10. EVALUATION OF DRIVER WORKLOAD DURING A SIMULATED AND AN ACTUAL DRIVING TASK

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10.1. INTRODUCTION

It is relatively easy to quantify driver-vehicle performance. It is possible, for example, to measure speed, acceleration, course deviations, control movements. This is made even easier when dealing with a driving simulator. On the other hand, however, little is known of the driver himself, of the difficulties he undergoes, fatigue, the risk he perceives etc.

Very early, interest was focused on the physiological measurements which could differentiate driver status: alertness, muscular tone, cardiac or respiratory rhythm, or even electro-dermal skin resistance. These measurements are, however, difficult to interpret as they can be affected by a large number of factors which can seldom be controlled.

Since the early 50s, work has been directed towards the measuring of "mental effort", also known as the mental load or workload. Seemingly simple, this is in fact an extremely complex concept, which differs from "attention" and on which no agreement has yet been reached. There is no place here to discuss the concept of load, which has been done in the reports this paper refers to.

This research is aimed at developing a method that could be used on a driving simulator or in an instrumented vehicle as well, and that would permit to measure any performance impairment or driver's workload increase. Such a method would be particularly valuable to monitor driving aids effects.

10.2 PRIMARY MEASURES

They are used to describe driver-vehicle performance, without imposing any specific restrictions on the subject.

The following are currently used :

- speed
- longitudinal and transversal acceleration
- yaw, yaw speed,
- position in relation to the side of the road (or the central white line)
- "time-to-line crossing" (TLC), which is the time a vehicle would take to leave the roadway if the actual controls (steering wheel angle, speed) were maintained in the same position. This concept has been developed by Godthelp, Milgram and Blaauw (1984) at the TNO
- steering wheel angle, steering-wheel rotation speed.

In general, however, use is made of other cues calculated using raw data. Literature contains essentially:

- Steering Reversal Rate or SRR (McLean and Hoffmann, 1975), which is the number of times per time unit when the rotation direction of the wheel is inverted, taking into account a range of several degrees to eliminate micro-oscillations.

- Spectral analyses of wheel angle, which are more complicated to carry out but which provide more detailed information, i.e. the movement variance distribution according to frequency (McLean and Hoffmann, 1971). These analyses use Fourier transforms, breaking down a phenomenon into a sine-cosine superposition.

In 1979, Hicks and Wierwille published results obtained on a simulator showing that from 5 measures (including 1 secondary task and 1 physiological measure), the SRR was most sensitive to load, which in this instance was a moderate or strong side wind. McLean and Hoffmann, (1971) analysed frequency spectrums and showed that there are usually two peaks, one at approximately 0.10-0.30 Hz, and the other at about 0.35-0.60 Hz. Referring to Weir and McRuer, (1968), they assumed that this corresponded to two control modes, one based on course or yaw (the highest frequency), the other on lateral placement error (shift in relation to the side of the road). There is also an excellent link between the high frequency energy spectrum and the SRR, which justified the use of the latter when seeking a cue which is relatively simple to calculate.

Nevertheless, McLean and Hoffmann (1975) showed that wheel activity was more likely to reflect the task difficulty and the demands for accuracy that the subjects had set themselves, than an absolute performance level. In fact, depending on the experimental conditions, an increase in load can either increase wheel activity (the subject wishes to maintain the same tracking accuracy), or lower it (the subject is satisfied with a less accurate adjustment to meet other demands).

Care should therefore be taken when handling these cues. They should be used in well-controlled experimental conditions and in relation to other performance and load indicators.

10.3. PHYSIOLOGICAL MEASURES

The most widely used measurements are probably pulse rate and sinus arrhythmia. Reference can be made to Meshkati (1988) who reviews the extensive work, sometimes contradictory, which exists in this field. One of the problems raised by pulse rate is that it may produce a great many indicators. The main indicators are:

- the average frequency (HR), expressed as an average number of pulsations per minute, or more often as an average of the intervals between beats (IBI),
- variability (HRV) or sinus arrhythmia. Egelund (1982), referring to Opmeer (1973), indicates that there are at least 26 ways of calculating this. Those most often used are either the average difference between two successive beats, or the standard deviation of the period between beats,
- spectral analyses of the cardiac signal.

The mean frequency is sensitive to fatigue, but also to occasional events which may not be task-related. It is generally considered that this is not a good indicator, although some surveys, performed in stable environments and involving little physical effort, have been able to show positive results (Wierwille and Connor, 1983).

Several authors have shown that the variability in cardiac rhythm decreases as the load increases (Blitz et al., 1970; Boyce, 1974). But results are contradictory depending on the experimental conditions and the methods used to calculate variability.

It would seem that the best results are obtained by performing a spectral analysis of the inter-beat time interval. According to Sayers (1973), and Egelund (1982), cardiac frequency would indeed seems to be connected to three mechanisms:

- respiratory rhythm,
- blood pressure,
- thermal regulation.

This recurs in the spectral analyses, as blood pressure is linked to the cardiac frequency component located between 0.05 and 0.15 Hz. It is this component which would appear to be linked to the workload (Hyndman and Gregory, 1975, Egelund, 1982, Cohen-Shmuelly et al., 1990). The drop in the energy spectrum in this region appears to be a heavy load indicator.

10.4. SECONDARY MEASURES

The qualities sought in the secondary task are as follows:

- There should be no structural interference with the primary task.

For example, the same sensorial procedure should not be called upon to perform two different things simultaneously (looking in two opposite directions at the same time, performing two manual tasks..).

- If reference is made to the multiple resource model, the secondary task must compete for the use of resources shared with the primary task.

If not, processings could be performed in parallel and the measurement would not be as sensitive. If reference is made to the single channel mode, the choice of task is less important as all the processings are said to be sequential.

- The difficulty of the secondary task must be adapted to that of the primary task, so that the maximum score cannot be obtained simultaneously for both tasks.

Indeed, should there be a residual capacity this could be used, as the subject desires to compensate should the primary task become more difficult, without this resulting in changes in secondary task performance.

- Finally, the measure should be as sensitive and as accurate as possible, whilst remaining non-intrusive.

We can find a lot of secondary tasks in the literature, even if we consider only those which have been used concurrently with a driving or a flying task. On the road, tapping tasks have been extensively used (Michon, 1966, Michaut, 1968, Neboit & Laya 1982...).

On simulators, batteries of secondary tasks are often applied successively in the same conditions, in order to study their relationship with difficulty, and their co-variance with performance measurements. Wierwille and Connor (1983), Casali and Wierwille (1983, 1984), Wierwille, Rahami and Casali (1985) continue to use these methods. The advantage of these studies is that they are systematic (up to 20 load measures studied in the same context).

Wierwille et al (1977), Wierwille and Gutmann (1978), Hicks and Wierwille (1979), have shown that the primary measures and subjective scales provide a clear differentiation between the levels of difficulty which occur when driving (a moderate or strong side wind), whereas the secondary tasks and physiological measures do not show any significant difference. It should however be noted that this result is hardly surprising. Disturbances which affect trajectory control are bound to lead to changes in movement and position, but will make little demand on cognitive resources, which are reflected in many of the secondary measures used.

It could be assumed that the results would be reversed should the type of difficulties introduced arise from traffic, manoeuvres to be performed or navigational problems to be solved. We also find some validation studies, which aim at comparing real and simulation situations. The load is then one of the comparison criteria and is often measured using subjective scales. Blaauw (1982) for example, perceived that both beginners and experienced drivers thought driving was more difficult on a fixed-base simulator than on a track (which is to be expected if the task is more difficult).

This type of research is currently being carried out at the TNO (Harms, 1991). Riemersma et al. (1990) used the Daimler-Benz simulator. They compared decreases in speed obtained in real situations after modifying approaches to built-up areas with those obtained on a simulator. They found that the modifications really did produce the expected decreases in speed, but that speed levels were slightly higher on the simulator than they were in a real situation.

The research work presented below consists of two parts:

- a simulator study, in which different measurements were made in controlled conditions, in order to detect the best indicators adapted to our goals,
- a field experiment, (or more exactly the pre-test of it), in order to validate the method.

10.5. CHOOSING A SECONDARY TASK (SIMULATOR STUDY)

10.5.1 Principle and method

This experiment consisted in putting drivers at the wheel of a rustic simulator, and recording the various dependent variables simultaneously (primary and physiological measures) or successively (secondary tasks). The simulated route, lasting approximately 10 minutes, contained varying levels of difficulty, linked to specifications such as visibility distance (simulation of fog), alignment. The route was covered as many times as there were secondary

tasks, and more than once without any secondary task so as to determine the effects of intrusion.
The aim was to determine which measures best reflected the variations in difficulty of the driving task presented to the subjects. The methodology used was fairly similar to that used by Wierwille and Gutmann in 1978.

10.5.2. Apparatus

It consisted of a vehicle mock-up, the controls of which being connected to a numeric image generator, namely the INRETS GSI, based on a Silicon Graphics station. The image frequency was about 15 Hz, and there was no movement restitution.

10.5.3. Subjects

16 subjects were selected, for the most part members of the INRETS staff, and with varying degrees of experience. For this first experiment, little importance was given to the individual characteristics of the subjects, insomuch as no assumption was made as to the part played by variables such as sex or experience on the mental load.

10.5.4. Circuit

The circuit covered 9800 meters, consisting of 14 sections, straight or winding, of varying widths (300, 500 and 700 meters), and with different visibility distances. To achieve this fog of varying density was simulated. It should be noted that this fog was simulated only very sketchily, and was indicated only by a change of colour and contrasts and that the mantle effect produced by fog did not increase in relation to depth. The effect, even if not realistic, nonetheless considerably impeded the driver. It was assumed that this impediment would be in proportion to the thickness of the simulated fog.

Note that to compensate for possible sequence effects, the sections were not put together in the same order for all the subjects.

10.5.5. Physiological measures

Cardiac beats were recorded using portable equipment designed for sportsmen. This was a Baumann BHL 5000 cardiac rhythm recorder, which recorded the time intervals between successive beats in milliseconds. It consisted of a belt fitted with three electrodes to be placed directly on the chest, and a recording unit the size of a cigarette packet connected by a wire to the belt. At the end of each sequence, the data were then transferred from the unit to a PC, using software provided with the device.

It was then easily possible to calculate cardiac frequency, and the variability cues (standard-deviation or average deviation between successive beats). We expect to perform more complex processing, such as spectral analyses of the cardiac signal, at a later date.

10.5.6. Primary measures

Using this generator it was easy to record the following parameters:

- speed (S)
- Steering-wheel angle (SA)
- yaw angle (YA)
- distance in relation to the median line (MLD)

Another indicator was calculated in real time:

- Time to Line Crossing (TLC), calculated in real time, which is at each moment, the time the vehicle would take to leave the road if the driver maintained the same status for the various controls. It is therefore the available time margin during which it is possible not to react. The data were stored on Unix files managed by one of the INRETS network hosts.

- The Steering-wheel reversal rate (SRR) was calculated a posteriori.

10.5.7. Secondary measures

- Reaction time

This is the simple reaction time to an audible signal. The signal and the response were given verbally, using a headset fitted with a microphone. the entire unit being linked to a portable PC 386, sequenced at 33 MHz. The audible signal lasted for approximately 0.5 seconds and the random interval between the two signals varied between 1.9 and 3.1 seconds

- Offset discrimination and high and low sounds (OBA).

Using the same equipment. high (1400 Hz), or low (440 Hz) sounds were presented to the subject in a random order at a rate of one signal every 2.5 seconds. The interval between the two sounds was therefore approximately 10 tones. The subject was asked to respond by offsetting his response i.e. he was asked to indicate if the signal before last was high or low. For example, for the following sequence the subject should have answered:

signal	high	low	low	low	high	low	high	high	
response		high	low	low	low	high	low	high	high

Verbal responses were recorded on the PC through a digitising card. This task called upon short term memory.

- Reading numbers on a screen (shadowing)

A 14" monochrome screen was placed at eye level but to the right of the control panel. The 2 figure random numbers appeared. one number every 1.5 seconds. Each figure was 3 cm high and 1.5 wide. The place on which they appeared on the screen was also random. As the subject had to turn his eyes away from the road to read these figures, this was probably more a load or visual availability measure than an actual mental load measure. Note that it was initially planned to use a tapping task (producing regular intervals), but technical difficulties linked to recording responses forced us to abandon this task. The following were then calculated:

- average and standard deviation for reaction times (more the 3 tasks).
- error or omission % (for the OBA).
- % of figures read (for reading on screen).

10.6. PROCEDURE AND INSTRUCTIONS

Each subject was first fitted with a cardiac beat recorder. He was then installed at the wheel of the simulator. He then drove for a minimum of 15 minutes to familiarise himself with the circuit, as because of a considerable "transport delay" course control required an adaptation time. He then performed the 4 circuits at his own speed.

For the first (cardiac recording only) he was simply asked to drive normally, remaining if possible in the centre of his lane.

Each of the three other circuits started by familiarising him with the secondary task, performed first when the vehicle was stationary, then when maximum performance was acquired with a moving vehicle. When the subject was ready, he was instructed to perform the secondary tasks as well as he can, but without impairing the driving task. The order of passage of the different circuits was counterbalanced to avoid sequence effects. There was a pause between the circuits. The same procedure was then replicated with speed monitored by the system at 90 km/h.

10.6.1. Independent variables

- There were three thicknesses of fog, which produce 4 levels of visibility, the first level being the no-fog reference (visi1 to visi4).
- two alignment conditions (straight and winding).
- four successive circuits, i.e. 1 per secondary task procedure (cardio, reaction, OBA, screen).
- two speed procedures (unrestricted and imposed).

10.6.2. Dependent variables

- primary measures (S, MLD, SRR, TLC, SA, YA),
- physiological measures (intervals between successive cardiac beats),
- secondary measures (performance in the three secondary tasks, calculated in 3 different ways: mean reaction time, standard deviation, % of errors).

10.7. RESULTS

10.7.1. Effect of experimental factors on performance

A two-fold assumption was made:

- that difficulty increased as visibility decreased.
- that the difficulty would be greater on bends than on straight stretches.

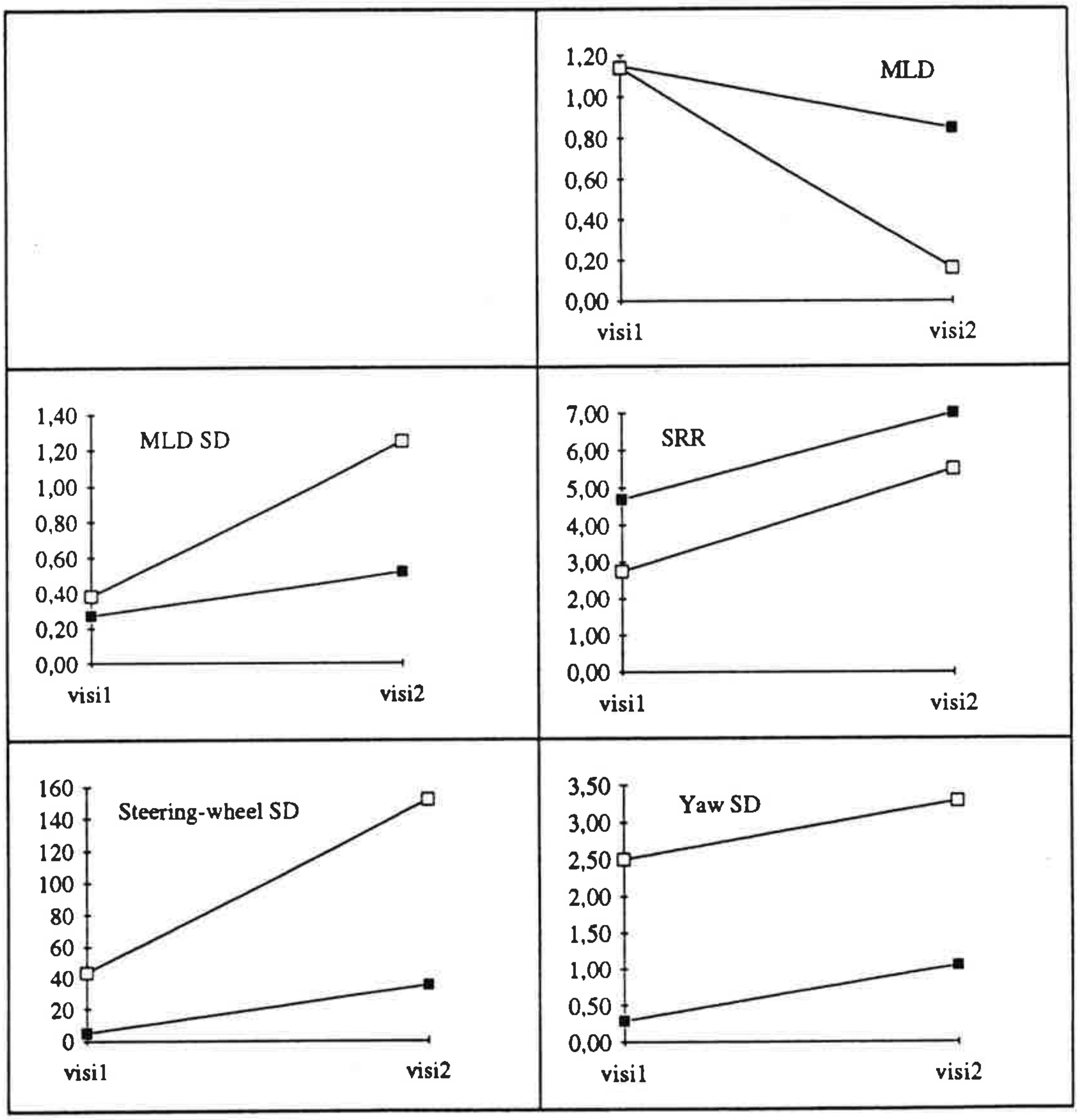
Before examining the results of the secondary tasks, we therefore studied the reference measurements, i.e. those during which only cardiac beats were recorded.

This measure was considered to be a priori non intrusive, i.e. no influence on performance. We will show results only for runs executed at imposed speed. There were several justifications for this imposed speed :

- It is known that there is an accuracy-speed relationship, as subjects tend to reduce speed when the difficulty increases.
- This simulator was too rudimentary to allow for a precise speed adjustment as there was no feedback with regard to acceleration, restored efforts to the steering-wheel and gas pedal, and as there is no lateral vision.

To make the results clearer, we will present only comparisons between visi1 (no fog) and visi2 (fog), because the simulation of fog was not good enough to ensure the linearity of the perceptual effect.

Figure 1: Effect of visibility and road curvature on performance measurements



A clear differentiation can be seen between visi1 and visi2 (factor 1). and between straight and winding (factor 2).

The significance of the difference was controlled using variance analyses performed with SAS or Systat. The Anova model was used with repeated measures. the successive sections (combination of the 2 factors) being the repetitions. The statistic F and the associated probability (1 dl) were computed and show significant differences :

- for factor 1 for every indicator,
- for factor 2 for every indicator except SRR,
- for interactions except for SRR and Yaw SD.

10.7.2. Secondary tasks sensitivity

A measure is likely to be sensitive if we can observe:

- an increase or decrease in relation to visibility.
- a differentiation between a straight and a curved alignment.

10.7.3. Cardiac rhythm

No significant effect was found concerning this indicator.

10.7.4 Reading numbers on the screen

Only the percentage of omitted responses would seem really to differentiate visi1 and visi2. for the two types of alignment (significant at a threshold of 3% for each of the two factors). However, the standard deviation does not provide any interpretable result.

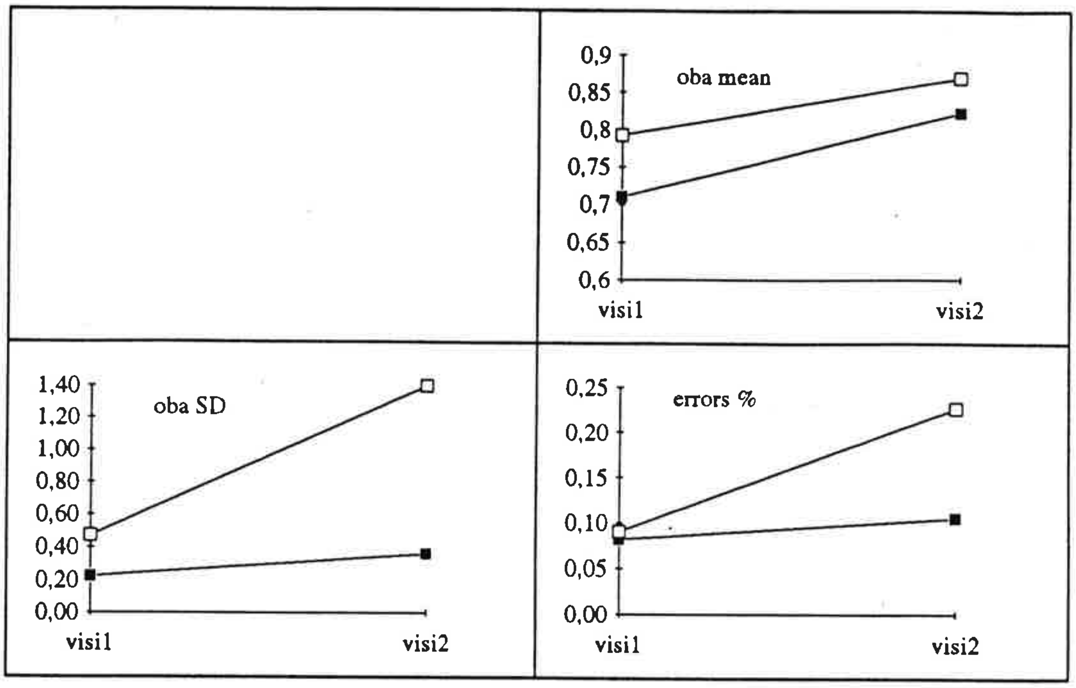
10.7.5. Simple reaction time

This measure does not provide any significant result.

10.7.6. OBA

Performance to this secondary task is presented in the charts below. These results consist of mean reaction time (RT) to the signals, standard deviation of RT, % of errors.

Figure 2: Mean reaction time, standard deviation and % of errors to the OBA task, while driving at an imposed speed of 90 km h.



For this task, the standard deviation and the % of errors differentiate visi1 and visi2, on straight stretches and on bends. An interaction effect can also be noted. As this is the task which produced the best results, the following tables show the results of the variance analyses.

The Anova results show significant differences on RT (SD) and errors % :

	df	mean square	F Snedecor	sign. level
visibility	1	4.537	3.596	.007
road profile	1	6.639	4.806	.045
interaction	1	2.506	4.477	.051

Table 1 : Effect of the factors on reaction time (RT) standard deviation.

	df	mean square	F Snedecor	sign. level
visibility	1	0.102	3.673	.075
road profile	1	0.065	4.253	.057
interaction	1	0.052	3.234	.092

Table 2 : Effect of the factors on the percentage of false responses (% errors).

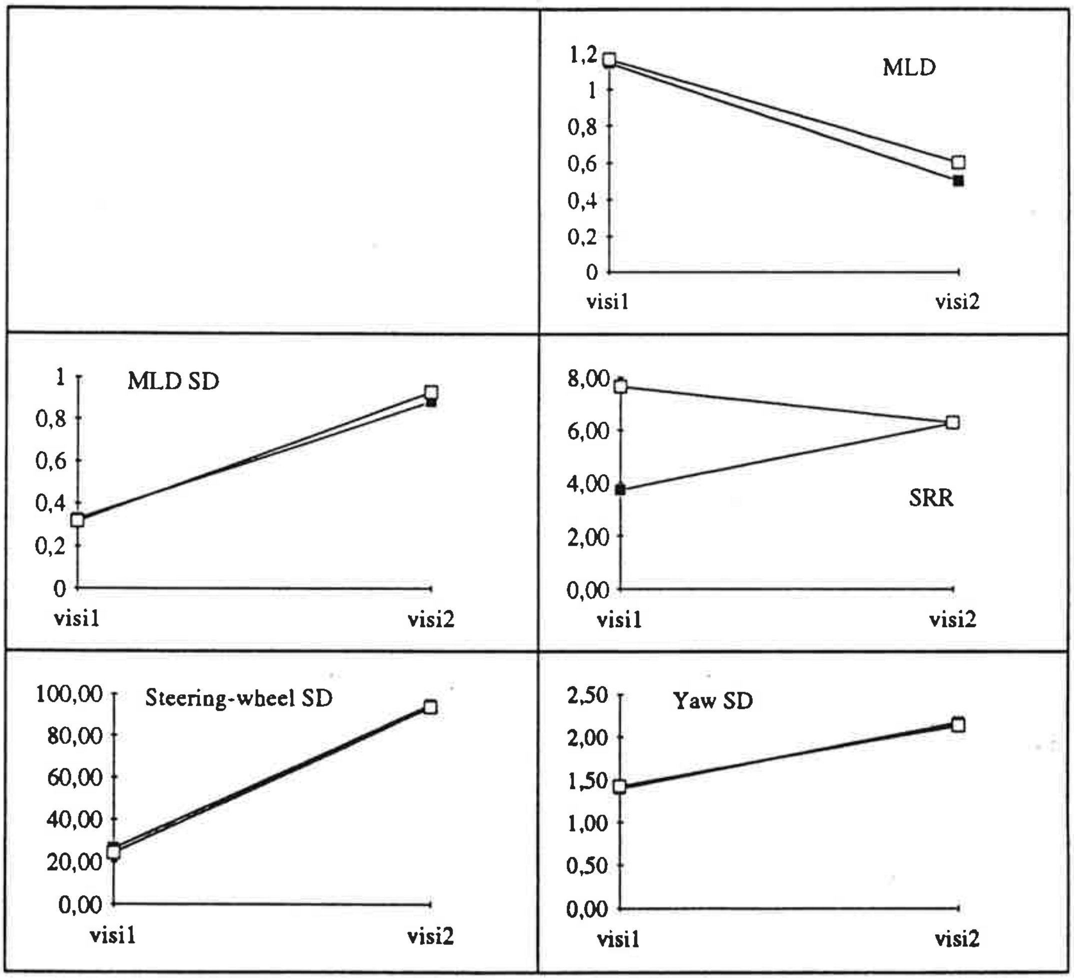
On both these criteria, standard deviation for reaction time and the number of errors, we can observe a significant effect of visibility and road profile factors, together with an interaction effect. This secondary task would seem therefore to be an acceptable workload measurement tool in a given driving situation, on condition it does not impair driving, which will be examined in the paragraph dealing with intrusion.

From this chapter it can be concluded that the OBA task produced the best results.

10.7.7. Intrusion of secondary measures on performance

We will examine the effects for OBA only, the only secondary task sensitive enough to be used. The effect of intrusion will be measured by comparing performance with and without the secondary task (in this instance OBA versus the reference measurement, i.e. cardio).

Figure 3 : performance modifications produced by the secondary task (intrusion)



It can be seen that there is no major difference between cardio and OBA, except for SRR. The similarity of these curves is even remarkable. F and the probabilities linked to the different comparisons were computed, including visibility 3 and 4. No significant difference was found, except for SRR ($p = .016$).

To conclude this first experiment results, we can therefore say that the OBA task proved to be relatively simple and barely intrusive. This is why it was chosen to be validated in a real situation.

10.8. ON-THE-ROAD VALIDATION STUDY (SECOND EXPERIMENT)

The second part of this research work consists in a field experiment, using the same methods as those used on the driving simulator : The aim was to try to validate the results obtained on the simulator.

10.8.1. Apparatus

We instrumented a car with different sensors, video camera, and PC computer, in order to collect the following parameters:

- speed,
- distance,
- steering-wheel angle,
- pulse rate,
- response to the secondary task.

We used exclusively the "OBA" task. The visual field was recorded by a video camera synchronised with the computer.

10.8.2. Subjects

In order to test the vehicle and the method, in this first step we used only 5 drivers. They were trained to the oba task in the laboratory. After that, each of them drove the vehicle on a journey of about 90 minutes, in the neighbourhood of Paris. Actually, they performed three runs, in order to eliminate practice effects. Only the third one was recorded.

10.8.3. Circuit

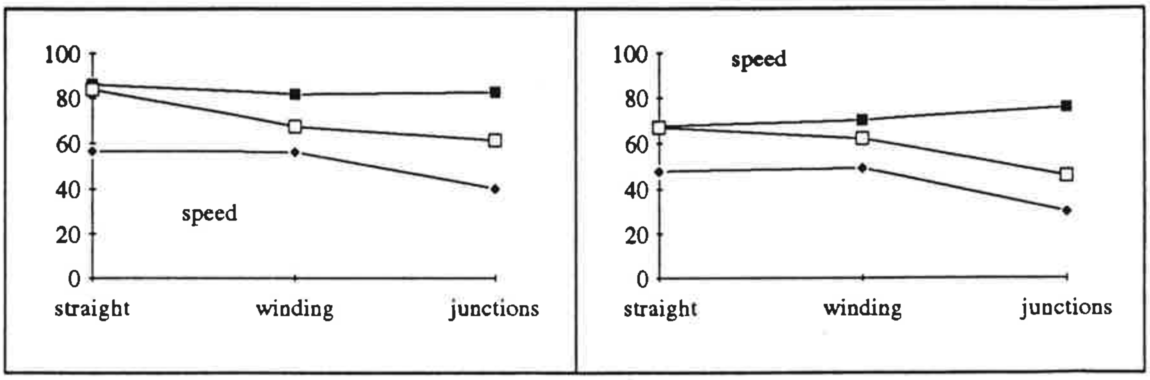
This journey combined different locations, (motorway, two-lane roads, villages), different road characteristics (straight, bends, junctions), and different traffic conditions (low and high). The combination of these variables gave 18 possibilities, unequally represented among the drivers, according to traffic conditions. With a greater number of drivers, this method will make it possible to use Anova with repeated measures <3*3*2>, to test the factors´ effects.

10.9. RESULTS

10.9.1. Sensitivity

At the moment, we will only show tendencies on charts. It is obvious that no statistical differences will show up with only 5 people, with regard to the relatively small expected effects.

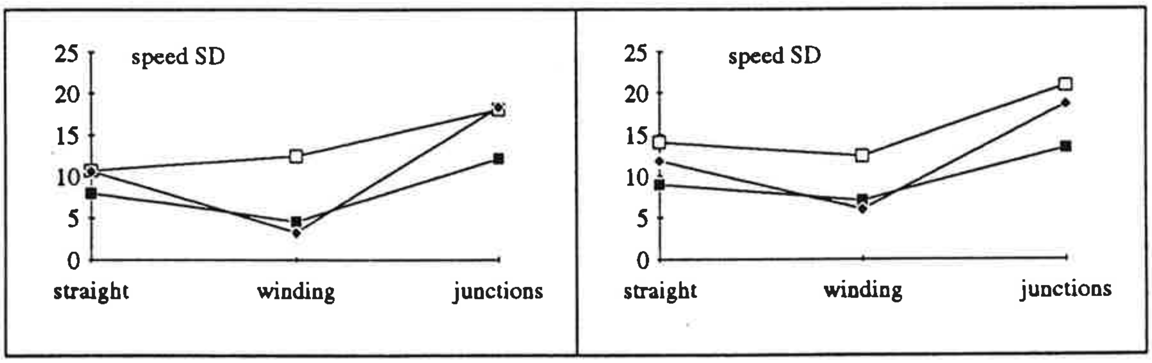
Legend applicable to all the following charts



low traffic heavy traffic

Figure 4 : Speed according to location and road characteristics

It can be seen that speed is of course lower when traffic is heavy. On two-lane roads and in villages, speed is lower than on straight stretches.



low traffic heavy traffic

Figure 5 : Standard deviation of speed according to location and road characteristics

On two-lane roads and in built-up areas, bends and junctions lower standard deviations. This is not the case on motorways, where there is no strong physical constraint (great radii).

Dispersion is always higher at intersections, because this class includes intersections with different priority status, some of them requiring to slow down, some others not.

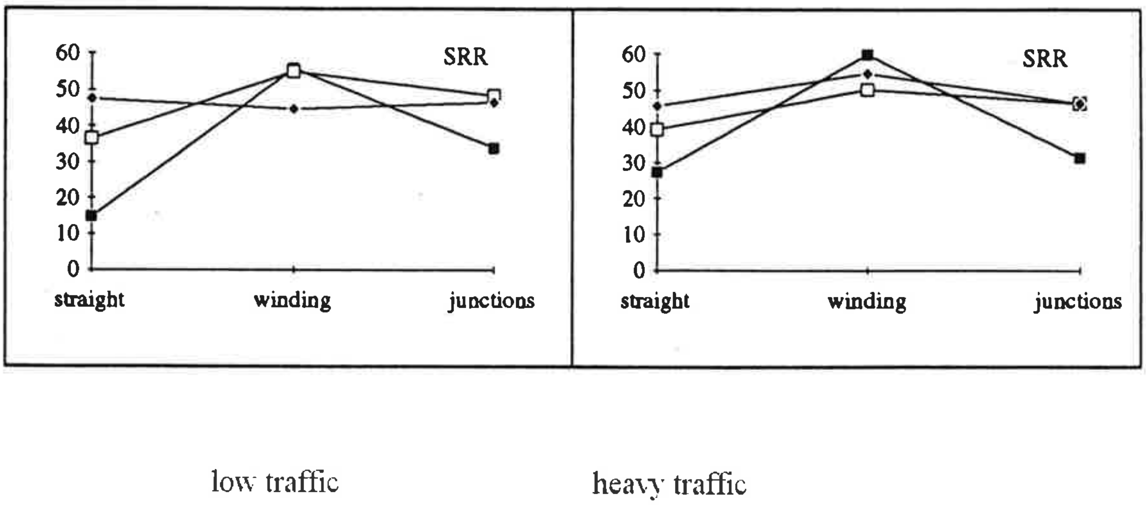


Figure 6 : SRR according to location and road characteristics

Curves and intersections tend to make this indicator more even, whereas on straight sections the different types of road can be distinguished.

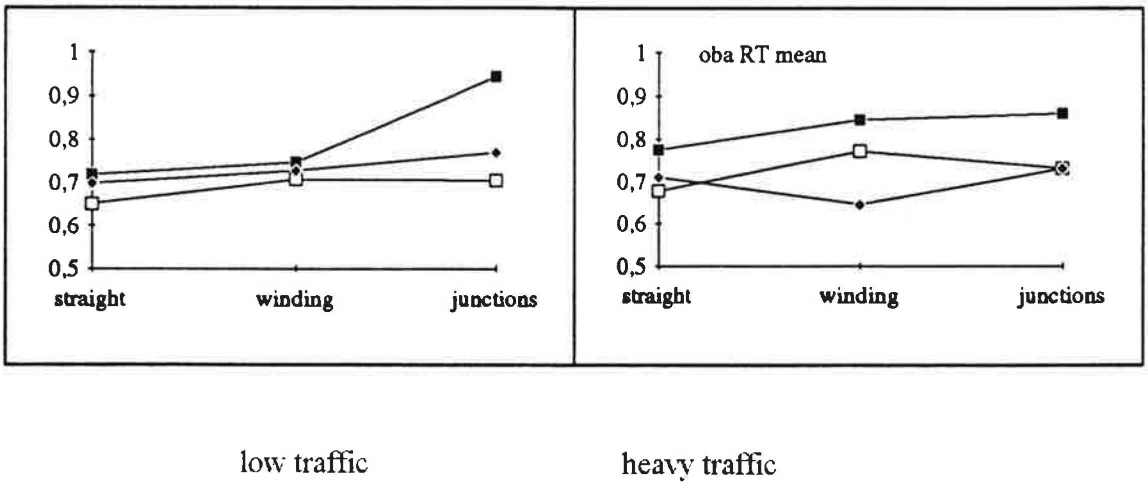
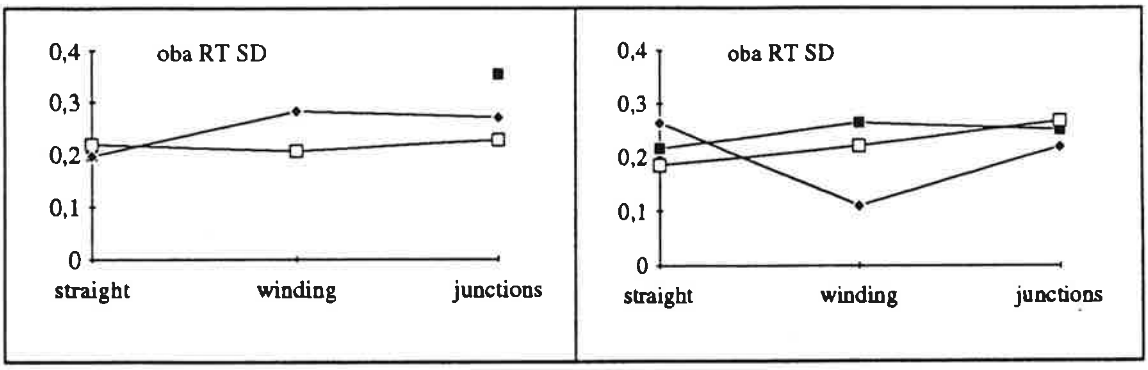


Figure 7 : mean reaction time to the secondary task according to location and road characteristics

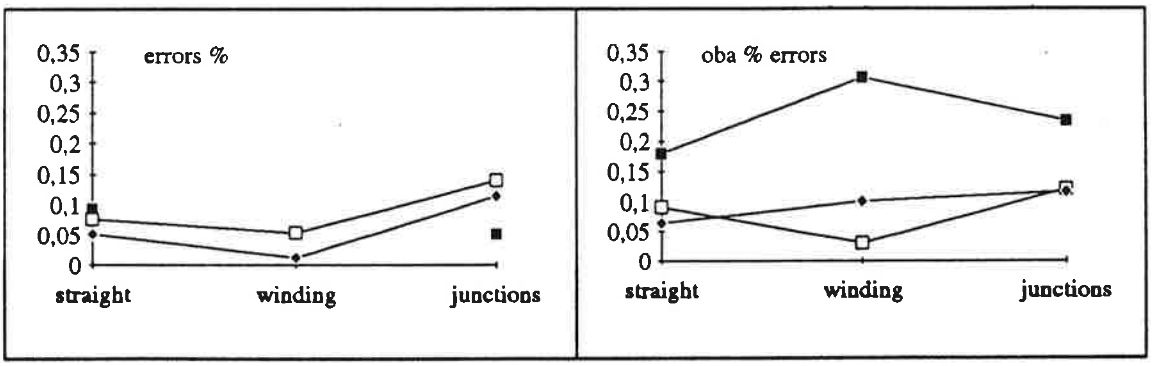
There is no obvious variation of the mean reaction time according to the considered variables.



low traffic heavy traffic

Figure 8 : Standard deviation of reaction time according to location and road characteristics

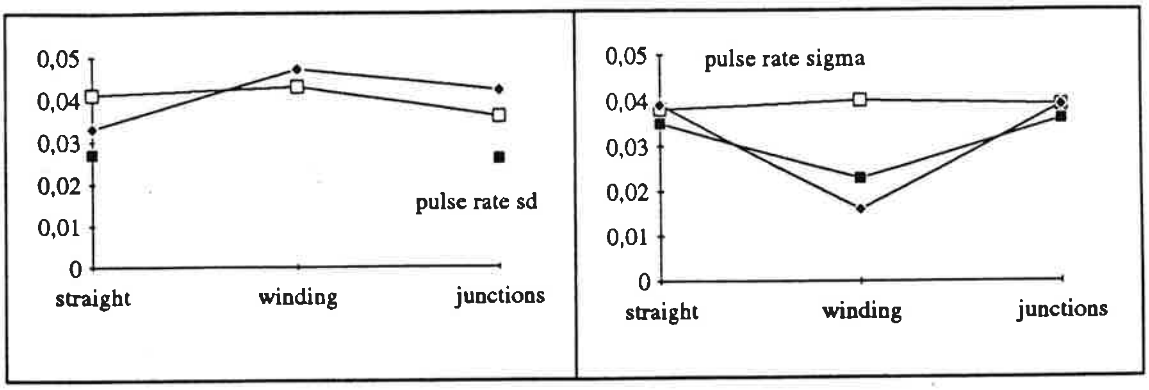
The standard deviation, which is supposed to be the best indicator, does not show any significant tendency.



low traffic heavy traffic

Figure 9 : Error percentage to the secondary task according to location and road characteristics

It can be noticed that this percentage is higher at intersections, and when traffic is heavy, particularly on motorways, where, next to Paris, driving conditions are particularly severe.



low traffic heavy traffic

Figure 10 : Pulse rate standard deviation according to location and road characteristics.

We can see that none of the indicators provides a clear differentiation between the experimental conditions.

The trouble with this "factorial approach", is that in a same cell we sum up different sections of road, different curves and different intersections. In other words, each cell is a mixture, and this cancel all possible diachronic effects.

This is why we attempted more simple treatments, consisting in comparing only two consistent sections, the first one considered as "easy", and the second as "difficult", although it is impossible to describe the difficulty in the same terms as previously. As a whole, difficult means more traffic, alignment more winding, more time spent in built-up area.

	easy	difficult	signif.
RT (m)	0.620	0.724	.20
RT (s)	0.204	0.254	.38
% errors	3.9	5.6	.13

Table 3 : Performance to the secondary task, on easy and difficult stretches of road (results concerning only 4 drivers).

We cannot reach the significance thresholds with only 4 subjects, but we can see that all the tendencies are compatible with the assumptions made. This result is fairly encouraging.

10.9.2. Intrusion effects

During the experiment, we didn't notice any modification in the drivers' behaviour when performing the secondary task. Nevertheless, we investigated this point by comparing primary measures without and with the oba task on two sections. Unfortunately, we failed finding strictly comparable stretches of road. It must be said that the road with oba was minor than the one without, and that it was a little more winding. This will impair the conclusions. This work will have to be done over on the same road, one run without and one run with. This will be done next year. At the moment, results are as follows :

	without oba	with oba	probability
speed (m)	85.04	75.01	.008
speed (s)	15.28	17.74	.146
S-W angle (s)	7.31	12.46	.045
SRR	30.99	46.48	.003

Table 4 : Comparison of driver behaviour on two stretches of road, as comparable as we could find, one without and one with the secondary task (results on 4 drivers only).

It can be seen that without OBA speeds are higher, with a lower SD, that steering-wheel angle SD and SRR are lower. These results seem to indicate an intrusion effect, which was not demonstrated on the driving simulator. This point deserves further experiments, under good statistical conditions.

10.10. CONCLUSION

The inherent difficulty in this type of experiment is that it is extremely difficult to control the effects of learning. Despite a relatively lengthy familiarisation period, which gave the subjects the impression they were in control of the driving situation and the double task, it is probable that they modified their performance throughout the experiment. These learning effects were in part neutralised on an experimental level, which counterbalanced the sequence effects.

This initial research work on the driving workload has yielded encouraging results. We have been able to show that the task used was sensitive, and that these results were easy to record using the calculation facilities at our disposal. As with the vehicle-driver performance parameters, data analysis makes it possible to clearly differentiate the levels of difficulty introduced on the simulator. The problems which remain are comparisons with the actual driving task, in traffic. It can be assumed that the resources called upon by decision-making during actual manoeuvres will differ from those used in the tracking task, even complex, on a simulator. The adequacy of our secondary task has therefore still to be validated. It has a disadvantage when compared with tapping, in that it is performed at a set rhythm. It will therefore be necessary to seek the optimal value for this rhythm, which was in this instance a signal every 2.5 seconds. This will perhaps be a little too fast in a real situation. On the other hand, the considerable advantage of this task is that it is very difficult to automatise by the driver, unlike tapping. This is its advantage, particularly when dealing with the study of more complex tasks, e.g. which make use of screens or keyboards when driving.

With only 5 drivers in actual driving conditions, we failed to validate the results obtained on the driving simulator, which is perfectly normal. Nevertheless, the results proved to be encouraging, and permit to tune up the method. Of course new field experiments will follow, with an improved instrumented car, a new circuit, and above all more subjects. A positive aspect is that the data processing chain is now in place, and that it will allow us to get results very fast after resuming the data collection. A negative aspect is that the reliability of the instrumented car is not good enough to start right away a new experiment, and this is what we are working on at the moment. If we consider both experiments, we think that our method with some improvements will be a good tool in both aspects :

- assessing driving difficulties in various situations, and conditions (including use of driving aids),
- comparing driving simulator with real world driving.

ACKNOWLEDGEMENTS

The author thanks all the team who participated in this work, and mainly Pierre Gauriat, Stephane Martinez, Olivier Aubert, Frangois Lenoir, Claude Perrot, Jean-Louis Mondet. This research work was sponsored by the french ministry of transportation (DSCR).

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