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Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study

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The validity of research results obtained using the fixed-base vehicle simulator of the Institute for Perception TNO was studied during straight-road driving. Absolute and relative validities were mainly evaluated in terms of system performance and driver behavior for inexperienced and experienced drivers, who had to perform lateral and longitudinal vehicle control both in the simulator and in an instrumented car on the road. Task demands for each control were varied with a free and forced accuracy instruction. Overall results showed good absolute and relative validity for longitudinal vehicle control; lateral vehicle control offered good relative validity. Lateral control performance lacked absolute validity due to the drivers' diminished perception of lateral translations (absence of kinesthetic feedback). Drivers were easily able to perceive yaw rotations in the simulator. Performance in the simulator was a more sensitive discriminator of driving experience than was performance in the instrumented car on the road.

INTRODUCTION

Although many vehicle simulators have been developed (O'Hanlon, 1977; Allen, Klein, and Ziedman, 1979; Blaauw, 1979), the validity of these simulators has only rarely been investigated in detail. In the literature, validity is generally defined with respect to two aspects (Mudd, 1968; McCormick, 1970). The first concerns the correspondence between the behavior of the human operator in the simulator and in the real, operational system. The second focuses on the physical correspondence between the two systems and includes, for example, layout and dynamic characteristics. The two aspects of validity are not necessarily related. Generally, the behavioral correspondence is assumed to be more important for the validity of a simulator for a specific task. Rolfe, Hammerton-Frase, Poulter, and Smith (1970) state: "The value of a simulator depends on its ability to elicit from the operator the same sort of response that he would make in the real situation" (p. 761). Validity is a determination of the way in which the simulator "reproduces a behavioral environment" (Mudd, 1968, p. 352). Most simulator studies, however, mention the physical correspondence at best and do not analyze the behavioral correspondence.

Several methods can be used to study the behavioral correspondence. The methods focus on the behavior of the complete driver-vehicle-road system during a specific task (Brown, 1975). They are:

(1) Comparison of simulator and real car during identical tasks and circumstances in terms of *system performance* and/or *driver behavior*.
(2) Measurement of physical and/or mental load by an analysis of *physiological variables*. Until

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recently, this method has failed to produce unique conclusions, due to our lack of knowledge about the relationship between the driving task and the physiological responses of drivers.

(3) *Estimation of subjective criteria by drivers.* They can, for example, give detailed information on questionnaires about the execution of selected maneuvers in the simulator. Special observers can also be used to scale the behavior of experienced drivers in a simulator.

(4) *Evaluation of transfer effects.* Validity can also be measured by a study of driver transfer from the simulator to the real car or vice versa (Moraal and Poll, 1979). The latter transfer is used when the performances or judgments of experienced drivers are taken as criteria for simulator validity. The transfer can be measured in terms of reduction in training hours, first-shot performances after transfer, or by questionnaires. The first-shot performance of experienced drivers can provide essential information on the validity of a simulator system.

All methods give parameters describing validity by comparing conditions of driving in the simulator in relation to driving under the same road conditions. A modification of this approach is to compare performance differences between experimental conditions in the simulator with performance differences between similar conditions in the car. When these differences are of the same order and direction in both systems, then the simulator is defined to have *relative validity.* If, in addition, the numerical values are about equal in both systems, the simulator can be said to have *absolute validity* as well.

This paper presents a validation study based on straight-road driving, using the vehicle simulator of the Institute for Perception TNO. In addition, driving performance and driver behavior as such are analyzed in detail, especially with regard to differences in experimental conditions.

METHOD

Subjects

Forty-eight male subjects took part in the experiment, 24 experienced drivers and 24 very inexperienced drivers. The experienced drivers had had their licenses for at least three years and each had driven at least 30 000 km. The inexperienced drivers either had followed a driver-training course or had just passed their driving tests. None of the subjects had previous experience with the instrumented vehicle or the simulator. All subjects were between 18 and 36 years of age. They were paid for their participation.

Procedure

Each driver had to drive in the simulator and in the instrumented vehicle on a straight section of a four-lane highway with divided traffic lanes, having a constant road geometry and lane width (3.60 m). There were no disturbances such as sidewind gusts.

The task demands were varied between subjects and, consequently, each subject drove in accordance with one task only. The tasks were manipulated by instruction. Both lateral and longitudinal vehicle control had two instructions, resulting in four conditions for both groups of driving experience:

(1) *Free driving.* No specific instructions were given.

(2) *Forced lateral control.* Subjects were informed that their variations in straight driving were recorded and that they should therefore concentrate on driving as straight as possible. This instruction attempted to provoke an internal criterion that was very strict for lateral control performance.

(3) *Forced longitudinal control.* Subjects' instructions were similar to those in Condition 2, but now with respect to the variations in velocity: they should therefore concentrate on driving with a constant velocity (100 km/h). This instruction was intended to provoke a very strict internal criterion for longitudinal control performance.

(4) *Forced lateral and longitudinal control.* This was a combination of Conditions 2 and 3.

Before the first run, subjects were instructed on the type of task to perform as well as on some additional procedures. They were urged to drive in the right lane most of the time. Overtaking was allowed for short periods only. For the conditions without specific longitudinal instruction (1 and 2) subjects were advised to drive at normal highway speed.

Each subject drove the specific experimental condition in two one-hour sessions during one day, one hour in the simulator and one hour in the instrumented vehicle. From the group of six subjects each day, three started in the simulator in the morning and transferred to the instrumented vehicle in the afternoon, whereas the remaining three did the reverse. The subjects did not receive any training with the systems before the experimental runs. The initial position was in the emergency lane, where subjects were given instructions on how to handle the car or simulator. They then accelerated to the desired speed and changed to the correct lane. In the subsequent one-hour period, the driver's vehicle control was measured regularly, during six intervals in which interacting traffic was absent.

During all runs, two experimenters were present in the instrumented vehicle. One took care of the apparatus while the other instructed the subject. The latter experimenter was a driver-training instructor (whose presence also served to legalize the runs with the inexperienced drivers). Only one experimenter was present in the mock-up of the simulator.

Questionnaires

At the end of each one-hour period, subjects completed a questionnaire on several aspects of driving, which featured a continuous, ordinal scale with five reference points. The general questions were related to task difficulty, required attention, and monotony. Specific questions dealt with lateral and longitudinal control.

At the end of the second period, an additional questionnaire was given on which subjects had to directly compare the simulator and the instrumented vehicle by responding to multiple-choice questions. They were also asked to add comments. The questions were related to observed differences between both systems during straight-road driving, possible effects on driving behavior, difficulty of driving in both systems, and motion sickness.

Apparatus

The vehicle simulator consists of the following main features (Institute for Perception TNO, 1978):

(1) The visual presentation to the driver is created using three TV projection systems (black and white) on screens surrounding the mock-up of a vehicle. Horizontal and vertical field of view are 120 and 30 deg respectively (Figure 1).
(2) The TV recordings are made in-line from a 1:87.5 scale model (dimensions 23 × 17 m maximally) by a mirror block with three endoscopes and three cameras. The movements of this recording system are computer controlled and consist of three translations and one rotation (yaw around the vertical axis). Due to the implementation of a moving-belt system, driving time is unlimited (Figure 2).
(3) The movements of the mirror block are controlled by the actions of the driver via a mathematical representation of the vehicle dynamics. This mathematical model allows velocities between 0 and 120 km/h, clutching and changing gears included. Lateral accelerations are restricted up to 3 m/s^2. The coefficients of the model were calculated by an experimental program that included static as well as dynamic tests in measuring the characteristics of the instrumented vehicle (Godthelp, Blaauw, and Horst, 1982).
(4) The mathematical model of the vehicle includes the dynamic calculation of steering-wheel forces that are presented to the driver by an electric torque motor.
(5) The simulator is fixed-base; that is, drivers have no kinesthetic feedback.
(6) Engine and wind sound are simulated by a four-channel system that relates sound to velocity, engine torque, and rotational speed of the engine.
(7) The vehicle (mock-up as well as mathematical representation) is a copy of the instrumented vehicle ICARUS (Blaauw and Burrij, 1980).

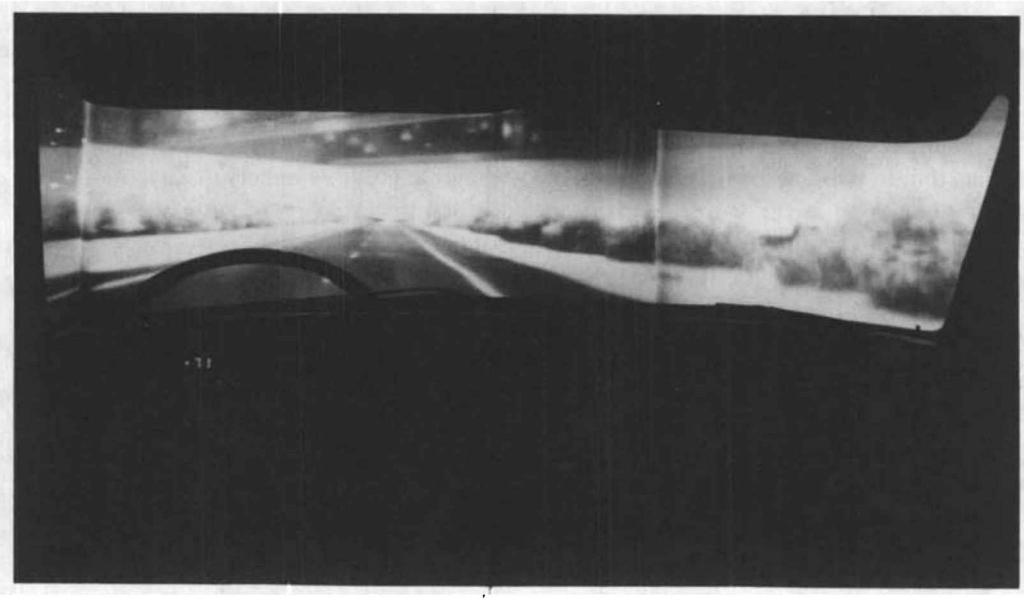

Figure 1. *The 120-deg TV image, as presented to the driver in the simulator.*

Dependent Variables

Both simulator and instrumented vehicle allow measurement of the following variables for lateral and longitudinal vehicle control: steering-wheel angle, lateral position (distance between driver and right lane marker), yaw rate, position of the accelerator, and velocity. All variables were recorded on magnetic tape for subsequent computer processing.

Data Analysis

For each run in the simulator and the instrumented vehicle, all variables were sampled over six periods of 32 s each, with a sampling frequency of 4 Hz. Mean values, standard deviations, and normalized amplitude density functions were computed. Spectral density functions were estimated for the steering-wheel angle.

These results were analyzed by means of Pearson product-moment correlation coefficients, analysis of variance, and subsequent Newman-Keuls tests, in order to investigate whether any main effects of the experimental conditions or interactions may have occurred, whether by chance or not (Winer, 1962). All experimental conditions are summarized once in their hierarchical order: two groups of driving experience, four task demands, two sequences of treatments (car to simulator and simulator to car), three subjects for each group of driving experience, task demands and sequence, two systems (simulator and instrumented car), and six intervals during each run.

RESULTS

Lateral Vehicle Control

Table 1 presents the results for four parameters describing lateral vehicle control (the distance between the car and the right lane marker) in the simulator and instrumented car, for both experienced and inexperienced drivers. Both the mean and the standard deviation of the lateral position were significantly larger ($p \leq 0.01$) in the simulator than in the car, for both experienced and inexperi-

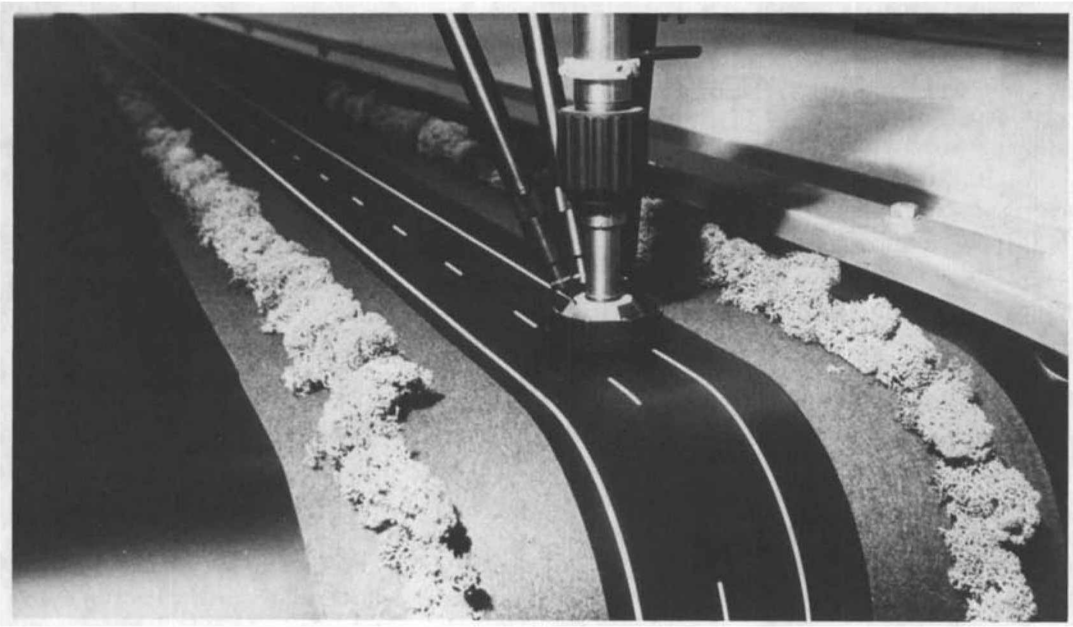

Figure 2. *The mirror block that simulates the eye of the driver during straight-road driving on the moving-belt system.*

enced drivers. The standard deviations of the yaw rate and steering-wheel angle were significantly smaller ($p \leq 0.01$) in the simulator than in the car for the experienced drivers, whereas no significant differences were found between these variables for the inexperienced drivers when comparing their runs in the simulator with those in the instrumented car. Greater driving experience did not affect the mean lateral position, but resulted in significantly smaller ($p \leq 0.01$) standard deviations for the lateral position, yaw rate, and steering-wheel angle in the simulator. Driving experience had no effect on these measures in the instrumented car (Table 1).

Task demands interacted with driving experience based on two measures, standard deviations of both lateral position and steering-wheel angle; however no significant effects were found for the mean lateral posi-

TABLE 1

Mean Values of Lateral Vehicular Control as a Function of Driving Experience in the Instrumented Car and the Simulator

		Instrumented Car		*Simulator*	
Performance Index		*Inexperienced*	*Experienced*	*Inexperienced*	*Experienced*
Lateral Position	(cm)	178.4	171.2	190.6	194.2
SD Lateral Position	(cm)	19.4	16.6	36.4	24.3
SD Yaw Rate	(deg/s)	0.32	0.32	0.31	0.26
SD Steering-Wheel Angle	(deg)	1.6	1.4	1.8	1.2

tion or the standard deviation of the yaw rate. Figure 3 presents the standard deviations of the lateral position; the relationships were identical for the standard deviations of the steering-wheel angle. For both the simulator and the instrumented car, lateral variations changed significantly ($p \leq 0.01$) as a function of the longitudinal task demands and driving experience. In both systems, inexperienced drivers showed a significant increase in the standard deviation of the lateral position when the forced longitudinal task was imposed, whereas the experienced drivers then showed a decrease in the standard deviation. No effects were found due to the lateral task demands. Consequently, variations between driving experience and task demands discriminated about equally with respect to the standard deviations of the lateral position and steering-wheel angle in the simulator and the instrumented car. The absolute values, however, were higher in the simulator (see also Table 1).

Simulator validity can also be measured by an analysis of the performance of the individual subjects on both systems. Unless there are relevant system differences, it may be expected that individuals will perform about equally in the simulator and the instrumented car; that is, a skilled driver will perform well on both systems. Pearson product-moment correlations were computed over all 48 subjects in the simulator and the instrumented car for the four parameters describing lateral vehicle control. The correlation coefficients were, respectively, 0.36, for the mean lateral position, 0.57 for the standard deviation of the lateral position, 0.14 for the standard deviation of the yaw rate, and 0.32 for the standard deviation of the steering-wheel angle. With the exception of the value for the standard deviation of the yaw rate, all correlation coefficients were significant ($p \leq 0.05$).

The sequence between both systems interacted with the type of system (car or simulator). The standard deviation of the lateral position increased when subjects transferred from the first to the second system. When subjects drove first in the instrumented car, the standard deviation was 16.7 cm. When the car driving followed the one-hour session in the simulator, the standard deviation increased significantly ($p \leq 0.01$) to 19.3 cm. A similar effect was found in the simulator. When the subjects drove first in the simulator, the standard deviation was 28.8 cm. When simulator driving followed car driving the standard deviation increased to 31.9 cm.

With respect to training over the six intervals, the standard deviations of the yaw rate

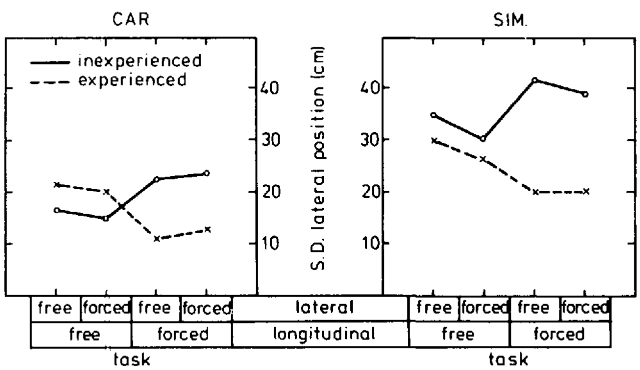

Figure 3. *Standard deviation (SD) of the lateral position as a function of driving experience and free or forced task demands for lateral and longitudinal vehicular control.*

and steering-wheel angle were significantly larger ($p \leq 0.05$) in the first interval for inexperienced drivers. These initial effects were observed in both the simulator and the instrumented car and were not affected by the sequence between both systems.

The differences in steering-wheel angle for both groups of driving experience were also studied by spectral density functions. Figure 4 presents these functions for the simulator and the instrumented car, averaged over 144 separate spectral functions. Because the area under each function corresponds to the variance of the signal, a link can also be made with the standard deviations of the steering-wheel angles presented in Table 1. The inexperienced drivers in the simulator had a higher spectral density than the experienced drivers. This indicates a greater expenditure of energy in steering (Table 1: standard deviation of 1.8 and 1.2 deg, respectively). These differences were less pronounced for the runs in the instrumented car. Between the simulator and the instrumented car the primary peak shifted towards lower frequencies; the simulator showed a peak of about 0.2 Hz, whereas the car had a corresponding, but less pronounced, peak at 0.1 Hz. Consequently, drivers steered at higher frequencies and in a more oscillatory fashion in the simulator than in the instrumented car. In this respect there were no differences related to driving experience. No significant differences were found with respect to other bands of spectral energy.

Longitudinal Vehicle Control (Velocity)

Table 2 presents the results for three parameters describing longitudinal vehicle control in the simulator and the instrumented car for both groups of driving experience. Greater experience produces significantly smaller standard deviations ($p \leq 0.05$) for velocity and accelerator position in the simulator and the instrumented car. Consequently, the experienced drivers maintained a more constant velocity. In the simulator, the inexperienced drivers showed much larger variations ($p \leq 0.01$) in accelerator position when compared with their performance in the instrumented car, and compared with the experienced drivers. These effects were not affected by task demands or the sequence between both systems. Obviously, longitudinal vehicle control did not improve with the forced longitudinal instruction. Mean velocity was significantly higher ($p \leq 0.06$) for the experienced drivers in that car; these differences were absent in the simulator. The four task demands in the simulator and the instrumented car resulted in differences for both groups of driving experience, as shown in Figure 5.

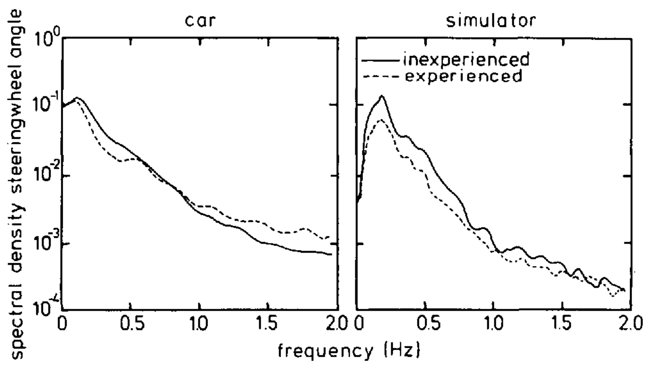

Figure 4. *Spectral density function estimates for steering-wheel angle as a function of driving experience (averaged over 144 runs).*

TABLE 2

Mean Values of Longitudinal Vehicular Control as a Function of Driving Experience in the Instrumented Car and the Simulator

Performance Index		Instrumented Car		Simulator	
		Inexperienced	Experienced	Inexperienced	Experienced
Velocity	(km/h)	104.3	109.7	104.9	103.4
SD Velocity	(km/h)	1.1	0.8	1.3	1.0
SD Accelerator	(%)	1.4	1.1	2.3	1.3

In the free driving condition, experienced as well as inexperienced drivers maintained a similar velocity of about 110 km/h in both the simulator and the instrumented car. The velocity when free driving was significantly higher ($p \leq 0.01$) in both systems for both groups when compared with the velocities during the forced longitudinal conditions (constant velocity of 100 km/h). In the simulator, drivers then maintained 100 km/h, but in the instrumented car the experienced drivers in particular tended to drive faster.

Pearson product-moment correlation coefficients were computed over all 48 subjects in the simulator and the instrumented car for the three indices describing longitudinal vehicle control. With the exception of the standard deviation of the accelerator ($r = 0.28$; $p \leq 0.05$), none of the indices was significantly correlated with any other index. A small correlation coefficient, however, does not necessarily indicate different longitudinal control between simulator and car. The homogeneity of the groups of subjects with respect to the specific variables could produce a restriction of range.

The sequence between both systems interacted with the type of system (car or simulator) for the mean velocity and mean position of the accelerator, and showed an increase in both measures when subjects transferred from the first to the second system during the day. When subjects drove first in the instrumented car, the mean velocity was 104.1 km/h, but when car driving followed simulator driving, the velocity increased significantly ($p \leq 0.01$) to 107.0 km/h. A similar effect was found in the simulator. When sub-

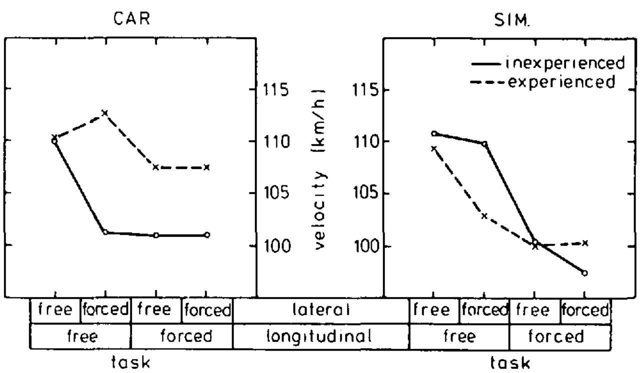

Figure 5. *Mean velocity as a function of driving experience and free or forced task demands for lateral and longitudinal vehicular control.*

jects drove first in the simulator, their mean velocity was 101.2 km/h, which increased to 109.8 km/h ($p \leq 0.01$) when simulator driving followed car driving. The standard deviations failed to show similar effects.

Training over the six intervals showed a significant initial effect for the inexperienced drivers on the simulator. Mean velocity and mean position of the accelerator were significantly smaller ($p \leq 0.01$), whereas the standard deviations of the velocity and accelerator had significantly larger ($p \leq 0.01$) values in the first interval compared with the later intervals. No significant differences were present for the experienced drivers. These different values for the inexperienced drivers during their first interval in the simulator were even more pronounced when they completed the one-hour session in the instrumented car first.

Questionnaires

The first questionnaire related the drivers' opinions to task difficulty, required attention, and monotony, and to lateral and longitudinal vehicle control. The opinions were given on a continuous scale between 0 (extremely unfavorable) and 100 (extremely favorable).

Almost all opinions discriminated significantly ($p \leq 0.01$) between the simulator and the instrumented car for both groups of driving experience and for all task demands. As shown in Table 3, drivers judged the simulator considerably more unfavorable (greater task difficulty and monotony, more attention) than the instrumented car, with an exception for longitudinal control. This latter task was considered to be easier in the simulator. Experienced drivers gave more favorable judgments ($p \leq 0.01$) than the inexperienced drivers. Monotony in the simulator scored about equal (at a very unfavorable level) for both groups of driving experience, but inexperienced drivers judged the instrumented car to be less monotonous than did the experienced drivers. Task demands only caused significant changes in opinion about required attention for longitudinal vehicle control and indicated, as expected, more attention during the forced longitudinal condition. There was no perceived difference in attention required for lateral vehicle control. Drivers' rated the simulator to be somewhat more monotonous after initial training in the instrumented car (12 for the simulator without and 7 with initial runs in the car). In addi-

TABLE 3

Mean Ratings of Driver's Opinions on Various Aspects of Driving Tasks

	Instrumented Car		*Simulator*	
Questionnaire Item	*Inexperienced*	*Experienced*	*Inexperienced*	*Experienced*
Task Difficulty				
Overall	59	73	36	46
Lateral Control	57	63	21	41
Longitudinal Control	61	69	73	75
Required Attention				
Overall	35	45	29	31
Lateral Control	38	44	18	28
Longitudinal Control	54	63	72	77
Monotony	55	38	9	9

n = 48.
0 = extremely unfavorable; 100 = extremely favorable.

tion, runs in the instrumented car were judged to be less monotonous after initial training in the simulator (37 without and 56 with initial simulator training).

In the second questionnaire the subjects had to directly compare runs in the simulator and the instrumented car. The results confirmed the findings of the first questionnaire and again indicated greater task difficulty in the simulator. Details of monotony in the simulator were made more explicit by mentioning such missing elements as traffic, curves, and road signs. No one reported experiencing motion sickness while in the simulator.

DISCUSSION

Simulator Validity

The comparison of system performance and driver behavior showed similar effects of driving experience and task demands in the simulator and the instrumented car for most indices describing lateral and longitudinal vehicle control; this indicates relative simulator validity. In this respect Figure 3 shows characteristic simulator validity with identical interaction effects of driving experience and task demands in simulator and instrumented car on the standard deviation of lateral position. On an absolute scale, however, performance in the simulator produces significantly larger values than that in the instrumented car for the four indices of lateral vehicle control than did the instrumented car. However, significant correlations were obtained for three of these indices, showing comparable individual behavior for each subject in the simulator and the instrumented car. Lateral control indices discriminated between both groups of driving experience only in the simulator and indicated a higher sensitivity of inexperienced drivers to less redundant information. Longitudinal control indices discriminated between both groups of driving experience in both the simulator and the instrumented car and showed larger variations in velocity for the inexperienced drivers in both systems. Accelerator usage provided even more pronounced evidence of these differences than velocity did. Drivers selected comparable velocities during the free driving condition in the simulator and the instrumented car. No differences were found between the forced and free task demands for the standard deviation of lateral position in lateral control and the standard deviation of velocity in longitudinal control. This suggests that the performance of drivers did not change as a result of imposed task accuracy.

The subjective criteria differentiated significantly between the simulator and the instrumented car for lateral and longitudinal vehicle control. Almost all opinions were less favorable for the simulator. With regard to longitudinal vehicle control, however, the simulator was judged easier to control.

The transfer between both systems did not result in different performance and behavior for the simulator and the instrumented car; however, the intervals within the one-hour session on both systems showed that lateral control was initially worse for the inexperienced drivers in both the simulator and the instrumented car. With respect to longitudinal control in the simulator, initial performance was worse only for the inexperienced drivers. The experienced drivers showed no deterioration of performance in the simulator and the instrumented car, indicating a good match between the driver's expectation and the actual behavior of the simulator.

When the results are summarized, it can be concluded that the simulator offers good absolute and relative validity for longitudinal vehicle control, but only good relative validity for lateral vehicle control. There is a lack of absolute validity for lateral vehicle control due to the larger variations in the lateral position in the simulator. The significantly high correlation between the systems still suggests a practically identical individual behavior on the simulator and the instrumented car. These results, however, are in terms of system performance and driver behavior. With respect to the driver's workload in both systems no direct measurements were taken; however, information was gathered from the questionnaires. Driver's opinions suggested a higher task difficulty for lateral vehicle control in the simulator and a lower task difficulty for longitudinal vehicle control. Obviously, the drivers in the simulator must pay more attention to lateral vehicle control to compensate for a lack of redundant information. The opinions on task difficulties for lateral and longitudinal control agree with the correlation coefficients for the measures of both controls. The questionnaires suggested that inexperienced drivers perceive higher workload levels than do experienced drivers, and indicate that experienced drivers were able to compensate better for having less information available in the simulator. This aspect is confirmed by the better performance for the experienced drivers in the simulator. Their simulator performance also corresponded more closely to their performance in the instrumented car. The simulator appeared to be more discriminative between levels of driving experience than the instrumented car.

Simulator Dynamics

With respect to the absolute validity for lateral vehicle control a comparison can be made with the results of an earlier validation study (Blaauw, Horst, and Godthelp, 1978). The two studies differed principally in the lateral simulator dynamics; in the earlier study an equivalent time delay of 0.3 s was added to the original car dynamics, while the present study was performed without this additional delay. Figure 6 presents the standard deviations of lateral position and yaw

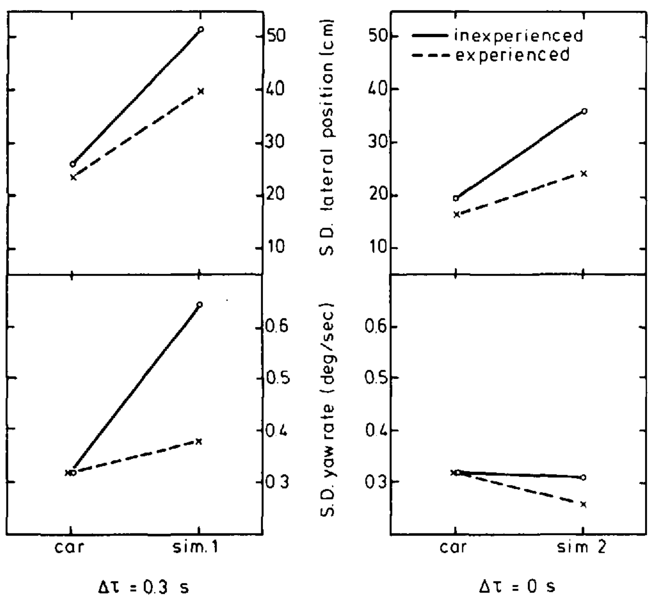

Figure 6. *Standard deviations of the lateral position and yaw rate for both groups during the earlier (time delay = 0.3 s) and the present (time delay = 0 s) studies.*

rate for the inexperienced and experienced drivers in simulator and instrumented car for both studies. In the first study significant differences ($p \leq 0.01$) were shown in the standard deviations of lateral position and yaw rate between the simulator and the instrumented car. These were explained as a combined effect of the additional time delay in the simulated vehicle dynamics and the absence of kinesthetic feedback in the fixed-base simulator. This conclusion was based on results in the literature. Repa and Wierwille (1976) and McRuer and Klein (1976a) studied the separate effect of vehicle dynamics and found larger variations in lateral position and yaw rate for more slowly responding cars (smaller bandwidths in vehicle dynamics). The effects of the absence of kinesthetic information have been reported, among others, by McRuer and Krendel (1974), McLane and Wierwille (1975), McRuer and Klein (1976b), and McRuer, Allen, Weir, and Klein (1977). These studies all indicated poorer system performance in terms of larger standard deviations of lateral position and yaw rate. Using the results of the first study and this one, it is possible to separate the effects of additional time delay and the absence of kinesthetic information for the results of the present study; permanent effects of the present study can now be uniquely imputed to the absence of kinesthetic feedback.

The present study succeeded in differentiating between inexperienced and experienced drivers in the simulator (Figure 6), replicating the results of the first study. Inexperienced and experienced drivers did not differ in the runs with the instrumented car. As a consequence, a reduction in equivalent time delay of the lateral simulator dynamics does not reduce the capacities of the simulator system to discriminate between levels of driving experience, although the absolute performance values changed considerably. With respect to the standard deviations of the yaw rate (Figure 6), the values for the simulator in the present study were significantly smaller, and more in accordance with the values of the instrumented car on the road, than were the variations derived in the first simulator study. With the absence of the additional time delay of 0.3 s in the present lateral simulator dynamics, drivers are able to perceive yaw rotations in the simulator quite well, and they perform about comparably with the instrumented car. It has to be kept in mind, however, that visual perception in the simulator is possible over a large horizontal field of view (120 deg); it would be interesting to investigate driver perception of yaw rotation with a more restricted field of view (e.g., 40 deg). The standard deviations of lateral position in the simulator were considerably smaller in the present study due to the decrease in time delay, but were still larger than the values derived with the instrumented car. As a consequence, it can be concluded that drivers performed more poorly in the fixed-base simulator due to a diminished perception of lateral translations (absence of kinesthetic information).

Experimental Conditions

Finally, some remarks should be made with respect to the experimental conditions used in this study. Driving experience affected performance significantly in the present experiment, suggesting the need for further studies in which the level of driving experience is taken into account. Task demands were studied with respect to critical elements of the "internal criterion" of the drivers, varied accuracy (free versus forced control), and the number of tasks that had to be performed simultaneously (lateral vehicle control, longitudinal vehicle control, or both). Neither the standard deviations of lateral position nor velocity changed as a result of the accuracy instructions. The addition of the forced accuracy instruction for velocity control, however, did substantially affect driver and system performance with respect to lateral control. Consequently, this forced accuracy instruction can be seen to produce an essential increase of task difficulty in driving. It is therefore recommended that this be considered as a way to manipulate driver's task difficulty in future studies.

With respect to the free and forced conditions, some differences were found when compared with an earlier study by Blaauw, Godthelp, and Moraal (1977). In that study, instructed task accuracy was found to significantly affect lateral and longitudinal control. These results, however, can be fully explained by the tasks each driver had to perform. In the earlier study (Blaauw et al., 1977) a within-subjects design was used and each driver was confronted with all task demands, which could be distinguished individually very clearly. The present experiment was based on a between-subjects design and each driver had knowledge of only one type of task. Consequently, drivers were not able to compare the several task demands and thus distinguished only one strategy in driving. This resulted in less pronounced differences in system performance and driver's behavior.

CONCLUSIONS

A fixed-base simulator offers a valid method for studying straight-road driving. Performance based on longitudinal vehicle control had good absolute and relative validity, while lateral vehicle control gave evidence of good relative validity between the instrumented car and the simulator.

The lack of absolute validity for lateral vehicle control is apparently due to a diminished perception of lateral translations (absence of kinesthetic information in the fixed-base simulator).

Yaw rotations were perceived quite well in the simulator. Future studies will have to determine whether this performance is a result of the large horizontal field of view (120 deg).

Finally, the results, which suggest that perception of translational and rotational movement may serve as a means for discriminating between experienced and inexperienced drivers, could be used as a basis for the design of a driving simulator.

The simulator is more sensitive to differences between levels of driving experience than is the instrumented car on the road. This potential of the simulator system is not dependent on the equivalent time delay of the lateral simulator dynamics.

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REFERENCES

Allen, R. W., Klein, R. H., and Ziedman, K. Automobile research simulators: A review and new approaches. *Transportation Research Record*, 1979, *706*, 9-15.

Blaauw, G. J. Simulatie en wegontwerp (Simulation and road design). Soesterberg, The Netherlands: Institute for Perception TNO, Report IZF 1979-C21, 1979.

Blaauw, G. J., and Burrij, S. ICARUS: An instrumented car for road user studies. *Journal A*, 1980, 21 (3), 134-138.

Blaauw, G. J., Godthelp, J., and Moraal, J. Driver's lateral control strategy as affected by task demands and driving experience. SAE Paper No. 770876, Detroit, MI: Society of Automotive Engineers, 1977.

Blaauw, G. J., Horst, A. R. A. v. d., and Godthelp, J. De voertuigsimulator van IZF-TNO: een valideringsonderzoek bij het rijden op een rechte autosnelweg, Voortgangsrapport I (The vehicle simulator of the Institute for Perception TNO—A validation study during straight-road driving, Progress Report I). Soesterberg, The Netherlands: Institute for Perception TNO, Report IZF 1978-16, 1978.

Brown, J. L. Visual elements in flight simulation. Report of Working Group 34. Washington, DC: Committee on Vision, Assembly of Behavioral and Social Sciences, National Research Council, National Academy of Sciences, 1975.

Godthelp, J., Blaauw, G. J., and Horst, A. R. A. v. d. Instrumented car and driving simulation: Measurements on vehicle dynamics. Soesterberg, The Netherlands: Institute for Perception TNO, Report IZF, 1982.

Institute for Perception TNO. A large-scale simulation system for the study of navigation and driving behavior. Soesterberg, The Netherlands: Author, TNO Documentation Sheet 39e, May, 1978.

McCormick, E. J. *Human factors engineering*. New York: McGraw-Hill, 1970.

McLane, R. C., and Wierwille, W. W. The influence of motion and audio cues on driver performance in an automobile simulator. *Human Factors,* 1975, *17,* 488-501.

McRuer, D. T., Allen, R. W., Weir, D. H., and Klein, R. H. New results in driver steering control models. *Human Factors,* 1977, *19,* 381-397.

McRuer, D. T., and Klein, R. H. Effects of automobile steering characteristics on driver/vehicle performance for regulation tasks. Dearborn, MI: Society of Automotive Engineers SAE Paper No. 760778, 1976. (a)

McRuer, D. T., and Klein, R. H. Comparison of human driver dynamics in an automobile on the road with those in simulators having complex and simple visual displays. Paper presented at the 55th Annual Meeting of the Transportation Research Board, Washington, DC, 1976. (b)

McRuer, D. T., and Krendel, E. S. Mathematical models of human pilot behavior. Paris: NATO AGARD-AG-188, 1974.

Moraal, J., and Poll, K. J. De Link-Miles rijsimulator voor pantservoertuigen; verslag van een validatieonderzoek (The Link-Miles driver simulator for tracked vehicles; a validation study). Soesterberg, The Netherlands: Institute for Perception TNO, Report IZF 1979-23, 1979.

Mudd, S. Assessment of the fidelity of dynamic flight simulators. *Human Factors,* 1968, *10,* 351-358.

O'Hanlon, J. F. Directory of research laboratories operating driving simulators and research vehicles in North America. Washington, DC: Transportation Research Board, Committee Report No. A3B06, January, 1977.

Repa, B., and Wierwille, W. W. Driver performance in controlling a driving simulator with varying vehicle response characteristics. Detroit, MI: SAE Paper No. 760779, 1976.

Rolfe, J. M., Hammerton-Frase, A. M., Poulter, R. F., and Smith, E. M. B. Pilot response in flight and simulated flight. *Ergonomics,* 1970, *13,* 761-768.

Winer, B. J. *Statistical principles in experimental design.* New York: McGraw-Hill, 1962.