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A high performance / low-cost mini driving simulator alternative for human factor studies

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ABSTRACT

Nowadays, thanks to the improvement of PC technology, it is possible to design high quality visual loop at low cost. Since human factor studies implies a minimal "ecological" immersion, the direct use of ultra low-cost game hardware is not acceptable: the ergonomics of the driving cab and the cues of the various controls (steering-wheel, pedals, gearbox if any...) are insufficiently realistic.

Driving simulators have been used for some years for initial training. Many car driving simulators have been designed for that particular purpose. The cab is often representative of an actual one and cues are sometimes acceptable. This kind of tools could be used for research purpose. Unfortunately they are not open to any modification (models, databases, scenarii...) and thus do not allow to undergo experiments.

Based upon, in the one hand, INRETS experience in simulator architecture design for human factors studies, and, on the second hand, FAROS experience in the design of low-cost driving simulators for training purpose, our new tool is a good compromise between performance and cost. It is dedicated mainly to research studies. This tool uses FAROS hardware (driving cab) and INRETS electronics and software.

A particular emphasis has been put on the development of a haptic feedback steering-wheel . The aim is to help the driver on the fixed-base simulator, thus without any kinestesic feedback, to drive the virtual model. Two modes have been implemented. The first one, based upon a car dynamic model, uses virtual reality techniques coming from teleoperation domain. The second one mixes the previous one with a lane-keeping model.

In this paper we introduce the architecture of the simulator and describe the designed steering-wheel haptic feedback system. Then we discuss the various possible uses of the tool. We conclude with perspectives in terms of development. Results of an experiment are also presented.

INTRODUCTION

Pushed by the SOHO game market, the technology of the "low cost" PC graphical engines has made recent progress, which allow their use for a quite good visual rendering. However, problems already exist with aliasing but one can expect that they will disappear in the near future.

Coming one more time from the SOHO game market one can find some devices like pedals or steering wheels with force feedback, but the quality of the haptic cue provided to the driver is poor for a reasonable "ecological" immersion. Due to the limited capacity of the actuators, the diameter of the steering-wheels is very small and far from actual one.

In the driving simulation area one can find some products (steering-wheel, pedals, gearbox) which looks more like the actual ones. These devices come with simulation software, and offer a "low cost" (about 40 000 Euros) solution for people wanting an operational "mini" driving simulator for research purposes. However, we identify three limits for these kinds of solutions:

1. there is no cab at all, thus the immersion is very poor
2. on systems we tested, and focusing only on the haptic devices, the feedback provided was not very good
3. the cost/quality ratio is also quite poor.

In the training area, one can find products which integrate mini-cabs with haptic devices (sometime small motion base), and all the training software applications. Some products are quite good and cheap (the first price at around 10 000 Euros). Unfortunately, the software, dedicated for training purpose, is proprietary. These solutions do not appear to be pertinent for research and development use.

Based upon the know-how gained on our previous driving simulator construction, INRETS MSIS team decided to design a "high performance" / "low cost" mini driving simulator tool for research and development purposes. This work took place within the French National PREDIT project ARCOS, for which MSIS had to provide two human factors research labs with mini-simulators facilities.

HARDWARE & SOFTWARE ARCHITECTURE

For more than ten years, INRETS MSIS team has been developing the ARCHISIM traffic model and the SIM² architecture, which offer the original capability to host a driving simulator within the traffic model (2, 3). We distinguish the traffic animation models, which are not validated in terms of traffic theory, from the traffic simulation models, which are. When suited for hosting driving simulators, traffic simulation models offer new capabilities in terms of human factors studies and impact on traffic capacity and safety (4).

Since SIM² architecture is efficient, simple, robust, and open, we decided to use it as the kernel of this new driving simulator.

Concerning the cab, we found an agreement with the FAROS company. Faros sells training car simulators, and had just started a product based upon a new mini-cab (cf. Figure 1). This mini-cab includes a generic dashboard, safety belt, park brake... but the steering device was not interactive. So we decided to improve it by designing an "haptic" feedback.

A key point of the INRETS SIM² architecture is the use of a dedicated electronic board for managing the simulator cab. This electronic board (cf. Figure 2) is called CEGI (i.e. Generic Instrumentation Electronic Card); it is based upon the use of an automotive micro-controller that allows:

1. to avoid real-time problems when using "on the shell" Operating Systems, and also the fastidious quest of driver's update...
2. to separate actuators controlling processes from the car dynamic model computation process;

3. to use the micro-controller for computing time-critical sub-models;
4. to allow a flexible adaptation to various cabs by software options.

We currently use this electronic board for computing the “haptic” feedback.

Figure 1: FAROS mini-cab

Figure 2: INRETS CEGI

Using ARCHISIM and SIM² we can distribute the various simulation modules over various, and possibly heterogeneous, computers, with a few technical limitations explained bellow. Since our visual module is based upon the use of the SGI Performer software library, we can use either a SGI or a PC for visual rendering. Since this library is nowadays not fully reliable on Windows, we used Linux for hosting the visual module. Our 3D sound library is based upon the AEX library, thus for the time being we need to host this module on Windows. Due to these few constraints we suggest the current “low cost” architecture for hosting our various simulation modules:

1. CEGI for steering wheel model and cab management;
2. PC (Windows) for pavement, car dynamic, traffic, 3D sound models;
3. PC (Linux) for the visual rendering.

Our choice is not between Linux and PC, but relies upon the availability of sound facilities and libraries. As soon as Performer library reaches the same reliability on Windows, we will suggest mono PC (Windows) solutions (either mono- or bi-processor, according to the complexity of the expected simulated road situations). As soon as we port our sound facility on Linux world, we will suggest mono PC under Linux.

THE “HAPTIC” STEERING WHEEL

The INRETS MSIS driving simulators are dedicated for human factors studies. Since it is impossible to provide the driver of a simulator with all the actual experienced accelerations, we promote the concept of “psychologically” realistic simulator. In other words we think that the validation of a simulator has to be done by validating the driving tasks on the simulator, and not by validation on the various sub-models that make the simulator.

We designed the “haptic” steering wheel based upon this idea. Thus the model deals with the efforts endured by the driver. The goal is to let the driver endure inertia, stiffness, and friction that come actually from road/tyres interaction, steering system... We naturally chose to promote a teleoperation model (cf. Figure 3) because that kind of model focuses on the rendering of “haptic” sensations (1).

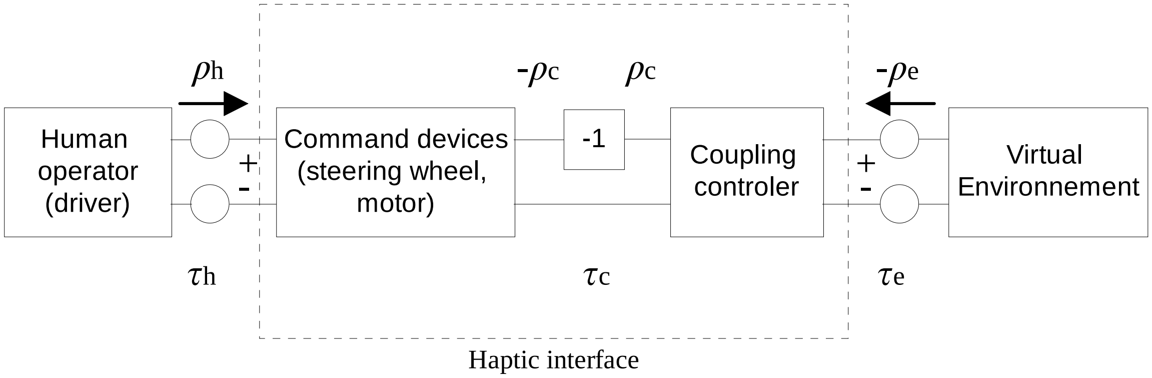

Figure 3: generic virtual reality haptic interfacing model (also adapted from teleoperation techniques)

In our case the virtual model consists in two simplified sub-models dealing with road/tyres interaction and with the steering system. This model calculates the main forces experienced in real vehicles. Depending on the roll angle, the steering wheel angle and the speed of the vehicle, the lateral force and the normal force are computed in real-time. These forces stimulate the virtual model which computes the steering-wheel torque.

Our haptic interface uses a motorised steering-wheel composed of a CC actuator driven by a Pulse Width Modulation signal (PWM). The coupling controller acts as a viscous-elastic system linking two inertia. One of the advantages of this model lies on its few calculations, which makes it adequate for real-time haptic feedback. Consequently this model is embedded on our CEGI card (cf. Figure 4).

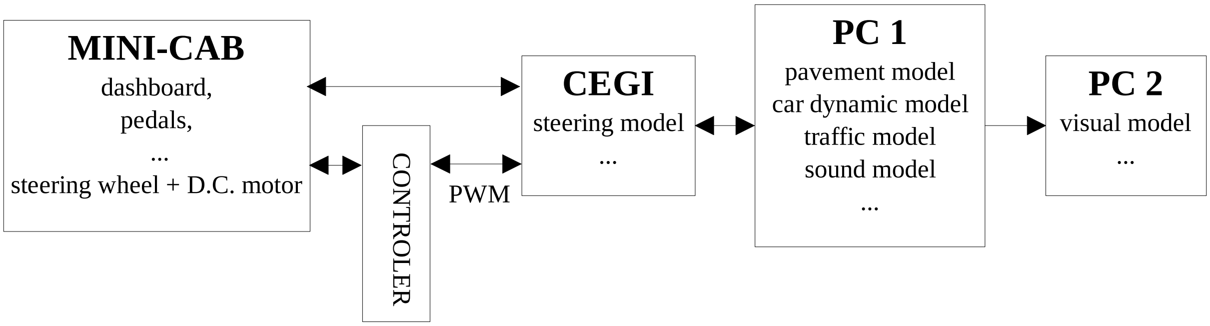

Figure 4: general architecture of the simulator

HAPTIC" STEERING WHEEL WITH DRIVER ASSIST SYSTEM

A well known reason of lateral control difficulty in a driving simulator is the latency, which is the time between driver input and the response evaluated by visual cue. The bet is important, since, for the driver, difficulties to laterally control the virtual vehicle imply often either simulator sickness or a driving task which is far from the actual one in terms of workload.

In order to reduce these effects, we decided to design a driver assist system based upon automatic lane keeping technique (6,7). Our solution to help the driver is a predictive lateral control algorithm with haptic feedback assistance. This algorithm acts like a phase corrector on the simulator response.

Before explaining our algorithm we have to explain what we call "neutral point". The neutral point is the condition of equilibrium of the steering-wheel when the vehicle speed is not equal to zero. If the speed is not null and if the steering-wheel is not in neutral position, the self aligning torque of the front wheels generates a torque at the steering-wheel. This torque tends to bring back the steering-wheel in neutral position.

When there is a constant speed, and on regular tyre adherence of the wheels, the feed back of the torque on the steering

$$C_{COL} = k.f(v).(\theta_2 - \theta_1)$$

column is principally a type of self aligning torque. This torque is proportional to the steering wheel angle, and one can say that:

with k constant, *f(v)* parameter depend on the vehicle speed, θ_2 steering-wheel angle, θ_1 angle of the « neutral » point and Ccol torque of the steering column.

When a driver takes a curve, he positions the steering-wheel in order to give the vehicle the desired direction. For a constant radius curvature the position of the steering-wheel is constant. When entering the curve (zones with uniformely various curvature radius) the position of the steering-wheel goes from « neutral » to the position forced upon by the curve curvature radius. When exiting the curve the phenomenon is reversed.

Our proposed algorithm is aiming to help the driver to position his steering-wheel in the appropriate way, to couple the neutral position and the steering-wheel position imposed by the road design. It is made possible by using the local control loop of the motor D.C, which is as follows:

$$\tau_c = \tau_r + c_\tau(s)(\tau_r - \tau_h)$$

with τ_c, control torque, τ_h operator's torque (driver), c_τ torque corrector (PI type), τ_r reference torque. The reference torque is the torque the driver should feel through the steering-wheel.

We simulate a sensor that provides our system with information about the expected position (let say P1) of the vehicle 30m ahead (with the hypothesis that the vehicle keeps the same lateral position relative to the road). We then use this information for calculating the difference between the current "heading" and the "heading" defined by the current position and P1 (cf. Figure 5).

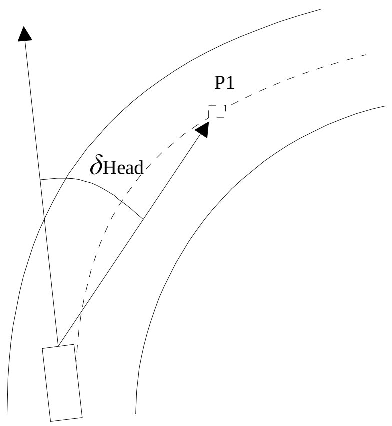

Figure 5: driver assist system concept

This difference is finally taken into account by the steering wheel system. Operatively, the system moves the “neutral” point of the steering-wheel at the suitable position θn to reach P1.

$$\theta = \theta_n + c_{Heading} \times dHeading$$

with $c_{Heading}$ PD type corrector.

Of course, with this algorithm, the driver can override the proposed position.

Some pre-tests, conducted with five subjects, demonstrate that the general feeling was good for straight sections but quite bad for the sinuous ones. We analysed this result in the following manner: in straight sections the vehicle goes naturally straight thus the driver does not actively interact with the steering wheel. In sinuous section the driver takes the control and does not want to share this activity. For the driver the system appears in the first case as an assist system, in the second one as an element disturbing his control process.

Consequently, we proposed a second version of the system, which tries to correct the problem. In this second version we adapt the behaviour of the system to the curvature of the road. For straight sections we keep the previous algorithm, for sinuous parts we reduce the algorithm effects. In this case, the effect of the support system is undetectable for the driver; so far the difference, between the current heading and the algorithm expected one, is low.

VALIDATION

In order to validate the proposed system we conducted some experiments, for the assessment of the driver’s performance when the “haptic” steering-wheel systems are used. We designed the experiment in order to study driver’s performance for various levels of difficulties when keeping the virtual vehicle on its lane. The studied indicators were lateral deviation and relative heading between the virtual vehicle and the road.

In order to allow comparison between the performance indicators, we chose to use fixed speeds 65km/h and 85 km/h (the subjects had only the control of the steering wheel). The network consisted in a rural 2-lane road (cf. Figure 6). The road was very sinuous, with 10 curves (curvature: 400m, 150m and 75m). Traffic came in opposite direction, so the driver had to stay on his lane.

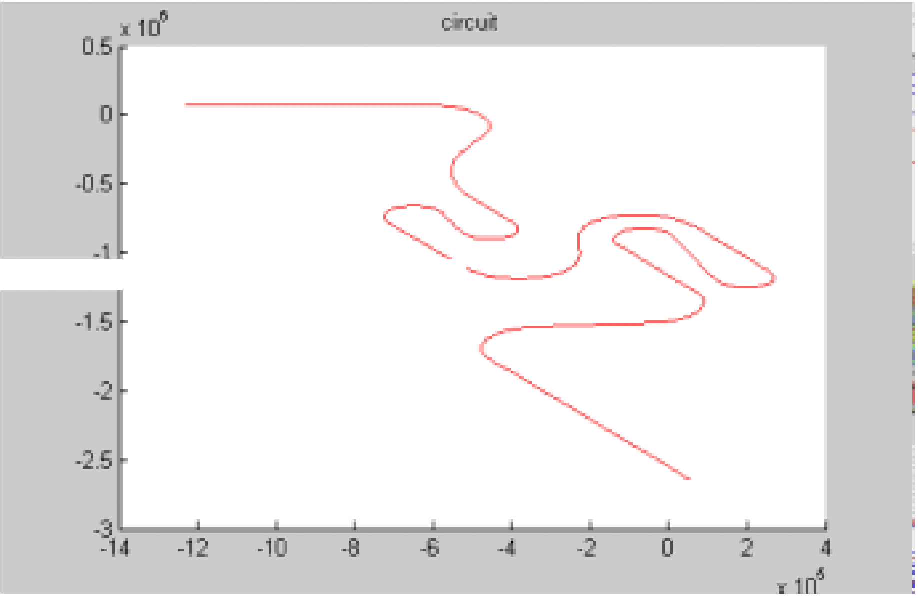

Figure 6: road used for experiment (in millimeter)

We studied three modalities: 1) without steering cue, 2) “normal” steering cue and 3) steering cue with the assist system.

Twelve people took part in the experiment. Trial order was randomised.

On the basis of a previous study (5), we focused our analysis on straight sections and on the straight sections following the curves (40-m sections after the curves).

RESULTS

The following figures summarise the results (where SWHFF means Steering Wheel Haptic Force Feedback).

1. Relative heading

Simple result speed:

Speed	Averages of varaiances of relative heading
85	0,40
65	0,19

There is a simple result of speed: at 85km/h relative heading is significantly higher than at 65km/h

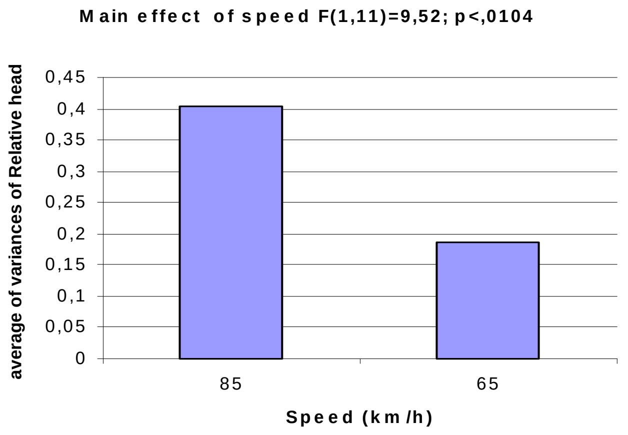

Figure 7

Simple result of steering-wheel:

Steering-wheel	Average of varaiances of relative heading
without SWHFF	0,49
SWHFF	0,25
SWHFF + driver assistance	0,15

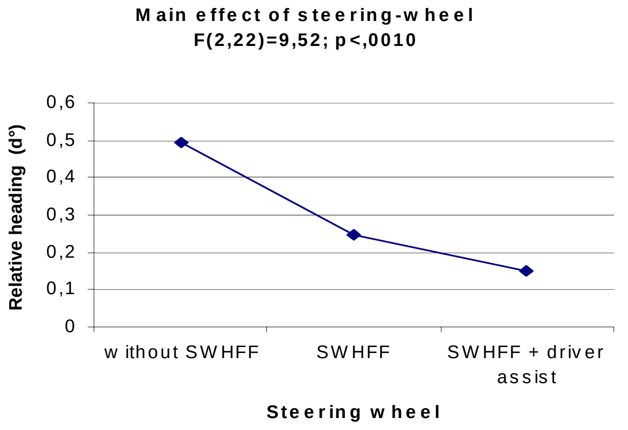

Figure 8

post-hoc test of Newmans and Kheuls:

	without SWHFF	SWHFF	SWHFF + driver assist
without SWHFF			
SWHFF	0,006		
SWHFF + driver assist	0,001	0,25	

There is a simple result of the steering-wheel: without driver assistance, the relative heading is significatively higher than with SWHFF or SWHFF+ driver assist (respectively p<0.006 et p<0.001). one ca also note that the SWHFF+

driver assist tends to lower the variance of relative heading of subjects compared with SWHFF condition.

Result of the interaction Speed x Steering-wheel modality:

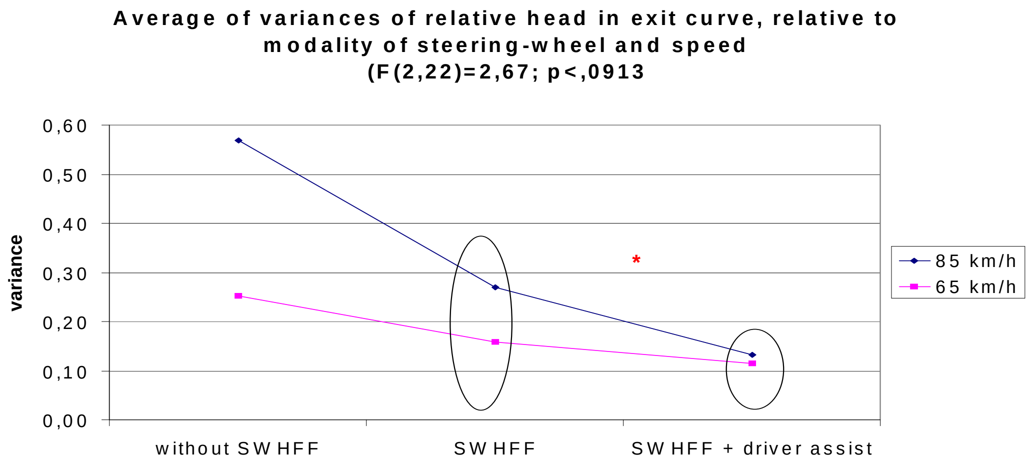

Figure 9

Post-hoc planned comparisons show that speed has a significant impact on the modality of the steering-wheel: the difference in relative heading is significatively higher with « SWHFF » than in condition of « SWHFF+ driver assist » (planned comparison F(1,11)=5.08 ; p<.05). In other words, the difficulty due to high speed (85 km/h) witnessed with SWHFF, is less with SWHFF+ driver assistance.

2. Lateral position

Impact of speed:

Speed	Averages of variances of lateral deviation
85	63434,09
65	23959,62

There is a simple impact of speed: at 85 km/h lateral deviations are significatively higher than at 65 km/h.

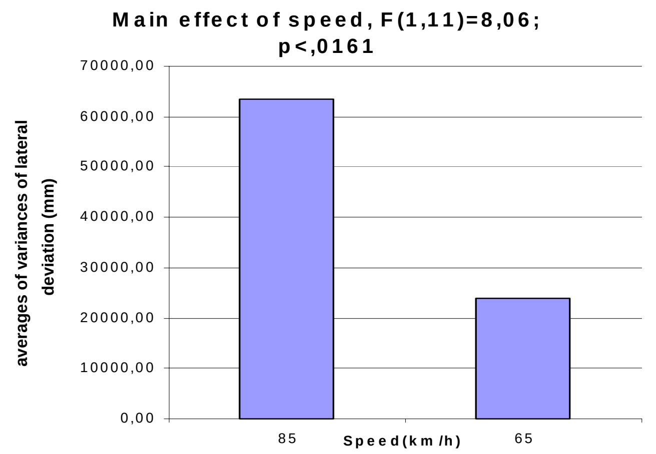

Figure 10

Impact of modality of steering-wheel:

Steering wheel	Averages of variances of lateral deviation
without SWHFF	74278,73
SWHFF	36544,72
SWHFF + driver assist	20266,95

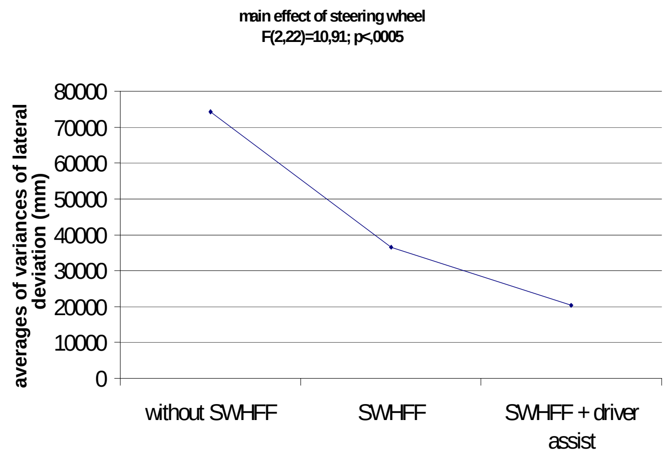

Figure 11

Post-hoc test of Newmans and Kheuls

	without SWHFF	SWHFF	SWHFF + driver assist
without SWHFF			
SWHFF	0,005		
SWHFF + driver assist	0,001	0,25	

There is a simple impact of the steering-wheel: without SWHFF, the lateral position is significatively higher than with SWHFF or SWHFF+ driver assist (respectively $p<0.005$ et $p<0.001$). it is also observed that the SWHFF + driver assist tends to decrease the variance of lateral deviation compared with SWHFF condition ($p<0.25$).

Impact of interaction Speed x Modality of steering-wheel

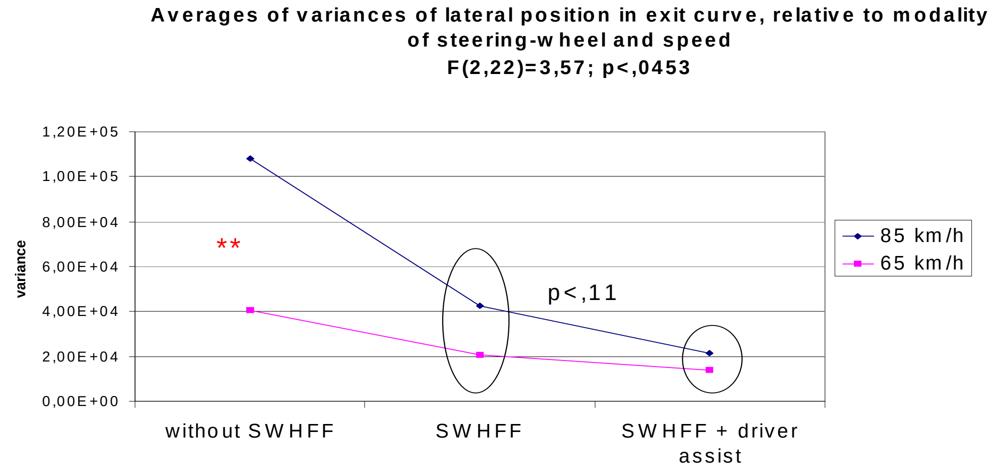

Figure 12

There is an interaction "Speed x Steering-wheel modality": without SWHFF+ driver assist or SWHFF at the steering-wheel, the variance of the lateral position is significatively higher at 85 km/h than at 65 km/h (post-hoc test of Newmans and Kheuls $F(1,11)=6,53$, $p<.02$). One can also note that the driver assist tends to lower the variance of the lateral position of the subjects relatively to the condition "SWHFF" (planned comparison: F(1,11)=3,01, p<.11), i.e. the driver assist tends to lower the effect of of difficulty due to speed.

One can see that steering wheel cue improves the driver's performance by a significant decrease of variances measured between the "without SWFF" condition and " SWFF or SWFF +assist" condition. (figure 8,11), it is demonstrated our proposed support system is improving the driver's performance.

When the speed increases the level of the driving of the simulator difficulty grows, the variance of the relative heading is significantly reduced with SWFF + driver assist compared with SWFF condition (figure 9). It seems to show that the more the control of the virtual vehicle is difficult the more the assistance system is indeed useful.

The reduction of variance of the lateral deviation between SWHFF et SWHFF + driver assist is non significant as showed in fig 12. This is probably caused from the reduced number of subjects and/or the small degree of difficulty resulting from the low speed of 85 km/h. Nevertheless we can witness that SWHFF + driver assist tends strongly to reduce the compared variance to the condition SWHFF.

CONCLUSION

The new "mini-driving" simulator we designed is now efficient and used in two human factors labs. It mixes the better of two worlds in order to offer a "low cost" / "high quality" solution for research and development studies related to human factors. From the commercial training simulators it uses the "real-like" but low cost mini-cab. From the research simulators it use the opening, the respect of some *de-facto* standards, the modularity and evolutivity aspects.

The "haptic" steering wheel we designed is simple, low-cost and the subjective opinions are that it offers a good "haptic" feedback, also when the vehicle is stopped. At least, for a fixed base-driving simulator, the driver assist system we developed seems to help keeping the vehicle on the lane.

The experiments we conduct focus on driver's performance and show that the lateral control task seems easier with the assist system. However, we have now to assess the workload of the driving task. That will be the purpose of a future experiment where we will use a secondary task in order to estimate the cost of the lateral control one.

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