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Study on Evaluation of Personal Mobility Vehicle with Leaning Behavior using Driver Model

Meiko MATSUDA [*], Ichiro KAGEYAMA [*], Yukiyo KURIYAGAWA [*], Tetsunori HARAGUCHI[#], Tetsuya KANEKO[†], Masanori KOBAYASHI[☆], Tetsuya MURAYAMA[☆]

[*] College of Industrial Technology
Nihon University
1-2-1 Izumi-cho Narashino-shi Chiba,
275-8575, Japan
e-mail: cime18029@g.nihon-u.ac.jp
e-mail: kageyama.ichiro@nihon-u.ac.jp
e-mail: kuriyagawa.yukiyo@nihon-u.ac.jp

[#] Institutes of Innovation for Future Society
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
e-mail: haraguchi@nagoya-u.jp

[†] Department of mechanical engineering for transportation, Faculty of engineering,
Osaka Sangyo University
3-1-1 Nakagakiuchi, Daito City, Osaka Prefecture
574-8530, Japan
e-mail: kaneko@tm.osaka-sandai.ac.jp

[☆] IPG Automotive K.K.
PMO Nishi Shimbashi 9F, 2-9-1 Nishishinbashi,
Minato-ku, Tokyo 105-0003, Japan
e-mail: masanori.kobayashi@ipg-automotive.com
e-mail: tetsuya.murayama@ipg-automotive.com

ABSTRACT

In this study, we investigate an adaptability of drivers to a personal mobility vehicle (PMV) using leaning process. In this paper, control behavior of the drivers were analyzed by running experiment using the driving simulator(DS). First, The equivalent preview time was calculated from the data obtained in the DS experiment. As a result, it is found that there are "driving behavior in which the main control algorithm with a positive equivalent preview time is feedforward control" and "driving behavior in which the main control algorithm with a negative equivalent preview time is feedback control". In addition, it was shown that the equivalent preview time used to calculate feedforward steering can be grasped by a check sheet on driver's workload sensitivity. Next, the feedforward steering angle of the driver whose equivalent preview time is positive was calculated. As a result, the steering angle of the selected driver can be almost reproduced by feedforward steering. In addition, it is shown that steering gain, constitute steering of the feedforward, is depending on the vehicle characteristics, and also the preview time is depending on each driver.

Keywords: personal mobility, driving simulator, driver model, driving behavior.

1 INTRODUCTION

In recent years, with the increase in the number of vehicles owned in Japan, there are many problems such as traffic jam and lack of parking space. In addition, the average travel distance by passenger cars in Japan is relatively short, for example, the percentage of vehicles with one mileage less than 10 km/h reaches around 60%. And, the domestic average number of passengers in Japan is less than two persons for one car on weekdays or holidays. In addition, Personal Mobility Vehicle (PMV) is attracting attention as a new small and simple transportation method from the viewpoint of CO_2 reduction [1]. The PMV is a small vehicle for one or two people, and the width of the vehicle body is narrowed compared to the overall height in order to ensure a small but comfortable boarding space. As a result, PMV has a risk of rolling over at cornering. To reduce such a risk, it was proposed that a PMV with learning mechanism inward while cornering is effective such as a two-wheeled vehicle although it is a three wheel [2]. However, Since vehicles with such characteristics are not currently on the market, it is unclear whether the PMV with the leaning mechanism will be accepted by the driver or not. Therefore, it is necessary to establish a PMV evaluation method with leaning mechanism that incorporates evaluation of ride comfort as a driver. The driver does not evaluate the characteristics of the vehicle itself when evaluating the ride comfort the vehicle. It is thought that the driver evaluates the operability and vehicle behavior obtained by changing the operation amount so as to approach the vehicle behavior assumed by the driver. Therefore, in order to evaluate the ride comfort as a driver sensation, it is necessary to consider an evaluation method from the viewpoint of the human-vehicle system that correlates the driver's sense of PMV with leaning mechanism and vehicle behavior. Therefore, PMV with multiple vehicle characteristics were reproduced on that we conducted experiments using a large five-sided stereoscopic immersive driving simulator (DS) for PMV [3][4]. In the DS experiment, a subjective evaluation was taken for each run in order to get a sense of the driver. Furthermore, in order to consider the driver's background, the driver's characteristics were ascertained by conducting a check sheet on driving style and workload sensitivity in advance. We analyzed the driving behavior of each driver based on the data obtained in the DS experiment. In this study, we consider the construction of a driver model as an expression of the driving behavior, and clarify the relationship between the input and output of the driving behavior. In this report, the driver's equivalent preview time was calculated by focusing on the steering angle as a basic behavior of driving a vehicle as one stage of driver model construction. In addition, we calculated feedforward steering and feedback steering, and consider the construction of a driver model.

This study was conducted with the approval of Ethics Review Committee of College of Industrial Technology, Nihon University(S2017-012).

2 EXPERIMENTS USING DS

PMV with a leaning mechanism is not available on the market, and in order to obtain driving behavior and vehicle behavior, we conducted a driving experiment using DS that simulated PMV.

2.1 Vehicle characteristics

In order to evaluate the ride comfort, it is necessary to evaluate by changing multiple vehicle characteristics using DS for PMV. Therefore, in order to understand the turning characteristics, the steering characteristics obtained from the equation of motion used as the characteristics during steady circle turning were set. The steer characteristics and the sideslip characteristics are described using equation (1):

$$\frac{\delta}{\delta_0} = 1 + K_\delta v^2 \qquad \frac{\beta}{\beta_0} = 1 + K_\beta v^2 \qquad (1)$$

Here, $\boldsymbol{\delta_0}$ and $\boldsymbol{\beta_0}$ are the geometrical values of the steering angle and sideslip angle at constant radius turning, $\boldsymbol{K_\delta}$ is a steer factor, and $\boldsymbol{K_\beta}$ is a sideslip factor and described as follows,

$$K_\delta = \frac{m(K_{S_2} l_2 - K_{S_1} l_1)}{K_{S_2} K_{S_1} l^2} + \frac{K_{C_2} K_{S_1} - K_{C_1} K_{S_2}}{g K_{S_2} K_{S_1} l}$$
$$K_\beta = \frac{-l_1 m}{K_{S_2} l_2 l} + \frac{K_{C_2}}{g K_{S_2} l_2} \qquad (2)$$

Here, Kc_i means camber stiffness, and Ks_i means cornering stiffness, respectively [5].

The vehicle characteristics were changed by using of the camber stiffness and the cornering stiffness of the tire. he vehicle in this study has almost same behavior as a motorcycle, so the vehicle characteristics for Steer 2 are designed using it's theory, and Steer1 and Steer3 are determined by setting widely, as shown in Table 1. As shown in Figure1, the set vehicle characteristics were set to 3 conditions for K_δ to under constant K_β conditions. The vehicle characteristics are reproduced by CarMaker of IPG Automotive on a DS vehicle simulation system [6], and the ISO coordinate system is used for measurement. The lean angle γ and steering angle δ by the leaning mechanism of the vehicle in this experiment are described by Eq. (3):

$$\gamma = A\tan^{-1}\left(\frac{\sin(\delta)v^2}{lg}\right) \qquad (3)$$

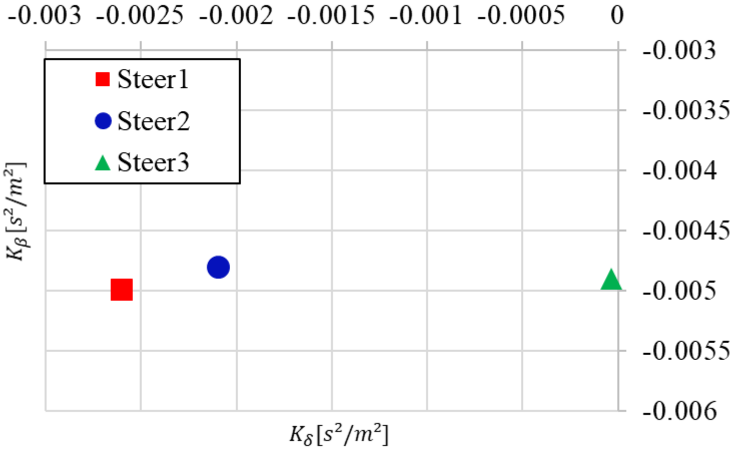
Here, l means the wheelbase, and A means the lean angle ratio divided by the lean angle at neutral steer characteristics.

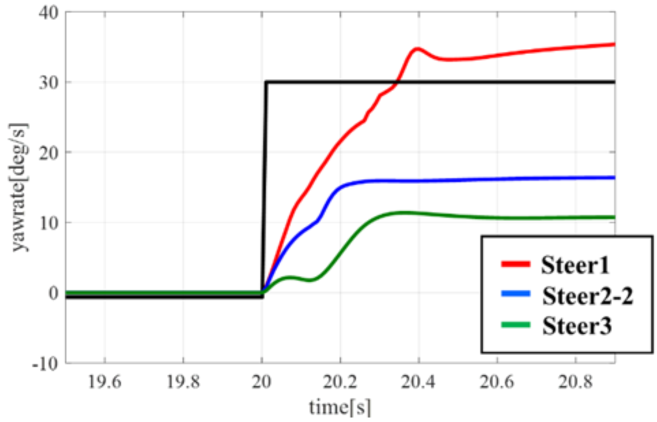
Therefore, step input was performed on CarMaker, and responses of yaw rate, roll rate, and roll angle were confirmed, and responsiveness in each vehicle characteristic was grasped. Figure 2 shows the response when step input is performed at a handle angle of 30 [deg], and Table 2 shows the max value and time constant of each response.

Table 1. Vehicle characteristics.

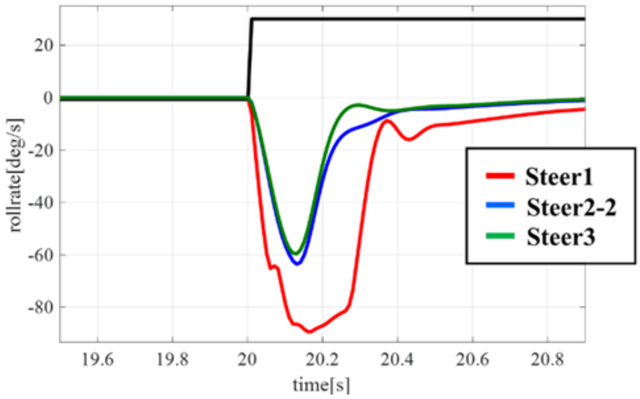
Vehicle characteristics	K_δ
Steer1	$-2.6\times10^{-3}[s^2/m^2]$
Steer2	$-2.1\times10^{-3}[s^2/m^2]$
Steer3	$-0.035\times10^{-3}[s^2/m^2]$

Figure 1. Relationship between K_δ and K_β

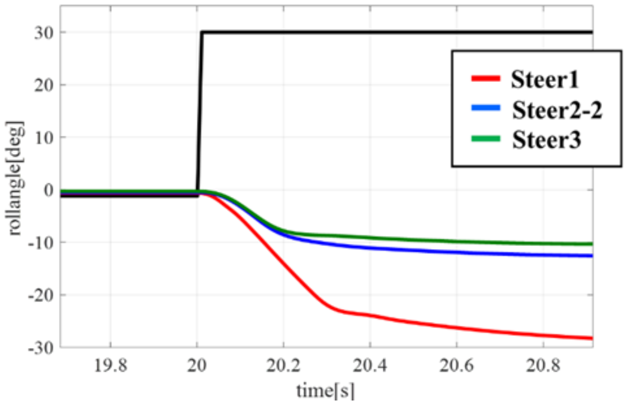




(a) Yaw rate



(b) Roll rate



(c) Roll angle

Figure 2. Step response.

Table 2. Time constant and max value for step response.

	YawRate		RollRate		Rollangle	
	time constant (63.2%)	MAX	time constant (63.2%)	MAX	time constant (63.2%)	MAX
Steer1	0.25[s]	37.76[deg]	0.051[s]	89.34[deg]	0.27[s]	30.54[deg]
Steer2-2	0.15[s]	16.63[deg]	0.071[s]	63.53[deg]	0.19[s]	12.95[deg]
Steer3	0.23[s]	11.39[deg]	0.071[s]	59.57[deg]	0.17[s]	10.61[deg]

2.2 Experiment

The experimental equipment is a DS with Stereoscopic vision of five large screens in Nagoya University's National Innovation Complex (NIC), and the steering wheel is a round handle, similar to four-wheeled vehicles. Figure 3 shows the DS used in the experiment. Before carrying out the experiments, in order to get used DS before the experiments, each participant has 10 minutes practice to travel on a course with gentle curves and then started running this experiment. The experiment course was a descending in the Nihondaira Parkway Japan with many curves as shown in Figure 4. The driving speed was determined by each driver to be safe. In order to consider the influence of getting used to drive, the experimental conditions were carried out in the order of Steer2-1, Steer1, Steer2-2, Steer3 so as to sandwich the reference vehicle characteristics Steer2 between Steer1 and Steer3, respectively. These orders and the total number were kept secret to the participants. In this study, we analyze Steer1, Steer2-2, and Steer3 as representative values. After running, 13 items for “Ride comfort” and for operability of the vehicle were evaluated subjectively for each characteristic using Visual analog scale (VAS) after the experiment. In addition, in order to understand the personal characteristics of the driver, each participant answered in advance to the Driving Style Questionnaire (DSQ) [7] and Workload Sensitivity, Questionnaire (WSQ) [8] constructed by Research Institute of Human Engineering for Quality Life (HQL). The participants are 12 Japanese males and females, named from participant A to L in their 20s and 40s, who have obtained informed consent and to have ordinary driving license.

Figure 3. Immersive driving simulator with stereoscopic vision.

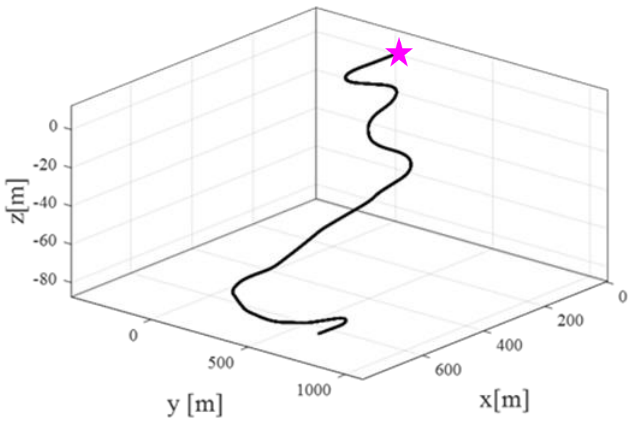


Figure 4. Experiment course.

Table 3. Subjective evaluation questionnaire.

No.	Question
1	The gain of the vehicle response to the steering
2	Timelag of vehicle response to steering
3	Convergent after curve end
4	Adjustment level of steering wheel during turning
5	Ride comfort of the vehicle
6	Discomfort level to the leaning of the vehicle body
7	Discomfort level to the car body tilting
8	The leaning speed for the car body tilting
9	Controlability of the vehicle for the target course
10	Time delay in response to steering wheel operation
11	The target orientation course controlability of yaw angle
12	The preference level of the weight of the handle
13	Vibration level of the vehicle

3 EQUIVALENT PREVIEW TIME

3.1 Steering model

The points for construct the driver model in this study are as follows:

(1) The vehicle in this study is a steering input with a round handle, and the operation method is the same as that of a four-wheeled vehicle.

(2) The input and output must be clarified when analyzing using the model to clarify the driving behavior of the driver.

Therefore, (3) It is necessary to aim to construct a model as simple as possible.

For this reason, the driver model in this study was constructed based on a linear model of a four-wheeled vehicle. In ordinary four-wheeled vehicles, it is thought that steering characteristics which are the basic driving behavior, are decided by feedforward which determined by the road shape and feedback which determines by an amount of vehicle behavior [9] [10] [11]. Based on this, Figure 5 shows a conceptual diagram of the driver model used in this study. First, as the first stage of the driver model for PMV with a leaning mechanism, we focus on the feedforward steering $\boldsymbol{\delta_{ff}}$ and feedback steering $\boldsymbol{\delta_{fb}}$ as in the four-wheeled vehicle driver model, and consider the construction of the driver model.

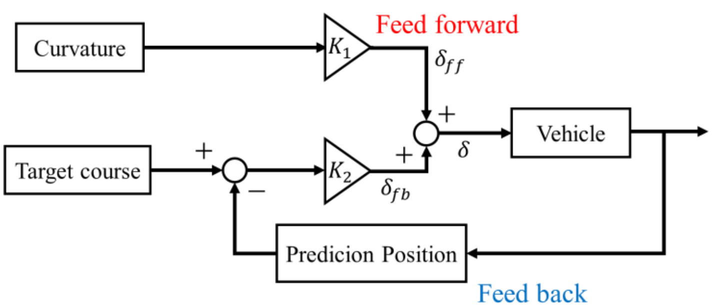


Figure 5. Outline of driver model.

3.2 Lead time and lag time

It is consider that the driver is driving by predicting the steering angle with respect to the road shape ahead. In Feedforward steering, the driver performs steering at an appropriate timing based on road information obtained from the forward. At this time, it is generally considered that the road curvature and the steering angle have a high correlation. The equivalent preview time of the point at which the steering starts determined from this curvature information is defined as the equivalent preview time. Namely, the equivalent preview time is not the point where the driver is actually looking forward (forward gaze point) but the time when the driver steers the vehicle based on deviation information between desired course and prediction position of the own vehicle.

When calculating the equivalent preview time, the analysis is performed as a two-dimensional plane shown in Figure 6 in order to perform a lateral control analysis when the steering angle is input. The equivalent preview time is calculated using the cross-correlation function between the curvature when the center of the lane is the target course and the steering angle obtained by DS. First, the cross-correlation function is checked at the peak when the steering angle waveform was shifted one by one data (0.01 second span) with respect to the curvature. When the correlation coefficient with the steering angle before several seconds from the original time stamp is higher than the others, this time difference (forward side) is taken as the lead time. On the other hand, when the correlation coefficient with the steering angle after a few seconds is higher than the others (steering angle with vehicle locus is high correlation coefficient), this equivalent preview time (back side) is defined as the delay time. Figure 7 shows a scatter plot of Participant A (Steer 2-2)'s steering angle and curvature calculated by the cross-correlation coefficient. In this case, the correlation coefficient is 0.977, which is very high. Figure 8 shows the equivalent preview time for the 12 participants. From the figure, it can be considered that the main control algorithm is feedforward control because the driving behavior with the equivalent preview time is determined by steering from the course ahead. On the other hand, it can be considered that the main control algorithm is feedback control because the driving behavior with a equivalent lag time has a high correlation with the vehicle path. In this report, we focus on the driver whose main control algorithm is feedforward control. Thereby, "①Participants with feedforward control as the main control algorithm for all vehicle characteristics" 4 participants (Participants A, B, D, J) and "②Participants whose main control algorithm of the vehicle that is most comfortable to ride in the "ride comfort" term of subjective evaluation is the feedforward control" 3 participants (Participants E, G, H), the driving behavior of a total 7 drivers was analyzed. The equivalent preview time for 7 participants is shown in Figure 9. In the figure, the vehicle selected as the easiest to ride with subjective evaluation No.5 is shown. From the figure, it can be seen that Steer1, which is the most oversteered, has a longer equivalent preview time for all participants. In addition, the 3 participants who answered that it was easy to ride Steer3 were among "①Participants with feedforward control as the main control algorithm for all vehicle characteristics". For these 3 participants, Steer3's equivalent preview time is the shortest of the 3 vehicles. On the other hand, 1 participants of J in "①Participants with feedforward control as the main control algorithm for all vehicle characteristics" and 3 participants of "②Participants whose main control algorithm of the vehicle that is most comfortable to ride in the "ride comfort" term of subjective evaluation is the feedforward control" chose Steer2-2. Participant J had the shortest Steer2-2's equivalent preview time. The remaining 3 participants did that Steer3's equivalent lag time was negative and feedback control was the main control algorithm. And among Steer1 and Steer2-2 where the equivalent preview time is positive, there answered that it was easy to ride Steer2-2 with the equivalent preview time shortened.

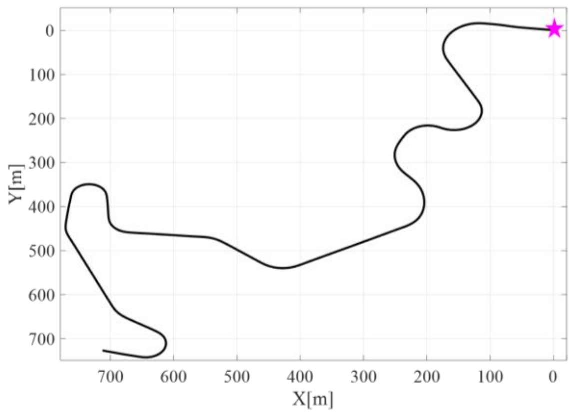


Figure 6. Analysis course.

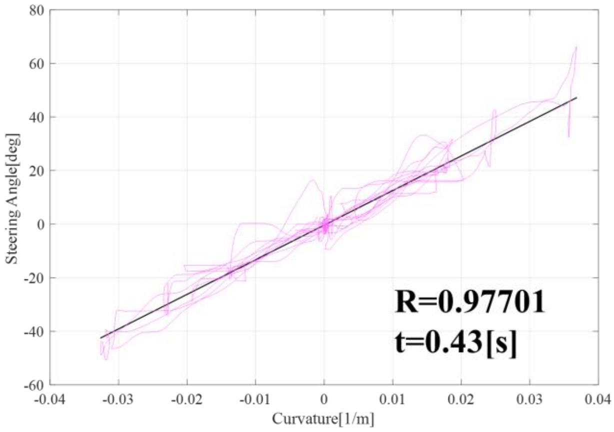


Figure 7. Correlation coefficient（Participant A， Steer2-2）.

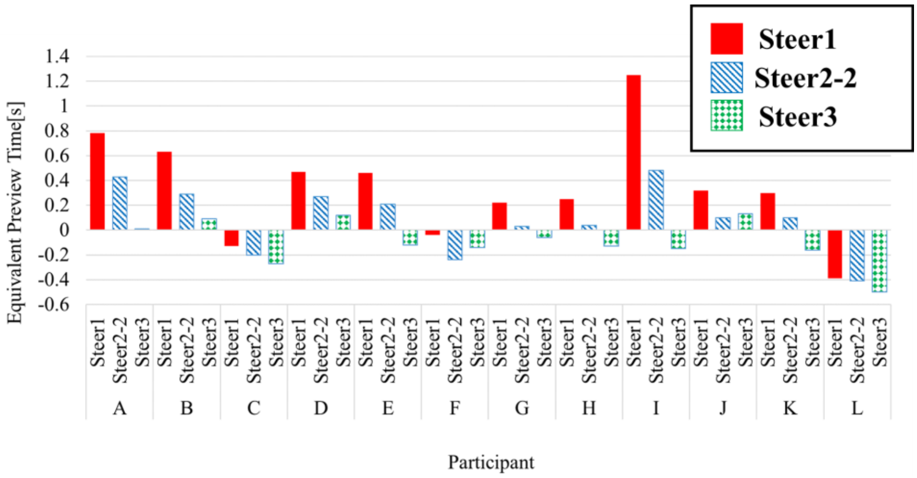


Figure 8. Equivalent Preview Time.

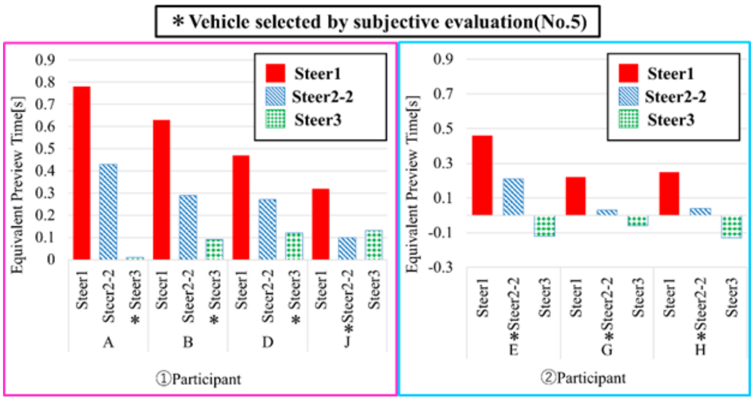


Figure 9. Equivalent Preview Time (7 participants).

3.3 Driver characteristics difference in Equivalent Preview Time

In the previous section, driver's selection was made based on the equivalent preview time. Therefore, we graspe the driver characteristics of the selected 7 drivers. In this experiment, we were used two check sheets, DSQ and WSQ, which are publicly available by HQL. Driving style is driving attitude, orientation, and way of thinking that affects daily driving behavior. DSQ is chuck sheets that is a driver characteristic for those. The check sheets consist of 8 scales: "1: Confidence in driving skill", "2: Hesitation for driving", "3: Impatience in driving", "4: Methodical driving", "5: Preparatory maneuvers at traffic signals", "6: Importance of automobile for self-expression", "7: Moodiness in driving" and "8: Anxiety about traffic accidents", and the score of each scale is determined from the answers of 18 questions [7]. The higher score of each scale, the more driving attitude and way of thinking applies.WSQ is a check sheet for driver characteristics that measures how driver feel about each workload in order to understand the individual differences in daily driving behavior from the perspective of coping behavior against driving workload. The check sheets consist of 10 scales: "1: Awareness of traffic situation", "2: Recognition of road environment", "3: Tendency to become distracted while driving", "4: Physical condition", "5: Patience with driving pace", "6: Physical pain/discomfort", "7: Comprehension of driving route", "8: In-vehicle environment", "9: Control and operation", and "10: Driving posture", and the score of each scale is determined from the answers to 38 questions [8]. The higher the score of each scale, the more sensitive the degree of Workload Sensitivity.

We investigate which of the two check sheets shows the difference in driver characteristics. First, we calculate the vector of each participant that using values of 8 scales for DSQ and 10 scales for WSQ. Figure 10 shows the relationship between the DSQ vectors and the WSQ vectors using the calculated values. In the figure, the FF-groups shown "①Participants with feedforward control as the main control algorithm for all vehicle characteristics"and "②Participants whose main control algorithm of the vehicle that is most comfortable to ride in the "ride comfort" term of subjective evaluation is the feedforward control" that are drivers selected in the previous section. On the other hand, the FB-groups shown "③Participants whose main control algorithm of the vehicle that is most comfortable to ride in the "ride comfort" term of subjective evaluation is the feedback control"and "④Participants with feedback control as the main control algorithm for all vehicle characteristics". From the figure, DSQ showed no difference for each driver, while WSQ showed a difference for each driver. Therefore, there is a possibility that the difference in equivalent preview time may be seen in the driver characteristics depending on the WSQ term. Also, looking at the 7 participants selected using the equivalent preview time, it can be seen that they are locate on the left side with a value of "9" as the boundary. In other words, it is found that among the participants in this experiment, the drivers are classified as having a low work load sensitivity. As future work, it is necessary to examine the tendency of the driver by the term of WSQ.

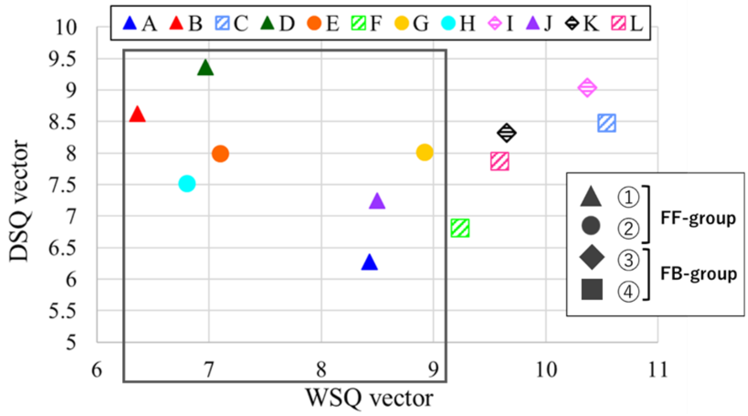


Figure 10. Vector of driver characteristics.

4 DRIVING BEHAVIOR ANALYSIS

4.1 Analysis of feedforward steering

First, we calculate feedforward steering in participant A. From Figure7, the equivalent preview time is 0.43 [s], and the correlation coefficient R is very high at 0.977. Therefore, the inclination at this time is defined as the Steering gain. Next, the feedforward steering is calculated multiplying the by the curvature at the equivalent preview time and the steering gain [11]. Figure 11 shows the relationship between the calculated feedforward steering and the steering angle performed by the driver in DS. From the figure, it is almost the same and the steering angle can be reproduced with FF steering. Similarly, we calculate the feedforward steering of Steer1 and Steer3. Table 4 shows the equivalent preview time for each vehicle characteristic of participant A. Figures 12 (a) and 12 (b) show the relationship between the Steer1 and Steer3 feedforward steering from the equivalent preview time and steering angle obtained in DS. From the table and figure, it can be seen that all vehicle characteristics have a high correlation coefficient of R=0.9 or higher. Therefore, it can be seen that the calculated feedforward steering is determined by the forward curvature and expresses the driver's control behavior well. Similarly, we calculated the feedforward steering of the 7 participants selected in this report. Table 5 shows the correlation coefficient between the calculated feedforward steering and the steering angle obtained in DS. From the table, it is found at all participants and all running that very high with a correlation coefficient of about R=0.95 or more, and the steering angle could be expressed by feedforward steering.

Here, we focus on the equivalent preview time and steering gain that constitute feedforward steering. It is thought that there are individual differences in the acquisition of surrounding information depending on the driver, and the equivalent preview time to obtain forward curvature information and steer is different. Figure 13 shows the equivalent preview time and Steering gain for each participant in the steering characteristics. From the figure, it can be seen that the Steering gain does not vary between drivers and depends on vehicle characteristics. It is seen that the driver increases the Steering gain as the vehicle has a smaller step response gain. In contrast, the larger the Steering gain, the shorter the equivalent preview time. Furthermore, it is seen that the equivalent preview time varies depending on the driver. The reason for this is thought to be that the driver is driving while supplementing the characteristics of the vehicle so that each driver will behave appropriately by changing the equivalent preview time. Since the equivalent preview time is the time to start steering, it is conceivable that driver is shortening the equivalent preview time for improving the response for Steer3. On the other hand, Steer1 had the longest equivalent preview time among the 3 vehicles in all the participants, but there is a big difference among the drivers. This is due to the driver characteristics, and it Indicated that the equivalent preview time required to control the vehicle behavior differs depending on the driver.

From the above, for vehicles with low vehicle response, all drivers control by increasing the Steering gain and changing the time until steering (equivalent preview time). It turns out that only this equivalent preview time depends on the driver.

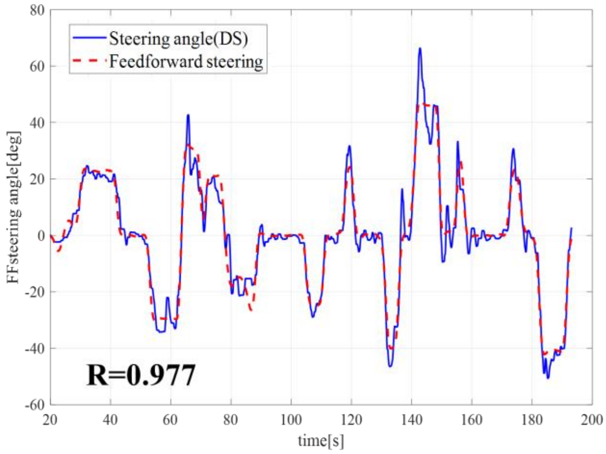
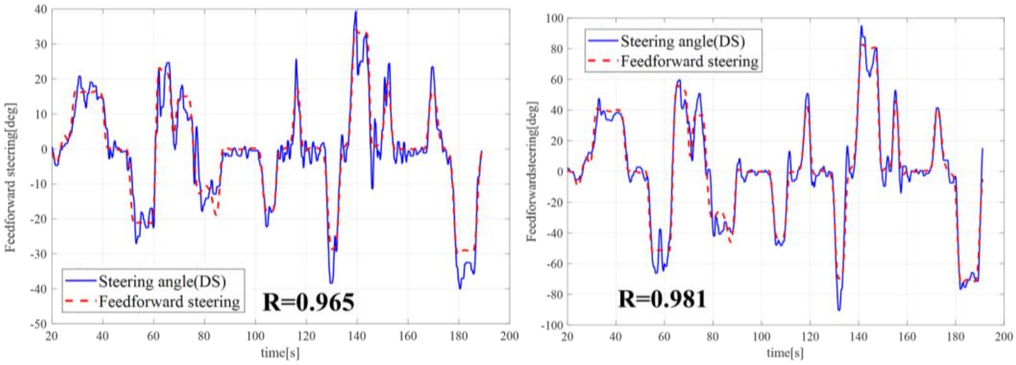


Figure 11. Feedforward Steering（Participant A, Steer2-2）.

Participant	Characteristic	Equivalent Preview time[s]	R
A	Steer1	0.78	0.965
	Steer2-2	0.43	0.977
	Steer3	0.01	0.981

Table 4. Equivalent Preview Time（Participant A）.



(a)Steer1 (b)Steer3

Figure 12. Feedforward Steering(Participant A).

Table 5. Equivalent Preview Time (7 participants).

Participant	Characteristic	Equivalent Preview time	R
A	Steer1	0.78	0.965
	Steer2-2	0.43	0.977
	Steer3	0.01	0.981
B	Steer1	0.63	0.972
	Steer2-2	0.29	0.979
	Steer3	0.09	0.979
D	Steer1	0.47	0.970
	Steer2-2	0.27	0.976
	Steer3	0.12	0.986
J	Steer1	0.32	0.980
	Steer2-2	0.1	0.987
	Steer3	0.13	0.984
E	Steer1	0.46	0.947
	Steer2-2	0.21	0.975
	Steer3	-0.12	0.981
G	Steer1	0.22	0.967
	Steer2-2	0.03	0.983
	Steer3	-0.06	0.985
H	Steer1	0.25	0.965
	Steer2-2	0.04	0.985
	Steer3	-0.13	0.982

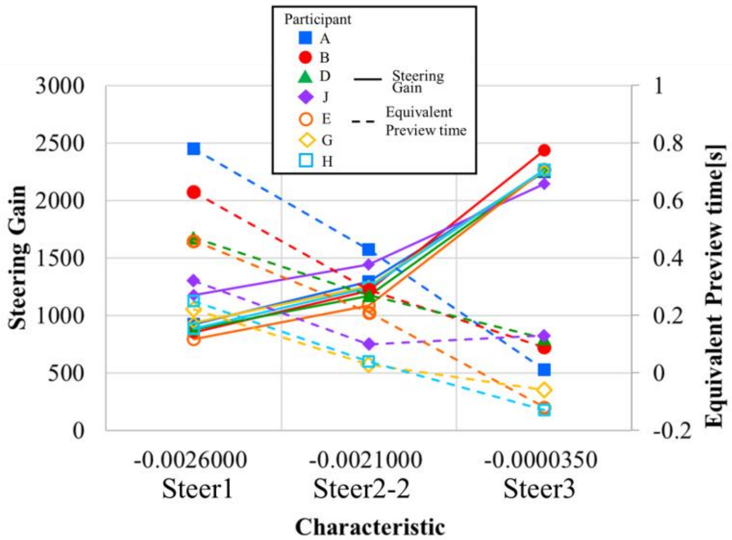


Figure 13. Relationship between Steering Gain and Equivalent Preview Time by different vehicle characteristics.

4.2 Analysis of feedback steering

Next, we examine the feedback steering which adjustment based on the vehicle behavior. In this study, since a linear model is used, the part obtained by subtracting the feedforward steering angle from the steering angle during driving is defined as feedback steering in order to remove noise. Figure 14 shows the relationship between the analytical feedback steering and the steering angle of the real data. From the figure, it is seen that the feedback steering is relatively small in the steering characteristics mainly of feedforward steering. In order to evaluate from the viewpoint of human-vehicle system, it is necessary to model feedback control in order to clarify the vehicle behavior that affects control. Therefore, it is necessary to study the optimal model in the future. The 7 participants selected in this report use feedforward control as the main control algorithm, it is considered that the driver has made to control so as to adjustment the difference between the target course obtained by feedforward control and the course in actual driving. In addition, it is shown a schematic diagram of a general feedback model. Figure15 shows the 1st order prediction model, and Figure16 shows the 2nd order prediction model. In the future, we aim to construct an optimal feedback model based on these.

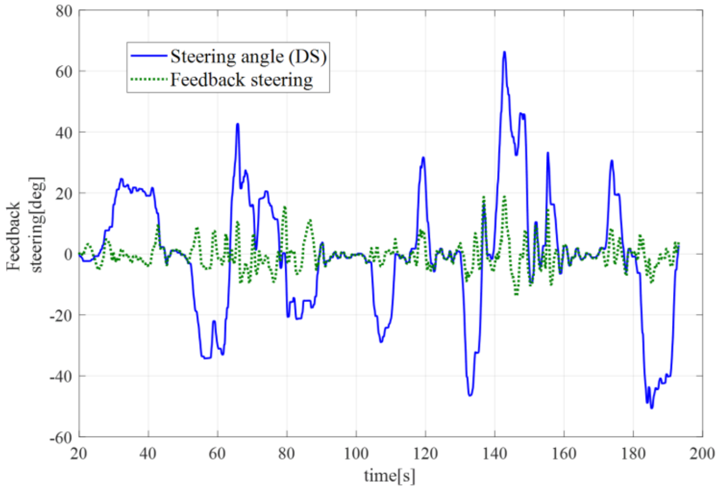


Figure 14. Feedback Steering（Participant A， Steer2-2）.

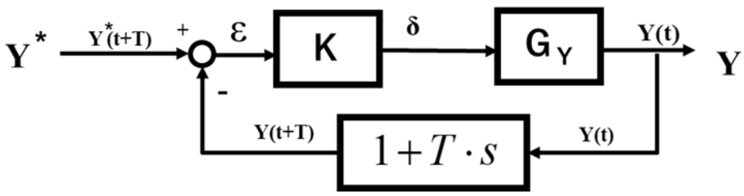


Figure 15. 1st order prediction model.

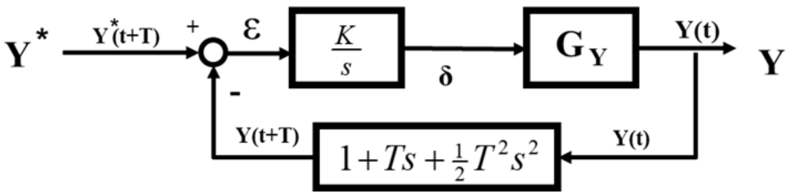


Figure 16. 2nd order prediction model.

5 CONCLUSIONS

In this study, the driver model was examined for the evaluation method from the viewpoint of human-vehicle system of PMV with leaning mechanism. Therefore, the vehicle characteristics were changed, reproduced on the DS and experimented, and the difference in the equivalent preview time of each driver was examined. As a result, it indicated that PMV with a leaning mechanism have a driver with the feedforward control as the main control algorithm and a driver with the feedback control as the main algorithm. In addition, it is suggested that the characteristic difference of the driver whose main control algorithm is the feedforward control may be seen by WSQ. Also, in this report, we examined 7 drivers with feedforward control as the main control algorithm. As a result, the feedforward steering angle was determined only by road information and could be expressed by steering gain and the curvature for equivalent preview time. Moreover, vehicles with low vehicle response, all drivers control by increasing the Steering gain and changing the time until steering (equivalent preview time). It turns out that only this equivalent preview time depends on the driver. As a result, it is indicated that the driver changes the equivalent preview time, because the driver controls the PMV of each characteristic so that it behaves as desired. In addition, it conceivable that the driver has made to control so as to adjustment the difference between the target course obtained by feedforward control and the course in actual driving. For the future, we will investigate an optimal model for feedback control.

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