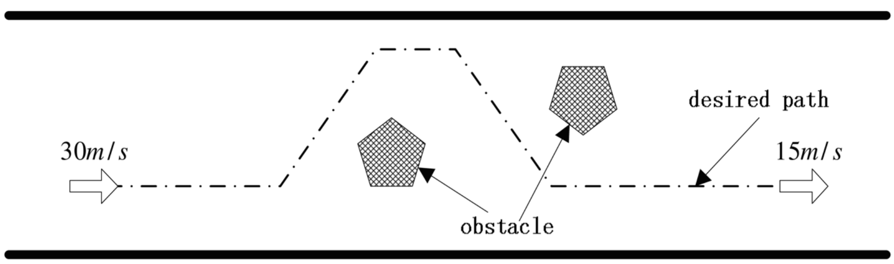


Figure 15 Obstacle avoidance simulation using the combined driver model

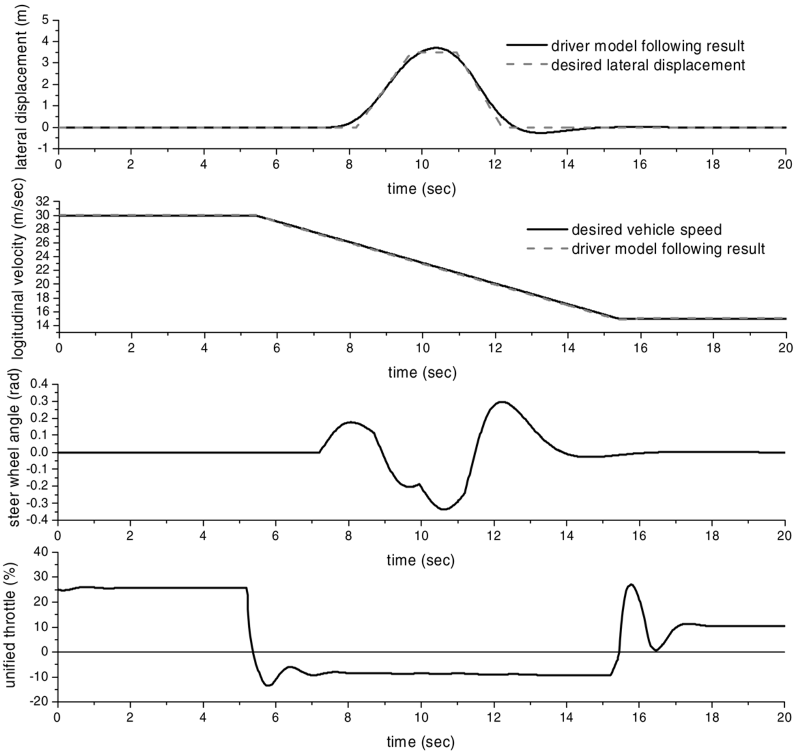
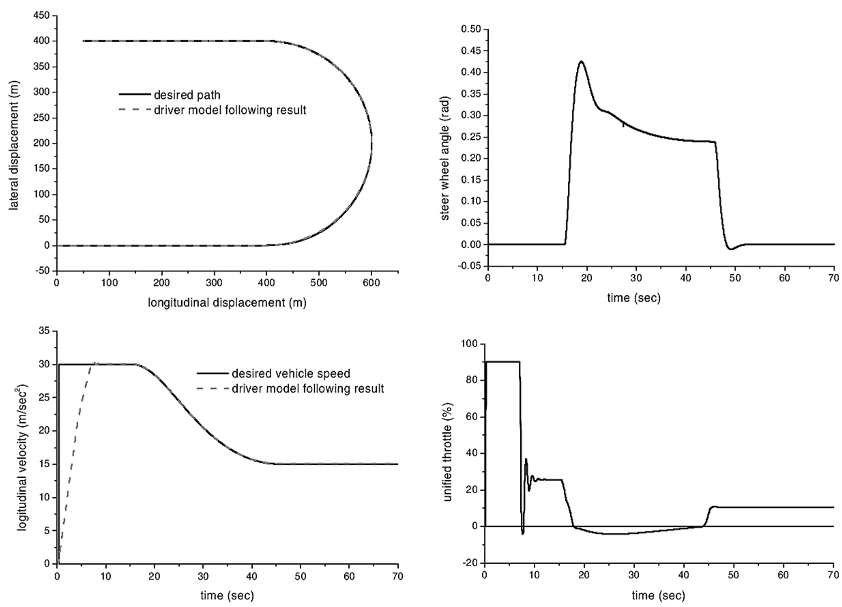


Figure 16 U-turn following simulation using combine driver model



The driver following path in Figure 14 is still a small curvature path. In order to verify the proposed driver model, a U-turn path is designed as shown Figure 16. The vehicle enters the U-turn path at 30 m/s, decelerates linearly along the circle and exits the path at 15 m/s.

The steering wheel angle and unified throttle derived from the longitudinally and laterally integrated driver model are shown in the Figure 16. The comparison between the desired vehicle path and the driver model following path manifests the great accuracy of the combined driver model even when following the big curvature path. During the half circle following, the vehicle speed also has good following capability. In summary, the longitudinal and lateral combined driver model based on the preview-follower theory has good performance to follow the decided path and vehicle speed. It is therefore recommended that the combined driver model be used in the application to autonomous vehicle control to follow the driver's decision.

6.2 Some Issues for application to autonomous vehicle control

Figure 1 shows the overview of the autonomous vehicle control using the driver model. With the difficulties in covering the full range of environments in which the autonomous vehicle may operate, several typical auto-driving modes such as adaptive cruise control, collision avoidance, lane keeping, platoon, etc. are highlighted for the design on the autonomous vehicle controller (Tsugawa et al., 1998; Ukawa et al., 2002). For these auto-driving modes, it is relatively easy to determine the driver's following path and speed. For example, for lane keeping control, the vehicle desired path can be determined by detecting the magnetic nail line or white lane marker. For platoon mode, the previous vehicle's path and speed can be the desired path and desired speed. Since the driver model demonstrates the quality of the following capability, given the driver decisions, the autonomous vehicle controller can be designed using the combined driver model for a different auto-driving mode.

Two basic steady state relationships are essential in the longitudinally and laterally combined driver model. One is the relationship between the lateral acceleration and steering wheel angle; the other is the relationship between the longitudinal acceleration and the unified throttle. The former can be acquired by step steer experiments at different vehicle speeds. The latter relationship can be calculated using the engine power map and powertrain parameters. In the driver model, t_{xd}, t_{xh}, t_{yd}, t_{yh}, are time delay constants, which reflect the human driver's response delay. These will reflect the actuator's response delay in autonomous vehicle control.

7 Conclusion

The paper presents the unexceptional capability of a longitudinally and laterally integrated driver model in terms of human driver simulations as well as the model's applications to the task of autonomous vehicle control. Firstly, the vehicle model with ideal CVT is established and the longitudinal acceleration map between vehicle longitudinal acceleration and unified throttle at different vehicle speeds is discussed. Secondly, the longitudinal and lateral driver model based on preview-follower theory is developed. Finally, it is concluded, through simulation outcomes, that the driver model proposed in this paper is capable of following the driver's decision to a high degree of accuracy and, therefore, has great potential in autonomous vehicle control with the given desired path and vehicle speed.

References

Guo, K. and Ren, L. (1999) 'A unified semi-empirical tire model with higher accuracy and less parameters', *SAE Technical Paper Series* 1999-01-0785.

Guo, K., Lu, D. and Ren, L. (2001) 'A unified non-steady non-linear tyre model under complex wheel motion inputs including extreme operating conditions', *JSAE Review*, Vol. 22, No. 4, pp.395–402.

Guo, K. et al. (1983) 'Preview-follower method for modeling closed-loop vehicle directional control', *Symposium of 19th Annual Conf. on Manual Control*, Cambridge MA, May 23.

Guo, K. and Guan, H. (1993) 'Modeling of driver/vehicle directional control system', *Vehicle System Dynamics*, Vol. 22, Nos. 3–4, May/July, pp.141–184.

Guo, K., Guan, H. and Zong, C. (1999) 'Development and applications of JUT-ADSL driving simulator', *Proceedings of the IEEE International Vehicle Electronic Conference*.

Ukawa, H., Idonuma, H. and Fujimura, T. (2002) 'A study on the autonomous driving system of heavy duty vehicle', *Int. J. of Vehicle Design*, Vol. 29, Nos. 1/2, pp.65–82.

Tsugawa, S., Yanagiya, M. and Tomita, K. (1998) 'Optimal design of vision system for lateral control of autonomous vehicle', *Proceeding of International Symposium on Advanced Vehicle Control*, pp.369–374.