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Virtual Running Tests of Automobile with Driving Simulator

Taichi SHIIBA
Dept. of Mechanical Engineering,
Tokyo University of Science
1-3 Kagurazaka, Shinjuku, Tokyo
162-8601 JAPAN
TEL: +81-3-3260-4781
E-mail: shiiba@rs.kagu.tus.ac.jp

Yoshihiro SUDA
Center for Collaborative Research,
The University of Tokyo
4-6-1 Komaba, Meguro, Tokyo
153-8505 JAPAN
TEL: +81-3-5452-6193
E-mail: suda@iis.u-tokyo.ac.jp

Yusuke TANABE
Graduate School of The University of Tokyo
4-6-1 Komaba, Meguro, Tokyo
153-8505 JAPAN
E-mail: yusuke@satie.iis.u-tokyo.ac.jp

Masaaki ONUKI
Simulation & Visual Systems Group
Mitsubishi Precision Co., Ltd.
345,Kamimachiya, Kamakura-City,
Kanagawa, 247-8505 JAPAN
E-mail: monuki@mpcnet.co.jp

Virtual running tests of safety technology for Intelligent Transport Systems (ITS) are proposed in this paper. Precise evaluation of control device can be realized by making use of the driving simulator with multibody automobile model. A closed loop test of an automobile with four wheels steering system was achieved as an example of virtual running tests, and it was shown that the performance of four wheels steering system could be examined with proposed virtual proving ground.

Keywords: *Driving Simulator, Vehicle Dynamic Control, Human-Automobile System, Multibody Dynamics, Real-time Calculation*

1. Introduction

Many kinds of vehicle control technologies are proposed concerning Intelligent Transport Systems (ITS), such as advanced cruise control, lane keeping, collision avoidance system, and so on. These technologies are directly affects the motion of an automobile, and they should not violate the driver's intention of maneuvering. Therefore, evaluation of these technologies from the viewpoint of human-automobile system is indispensable for development. However, closed loop tests of human-automobile system in emergency situation with actual automobiles are very dangerous, so that only expert drivers can execute these tests.

In this paper, the authors propose virtual running tests of vehicle control technologies with a driving simulator. Driving simulators can safely provide emergency situation, and closed loop tests by ordinary drivers in dangerous situation can be realized. In addition, vehicle dynamics of developed driving simulator is based upon multibody automobile model, and detail movements of each element of suspension and forces acting on each component in moving automobile can be observed. Hence the specific conditions of control device such as power requirement of an actuator can be evaluated with developed driving simulator.

Figure 1 shows the concept of proposed "virtual proving ground", which means a virtual running test environment with a driving simulator. In this paper, a closed loop test of an automobile with four wheels steering system was achieved as an example of vehicle control technologies, and the effects of four wheels steering system to ordinary drivers on this virtual proving ground are discussed.

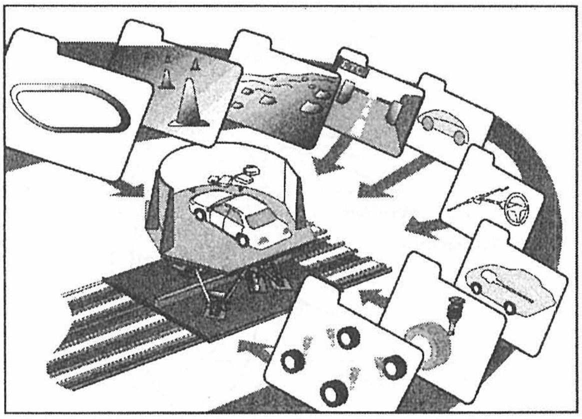

Fig. 1 The concept of virtual proving ground

2. Vehicle model and test environments

2.1. Multibody automobile model

Multibody automobile model used in developed virtual proving ground is shown in Fig. 2. A small sized passenger car with independent double wishbone suspension is supposed. The specifications of this model are shown in Table 1. This automobile model is composed of 13 rigid bodies. Euler parameter is used as a generalized coordinate for describing the direction of each body. As a result, the total number of degrees of freedom is 91. Equations of motion of this multibody automobile model are described as differential algebraic equations as follows [1][2]:

$$\begin{bmatrix} \mathbf{M} & \mathbf{0} & \mathbf{\Phi_r}^T & \mathbf{0} \\ \mathbf{0} & 4\mathbf{G}^T\mathbf{J}'\mathbf{G} & \mathbf{\Phi_p}^T & \mathbf{\Phi^p}_\mathbf{p}{}^T \\ \mathbf{\Phi_r} & \mathbf{\Phi_p} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{\Phi^p}_\mathbf{p} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{r}} \\ \ddot{\mathbf{p}} \\ \boldsymbol{\lambda}^c \\ \boldsymbol{\lambda}^p \end{bmatrix} = \begin{bmatrix} \mathbf{F}^A \\ 2\mathbf{G}^T\mathbf{n}^A + 8\dot{\mathbf{G}}^T\mathbf{J}'\dot{\mathbf{G}}\mathbf{p} \\ \boldsymbol{\gamma} \\ \boldsymbol{\gamma}^p \end{bmatrix}$$

where,

$\mathbf{M}$: Mass matrix
$\mathbf{J}$: Inertia tensor
$\mathbf{r}$: Position of centers of gravity
$\mathbf{p}$: Euler parameter
$\boldsymbol{\lambda}^c$, $\boldsymbol{\lambda}^p$: Lagrange multipliers
$\mathbf{\Phi_r}$, $\mathbf{\Phi_p}$: Jacobian of constraints
$\boldsymbol{\gamma}$, $\boldsymbol{\gamma}^p$: Acceleration equations of constraints

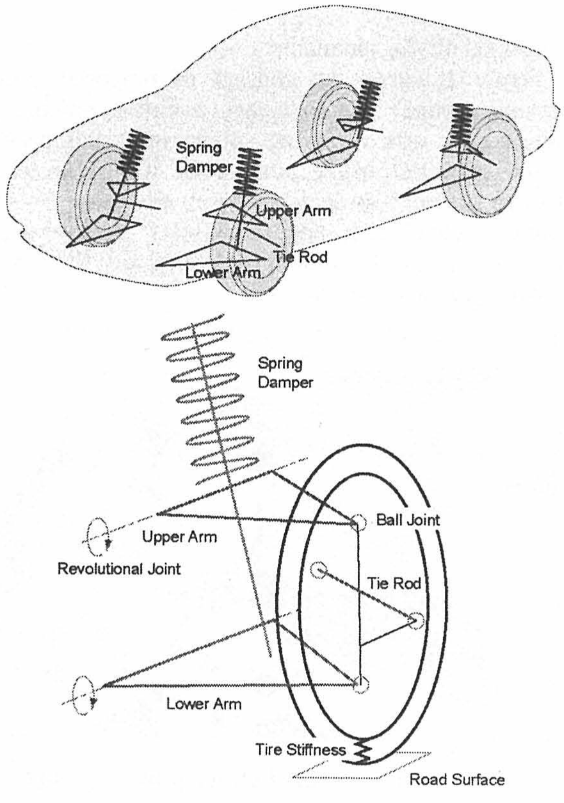

Fig. 2 91-DOFs multibody automobile model

Table 1 Specification of automobile model

Parameter	Value
Mass of Body	1372 kg
Wheel Base	2700 mm
Load Distribution Ratio	55:45 (Front : Rear)
Spring Stiffness, Front	29400 N/m
Spring Stiffness Rear	23520 N/m
Damping Coefficient, Front	5000 Ns/m
Damping Coefficient, Rear	4000 Ns/m

Although multibody dynamic analysis requires a huge amount of calculation, the authors have proposed a real-time calculation algorithm with multibody automobile model [1]. Based on this algorithm, real-time calculation of 500 Hz (2ms of step size) with 91-DOFs multibody model can be realized. Originally developed multibody analysis program by the authors is used for this calculation. Magic formula model [3] is applied for the calculation of tire lateral and longitudinal force.

As for the accuracy obtained by using multibody model, our past research [4] had made the comparison between multibody model and simplified model such as bicycle model. Figure 3 shows one of the results of this comparison, which indicates steering characteristics of an automobile analyzed with multibody model and with bicycle model. The parameters of bicycle model were just same as those of multibody model shown in Table 1, and same tire model was used. Although these models represented same automobile, it was shown that the bicycle model could not explain the drastic changes of steering characteristics in high lateral acceleration area. The advantage of multibody model was also discussed in many literatures such as [5], [6], and [7].

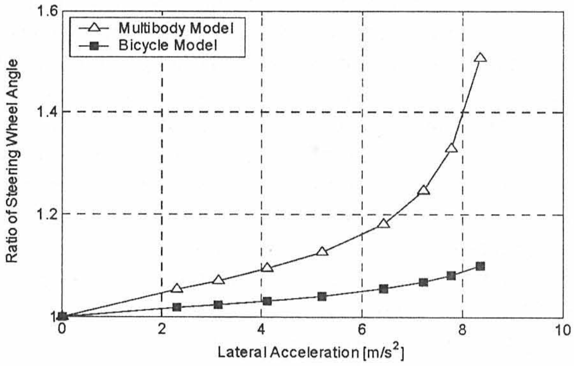

Fig. 3 Estimation of calculation accuracy [4]

Most of previously developed simulators are based upon simplified analysis model [8][9]. Some of these simulators can evaluate the effect of roll steer characteristics by using look-up table of wheel alignment, nevertheless an automobile is treated just as one rigid body in these driving simulator. In addition, they cannot evaluate the interaction between suspension elements, such as wheels, arms, springs, and dampers. On the other hands, multibody model can treat each element as an independent body, so this interaction is estimative. Therefore, definite conditions of control devices such as power requirement, range of motion, and strength of components can be evaluated by using multibody model.

2.2. Specifications of driving simulator

Our driving simulator system for virtual proving ground is shown in Fig. 4. This driving simulator is located at the University of Tokyo. It has 6-axes motion system, and lateral acceleration in cornering and longitudinal acceleration in braking and accelerating can be simulated with this motion system. Hardware specifications of our driving simulator are also shown in Table 2.

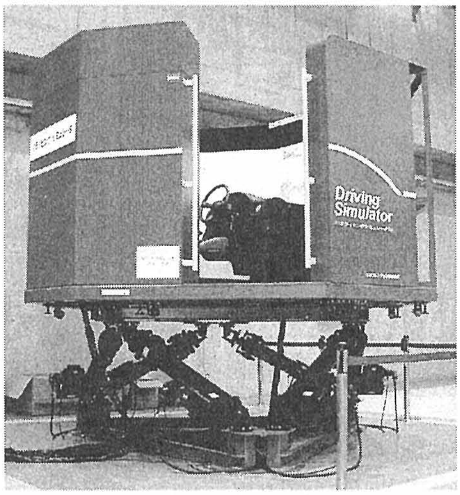

Fig. 4 Appearance of driving simulator

Table 2 Specifications of driving simulator

Motion system	
Actuator	Electro-mechanical
Translational stroke	250 mm
Max. trans. Acceleration	0.5 G
Roll Angle:	±20 deg
Pitch Angle:	±18 deg
Yaw Angle:	±15 deg
Maximum payload	3,000 kgf
Visual system	
Screen	3 flat panels
Frame rate	60 Hz

3. Performance of virtual proving ground

In order to show the fundamental performance of developed virtual proving ground, some handling tests on virtual proving ground are briefly mentioned in this chapter [10]-[12].

3.1. Transient response test (J turn test)

A transient response test was carried out on virtual proving ground to examine the effect of variation of suspension geometry. Steering maneuver and vehicle speed were determined based upon the regulation of ISO/TC22/SC9 (Lateral transient response test method). Three kinds of vehicle model were used in this test. The difference between these models was the connection point of tie rod and car body in front wheel, which is indicated as Point G in Fig. 5. Only the height of this point was changed in the length of 10 mm, and the other conditions of model remained same. The roll steer characteristics of these models are shown in Fig. 6.

The results of transient response test are shown in Fig. 7 and Fig. 8. Initial running speed was 100 km/h. Figure 7 shows the loci of automobiles for 20 sec, and this result indicates that the locus of an automobile varied by changing suspension geometry, and that the developed virtual proving ground can express the effect of geometric modification of suspension. In addition, the response of lateral acceleration and yaw rate are presented in Fig. 8. It is shown that the transient responses of an automobile also varied by suspension geometry setting.

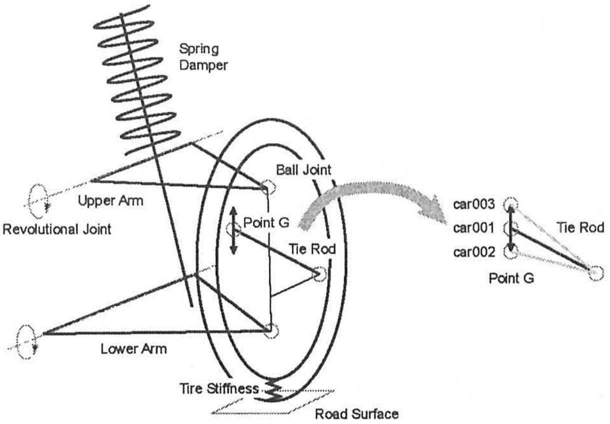

Fig. 5 Modification of suspension setting

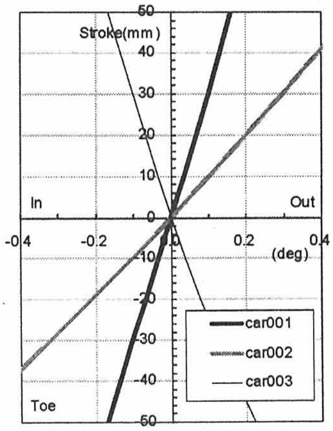

Fig. 6 Roll Steer Characteristic of Each Model

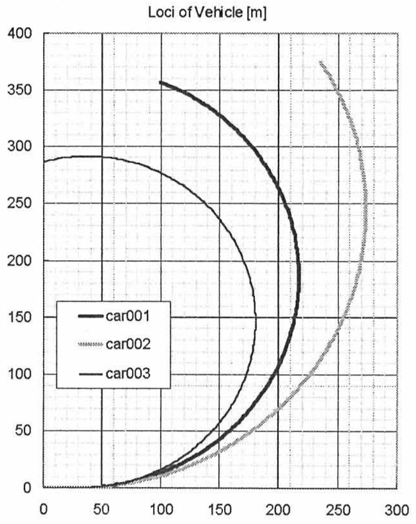

Fig. 7 J-turn test result, loci of automobile

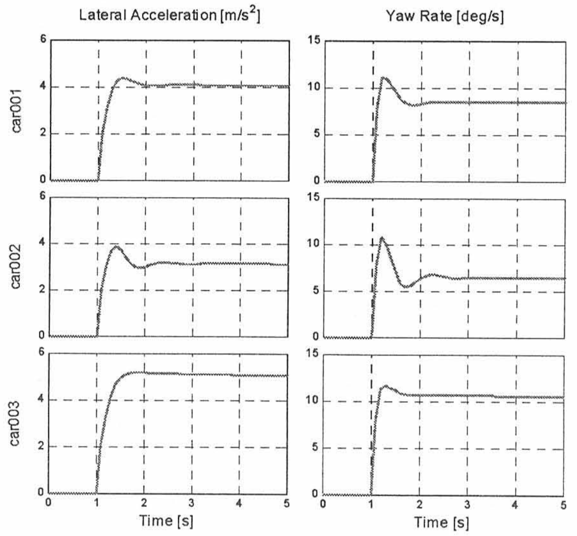

Fig. 8 J-turn test result, time history

3.2. Frequency response test

For further investigation of transient characteristics of automobiles on virtual proving ground, a frequency response test based on JASO (Japanese Automobile Standards Organization) Z110-91 was carried out. Impulse steering maneuver regulated in this standard was applied as an input to the automobile, and transfer functions of lateral acceleration and yaw rate were examined for three kinds of automobile model described before. Figure 9 shows the test results under the condition of 100 km/h of speed. These results indicate that the effect of suspension geometric setting upon the frequency characteristics of an automobile can be analyzed with developed virtual proving ground.

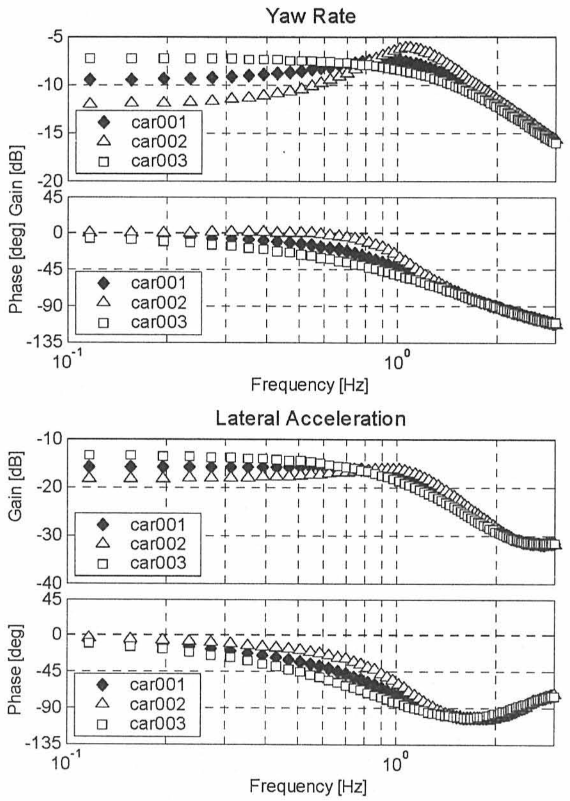

Fig. 9 Results of frequency response test

4. Evaluation of vehicle dynamic control

Evaluation of vehicle dynamic control technology on virtual proving ground is discussed in this chapter. Virtual proving ground can provide a driver with driving feelings through computer graphics and motion cues, so closed loop system evaluations of human-automobile system can be realized. A lot of safety and control technologies are proposed through ITS projects, and our virtual proving ground would play a role of an effective test environment for these technologies.

4.1. Control theory of four wheeling system

A closed loop test of four wheels steering system was executed on virtual proving ground. Four wheels steering system has already been put to practical use, and it can improve the stability of lane changing. In this study, control theory of four wheels steering system was based on the bicycle model shown in Fig. 10. Steering angle of rear wheel was determined to satisfy the condition that the steady slip angle of body becomes zero [13]. This condition can be expressed as following equation:

$$\delta_r = \frac{-l_r + \dfrac{ml_f}{K_r(l_f + l_r)}V^2}{l_f + \dfrac{ml_r}{K_f(l_f + l_r)}V^2} \cdot \delta_f$$

where,

m	Vehicle mass
V	Vehicle velocity
l_f, l_r	Distance between gravity center and axle
K_f, K_r	Cornering power of front / rear wheel
δ_f, δ_r	Steering angle of front / rear wheel

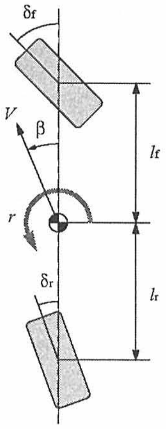

Fig. 10 Bicycle model

At first, a frequency response test described in previous chapter was executed to assess the fundamental performance of four wheels steering system. Figure 11 shows the comparison of ordinary front steering system (2WS) and four wheels steering system (4WS) in 140 km/h. Vehicle parameters of 2WS and 4WS automobile were same. It is shown that the phase lag of lateral acceleration, which yields instability in lane changing, can be diminished by using four wheels steering control.

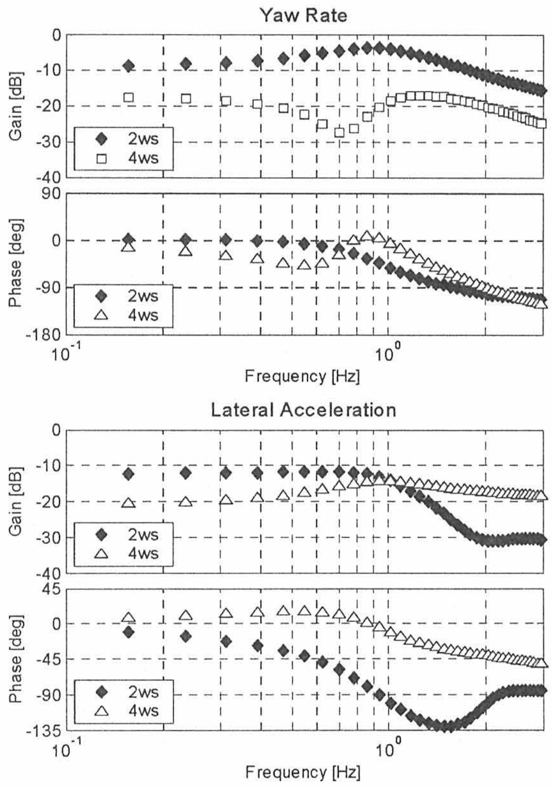

Fig. 11 Comparison of frequency response

4.2. Closed loop test on virtual proving ground

Closed loop tests of lane changing by five drivers were executed on virtual proving ground to evaluate the effect of four wheels steering system in emergency situation. Running course for evaluation is shown in Fig. 12. The condition of running speed was decided to keep 140km/h, and drivers were told to avoid collision to obstacles as far as possible.

The performance of vehicle control was evaluated by the number of successful lane changing without collision, that is, the score was 3 points when driver was able to pass through these obstacles without collision, and, when the driver crushed into the second obstacle (a trailer, shown in Fig. 13) the score was zero. For comparison, 2WS and 4WS vehicle models were used, and fifteen times of running were executed with each model. The order of running was random, as is shown in Table 3. The information that which vehicle model they were driving was not given to drivers.

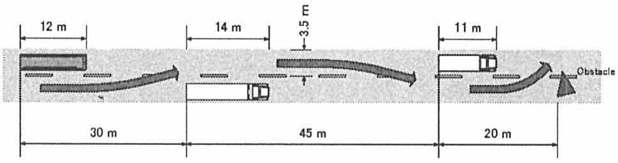

Fig. 12 Configuration of running course

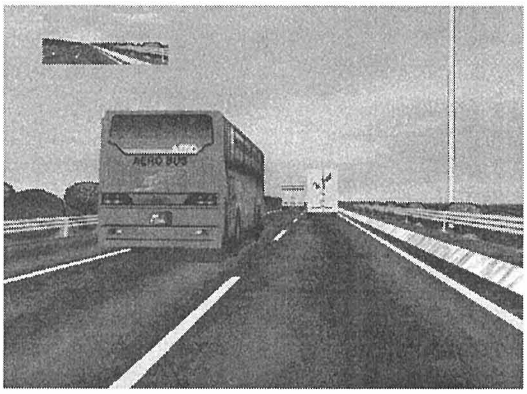

Fig. 13 The scenery of driving simulator

Closed loop test results were shown in Table 3 and Fig. 14. Table 3 shows the score of all trials, and Fig. 14 shows the average score of each driver. From these results the tendencies are summarized as follows:

- Scores were remarkably enhanced by four wheels steering about driver A and E.
- On the other hand, the effect of vehicle control cannot be observed about driver B-D.
- Good performance more than 2-point could be obtained only when four wheels steering was adopted.

It is certain that the advantage of four wheels control could not be observed in some drivers. However, it can be said that the four wheels control did not disturb the avoiding maneuver of drivers, for there was no example of extremely declined score with it. The conclusion of this chapter is that the effect of vehicle control technologies can be thus evaluated with developed virtual proving ground.

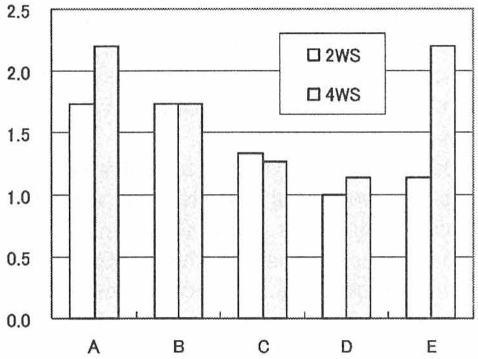

Fig. 14 Comparison of test score

Table 3 Results of closed loop tests

Driver	A	B	C	D	E
No. 1(4WS)	2	0	1	0	3
No. 2 (2WS)	1	0	2	0	0
No. 3 (4WS)	3	2	2	1	3
No. 4 (2WS)	2	2	2	0	1
No. 5 (2WS)	2	0	2	0	0
No. 6 (2WS)	0	2	3	0	2
No. 7 (4WS)	2	1	2	0	2
No. 8 (2WS)	2	2	0	0	3
No. 9 (4WS)	0	1	1	0	2
No. 10 (4WS)	2	1	2	1	2
No. 11 (2WS)	2	1	2	0	0
No. 12 (4WS)	0	3	2	1	2
No. 13 (2WS)	1	3	0	1	0
No. 14 (4WS)	2	2	1	1	3
No. 15 (4WS)	2	3	1	1	1
No. 16 (4WS)	3	1	1	1	1
No. 17 (2WS)	2	3	2	1	0
No. 18 (4WS)	2	2	1	1	2
No. 19 (2WS)	2	1	2	1	3
No. 20 (2WS)	2	3	2	1	2
No. 21 (4WS)	3	1	1	1	2
No. 22 (2WS)	1	0	1	2	3
No. 23 (2WS)	2	1	0	2	0
No. 24 (4WS)	3	1	1	2	1
No. 25 (4WS)	3	3	1	3	3
No. 26 (2WS)	3	2	0	2	0
No. 27 (2WS)	2	3	1	3	0
No. 28 (4WS)	3	3	1	2	3
No. 29 (2WS)	2	3	1	2	3
No. 30 (4WS)	3	2	1	2	3
Average score					
2WS	1.73	1.73	1.33	1.00	1.13
4WS	2.20	1.73	1.27	1.13	2.20

5. Conclusion

The concept of virtual running tests with driving simulator is proposed in this paper. The potential of driving simulator can be improved by adopting multibody automobile model to driving simulator. Real-time calculation of multibody dynamics is a key technology for realizing virtual proving ground. By this proposal, human-automobile system evaluation of safety technologies for Intelligent Transport System can be realized, and the performance of vehicle control technologies can be estimated. It is a great advantage of virtual proving ground that the precise and safety investigation of human-automotive system can be realized with it.

As a future plan, we are trying to realize hardware-in-the-loop (HIL) evaluation system for vehicle control system. Virtual proving ground can provide precise information of elements of an automobile from multibody dynamics analysis. This information can be used as input signals to control devices, and the outputs from control devices can also be used as inputs of multibody dynamic analysis. Efficient development of control devices for Intelligent Transport System would be realized with virtual proving ground.

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Dr. Taichi SHIIBA Received Doctor of Engineering from The University of Tokyo in 2001. Research associate of Tokyo University of Science from 2002. Major fields are multibody dynamics, vehicle dynamics, and Simulators. Member of JSME and JSAE.

Prof. Dr. Yoshihiro SUDA Received Doctor of Engineering from The University of Tokyo in 1987. Professor of The University of Tokyo, Center for Collaborative Research (CCR) and Institute of Industrial Science (IIS) from 2000. Major fields are vehicle dynamics and control. Board member of ITS Japan, member of ASME, JSME, JSAE and SICE.

Yusuke TANABE Received Bachelor of Engineering from The University of Tokyo in 2002. Post graduate student of The University of Tokyo.

Masaaki Onuki Received Bachelor of Engineering from Nihon University in 1986. Head Engineer of Mitsubishi Precision Co., Ltd. Researcher of Sustainable ITS Laboratory Center for Collaborative Research, The University of Tokyo. Major fields are hi-fidelity driving simulator development, modeling of real-time vehicle dynamics and microscopic traffic control, simulator sickness analysis, and man-machine interface for simulator. Member of JSTE and JSAE.

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