Do you feel the difference?
A motion assessment study

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Abstract

Since June 2005, a new moving-base driving Simulator (6 DoF) is in operation at the DLR Institute of Transportation Systems. Initial experiments were conducted in order to evaluate the participant's ability to control a car within a virtual environment with different motion platform characteristics. In addition, the subjects assessed the quality of the perceived motion. The driving behaviour in the simulator was compared to driving in the real world with an equipped car (the DLR ViewCar).

The parameters for the motion cueing algorithm were tuned for certain manoeuvres (curve driving and braking) in order to obtain different motion characteristics. The resulting parameter sets were used in the three sections of the experiment each consisting of three specific courses. The analysis of the questionnaires and the driving data revealed that the essential tuning with regard to longitudinal control was successful whereas further considerations of how to tune with regard to lateral control will be necessary. Comparing real and simulator driving identified the average speed to play an important role in simulation validation tasks. The chosen approach to improve the impression created by moving-base simulators showed to be promising and will be extended in the future.

Keywords: simulator study, motion cueing, evaluation

Introduction

For research and training in automotive and aviation, increasingly sophisticated moving-base simulators are being developed in order to create a realistic experience for the operator. The motion algorithms used are essential in attaining this goal. Open questions remain whether well-tuned classical algorithms are sufficient or whether complex new strategies have to be developed. Further, a driver- or pilot-in-the-loop tuning as suggested by Grant and Reid (1) is very time-consuming. Thus it has to be investigated whether other tuning methods, such as a manoeuvre-specific tuning, can be satisfactory as well. In order to answer these questions, methods are required with which the effects of motion algorithms can be evaluated. On the one hand, the subjective impression of the operator including motion-sickness has to be considered. On the other hand, it has to be shown that the behaviour of the operators is comparable to behaviour in reality. The Institute of Transportation Systems of the DLR is developing an approach towards these goals. The paper presents the results of an experiment where different motion-tuning parameter sets were compared with regard to their subjective and behavioural effects in a moving-base simulator as compared to real driving with the DLR ViewCar.

Method

Experimental Design

Building up from comparisons between real vehicle drives and driving simulator runs (2), the experiment consisted of two parts: driving in normal traffic with the DLR ViewCar and driving in the DLR moving-base simulator. The first part provided data about normal driving behaviour to which the trips in the simulator were compared. In the simulator, the subjective assessment of the motion and the driving behaviour with different motion parameter sets were examined. Both parts are described in detail in the next two paragraphs.

Real World Driving

The real world track (Track *R*) was chosen to be a 10 to 15 minutes drive. It was comprised of several curves with different degrees of curvature as well as sections forcing the driver to stop or to reduce speed (FIGURE 1). By means of the DLR ViewCar (3, 4) driving behaviour and car dynamics were measured. For the analyses, the focus was placed on variables describing lateral (steering wheel reversals, lateral position) and longitudinal (speed) control.

Simulator Run

Before starting the simulator experiments, the subjects were trained in a fixed-base simulator. This reduced the probability of simulator sickness during the experiment and let the test drivers get used to driving in a virtual environment. In the main run, three virtual test track sections were driven (cf. FIGURE 1). The first of these is a copy of the real world test track (*S1*). The second section was constructed to concentrate on the lateral control by introducing a curvy road with different speed limits. The third part (*S3*) was generated to focus on longitudinal control. In a first long straight section, changing speed limits were introduced in order to examine acceleration and braking in the higher speed range. Afterwards, short straight sections with different speed limits were introduced followed by crossroads where the drivers had to stop. In both sections, speeds of 50, 80, or 120 kph were driven.

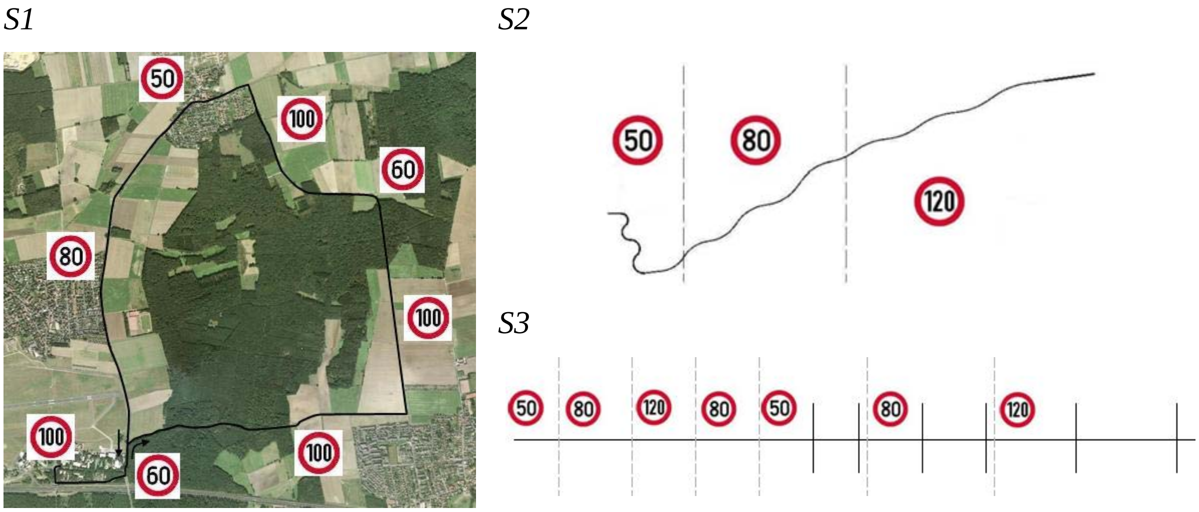

FIGURE 1 The pictures show the test tracks. To the left, the real world track "*R* (*S1*)" is shown including the speed limits at the different sections. At the top right the curve driving track "*S2*" with three speed limits is given and below, the longitudinal manoeuvre track "*S3*" is depicted with changing speed limits in the first part and braking manoeuvres in the second part.

Each subject drove these three sections three times. At each time, a different parameter set for the motion washout algorithm was used. This is a classical washout filter as described by Reid and Nahon (5). The different sets are based on untuned initial parameter states combined with manoeuvre-specific tuned values (TABLE 1). The parameter set a is optimized for acceleration and braking manoeuvres, whereas b should be optimal for curve driving. Set c combines both manoeuvre specific tunings.

TABLE 1 The first part of the cells show the overall tuning states of the three parameter sets with regard to curve driving and acceleration (++ tuned / - - not tuned for the respective manoeuvre, e. g. set a is tuned for braking but not tuned regarding curve driving manoeuvres). In the second part the varied parameter values are given. k – gain [ ]; ωHP – high pass filter frequency [rad/s]; ωLP – low pass filter frequency [rad/s]; $ß_{lim}$ – tilt rate limit [rad/s].

		manoeuvre		***parameter values***							
		curve driving	**braking**	**k_y**	**ωHP_y**	**ωLP_y**	**$ß_{lim,y}$**	**k_x**	**ωHP_x**	**ωLP_x**	**$ß_{lim,x}$**
parameter set	**a**	--	++	0.5	2.0	4.0	3	0.2	1.5	3.0	30
	b	++	--	0.3	2.0	1.0	30	0.5	2.0	4.0	3
	c	++	++	0.3	2.0	1.0	30	0.2	1.5	3.0	30

Furthermore, the varying parameter values are given in TABLE 1 (second part) and the effect of the different tuning conditions can be seen in FIGURE 2. The tuned parameters guarantee a rather smooth transition between the initial and the sustained cues. For the untuned state, there is instead a perceivable gap due to the late appearance of the tilt coordination effect. Additionally, the maximum introduced acceleration is reached between 2 and 4 seconds later than with the manoeuvre specific tuning. However, these positive tuning effects are at the expense of a very strong downscaling of the input acceleration.

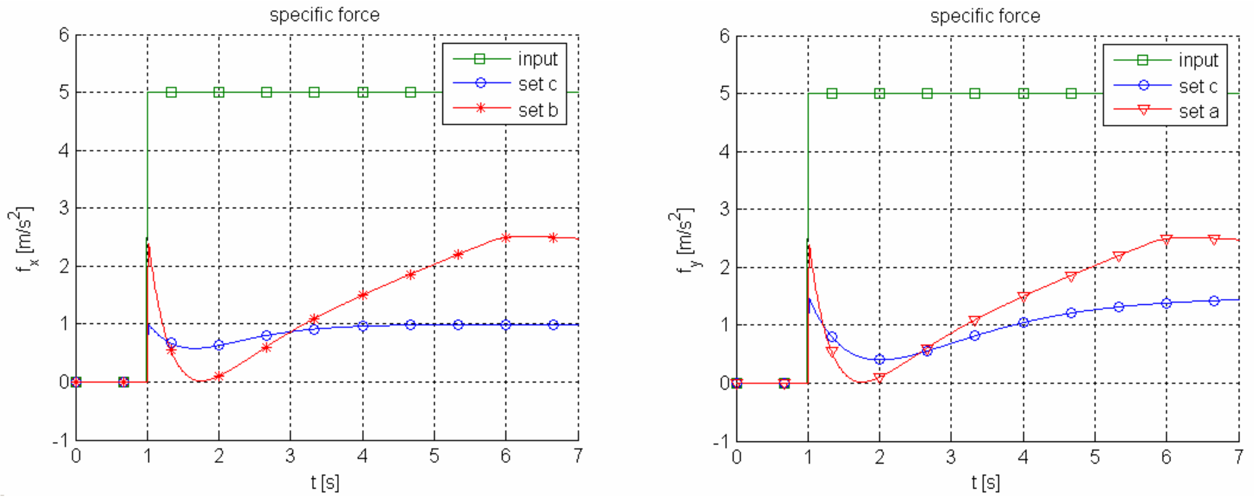

FIGURE 2 Specific force step responses. Set c vs. set b for longitudinal acceleration (left). Set c vs. set a for lateral acceleration (right).

To exclude an effect of the parameter set sequence, the sets were applied in varying order. Additionally, the order of the tracks *S2* and *S3* was changed, resulting in twelve different set-ups. In the experiment twelve subjects aged 25 to 50 years were included, with eight male and four female drivers. More details on the experimental set-up are given in (6).

Questionnaires

After every section, the drivers were asked to report any symptoms of simulator sickness and to assess the motion with regard to four different evaluation criteria:

- How realistic is the motion experience during driving?
- How accurately can the car be handled?
- How well do the movements match reality?
- How safe does the driver feel?

On a two-level assessment scale, the drivers first conduct a verbal categorization and then further differentiate between different levels within the selected category (TABLE 2). This procedure yields answers on a 15-point scale.

TABLE 2 Two-level assessment scale - Verbal categorisation and further differentiation (above). Corresponding 15-point scale (below).

very poor			**poor**			**okay**			**good**			**very good**		
-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Driving Data

For the analysis of the driving data vehicle speed, steering wheel angle and lateral position were examined. The average of speed shows how well the speed limits are followed and additionally the individual speed preferences of the driver. Its standard deviation reflects the accuracy of keeping a chosen speed. The standard deviation of the lateral position gives an indication about how well the driver can keep the lane. The number of steering wheel reversals was computed to describe the effort that the driver required to keep the lane. The latter is described and defined within the HASTE project report (7). In the performed analysis the accordant algorithms parameter (threshold: 0.01°; cut-off frequency: 10Hz; window size: 0.08s) were chosen to be a very fine measure for variations in steering movements. Due to different road section lengths the absolute number of this value would not be comparable. For this purpose the steering wheel reversal rate was calculated. These parameters are all common measures for the evaluation of simulator drives (8).

For the computation, each track was split into the four road section types “left curve”, “right curve”, “intersection” and “straight road”. Each street section was first analysed separately. As other traffic and surrounding conditions modify driving behaviour especially in real driving, data were averaged for different road types and speed ranges. Only those sections are analysed where sufficient data from each driver were present.

Analyses

The questionnaires as well as the driving data were analyzed with regard to two aspects: 1. It was examined whether different parameter sets are useful for different manoeuvres. 2. It was analysed for which parameter set the behaviour and subjective assessment is most similar to real driving. In order to evaluate the effects, within-subject analyses of variance and t-tests were used.

Results

Subjective Motion Assessment

On the first track *S1*, which corresponds to the real driving course, a comparison of different speed ranges was done for speeds below and above 50 kph. A significant effect for different parameter sets ($p = 0.04$) was only found with regard to the assessment of a safe feeling. However, descriptively the other questions showed a similar effect (cf. FIGURE 3). Parameter set b shows the lowest ratings (about “8” on the scale, which is corresponding to “ok”) and sets a and c are very similar (varying between “9” and “10”).

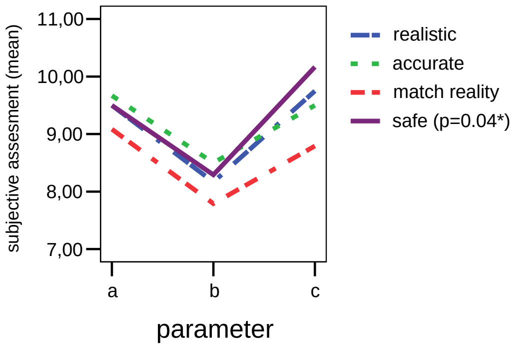

FIGURE 3 Means of the four subjective scales with the different parameter sets on track *S1*.

The second track *S2* concentrated on curve driving. No main effect of the parameter set was found. When different speed levels were examined, an effect could be detected only for the assessment of safety, showing that subjects felt less safe at high speeds. Finally, a tendency of an interaction (p = 0.06) was found for the subjective assessment of the handling accuracy. Like above, the ratings are better for lower speeds. This is especially true for parameter set a, which is rated better than b and c at low speeds (FIGURE 4). Overall, set b which was especially tuned for curves and set c which includes these settings are not better than set a. At low speeds set a is even better.

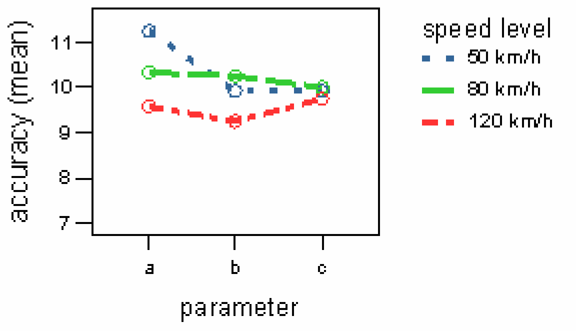

FIGURE 4 Mean ratings of the handling accuracy on track *S2* at different speed levels.

Third, the longitudinal control was examined by looking at test track *S3*. As very similar results were found for the different questions, only the results from the question “How realistic is the motion experience?” are shown. Here, a significant interaction of parameter set and speed level (p=0.01) was found which is shown in FIGURE 5. With parameter set b the impression is least realistic at all speed levels. However, the difference to parameter sets a and c increases at lower speeds. Overall, all parameter sets including b are rated as “ok” (corresponding to “7” on the scale). At low speeds of 50 kph a good impression is achieved (corresponding to “10”).

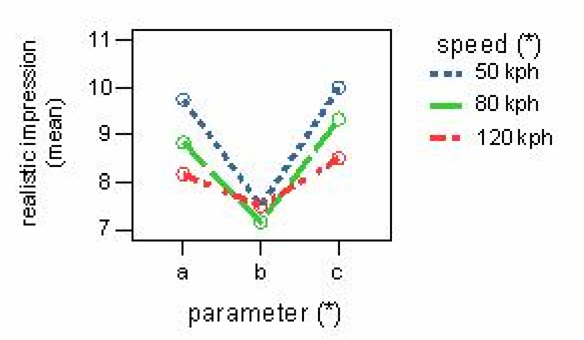

FIGURE 5 Means of the subjective rating of how realistic the motion experience was with regard to different parameter sets and speed limits on track *S3*.

Finally, there is a significant influence of the parameter set on the occurrence of simulator sickness (p=0.01). Parameter set b causes some symptoms of simulator sickness, set a causes hardly any symptoms and set c causes none.

Objective Driving Behaviour Analysis

First, real driving (track *R*) was compared to driving in the simulation (track *S1*) with different parameter sets. The analyses were done separately for straight sections and curves to the right or left. In all three sections, a comparable main effect was found in the average speed. FIGURE 6 shows this for straight sections. The average speed is significantly lower in real driving and faster in the simulation. However, the difference is not very large (on the average 3 to 5 kph).

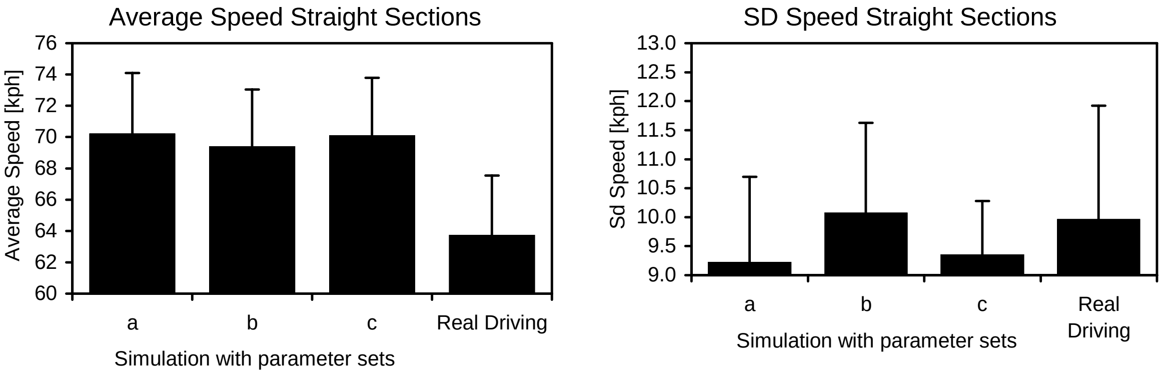

FIGURE 6 Average speed (left) and standard deviation of speed (right) in the straight sections of track *S1* in the simulation with the different parameter sets and in real driving. The figure gives means and standard deviations.

For the standard deviation of speed there is a tendency that parameter set b leads to larger variation of speed than either sets a (p = 0.079) or c (p = 0.088). However, none of the parameter sets differs significantly from real driving. With regard to the standard deviation of the lateral position, parameter sets b and c lead to a larger variation as compared to set a (p = 0.004 and p = 0.001, respectively). Again, none of the parameter sets differs significantly from real driving. Finally, as FIGURE 7 shows for straight sections, steering wheel reversal rate is substantially larger in real driving than in the simulator. Additionally, there is a tendency that parameter set b leads to a somewhat larger steering wheel reversal rate (p = 0.097).

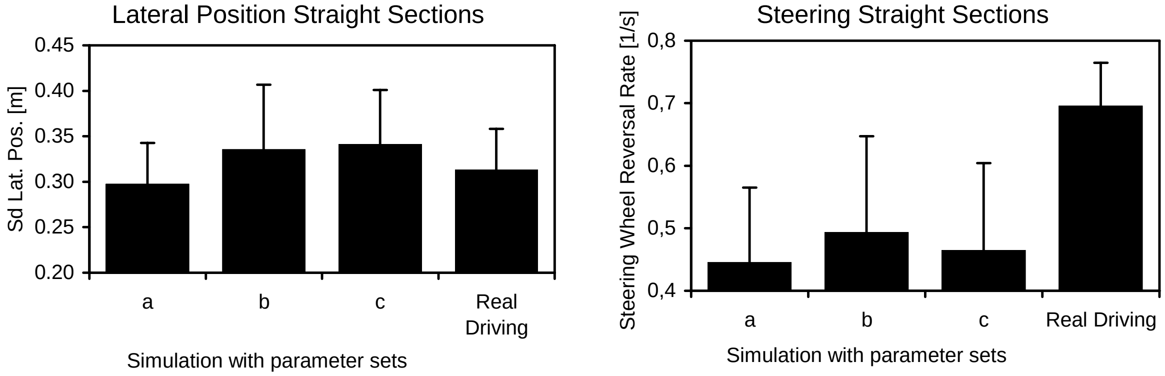

FIGURE 7 Standard deviation of the lateral position (left) and steering wheel reversal rate (right) in the straight sections of track *S1* in the simulation with the different parameter sets and in real driving. The figure gives means and standard deviations.

In a second step, longitudinal and lateral control were analysed separately at tracks *S2* and *S3*. As instructed, all subjects kept the speed limits very well on both tracks with a very small variation between the subjects. This was contrary to track *S1*, where it was requested to behave more naturally which caused larger differences between the individual speed choices.

On track *S2* subjects concentrated on curve driving. All analyses were done separately for straight sections and curves to the right and left. No differences between the three parameter sets were found for average speed and the standard deviation of speed. For the standard deviation of the lateral position and for steering wheel reversal rate on the curvy sections no significant effect was found, either. However, when looking at standard deviation of the lateral position at the straight sections a similar picture emerges as in the straight sections of track *S1* with slightly larger standard deviations with parameter sets c and b (FIGURE 8).

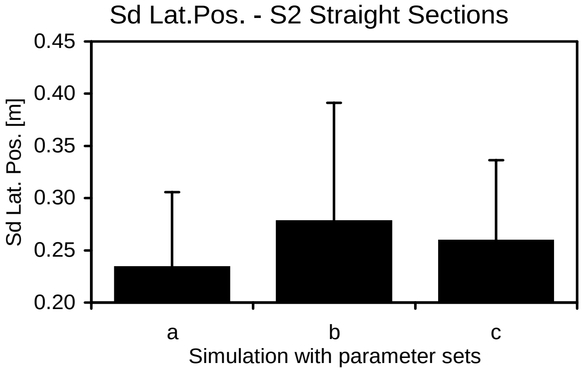

FIGURE 8 Standard deviation of the lateral position in the straight sections of track *S2* in the simulation with the different parameter sets. The figure gives means and standard deviations.

In track *S3* where subjects concentrated on accelerating and braking, the different parameter sets did not influence the average speed or the standard deviation of the lateral position. However, in the first section with different speed limits parameter set b lead to a significantly larger variation of speed than set a (p = 0.005) and set c (p = 0.033) (FIGURE 9). Additionally, set c differed somewhat from set a (p = 0.056). When comparing single braking manoeuvres in the second part of track *S3*, a tendency (p = 0.065) was found for steering wheel reversal rate with a somewhat larger rate with parameter set b.

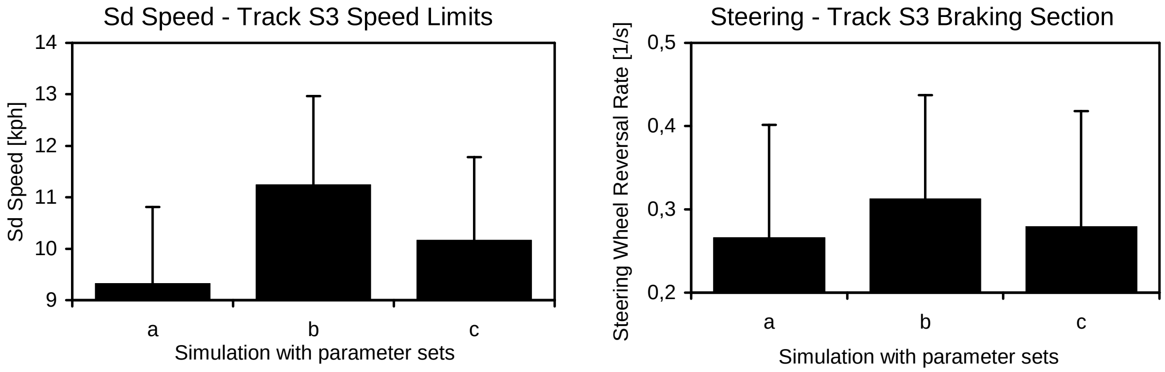

FIGURE 9 Standard deviation of average speed (left) on the first section and standard deviation of the lateral position (right) on the second section of track *S3* with the different parameter sets. The figure gives means and standard deviations.

Conclusions

Regarding the influence of the motion parameter variation, two aspects can be noticed.

1) Parameter set b received the least positive subjective ratings, induced the largest amount of simulator sickness and lead to larger variations in speed and in the lateral position and a higher rate of steering wheel reversals. This set b was just optimized for curve driving and not tuned for acceleration and braking. Thus, a tuning with regard to longitudinal control seems essential for a good evaluation and to avoid simulator sickness.

2) Parameter sets a and c were quite similarly with regard to the subjective assessment and the effect on driving behaviour. A very strong effect of the tuning with regard to lateral control could not be shown. In contrast, some findings even evaluated set a (not tuned for curve driving) better than set c. Here, further considerations of how to tune with regard to lateral control are clearly necessary.

Additionally, the analyses showed that the average speed plays an important role. When comparing real and simulator driving, subjects drive somewhat faster in the simulator which may be due to the larger difficulty to estimate speed in a virtual environment (cf. (9)). More important it was shown that the subjective difference between the parameter sets increases with lower speeds. This may be due to the fact that the performed manoeuvres cause stronger accelerations at lower speeds. This has to be considered for future improvements and examinations of motion tuning.

Overall, it was shown that the combination of subjective and objective parameters as well as the combination of real and virtual driving in the assessment of motion tuning is a promising approach to improve the impression created by moving-base simulators. It is encouraging that even relatively simple differences in motion parameters which were just tuned regarding two different basic manoeuvres were recognized by the drivers very clearly. The next step will be to concentrate on curve driving especially in the area of low speeds (e.g. at intersections) in order to further improve the motion cueing and to validate the simulator for more numerous and complex manoeuvres.

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References

(1) P. R. Grant and L. D. Reid, Motion Washout Filter Tuning: Rules and Requirements. Journal of Aircraft, Vol. 34, pp. 145 - 151 (1997).

(2) G. Reymond, A. Kemeny, J. Droulez, and A. Berthoz, Role of Lateral Acceleration in Curve Driving: Driver Model and Experiments on a Real Vehicle and a Driving Simulator. Human Factors, Vol. 43, pp. 483 – 495 (2001).

(3) M. Vollrath and J. Rataj, Virtual and Real Driving - Tools for the Design and Assessment of Driver Assistance. Proceedings of 5th European Congress and Exhibition on Intelligent Transport Systems and Services (CD-ROM), June (2005).

(4) M. Vollrath and C. Schießl, Advance Driver Assistance at Intersections - What Do Drivers Need and Want? Automation, Assistance and Embedded Real Time Platforms for Transportation, pp. 221-233 (2005).

(5) L. D. Reid and M. A. Nahon, Flight Simulation Motion-Base Drive Algorithms: Part 1 - Developing and Testing the Equations. UTIAS Report, No. 296 (1985).

(6) M. Brünger-Koch, Motion Parameter Tuning and Evaluation for the DLR Automotive Simulator. Proceedings of Driving Simulator Conference - North America (CD-ROM), November (2005).

(7) HASTE-Report from the University of Iowa, http://www.uiowa.edu/~neuroerg/HASTE.htm. Accessed Feb. 10, 2006.

(8) H. Jamson and S. Mouta, More bang for your buck? A cross-cost simulator evaluation study. Proceedings of Driving Simulator Conference - Europe (CD-ROM), September (2004).

(9) E. R. Boer, T. Yamamura, N. Kuge, and A. Girshick, Experiencing the same Road Twice: A Driver Centered Comparison between Simulation & Reality. Proceedings of Driving Simulator Conference (CD-ROM), September (2000).