THE INFLUENCE OF LATERAL TILT/TRANSLATION, ROLL AND YAW SCALE FACTORS ON DRIVING PERFORMANCES ON AN ADVANCED DYNAMIC SIMULATOR

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Abstract – The present study investigates the importance of lateral acceleration, roll angle and yaw acceleration as scale factors (motion gains) on these components, in the driving perception and behavior in curve. Recent study advises to use down scale-factors (0.4-0.75) on the three car lateral motions felt in curve. In the current study, we used the same slalom task, and increased the range of lateral acceleration produced by the slalom, as the scale factors. The principal result is that the lateral motion gain has to decrease with the increase of lateral acceleration, in order to improve the perception and the driving performance. Concerning the roll motion gain, we advise to use it with a unit gain whether the quantity of lateral acceleration. However, the important of yaw motion is more controversial, it only seems to facilitate the driving control, at less in this slalom task.

Key words: Lateral acceleration, scale factors, multisensory perception, driving performance, tilt-coordination.

1. Introduction

On dynamic driving simulators, the motion perception is produced by stimulating the vestibular and somatosensory systems in addition to the visual system [Kem1]. However, the intricacy of the multisensory stimulations undergone when driving a car makes the optimization of the motion based simulators quite complex. For instance, it has already been proven that the motion on driving simulator is overestimated when simulated at 1-to-1 rate [Gro2], [Str3], [Str4] and that the inertial magnitude (gain) and the way (distribution between tilt and translation) to reproduce a positive or negative acceleration e.g. take-off or braking, is highly dependent on the level of the simulated acceleration [Ber5], [Str4].

For turning manoeuvers, the control of the simulator appears to be even more complex than for longitudinal manoeuvers because, in addition to lateral acceleration, yaw and roll motions of the car have to be simulated. The main source of information on which the driver bases his manoeuvers is the lateral acceleration. Indeed, the driver controls his speed or trajectory to keep this acceleration in a comfortable range and to insure a safety margin [Fel6], [Rey7]. In most dynamic driving simulators, simulation of the lateral acceleration is produced by using tilt coordination technique (lateral translation and roll tilt). However, in natural driving and for simulation, rotational components i.e., roll and yaw movements, are also associated to steering behavior of the car during cornering. This very last component, that is yaw motion, seems to be an influent component for realistic driving simulations. Indeed, recent studies [Dam8], [Hog9] have confirmed that a yaw component associated to the other lateral acceleration components (translations and/or roll) leads to better driving performances and improve motion perception, than when it is absent. In addition, Berthoz et al. (2013)

[Ber10] proposed that motion scale factors (for lateral and rotational acceleration) have to be comprised within the range 0.4-0.75. One limitation of this study is that the gain of linear translations, roll movements and yaw movements and their relationships were not systematically varied for different levels of acceleration.

To go further, the present study, conducted on the dynamic driving simulator Sherpa² by PSA, is focused on cornering manoeuvers. It aims at systematically revisiting the gains of the three lateral motion components (lateral, yaw and roll movements) for several levels of lateral accelerations. In order to evaluate the individual effects of the three parameters on the driving behavior, we chose a slalom driving task.

Through subjective and objective analyses, we seek to identify and quantify the major sources of movements for perception and driving performance in cornering and to identify the best set of parameters according to the level of acceleration to simulate. A precise cartography of the settings of the dynamic driving simulators will make it more realistic in a wider range of lateral accelerations. We make the hypothesis that the motion gains on the different parameters are not necessarily linked [Cor11], [Dag12], and could be different depending on the level of lateral acceleration to be simulated.

2. Methods

2.1. Participants

27 volunteers (2 women and 25 men), aged between 22 and 49 (mean age: 28) participated in the study. All were PSA's employees who volunteered for the study, and none had significant experience of the simulator (average dynamic driving simulator experience less than 1.5 hours).

2.2. Experimental devices

SHERPA² is a dynamic driving simulator equipped with a hexapod and an X-Y platform (10 x 5 m). The cell placed on the hexapod contains a half-cab Citroen C1 fully-equipped (2 front adjustable seats, seat belts, steering wheel, pedals, gearbox, rearview mirror and side-view mirrors) where the driver is sitting. The motion limits of the hexapod are ±30 cm, ±26.5 cm and ±20 cm, on X, Y and Z respectively [Cha13]. The rotational movements are limited to ±18 deg, ±18 deg and ±23 degrees, on pitch, roll and yaw respectively. The X-Y motion platform can reproduce linear movements of 10 and 5 meters. The maximum longitudinal and lateral acceleration is 5 m/s², and is actually produced by combination of tilt and translation (termed "lateral motion" in this paper).

2.3. Experimental Scenario

The vehicle dynamics model (car dynamic and audio) tuned for the present experiment was a Peugeot 208 1.4 HDi. The visual scene consisted in a straight two-lane road (road width: 8m). Guardrails were placed at both sides of the road to delimit the allowed maximum excursion of the car. The slalom driving scenario consisted of a series of 8 pylons separated by a constant distance (for a given condition). In addition, multiples mini-cones were used to represent the optimal sinusoidal pathway (Figure 1). The pylons were alternately placed 0.9 m to the right and left side of the road centerline. Sinusoidal magnitude was always 2m, the sinusoidal pathway was forming by two mini-cones path of 2m of width. The velocity of the car was regulated to 70 km/h. By adjusting the distance separating two pylons, we imposed the theoretical lateral acceleration, while keeping constant the longitudinal velocity of the car, the lateral pylons placements as well as the magnitude of sinusoidal pathway. Hence, we designed three different slaloms scenario leading to 3 theoretical lateral accelerations i.e., 1, 2 and 4m/s², corresponding to a pylons spacing of 86.39, 61.09 and 43.19 meters respectively. The equation enabling to compute theoretical lateral acceleration was borrowed from Grácio et al. (2011) [Grá14].

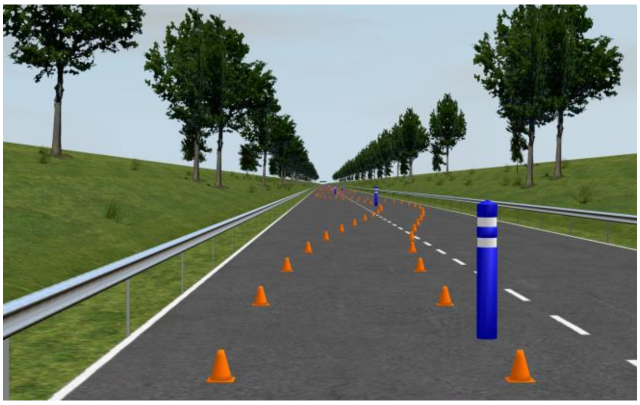

Figure 1. Visual environment of slalom task.

2.4. Task

Drivers were asked to perform a slalom course on the dynamic driving simulator in following the mini cones path, without touching any pylons or going out of the road (no damage on the car). The run was realized in cruise control at the constant speed of 70 Km/h. Nonetheless, to activate the cruise control, participant had to accelerate himself to 30 Km/h.

2.5. Experimental Design

For each level of lateral acceleration (1, 2 and 4 m/s²), we manipulated the scale factors (0 0.2 0.4 0.5 0.6 0.8 1 depending on the slalom scenario) of the 3 motion components (lateral tilt-translation; yaw and roll movements) leading to a total of 25 different conditions (Table 1). Each participant realized 3 trials per conditions for a total of 75 trials divided into two sessions to avoid fatigue effect. The overall trials were organized by using a central composite experiment design [Tin15]. The choices of scale factors (or motion gains) were made by taking into account the physical limitations of the simulator (position, speed, linear and angular acceleration). During the first session, realized the morning, participants first started with a simulator familiarization phase (10min of rural drive in dynamic simulator) and a learning slalom phase (one trial for each slaloms without motion). This first session was continued with twenty-five trials of a same slalom (same level of acceleration). The second session, performed the afternoon (of the same day), included another learning slalom phase along with the 50 resting trials. The order of slalom was balanced over the total panel of participants. The orders of stimuli were presented using William's Latin Square, which allowed balancing the order and report effects. The use of a central composite experiment design enable to obtain a maximum information in a minimum experience, and to build a model estimating nonlinear effects. Furthermore, at the end of each trial, the participants answered a couple of questions to provide us with information about their subjective perception of the realism of the vehicle behavior and the facility of the task (Table 2). In addition, their motion sickness level was monitored throughout the experimentation by using a motion sickness questionnaire (MSSQ) [Cor11].

Table 1. The 25 motions conditions for each specific slalom. The motions conditions varied according to different gains (scale factors) applied to the three simulator motion components. Slalom 1, 2 & 3 respectively correspond to 1, 2 and 4m/s² slalom levels. The condition number 20 corresponds to the actual Sherpa² configuration.

	Gain Lateral motion acceleration			Gain Roll angle	Gain Yaw acceleration
Slalom	**1**	**2**	**3**	**1, 2 & 3**	**1, 2 & 3**
Condition					
1	0.2	0.2	0.2	0.2	0.2
2	0.8	0.8	0.6	0.2	0.2
3	0.2	0.2	0.2	0.8	0.8
4	0.8	0.8	0.6	0.8	0.8
5	0.2	0.2	0.2	0.2	0.2
6	0.8	0.8	0.6	0.2	0.8
7	0.2	0.2	0.2	0.8	0.8
8	0.8	0.8	0.6	0.8	0.8
9	0	0	0	0.5	0.5
10	1	1	0.8	0.5	0.5
11	0.5	0.5	0.4	0	0.5
12	0.5	0.5	0.4	1	0.5
13	0.5	0.5	0.4	0.5	0
14	0.5	0.5	0.4	0.5	1
15	0.5	0.5	0.4	0.5	0.5
16	0.5	0.5	0.4	0.5	0.5
17	0.5	0.5	0.4	0.5	0.5
18	0.5	0.5	0.4	0.5	0.5
19	0.5	0.5	0.4	0.5	0.5
20	-1	-1	-1	-1	-1
21	0	0	0	0	0
22	1	1	0.8	1	1
23	1	1	0.8	0	0
24	0	0	0	1	0
25	0	0	0	0	1

2.6. Data analysis

During the driving task, some vehicle and simulator dynamics variables e.g. lateral acceleration, steering wheel angle, lateral position were recorded. All these measurements were used to conduct an objective analysis of the driver's behavior. From the steering wheel angle, we can compute the steering wheel reversal rate. The steering wheel reversal rate (SWRR) is a performance indicator that quantifies the amount of steering corrections, and enables to determine the effort required to accomplish a certain task [Fee16]. This metric measures the frequency of steering wheel reversals larger than a finite angle, or *gap*. The magnitude of this gap, the *gap size*, is thus a key parameter for this metric [Öst17]. In the present study, the number of reversals per slalom course was counted. To this end, the steering signal was filtered with a second-order low-pass Butterworth filter with a cutoff frequency depending on the slalom level i.e., 0.6, 2 and 5 Hz for the 1, 2 and 4m/s² slalom levels respectively. The algorithm for detection of reversal was extracted from the "Reversal Rate 2" in the Östlund's study (2005), and a difference greater than or equal to 2° (*gap size*) indicates one reversal.

The driving accuracy was quantified as lateral deviation from the reference trajectory (center of mini cones path) and computed as Root Mean Squared Error (RMSE) of the vehicle path [Pre18].

The subjective and objective data were analyzed with the software NEMRODW, which enables to construct experimental plans, and the analysis of experimental results. A principal component analysis (PCA) was realized for all kind of variables (subjective and objective) in order to determine if there was a consensus among subjects. PCA were realized with the software SPAD 7.

Table 2. Two 11 points qualitative scale.

Not Realistic 0	1…9	Very Realistic 10

1-Assessing the quality of realism of vehicle behavior

Not Easy 0	1…9	Very Easy 10

2-Evaluate the facility of achieving slalom

3. Results

3.1. Subjective analysis

3.1.1. Motion Sickness

During the experiment, four subjects felt motion sick and were not able to finish all experimental conditions (MISC ≥6). Three of these participants felt motion sick during the higher slalom level and following to higher lateral acceleration gains (condition 10, 22 or 23 in Table 1). The remaining twenty-three subjects were able to conduct the experiment without serious motion sickness (average MISC = 0.78 ± 1.2).

3.1.2. Realism of Vehicle Behavior

Following to PCA, no consensus among participants was found, so we centered the data, and realized a hierarchical clustering to identify homogeneous groups of subjects: 2 groups were identified. We analyzed the experimental results for the two groups separately. The analysis of model coefficient enabled us to determine the optimal motion configuration. The coefficient are named as follow: "B0" is the model's constant, "B1" is the linear coefficient applied to lateral motion gain, "B2" is the linear coefficient applied to roll gain, "B1-1" is the square coefficient of lateral motion gain.

For the first slalom level (1m/s²), and for the two groups, the lateral motion was a significant factor for both groups, and roll motion was a significant factor for the second group. The model coefficients are presented in the Table 3 for the 2 groups.

Table 3. Model's coefficient and significance for both groups G1 and G2, concerning the realism of vehicle behavior for the first slalom.

Name	G1 Coeff	Sign	G2 Coeff	Sign
B0	7.756	<0.01***	6.889	<0.01***
B1	-0.374	0.518***	1.174	<0.01***
B2	-0.081	48.5	0.405	2.13*
B1-1	-1.227	<0.01***	-4.5	0.05***

According to G1 answers, the experimental model asses as more realistic a motion configuration with: lateral motion gain = 0.5, roll motion gain = 1, and yaw motion gain = 0.

According to G2 answers, the best set of parameters concerning the realism is: lateral motion gain = 0.85, roll motion gain = 1, and yaw motion gain = 0. The Fig. 2 shows a 2D representation of experimental model of Lateral and Roll motion gains for the realism of vehicle behavior in the first slalom and according to G2. In this figure, the yaw motion gain is fixed to 0, because it do not significantly influences the results, but a best result is obtained if it equal 0.

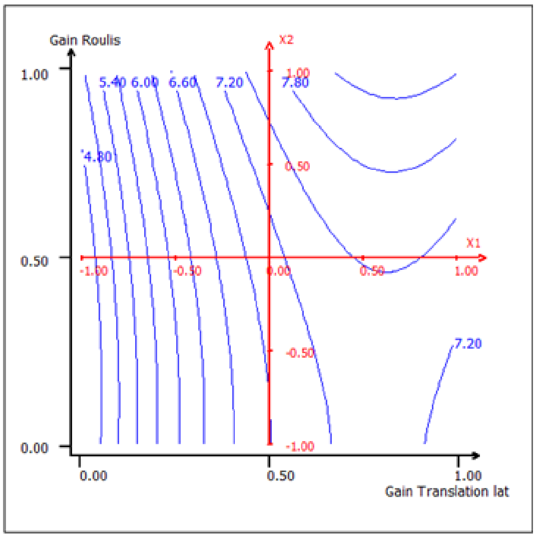

Fig. 2. 2D representation of experimental model for the realism of vehicle behavior, for the 1st slalom and 2nd group.

For the second slalom, the only significant factor was the lateral motion (p<0.01), for both group. In the third slalom, and G1, the significant factors were: the lateral motion

($p<0.01$), as the roll and yaw motion, the lateral motion-yaw motion interaction and the roll-yaw motion interaction.

The Fig. 3 presents the most realistic lateral motion gains, according to the two groups. The lateral motion gains are digressive for both groups. Note that, yaw motion = 0 was still computed by the model as giving best results for both groups and all slaloms, but was only a significant factor for G1 in the third slalom. For both groups, a roll motion gain of 1 always gives a best result in all slaloms.

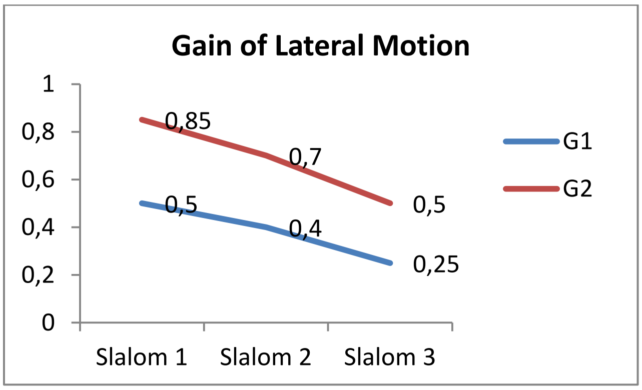

Fig. 3. Best Lateral motion gains according to the two groups and the three slaloms.

3.1.3. Facility of Achieving Slalom

In the first slalom, for judging the facility of achieving slalom, no difference was found between all configurations. The first slalom was certainly too easy to realized, and so drivers had not need to external help to realized the task, and inversely, did not feel perturbed by motions.

In the second and the third slalom, a consensus was found between the participants, so one groups was used to compute the experimental model. The only significant factor was the lateral motion ($p<0.01$), for the second and the third slalom. The best motions gains are presented in the Table 4.

Table 4. Best motion gains to the second and the third slalom, concerning the facility of achieving slalom.

	Gain Lateral Motion	Gain Roll	Gain Yaw
Slalom 2	0.2	0.3	0
Slalom 3	0	1	1

Contrary to the first slalom, participants found the second and the third slalom less easy, notably with lateral motion gain superior to 0.2 in the second slalom and superior to 0 in the third.

3.2. Objective Analysis

3.2.1. Steering-Wheel Reversal Rate

The PCA revealed a consensus among the participants, for all slalom levels. Hence, the 23 participants were analyzed together, for the three experimental models. The significant factor was the lateral motion gain for all slalom level.

For the first slalom level, the results show that number of reversals decreases with an increase in lateral motion gain, and so that more steering correction was required for a reduced lateral motion gain (Figure. 4)

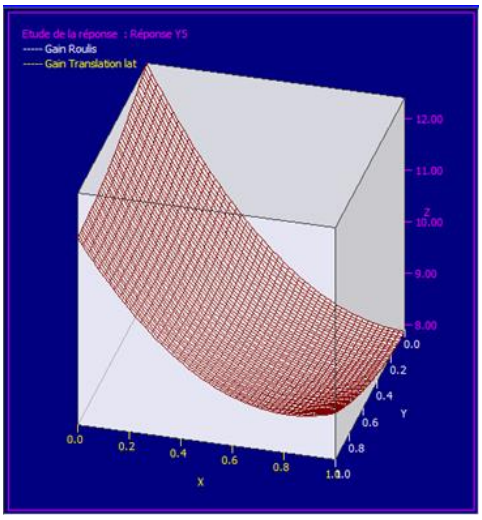

Figure. 4. 3D representation of response surface for the SWRR variable and for the first slalom.

The Figure. 4 shows that the roll motion gain is not very important, however, best result was obtained for a roll motion gain of 0.

Contrary to the first slalom, in the second and in the third, a best model is obtained with a roll motion gain of 1. However, as for the Realism variable, the best lateral motion gain decrease with the increase of lateral acceleration. The yaw motion effect, although not being significant for the model, give a better result with a motion gain of 1 (Table 5).

Table 5. Best motion gains to the SWRR variable and for the three slaloms.

	Gain Lateral Motion	Gain Roll	Gain Yaw
Slalom 1	1	0	0
Slalom 2	0.5	1	1
Slalom 3	0.25	1	1

3.2.2. Path Root Mean Square Error

As for the previous variable, one group was kept for the model construction. No difference was found between the motion configurations for the first and the second slalom. Maybe the mini cones path was very helpful to accurate drive. Nonetheless, differences were found in the third slalom (4m/s²). The significant factor was again the lateral motion gain.

The experimental model found two configuration settings, giving the same performance (Table 6).

Table 6. Best motion gains to the RMSE variable for the third slalom.

Slalom 3	Gain Lateral Motion	Gain Roll	Gain Yaw
1st configuration	0.25	1	0
2nd configuration	0.35	0 or 1	1

The Figure. 5 shows the results for the second configuration (0.35 lateral motion gain), as we can see, extreme lateral motion gains decrease the drive accuracy.

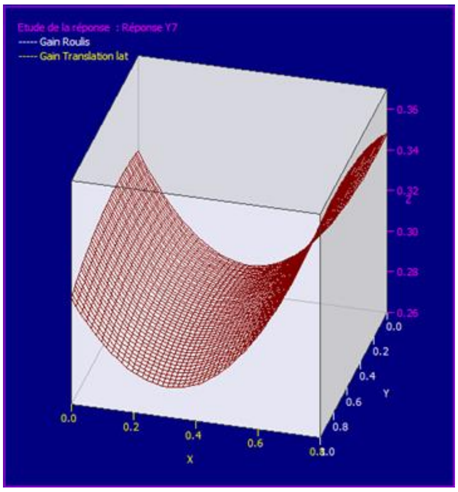

Figure. 5. 3D representation of response surface for the RMSE variable, for the third slalom and the second configuration.

4. Discussion of Results and Conclusion

Previous researches in dynamic driving simulator, advise to use under-unit scale factors in cornering, in order to improve perception and driving behavior [Fee16], [Pre18], [Fee19] and [Fil20]. The present research aims to develop knowledge of driver perception and simulator setting in curve. The slalom task was already validated by several studies, however, these studies did not question if preferred motion gains could evolve as function of slalom intensity, i.e., several lateral accelerations.

We asked drivers to assess the quality of realism of vehicle behavior and the facility of achieving slalom. For the first question, we found that the more important factor is the lateral motion gain i.e., the quantity of lateral acceleration produced by the simulator and felt by the driver. Two groups emerged and were analyzed separately. Despite the fact that the two groups preferred different motion gains, the experimental model showed a roll motion gain = 1, is evaluated as more realistic. Similar results were found in a previous research [Dag12] but with expert drivers, which was not the case in the current study, where the population was "normal" drivers. Our driving simulator reproduces exactly the roll angle and its derivates, and is temporally coherent with the visual roll. Absolute threshold of roll motion is around 2°/s [Ben21], hereby; the roll velocity could attempt this threshold from the second slalom. Thus, a roll motion with downscale factor is not forcedly felt by the driver.

Surprisingly, the yaw motion influences very little the final perception, maybe its intensity was not felt or masked by the two others component i.e., the lateral and roll motion, more works are required to elicit this point.

The more important result concerns the lateral motion gain, which is digressive for both groups with the increase of lateral acceleration. Although we asked participants to evaluate the realism of vehicle behavior, it is not impossible that a "comfort level" was also evaluated. Higher lateral amplitude can be more uncomfortable, so the decrease of lateral motion gain could be due to the decrease of discomfort. Nevertheless, we use the tilt coordination technique for the reproduction of lateral acceleration, it is also possible than the tilt is easier perceived with the increase of lateral acceleration. A previous study [Nes22] showed that limit of lateral tilt (before to be perceived as a tilt and no a lateral acceleration), is higher for active drivers than for passive passengers [Gro2]. This research advised to limit the tilt to 6°/s, twice the limit found for passive subjects. In our study, for the second and third slalom and for the higher lateral motion gains, the lateral tilt could attempt 14° of inclination and an angular velocity of 12°/s (limit fixed by our motion cueing algorithm or MCA). These magnitudes are higher than recommended by the Nesti's et al. study [Nes22], and higher than the threshold of roll tilt [Bri23]. Hence, more investigations are required to definite the tilt limits of our simulator, whether in velocity or total angle.

Concerning the subjective perception of facility, we also found a decrease of lateral motion gain with the increase of slalom level. Drivers found more difficult to realize the second and the third slalom for configurations with lateral motion gains higher than 0.2 and 0 respectively. The increase of discomfort is probably one cause.

Nonetheless, as showed by the objective analysis of steering-wheel corrections and lateral deviations, lateral motions gains inferior to 0.2 is not advised. Except the first slalom, where a lateral motion gain of 1 enables optimal steering, the driving accuracy for the two others slaloms is better with lower lateral motions gains. However, a lateral motion gain of 0 is not recommended in order to improve driving performances and accuracy, as shown by the RMSE variable (Table 6). A previous research [Fee16] showed a decrease of steering correction with the increase of lateral motion gain. Nevertheless, they analyzed only one level of slalom (1.2m/s²). Hereby, we show that with the increase of lateral acceleration (and so the slalom level), the effort required to accomplish the slalom is more important whit a unit or near unit lateral motion gain.

In order to improve the driver's perception and control performances, it is recommended to setup the MCA with a decreasing lateral motion gain, while keeping the roll gain to 1 and yaw motion gain to 0

5. Conclusions

If the lateral motion seems to have the most influence in the perception of lateral acceleration on dynamic driving simulators, surprisingly, the roll and the yaw motions are less influential than expected. However, given the results of previous studies, we should investigate more closely this matter in order to better understand the interaction between these 3 motion components from a perceptive point of view.

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