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JUT—ADSL驾驶模拟器的开发和应用*

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摘　要：概要介绍了JUT-ADSL驾驶员模拟器，探讨了驾驶模拟建模中的一些问题，如模拟滞后、轮胎模型、转向迟滞表达、滚动阻力和制动力矩。描述了驾驶模拟器在汽车研究和开发中的一些应用实例，如视野设计和车辆操纵试验、实车控制研究、客观评价技术和驾驶员行为及建模研究。

关键词：驾驶模拟器；汽车；开发
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Development and Applications of JUT-ADSL Driving Simulator

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Abstract: This paper gives an outline of the JUT-ADSL driving simulator. Some modeling problems of the driving simulator, such as simulation delay, tire model, expression of steering hysteresis, rolling resistance and braking torque are discussed. Some examples of application of the driving simulator for research and development (R&D) activities, such as virtual design and testing for vehicle handling, studies of active vehicle control, the study of objective evaluation technology and driver behavior and modeling are described.

Key words: driving simulator; automobile; development

1　Introduction

A driving simulator is developed in the National Key Lab of Auto-Dynamic simulation (ADSL) in Jilin University of Technology, for R&D purpose. The aims of the ADSL driving simulator are to simulate the motion response of a man-vehicle-environment closed-loop system, to predict and to test the system performances for the improvement

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of a vehicle design and a transportation environment. The basic configuration of the driving simulator is something similar to the one of Daimler Benz without additional lateral motion[1]. The simulator consists of a simulation dome, a motion simulation system, a real time control and computation system, a visual simulation system, a noise simulation system, a tactile impression simulation system and a control panel.

The project for developing ADSL driving simulator was started in 1990, supported by China National Government and the World Bank. The project was passed through the governmental inspection by the end of 1996.

In this paper, the basic features of the driving simulator are described. Some modeling problems and some examples of its application are discussed.

2 Basic features of ADSL driving simulator

The basic features of the driving simulator are as follows:

2.1 Real Driver/Vehicle Operation Interface

A realistic driver-vehicle-environment is realized by setting a real car in the simulation dome, driven by a real driver in a virtue traffic environment which gives the driver with realistic visual, audio, kinematics senses and tactile impression. All control elements for driver's operation have been connected to the computer system. Therefore, a driver who is most difficult to simulate in mathematical form, can play his important role in the closed-loop system without any artificial modeling mistakes (Fig. 1, Fig. 2). The driver's feeling of handling is simulated by a servo-electric motor according to the dynamic steering torque generated by the vehicle dynamics model. The motion senses are generated by not only the visual traffic image, but also the 6 DOF dome motion which generated by six hydraulic cylinders controlled by the vehicle model outputs, which transformed to cylinder lengths through the "wash-out algorithm".

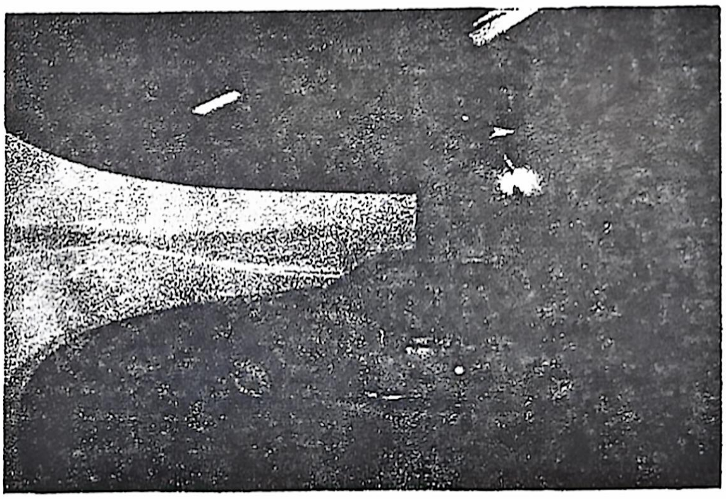


Fig. 1 A real car in the simulation dome driven by a driver in a virtue traffic environment

The reality of the system provides the preferable platform for studying driver behavior, traffic regulations, and the driver-vehicle-environment closed-loop system even under safety limit condition.

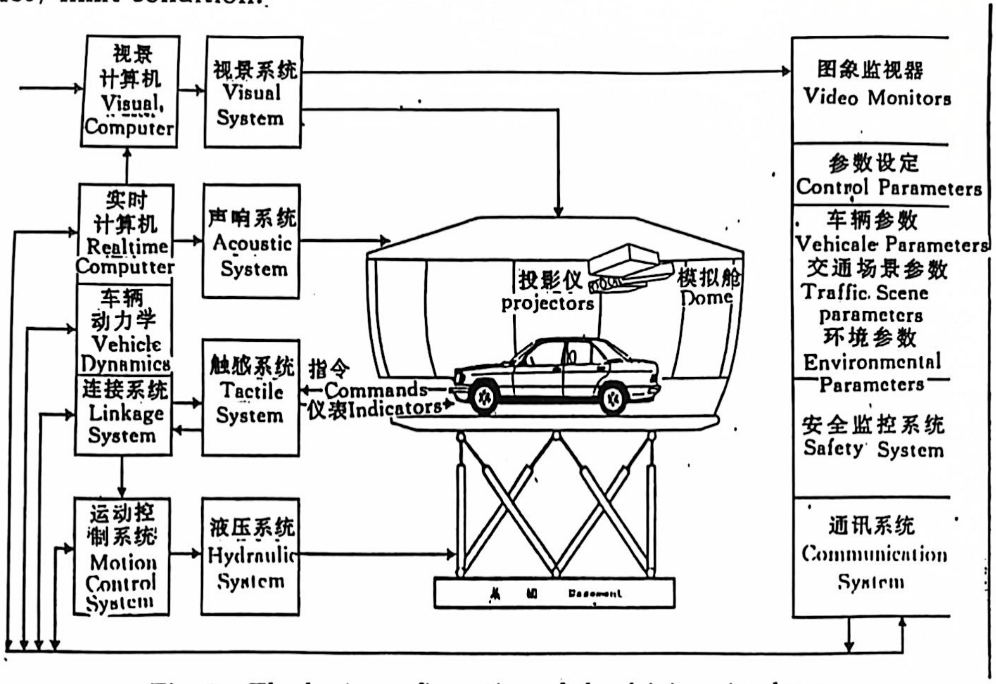


Fig. 2 The basic configuration of the driving simulator

2.2 Easy Construction of a "Virtue Prototype"

A 29 DOF vehicle dynamics model with different kinds of non-linearity, hysteresis in steering, braking and suspension systems as well as a meticulous non-steady non-linear tire model, is installed in the driving simulator. Different construction of vehicle designs can be easily set up through the control panel to input different parameters, which represent the characteristics of each subsystems and components (Fig. 3). In this way, it provides an efficient tool for optimization of vehicle dynamics in design stage.

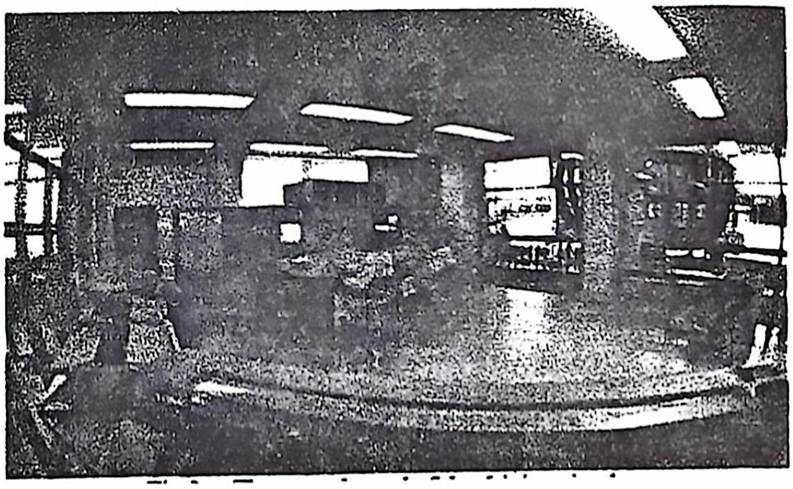


Fig. 3 The control panel of the driving simulator

2.3 Combined with Other Physical Tests

The ADSL driving simulator provides large capability of data sampling, processing and control system with 48-inputs and 24-outputs analog channels, and 64 digital inputs and 64 digital outputs.

Its application capability can be further extended to real time simulation by combining the computer digital simulation with some physical parts, which may be difficult in modeling or needs to be validated or evaluated by a real test.

3 Some problems in driving simulator modeling

Some modeling problems occurred in the development process of ADSL driving simulator, and the ways to solve them are described as follows:

3.1 Simulation Delays

There are several kinds of delays in driving simulator due to signal transportation and computation. The most important one of these delays may be considered as the image delay, which was measured to be 0.12 Sec in the early stage. That is almost at the same level of the response time of a modern car. Because the response of the simulator car is so much slower than the real one, some invalid results may occurred for the response delay. To solve this problem, a correction block is introduced between vehicle motion signals and image generation inputs as shown in Fig. 4.

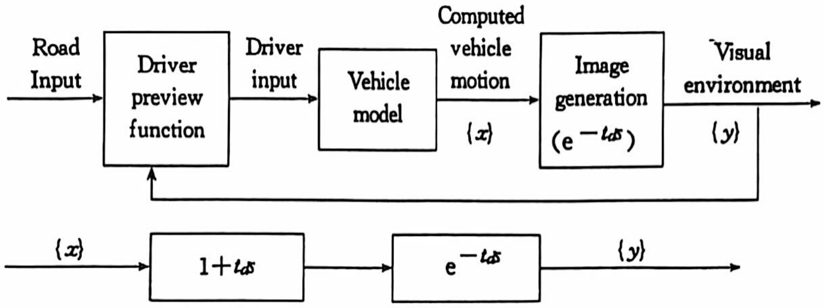


Fig. 4 Image generation delay and compensation

It can be seen in Fig. 4 that a linear prediction block $(1+d_d s)$ is introduced to compensate the computational delay block $e^{-t_d s}$. The phase lag is corrected within the frequency range up to $\omega_c=1/t_d=8.3$ rad/s. After this correction, the driver feeling of simulator response is much closer to the real one.

3.2 Tire Model at Very Low Speed

At the beginning, a "Unified Steady State Tire Model" (called "USES" Model which includes both longitudinal and lateral slips as well as camber effect[2]) was used for vehicle dynamics modeling. Some ridiculous vehicle behavior occurred due to terrible jerks of tire forces at very low vehicle speed. It is found that the tire force jerks are due to jumping of slip ratios, $s_x=(v_x-\omega R)/|\omega R|$ and $s_y=v_y/|\omega R|$, when wheel speed $|\omega R|$, the denominator of s_x and s_y become very small.

To cope with this problem, a non-steady non-linear tire model (called "USENN") is developed for the driving simulator[3], and the block diagram of the USENN tire model are shown in Fig. 5. With the tire model USENN, the tire function in longitudinal and lateral direction will turn automatic ally from "quasi-damper" to "quasi-spring" when wheel speed becomes lower and lower. Therefore, computations of s_x and s_y are avoided at very low wheel speed.

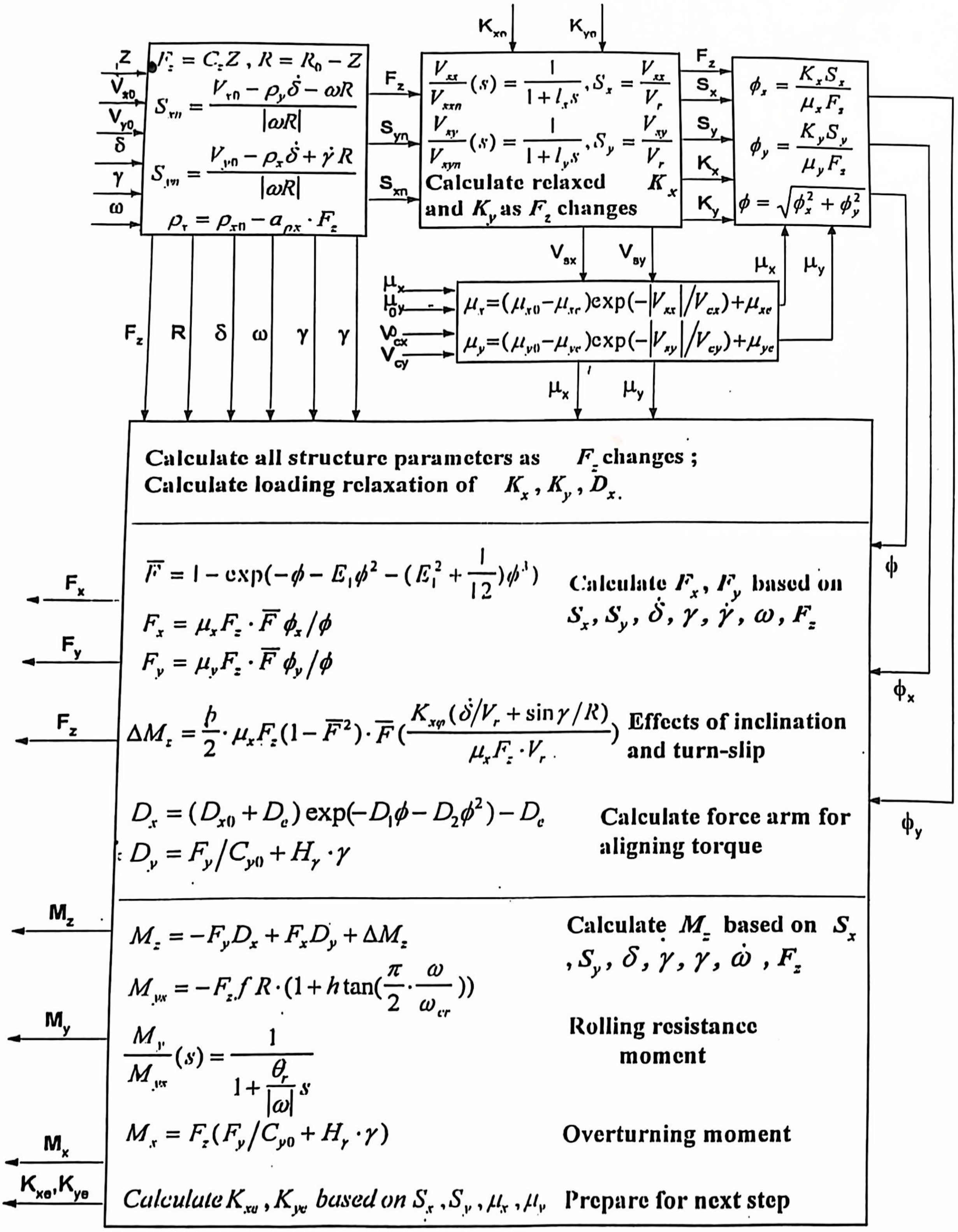


Fig. 5 The computational block diagram of the non-steady non-linear tire model (USENN)

3.3 Hysteresis in Steering System

Steering hysteresis is very important to driver feeling. To express the hysteresis by Coulomb's friction is an original choice. However, the ideal Coulomb's friction causes jerks and abnormal noise in steering system. In addition, usually the frictional magnitude in steering system is not a constant but a function of steering wheel angle. For more accurate simulation, the model we developed for steering hysteresis is described as:

$$\begin{cases} \theta_r \dfrac{dT_{st}}{d\theta} + T_{st} = T_H \cdot S_{gn}(\theta) \\ T_H = T_H(\theta) \end{cases} \tag{1}$$

where, T_{st} stands for steering wheel torque; θ for steering wheel angle; and $T_H(\theta)$ for the static hysterical magnitude, which is a function of θ, e. g:

$$T_H = -(c_0 + c_1|\theta| + c_2\theta^2) \tag{2}$$

The measurement data and simulation result are shown in Fig. 6.

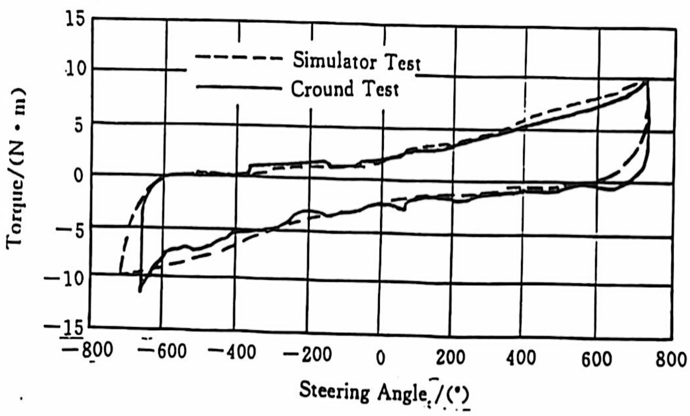


Fig. 6　Steering hysterics of the measurement data and simulation result

3.4 Rolling Resistant and Other Coulomb-Type Resistant

In many cases of vehicle dynamics analyses, rolling resistance are usually calculated in a form as:

$$M_y = \text{sgn}(\omega) f F_z R \tag{3}$$

where M_y is rolling resistant moment, F_z is wheel load, R is rolling radius of the wheel, and f is a coefficient.

This expression of rolling resistant moment has caused two problems in simulation: one was the difficulty of static balance when the virtual vehicle stands still; the other problem occurred when the vehicle speed varied around zero where the rolling resistant would jump back and forth between positive and negative boundaries, which caused abnormal behavior of the virtual vehicle. To solve these problems, the following expression for rolling resistant moment is adopted:

$$\begin{cases} \dot{M}_y = \frac{|\omega|}{\theta_r}(\mathrm{sgn}(\omega)M_{ys} - M_y) \\ M_{ys} = -F_z fR\left[1 + h\tan(\frac{\pi|\omega|}{2\omega_{cr}})\right] \end{cases} \tag{4}$$

where θ_r stands for relaxation angle, h for first order coefficient of rolling resistance, and ω_{cr} for critical rotation speed.

When $\omega = \omega_{cr}$, the occurring of tire stationary wave leads M_y to infinity.

This expression avoids the simulator shocks successfully when the virtual vehicle is accelerating or braking; and also provides a more precise expression of rolling resistant moment for whole range of vehicle speed (see Fig. 7).

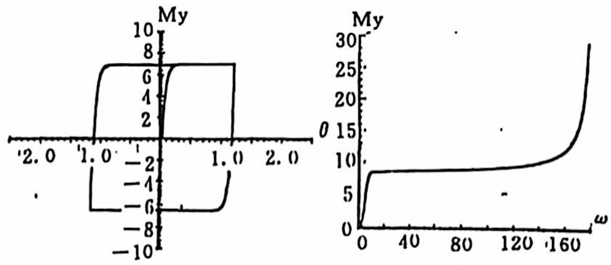


Fig. 7 Rolling resistant moment as vehicle speed changes

Similar to rolling resistance, the braking torque also subjects to dry friction characteristics. The following model can be used in simulations:

$$\begin{cases} \dot{T}_b = \frac{|\omega|}{\theta_b}(\mathrm{sgn}(\omega)T_{bs} - T_b) \\ T_{bs} = -\beta P\exp(-\frac{\omega}{\omega_b}) \end{cases} \tag{5}$$

where, P is braking line pressures, β、θ_b and ω_b are constants describing function characteristics relevant to the relative materials.

4 Examples of application

Some applications we are doing are as follows:

4.1 Virtual Design and Testing for Vehicle Handling

The National Lab (ADSL) is cooperating with Chinese Auto Industry to carry out some analysis and improvement of performances of domestic cars. The "virtual test courses" built in driving simulator provide a convenient platform for vehicle performance analysis.

4.2 Studies of Active Vehicle Control

We are working on some modern active vehicle control systems, such as ABS, TCS, VDC (DYC), 4WS etc, by using the driving simulator. As an example, a VDC system is set up in driving simulator as shown in Fig. 8. The driving simulator performs both open-loop test (Fig. 9) and closed-loop test (Fig. 10). These studies give some opportunities to gain insight into the active vehicle control systems.

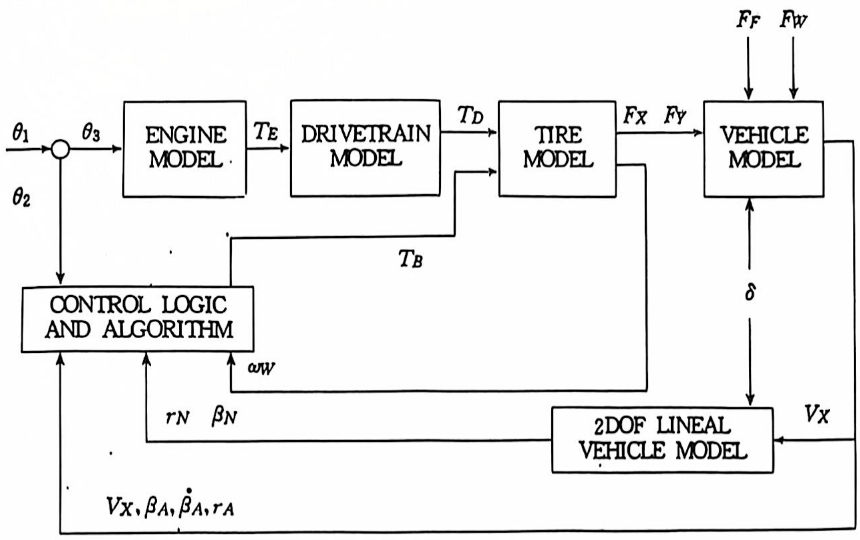


Fig. 8　VDC simulation model chart

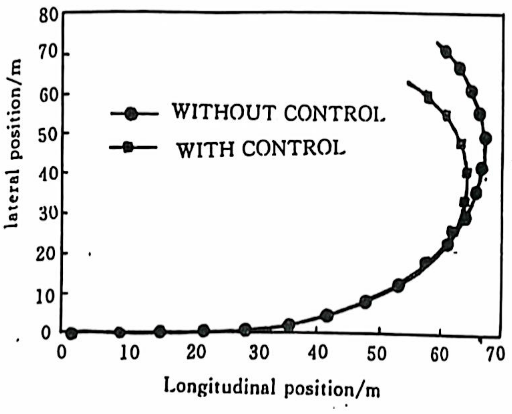


Fig. 9　Effect of open-loop VDC in ramp-step steering input

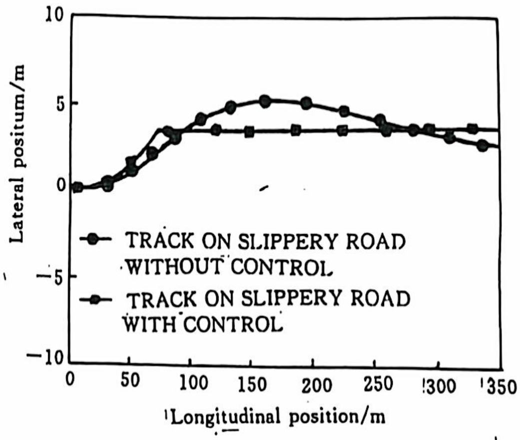


Fig. 10　Effect of close-loop VDC in single lane change

4.3　Study into the Handling Evaluation Method

For a long time we have been working on the objective evaluation of vehicle handling, which is considered as the foundation of the optimal design of vehicle handling.

A study of objective evaluation method of vehicle handling based on the subjective evaluation with driving on different configurations of vehicle designs has been performed in the driving simulator.

The theoretical comprehensive objective evaluation index is proposed as[4]:

Comprehensive Index:

$$J_T = J_P \cdot J_{DI} \quad (6)$$

Direct Index:

$$J_{DI}=\sqrt{\frac{W_1J_E^2+W_2J_B^2+W_3J_R^2+W_4J_S^2}{W_1+W_2+W_3+W_4}} \tag{7}$$

Penalty factor:

$$J_P=\left(1+(\frac{T_c}{T_c})^2+(\frac{T\cdot u}{D})^4\right) \tag{8}$$

where,

$$J_E=\sqrt{\frac{W_{e1}J_{e1}^2+W_{e2}J_{e2}^2}{W_{el}+W_{e2}}} \tag{9}$$

$$J_{e1}=\int_0^{t_n}\left[\frac{f(t)-y(t)}{\bar{E}}\right]^2\mathrm{d}t \qquad J_{e2}=\int_0^{t_n}\left(\frac{u\beta}{\bar{B}}\right)^2\mathrm{d}t$$

$$J_B=\sqrt{\frac{W_{b1}J_{b1}^2+W_{b2}J_{b2}^2}{W_{b1}+W_{b2}}} \tag{10}$$

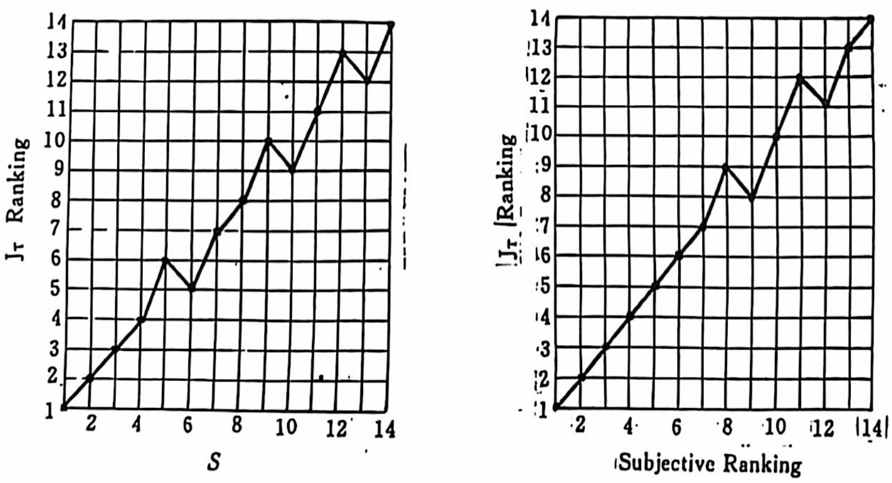
$$J_{b1}=\int_0^{t_n}\left[\frac{\delta(t)}{\bar{\delta}}\right]^2\mathrm{d}t \qquad J_{b2}=\int_0^{t_n}\left[\frac{T_{SW}}{\bar{T}_{SW}}\right]^2\mathrm{d}t$$

$$J_R=\sqrt{\frac{W_{r1}J_{r1}^2+W_{r2}J_{r2}^2}{W_{r1}+W_{r2}}} \tag{11}$$

$$J_{r1}=\int_0^{t_n}\left(\frac{\ddot{y}}{\bar{\ddot{y}}}\right)^2\mathrm{d}t \qquad J_{r2}=\int_0^{t_n}\left(\frac{\phi}{\bar{\phi}}\right)^2\mathrm{d}t$$

$$J_{Si}=\int_0^{t_n}\left(\frac{S_i(t)/F_{zi}}{\bar{\mu}}\right)^2\mathrm{d}t,\quad i=1,2 \tag{12}$$

The preliminary results of correlation between the comprehensive objective evaluation and the subjective evaluation of nine drivers are shown in Fig. 11. The results seem to be promising for further study.



(a) Speed=90km/h (b) Speed=110km/h

Fig. 11 Correlation between the comprehensive evaluation and the subjective evaluation of nine drivers

4.4 Driver Behavior and Modeling Study

Since all inputs and outputs of the virtual car are very convenient to record, it provides an efficient tool for studies of driver behavior and modeling.

Fig. 12 show the comparisons of driving by real drivers (average of nine drivers driving on the driving simulator, doted lines) and simulation by driver model (solid lines) executing a double lane-change test.

The control behavior of the modeled driver is computed based on the optimal lateral acceleration theory[4] with minimizing the objective function J_T expressed as shown in Eq. (6)－(12).

It is found that the different behaviors between the modeled driver and the real driver are due to that the preview time of the model driver is longer than the real one, which is caused by setting too large of the weighting coefficient of steering burden W_2, and relatively too small of the path error weighting coefficient W_1.

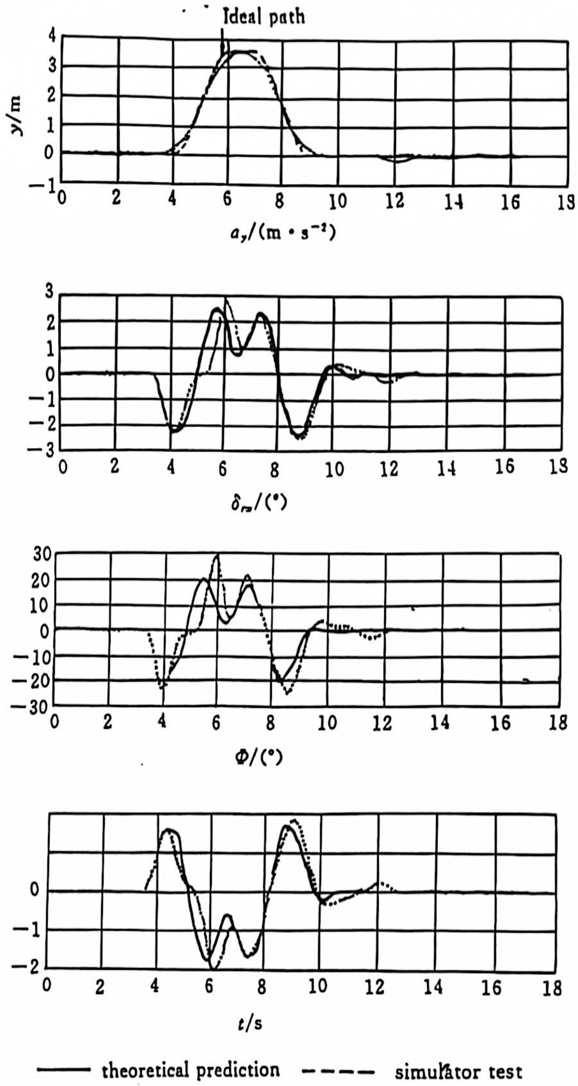


Fig. 12 Comparisons of driving by real drivers on the simulator and simulation by driver model executing a double lane-change test

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