Effects of Yaw Motion on Driving Behaviour, Comfort and Realism

Jeroen Hogema[1], Mark Wentink [2], Gary Bertollini [3]

(1) TNO, Kampweg 5, 3769 DE Soesterberg, The Netherlands. E-mail: jeroen.hogema@tno.nl
(2) Desdemona BV, Kampweg 5, 3769 DE Soesterberg, The Netherlands, E-mail: mark.wentink@desdemona.eu
(3) General Motors Research and Development, VDR Laboratory, 30500 Mound Rd., Warren, Michigan, USA, E-mail: gary.p.bertollini@gm.com

Abstract *– The use of large displacement yaw cueing is becoming more common as a part of the motion cueing in driving simulators. It is expected that driving behaviour, comfort and realism will be positively affected by adding a yaw table, especially during low-speed turning manoeuvres.*

We used TNO's advanced motion platform Desdemona to explore the effects of yaw motion during highway and urban turning manoeuvres: 14 participants drove the simulator with and without yaw motion.

Questionnaires results showed that the simulation was rated as quite realistic. Effects of yaw motion on the subjective ratings were not found. In terms of driving behaviour, we found statistically significant effects of yaw motion in curve driving, especially in small-radius curves. With yaw motion present, driving behaviour became more cautious, and (compared against the literature) more realistic. This suggests that adding yaw motion to a driving simulator improves the external validity for low-speed corner driving manoeuvres.

Key words: *driving simulator; yaw table, motion cueing, driving behaviour.*

Introduction

In driving simulators, the simulation of cornering manoeuvres is considered particularly challenging, especially in city environments, where the curve radius is typically small [Wen1]. The discrepancy between the high yaw rates in the car and the lack thereof in the simulator, plus the associated mismatch in lateral acceleration, often cause disorientation or even motion sickness [Ken2]. This explains the growing interest in the use of large displacement yaw cuing platforms in driving simulators, such as those at the University of Tokyo [Yam3], the US National Advanced Driving Simulator [Sch4] and Toyota [Toy5].

Such yaw cueing systems would ideally generate yaw rates and displacements corresponding to the real car yaw dynamics. It is believed this may reduce simulator disorientation effects during low speed turning manoeuvres as typically encountered in city intersection scenarios. See e.g. [Mou6], who reported beneficial effects of yaw motion compared to no motion. Consequently, it is expected that driving behaviour, comfort and realism will be positively affected by this new yaw motion capability. We investigated the effects of adding yaw motion to other motion components by means of a driving behaviour experiment.

Method

The Desdemona simulator was utilized for the experiment. Desdemona is a moving-base research simulator located at TNO (Soesterberg, The Netherlands). It was built in close co-operation with AMST (Ranshofen, Austria). The simulator has 6 Degrees of Freedom (DoF). The cabin (see Fig.1) is mounted in a gimballed system (3 DoF, >2π radians), which as a whole can move vertically along a heave axis (1 DoF, ±1m) and horizontally along a linear arm (1 DoF, ±4m). This structure can rotate as a whole around a central axis to facilitate centrifugal motion (1 DoF, <3G).

For the current experiment, the Desdemona cabin was equipped with a generic car cockpit (see Fig.1). The cockpit contained force feedback on steering wheel, and on gas and brake pedals. Direct drive electrical motors generated the control loading for the steering wheel and pedals. The out-the-window visuals were projected at a screen in the cabin by three projectors. The driver was approximately 1.5 meters away from the central screen, which had a field-of-view of 120 degrees horizontally and 32 degrees vertically. Driving sounds were not simulated in this experiment.

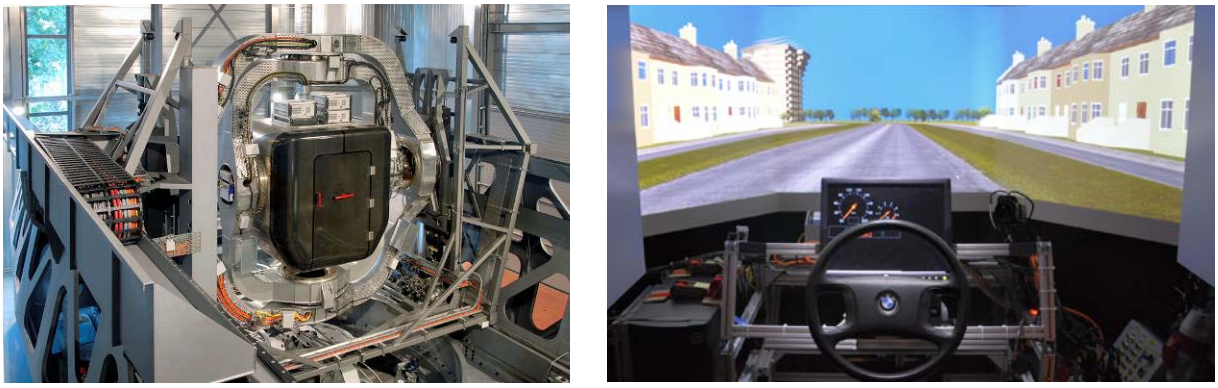

Figure 1 The Desdemona research simulator (left); the interior of the car cabin (right).

The motion cueing consisted of the following elements.

- A yaw component: the yaw motion of the vehicle model was simulated by yaw motion of Desdemona. This component could be switched on or off, and was used as an independent variable (the 'yaw motion' versus 'no yaw motion' condition). The participant’s head position was 0 to 20 cm behind the yaw axis (dependent on the chair position).
- A 'road rumble' signal on the heave and the roll axis, consisting of a low-pass filtered noise signals.
- A pitch component that followed the pitch angle of the vehicle model (i.e. no tilt coordination)
- A roll component that followed the roll angle of the vehicle model (scaled by 50%).

The vehicle dynamics were representative for the dynamics of a C-Class Hatchback with automatic gear shift. The steering feedback torque was based on a spring-damper characteristic.

Figure 2 Straight road (left picture); curve to the left (right picture).

Two persons participated in blocks of two hours: while one was driving, the other one was resting. Each participant completed two runs. Each run consisted of two parts that were presented in a fixed order.

1. Lane changing on the straight road: four pairs of lane changes with, and four without yaw motion. The first was a straight road, which had 2 lanes with a standard lane width of 2.75 m. There were continuous lane markings on the outside and dashed markings on the centre line. The road was entirely straight. The vehicle's speed was limited at 82 km/h. Participants were instructed to press the gas pedal fully to ensure they would drive at a constant speed. They were instructed to carry out the lane changes manoeuvres swiftly.
2. Curve driving in an urban environment (four curves with, and four curves without yaw motion). In this environment the focus was on two types of corner driving such as that experienced in a tight curve and at an intersection crossing. The urban square circuit road had straight segments of 150 meters each and four 90 degrees corners. Two of these corners, in diagonally opposite corners, were curves with a radius of 20 m. The

other two were intersection crossings with rounded shoulders (radius of the rounded shoulders: 8.5 m). Participants were instructed to turn left on each corner / crossing, and not to exceed a speed of 50 km/h.

After a familiarisation procedure, the participant conducted four pairs of lane change manoeuvres, which typically took about two minutes in total. Then the participant was asked to stop the vehicle. After that, questionnaires were completed. These consisted of six questions about the experienced level of realism of the simulator (Likert scales). For motion sickness, we used the misery scale (MISC), developed and validated at TNO [Wer7]. A MISC score of 7 or higher (nausea – medium) was used as a termination criterion: if this level was reached, the run would be terminated and the participant would be excluded from the experiment. Then, the motion condition was changed and the second set of four lane changes was completed. Again the participant stopped the vehicle and the questionnaires were completed. This time a forced-choice selection of the most realistic simulation (first or second block) was asked as well.

Next, the set-up was changed to the urban environment. With the first motion condition operational, participants had a brief familiarisation run to get used to the task, the vehicle dynamics and the motion. After a brief stop, they conducted four curve driving manoeuvres, which typically took about two minutes. Then they were asked to stop the vehicle and give their ratings. Then the motion condition was changed and a second set of four curves was completed. Again the participant stopped the vehicle and the questionnaires were completed. This time a forced-choice selection of the most realistic simulation (first or second block) was asked as well.

In total, 14 subjects participated in the experiment (7 males, 7 females). Their average age was 40 years (s.d. 12). They had an average driving experience of 20 years (s.d. 11). They drove 15,000 km / year on average (9,3000 s.d.).

During the runs, driver input and vehicle state variables were logged with a frequency of 50 Hz.

The following dependent variables were derived for each lane change:

- maximum (absolute) steering wheel angle (^{o})
- the maximum lateral position (with respect to centre of new lane, in m)
- maximum yaw rate (^{o} /s)
- maximum lateral acceleration (m/s^2)
- SRR (Steering wheel Reversal Rate, s^{-1})
- percentage of time that any part of the vehicle was outside the lane (%)

In addition, the following the following dependent variables were determined for each corner:

- maximum braking pedal input (normalised)
- maximum deceleration (m/s^2)

Results

Motion sickness

In 89% of all observations, the MISC remains at 0 ('no problem at all'). In 10% of the cases, a MISC of 1 was given. The highest value that occurred, only once, was 2 (0.9% of observations). Thus, motion sickness was not an issue in this study.

Forced choice preference

After each pair of motion conditions, the participant was asked which of the two runs was perceived as most realistic. In total, the without yaw was selected 30 times (55%), and with yaw 25 times (45%). A Chi-square test showed no difference [$\chi 2 = 0.45$, $p=0.50$].

The preferred motion condition was with yaw in 44% on the straight road and 46% on the urban road. A Chi-square test showed no significant relationship between environment and preferred motion condition [$\chi 2=0.02$, $p=0.88$].

Thus, there is no indication that environment/task was related to preference of yaw motion.

Level of realism of the simulation

The results from the Likert scale questions were averaged over replications for each participant. Next, the results were analysed in separate ANOVAs, with two independent variables: environment (straight = lane changing task; urban = curve driving task) and yaw motion (without, with).

The results are shown in Table 1 and in Table 2 in terms of the main effects. The effect of yaw motion never reached statistical significance (see Table 1).

Table 1. ANOVA results: main effect of yaw motion (scale minimum 1; scale maximum 7).

Question	Without	With	Main effect significance
Q1: Felt like I was really driving	6.13	6.18	F(1,13)=0.1, p=0.74
Q2: I drove as I normally would	6.02	5.88	F(1,13)=0.8, p=0.40
Q3: I adjusted my driving to simulator	3.00	3.13	F(1,13)=0.5, p=0.48
Q4: I executed the task well	5.88	5.80	F(1,13)=0.2, p=0.68
Q5: motion and forces helped control the car	4.61	4.77	F(1,13)=0.1, p=0.82
Q6: motion and forces felt realistic	5.16	5.21	F(1,13)=0.0, p=0.84

As Table 2 shows, there were significant effects of the road environment. On the straight road, compared to the urban road:

- participants felt more like really driving a car,
- more like driving as normal,
- had to adjust their driving to the simulator to a lesser extent,
- had a higher rating of their task performance, and
- found that the forces and motion were more realistic.

Table 2. ANOVA results: main effect of environment/task (scale minimum 1; scale maximum 7).

Question	Straight / lane change	Urban / curve driving	Main effect significance
Q1: Felt like I was really driving	6.45	5.86	F(1,13)=6.0, p=0.03
Q2: I drove as I normally would	6.61	5.29	F(1,13)=16.6, p=0.002
Q3: I adjusted my driving to simulator	2.29	3.84	F(1,13)=12.2, p=0.004
Q4: I executed the task well	6.66	5.02	F(1,13)=34.3, p<0.001
Q5: motion and forces helped control the car	4.77	4.61	F(1,13)=0.3, p=0.57
Q6: motion and forces felt realistic	5.68	4.70	F(1,13)=11.5, p=0.005

Objective data: lane changes

Since no effects of replication were found, we averaged results over both replications before conducting the ANOVA.

Independent variables were yaw motion (off/without – on/with) and direction (to the left – to the right). The main effect results of yaw motion are summarised in Table 3. The effect of yaw motion never reached statistical significance. Thus, these results give no indication that yaw motion was of influence on driving behaviour in this part of the experiment.

Table 3 ANOVA results: main effect of yaw motion for lane changes.

Variable	Mean without	Mean with	Units	Effect yaw motion
max steering wheel angle	7.95	7.84	^{o}	F(1,13)=0.2, p=0.66
maximum lateral position	0.013	-0.002	m	F(1,13)=1.3, p=0.27
maximum yaw rate	2.05	2.05	^{o} /s	F(1,13)=0.0, p=0.98
max lateral acceleration	0.90	0.90	m/s^2	F(1,13)=0.0, p=0.99
Steering Reversal Rate	0.67	0.68	/s	F(1,13)=0.1, p=0.79
percentage outside road	2.45	2.26	%	F(1,13)=0.1, p=0.74

Objective data: curve driving

Initial analyses revealed several effects of corner type (curve or crossing), as did [Val8]. Therefore, this variable was included in the final analysis as reported here. An ANOVA was conducted for each dependent variable, using the independent variables yaw motion (off/without – on/with) and corner type (curve - crossing).

Table 4 ANOVA results: main effect of yaw motion for curve driving.

Variable	Mean without	Mean with	Units	Effect yaw motion
maximum steering wheel angle	201.9	188.1	^{o}	F(1, 13)=9.6, p=<0.01
Steering reversal rate	0.93	0.87	/s	F(1, 13)=1.7, p=0.21
Maximum path deviation	1.97	1.89	m	F(1, 13)=2.6, p=0.13
Maximum yaw rate	32.4	29.5	^{o}/s	F(1, 13)=21.0, p<0.001
Maximum lateral acceleration	5.6	4.8	m/s^2	F(1, 13)=13.8, p=0.01
average speed	30.4	29.0	km/h	F(1, 13)=11.9, p<0.01
Maximum braking	30	25	%	F(1, 13)=11.4, p<0.01
Maximum deceleration	4.4	4.0	m/s^2	F(1, 13)=3.38, p=0.088

The results revealed several effects of corner type, reflecting the smaller radius of the intersection crossing compared to the curve:

- Maximum steering wheel angle [F(1, 13)=273, p<0.001]: averages of 237 degrees on the crossing and 153 degrees in the curve.
- Maximum path deviation [F(1, 13)=12.7, p=0.01]: averages were 2.03 m on the crossing and 1.84 m in the curve.
- Maximum yaw rate [F(1, 13)=120.7, p<0.001], showing a higher yaw rate on the crossing (35.1 ^{o}/s) than on the curve (26.8 ^{o}/s).
- Maximum lateral acceleration [F(1, 13)=9.3, p<0.01]: the mean on the crossing was higher than on the curve (5.5 m/s^2 and 4.9 m/s^2, respectively)
- Average speed [F(1, 13)=74.2, p<0.001]: in the crossing, the average speed was 26.9 km/h, and in the curve 32.5 km/h.
- The maximum braking [F(1, 13)=52.2, p<0.001]: the on the crossing more braking was applied than in the curve (means 34% and 21%, respectively).

Several significant interactions were found between yaw motion and corner type. This was the case for the maximum steering wheel angle [F(1, 13)=11.9, p<0.01] and for the maximum yaw rate [F(1, 13)=19.7, p<0.001]. As Fig. 3 and Fig. 4 show, the effect of yaw motion was only present on the crossing, not in the curve.

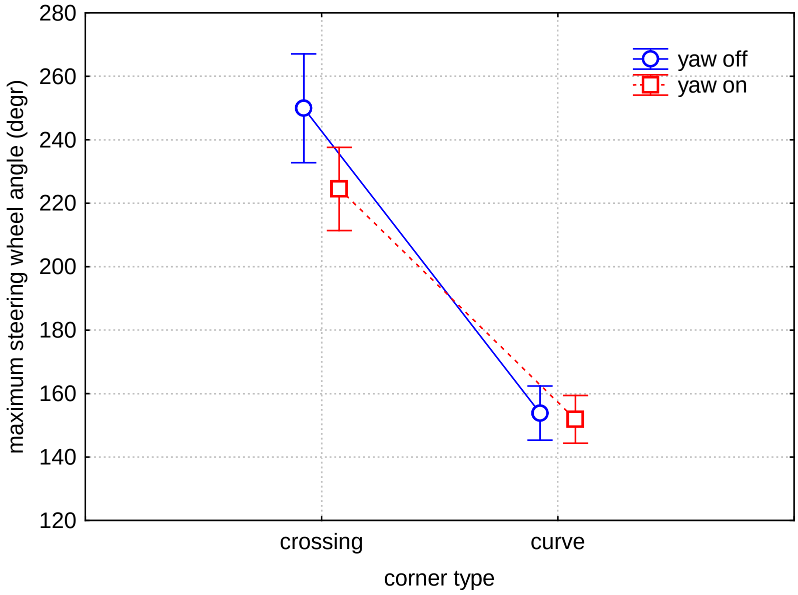

Figure 3: Maximum steering wheel angle as a function of yaw motion and corner type (means and 95% confidence interval).

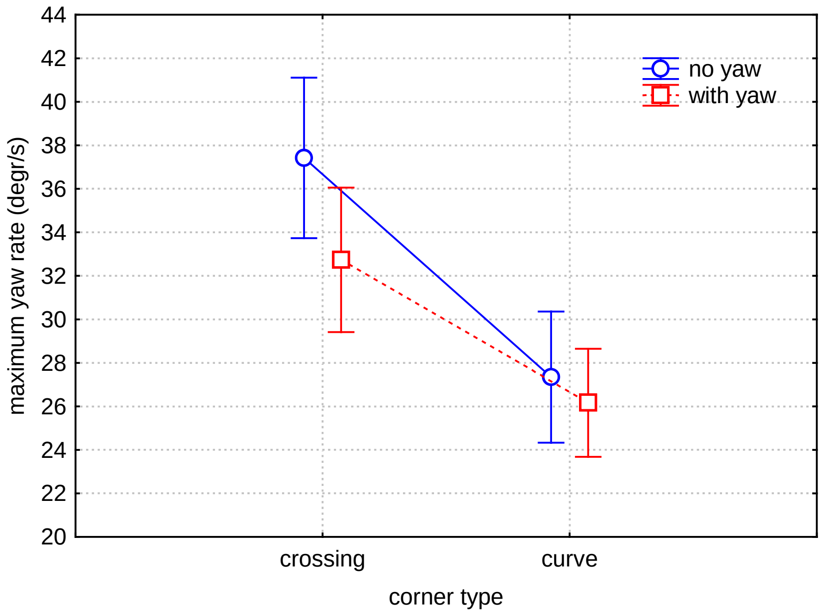

Figure 4: Maximum yaw rate as a function of yaw motion and corner type (means and 95% confidence interval).

Discussion and conclusions

The two combinations of task and environment (lane changing on the straight road, and corner driving in the urban environment) were deliberately designed to cover a wide range of lateral acceleration and yaw motion. The objective data confirmed that they did differ strongly. The maximum lateral acceleration was 0.9 m/s^2 in lane changing, and 5.2 m/s^2 in curve driving. The difference was even larger in terms of yaw rate: 2 $^{o}/s$ in lane changes, and 31 $^{o}/s$ in curve driving.

Reviewing the results of the questionnaires, it can be stated that the overall simulation was rated as quite realistic. Motion sickness was not an issue in this experiment. Typically, participants felt like they were "really driving a car", and "drove as they normally would" (scores above 6 on a scale from 1 to 7). Questions that focused on the motions and forces ('they helped', and 'felt realistic', respectively) scored a bit lower (4.7, and 5.2, respectively), but still clearly in the upper half of the scale. In informal debriefings, it became apparent that some subjects based their scores for these questions more on steering wheel forces rather than the forces associated with vehicle motion.

A statistical analysis showed that the ratings for the lane changing manoeuvres on the straight road were better than those for the cornering manoeuvres on the urban road. This illustrates the difficulty of simulating cornering manoeuvres in city environments.

In total, the questionnaires did not reveal effects of the yaw motion component (neither on the Likert scales, nor on the forced-choice preference). Informal debriefings showed that there were some participants who correctly identified the runs that had an 'extra' motion component, and some of them specifically stated that they felt this motion was not correct (e.g., 'felt like my rear wheels were steering', or 'felt as if I was driving a forklift').

When looking at the objective data of the lane change task, no differences were found between the conditions with and without yaw motion. In the corner driving task, several significant effects of yaw motion were found. With yaw motion present, we observed:

- smaller steering wheel amplitude (only on the crossing, not in the curve),
- smaller yaw rate amplitude (only on the crossing, not in the curve),
- smaller lateral acceleration amplitude,
- lower average speed,
- lower maximum braking, and
- lower maximum deceleration

All these effects show more cautious driving behaviour in the presence of yaw motion. This is in line with [Cor9] who found more cautious driving due to motion feedback in (more extreme) slalom driving in Desdemona. They concluded that with motion feedback, subjects drove more carefully and had better control of the car; therefore they could anticipate the car dynamic behaviour better and were not that surprised when the car did crash. Still, this was in rather extreme slalom driving. More in line with the current experimental setting, [Val8] reported a study in Desdemona, using the same urban environment as we did. There results showed that maximum deceleration levels were lower with their one-to-one yaw motion condition compared to rumble-only motion. Again, this is in line with the current results, i.e., showing more cautious behaviour with yaw motion present.

Now that we have found more cautious curve driving behaviour due to yaw motion, the question remains if this is an effect 'in the right direction', i.e. more towards driving behaviour in reality. [Fel10] reported test track results on speed choice and lateral accelerations on horizontal curves. In their smallest curve (R=16m), and under a comfortable driving instruction, the lateral acceleration levels were in the order of magnitude of 3 m/s^2. In the current experiment, we found maximum lateral accelerations of 4.8 m/s^2 with, and 5.6 m/s^2 without yaw motion. Thus, compared against the results from [Fel10], adding yaw motion appears to elicit more realistic driving behaviour.

In the urban environment, several differences were found between steering through the curve (R=20 m) and through the crossing (R=8.5 m). When the curve radius was smaller, we found:

- larger steering wheel angles,
- lower speed, and
- higher lateral accelerations.

These effects of curve radius are in line with the literature, see e.g. [Win11], [Fel10]. Furthermore, an earlier experiment in Desdemona in the same urban environment showed similar differences between the curve and the crossing [Val8].

In conclusion, the experiment has shown that adding yaw motion to the simulation changed driving behaviour in curve driving. With yaw motion present, driving behaviour became more cautious, and (compared against the literature) more realistic, especially in small-radius curves. This suggests that adding yaw motion to a driving simulator improves the external validity for corner driving manoeuvres.

Acknowledgements

This work was supported by General Motors.

References

[Cor9] Correia Grácio, B., Wentink, M., Feenstra, P.J., Mulder, M., Van Paassen, M.M., Bles, W. “Motion feedback in advanced driving manoeuvres”. *Proceedings of the Driving Simulation Conference DSC2009.* Monaco: 4-6 February 2009.

[Fel10] Felipe, E., Navin, F. “Automobiles on horizontal curves: experiments and observation”. *Transportation Research Record,* 1998, *1628,* 50-56.

[Ken2] Kennedy, R.S., Fowlkes, J.E., Berbaum, K.S., Lilienthal, M.G. “Use of a motion sickness history questionnaire for prediction of simulator sickness”. *Aviation Space and Environmental Medicine,* 1992, *63,* 588-593.

[Mou6] Mourant, R.R., Yin, Z. “A Turning Cabin Simulator to Reduce Simulator Sickness”. *Proceedings of SPIE - The International Society for Optical Engineering,* 2010, *7525, art. no. 752503.*

[Sch4] Schwarz, C., Gates, T., Papelis, Y. “Motion characteristics of the national advanced driving simulator”. *Proceedings of the North American Driving Simulation Conference,* Michigan: October 8-10, 2003

[Toy5] Toyota “*Toyota Develops World–Class Driving Simulator”.* News release November 26, 2007. http://www.toyota.co.jp/en/news/07/1126_1.html.

[Val8] Valente Pais, A.R., Wentink, M., van Paassen, M.M., Mulder, M. “Comparison of three motion cueing algorithms for curve driving in an urban environment”. *Presence: Teleoperators and Virtual Environments,* 2009, *18* (3), 200-221.

[Win11] Van Winsum, W., Godthelp, J. “Speed choice and steering behaviour in curve driving”. *Human Factors,* 1996, *38,* 434-441.

[Wen1] Wentink, M., Valente Pais, R., Mayrhofer, M., Feenstra, P., Bles, W. (2008). “First curve driving experiments in the Desdemona simulator”. *Proceedings of the Driving Simulation Conference DSC2008.* Monaco: 31 January - 1 February 2008.

[Wer7] Wertheim, A.H., Ooms, J., De Regt, G.P., Wientjes, C.J.E. “Incidence and severeness of seasickness: Validation of a rating scale” 1992, Tech. Rep. No. IZF 1992 A-41, Soesterberg, Netherlands: TNO Human Factors.

[Yam3] Yamaguchi, D., Suda, Y., Onuki, M., Shimoyama, O. “Approach to Improvement of Realistic Sensation on Universal Driving Simulator”. *Proceedings of the Driving Simulation Conference DSC 2010.* Paris, France: 9-10 September 2010.