EFFECT OF SIMULATOR MOTION SPACE ON REALISM IN THE DESDEMONA SIMULATOR

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Abstract

The goal of this study was to assess the effect of an increasing motion space on the fidelity of driving simulation in the Desdemona research simulator. The experimental task was a standardized slalom maneuver where the car velocity was limited to 70 km/h.

Subjective measures, which included eight statements on realism and task performance were used to assess simulation fidelity. The slalom task was driven in four conditions: 1) one-to-one motion space, 2) 0.7 times the motion space, 3) 0.4 times the motion space, and 4) no-motion. The conditions were compared pair-wise. In total 16 participants completed the experiment. Compared to the no-motion condition, driving a slalom maneuver in Desdemona was judged more realistic when motion cues were available, where the magnitude of the motion, within the range of 0.4 to 1, has less to no effect on the realism compared to the issue of motion versus no-motion. Furthermore, the participants indicated that motion and forces actuated by Desdemona helped to conduct their task better.

Introduction

The goal of this study was to assess the effect of an increasing motion space on the fidelity of driving simulation in the Desdemona simulator. Subjective variables, e.g. realism, and the objective driver performance were used as measures of simulation fidelity. The subjective measures are described in this paper. A standardized slalom maneuver is simulated while varying the simulator motion space across conditions, ranging from no-motion to one-to-one motion.

In flight simulation it has been shown that motion has a beneficial effect on pilot performance, especially in high-gain control tasks where the pilot has to stabilize the aircraft during (atmospheric) disturbances [Hosman 1996, Pool 2007]. In those conditions, the inertial motion perceived by the equilibrium system provides phase-lead over the motion information perceived by the visual system (i.e. the information is faster). In addition, the delay time in the vestibular pathway is shorter than the delay in the visual pathway. Already in the 1960's, McRuer showed that phase-lead from motion feedback improves control performance [McRuer et al., 1965, 1967, Weir & McRuer 1968]. Over the years, the motion cueing systems of full flight simulators were more or less optimized to render disturbance motion correctly in order to achieve comparable pilot behavior in the simulator.
Although it is generally assumed that visual feedback is the primary source of information when driving a car [Kemeny & Panerai, 2003], motion feedback will most probably help the driver to stabilize the car and to keep it on track. It is hypothesized that the role of motion in driving simulation is equivalent to that in flight simulation, and that the addition of motion in demanding, simulated driving tasks improves control performance and realism. Since driving simulators are far from standardized, the question that arises is: how much simulator motion and what type of motion platform and cueing logic is required to provide realistic motion feedback.

Among others, [Groen et al., 2001] found in their study that the simulator motion was perceived as too strong when in fact the motion was already scaled-down and filtered. Therefore, it is expected to find the best driver performance and the highest degree of realism in a scaled motion space condition, and the worst results in the no-motion condition.

The work described in this paper is carried out in the framework of the MOVES (MOtion cueing for VEhicle Simulators) Eureka project. One of the main purposes of the project is to evaluate and compare simulation fidelity of different driving simulators. Driving simulators involved are KUKA (Max Planck Institute), Ultimate (Renault), CarSim (DLR) and Desdemona (TNO, AMST). A comparable experiment on driver performance in a standard slalom maneuver was carried out on each of these simulators. In addition to the study described in this paper, an extended slalom driving experiment was performed. This addition addresses Advanced Driving Simulation that involved faster slalom maneuvers and higher accelerations and forces [Correia Grácio et al., 2009].

Method

Apparatus

The Desdemona simulator (Figure 1) was utilized for the slalom experiment. Desdemona is a moving-base research-simulator located at TNO (Soesterberg, The Netherlands) that was designed with a special focus on spatial disorientation demonstrations, flight simulation, and driving simulation. It was built in close co-operation with AMST (Ranshofen, Austria). The simulator has 6 Degrees of Freedom (DoF). The cabin is mounted in a gimbaled system (3 DoF, $>2\pi$ 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 as a whole rotate around a central axis to facilitate centrifugal motion (1 DoF, <3G). For the experiment, the Desdemona cabin was equipped with a generic car cockpit. The cockpit contains force-feedback on steering wheel, and on gas and brake pedals. Direct drive electrical motors generate the control loading for the steering wheel and pedals. The out-the-window visuals have a width of 120x40 degrees visual angle.

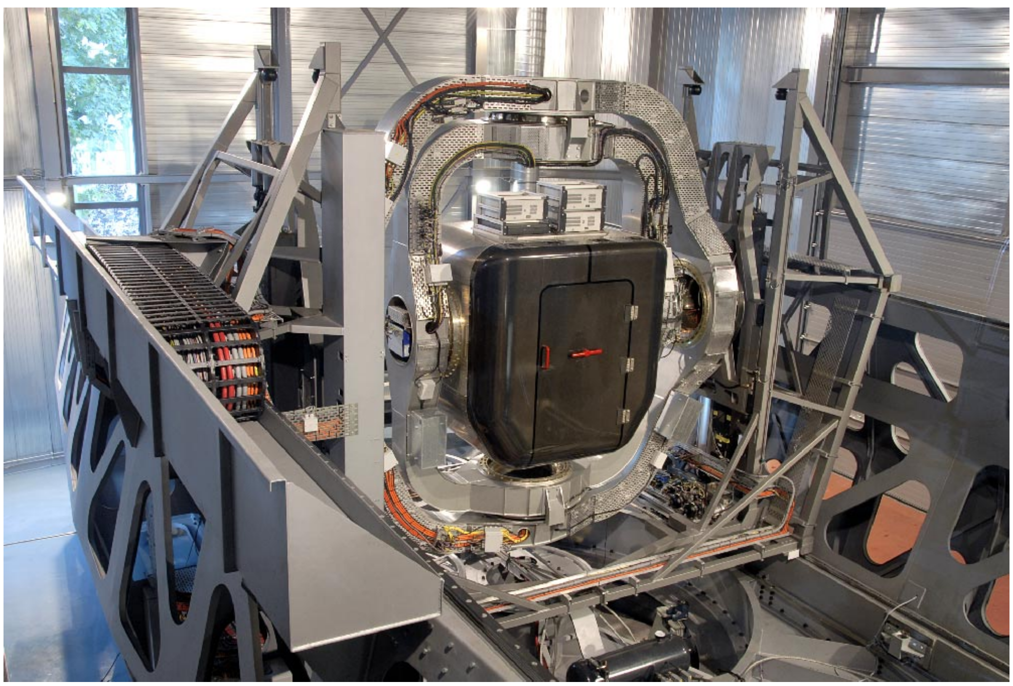

Figure 1 The Desdemona Research simulator

The vehicle dynamics were calculated by a Carsim vehicle model (Ann Arbor, MI, USA) and were comparable with the dynamics of a Volkswagen Passat with automatic gear shift. In the experiment, the velocity was limited to 70 km/h. The vehicle model ran in a Matlab-Simulink thread using shared memory [Hogema et al., 2004].

The motion cueing filter ran in a separate Matlab-Simulink thread as well. Figure 2 shows the global structure of the applied filter. The lateral position – and thereby the lateral acceleration – of the vehicle was cued by the 8 m linear arm. The width of the road is 6m, which enables the possibility to cue one-to-one. Pilot tests showed that participants were able to drive the slalom trail with the maximum velocity of 70 km/h. Therefore, the longitudinal force was not cued. The roll and pitch vehicle motions were cued directly by the corresponding Desdemona gimbals. The paths only contain a scaling gain and a limiter block. The car heading was cued by two degrees of freedom, i.e., the high frequencies were cued by the cabin yaw and the remaining low frequencies were cued by the central yaw. The lateral cues by the linear arm remain in the proper direction when only high frequencies are actuated by the cabin yaw. The high and low pass filters were complementary, i.e., the output of the two filters add up to 1 such that the total heading is also cued directly. Finally, a velocity depending road rumble and a stimulus when hitting a pylon were applied by the heave axis. Note that the filter does not contain tilt coordination. A previous experiment on curve driving [Wentink et al., 2008] suggested that false cues were receiving more attention than correct cues. Tilt coordination or rather the washout associated with tilt coordination is an example of a false cue, which could disturb the judgment of a condition.

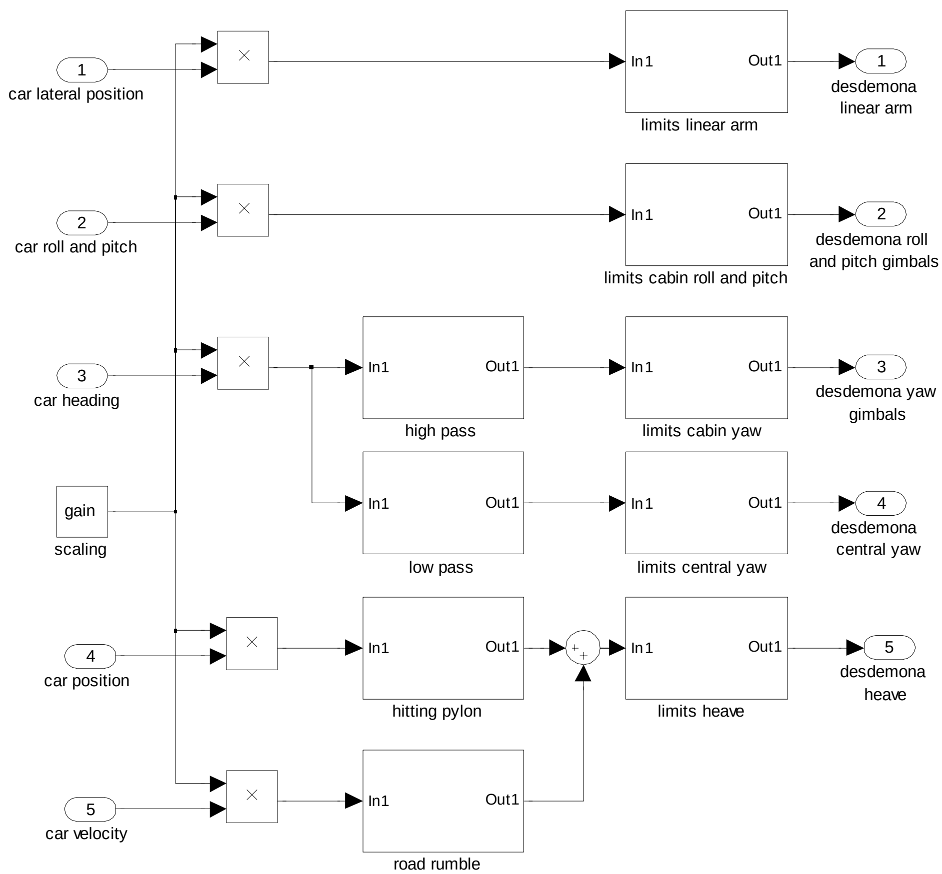

Figure 2 Global structure of the applied motion cueing filter

Scenario and conditions

The experiment took place at a two-lane rural road (Figure 3). The lane width was (3 m). Guardrails were placed at both sides of the road. During the experiment, the participants had to drive multiple times the slalom trail that was indicated by the pylons. The pylons were alternately placed at 0.5 m to the right and left of the road centerline. Within each trail, the distance between the first nine pylons was 62.5 m and the distance between the last three pylons was 50 m. The change of the spatial frequency in a slalom prevents that the driver can drive the whole slalom with the same cadence.

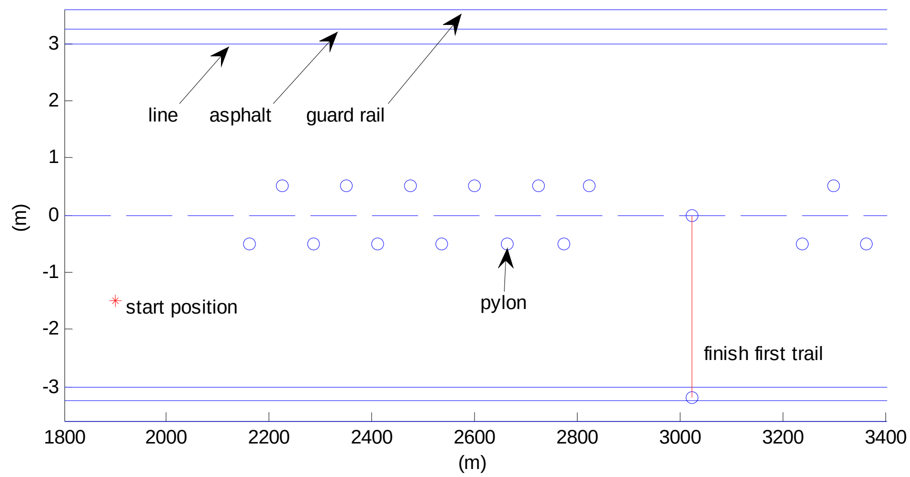

Figure 3 The road geometry (the axes are not scaled)

In total four gain settings (conditions) of the motion cueing filter (Figure 2) were compared. The gains were 0 for no-motion and 0.4, 0.7 and 1 for motion. In terms of lateral displacement, the motion space used was 0, <2.8, <4.2 and <6 m, respectively. Twelve different pairs can be composed out of four conditions. These 12 pairs were assigned to two sets such that per set all gains were compared (but not in all orders). One group of participants tested set 1 and the second group of participants tested set 2. In one run, one pair was driven, i.e., one gain setting for the first trail and another gain setting for the second trail. Each participant compared six pairs in six runs in a randomized order.

Participants, procedures and data registration

Sixteen participants (4 female and 12 male) completed the experiment. Two participants did not finish the experiment due to motion sickness. They were all TNO employees and not professional drivers. The average age was 36 (s.d. – standard deviation – 10) years, the average mileage per year was 14281 (s.d. 9252) km and the average driving simulator experience was 28 (s.d. 65) hours.

After arrival, the participant was briefed about the experiment. The goal was to complete a run in the lowest possible time. That was, to drive as fast as possible (maximum was 70 km/h), without damaging the car. It was allowed to reduce the velocity when he/she expected to loose the control of the car. For example, when the car was going to leave the road or when they were hitting pylons. The experimenter answered questions that the participant might have. Subsequently, the participant signed an informed consent (stating that he/she was in good health, had understood the instructions and participated voluntarily).
To get used to the simulator and the car dynamics, the experiment started with a practice slalom run (gain 0.5 with a rather similar filter). Next the real runs started. A pylon at the right side of the road indicated the finish of a trail (Figure 3).

Both objective and subjective data was collected during the experiment. The objective data included the position, velocities, accelerations and the control inputs of the car. This paper does not include the results of the objective data. The subjective data were collected by means of a questionnaire. After each trail, a questionnaire with 8 statements and a misery-score was filled-out. Regarding the statements, so-called *constructs* have been used [Field, 2005]. Variables that cannot be measured directly like realism are called constructs. Firstly one has to determine which observable 'variables' can be measured that represent the construct. Therefore, different statements have been used that have an association with one construct, for example realism. The validation of the constructs is not covered in this paper. The participants had to agree or disagree with the statements using a 7-point Likert scale (Figure 4). The misery score is a 6-point scale, ranging from 'feeling OK, no symptoms' to 'vomiting'. After each pair, the participant did a pair-wise comparison, that is, the participant indicated which of the two trails was the most realistic. Finally, at the end of the total run the participant could give general comments.

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

Figure 4 The 7-point Likert scale to judge the statements

Results

Pair-wise comparison

After each pair, the participant was asked to indicate which of the two trails he found the most realistic. Figure 5 shows the result for the four gain settings. The value at the vertical axis indicates the number of times the particular gain setting was preferred. The sum of all preferences is 96, which corresponds to 16 participants times 6 pairs.

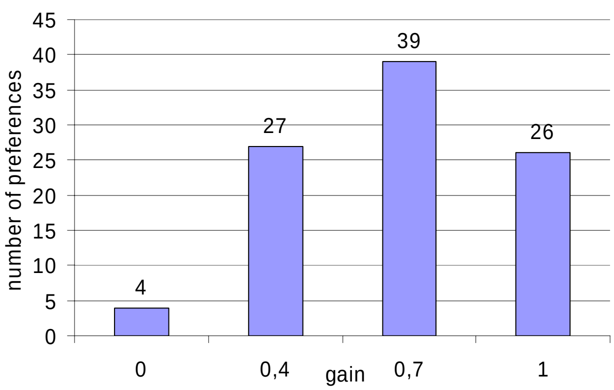

Figure 5 Result of a pair-wise comparison on realism between 4 different gain settings

A significant effect was found by comparing all four gains in one Chi-square test ($\chi^2 = 26.58$, $df = 3$, $p < 0.01$). This implies that a difference was found in realism between the different gain settings. In order to differentiate between the gain settings, 6 separate (6 combinations) Chi-square tests were done. Consequently the significance level reduces according to the Bonferroni correction, i.e. there is a difference between two setting when $p < 0.05/6 = p < 0.008$. Table 1 shows the results. It can be concluded that the gain setting 0 (no-motion) differs with the other 3 gains setting. The remaining gain settings are not found to be different.

Table 1 Pair-wise comparison on realism between the 4 gain settings (= p<0.01)**

Compared gains	χ^2	*df*	*p*	significance
0 and 0.4	17.06	1	0.000036	**
0 and 0.7	28.49	1	0.000000	**
0 and 1	16.13	1	0.000059	**
0.4 and 0.7	2.18	1	0.139650	-
0.4 and 1	0.02	1	0.890746	-
0.7 and 1	2.60	1	0.106865	-

Statements

After each trail, a questionnaire with 8 statements was filled-out. Each participant rated the 4 gain settings 3 times (6 pairs/4 gains = 12 trails/4 gains). The 4 gain settings, 8 statements and 4 repetitions where tested in a repeated measures ANOVA. No effect for the repetitions was found for the statements; therefore the influence of the repetition was left out of the analysis. Figure 6 shows the mean scores for the statement for each gain setting. A post-hoc Tukey HSD test showed a significant effect between gain 0 and the other gains for the statements. This implies that slalom driving with motion was experienced as more realistic and helped the participants by conducting their task better as compared to the no-motion condition. In this experiment, no statistical significant differences in realism and conducting the task were found between the gain settings 0.4, 0.7 and 1, except for the utmost right statement in Figure 6. A significant effect ($p<0.05$) was found between gain 0.4 and gain 0.7. The forces for gain-setting 0.7 were found to be more realistic compared to gain setting 0.4. A trend or a marginal effect ($p<0.1$) was found for the statement that 'motion and forces helped conducting the task' between gain setting 0.4 and 0.7.

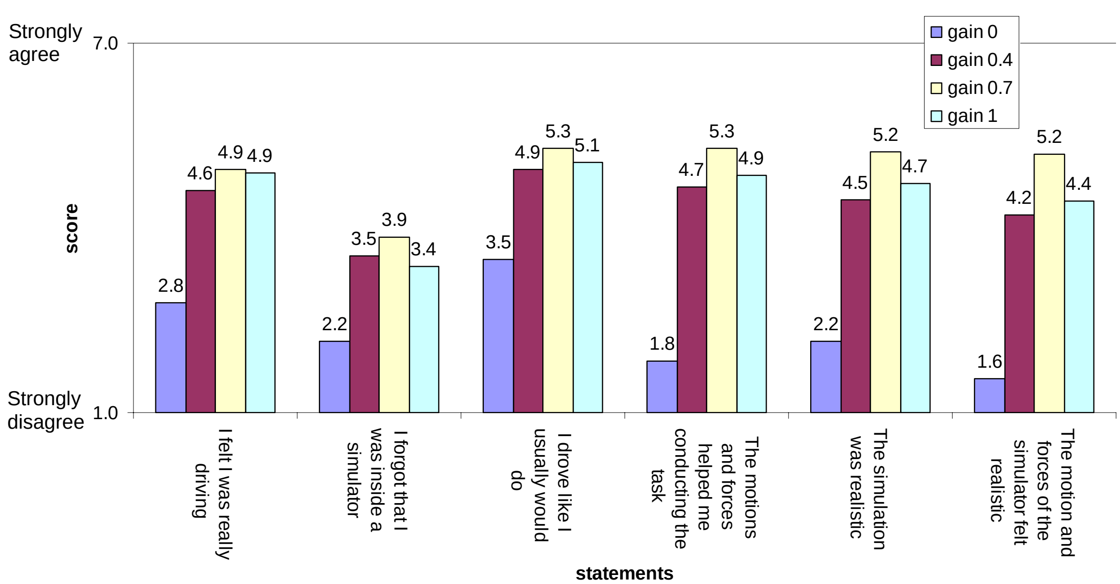

Figure 6 The mean scores for 6 statements

The overall result is in line with the pair-wise comparison. Although, for both the pair-wise comparison (Figure 5) and the statements (Figure 6), a visual inspection indicates a slight preference for a gain setting of 0.7.

Misery Score

After each trail, the participant indicated the MISC (misery score). The mean MISC was 1.35 (for the 16 participants that completed all runs). The mean value was between 'feeling OK, no symptoms' and 'initial symptoms, such as stomach awareness, but no nausea'.
The MISC was analyzed with an ANOVA and a post-hoc Tukey test. The sequence of gain settings were randomized among the participants and the time-constant of misery is relatively low compared to the duration of a trail. Therefore, no effect was found for the Misery Score as a function of the gain settings.
For the repetition, a significant effect ($p<0.01$) for the MISC was found between repetition 2 and 3 (for all conditions together). Hence, during the experiment the MISC changed from 1 (feeling OK) to 2 (initial symptoms).

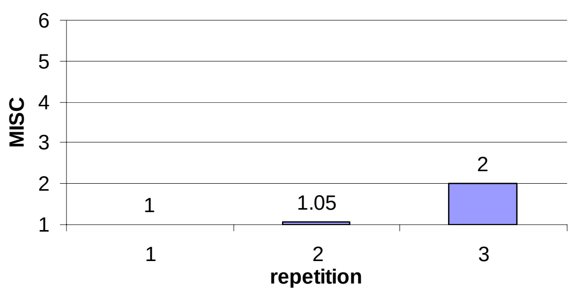

Figure 7 The (misery score) MISC as a function of the repetition

Discussion

The participants had rather limited to no experience with real slalom driving. However, one can assume that they have driven similar kind of maneuvers, such as sudden lane changes and driving a roundabout with a relative high velocity. Comparable lateral forces and roll rates are present in these maneuvers. This indicates that the participants were able to differentiate between the conditions.
Compared to the no-motion condition, the analysis showed that driving a slalom trail has been judged more realistic when motion cues were available. The pair-wise comparison and the statements showed this. It also appeared that the magnitude of this motion, within the range of 0.4 to 1, is less important compared to issue of motion versus no-motion. Only for one statement a distinction between motion gain 0.4 and 0.7 was found, where a motion gain of 0.7 was found to be more realistic. As mentioned earlier, the cueing filter did not provide false cues due to washout effects associated with tilt coordination. In a previous experiment concerning curve driving [Wentink et al., 2008], the participants criticized false cues, which influenced the judgment between no-motion and motion. The participants did not mention false cues in the present experiment. Consequently, absence of washout is likely to be a reason for the clear distinction between the motion and no-motion conditions.
The experiment described in this paper applied a road rumble that was scaled with the gain setting. This implies no road rumble for the gain 0 condition and maximal road rumble in the

one-to-one motion condition. The effect of road rumble is important for driving immersion. Therefore, the absence of road rumble in no-motion condition has influenced the results.
It was found that the motion and forces actuated by Desdemona helped the participants to conduct their task better. This is a first result regarding the effect of motion on driver performance. Motion feedback will most probably help the driver to stabilize the car and to keep it on track. It is hypothesized that the role of motion in driving simulation is equivalent to that in flight simulation, and that the addition of motion in demanding, simulated driving tasks improves control performance. In ongoing work, we will verify this hypothesis by analyzing the objective data.
Finally, no effect has been found for the Misery Score as a function of the gain settings because the 'time-constant of misery' is relatively low compared to the duration of a trail. Only a slight increase of the Misery Score over time was found.

Conclusions

The present study showed the following results:

1) Compared to the no-motion condition, driving a slalom trail in Desdemona has been judged more realistic when motion cues were available, where the magnitude of the motion, within the range of 0.4 to 1, has less effect on the realism compared to issue of motion versus no-motion.
2) The participants indicated that motion and forces actuated by Desdemona helped to conduct their task better. An analysis of the objective data will be performed to strengthen this conclusion.

Acknowledgements

This work was conducted in the framework of the MOVES (Motion cueing for Vehicle Simulators) Eureka #3601 European research project, which aims at increasing the scientific knowledge on the human multi-sensory perception of motion in virtual environments, and to explicitly define the possibilities and limitations of several high-end European driving simulators. The MOVES consortium is composed of LPPA/CNRS, Renault, TNO Human Factors, MPI-Biological Cybernetics, AMST, and collaborates with DLR and SIMTEC. The standard slalom manoeuvre described here was designed in agreement with this consortium.

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