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HUMAN-MACHINE COOPERATION IN CAR DRIVING FOR LATERAL SAFETY : DELEGATION AND MUTUAL CONTROL

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RÉSUMÉ

COOPÉRATION HOMME-MACHINE EN CONDUITE AUTOMOBILE POUR LA SÉCURITÉ LATÉRALE : DÉLÉGATION ET CONTRÔLE MUTUEL

Deux expériences ont été réalisées sur piste pour évaluer les effets bénéfiques, autant que les effets négatifs à combattre, de deux principaux modes de coopération homme-machine pour la sécurisation du contrôle latéral en virage. Avec le mode de délégation de fonction, *l'automate prend entièrement en charge le contrôle latéral (conduite au centre de la voie), en laissant au conducteur le contrôle longitudinal. Avec le mode* contrôle mutuel, *l'automate se contente de critiquer le comportement du conducteur. La* première expérience *a été conçue pour évaluer d'éventuels effets négatifs de la* délégation de fonction *sur la reprise en main du véhicule en situation d'invalidité de l'automate (contournement d'obstacle). Trois résultats principaux ont été retirés de cette expérience. En premier lieu, des difficultés de reprise en main ont été observées dans le contournement d'obstacle, avec une suspicion de négligence de la prise d'information nécessaire à la réalisation de la fonction déléguée. En second lieu, une certaine expérience du dispositif est apparue nécessaire pour atteindre un niveau acceptable de confiance et de maîtrise de l'interaction avec le dispositif. Les verbalisations révélaient encore l'élaboration d'un modèle de l'interaction avec le dispositif et la difficulté de se faire une idée précise de la répartition des fonctions entre le conducteur et le dispositif. Enfin, en troisième lieu, les styles de prise de virage des participants et du dispositif se sont avérés provoquer des interférences négatives, alors que des interférences positives étaient verbalisées en ligne droite. La* seconde *expérience visait à évaluer les effets bénéfiques de deux réalisations du*

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mode contrôle mutuel, *produisant une critique du conducteur quand la voiture s'écartait de plus de 60 cm du centre de la voie. Avec le mode* avertissement, *le conducteur entendait un son latéralisé du côté de la déviation de trajectoire et ressentait une oscillation non spécifique du volant. Avec le mode* suggestion d'action, *le conducteur ressentait une oscillation du volant qui l'incitait à le tourner dans le sens contraire à la déviation. Le mode* avertissement *s'est révélé parfois efficace dans des situations critiques où une déviation de trajectoire était provoquée par une occlusion visuelle. Le mode* suggestion d'action *n'a pas été concluant, notamment du fait d'une plus grande variabilité interindividuelle des effets et de conditions contextuelles défavorables. Il n'a été relevé aucun effet de contentement, ni de comportement de conformité à la norme (conduite au centre de la voie). Le contournement d'obstacle a été peu affecté par les modes de contrôle mutuel. Bien que ces résultats doivent être confirmés dans des situations plus riches et pendant de plus longues périodes de temps, s'il faut encore rester très prudent sur l'adoption du mode de délégation de fonction (contentement), relativement prudent pour le mode suggestion d'action, le mode avertissement paraît un bon candidat pour sécuriser la prise de virage.*

Mots-clés: *Coopération homme-machine, Assistance à la conduite automobile, Délégation de fonction, Contrôle mutuel, Sécurité, Prise de virage, Contrôle latéral, Signaux haptiques.*

I. INTRODUCTION

Many studies have been devoted to driving support to assist longitudinal control of the trajectory: in particular, these studies have focussed on the function delegation cooperation mode with ACC (Adaptive Cruise Control) and the mutual control mode. With the function delegation mode, one part of the driving task is automated (longitudinal control for ACC: braking and acceleration), whilst the other part (lateral control of the trajectory so that the car remains in the lane centre) remains under the driver's control. The mutual control mode is more remote from the action, usually occurring between humans working together (e.g., between the captain and the first officer in a cockpit). Here, the device is designed so that it can criticise the driver's behaviour when the time headway to a lead vehicle is too short. This paper presents some well-known results from within the domain of human-automation cooperation as well as a number of new findings. Some forms of behavioural adaptation in particular have been identified with ACC; for example, bypassing the device (resulting in more frequent left lane occupation) when its time headway control procedure renders overtaking more difficult (Nillson, 1995; Saad & Villame, 1999). Complacency has also been identified as being related to a reduction in mental workload and correlated to a decrease in attentional resources (Young, 2002). It is also likely to produce a decrease in the response time to hazards (Rudin-Brown & Parker, 2004). Finally, the need for the driver to acquire a correct model of the device function, excluding the collision avoidance capacity, is also demonstrated (Stanton & Young, 1998). The mutual control mode, which gives a warning when an incorrect time headway is adopted, has been positively evaluated, not only in the short term, when the device is available, but also in the long term, without the device (Ben-Yaacov, Maltz, & Shinar, 2002).

However, few studies have been devoted to driving support to assist lateral control. A function delegation mode –AS, or active steering– has been compared to a kind of ACC on a simulator, as well as to a control situation without assistance (Stanton, Young, Walker, Turner, & Randle, 2001). A higher decrease in workload resulted from AS than from ACC; however, AS did result in difficulties when returning to manual control to avoid collision. This difficulty was more considerable with ACC and with a combination of the two. Lateral control support has also been studied with cooperation modes of a mutual control type, using auditory warning or action suggestion on the steering wheel (Suzuki & Jansson, 2003). However, there was no control condition in this experiment, which nevertheless concluded in favour of the auditory warning when the participants were not informed of the meaning of the stimulations. There was a variable effect of the action suggestion, with some participants misinterpreting the direction of the action.

There are two reasons why studies of human-automation cooperation of lateral control support in car-driving are as worthy of development as those relating to longitudinal support. First, depending on the type of indicator used (for example, global statistics, accident detailed analysis, fatality) and the country, road departure accidents make up a significant proportion of all road accidents (from 35% to 70%: Bar & Page, 2002). Second, studies of the automation of various driving functions are likely to provide us with more general results and more robust theoretical interpretations than studies that are too restricted to one kind of function and one type of device. For these reasons, we have designed two experiments on lateral control, taking advantage of the availability of equipped vehicles in a cooperating laboratory (LIVIC). Recent studies conducted at LIVIC (Netto *et al.,* 2003) have resulted in the definition of three kinds of lateral control assistance aimed at maintaining the vehicle in the lane centre –a warning mode, an action suggestion mode and a function delegation mode. They operated on the basis of information obtained by frontal and lateral cameras that enable the vehicle to be located between lane markers. The three modes were conceived to be autonomous. The interference level with respect to the driver increases from the first (warning) to the third (function delegation) mode. The first two modes are passive in the sense that no trajectory correction is applied to the vehicle and only haptic/sound alarms are activated when a dangerous situation is signalled. In the third one, the lateral motion of the vehicle is delegated to the device. An important feature of the devices is that, at any moment, they can be deactivated by a counter action to the steering wheel applied by the driver.

The aim of the two experiments presented in this paper was to evaluate these different human-machine cooperation modes with this kind of assistance, focussing on bend taking. They took place within the framework of a large French research program on driving automation for safety

(Blosseville *et al.,* 2003) –ARCOS[1] and of the European Program, Safe-Lane (PReVENT). The philosophy of the ARCOS program was to consider the driver as the entity that has priority over the driving task. Thus, the goal was not to automate driving at any price, but to restrict the intervention of automation to that which is strictly necessary to avoid accidents, whilst integrating a prediction capability. More precisely, these experiments took place within the theoretical framework delineated by Hoc and Blosseville (2003) in order to approach human-machine cooperation in car-driving. The first experiment aimed at evaluating the function delegation mode with an automatic lateral control, leaving longitudinal control to the driver. This type of cooperation could be applied to very dangerous situations (e.g., a snaking tunnel or mountain road). The evaluation did not concern the automated function, which is considered to be efficient, but rather the return to manual control in a situation where the device becomes invalid; for example, when there was an obstacle to skirt in the centre of the lane in a bend. In this case, when driving in the lane centre, the device led the car towards the obstacle. Thus, the main problem was to characterise the difficulties in returning to manual control when the instruction was to skirt the obstacle rather than to apply the brake, as was the case in an earlier experiment (Stanton *et al.,* 2001). In contrast, the second experiment was designed in order to evaluate the two cooperation modes of a mutual control type –the warning mode and the action suggestion mode– in relation to a control situation without assistance (Suzuki & Jansson, 2003). The warning mode was implemented through a lateralised sound in the direction of the deviation and non-specific oscillation on the steering wheel. The action suggestion mode was implemented through a lateralised oscillation on the steering wheel, prompting a response in the relevant direction without the steering wheel being turned. The aim of these evaluations was to increase our knowledge of human-machine cooperation borrowing a theoretical framework of human-machine cooperation, initially used at the level of symbolic information processing in aeronautics and process control, in order to model cooperation at subsymbolic levels (e.g., sensorimotor coordination): see, for example, Stanton and Marsden (1996).

II. THEORETICAL FRAMEWORK

II.1. Human-Machine Cooperation

According to Hoc (2001), cooperation implies several agents pursuing interfering goals and trying to manage this interference in order to facilitate their tasks. The definition of "interference" used here is borro-

1. « Action de recherche pour une conduite sécurisée » [Research Action for Safe Driving] (http://www.arcos2004.com) funded by the French PREDIT3 Program.

wed from Castelfranchi (1998) and assumes that one agent's goal is relevant to that of another agent. More precisely, one agent's goal can either facilitate the other agent's goal (positive interference) or it can jeopardise the latter (negative interference). In the following experiments, we will see that the warning mode, for example, can facilitate the drivers in their task to return to the lane centre after a displacement (positive interference). On the other hand, the function delegation mode can also create problems during bend taking because of a difference between the device's driving style (lane centre) and that of the drivers (straightening the bends).

Interference management can take place at three possible levels, both in terms of abstraction and anticipation.

— *Action level*. Interference is managed locally and in the short term. Anticipation is minimal.

— *Planning level*. Interference is managed at a less local level and in the medium term. At this level, the activities consist of generating or maintaining a common frame of reference between the agents. This framework is composed of representations (not necessarily symbolic) of the environment and of the team's activity (e.g., function allocation between the agents).

— *Meta-cooperation level*. As the agents gain experience of cooperating between themselves, they generate mental models of their operation mode and of their interactions (for ACC, see for example, Rajaonah, Anceaux, & Hoc, 2003).

Among the difficulties usually encountered in human-machine cooperation, we place particular emphasis on the complacency phenomenon (Moray, 2003; Parasuraman, Molloy, & Singh, 1993; Wiener, 1981). Under particular conditions (multi-task situations, high workload level, etc.), the delegation of a function to a machine can generate complacency with regard to the result produced by the machine; no attempt is made to improve it, whenever possible. Although the concept remains ill defined, there is a consensus on some of its main features –the information necessary to perform the function is neglected, as is supervision, and finally there is no correction. A minimal level of trust is usually considered as being necessary to the development of complacency, although the two concepts are different. The reasons for complacency can be very diverse and can also include the correlation between a decrease in workload and a decrease in attentional resources, as described by Young (2002).

II.2. Cooperation Modes in Car driving

Hoc and Blosseville (2003) have proposed the categorisation of cooperation modes with automation into four classes, in relation to the assumed cooperation activities. Each cooperation mode can imply the three levels of cooperation activities; these must be considered as orthogonal to the cooperation modes. The classes range from the device that is most remote from action through to that which is the most active. However, this must not be confused with a dimension of increasing intrusion into the driver's activity.

— *Perception mode.* Nowadays, this is mainly restricted to the presentation of symbolic information like measures displayed on the dashboard or road signs. However, it may consist of reinforcing or augmenting the driver's perception in order to enter into the sensorimotor loops and to immediately trigger the expected response. If this mode is efficient, it is very intrusive because the strength of the relationships between perception and action can be very high. A typical example is the test of vision enhancement in fog or at night by infrared perception and head-up display (Parkes, Ward, & Bossi, 1995).

— *Mutual control mode.* Already presented above and studied in Experiment 2, this mode aims at criticising the driver's behaviour. We have chosen two modes, the warning mode being more remote from action than the action suggestion mode. Closer to action could be two other modes, not evaluated here –the limit mode offers a resistance against the driver's action when the latter brings the vehicle out of the lane and the correction mode corrects incorrect actions.

— *Function delegation mode*. As mentioned above and studied in Experiment 1, the driver delegates part of the driving task to the device. The set point can be defined by the driver or by regulation (e.g., a two-second headway in France for ACC).

— *Fully automatic mode.* In this case, the overall driving task is automated, although the navigation task can remain under driver control.

II.3. Sensorimotor coordinations during bend taking

The literature devoted to the sensorimotor aspects of bend taking is now quite abundant (see Milleville-Pennel, Mars, & Hoc, 2005). Indeed, it deals not only with visual information processing, but also with other perceptual modalities, including kinaesthesia, proprioception and haptic feeling. Three types of results are particularly relevant to the following experiments.

There is general agreement on the fact that a particular point in the visual scene plays an important role in the precise and medium-term control of the trajectory (approximately a one-second anticipation). That point is the *tangent point*; that is to say, it is the point where the inside edge of the curve changes direction. The angle between the direction of that point and the direction of the car is geometrically related to the radius of the curvature of the road (Figure 1). Moreover, it is the point where the horizontal component of optic flow changes direction. In other words, it is a point that is perceived to be motionless in the optic flow when the curve has a constant radius. Many authors have produced convincing evidence that sees the tangent point as being critical for the lateral control of the vehicle (high rate of ocular fixation; Land & Lee, 1994; positive effect of its enhancement: Mestre, Mars, Durand, Vienne,

& Espié, 2004; role in trajectory anticipation: Land & Horwood, 1995). Thus, in order to try to identify a possible complacency effect of the function delegation mode, we made use of an indirect method to identify a possible negligence of visual information processing close to this point.

Complementary to this literature, analyses of eye movements before a bend is taken have indicated that drivers begin to explore bends early on (Cohen & Studach, 1977; Land & Horwood, 1996; Shinar, McDowell, & Rockwell, 1977). This exploration is aimed at informing drivers about the nature of the oncoming bend. This anticipated evaluation of the bend properties –for instance, its curvature– is most probably essential in order to adopt an appropriate speed. While using the function delegation mode, the driver is still in charge of longitudinal control. Thus, the straight-ahead zone should still be visually explored.

One final property of sensorimotor control while taking a bend was also used. An analysis of trajectories adopted by experienced drivers has shown that they straighten up the bend (Treffner, Barret, & Petersen, 2002). This kind of driving style in bends is probably related to the management of a balance between speed and maximum lateral acceleration (Reymond, Kemeny, Droulez, & Berthoz, 2001). However, it can also be related to visibility and hazard identification, as well as to vehicle control. This point is relevant to our studies, since driving assistance devices tend to keep the car at the centre of the lane. As a consequence, we will look into the potential negative interference between the lateral control device's driving style (lane centre) and the driver's driving style (straightening up the bends).

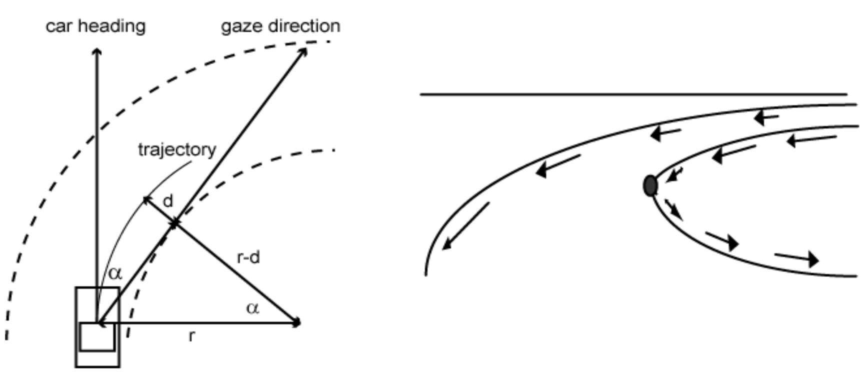

Fig. 1. — The tangent point is correlated to the bend radius

Le point tangent est corrélé avec le rayon de courbure du virage

II.4. General Hypotheses

The function delegation mode was evaluated in Experiment 1. Taking into account the classical results of studies on human-machine cooperation, we expected a complacency effect that contributed to difficulties in returning to manual control in situations where the device was invalid (obstacle skirting), in relation to a negligence of visual information necessary to lateral control. Such a reduction in visual needs when haptic feedback is provided to the driver on the steering wheel has already been shown (Steele & Gillespie, 2001). This kind of difficulty has already been demonstrated in a simulator study (Stanton *et al.,* 2001). Possible negative interference between the device's style and that of the driver in bends was also expected. Finally, we wondered whether there could be a notable familiarisation effect in using the device.

The two mutual control modes were evaluated in Experiment 2. Here, the possible improvement in recovering from a critical situation (provoked by a visual occlusion) was at the core of our interest. Mutual control at the time of the critical displacement was expected to reduce the time needed to return to the lane centre. The warning mode was expected to facilitate the diagnosis of the situation and the response preparation, as well as the action suggestion mode, the diagnosis and response triggering. However, the action suggestion mode could interfere with the driver's response. A previous simulator study (moving base) has shown that the warning mode was more efficient than the action suggestion mode, when the drivers were not informed of their meaning (Suzuki & Jansson, 2003). The implementation of the action suggestion mode in this study led to very different results from one driver to another. Some of the participants were prompted to move in the correct direction, others in the wrong one. In our experiment, if the auditory signal was lateralised, there was also a symmetric oscillation of the steering wheel (haptic modality) with the warning mode. Thus, there was no specific action suggestion on the effector, as was the case with asymmetric oscillation. The two implementations of the mutual control mode did not mainly differ in terms of perceptual modality –auditory versus haptic– but in terms of direct relations with a distinct activity module, namely diagnosis or response.

III. EXPERIMENT 1: EVALUATION OF A FUNCTION DELEGATION MODE IN SITUATIONS WHERE THE DEVICE IS INVALID

III.1. Method

III.1.A. *Participants*

Two groups of 6 participants performed the experiment, either with no assistance (NA) followed by with assistance (WA) or the reverse, thereby counterbalancing for order effects. All the participants (10 men and 2 women) had been driving on a regular basis for between 5 and 33 years.

III.1.B. *Material*

The experiment[1] took place on the GIAT test track in Satory (Versailles, France). The track is similar to a main road,[2] including 14 bends (of diverse radii) and 15 straight lines along 3.4 km (Figure 2). The experimental vehicle (Renault Scenic) was equipped by LIVIC in order to enable the driver to delegate the lateral control function (automatically maintaining the vehicle in the lane centre and leaving the longitudinal control –in other words, speed control– to the driver) and to record some of the main vehicle parameters and the driver's actions (e.g., steering wheel angle and speed).

The overall working principle of the device implementing the function delegation mode is that, based on vehicle positioning measures, a desired steering angle is continuously computed. An actuator (a direct current electric motor) in the vehicle's steering column, itself driven by a control loop, then ensures that the vehicle's steering angle follows this desired computed angle. It is thus an active system. It was constructed on the basis of commonly used driver variables. A proportional controller was elected to carry out the task. The control action on the steering wheel (angle) was then chosen to be proportional to the yaw angle error (which gives information about the direction of the vehicle axis with respect to that of the road) and to the vehicle lateral displacement (which indicates how far the vehicle is from the lane centre) (Chaib, Netto, & Mammar, 2004; Netto *et al.*, 2003). The

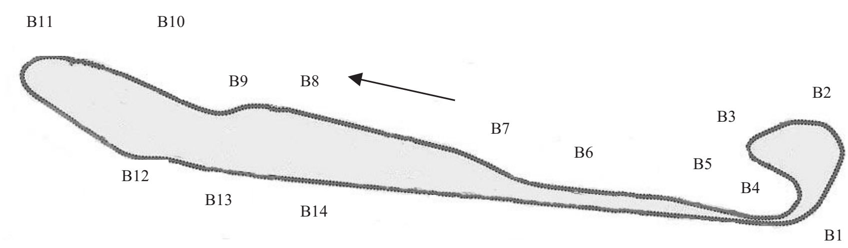

Fig. 2. — Map of the Satory test track. The bend numbers are referred to below. The arrow indicates the direction of the trajectory

Carte de la piste d'essai de Satory. Les numéros de virage seront utilisés par la suite. La flèche indique la direction de la trajectoire

1. More details can be found in Jolly and Hoc (2004).
2. Two opposite lanes were available. However the participants drove in the left lane, without traffic, for safety reasons.

reason is that these two variables clearly have a fundamental role in the driving task. Many other visual variables are certainly involved in the driving action (§ II.3) and could be used in the future in order to render the device's driving style similar to that of the average driver whilst, at the same time, increasing safety. An important feature of the current device is that prediction is introduced into the controller. Intuitively, the driver cannot drive without looking ahead of the vehicle and, as speed increases, the tendency is to look farther. The device is then conceived in such a way that the distance used to search for the (predicted) yaw angle error and lateral displacement increases linearly with the vehicle speed. This linear function between distance and speed had been used by Broggi, Bertozzi, Fascioli, Guarino lo Bianco and Piazzi (1999). Visual information is obtained by means of cameras and lane detection algorithms (Ieng, Tarel, & Labayrade, 2003; Labayrade, Ieng, & Aubert, 2004). As mentioned before, this assistance can be deactivated, with the control of the vehicle given back to the driver, by a counter action in the steering wheel by the driver. This fact is central for the understanding of the experiment, since this was exactly the situation under study, as one of the scenarios consisted in skirting obstacles on the lane.

III.1.C. *Procedure*

After 2 laps to allow for familiarisation with the device, each participant drove 2 blocks of 2 experimental laps at free speed. Within each block, one lap was performed with no assistance and the other with assistance, in the order defined for the participant's group. Two bends (to the left) with short curvature radii (B1: 85 m and B11: 44 m; see Figure 2) were selected for the sudden appearance of an obstacle (cardboard box). Each experimental lap included an obstacle to skirt. The allocation of obstacles to bends was counterbalanced so that a comparison between the two experimental conditions was possible for each bend.

In order to access symbolic information processing, spontaneous and concurrent verbal reports were recorded. A content analysis was performed, distributing the verbal report contents over the three main classes of cooperative activities –cooperation in action (interference during action execution), cooperation in planning (common frame of reference elaboration and maintenance), and meta-cooperation (elaboration of models of partners and of their interaction). An additional class related to complacency was introduced. An overview of the classes and sub-classes, with examples, is presented in Figure 6 below, including the distributions, in the results section (§ III.2).

In order to indirectly access visual information processing, a recognition technique was used. For each participant, during the first lap without assistance and during the last lap with assistance, nine non-familiar advertising logos were placed close to one of two possible bends (different from those where obstacles were possible: B7 and B12; see Figure 2), with counterbalance. Three logos were placed in the straight-ahead visual field (visible when approaching the bend and in relation to the identification of the bend's visual angle and possibly in relation to speed adjustment). Three other logos were placed on the internal side of the lane (smaller than the former and in relation to visual processing of the tangent point used for lateral control). The last three were placed, like hoardings, off the road. Three distractors were also used. After the bend, the participant was invited to stop the car and to give a judgement on each logo by means of drawing a cross on a 10 cm scale: 0 meaning that the participant is sure not to have seen the logo; 10 meaning that the participant is absolutely certain to have seen it.

III.1.D. *Data analysis*

As usual, in order to conclude on a population effect (δ) on the basis of an observed effect (*d*), a Student's *t*-test of significance was calculated. However, in order to draw conclusions in terms of population effect sizes (generalisation from judgements on the size of observed effects), a variant of Bayesian statistical inference (fiducial inference: Lecoutre & Poitevineau, 1992; Rouanet, 1996) was used. On the basis of a maximal *a priori* uncertainty, the technique enables the user to emit a probabilistic judgement on the population effect size. For example, if the observed effect can be considered as large, then a conclusion such as, "there is a high probability that the population effect is larger than a notable value" is tried ($P(\delta)>a$). Conversely, if the observed effect is negligible, the expected conclusion is that, "there is a high probability that the absolute population effect is lower than a negligible value" ($P(|\delta|)<\varepsilon$). The computations are carried out on *a posteriori* distributions representing the uncertainty on the population effect. These Bayesian distributions have the same scale parameters and form as the sampling distributions (Student *t* in the cases considered in this paper). Below, when an observed notable (negligible) effect corresponds to a population notable (negligible) effect, we will say that the judgement on the observed effect size can be generalised. On the other hand, the lack of experimental precision can sometimes lead to a conclusion without relevance, either in terms of notable or negligible effect. In this case, generalisation of the observed effect is impossible. Although the meaning is very different, this alternative between notable or negligible effect vs. no generalisation is analogue to the alternative between a significant result (existence of a non-nul effect) and a non-significant result (no conclusion)[1].

1. Good statistical practice avoids the confusion between non-significance and absence of the effect.

III.2. Results

III.2.A. *Difficulty in returning to manual control and complacency*

Three variables were used in order to evaluate the quality of obstacle skirting[1]. The first variable was the steering wheel angle amplitude, which was defined as the difference between the maximum angle during obstacle skirting and the angle at the beginning of the skirting manœuvre. In this way, we were able to evaluate how smoothly an obstacle is skirted. The second variable was the time needed to skirt the obstacle, from the first response on the wheel through to the return to the lane centre when the obstacle has been overtaken. In this way, we were able to evaluate response anticipation. The third variable was the speed.

Figure 3 and Table 1 show the effects of the experimental conditions on the steering wheel angle amplitude. In every case (NA→WA or WA→NA orders) and on average, the observed amplitudes are notably larger with assistance than without assistance (observed effects larger than 0.4 rad.). This observation is easily generalised for the order WA→NA and, to some extent, the average. Thus, the response is less smooth with assistance than without assistance.

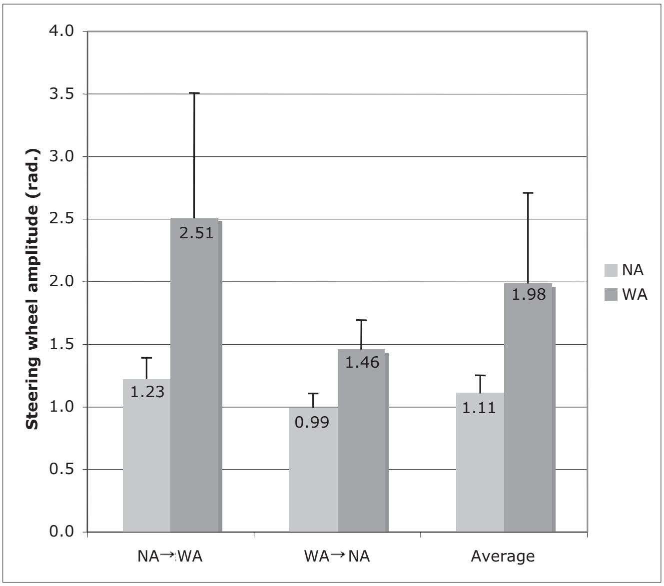

Fig. 3. — Effect of the lateral control mode on steering wheel amplitude (rad.) while skirting an obstacle. NA: No Assistance. WA: With Assistance. In abscissa: each presentation order and average. Lines on the rectangle tops represent standard errors.

Effet du mode régulé de contrôle latéral sur l'amplitude de l'angle volant (rad.) pendant le contournement d'obstacle. NA: Sans assistance. WA: Avec assistance. En abscisse: chaque ordre de présentation et moyenne. Les lignes au-dessus des rectangles représentent les erreurs types.

1. Due to the fact that the vehicle localisation with respect to the lane was carried out by means of vision lane detection algorithms, it was not possible to record the precise position of the car on the road whilst overtaking the obstacle during this particular experiment.

TABLE 1

Effect of the lateral control mode on steering wheel amplitude (rad.) while skirting an obstacle. NA: No Assistance. WA: With Assistance. In lines: each presentation order and average. The effect is defined as the difference between WA and NA. "No gen.": no generalisation

Effet du mode régulé de contrôle latéral sur l'amplitude de l'angle volant (rad.) pendant le contournement d'obstacle. NA: Sans assistance. WA: Avec assistance. En ligne: chaque ordre de présentation et moyenne. L'effet est défini comme la différence entre WA et NA. "No gen.": pas de généralisation

Order	Observed effect	Population effect	*t* test and two-tailed level of significance
NA→WA	1.28 notable	P(δ>–0.10)=.90 no gen.	$t(5)=1.37$ $p>.225$ NS
WA→NA	0.47 notable	P(δ>0.26)=.90 notable	$t(5)=3.26$ $p<.025$ S
Average	0.88 notable	P(δ>0.22)=.90 notable	$t(10)=1.84$ $p>.095$ NS

Figure 4 and Table 2 show the same effects, but on the time needed to skirt an obstacle. In each case, the duration of the manœuvre is shorter with assistance than without assistance. The effect is larger for the order NA→WA but still sizeable on average (about 1 sec.). In these two cases, the observation can be generalised. However, the effect for the order WA→NA

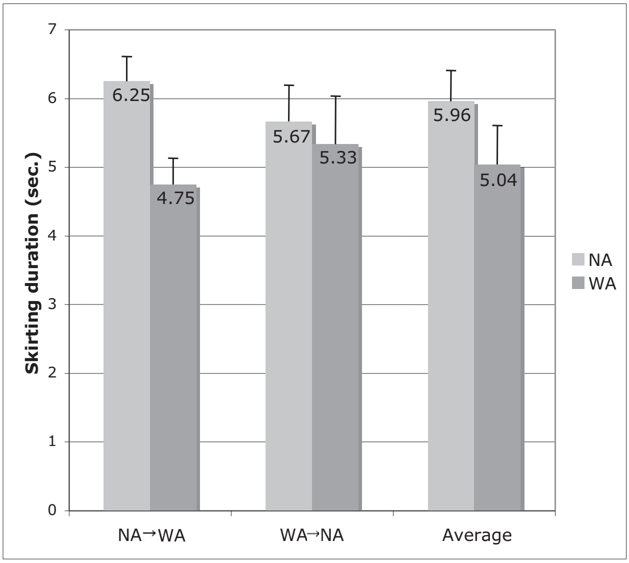

Fig. 4. — Effect of the lateral control mode on time needed to skirt an obstacle (sec.). NA: No Assistance. WA: With Assistance. In abscissa: each presentation order and average. Lines on the rectangle tops represent standard errors.

Effet du mode régulé de contrôle latéral sur la durée de contournement d'obstacle (sec.). NA: Sans assistance. WA: Avec assistance. En abscisse: chaque ordre de présentation et moyenne. Les lignes au-dessus des rectangles représentent les erreurs types.

is lower than the former and it cannot be generalised. In Section III.3.C, we will see that the speed is slower with assistance than without assistance. Thus, if the time needed to skirt an obstacle is shorter with assistance than without assistance, this fact reinforces the interpretation of a response that is less smooth with assistance than without assistance. The fact is also compatible with a more anticipated response without assistance than with assistance, in relation to lower steering amplitude.

TABLE 2

Effect of the lateral control mode on the time needed to skirt an obstacle (sec.). NA: No Assistance. WA: With Assistance. In lines: each presentation order and average. The effect is defined as the difference between NA and WA. "No gen.": no generalisation

Effet du mode régulé de contrôle latéral sur la durée de contournement d'obstacle (sec.). NA: Sans assistance. WA: Avec assistance. En ligne: chaque ordre de présentation et moyenne. L'effet est défini comme la différence entre NA et WA. "No gen.": pas de généralisation.

Order	Observed effect	Population effect	t test and two-tailed level of significance
NA→WA	1.50 notable	P(δ>0.96)=.90 notable	$t(5)=4.11$ $p<.01$ S
WA→NA	0.33 small	P(|δ|<1.42)=.90 no gen.	$t(5)=0.51$ $p>.63$ NS
Average	0.92 notable	P(δ>0.40)=.90 notable	$t(10)=2.45$ $p<.035$ S

In order to understand the reason for this clear difficulty in returning to manual control, the recognition task was analysed. Figure 5 shows the observed effects of the experimental conditions on the judgements made on the logos.[1] First, all participants chose a 0 value (sure to have not seen) for the distractors (not displayed close to the bend), with or without assistance. In one way, this result validates the technique. Second, on average, the participants' judgements were lower than 5, with or without assistance; thus, they thought that they had not seen the logos rather than they had seen them. Third, the recognition scores are notably higher with assistance than without assistance ($d=2.15$; P(δ>1.51)=.90; $t(5)=4.95$; $p<.005$). This effect is trivial because the NA scores were always obtained before the WA scores so that the participants were more prepared to do the task with assistance than without assistance. Nevertheless, the participants could have more time available for processing logos with assistance than without assistance. Although it is not possible to generalise the result, Figure 5 shows an inversion of the judgements from NA to WA. This was compatible with a negligence of information (TP) necessary to control the lateral dimension of the trajectory when this function is automated, compared with information relevant to the longitudinal control (SA).

1. Unfortunately, the data were only available for 6 out of the 12 participants.

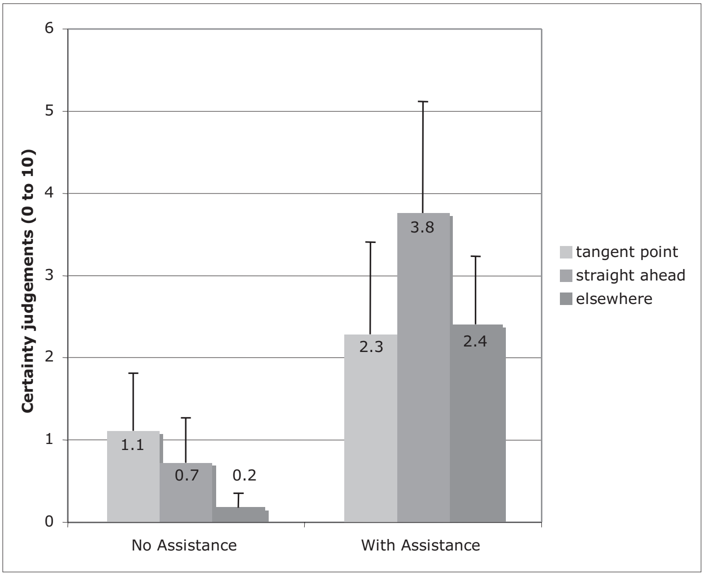

Fig. 5. — Recognition certainty judgements (from 0 to 10) for logos situated near the tangent point, straight ahead, or elsewhere in the two conditions (No assistance, With the lateral control mode of assistance). Lines on the rectangle tops represent standard errors.

Jugements de certitude (de 0 à 10) de reconnaissance des logos disposés près du point de corde, droit devant ou ailleurs dans les deux conditions: sans assistance et avec l'assistance du mode régulé de contrôle latéral. Les lignes au-dessus des rectangles représentent les erreurs types.

Figure 6 presents the distribution of the verbal report contents over the classes defined in relation to human-machine cooperation. A particular class concerns reports on complacency, which was observed, but with a modest contribution (about 4%). This figure will be referred to below when commenting on the other classes.

III.2.B. *Negative interference between the driver's and the device's styles of bend taking*

For the bends used to set obstacles, when there was no obstacle, a comparison between the numbers of steering corrections with and without assistance was performed. The device produced more corrections (4.0) than did the participants (2.3) (d=1.7; P(δ>1.2)=.90; $t(10)=4.70$; $p<.0008$), probably because the device drove in the lane centre, whereas participants straightened up the bends. Unfortunately, for technical reasons, it was not possible to get a reliable measure of the trajectory during this experiment.

This difference in driving styles for bend taking created negative interference with the driver. Figure 6 shows that about 19% of the verbal reports were related to this kind of negative interference. It is not the case in straight lines, where interference was judged rather more positively.

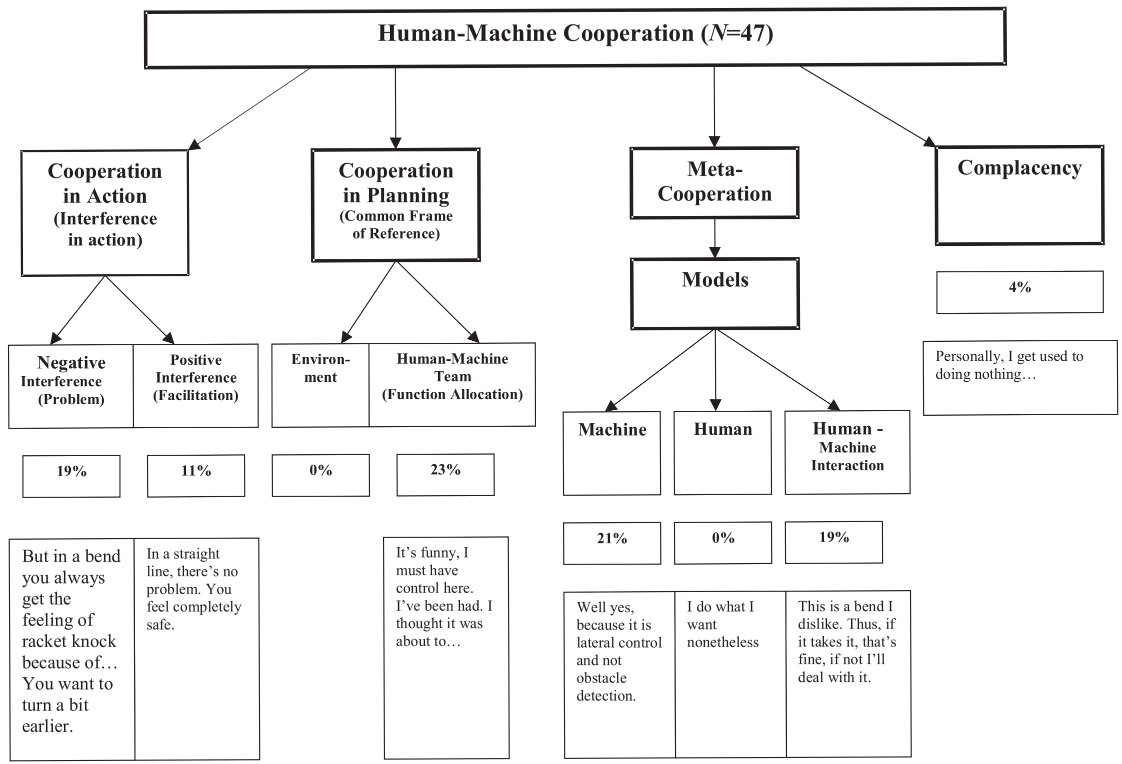

Fig. 6. — Distribution of percentages according to the contents of verbal reports dealing with human-machine cooperation

Distribution de pourcentages selon le contenu de la verbalisation en relation avec la coopération homme-machine: coopération dans l'action (interférences négatives ou positives), coopération dans la planification (élaboration ou maintien d'un référentiel commun portant sur l'environnement ou sur l'activité de l'équipe homme-machine), métacoopération (élaboration ou usage de modèles de la machine, de l'humain ou de l'interaction homme-machine) et mention explicite du contentement

III.2.C. *Familiarisation effect*

Figure 7 and Table 3 present an analysis of the speed for each lap and for each experimental condition. On average, the speed is slower (6.6 km/h) with assistance than without assistance, probably because the driver is not very confident in the function delegation mode. This result can be generalised. Familiarisation between the first and the second lap without assistance is not very meaningful (increase of 0.4 km/h in speed between the first and the second lap). However, it is difficult to generalise this conclusion. In contrast, there is a notable familiarisation effect during the laps with assistance (increase of 4.4 km/h) and this conclusion can be generalised.

The verbal reports (Figure 6) reflect this familiarisation process. About 30% of reports concern cooperation in action (interference). This reflects a vivid symbolic representation of the difficulties and facilitations which familiarisation is expected to reduce. About 20% of reports are related to cooperation in planning (common frame of reference), particularly function allocation within the human-machine team. Finally, about 20% reflect the elaboration of a model of the device and of the interaction between the driver and the device (40% in total).

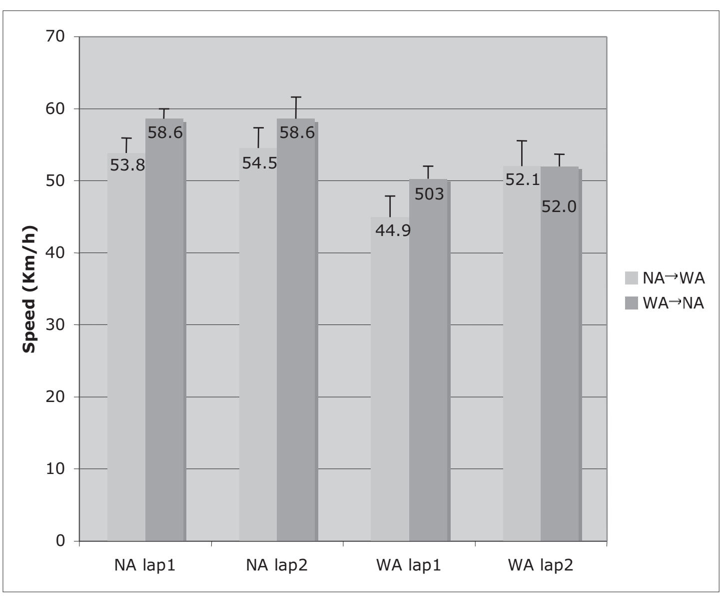

Fig. 7. — Effect of the lateral control mode on speed (Km/h) and familiarisation effects. NA: No Assistance. WA: With Assistance. In abscissa: the two successive NA laps and the two successive WA laps. Order NA→WA: NAlap1→WAlap1→NAlap2→WAlap2. Order WA→NA: WAlap1→NAlap1→WAlap2→NAlap2. Lines on the rectangle tops represent standard errors.

Effet du mode régulé de contrôle latéral sur la vitesse (Km/h) et effets de familiarisation. NA: Sans assistance. WA: Avec assistance. En abscisse: les deux tours successifs NA et les deux tours successifs WA. Ordre NA→WA: NAlap1→WAlap1→NAlap2→WAlap2. Ordre WA→NA: WAlap1→NAlap1 →WAlap2→NAlap2. Les lignes au-dessus des rectangles représentent les erreurs types.

TABLE 3

Effect of the lateral control mode on speed (Km/h) and familiarisation effects. NA: No Assistance. WA: With Assistance. For the first comparison, the effect is defined between NA and WA, for the two others, between lap 2 and lap 1. "No gen.": no generalisation

Effet du mode régulé de contrôle latéral sur la vitesse (Km/h). NA: Sans assistance. WA: Avec assistance. En ligne: chaque ordre de présentation et moyenne. Pour la première comparaison, l'effet est défini comme la différence entre NA et WA, pour les deux autres, entre le tour 2 et le tour 1. "No gen.": pas de généralisation.

	Observed effect	Population effect	*t* test and two-tailed level of significance
NA-WA	6.58 notable	P(δ>5.33)=.90 notable	$t(10)=7.22$ $p<.0001$ S
*l*2-*l*1/NA	0.36 negligible	P(|δ<2.83)=.90 no gen.	$t(10)=0.23$ $p>.83$ NS
*l*2-*l*1/WA	4.42 notable	P(δ>2.36)=.90 notable	$t(10)=2.95$ $p<.015$ S

III.3. DISCUSSION

The delegation of lateral control to the device has clearly created difficulties in returning to manual control when the device is invalid, that is to say when the car has to skirt an obstacle in the centre of the lane. Although it was not possible to precisely locate the car in this experiment, the pattern of higher steering wheel amplitude, shorter time needed and reduced speed led us to conclude that the response was later and less smooth with the delegation mode than without assistance. These difficulties can be due to diverse kinds of phenomena. Complacency is one of them, but the addition of two activity levels can also be an explanation. As a matter of fact, when confronted with this kind of situation, the driver must simultaneously: (a) decide to interrupt the function delegation, and (b) skirt the obstacle. This can produce a late response. However, there is a link between complacency, which leads to neglect of the delegated function, and the time needed for diagnosis and execution. Although the results cannot be generalised, the indirect information we have gathered from the recognition task is an argument for interpretation in terms of complacency. Within the function delegation mode there is some trace of negligence of the information necessary to perform the function (visual attention to the tangent point).

In addition to this main result, two complementary observations must be highlighted. First, there was clearly interference between the driver's and the device's bend-taking styles. This was expressed on the one hand by a sensation of uneasiness on the steering wheel. On the other hand, positive interference was reported in straight lines. However, the main problem to address is possibly when the driver learns a new calibration of the balance between speed and lateral acceleration. Second, the evaluation of this kind of cooperation mode should develop during a longer period of time, because we have noticed that there are still familiarisation effects. At first, the participants slowed down with the delegation mode and then accelerated, at the same time developing complacency. In addition, verbal reports have enabled us to identify learning mechanisms concerning function delegation, the understanding of device operation and of the management of human-machine interaction.

IV. EXPERIMENT 2: EVALUATION OF MUTUAL CONTROL MODES (WARNING MODE AND ACTION SUGGESTION MODE) IN CRITICAL SITUATIONS

IV.1. METHOD

IV.1.A. *Participants*

Twenty participants (mostly men, of various ages –from 24 to 50, 34 on average– and driving experiences –from 1 month to 34 years, 15 years on average) took part in Experiment 2.

IV.1.B. *Material*

Experiment 2 took place on the same test track as did Experiment 1. The experimental vehicle (Renault Scenic) was also equipped by LIVIC in order to implement two mutual control modes –the warning and the action suggestion modes. In contrast to the function delegation mode previously described, these two devices are passive in the sense that no trajectory correction is applied to the steering wheel; as a consequence, the control of the vehicle motion (longitudinal as well as lateral) is in the charge of the driver. For both of them, the goal is to let the driver drive and, whenever a lane departure is signalled, the system gives an indication to the driver that something is going wrong. It is then up to the driver to carry out the task of correcting the trajectory. The fundamental difference between these two modes is the interference level with respect to the driver. In the warning mode (WR), symmetric square form oscillations on the steering wheel, as well as a sound coming from the speaker situated on the side of the car's displacement, are activated. In the action suggestion mode (AS), dissymmetrical oscillations are generated in order to make the driver to turn in the opposite direction to that of the displacement. The oscillations in this case are of a sawtooth form. The triggering of both devices is based on the magnitude of the lateral displacement (threshold equal to 60 cm). In the warning mode, a suggestion to turn in the right direction comes from the speakers, whilst at the same time the symmetric oscillations warn the driver. In the action suggestion mode, the suggestion to turn comes from the asymmetric oscillations themselves.

IV.1.C. *Procedure*

Each participant performed 11 laps of the test track. The first lap was devoted to familiarisation with the track and the events that could occur. After that, for each implementation of the mutual control modes (warning and action suggestion), the participant performed 5 laps: 2 laps without assistance (NA) to provide us with control conditions, 1 lap for familiarisation with the assistance (not analysed), and 2 experimental laps with assistance (WA). The participant received the instruction to drive in the lane centre at between 50 and 60 km/h. The presentation orders of the modes were counterbalanced, the presentation order being WR→AS for 10 participants and AS→WR for the others.

Two types of incidents in bends were analysed. First, and specific to this experiment, we created a critical situation where a deviation of 60 cm was provoked by a visual occlusion. Passing a sensor, the car triggered a visual occlusion (glasses with shutters) until it reached a 60-cm deviation. Second, as was the case in Experiment 1, we made use of a situation where the device was invalid –obstacle skirting. Passing a sensor, the car triggered a catapult, launching a rubber ball in the centre of the lane 50 meters farther.

Four bends with reasonable curvature radii were selected for incident allocation. Table 4 presents the main features of these bends to assist with the later interpretation of the results (see also the track map in Figure 2). The allocation was defined in order to counterbalance the order effects and to enable comparisons to be made between the same bends, between control and experimental laps, and for each mode.

TABLE 4

Main features of the bends chosen for obstacles (7, 12 and 13) and for occlusions (6, 7 and 13)

Caractéristiques principales des virages choisis pour les obstacles (7, 12 et 13) et pour les occlusions (6, 7 et 13).

Bend	Direction	Curvature radius (*m*)	Preceded by	Followed by
Bend 6	Right	440	Straight line	Bend to the left
Bend 7	Left	231	Bend to the right	Straight line
Bend 12	Left	130	Straight line	Bend to the right
Bend 13	Right	354	Bend to the left	Straight line

IV.1.D. *Dependent variables*

Figure 8 summarises the dependent variables considered in the analysis of critical situations (occlusion).

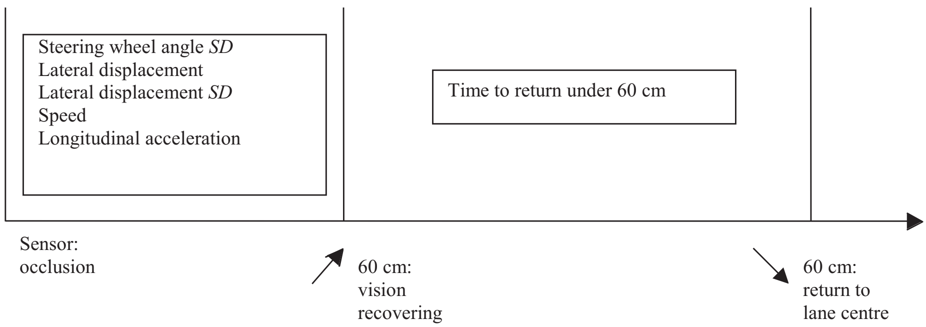

Fig 8. — Dependent variables for the study of the critical situation (visual occlusion)

Variables dépendantes pour l'analyse de la situation critique (occlusion visuelle)

Figure 9 summarises the dependent variables considered in the analysis of invalidity situations (obstacle).

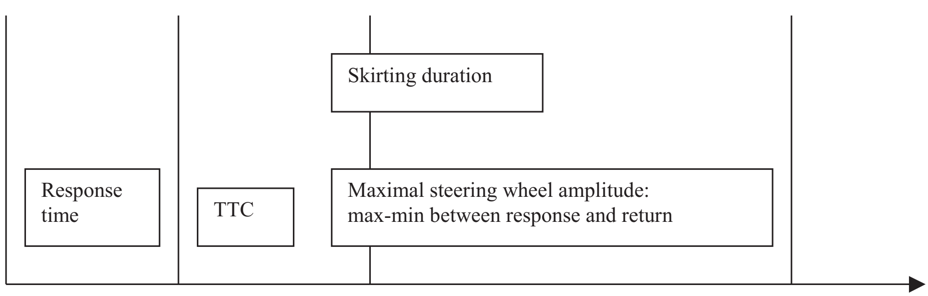

Fig. 9. — Dependent variables for the study of the invalidity situation (obstacle skirting)

Variables dépendantes pour l'analyse de la situation d'invalidité (contournement d'obstacle)

IV.2. Results

IV.2.A. *Critical situation (occlusion)*

Figure 10 and Table 5 present the results concerning the warning mode (WR) for Bend 6 and Bend 7[1]. For Bend 6, there is a slight reduction in the time taken to return to the lane centre after recovering vision when the mode is the first to be presented. Although this is impossible to generalise, there is, however, a notable reduction that can be generalised when it is the second to be presented, after familiarisation. On average, this positive effect is also notable and can be generalised. For this bend, the positive effect of the warning mode is quite well established. However, for Bend 7, although the effect of the mode is also positive, it is less accentuated and generalisation is impossible.

For the action suggestion mode (AS), the results for Bend 7 and Bend 13 are presented in Figure 11 and Table 6. For Bend 7, the results are similar to those obtained with the warning mode. There is a positive effect, but it is not very notable and is impossible to generalise. For Bend 13, the results are very different, because the effect of the mode is negligible. However, this conclusion cannot be generalised.

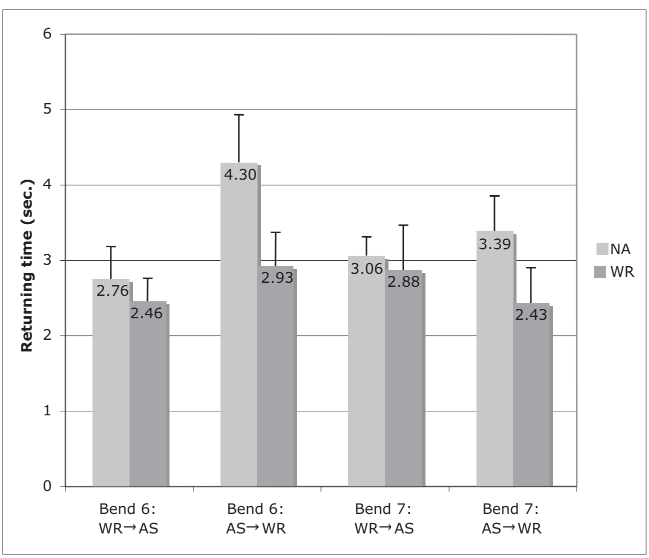

Fig. 10. — Effect of the warning mode on the time (sec.) needed to return to the lane centre (<60 cm). NA: No assistance. WR: Warning mode. AS: Action suggestion mode. Results for Bends 6 and 7 and for each presentation order. Lines on the rectangle tops represent standard errors.

Effet du mode avertissement sur le temps (sec.) de retour au centre de la voie (<60 cm). NA: Sans assistance. WR: Mode Avertissement. AS: Mode suggestion d'action. Résultats pour les virages 6 et 7, ainsi que pour chaque ordre de présentation. Les lignes au-dessus des rectangles représentent les erreurs types.

1. The *t* df can change in relation to the frequency of valid data for each comparison.

TABLE 5

Effect of the warning mode on the time (msec.) needed to return to the lane centre (<60 cm). NA: No assistance. WR: Warning mode. AS: Action suggestion mode. Results for Bends 6 and 7, for each presentation order and on the average. The effect is defined between NA and WR. "No gen.": no generalisation.

Effet du mode avertissement sur le temps (msec.) de retour au centre de la voie (<60 cm). NA: Sans assistance. WR: Mode avertissement. AS: Mode suggestion d'action. Résultats pour les virages 6 et 7, pour chaque ordre de présentation et en moyenne. L'effet est défini comme la différence entre NA et WR. "No gen.": pas de généralisation.

	Observed effect	Population effect	*t* test and two-tailed level of significance
Bend 6			
WR→AS	296 notable	P(δ>–151)=.90 no gen.	*t*(9)=0.92 *p*>.38 NS
AS→WR	1373 notable	P(δ>466)=.90 notable	*t*(6)=2.18 *p*>.07 NS
Average	834 notable	P(δ>399)=.90 notable	*t*(15)=2.57 *p*<.025 S
Bend 7			
WR→AS	187 notable	P(δ>–460)=.90 no gen.	*t*(9)=0.40 *p*>.69 NS
AS→WR	956 notable	P(δ>–44)=.90 no gen.	*t*(8)=1.34 *p*>.21 NS
Average	571 notable	P(δ>13)=.90 no gen.	*t*(17)=1.36 *p*>.19 NS

TABLE 6

Effect of the action suggestion mode on the time (msec.) needed to return to the lane centre (<60 cm). NA: No assistance. WR: Warning mode. AS: Action suggestion mode. Results for Bends 7 and 13, for each presentation order and on average. The effect is defined between NA and AS in msec. "No gen.": no generalisation

Effet du mode suggestion d'action sur le temps (msec.) de retour au centre de la voie (<60 cm). NA: Sans assistance. WR: Mode avertissement. AS: Mode suggestion d'action. Résultats pour les virages 7 et 13, pour chaque ordre de présentation et en moyenne. L'effet est défini comme la différence entre NA et AS. "No gen.": pas de généralisation

	Observed effect	Population effect	*t* test and two-tailed level of significance
Bend 7			
WR→AS	492 notable	P(δ>–1540)=.90 no gen.	*t*(8)=0.34 *p*>.74 NS
AS→WR	586 notable	P(δ>–537)=.90 no gen.	*t*(9)=0.72 *p*>.48 NS
Average	539 notable	P(δ>–542)=.90 no gen.	*t*(17)=0.67 *p*<.51 NS
Bend 13			
WR→AS	–37 negligible	P(δ<1303)=.90 no gen.	*t*(6)=–0.04 *p*>.96 NS
AS→WR	155 small	P(δ>–843)=.90 no gen.	*t*(5)=0.23 *p*>.82 NS
Average	59 negligible	P(δ>–751)=.90 no gen.	*t*(11)=0.10 *p*>.92 NS

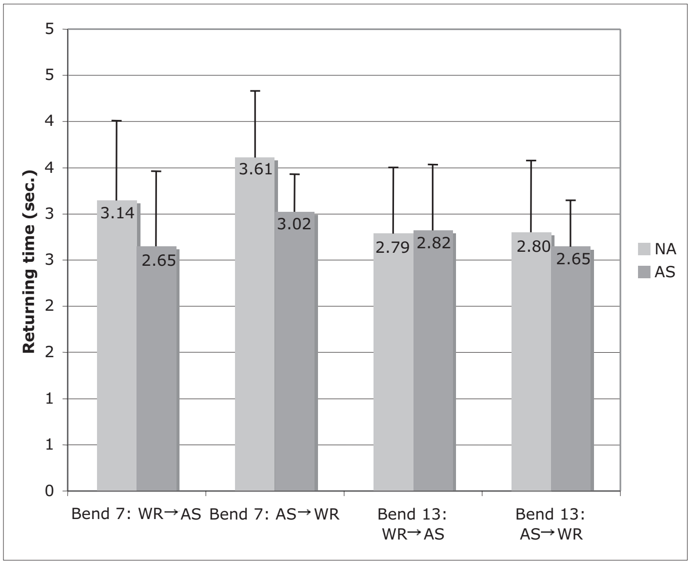

Fig. 11. — Effect of the action suggestion mode on the time (sec.) needed to return to the lane centre (<60 cm). NA: No assistance. WR: Warning mode. AS: Action suggestion mode. Results for Bends 7 and 13 and for each presentation order. Lines on the rectangle tops represent standard errors.

Effet du mode suggestion d'action sur le temps (sec.) de retour au centre de la voie (<60 cm). NA: Sans assistance. WR: Mode avertissement. AS: Mode suggestion d'action. Résultats pour les virages 7 et 13, ainsi que pour chaque ordre de présentation. Les lignes au-dessus des rectangles représentent les erreurs types.

Although they are not always significant and conclusive, the positive observed effects of the modes could have been due to familiarisation, because the situation with assistance always followed the control situation without assistance, although these situations were close to each other. Taking Bend 7 as a reference, we have compared the return times after recovering vision between the first and the second reference laps without assistance. According to the presentation orders, either a slight increase is observed (about 200 msec. for WR→AS) or there was a slight decrease (about 140 msec. for AS→WR), with a negligible effect on the average (about 30 msec.). However, this observation cannot be generalised. It is difficult to conclude that there is a familiarisation effect; thus, the interpretations in terms of effect of assistance are justified.

For each bend, we have tried to identify a possible behavioural change in the activity during occlusion from the non-assisted situation to the assisted one. In every case, the difference is negligible in terms of lateral and longitudinal control and the result can be generalised. The detail of these two last complementary analyses can be found in Hoc, Mars and Milleville-Pennel (2004).

IV.2.B. *Invalidity situation (obstacle)*

Although the results are not homogeneous from one bend to another, they are not the same as those established in Experiment 1 with the function delegation mode. They do not clearly show a negative effect of the mutual control modes on returning to manual control.

Observed effects of the warning mode (WR) are negligible on Bend 12, without possible generalisation, except for time needed to skirt the obstacle. The latter notably decreases with assistance (from 5.5 sec. to 4.7 sec.) and the result can be generalised (d=791 msec.; P(d> 253 msec.)=.90; $t(12)=1.99$; $p>.07$). On Bend 13, there is a slight reduction in the response time, which can be generalised (d=179 msec.; P(δ>82 msec.)=.90; $t(14)=2.47$; $p<.03$). Correlatively, there is an increase in TTC, which cannot be generalised. There is an increase in the steering wheel angle amplitude with WR in first rank, and a decrease in second rank, without any possibility of generalising these effects. Finally, there is a notable increase in time needed to skirt the obstacle with WR (from 3.6 sec. to 4.4 sec.) and the result can be generalised (d=777 msec.; P(δ>417 msec.)=.90; $t(14)=2.90$; $p<.02$).

The results concerning the action suggestion mode (AS) are not homogeneous and are very often impossible to generalise. On Bend 7, according to the rank, there can be an increase or a decrease in the response and obstacle skirting times with AS. Effects are negligible on TTC and steering wheel angle amplitude. On Bend 13, according to the rank, there can be a decrease in response time or a stability, an increase in TTC (from 3.1 à 3.5 sec.) in 2nd rank (d=369 msec.; P(δ>188 msec.)=.90; $t(8)=2.85$; $p<.03$) or a stability. According to the rank, with AS there can be a negligible effect on amplitude in 2nd rank ($|d|$=0.08 rad.; P$|\delta|$>0.17 rad.)=.90; $t(8)=1.17$; $p>.27$) or a notable decrease (from 0.95 to 0.67 rad.) in 1st rank (d=0.28 rad.; P(δ>0.23 rad.)=.90; $t(6)=7.29$; $p<.0004$). Obstacle skirting times are reduced with AS by 358 msec. (from 5.0 to 4.6 sec.), but the result cannot be generalised.

IV.2.C. *Individual différences*

The important fact here, which should be underlined, is that for every effect the action suggestion mode produced much larger individual differences than did the warning mode and that this result can be generalised (see Hoc *et al.*, 2004). For Bend 7, common to the two modes, the average (between the two orders) standard deviation of the individual effects, in terms of time needed to return to the lane centre, is larger with AS (confidence interval with a guarantee of .90: between 2.77 sec. and 4.94 sec.) than with WR (between 1.43 sec. and 2.55 sec.).

IV.3. Discussion

The positive effects of the two mutual control modes were expected in critical situations where we predicted a decrease in the time needed for returning to the lane centre after the displacement provoked by visual occlusion. Except for Bend 13, where the action suggestion mode had a negligible effect, the observed effects are always positive. However, only one effect can be generalised –the positive effect of the warning mode in Bend 6. This kind of result suggests we should be cautious in considering the bends as equivalent. There are some notable differences. The contextual situations at the end of the visual occlusion could partly explain the results. Bend 6 (to the right) was preceded by a straight line and followed by Bend 7 (to the left). An analysis of the lateral displacement during occlusion shows that, for Bend 6, the participants deviated to the right (toward the road centre). A typical straightening up strategy when approaching Bend 7 (to the left) is compatible with this displacement toward the right when processing Bend 6. The warning mode was efficient. On the contrary, Bend 13 (to the right) was preceded by a bend to the left (Bend 12). The typical straightening up of a bend to the left leads to a displacement toward the left at the end of the bend, so that the driver enters Bend 13 near the left side of the lane, that is to say near the left side of the road. This is exactly what is shown by the analysis of the lateral displacement during occlusion in Bend 13. The stress provoked by the imminence of road departure in this case could have been sufficiently high to mask the effect of the assistance. In Bend 6, the situation was not a road departure, but a lane departure, which is less stressful, and the warning was efficient. Finally, in Bend 7, common to the two modes, AS resulted in much larger individual differences in the effects than WR.

With the mutual control modes we could have observed a phenomenom of obstacle skirting conformity to the rule of driving in the lane centre, maintained by the negative reinforcement of a lateral displacement by the assistance. The results invalidate this expectation and do not support the idea of late and rough responses. When generalisation is possible, it leads to positive results most of the time –decrease in response time, increase in TTC or time needed to skirt an obstacle, and decrease in steering wheel amplitude. Complementary analyses show that the mutual control mode did not change the participants' driving habits in terms of deviation from the lane centre (Hoc *et al.,* 2004).

V. CONCLUSION

The two experiments call for a continuation of these studies using a simulator in order to better control some contextual effects and to draw conclusions over longer periods of time. Taking into account these two aspects, the test track method reveals itself to be inadequate, despite having an appearance of ecological validity. In reality, technical and safety constraints largely influenced the choice of the bends where incidents were presented, of the driving lane (the left one, although drivers were used to drive on the right), and of the absence of traffic. These constraints can be alleviated on a simulator. In addition, studying the long-term effects of the assistances with repeated driving tests will be easier and more affordable in a laboratory setting. Such a project is now in progress.

Experiment 1 was not designed in order to test the efficiency of the function delegation mode with regard to trajectory safety in ordinary conditions where the assistance is valid. On the contrary, our aim was to identify possible difficulties when returning to manual control in situations for which the assistance was invalid. In particular, it enables us to check whether a gain in safety on one side could result in a loss of safety on the other. Two types of negative effects were stressed –difficulty in returning to manual control and interference between driving styles. A complacency effect is suspected of being related to the negligence of visual information processing and calls for a confirmation over longer periods of time. At the same time, the importance of its contribution to difficulties in returning to manual control should be evaluated. Other determinants of these difficulties should also be evaluated; for example, the addition of a strategic decision (control takeover and execution). If the effect is confirmed, a search for a countermeasure will be necessary; for example, by enhancing sensory cues involved in trajectory lateral control (like the tangent point). The interference between driving styles in bends raises another kind of question. If a familiarisation effect with the assistance can be attained, any interference could be eliminated, possibly integrating speed control. If this is not the case, the action of the assistance in bends should be adapted in such a way that the assistance's behaviour approaches that of the driver during bend taking (e.g., on the basis of similar visual information).

The study of mutual control modes (Experiment 2) demands further investigation. These modes were at times and in certain conditions, revealed to be efficient, without drawbacks in terms of complacency or maladjusted conditioning. However, more established generalisation is needed. Contextual conditions of critical situations and the interaction between stress and warning must be addressed. The large individual differences for the action suggestion mode should also be investigated. Finally, the efficiency of the assistances in terms of processing steps should be further examined. Although the addition of direct effects on diagnosis and response triggering could be efficient, a pure warning mode (e.g., sound) should be compared to a pure action suggestion mode.

One should be cautious in adopting the function delegation mode for long periods of time on the sole basis of these two experiments. The warning mode looks like an efficient assistance, with a clearer effect than the action suggestion mode, but the comparison between the two modes was not conclusive. However, an important question remains concerning the types of situations where the different cooperation modes are expected to increase road safety. Is the function delegation mode relevant as a cooperation mode, with a sharing of driving functions between the assistance and the driver? In other words, does the delegation make sense outside the full automation perspective and is this perspective justified, at least within a certain class of situations that are difficult to manage by the driver? Are the mutual control modes relevant in critical (and stressful) situations or only upstream as the determinants of accidents (prevention strategy)? Finally, are these types of assistance more relevant to straight-line driving than to bend taking? Further research should rely on precise accident reconstructions, although these are not very numerous and reliable.

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REFERENCES

Bar, F., & Page, Y. (2002). *Les sorties de voie involontaires* [involuntary road departures]. Rueil-Malmaison, France : Ceesar, Lab.

Ben-Yaacov, A., Maltz, M., & Shinar, D. (2002). Effects of an in-vehicle collision avoidance warning system on short- and long-term driving performance. *Human Factors, 44,* 335-342.

Blosseville, J.-M., Hoc, J.-M., Riat, J.-C., Wautier, D., Narduzzi, C., Gerbenne, É., Artur, R., & Tournié, É. (2003). *A French Contribution to the Functional Analysis of four Key Active Safety Functions.* Paper presented at the *ITS Wold Congress*. Madrid, November.

Broggi, A., Bertozzi, M., Fascioli, A., Guarino lo Bianco, C., & Piazzi, A. (1999). The ARGO Autonomous vehicle's vision and control systems. *International Journal of Intelligent Control and Systems, 3*, 409-441.

Castelfranchi, C. (1998). Modelling social action for agents. *Artificial Intelligence, 103,* 157-182.

Chaib, S., Netto, M., & Mammar, S. (2004). Hinfinity, adaptive, PID and fuzzy control: A comparison of controllers for vehicle lane keeping Paper presented at the *IEEE Intelligent Vehicles Symposium*. Parma, Italy, June.

Cohen, A. S., & Studach, H. (1977). Movements while driving cars around curves. *Perceptual and Motor Skills, 44*, 683-689.

Hoc, J.-M. (2001). Towards a cognitive approach to human-machine cooperation in dynamic situations. *International Journal of Human-Computer Studies, 54,* 509-540.

Hoc, J.-M., & Blosseville, J.-M. (2003). Cooperation between drivers and in-car automatic driving assistance. In G. C. van der Veer & J. F. Hoorn (Eds.), *Proceedings of CSAPC'03* (pp. 17-22). Rocquencourt, France: EACE.

Hoc, J.-M., Mars, F., & Milleville-Pennel, I. (2004). *Coopération homme-machine en virage: évaluation de modes de contrôle mutuel en contrôle latéral dans des situations critiques, dans des situations d'invalidité du dispositif et dans des situations normales* [Human-machine cooperation in bend: Evaluation of mutual control cooperation modes for lateral control in critical situations, in device invalidity situations, and in normal situations]. (ARCOS Research Report). CNRS - Université de Nantes, IRCCyN, Nantes, France.

Ieng, S. S., Tarel, J.-P., & Labayrade, R. (2003). On the design of a single lane-markings detector regardless the on-board camera's position. In *Proceedings of the IEEE Intelligent Vehicle Symposium (IV'2003)*. (pp. 564-569). Los Alamitos, CA: IEEE.

Jolly, É., & Hoc, J.-M. (2004). *Coopération homme-machine en virage: évaluation du mode régulé en contrôle latéral dans des situations de reprise en main* [Human-

machine cooperation in bend: Evaluation of the lateral control cooperation mode in manual control returning situations]. (ARCOS Research Report). CNRS - Université de Nantes, IRCCyN, Nantes, France.
Labayrade, R., Ieng, S. S., & Aubert, D. (2004). A reliable road lane detector approach combining two vision-based algorithms. In *Proceedings of the IEEE Conference on Intelligent Transportation Systems (ITSC 2004)* (pp. 149-154). Los Alamitos, CA: IEEE.
Land, M. F., & Horwood, J. (1995). Which parts of the road guide steering? *Nature, 377*, 339-340.
Land, M. F., & Horwood, J. (1996). The relation between head and eye movements during driving. In A. G. Gale, I. D. Brown, C. M. Haslegrave, & S. P. Taylor (Eds.), *Vision in Vehicules-V* (pp. 153-160). Amsterdam: Elsevier.
Land, M. F., & Lee, D. N. (1994). Where wee look when we steer. *Letters to Nature, 369*, 742-744.
Lecoutre, B., & Poitevineau, J. (1992). *Programme d'analyse des comparaisons (PAC)* [Comparison Analysis Program]. Saint-Mandé, France: CISIA.
Mestre, D., Mars, F., Durand, S., Vienne, F., & Espié, S. (2004). *A Visual Aid for Curve Driving.* Paper presented at the *8th Driving Simulation Conference (DSC Europe 2004)*. Paris, September.
Milleville-Pennel, I., Mars, F., & Hoc, J.-M. (2005). *Processing of Sensory Information for Trajectory Control while Bend taking.* Manuscript submitted for publication.
Moray, N. (2003). Monitoring, complacency, scepticism and eutactic behaviour. *Industrial Ergonomics, 31*, 175-178.
Netto, M., Labayrade, R., Ieng, S. S., Lusetti, B., Blosseville, J.-M., & Mammar, S. (2003). *Differents Modes on Shared Lateral Control.* Paper presented at the *ITS*. Madrid, France, November.
Nilsson, L. (1995). Safety effects of adaptive cruise controls in critical traffic situations. *Proceedings 2nd World Congress Intelligent Transport Systems* (pp. 1254-1259). Tokyo: VERTIS.
Parasuraman, R., Molloy, R., & Singh, I. L. (1993). Performance consequences of automation-induced "complacency". *The International Journal of Aviation Psychology, 3*, 1-23.
Parkes, A. M., Ward, N. J., & Bossi, L. L. M. (1995). The potential of vision enhancement systems to improve driver safety. *Le Travail Humain, 58,* 151-169.
Rajaonah, B., Anceaux, F., & Hoc, J.-M. (2003). A study of the link between trust and use of adaptative cruise control. In G. C. van der Veer & J. F. Hoorn (Eds.), *Proceedings of CSAPC'03* (pp. 29-35). Rocquencourt, France: EACE.
Reymond, G., Kemeny, A., Droulez, J., & Berthoz, A. (2001). Role of lateral acceleration in curve driving: Driver model and experiments on a real vehicle and a driving simulator. *Human Factors, 43*, 483-495.
Rouanet, H. (1996). Bayesian methods for assessing importance of effects. *Psychological Bulletin, 119,* 149-158.
Rudin-Brown, C. M., & Parker, H. A. (2004). Behavioural adaptation to adaptive cruise control (ACC): Implications for preventive strategies. *Transportation Research. Part F, 7*, 59-76.
Saad, F., & Villame, T. (1999). Intégration d'un nouveau système d'assistance dans l'activité des conducteurs d'automobile [Integration of a new assistance system into the car-drivers'activity]. In J. G. Ganascia (Éd.), *Sécurité et cognition* (pp. 105-114). Paris: Hermès.
Shinar, D., McDowell, E. D., & Rockwell, T. H. (1977). Eye movements in curve negotiation. *Human Factors, 19*, 63-71.

Stanton, N. A., & Marsden, P. (1996). From fly-by-wire to drive-by-wire: Safety implications of automation in vehicules. *Safety Science, 24,* 35-49.

Stanton, N. A., & Young, M. S. (1998). Vehicle automation and driving performance. *Ergonomics, 41,* 1014-1028.

Stanton, N. A., Young, M. S., Walker, G. H., Turner, H., & Randle, S. (2001). Automating the driver's control tasks. *International Journal of Cognitive Ergonomics, 5*, 221-236.

Steele, M., & Gillespie, R. B. (2001). *Shared Control between Human and Machine: Using a Haptic Steering Wheel to Aid in Land Vehicle Guidance.* Paper presented at the *Human Factors and Ergonomics Society 45th Annual Meeting.* Minneapolis, MN, October.

Suzuki, K., & Jansson, H. (2003). An analysis of driver's steering behaviour during auditory or haptic warnings for the designing of lane departure warning system. *Japan Society of Automotive Engineers Review, 24,* 65-70.

Treffner, P., Barrett, R., & Petersen, A. (2002). Stability and skill in driving. *Human Movement Science, 21*, 749-784.

Wiener, E. L. (1981). Complacency: Is the term useful for air safety? In *Proceedings of the 26th Corporate Aviation Safety Seminar* (pp. 116-125). Denver, CO: Flight Safety Foundation, Inc.

Young, M. S. (2002). Malleable attentional resources theory: A new explanation for the effects of mental underload on performance. *Human Factors,44*, 365-375.

SUMMARY

An initial experiment was carried out which aimed to evaluate a particular function delegation mode on the test track. A car was equipped with an automatic device in order to replace the driver's lateral control of the trajectory (driving in the lane centre). The longitudinal control (speed) remained under manual control. The results showed difficulties in returning to manual control outside the domain of validity of the automatic device, with a suspicion of complacency. However, longer experience with the device would have been necessary to reach a higher level of trust and performance in the interaction between the driver and the device. In addition, negative interference between the bend-taking styles of the device and the driver were identified. A second experiment was carried out, again on the test track, in order to evaluate two types of mutual control modes. This took the form of criticising the driver when the car deviated more than 60 cm from the lane centre. With the warning mode, the driver heard a lateral noise on the side of the deviation and felt a non-specific steering wheel oscillation. With the action suggestion mode, the driver felt a steering wheel oscillation; this made the driver turn it toward the opposite side of the deviation. The two modes have revealed themselves to be sometimes efficient in critical situations where a trajectory deviation beyond 60 cm was provoked by a visual occlusion. Individual differences in effects were larger with the action suggestion mode than with the warning mode. No adverse cooperation effects were noticed.

Key words: *Human-machine cooperation, Car-driving assistance, Function delegation, Mutual control, Safety, Bend taking, Lateral control, Haptic signal.*

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