ROLL TILT THRESHOLDS FOR 8 DOF DRIVING SIMULATORS

Zhou FANG[1], Florent COLOMBET[2], Jean-Christophe COLLINET[1], Andras KEMENY[1]

(1): RENAULT, Virtual Reality and Immersive Simulation Center,
TCR AVA O 13, 1 avenue du Golf,
78288 Guyancourt
{zhou.fang, jean-christophe.collinet, andras.kemeny}@renault.com

(2): THEORIS
103 rue La Fayette
75010 Paris
+33(0) 1 53 25 02 32
florent.colombet@theoris.fr

Abstract –The tilt coordination technique is used in driving simulation for reproducing a sustained linear horizontal acceleration by tilting the simulator cabin. The rotational motion must be slow to remain under the perception threshold and thus be unnoticed by the driver.

However the acceleration to render changes fast. Between the slow rotational motion limited by the tilt threshold and the fast change of acceleration to render, the design of the coupling between motions of rotation and translation plays thus a critical role in the realism of a driving simulator. This study focuses on the acceptance by drivers of 8 different configurations for tilt restitution, for a slaloming task. Results show what thresholds have to be followed in terms of amplitude, rate and acceleration.

Key words: Driving simulator, Motion cueing algorithm, Explicit MPC algorithm, Tilt coordination technique, Scaling factor

1. Introduction

The role played in automotive industry by driving simulators is increasingly important. During the design phase, they allow testing new advanced driver assistance systems (ADAS)such as ACC, AEBA, etc. by studying driver's behaviour. They also allow testing the car's handling, ride comfort, drivability, behaviour, performance or fuel consumption without having to build a physical prototype. The 0.2Hz slalom is one of the most common scenarios performed for handling test. For Renault Company, being able to perform this test on a driving simulator could have a large number of interests in terms of cost and delay reduction. Unfortunately, the level of lateral acceleration rendered in simulation during this test is not enough according to professional test pilots who interpret the driving simulator feeling tightly connected to the driving commands, including the vehicle speed. Actually, the available X-Y rails strokes (5.2 meters) of the ULTIMATE simulator appear to not be enough to render the needed acceleration level. This is why we are focusing our research on the implementation of the tilt coordination technique in the motion cueing algorithm of the ULTIMATE simulator.

More generally, a sustained lateral acceleration is essential for the driver like in a curve for example [Rey1]. In this case, the obtained results could also be applied to perform the tilt-coordination task.

After presenting the tilt coordination technique and the difficulties generally encountered when using it in driving simulation, we will see that some thresholds needed for its implementation on a motion cueing algorithm remain unclear. Our experiment aims at comparing eight parameters configurations to see the acceptance of drivers and then determine what acceleration levels can be reached with the tilt coordination technique for the slalom test.

1.1. Tilt coordination technique

Accelerations are perceived by the human body mainly by the inner ear [Gra1]. The vestibular system is composed of the otholitic system and the semicircular canals. The first is sensitive to the linear accelerations while the seconds are sensitive to the angular accelerations. However the otholitic system presents a perception ambiguity: it cannot differentiate a horizontal acceleration from the gravity component due to an inclination around a horizontal axis. This ambiguity is thus used in motion cueing strategies to render a part of the vehicle accelerations by tilting the simulator cabin and is known as tilt coordination technique (Fig. 1). This rotation has to be done at a slow tilt rate to remain under the semicircular canals perception threshold. Visual rendering of the simulation has also to be compensated if the display screen is not fixed to the cabin.

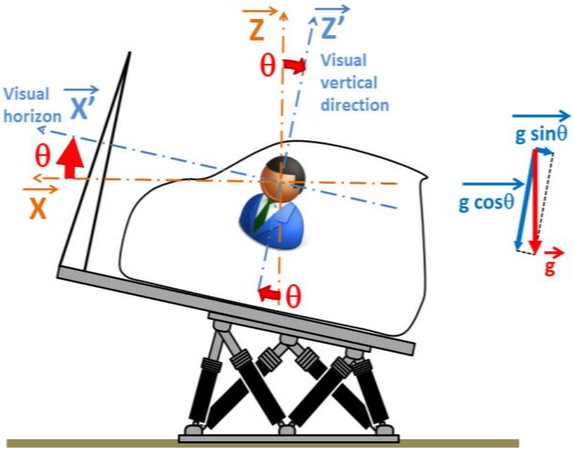

Fig. 1. Illustration of the tilt coordination technique. By tilting the simulator cabin of an angle θ, the component g*sinθ of the gravity may be interpreted by the driver as an horizontal acceleration.

Knowledge about rotation motion perception appears thus as primordial for the use of the tilt coordination technique, especially the detection threshold. According to the particular dynamics response of the inner ear semicircular canals model, Guedry [Gue1] has traced a relationship between the rotational acceleration and the time exposed to the excitation for the detection threshold. The theoretical model is correlated by Meiry's experience data and gives, e.g., a rotational acceleration threshold of about 8°/s² for 0,2s exposure and of 0.3°/s² for 10s exposure. Based on the step excitation and the canals' dynamic model, Mulder [Gue1] has adopted a rotational rate approach. He has proposed a perceived tilt rate perceived law and given a tilt rate threshold of about 2°/s which is independent of tilt acceleration. This low tilt threshold seems a reasonable value for general purpose driving simulation in the case of very low simulator's linear motion [Cha1]. By mean of a robotic simulator, Nesti *et al.* [Nes1] have showed with dynamic driving scenario and linear-tilt motion, that the roll rate threshold can be raised to a much higher value (about 5.2°/s) and suggested a high tilt rate threshold of 6°/s.

1.2. Problem

The tilt coordination technique appears thus to be quite difficult to implement in a motion cueing strategy for driving simulation. On one hand rotational motion has to be limited in terms of amplitude to avoid phase lag and in terms of rate and acceleration to avoid being noticed by the driver. On the other hand we need to tilt the cabin as much and as fast as possible to render an equivalent acceleration as high as possible. The motion cueing strategy has then to use a compromise between these two situations and unfortunately literature does not provide consistent thresholds values, and knowing which levels to use remains unclear.

For example by a simple sinus signal consideration for a 0,2Hz slalom scenario and assuming that no phase lag exists between reference and tilt signals, the relationship between the tilt level and the thresholds can be written in Table 1. If we choose to limit the tilt angle to 5°, the maximum equivalent acceleration we can provide is then 0.86 m/s². To reach this level when performing slalom at 0.2Hz, we will then have to rotate the cabin at a maximum tilt rate of 6.3 °/s and at a maximum tilt acceleration of 7.9 °/s². We see then that even with low levels of equivalent accelerations rendered with the tilt coordination technique, the theoretical perception thresholds are overtaken.

Table 1. Relationship between the tilt levels (amplitude, rate and acceleration) for a 0.2 Hz slalom scenario ($\omega=2\pi f=1.2566$ rad.s^{-1}).

Max tilt level (θ_{max})	Max equivalent linear acceleration ($g.\sin\theta_{max}$)	Max tilt rate ($\omega.\theta_{max}$)	Max tilt accel. ($\omega^2.\theta_{max}$)
3°	0.51 m/s²	3.8°/s	4.7 °/s²
5°	0.86 m/s²	6.3°/s	7.9 °/s²
8°	1.37 m/s²	10°/s	12.6 °/s²

It is found that in the case of multi-sensory stimulations, perception thresholds are modified in comparison of single sensory stimulation [Ber1, Nes1]. We think that if the rotational motion is accompanied with linear motion, perception thresholds could be higher. We aim then to determine what the acceptable thresholds for tilt acceleration and tilt rate are in an 8 DOF simulator. In the case of a slalom where lateral acceleration will be rendered both by linear acceleration and tilt coordination, is it possible to obtain a higher combined rendered level by overcoming the traditional thresholds?

2. Motion cueing algorithm

2.1. Renault ULTIMATE simulator

We intend to conduct our experiment on the high-performance dynamic ULTIMATE simulator [Dag1] at Renault Virtual Reality and Immersive Simulation Centre (VRISC) (Fig. 2). First developed in 2001, the simulator has been renewed in 2011 [Sch1] and consists now of a closed cabin based on a Renault Twingo 2 car which has been lightened and instrumented. Inside the cab, transmission is carried out using a manual gearbox, and a system of sound synthesis is used to reproduce engine noise and the audio environment for an interactive vehicle. Active steering force feedback is computed by a proprietary model and reproduced by a SENSO-Wheel system. The SCANeR© Studio 1.2 software package is used with a real-time version of the MADA (Advanced Modelling of Vehicle Dynamics) vehicle dynamics software, developed by RENAULT. The visual environment is displayed on a cylindrical screen (radius 1.9 m) thanks to five single-chip DLP projectors (Projection Design F12), each with a resolution of 1980 x 1080. The system covers a horizontal field of view of 210°.

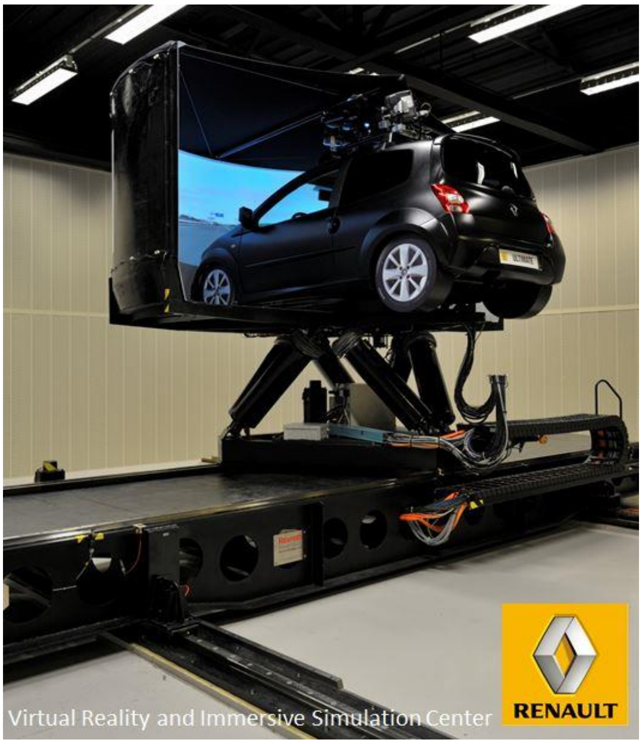

Fig. 2. Renault ULTIMATE driving simulator at Virtual Reality and Immersive Simulation Centre.

The cabin is mounted on a large X-Y table and a hexapod motion system to render physical accelerations and rotations. Table 2 presents the physical capabilities of the motion system.

Table 2. Physical capabilities of Renault ULTIMATE simulator

	Stroke	Speed	Accel.
X Rail	± 2.6 m	± 2.0 m/s	± 5.0 m/s²
Y Rail	± 2.6 m	± 3.0 m/s	± 5.0 m/s²
X Axis	± 0.28 m	± 0.7 m/s	± 7.5 m/s²
Y Axis	± 0.26 m	± 0.7 m/s	± 7.5 m/s²
Z Axis	± 0.20 m	± 0.4 m/s	± 5.0 m/s²
H Axis	± 15 °	± 40 °/s	± 300 °/s²
P Axis	± 15 °	± 40 °/s	± 300 °/s²
R Axis	± 15 °	± 60 °/s	± 600 °/s²

2.2. MPC-based motion cueing algorithm

The motion cueing algorithm is in charge of computing the physical displacements of the simulator cabin as a function of the simulated vehicle motion. It has to realize a compromise between rendering the vehicle accelerations (in terms of driver perception) and keeping the simulator within its physical limits. The algorithm used on the ULTIMATE simulator is a MPC-based (Model Predictive Control) motion cueing algorithm as described by Fang [Fan1]. Compared with classical or LQR optimal filters' approaches, the MPC integrates directly the system constraints into its optimization process, and then gives a real optimal solution and hardly needs the tuning process to check the workspace limits and the driver's perception thresholds.

In the motion cueing process, acceleration rendering with the tilt coordination technique has been added and is performed as a priority. The equivalent acceleration thus rendered is then subtracted to the vehicle acceleration before being rendered with the rails.

Tilt rotation thresholds (in terms of amplitude, rate and acceleration) are explicitly taken into account in the optimization process of the algorithm. Different configuration sets can be used and the possibility to switch online from one to another has been implemented. In this case, a transition phase between the two configurations is performed during 5 seconds.

We can also specify that rotation motions are rendered around the driver's head centre. Both vehicle and tilt coordination rotations are computed around this particular point. Specific modules are in charge of realizing the change of coordinates from the rotation point of the hexapod to the driver's head by adding linear motions (on the hexapod and not on the XY rails).

2.3. Tilt scaling factor

It is found that without any restriction the rendering by tilt coordination technique could induce a phase lag between the reference signal and the input signal of the linear restitution. It could thus lead into a global rendering worse than without tilt coordination. The solution we brought to this particular issue was to add an amplitude reduction of the reference signal (only for the tilt restitution part). In order to preserve at best the original signal profile, the scaling has been done with a hyperbolic tangent function as described in Eq. 1:

$$Y_{tilt\_ref} = Acc_{max} * tanh(Y_{ref} / (K * Acc_{max})) \qquad (1)$$

where $Acc_{max} = g*\theta_{max}$ and K is a form factor. K varies from 3 to 6 depending on the maximum roll angle and roll rate.

3. Experimental protocol

3.1. General purpose

We aim at determining the acceptable tilt coordination parameters for lateral acceleration rendering during slalom. Table 3 details the 8 compared tilt configurations in terms of maximum tilt angle, tilt rate and tilt acceleration.

Table 3. Compared tilt configurations

Configuration	1	2	3	4
Max tilt angle [°]	3	4	5	5
Max tilt rate [°/s]	5	4	4	5
Max tilt accel. [°/s²]	8	8	8	12
Configuration	5	6	7	8
Max tilt angle [°]	5	5	6	6
Max tilt rate [°/s]	6	6	6	7
Max tilt accel. [°/s²]	15	60	60	60

We varied the maximum tilt angle from 3 to 6°, the maximum tilt rate from 4 to 7°/s and the maximum tilt acceleration from 8 to 60 °/s². In fact 60 °/s² is never reached because maximum angle or maximum rate is reached first (it is observed that a more reasonable limit value is about 20-30°/s). So the 60 °/s² constraint can be seen as non-constraint instead. The purpose of the value is only for safety matters.

3.2. Road description

The road used for this experiment is a straight portion of a double-lane motorway. This portion is visually realistic and there was no traffic.

Orange cones were dispatched on the road so that the driver can perform slaloms. In total 16 groups of 9 cones were disposed on the road every 1250 m (Fig. 3). For each slalom, the distance between the cones (62.5 m) ensuresthat when driving at 90 km/h the slalom is performed at a 0.2 Hz frequency (Fig. 4).

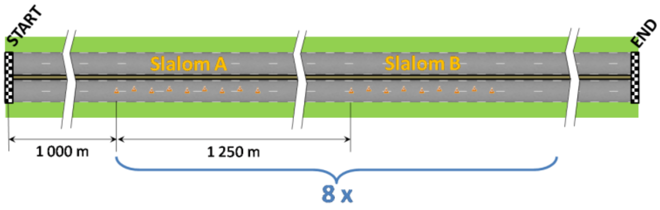

Fig. 3. Illustration of the road used for the experiment.

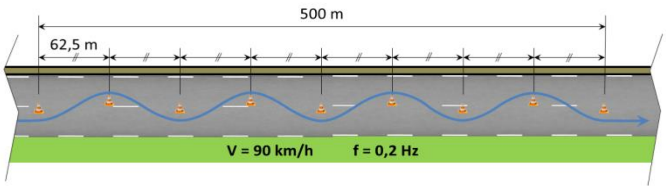

Fig. 4. Detailed illustration of the disposition of cones for one of the 16 slaloms. Cones are separated by 62.5m thus when driving at 90 km/h, the sinus trajectory is performed at a 0.2 Hz frequency.

3.3. Protocol

After presentingthem the simulator and the purpose of the experiment, subjects were proposed to perform a familiarization driving in which they could perform 4 slaloms: the 2 first with no tilt and the 2 others with tilt rendering.

For the experiment, there were 16 slaloms to perform in total. The slaloms were paired (1A/1B, 2A/2B, 3A/3B, ...). For each "A" slalom, no tilt coordination was done. For each "B" slalom, one of the 8 configurations (parameters set, see Table 3) was used for tilt rendering. Subjects were asked to drive at a constant 90 km/h speed in order to obtain a lateral acceleration around 3 m/s² when slaloming. In order to focus on the slalom performing and the motion rendering, subjects were asked to enable the cruise control. It ensured also that all drivers performed the experiment at the exact same speed. Finally, subjects were asked to verbally indicate after every "B" slaloms if they had found the motion rendering acceptable or not.

Eight volunteer subjects have participated to the experiment. Table 4 presents the configurations order for the 8 participants. We used a counterbalanced Digramlatin square in order to avoid rank effects (a given configuration is only once in a particular position) and report effects (any configuration is followed or preceded only once by each of the 7 other configurations).

Table 4. Configurations order for the 8 participants

Subject	Configurations order							
#1	1	8	2	7	3	6	4	5
#2	2	1	3	8	4	7	5	6
#3	3	2	4	1	5	8	6	7
#4	4	3	5	2	6	1	7	8
#5	5	4	6	3	7	2	8	1
#6	6	5	7	4	8	3	1	2
#7	7	6	8	5	1	4	2	3
#8	8	7	1	6	2	5	3	4

4. Results

4.1. Results analysis

Fig. 5 presents an example of lateral motion rendering with rails only ("A" slaloms). The vehicle lateral acceleration is represented by the solid line. We can see that the lateral acceleration rendered by the Y rail (dashed line) does not follow the reference signal every time. The rail stroke forces the cabin to slow down and approach to the limited ~~come back to the neutral~~ position.

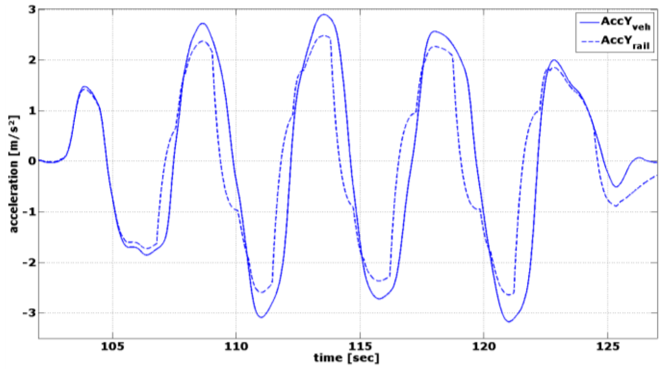

Fig. 5. Example of lateral restitution with rails only (without tilt)

On the other hand, Fig. 6 presents an example of lateral motion rendering with combined linear motion (Y rail) and tilt coordination technique ("B" slaloms). The vehicle lateral acceleration is represented by the solid blue line. The dashed red line is the equivalent acceleration rendered by tilt coordination. The solid red line is the acceleration rendered by the Y rail. And finally the dashed blue line is the combined rendered acceleration. The corresponding roll tilt angle, tilt rate and tilt acceleration are presented in Fig. 7. The configuration used for this particular slalom was the first (see Table 3). We can see tilt rate limited to 5°/s and tilt acceleration limited to 8°/s².

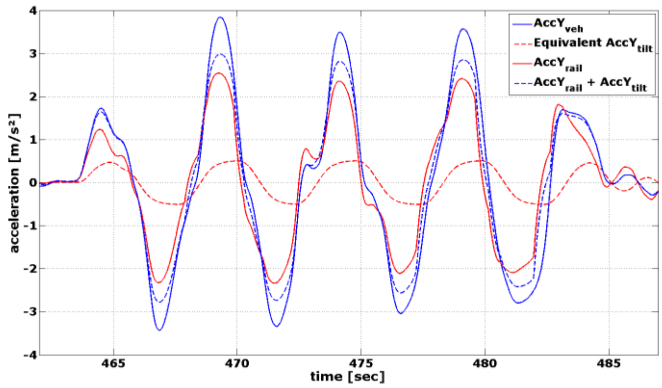

Fig. 6. Example of lateral rendering with combined rails and tilt coordination technique.

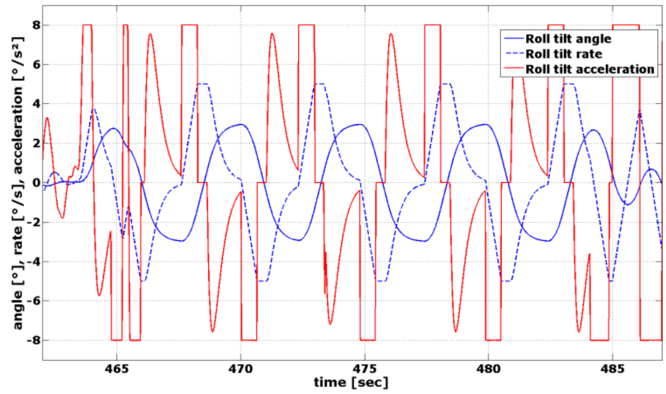

Fig. 7. Example of roll tilt angle, rate and acceleration for a slalom. The corresponding configuration is #1.

We can see on Fig. 6 the interest of tilt coordination. The combined rendered acceleration is closer to the vehicle acceleration than without tilt (Fig. 5).

Concerning subjects verbal answers, Table 5 presents the results of the 8 subjects (A = acceptable, NA = non-acceptable).

Table 5. Acceptance results of the 8 participants

Config.	1	2	3	4	5	6	7	8
Subj. 1	A	A	A	A	A	A	A	A
Subj. 2	A	A	NA	A	A	A	NA	NA
Subj. 3	A	A	A	A	NA	A	A	NA
Subj. 4	A	A	A	A	A	A	NA	NA
Subj. 5	A	A	A	A	NA	NA	NA	NA
Subj. 6	A	A	A	NA	A	NA	A	NA
Subj. 7	A	A	NA	NA	A	NA	NA	A
Subj. 8	A	A	A	A	NA	A	NA	NA

Except from subject 1, all drivers were able to notice a difference between configurations. From Table 5, we can trace the graph on Fig. 8 showing the percentage of acceptance for each configuration.

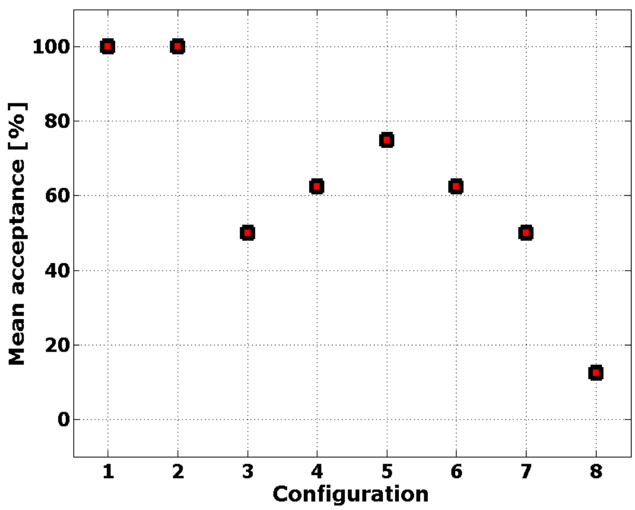

Fig. 8. Mean acceptance answer of the 8 subjects for each configuration.

4.2. Results discussion

What appears on Fig. 8 is that 100% of the subjects accepted the configurations 1 and 2. And if we exclude subject 1 who judged all configurations acceptable, none of the 7 other drivers judged the configuration 8 acceptable.

This shows that with the correct parameters (configuration 1 and 2), it is possible to use tilt coordination in terms of drivers acceptability, thanks to the coordination between tilt orientation and rails displacement. But what appears also is that tilt coordination cannot be used "too much". Results of the configuration 8 show clearly that: by using too high thresholds values, we can render higher levels of acceleration but no driver finds it acceptable in terms of perceived motion.

Finally for configurations 3 to 7, tilt coordination is accepted on average by 60% of the drivers (50% if we exclude subject 1). More subjects are needed if we would like to determine the 50% acceptance threshold but we think that limiting tilt in order to ensure that 100% of drivers accept it would be preferable, even if it doesn't allow rendering more than a 0.7 m/s² equivalent acceleration.

5. Conclusion and perspectives

We have presented a study on the use of tilt coordination technique for lateral acceleration rendering in the case of slalom performing, situation in which the tilt coordination technique is generally not recommended for an 8DOF driving simulator. We had to add an amplitude reduction (with a tanh function see Eq. 1) of the vehicle acceleration to reduce phase lag with the equivalent acceleration rendered by tilt.

Results show that if maximum tilt angle remains under 5 °, maximum tilt rate under 5 °/s and maximum tilt acceleration under 8 °/s² at the same time, every driver find it acceptable. And on the opposite, if both maximum tilt angle is beyond 6 ° and tilt rate beyond 7 °/s, no driver will find it acceptable.

What really is the cause of the non-acceptance by drivers remains yet unclear. Is it tilt amplitude, tilt rate, tilt acceleration or combined effects? Our results do not allow us to conclude. However they allow us to confine the values for our future experiments. For example we could keep tilt angles and rates at low levels and increase maximum reachable tilt acceleration to study its impact on drivers.

Are these results transposable? It is not a simple question. As reported by Chapron*et al.*[Cha1], the tilt perceived threshold varies according to the linear motion. In the experimental 0.2Hz slalom scenario, the tilt angle is nearly phased with linear motion, but tilt rate and tilt acceleration have respectively about 90° and 180° (opposite phase) phase lag. It could be considered as a rather bad situation to deduce high tilt rate and tilt acceleration thresholds. As a consequence, we think that in other driving situations, the values determined in our experiment could be transposable if the frequency of lateral accelerations remains under 0.2 Hz. For a slalom test beyond this level, tilt rate and acceleration levels may not be high enough to produce a significant tilt angle underphase lag constraint between the reference signal and the tilt angle. Moreover, tilt coordination becomes less necessary when frequency increases, because the higher the slalom frequency, the higher the lateral acceleration level which can be reproduced by linear motion if the simulator's frequency bandwidth allows to.

Concerning the transferability of our results for pitch tilt rendering, we presume that it is highly possible. In fact tilt detection thresholds for pitch and roll are often almost equal in literature.We have already implemented an MPC algorithm to render longitudinal motion by taking into account the rail linear acceleration level and the simulated vehicle's pitch rate. A good feedback has been obtained from internal professional drivers. However we intend to conduct an experiment similar to this one and quantify more precisely the tilt pitch tuning parameters.

6. References

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