The new PSA Peugeot-Citroën Advanced Driving Simulator Overall design and motion cue algorithm

Thomas Chapron, Jean-Pierre Colinot

PSA Peugeot-Citroën

Direction de la Recherche et de l'Innovation Automobile

2, route de Gisy F-78943 Vélizy Villacoublay Cedex

France

Email : thomas.chapron@mpsa.com

Email : jeanpierre.colinot@mpsa.com

Abstract

Realistic restitution of longitudinal and lateral acceleration significantly improves realism during a driving simulation. That is the reason why PSA Peugeot-Citroën has decided to build a simulator with a large motion base.
This paper presents a technical description of this new driving simulator, which will be operational in September 2007.
The motion base consists of a 10m by 6m XY-table topped with an hexapod. On the hexapod, a composite dome houses the vehicle cab. This dome can be rotated 90°, allowing the use of the longer stroke either for lateral or longitudinal acceleration restitution.
The dome structure and the vehicle cab are optimized to reduce weight and vibrations. An emphasis has been also put on acoustic and visual immersion of the driver, in order to allow use of cab tilting without any drawback.
The motion cue algorithm combines a classical tilt-coordination filtering approach with pre-positioning under perception thresholds and a lane position algorithm. Road database data are used to progressively switch between these three contributions and thus provide the driver with the best possible lateral motion cues depending on the occurring situation : straight line, curve etc...
Simulation results showing acceleration cues generated in different cases, are presented and discussed.

1. Introduction

PSA-Peugeot-Citroën has been involved in the driving simulation field for more than ten years. Throughout these years, the main purpose for this activity has mainly been to develop a new simulation tool enabling drivers' behavior study in realistic conditions as well as investigation, test and optimization of automotive components and systems in an early stage of the vehicle development process.
The main advantages of using such a tool are:
- reduced cost and time for the preparation and testing phase
- easy access of parameters to tune or to log, enabling a quick and efficient optimization phase and an easy comparison of different solutions
- driver-in-the-loop simulation, which allows subjective assessment. Such assessment is usually made by PSA specialists and is always relative: already existing components or systems are simulated and compared to the new one (and possibly its different configurations) using the simulator.

Historically, an 'all purpose' static simulator SHERPA was first developed in 1995. In 2000, a second one has been built, with an emphasis on visual restitution: large cylindrical screen allowing a lateral FOV of 180°, active stereoscopic vision etc... Since 2003, it has been systematically used in the PSA vehicle development scheme for visibility and headlights evaluation. As it has been used since then as an industrial tool, no major changes have occurred on this simulator except upgrades of software and hardware components according to the market offer. The first SHERPA then became more dedicated to other fields of vehicle development, in particular vehicle dynamics and driver assistance systems. Noticeable examples of use of this simulator were a study on driver's behavior in rear-end accident [1] or in 2002, the first assessment and tuning of the SSP (Steering Stability Program) innovation, which is currently available on the newly released car Peugeot 207 RC. Nevertheless, even though this simulator had a very realistic steering wheel force feedback and vehicle model, it was still static, which considerably limited its potential to evaluate systems in safety, driving pleasure, braking and comfort fields. For these applications, realistic restitution of accelerations is most of the time needed, that is why PSA decided to add a motion base to this simulator.
First, an 1000kg- hexapod system has been installed in 2004. Some dynamic experiments were conducted, for example comfort tests (bumps, speed humps situations), but the limited strokes available (20 inches jacks) restricted its realistic use to only medium frequency situations (about 0.7Hz to 10Hz). In normal driving conditions, realism was still to be largely improved, which led to the decision in 2005 to build a simulator with a large motion base.

This new simulator SHERPA^2 will be operational in September 2007 and is presented in this paper. The simulator, including its motion cue algorithm (MCA), has been fully specified by PSA. It has been integrated by ABB-MC company. The dome and cab have been designed by SEREME, under supervision of ABB-MC. The software that will be used is the SHERPA software (now entirely PC-based), which has been continuously developed and owned by PSA-Peugeot-Citroën throughout these past 12 years.

2. Simulator overall design

Motion base simulator design mainly consists in finding the best compromise to constraints, such as:
- building size (including available height), which often has to be accepted as it is
- cost
- performance of the motion system: stroke, max speed, acceleration, cross-talk between axes, bandwidth, smoothness, acoustic noise generated etc…
- choices in motion cueing (tilt-coordination use or not etc..) which can have large impacts on the volume available and the linear strokes of the system to be designed.

Motion base

To provide a consistent driving feel, our preference went to an XY motion base combined with a hexapod. To limit cost, only on-the-shelf products were considered.
An Ultimate motion base [2], produced by Bosch Rexroth, and already operational at Renault Technical Centre fulfilled most of our requirements in performance (max acceleration 0.5g, smoothness and acceleration noise below 0.03g, small cross-talk between axes, time response below 50ms and operational bandwidth superior to 5Hz). Moreover, it could be easily adapted to our existing motion base (1000kg payload electrical hexapod) which was also delivered by Bosch Rexroth.
Improvements have nevertheless been specified, such as acoustic noise reduction, increased stroke and increased max operational velocity on inferior axis.
The consequent characteristics of the system are summed up in table 1. Available X and Y linear strokes are more constrained by the building size than the motion base itself.

	Operational stoke	Max speed	Max acceleration
Pitch	+/- 18 °	20 °/s	300 °/s^2
Roll	+/- 18 °	20 °/s	300 °/s^2
Yaw	+/- 23 °	30 °/s	600 °/s^2
Linear X	+/- 5 m	3 m/s	5 m/s^2
Linear Y	+/- 2.75 m	3 m/s	5 m/s^2
Vertical	+/- 20 cm	2 m/s	5 m/s^2

Table 1: motion base main characteristics

In addition to that motion base, an electrically moving platform has been specifically designed to allow driver and passenger to easily embark in the vehicle cab when the moving system is in settled position.

Other choices and specifications

Our goal was to design a simulator able to use “tilt-coordination” technique (see part 3 of this paper for more details) because it is, to our knowledge, the only way (except infinite linear stroke) to provide a sustained acceleration feel to the driver. Indeed, in some conditions, tilt can be perceived by the driver as linear acceleration [3]. These conditions are still to be investigated; but in the simulator specification and design process, we mainly kept in mind the two ones listed below:

1. tilt movements must occur under human tilt perception thresholds: this implies to have sufficient linear stroke, if we do not want to distort too much the acceleration profile or use too low scale factors.
2. no contradictory (or disturbing) cue: good visual immersion, no air movement feel, limited driver perception of actuators sound and vibration.

Condition 1 is limited mainly by the available building size. Nevertheless, we tried to have maximum linear stroke by optimising what could be:
- volume reduction of what is on top of the hexapod, (which will be referred as *cell* further on in this paper). This is limited on the other hand by the will to keep a minimum distance between driver eye and screens (specified to be at least 2,1m), the size of the cab, along with accessibility and maintenance requirements
- *possibility of rotating the cell 90°* (easily, but off-simulation) in order to benefit from the 10m stroke in the direction the more needed by the experimentation.

From condition 2, the vehicle cab needs to be fully visually isolated from the motion base. Good acoustic and vibration isolation are also to be met. Thus, the following requirements for the cell and cab design have been specified:
- 160° (horizontal) x 25° (vertical) minimum visual field of view
- total cell weight below 750 kg (driver and one possible passenger not included)
- cell and cab first vibration mode superior to 12 Hz
- perceived movement of the projected image inferior to 1 mm (under max. solicitation)
- 20 dB(A) minimum acoustic isolation on all the frequency spectrum above 50Hz

In addition, a good feel of all the driving controls (pedals, gear shift etc..) is necessary: to minimise weight, passive mechanisms were accepted, except for the steering wheel force feedback which had to be an active system in order to allow different parameterisations.

Cell and cab design

Considering the severe weight and volume constraints, a small car (Citroën C1) has been chosen as vehicle cab. All equipment which cannot be seen by the driver have been removed, including everything behind driver and passenger seats. Seven loudspeakers have been placed around the cab for sound restitution. Acoustic reduction materials have been added to fulfil noise reduction requirements. A specific force feedback steering system already used in a steer-by-wire PSA prototype has been chosen to achieve an effective cost/high-performance/weight/volume compromise. A detailed description of this specific device and its controller can be found in [4].

The half-C1 cab is surrounded by a composite honeycomb structure. Three F1 (ProjectionDesign) projectors are fixed to the cell ceiling. Flat screens have been chosen for simplicity, cost and weight. A 10cm composite floor mounted on bushings isolates the cab from the hexapod in order to reduce structure-borne noise (coming from actuators) transmission. The dome has been designed using finite-element method. About 100 numerical iterations have been done in order to meet the vibration, deformation, weight and volume requirements. To reduce cell weight, most of electric and electronic devices concerning cab actuator or sensors (except A/D signal conversion) have been deported out of the cell, in specific cabinets embedded on the basis of the hexapod system.

Figure 1 shows a representation (during design) of the cell and hexapod. Table 2 illustrates the final weight repartition between the major cell components. Figure 2 presents an overview of the whole system as installed in July 2007 in our facility in Vélizy (France).

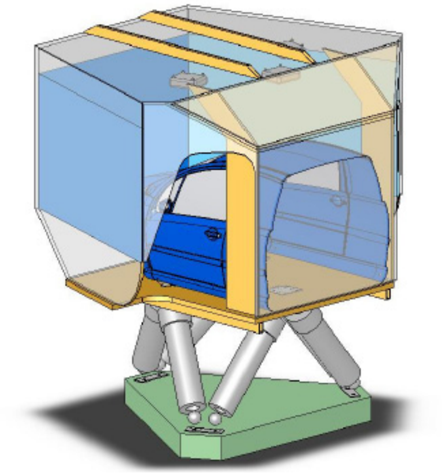

Figure 1: cell overview

Major cell component	Weight (kg)
Visual system (projectors etc..) including retrovision	30
Composite honeycomb structure	250
Fixation devices, bushings	40
Vehicle cab (body shell)	160
Vehicle standard equipment (dashboard, seats etc..)	150
Acoustic reduction material	30
Passive force feedback system	30
Steering wheel feedback system	20
Total	**720**

Table 2: cell weight repartition

Figure 2: PSA facility overview during integration

3. Motion Cue Algorithm

Principles

A specific motion cue algorithm (MCA) has been designed for this new simulator. It is based on PSA previous motion cueing software but has been considerably enhanced in order to fully benefit from our new motion base. The main idea have been to use "tilt-coordination" and to base our approach on classical filtering algorithm [5]. To our opinion, more complex algorithms, like optimal, adaptive or others (cf. review in [6]) still have to prove their superiority, while being usually difficult to parameter (see for example [7] for airline pilots subjective comparison of different algorithms).

In classical approach, a frequency splitting scheme is used, where high frequency components are fed to the linear actuator and resulting low-pass signal is limited (in rate and acceleration) and transformed in an equivalent tilt movement. If this tilting movement is done in adequate perceptive conditions (under vestibular semicircular canals thresholds, consistent visual cues etc…), a kind of inverted somatogravic illusion ([8] illustrates this illusion) is created: actual tilt is perceived as sustained acceleration. Total acceleration felt by the driver is then, the sum of linear acceleration and the gravity vector component (created by tilt) in the cell frame. In this paper, we call this sum, *equivalent* acceleration.
The difficulties of tilt coordination and of any MCA tuning and design based on it, are:
- tilt derivatives limiters necessary use (to be under thresholds), which implies that the equivalent acceleration profile is possibly deformed. On the perceptive level, this can be partly compensated by visual cues, but should ideally be limited as much as possible.
- difficult choice of the value of tilt derivatives limiters. The smaller they are, the higher is the equivalent acceleration deformation, but the better is the somatogravic illusion
- linear stroke available: empirically, it is always too small, all the more since any MCA has to guarantee to be within the stroke in any case of permitted driver solicitation
- choice of cut-off frequency value: it has a direct (inverse quadratic) influence on linear stroke. On the other hand, the lower it is, the lesser is the equivalent acceleration deformation and the better should be the "quality" of the somatogravic illusion.

Considering these issues, in our MCA, several items have been added to the classical filtering approach. The main ones are presented below:
<u>- non linear scale factor</u>
As long as more driver solicitation provides more acceleration feel, a non-linear scale factor can be used. This can allow a good scale factor (0.5) at low level accelerations and considerably limits stroke consumption at high accelerations. However, to remain consistent, it is advised to use the same factor for lateral and longitudinal acceleration.
<u>- variation of tilt derivative limiters with restituted linear acceleration</u>
Clearly, conditions in which somatogravic illusion appears in driving simulator have still to be investigated. They depend on the simulator quality (the less indirect false cues are generated, the better) but, to our opinion (based on extensive subjective testing made in 2005 and 2006 with VTI simulator [9]), seem as well to depend on the level of linear acceleration which is generated while tilting. For example, tilt sensation is far more noticeable if no linear movement occurs at the same time. In our MCA, sophisticated non linear filters have been designed to limit tilt in position, rate, acceleration and jerk, the limiting values in rate and acceleration varying (linearly) with linear acceleration restituted. The parameters will have to be tuned when the simulator is operational, but this should improve the somatogravic illusion quality and partially limit equivalent acceleration deformation.
<u>- pre-positioning under linear perception thresholds</u>
Under some circumstances, it is possible to anticipate driver's actions and therefore to pre-position the motion platform in order to increase available stroke. By doing so, filter cut-off frequency can be decreased for a better acceleration restitution. For longitudinal movements, depending on the modeled vehicle acceleration/deceleration characteristics (which can be time-varying according to the gear ratio or vehicle speed), an optimal pre-position is determined. For lateral movements, *road database information* is used to

generate this pre-positioning signal. At each time step, depending on the next curve radius of the database and the current vehicle speed, an estimated needed linear stroke is computed (for the oncoming curve). This information together with the estimated time-to-next-curve are used to generate a pre-positioning signal. In both lateral and longitudinal cases, these pre-positioning signals are limited (in speed, acceleration and jerk) using non linear filters (the same than for tilt limitations) which ensure that movements are performed under perception thresholds. Depending on the chosen linear acceleration threshold values, time tables are pre-computed in order to be able to trigger these movements well in advance.

- lane position algorithm (for lateral motion only)

Tilt-coordination is to be used only when there is no better choice i.e. when sufficient linear stroke is not available. When the vehicle is on a straight road, possible lateral movements are limited and, once scaled with a factor, can be directly restituted by the linear actuator if it is large enough. This is the so-called lane position algorithm (LPA), described in [10], which is implemented in our MCA as well. LPA main difficulty is the design of a continuous switch between this algorithm and the tilt-coordination one. During transition phase, depending on driver behavior, this continuous switch may create false cues (see figure 4). They should be reduced as much as possible, while the switch has to be suitably tuned to still permit pre-positioning before the next curve.

Simulation results

Before implementation in our SHERPA software, this MCA has been designed and tested using Matlab/Simulink. The simulated driving situation chosen in this paper is a double lane change followed by a 100m radius curve. Driving speed is about 70 km/h and a constant 0.5 scale factor is used for a simpler comparison. The cell is in normal position, which means that available total stroke in lateral direction is 5.5m.

Figures 3 and 4 compare equivalent acceleration from our MCA (A simulations) and from a classical approach MCA (B simulations), to scaled vehicle acceleration (input). Tilt and linear stroke values are shown as well, for A and B simulations. Input values have been generated by a real driver driving our previous dynamic simulator.

Two cases are considered (fig. 3 vs fig. 4), depending whether the driver performs the double lane change well ahead of the curve, or not. For all these simulations, main MCA parameter settings are given in Table 3. Thresholds settings come from *subjective* tests made by PSA at VTI simulator in 2005 and 2006. Filter cut-off frequencies are different in A and B simulations, since they are chosen to use the best of the available stroke.

Scale factor (constant)	0.5
A cut-off pulsation (for A simulations only)	0.67 rad/s
B cut-off pulsation (for B simulations only)	0.97 rad/s
Damping ratio (for frequency filter)	0.7
Linear acceleration perception threshold	0.15 m/s^2
Tilt rate threshold at 0 m/s^2 linear acceleration	2 °/s
Tilt rate threshold at 1 m/s^2 linear acceleration	6 °/s
Tilt acceleration threshold at 0 m/s^2 linear acceleration	8°/s^2
Tilt acceleration threshold at 1 m/s^2 linear acceleration	11°/s^2

Table 3: parameter settings for A and B simulations

All these settings are still indicative: only driver-in-the-loop tuning once our simulator is operational, will hopefully confirm the pertinence of our choices (for the parameters and for the MCA itself).

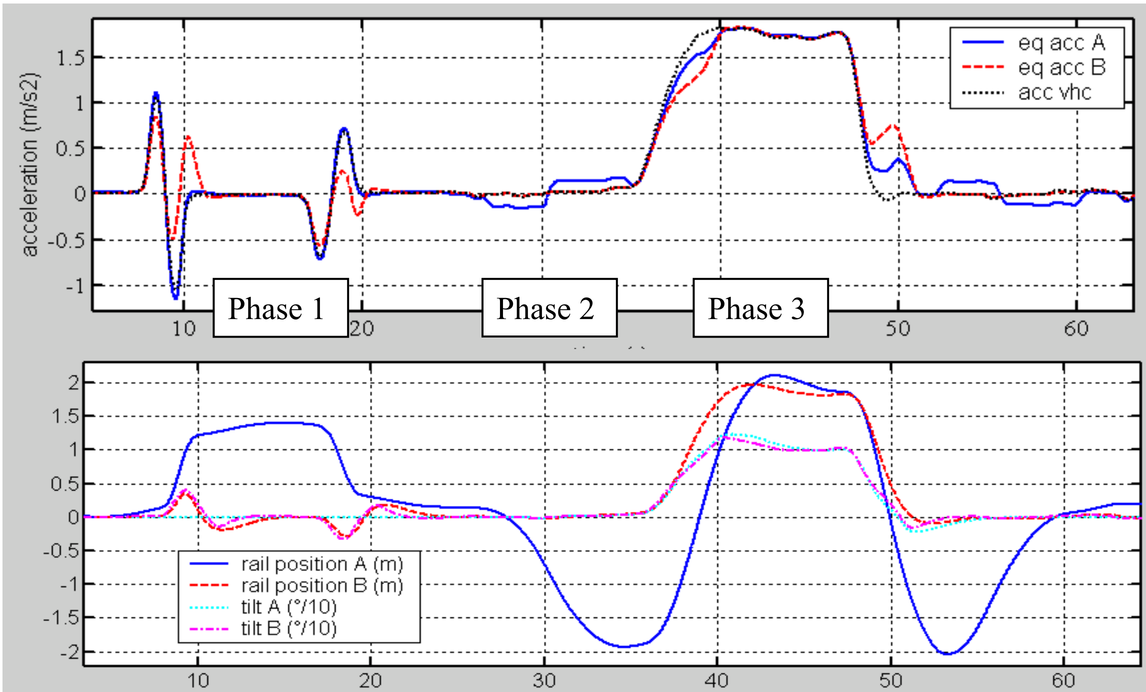

Figure 3: comparison results between our MCA (A) and classical algorithm (B)

In Figure 3, the lane change occurs well ahead of the curve. In that case, the MCA has enough time to switch from LPA to pre-positioning phase and then, to the classical algorithm (CA). Figure 3 shows a better acceleration profile for our MCA, with generated false cues very close to the supposed perceptive thresholds. During phase 1 (double lane change), false cues are suppressed; during phase 2 (pre-positioning), equivalent acceleration errors are generated but they are under supposed perception threshold. In phase 3 (curve), equivalent acceleration errors are divided at least by two and false cues probably by a lot more (since we have to subtract linear perceptive threshold).

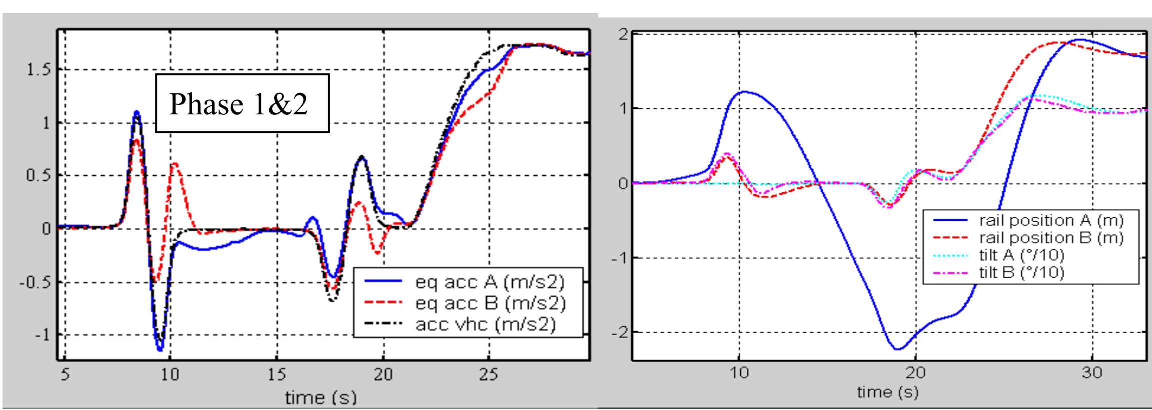

Figure 4: the driver performs a double lane change just before entering the curve

Figure 4 illustrates a similar but *a priori* less favorable case: the lane change occurs just before the curve. According to our algorithm, the switch between LPA and CA is then triggered during the lane change, to allow enough time to pre-position (the estimated value and necessary time of pre-positioning is computed on-line using cut-off frequency, threshold values and vehicle speed). Additional false cues are generated during phases 1&2, which happen simultaneously in that case. Nevertheless, equivalent acceleration is still less deformed with our MCA than with classical MCA, with a better use of available stroke. Indeed, pre-positioning provides more available stroke when needed, which allows to choose a lower cut-off frequency (for the same maximal stroke use), hence reducing equivalent acceleration deformation and false cues.

4. Conclusion

The PSA Peugeot-Citroën Advanced Driving Simulator aims to be a tool for validation and test of automotive systems in the whole range of dynamic driving simulation. The newly added XY moving base has been designed to do so, while keeping most of the software and experience from our previous dynamic simulator.
To fully benefit from this new motion base, a specific MCA, based on tilt-coordination and road database use, has been developed. Simulation results are encouraging but a great amount of parameters (impacted by perception threshold values) will need to be tuned. As they depend mainly on subjective evaluation, this will be done only once the simulator is operational, e.g. from September 2007 on. The simulator global performance will then be the result of the our design choices, the good achievement of them, and a good MCA parameter tuning.

References

[1] M. Kassaagi, T. Perron, E. Pean, H. Guillemot, J.-C. Bocquet, J.-Y. Le Coz, Study of the drivers' behavior in rear-end collision situations on driving simulator. Driving Simulation Conference, Paris 1999
[2] M. Dagdelen, J.-C. Berlioux, F. Panerai G. Reymond, A. Kemeny, Validation process of the ultimate high-performance driving simulator. Driving Simulation Conference, Paris 2006
[3] EL. Groen, W. Bles How to use body tilt for the simulation of linear self motion. Journal of Vestibular Research; 14(5):375-85
[4] D. Gualino, J. Adounkpe, Force-Feedback System Design for the Steer-By-Wire: Optimization and Performance Evaluation, IEEE Conference on Intelligent Transportation Systems, September 2006
[5] LD Reid and MA Nahon, "Flight Simulation Motion-Base Drive Algorithms: Part 1 - Developing and testing the equations" UTIAS Report n°296, December 1985
[6] Dagdelen, M. Restitution des stimuli inertiels en simulation de conduite. Thèse de Doctorat, Ecole des Mines de Paris, 2005.
[7] Lloyd D. Reid and Meyer A. Nahon. Response of airline pilots to variations in flight simulator motion algorithms. Journal of Aircraft, 25:639–646, 1988.
[8] Clement, G., Moore, S.T., Raphan, T., Cohen, B. Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight. Exp. Brain Res. 138:410-418, 2001.
[9] S. Nordmark, H. Jansson, G. Palmkvist, H. Sehammar, The new VTI driving simulator. Multi-purpose moving base with high performance linear motion, Driving Simulation Conference, Paris 2004
[10] P. Grant, B. Artz, M. Bloomer, L. Cathey, J.Greenberg, A paired comparison study of simulator motion drive algorithms, Driving Simulation Conference, Paris 2002