Speed and safety distance control in truck driving: comparison of simulation and real-world environment.

F. Panerai [1] **, J. Droulez** [1]
J-M. Kelada [2] **, A. Kemeny** [2,1]
E. Balligand [3] **, B. Favre** [4]

[1] CNRS/Collège de France, 11, pl. M. Berthelot,75005 Paris, France
[2] RENAULT Research Department, Driving Simulation and Virtual Reality
Technocentre Renault, 1, Av. du Golf, 78288 Guyancourt Cedex, France
[3] RENAULT V.I. Complete Vehicle Department
99, route de Lyon, 69802 Saint-Priest Cedex
[4] RENAULT V.I. Research Department
99, route de Lyon, 69802 Saint-Priest Cedex

Abstract

The present study compares the results of tests performed on speed and distance control by 8 professionals drivers on both Renault-V.I. truck simulator and on real trucks. Simulation tests were also run employing 30 non-professional drivers. The simulation environment featuring a moving platform, acoustic feedback and sophisticated visual rendering for frontal and rear viewing, provides a full-immersive truck driving environment. In separate experimental sessions, the drivers were required: i) to control the speed of the truck without reading the tachometric information, ii) to maintain the appropriate safety distance with respect to a preceding vehicle. The drivers' behavior was analyzed under different configurations of the simulation environment: day vs. night illumination condition, presence vs. absence of acoustic feedback and for two different simulated height of the truck's cabin. For professionals, in addition, we compared the performances obtained in simulation as well as in real-world situations.

In simulation, both groups of subjects drove at speeds very close to, and highly correlated with target values. For professional drivers, speeds in simulation were also highly correlated with real-world performance data. Professional drivers maintained a safety distance in simulation which was twice as great as the distance measured in real-road conditions. The analysis of variance of the safety distance revealed a significant main effect of the driving condition (i.e. simulation vs. real-road). Non-professional drivers, in simulation, maintained safety distances which were significantly higher (47% on the average) than those measured for professional drivers. Beside these findings, in simulation all the drivers were asked to report verbally the absolute distance of the preceding vehicle. In most of the cases, their judgment indicated a large underestimation of the distance, which could explain the difference observed between simulated and real-world environment driving.

Résumé

Cette étude vise à comparer la vitesse de conduite et la distance de sécurité de 8 conducteurs professionnels sur le simulateur Renault-V.I. et sur des véhicules poids-lourds réels. 30 conducteurs non-professionnels ont aussi participé aux essais sur simulateur. Le simulateur Renault-V.I. est constitué d'une plate-forme mobile, avec retour auditif et retour visuel frontale et arrière, permettant ainsi une immersion totale des sujets. Lors des différentes sessions expérimentales, la tâche des conducteurs était de (i) contrôler la vitesse de conduite sans avoir recours à la lecture du tachymètre; (ii) maintenir une distance de sécurité appropriée par rapport au véhicule précédent. Nous avons analysé le comportement des conducteurs sous différentes conditions de simulation: conduite de jour/ conduite de nuit, présence/ absence de retour auditif et pour deux hauteurs simulées de la cabine du tracteur. Les performances des conducteurs professionnels obtenues sur simulateur ont de plus été comparées à leurs performances en environnement réel.

Cette étude a montré qu'en simulation les deux groupes de sujets on conduit à des vitesses très proches de la vitesse demandée. Les conducteurs professionnels ont de plus adopté une vitesse très proche de leur vitesse de conduite en environnement réel. En revanche, la distance de sécurité qu'ils ont maintenu en simulation correspond à deux fois la distance mesurée en environnement réel. L'analyse de variance de la distance de sécurité a démontrée une différence significative entre conduite réelle et simulée. Le conducteurs non-professionnels ont maintenu en simulation une distance de sécurité significativement plus importante (47% en moyenne) que celle mesurée pour des conducteurs professionnels. Par ailleurs, nous avons demandé à tous les conducteurs de fournir verbalement une estimation de distance absolue (les séparant) du véhicule précédent. Leurs réponses ont révélé une sous-estimation systématique de la distance, qui pourrait expliquer les différences observées entre conduite en simulation et conduite en condition réelle.

1 Introduction

Building realistic and effective driving simulators requires a huge amount of engineering knowledge and a deep expertise of the perceptual processes underlying driving behavior. Driving is, first of all, a sensory-motor and cognitive activity in which patterns of sensory information are analyzed and exploited to control the state of the vehicle. It is somehow obvious that one of the main concerns of designers and users of driving simulators is to know to what extent the control strategies and the decision-making rules used by the drivers in real-world situations are transposed with fidelity in simulation conditions. Beside this point, designers are often confronted with the problem of evaluating the consequences that a modification in a simulation parameter may induce (or not) in the driver behavior. In the majority of studies on driving simulation (see for example [9], [21], [2]), the behavior of the driver is analyzed at the methodological level using particular behavioral indicators, also called behavioral signatures (for example, speed, lateral position, steering wheel angle and pedals). Indeed, these measurements represent the end product of a driving performance, and as such they may be insufficient or inaccurate to characterize the transient behavior of the driver (see for example [1], [8]). On the other hand, if the object of the study is not related to the transient behavior of the driver, then behavioral signatures directly related to the driving subtask are valuable indicators of the driver performance. In this work we present the validation study performed on the Renault-V.I. dynamic truck simulator. The validation framework has been conceived with a double perspective: on the one hand as a *comparative* study, with the goal of contrasting the behavior of the driver in simulation and in the real road. On the other, as an *in-depth* investigation in simulation, aimed at identifying the influence that specific parameters of the simulation environment may have on the driver behavior.

The validation study has been focused on two driving tasks: the control of *speed* and of the *safety distance*. For both tasks, the comparative approach has been pursued. In addition, especially in the case of speed control, an in-depth investigation of the role of simulation parameters has been performed. Simulation parameters such as the height of the viewpoint, the acoustic feedback and the illumination condition has been assessed. In this part of the study, parameters were changed one at a time and the effects produced by each change were compared with the behavioral signatures obtained for a nominal configuration of the simulated environment (i.e. a predefined set of parameters). The paper is organized as follows. Section 2 introduces to the Renault-V.I. truck simulator. Section 3 defines and present the speed control experiment. In section 4 the safety distance experiment is described. Subsections of each main section present the results consequent to a modification of a single simulation parameter. In most instances, a systematic change in the behavior of the driver is observed. In section 5 the comparison real-world vs. simulation and the effects of the simulator parameters are discussed, together with the differences found between the population of professional and non-professional drivers.

2 The Renault-V.I. truck simulator

The Renault-V.I. driving simulator is represented schematically in Figure 1. It is composed of a moving base and a multi-screen display for frontal and rear viewing. The frontal display is obtained by stationary screens which provide 180 degrees of horizontal visual field. The rear viewing is provided through two independent screens appropriately positioned with respect to the rear-view mirrors. Frontal and rear images are generated at a frequency between 30 and 60 Hz, respectively by an SGI Infinite Reality workstation and two

Pentium III PCs equipped with Quantum 3D Voodoo 3 graphics boards. Display is obtained for frontal viewing using 3 Barco CRT 808S projectors and for rear viewing using 2 Barco LCD projectors. The MOOG electro-mechanical platform features 6 axes, which are controlled independently at a frequency of 40 Hz. The platform moves a fully equipped, real Premium mockup. Active force feedback is provided on the steering wheel and the gearbox lever, and passive force feedback on the three pedals and the parking brake. In the current experiments, only four of the six axes were used. These axes enable vertical, longitudinal, pitch and roll movements. A comprehensive software package (SCANeR©II, 15 functional modules) developed by the Driving Simulation and Virtual Reality Research group of Renault was used to generate circuit scenarios, traffic conditions, to control vehicle dynamics and the image generation process [10]. Sound generation was obtained using a PC audio card, which reproduced the engine noise on the basis of the instantaneous driving conditions. Sound rendering was obtained by means of three loudspeakers positioned close to the simulator mockup.

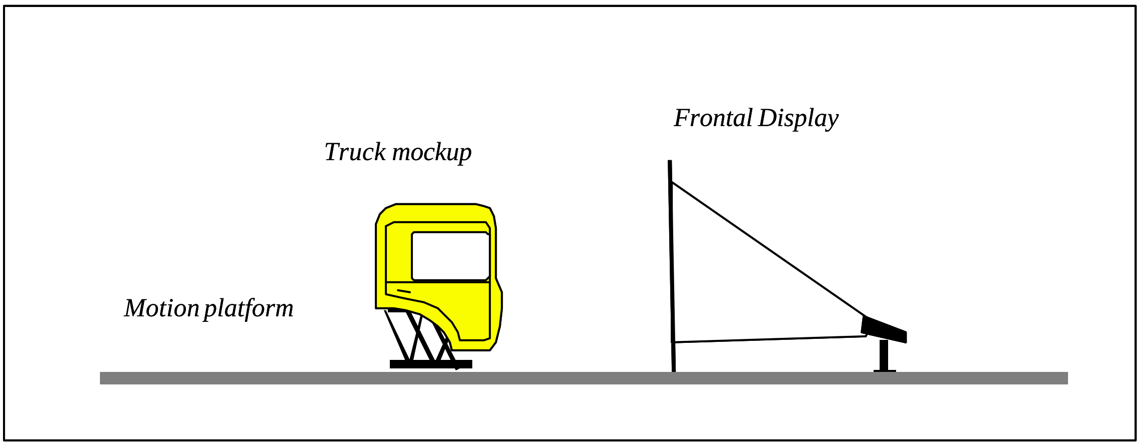

Figure 1. Schematic diagram of the Renault-V.I. truck simulator.

3 Experiment 1: speed control

The primary goal of the experiment was to compare the speed of a group of professional driver in two conditions: 1) real-road driving and 2) driving in the simulator. In both the real-world and the simulation, the truck instrumentation was masked (both the tachometric and the rpm indicator). Drivers were asked to drive naturally, respect the speed limits and follow speed instructions (i.e. the target speed). These were given to them across the different segments of the circuit. The target speed ranged from 40km/h to 80km/h.

3.1 Driving conditions

Real-road driving was performed in a country road located near Eyzin Pinet, France. A section of about 4 km was partitioned into five segments, according to the physical and topological characteristics (e.g. hilly, straight, tortuous and urban parts). A Premium truck with no trailer was used in the real-road driving situation.

The real-world circuit was fully reproduced in simulation. The virtual model was identical in terms of topology, changes in the elevation of the road plane, embankments and diggings. The model was appropriately and richly endowed of descriptive elements such as trees, houses, road signs.

3.2 Procedure

Four participants belonging to the Renault test pilot staff participated to both conditions of the experiment. They were familiar with the real-world circuit and with the truck simulator. Each driver covered the circuit (both the real and the simulated) for one practice lap (both directions). The practice lap was performed in absence of any feedback from the onboard instrumentation (i.e. tachometer, rpm indicator) and no particular instructions were given to the pilots, except the one of respecting the speed limits. The purpose was mainly to accustom drivers with the road topology.

More precisely, the task of the driver was: first, to respect any speed limits found along the circuit (i.e. speed panels were present in both directions) and second, to follow speed instructions issued along the circuit at the beginning of each new segment. In simulation, the instructions were given through an audio link from the control room. Each time a new target speed was communicated, the driver had to accelerate/decelerate to attain the new speed. The driver controlled the actual truck velocity according to his own perception of speed.

3.2.1 Simulation parameters

In the experimentation relative to the speed control, the role of the following simulation parameters was investigated: i) the height of the driver viewpoint, ii) night driving, iii) the acoustic feedback. The standard configuration of the simulation environment (i.e. control condition) was the following: 1) the height of the driver viewpoint corresponded to the real height experienced in a Premium truck. (i.e. the truck indoor ground floor measures 1430 mm). When this simulation parameter was modified, the new simulated height of the driver viewpoint was increased to correspond to the viewpoint experienced in a Magnum truck (i.e. indoor ground floor level is 1762 mm). The standard configuration of the remaining parameters were: 2) daylight illumination conditions; 3) acoustic feedback activated. One parameter at a time was changed in each experimental investigation.

3.2.2 Data recording and analysis

Vehicle speed was recorded throughout each driving session. In the real vehicle, embedded hardware sampled the instantaneous speed in real-time. The copilot used a laptop PC and a Renault proprietary software to record data at a frequency of 22 Hz. In simulation, speed data collection was performed at 20 Hz, using a dedicated software module of the SCANeR II environment.

The analysis of data was performed in terms of the average and standard deviation for each segment of the circuit. These parameters were computed independently for the outward and return path. Before the statistics was computed, a screening procedure was used to select the stable portion of the data for each segment. This screening consisted in analyzing the speed within each segment and determine the amplitude of the central interval containing stable values. Using this method, abrupt changes of the signal occurring at the transition from each segment to the next one, were excluded. In order to compare both performances in the real-world and in simulation, correlation measurements were used. We correlated the average speed across segments and the speed in simulation and in the real-world across the whole range of speeds.

3.3 Results

3.3.1 Real world vs. Simulation

The bar diagram of Figure 2 depicts the average speed across the five different segments. The *outward* (left side) and *return* (right side) path of the circuit are shown separately. Clearly, the real road speed (RW) and the speed measured in simulation (SIM) are highly correlated. The correlation measured along the different segments of the circuit is r=0.98. It is worth noting that in simulation standards deviation tend to be slightly larger than in real-road driving. Nonetheless, this difference could not be considered statistically significant for such a small population of drivers. Figure 3 shows the linear regression of the speed data in the real world and simulation conditions across the whole speed range (i.e. 40 km/h to 80 km/h). Interesting enough, the linear regression equation, $y=ax-b$, has the following coefficients: $a=1.05$ and $b=-2.6$ $(R^2=0.72)$. The a coefficient in particular, indicates an absolute validity for the driving speed in simulation. Moreover, the correlation of the speed data across the speed range (40 to 80 km/h) appears to assume also a relatively high value (r = 0.85).

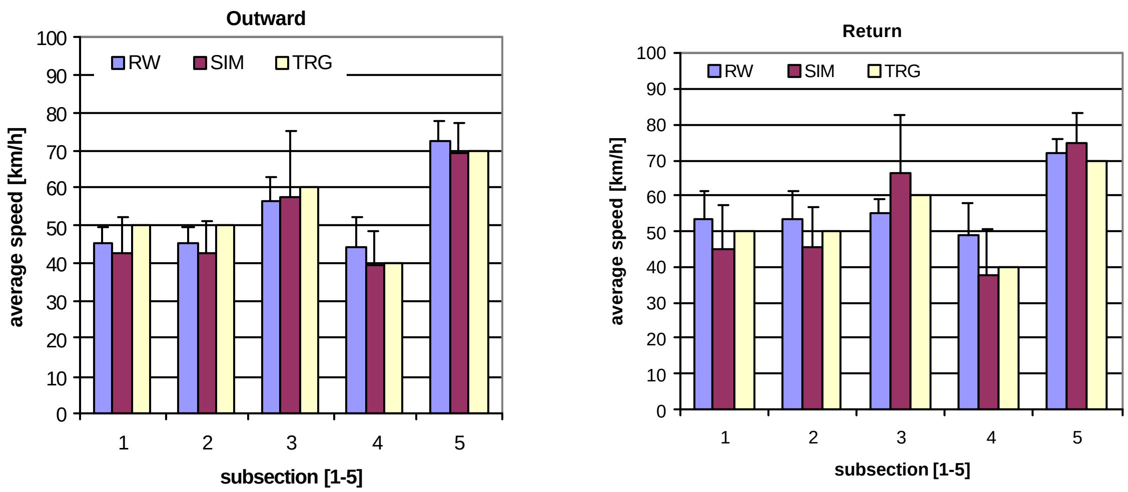

Figure 2. Speed control: average speeds along different segments of the Eyzin circuit. RW: real world. SIM: simulator, TRG: target speeds. The outward and the return paths are treated independently.

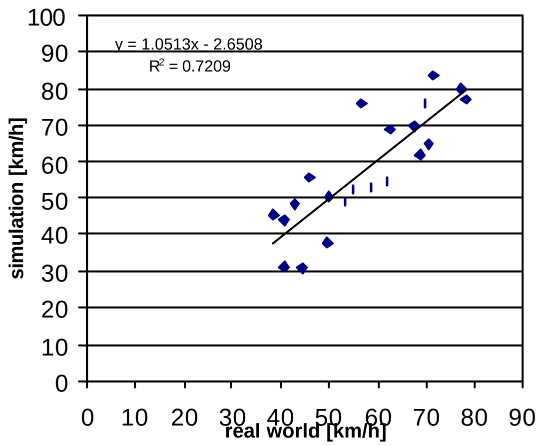

Figure 3. Speed control: relationship between simulator and real-road speeds.

3.3.2 Simulation: professional vs. non-professional drivers

Figure 4 shows the average velocity along the five different segments of the circuit for the professionals and non-professionals drivers. The design of a two between-group (*group factor* : pro, n-pro) analysis of variance was performed to test group effect on the speed data. The Raos R index [18] of significance ($R(5,10)=1.54$, $p<0.26$) indicates no main effect of the *group* variable (professionals vs. non-professional). Additionally, the correlation coefficient of the average speed along the different segments ($r=0.93$) seems to indicate a comparatively similar performance of the professional and non-professional drivers in the speed control task.

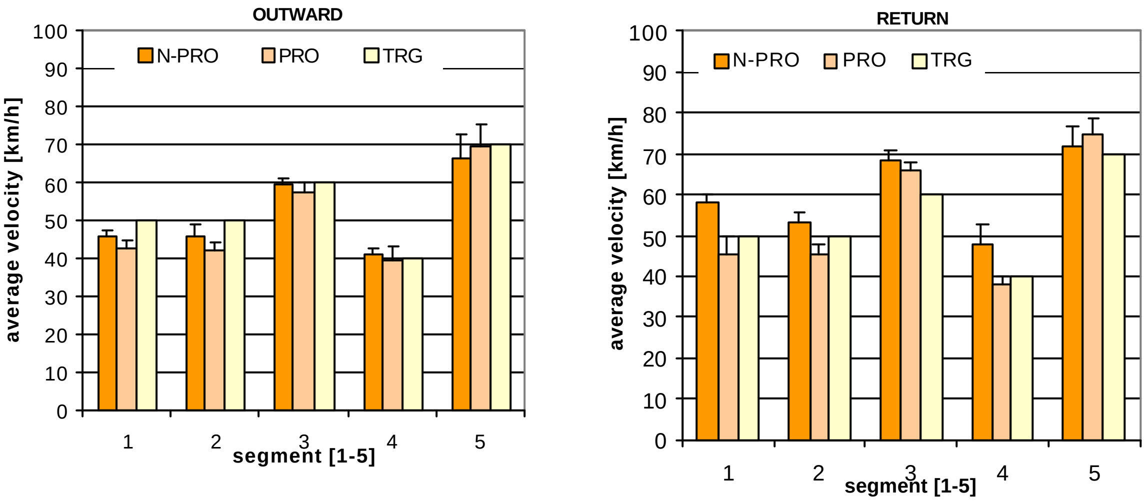

Figure 4. Speed control: professional and non-professional drivers. The left (OUTWARD path) and right (RETURN path) plots compare the average velocity for professionals (PRO) and non-professionals (N-PRO) drivers. Target speed (TRG) is also reported for each segment of the circuit.

3.3.3 Simulation: the height of the driver viewpoint

The influence of the height of observer viewpoint on the perceived velocity was tested in this experiment. From geometrical considerations, the higher the driver viewpoint, the lower the perceived speed of the ground surface (i.e. the road). A simple prediction follows: an increase in the simulated height, would induce the driver, who has not access to the tachometric information, to increase the speed of the truck. Figure 5 shows the average speed along the different segments of the circuit for the two configurations of the simulation environment: standard viewpoint (H), increased viewpoint (H+). Note that the average speed corresponding to the higher viewpoint (H+) is systematically grater. The increment measured in the H+ condition with respect to the control condition (H) is about 12% on the average. Although the systematic effect was observed along all the segments of the circuit, the analysis of variance on the average speed revealed no main effect of the viewpoint height on the four professional drivers ($F(1,3)=5.07$, $p<0.11$).

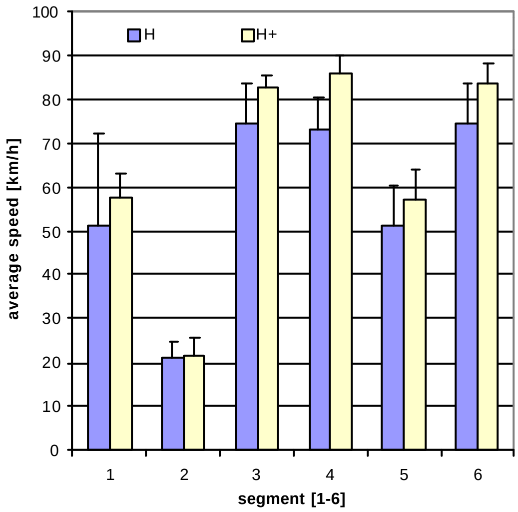

Figure 5. Speed control: the influence of the height of the driver viewpoint. The average speed along the different segments of the circuit for two configurations of the simulation environment: H standard height of the driver viewpoint, H+ increased height of the driver viewpoint.

3.3.4 Simulation: night driving

Figure 6 compares the average speed measured during day-time driving and night driving conditions. It is worth observing that during night driving, the average speed systematically increases. As a matter of fact, by switching to night driving condition, the driver visual field was reduced both in terms of angular amplitude and depth, the former comparatively more reduced that the latter. In night simulated condition, the driver was certainly confronted with impoverished peripheral visual signals. Assuming that the peripheral visual information (i.e. the induced peripheral visual motion) contributed to build an estimate of self-motion, the increment of speed observed in the data was somehow expected.

The increment is systematically present in all the circuit segments and from a numerical point of view corresponds to an average 9%. On the other hand, the analysis of variance performed on the speed data (factor were: *driving condition* (day, night) x 5 *segments* (1 through 5)) revealed no significant main effect of the *condition* factor ($F(1,3)=1.94$, $p<0.25$)). A second nonparametric test (i.e. Wilcoxon matched pair test) performed for each individual segment also revealed no significant difference (e.g. for segment five: $Z(4)=1.8$, $p<0.06$), although somehow close to a positive statistical significance.

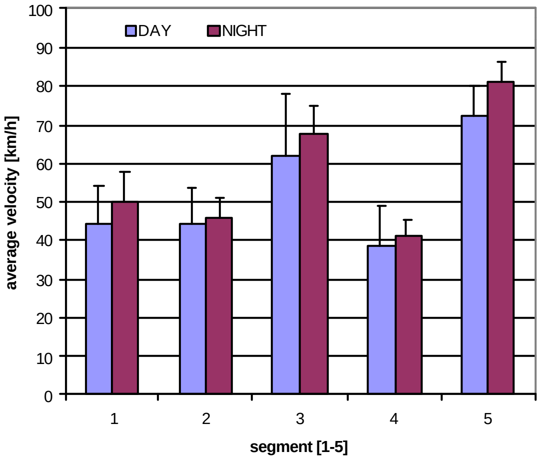

Figure 6. Speed control: driving in day time (DAY) and night time (NIGHT) conditions. The average speed measured along the five different segments of the circuit is reported**.**

3.3.5 Simulation: the acoustic feedback

The influence of the acoustic feedback on the speed control was tested in a repeated series of trials. In absence of the acoustic feedback, a systematic tendency to increase the speed was observed. Figure 7 shows the average velocity along the different segments in case of acoustic feedback activated (ON) or excluded (OFF). Note that, all segments except the segment 1, have standard deviation of comparable amplitude. If we restrain the comparison to segments which present a similar standard deviation, we can observe that the absence of the acoustic feedback (OFF) determine a systematic increase of the truck speed. Although the effect was systematically observed, the analysis of variance over the population of professional drivers (i.e. four drivers), did not reveal a significant difference between the two conditions ($F(1,3)=1.65$, $p<0.28$).

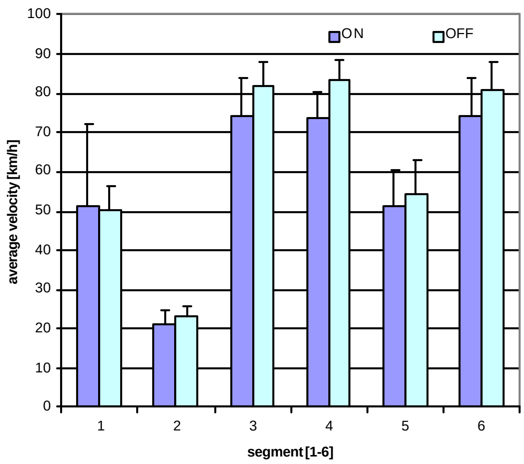

Figure 7. Speed control: the role of the acoustic feedback. The average speed for the two different configurations of the simulation environment: acoustic feedback on (ON) and acoustic feedback off (OFF).

4 Experiment 2: safety distance control

The primary goal of this experiment was to compare the safety distance maintained with respect to a preceding vehicle in two conditions: i) simulation, ii) the real-world. A group of professional drivers followed a vehicle the speed of which slightly varied along the circuit.

4.1 Driving conditions

The comparison real-road vs. simulation was performed using the same circuit of the previous experiment. (i.e. Eyzin Pinet, France). A Premium truck with no trailer was used in the real-road experiment.

The investigation on the role of simulation parameters was performed on a different circuit, i.e. the TRaCS circuit. This circuit presents six different segments, which include departmental, village and highway types of road.

4.2 Procedure

Four participants belonging to the Renault test pilot staff participated to the two conditions of the experiment (simulated vs. real-road). They were familiar with the real-world circuit and with the truck simulator. Each driver covered the circuit (both the real and the simulated one) for one practice lap (both directions) before starting data collection. The practice lap was performed with no particular instructions to the pilots, except the one of respecting the speed limits.

The task of the driver was to maintain an appropriate security distance with the preceding vehicle (i.e. a Renault Kangoo).

4.2.1 Simulation parameters

In the current experimentation, only the role of the simulated height of the driver viewpoint was investigated. The standard configuration of the simulation environment (i.e. for the control condition) was the following: 1) the height of the driver viewpoint corresponded to the real height experienced when in a Premium truck. (i.e. the truck indoor ground floor measures 1430 mm). The parameter was modified as in the speed control experiment The standard configurations of the remaining parameters were: 2) daylight illumination conditions; 3) acoustic feedback activated.

4.2.2 Data recording and analysis

In the real world, the distance between the two vehicles was measured using an electronic telemeter device (SONIN Combo Pro). The device was composed by two units: the active emitter and the passive echo reflector. The reflector was installed in the rear top part of the vehicle that had to be followed (i.e. a Renault Kangoo). The active emitter was positioned on the copilot side outdoor side of the truck cabin, close to the lateral window. In such a configuration, the measurement performed by the active emitter corresponded to the distance between the frontal part of the truck to the rear part of the preceding vehicle. Distance was sampled at an approximate frequency of 6 Hz. In simulation, the sampling of the distance data was provided by the SCANeR II environment at a frequency of 20 Hz.

4.3 Results

4.3.1 Real world vs. Simulation

Figure 8 shows the average safety distance measured along the different segments of the circuit. The data concerning the outward (left) and return (right) pathway are treated separately to keep apart possible effects of the sequence of segments. Note that the safety distance in real-world conditions is almost constant all along the segments. In simulation, we observe that the safety distance is substantially increased with respect to the average in segment 1 (outward pathway) and in segment 2 (both in the outward and return pathway). The rationale for the former increment is the fact that the driving task started from a stationary initial position. Inevitably, this fact introduced a lag, which drivers recovered at the end of segment 1. The increase observed in segment 2, on the other hand, is temporary with respect to the average safety distance and should be attributed to the curving shape of the road in the segment. An "S-shaped" profile of the road caused drivers to lose momentarily the sight of the preceding vehicle. From a quantitative point of view, the simulation average values of the safety distance along the different segments in simulation (Sd_S) are approximately twice the values measured in real-road driving (i.e. $Sd_S \cong 2 \cdot Sd_R$). Table 1 reports numerically the average safety distance for each segment of the circuit. A 2-way analysis of variance of the safety distance for the outward and return pathways was performed. The analysis (factors were: 2 (*driving condition*: simulator, real road) x 5 (*circuit segments*: 1 through 5)) revealed a significant main effect of the *driving condition* factor, for both the outward and return pathway tested separately (respectively, $F(1,2)=18.65$, $p < 0.05$ and $F(1,2)=41.31$, $p<0.05$).

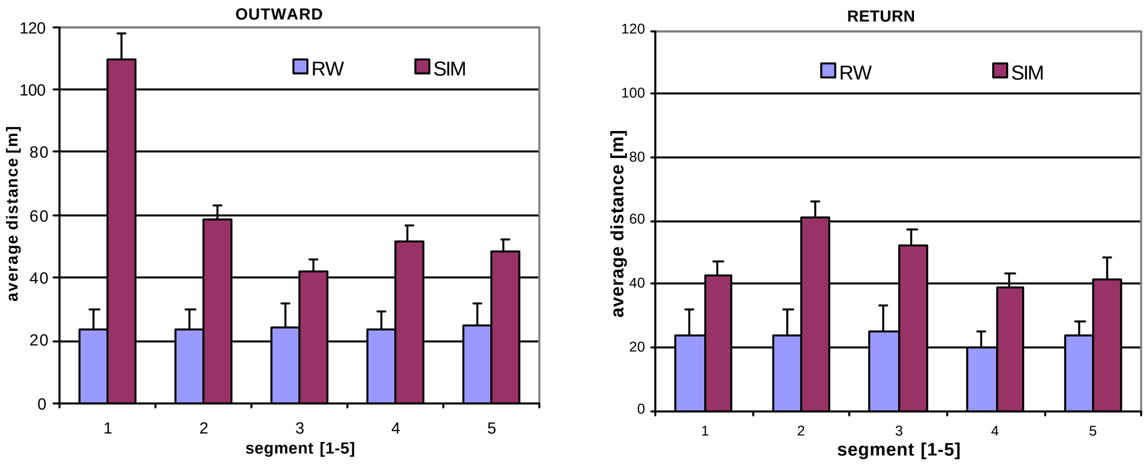

Figure 8. Safety distance control. Real-world (RW) and simulation (SIM) for the five different segments.

Table 1. Safety distance computed across the five circuit segments. The difference between real-road distances (Sd_r) and distances in simulation (Sd_S) is significant for all segments. Outward and return pathway are evaluated separately.

Segment	Real road Sd_r [m]	Simulation Sd_S [m]
1 - *outward*	23.6	57.3
2 - *outward*	23.6	58.5
3 - *outward*	24.4	42.2

4 - *outward*	23.5	51.7
5 - *outward*	25.	48.7
Mean	24.02(±0.6)	51.7(±6.6)
1 - *return*	24.1	42.8
2 - *return*	24.1	60.6
3 - *return*	25	52.3
4 - *return*	20.5	39.2
5 - *return*	23.8	41.7
Mean	23.5(±1.7)	47.3(±8.9)

4.3.2 Simulation: professionals vs. non-professional drivers

Figure 9 shows the safety distance maintained by professional (PRO) and non-professional (N-PRO) drivers all along the different segments of the circuit. Distance data are averaged here on the outward and the return pathways. We observe that non-professional drivers seem to use an increased margin of safety distance in comparison with professional drivers. Numerically, the increased margin corresponds to about 47% of the safety distance maintained by the professional group. A 2-way analysis of variance of the average safety distance (factor were: 2 (*subject category*: professionals, non-professional) x 5 (*circuit segments*: 1 through 5)) revealed a significant main effect of the *subject category* factor ($F(1,7)=14.2$, $p<0.05$). This result, although not surprising, can be due to lack of experience (either lack of knowledge of the truck or of the simulator) or can be caused by the unusual driving conditions (for example the unusual height of the driver viewpoint). Even a combination of the two aspects, may have led non-professional driver to drive with an increased margin of safety distance.

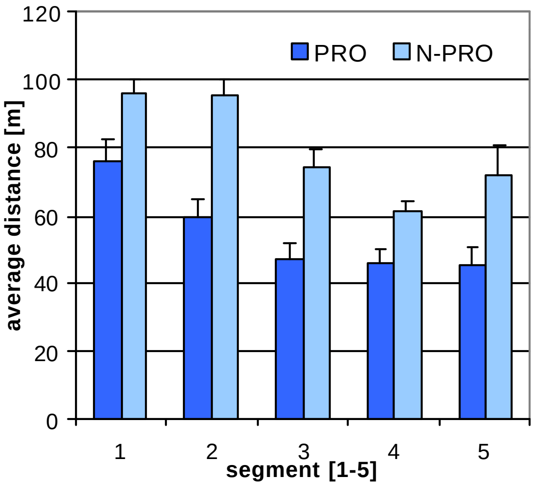

Figure 9. Safety distance maintained by professional and non-professional drivers.

4.3.3 Simulation: the height of the driver viewpoint

The influence of the simulated height of the driver viewpoint on the safety distance during driving was tested with four professional drivers and five non-professional drivers. Simple geometrical considerations can be used to predict that greater simulated heights would lead to larger safety distances. In fact, the height of an image with respect to the horizon is a cue that our visual system use to infer the absolute distance of an object [5]. Therefore, changing the simulated height corresponds to lowering the image of the target with respect to the horizon. As a consequence, drivers will tend to increase the actual distance to keep the height of the target image unchanged as to the horizon. In two different sessions we compared a standard height (corresponding to the height of a Premium truck, 1430 mm) to the height of a Magnum class vehicle (1762 mm).

Figure 10 shows the average safety distance for professional and non-professional drivers. Note that for professional drivers the increase of safety distance with simulated height is exaggerated in segment 2 and 3. Segment 2 in particular delimits the village of the circuit and it was noticed that drivers tended to drive at very low speed in order to minimize the discomfort due to the high speed of the image. The consequence is that they tended to increase the distance as to the preceding vehicle. This effect can be also remarked in segment 3, where the vehicle was momentarily lost due to accumulated distance. Although a systematic tendency was found in the data, no statistical significance could be obtained from the safety distance data obtained from the four professional subjects and the five non-professional subject, analyzed separately.

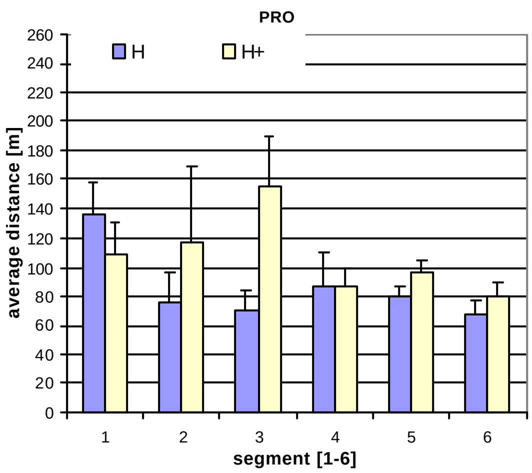

Figure 10. Influence of the simulated height on the safety distance. Standard height (H) and increased height (H+) for professional drivers.

5 Discussion

5.1 Real vs. simulated driving

The use of the comparative approach (i.e. real-road vs. simulation) has brought the attention to two particularly interesting results. First, in the simulated environment, drivers (professionals and non-professionals) controlled the speed of the truck reproducing correctly the performance observed in the real-road situations. Across different segments of a circuit, the average speed values obtained from a population of four professional drivers, were highly correlated with the speed data measured in the corresponding real-world circuit (correlation coefficient r=0.85). Second, in simulation the safety distance maintained with respect to a preceding vehicle was found for professional drivers to be about twice as much the safety distance observed in real-road driving. A similar effect was already reported in a study of Malaterre [14], although in different experimental conditions. Safety distances were found to be even greater (47% approx) for non-professional drivers. Since simulation conditions were exactly the same for both groups, this result quite probably reflects the lack of adaptation to some vehicle parameters, such as the truck dynamic behavior, or the uncommon height of the viewpoint. The latter point was in fact raised in section 4.3.3, where it has been observed that a change in the height of the viewpoint determines systematically an increase of the safety distance. Last but not least, the dynamics of a truck (and its braking behavior) is certainly unknown to non-professional drivers. Indeed, this factor might induce these drivers to be more cautious towards preceding vehicles. A fact to be considered is that for professional drivers, the difference in safety distance found between real-world (RW) and in simulation situations (SIM) is statistically significant. We suggest two possible interpretations to explain this outcome: a) the absence in simulation of full depth cues, b) a possible driver mistrust with respect to the behavior of preceding vehicles. As to the first hypothesis, it is worth considering that binocular and motion-parallax cues to depth perception were either missing or not fully reproduced in the current experimentation. In particular motion parallax due to the movement of the driver head inside the truck mockup was not reproduced at all. It is largely known that binocular cues are important to depth perception, although effective in a limited distance interval [4]. Motion parallax, on the other hand, are effective over greater distances (for a review see [4]. The second, but minor hypothesis, regards the behavior of the simulated vehicles. In one of the two circuit, which does not correspond to the data presented in section 4.3.1, some of the drivers reported verbally that the simulated vehicle changed its speed abruptly in correspondence of determinate positions on the circuit. Speed was either reduced or increased without a comprehensible reason: this could have induced mistrust and therefore larger safety distance margins. Taking into account that this abnormal vehicle behavior was limited to only one of the two circuits, and that each circuit was experienced by a different population of drivers, we consider it as being a minor hypothesis.

5.2 Simulation environment parameters

Visual information is considered the most important sensory signal apt to determine driving behavior (but see also [19], [20]). If the characteristics of the visual information are changed in simulation according to a predetermined amount so as to impact the perception of the driver, one can expect a corresponding change in his driving behavior. Principles of geometry, but also more sophisticated theoretical tools, like the optic flow equations [13], can be used to predict the behavior of the driver [6]. Many perceptual experiments in psychophysical literature have shown that dynamic visual information, such as the optic flow, play an important role in the control of motor variables (e.g. stance and walking variables) [22]. Suggestions about the role of optic flow in driving tasks have been recently resumed [12]. In order to give a theoretical support to the interpretation of our findings, the following elements are accounted: i) the theory of depth perception, ruling out the importance of different visual cues to depth perception (for example the position relative to the horizon of a surface) [15] and ii) the theoretical framework of the optic flow, which establishes a formal relationship between the amount of induced visual motion pattern and the movement of the observer in a three-dimensional environment [11]. For each of the two driving tasks, in separate experimental sessions we have evaluated the influence of different simulation parameters. Three parameters, in particular, were taken into account and these were varied with respect to standard control conditions: the height of the driver viewpoint, the day/night driving condition and the presence/absence of acoustic feedback. In section 3.3.3 and in section 4.3.3, for example, we have presented results which suggest that a change in the height of the driver viewpoint produces a corresponding change in the driver behavior in terms of speed and safety distance. An increase in the height of the viewpoint determines an increase of the speed of the truck, and a similar phenomenon is observed for the safety distance. The theory of optic flow certainly predicts the first finding: an increase in the height of the observer as to the ground surface reduces proportionally the amount of visual motion pattern experienced during his motion throughout the three-dimensional environment. As a consequence the driver, who during the experiment was following instructions to reproduce some target speed in absence of instrumentation feedback, increased the speed of the vehicle so as to experience the visual motion experienced in normal driving conditions. The second observation is somehow related to the first-one. During night driving the driver has a reduced visual field, both in terms of depth and of lateral view field. A reduction of the amount of visual information signaling the movement of the truck, produced an underestimation of the speed of the vehicle, which was actually compensated by driver with an increase of the truck speed.

Finally, the results of section 3.3.5 show that the acoustic feedback is somehow always held in consideration by the driver to maintain a stable cruising speed. In a series of trials, repeated with professional and non-professional drivers, the contribution of acoustic feedback to the control of cruising speed was tested. The acoustic feedback consisted mainly of the engine sound, resulting from the combination of several harmonics as a consequence of the control variable (i.e. the desired speed imposed by the driver). It was observed that in absence of acoustic feedback, drivers tended to increase systematically the speed of the truck. The increment of speed was systematic, although not statistically significant for the each driver population. The quantified average increase of speed was actually 8% when compared to the cruising speed maintained in the control (i.e. nominal) condition. Therefore we suggest that, not only acoustic feedback increases the realism of the driving situation [3], but that it also contributes to stabilize the driving behavior in an important task such as the control of cruise speed.

6 Conclusion

The validation of driving simulator from a perceptual point of view is an extremely important step in order to qualify driving simulators as a productive tool (i.e. reducing time and costs in prototyping new solutions) and as a realistic and controlled environments to study driver behavior. This study represents a step toward the perceptual validation of truck driving simulation. The Renault V.I. truck simulator features a moving platform which has been used to compare the behavior of drivers in simulation vs. real-road situations for two well defined tasks: speed and safety distance control. Two populations of drivers (professionals and non-professionals) participated to the experimental campaign, but obviously only professionals drivers have performed in real-road situations. The main result of this study is that in simulation drivers attain a quite a similar control of the speed of the vehicle with respect to the real-world condition. Conversely, the driving behavior concerning the control of safety distance presents rather different characteristics in simulation if compared to real-road situation. Safety distance almost doubles during simulation. This suggests that the visual information provided to the driver in simulation, although sufficiently rich to perform the control of speed, might be poor in terms of geometric contents when considering the three dimensional layout of the road environment. The increased amount of safety distance in simulation could be explained in terms of the two following hypotheses: a) the drivers experience visual information which is an impoverished version of the one experienced in the real-world. In particular, some of the visual cues to depth used by the visual system most effectively are absent. For example, binocular cues to depth and motion parallax cues due to the observer movement in the mockup of the truck were not provided or rendered in the current experiments. It is largely known that both cues are important for perception of three-dimensional layouts. On the other hand, several studies reported that the contribution of binocular cues to the perception of depth is to be considered irrelevant if the distances considered are greater that 6m [7] (for a review see [4]). We suggest that motion parallax, which has been recently reported to be a very effective cue to absolute distance in the near space [16,17], can possibly play an important role to improve the distance estimation abilities in simulation. A further hypothesis, which seems plausible but does not explain completely what has been observed, is that drivers mistrusted the vehicle followed. They somehow perceived its behavior as unnatural (e.g. the acceleration and deceleration of the vehicle sometimes changed abruptly). It is worth of notice, that this hypothesis applies only to one of the two circuits, and is consequently considered less probable. Clearly further investigations are necessary to assess these issues, and particular attention should be paid to the definition of validation protocols concerning the perception of depth of the simulated road environment.

7 Acknowledgements

The authors would like to acknowledge the engineering staff at the Renault V.I. site for their support and collaboration during the whole experimental campaign. Rudy Cottin in particular deserves a special thanks for his technical assistance and joyful enthusiasm which made possible the accomplishment of this study.

8 References

[1] E.R. Boer, T. Yamamura, N. Kuge, and A. Girshick, Experiencing the same road twice: a driver comparison between simulation and reality. *Proceedings of the Driving Simulation Conference DSC 2000*, 2000. Paris, France.

[2] P.C. Burns and D. Saluäär, Intersection between driving in reality and virtual reality (VR). *Proceedings of the Driving Simulation Conference DSC 1999*, pp. 153-164, 1999. Paris, France.

[3] J.-P. Colinot and G. Belay, A multifunctional sound generator for the PSA's Sherpa driving simulators. *Proceedings of the Driving Simulation Conference DSC 2000*, pp. 165-179, 2000. Paris, France.

[4] J.E. Cutting and P.M. Vishton. Perceiving Layout and Knowing Distances: The Integration, Relative Potency, and Contextual Use of Different Information about Depth. In: *Perception of Space and Motion*, eds. W. Epstein and S. Rogers. Academic Press, 1995.pp. 69-117.

[5] J.J. Gibson. *The perception of the visual world*, Boston: Houghton Mifflin, 1950.

[6] J.J. Gibson and L.E. Crooks, A theoretical field-analysis of automobile-driving. *The American Journal of Psychology*, vol. 51, pp. 453-471, 1938.

[7] V.W. Grant, Accommodation and convergence in visual space perception *Journal of Experimental Psychology*, vol. 31, pp. 89-104, 1942.

[8] R. Gray and D. Regan, Risky driving behavior: a consequence of motion adaptation for visually guided motor action. *Journal of Experimental Psychology: Human Perception and Performance*, vol. 26, pp. 1721-1732, 2000.

[9] H. Jamson, Driving simulation validity: issues of field of view and resolution. *Proceedings of the Driving Simulation Conference DSC 2000*, pp. 57-64, 2000. Paris, France.

[10] J.-M. Kelada and A. Kemeny, Event-driven traffic generation: a tool for testing on-board driver assistance systems on driving simulators. *Int. Conference on Vehicle Comfort and Ergonomics*, ATA, pp. 317-325, 1995. Orbassano, Italy.

[11] J.J. Koenderink, Optic flow *Vision Res*, vol. 26, pp. 161-180, 1986.

[12] M. Lappe, A. Grigo, F. Bremmer, H. Frenz, R.J.V. Bertin, and I. Israel, Perception of heading and driving distance from optic flow. *Proceedings of the Driving Simulation Conference DSC 2000*, pp. 25-31, 2000. Paris, France.

[13] D.N. Lee, The optic flow field *Philosophical Transactions of the Royal Society, London, B*, vol. 290, pp. 169-179, 1980.

[14] G. Malaterre, Evaluation d'un dispositif d'aide au respect des interdistances sûres. Comparaison des résultats obtenus sur piste et sur simulateur (SCANeR). INRETS, Paris, 1994.

[15] S.E. Palmer. *Vision Science. Photons to Phenomenology*, Cambridge, MA: Mit Press, 1999.

[16] F. Panerai, V. Cornilleau-Pérès, and J. Droulez, Contribution of extra-retinal signals to the scaling of object distance during self-motion *Perception & Psychophysics*, vol. 2001 (submitted).

[17] C.H. Peh, F. Panerai, J. Droulez, V. Cornilleau-Peres, and L.F. Cheong, Absolute distance perception during in-depth head movement: calibrating optic flow with extra-retinal information. *Vision Research*, vol. 2001 (submitted).

[18] C.R. Rao. *Linear statistical inference and its application.*, New York: Wiley, 1965.

[19] G. Reymond and A. Kemeny, Motion cueing in the Renault driving simulator. *Vehicle System Dynamics*, vol. XX, 2000.

[20] G. Reymond, A. Kemeny, J. Droulez, and A. Berthoz, Role of lateral acceleration in curve driving: driver model and experiments on a real vehicle and a driving simulator. *Human Factors*, vol. 2001.

[21] M.G. Wade and C. Hammond, Simulation validation. *Proceedings of the Driving Simulation Conference DSC 2000*, 2000. Paris, France.

[22] W.H. Warren, B.A. Kay, W.D. Zosh, A.P. Duchon, and S. Sahuc, Optic flow is used to control human walking. *Nature Neuroscience*, vol. 4, pp. 213-216, 2001.