SIMULATION STUDY OF DRIVER STRESS AND PERFORMANCE TO AN UNEXPECTED STEERING CRITICAL EVENT

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Abstract

In this paper, we study the effect of unexpected behaviour of a Driving Assistance System (DAS) on the driver, during a common task of driving in a virtual environment. The considered system is an electrical steering, which allows drivers to reduce efforts needed to handle the steering wheel during cornering manoeuvres. A failure of such system could produce a sudden and permanent loss of steering assistance and make the steering wheel more difficult to turn.

The objective of this study is to determine how this event will affect the driver's performance, particularly in terms of stress and visual performance. At last, drivers are able to adapt to this kind of event if it occurs before entering a curve. Moreover, an increase of muscle stiffness has been observed during lane change manoeuvres, which provide a more robust control of the steering wheel to external perturbations. At last drivers are able to manage a sudden increase of stress. The experiment was conducted on the ULTIMATE dynamic driving simulator developed by the Technical Centre for Simulation of RENAULT. The simulator has been fitted with a new steering force feedback system improving dynamical performance. This simulator upgrade and assessment methodology will be presented in more details in this paper.

The driver behaviour was studied through questionnaires to assess the stress produced by the different situations. Detection and/or recognition of objects in the virtual scene give cues on the DAS failure effects on the driver's visual attention. In order to quantify the drivers' performance, objective indicators such as steering reversal rate, steering entropy and time-to-lane-crossing were also used. In spite of the unexpected steering event, all drivers have achieved their driving task, without leaving the road. Results show an increase of stress for drivers when the unexpected event occurs. We also notice an alteration of the visual performance revealed by drivers' difficulties to recognize critical objects in the environment. This study suggests that high-performance driving simulators may be valuable to assess the effects of safety-critical events on driving performance.

Résumé

Dans cet article, nous étudions l'effet sur le conducteur d'un comportement inattendu d'un système d'aide à la conduite (DAS) et ceci lors d'une tâche de conduite ordinaire en environnement virtuel. Le système retenu est une direction assistée électrique qui permet au conducteur de réduire les efforts nécessaires à produire pour le maniement du volant en virage. Une défaillance d'un tel système peut produire une perte soudaine et permanente d'assistance et rendre ainsi le volant plus difficile à tourner.

L'objectif de cette étude est de déterminer l'impact de ce type d'évènement sur les performances du conducteur. Seront considérés en particulier la performance visuelle et la production de stress. Il a été constaté que lorsque cet évènement apparaît avant l'entrée en virage, les conducteurs sont capables de s'y adapter. De plus, une augmentation de la raideur des muscles du bras a été observée lors de manœuvres de changement de file, ce qui rend le contrôle du volant plus robuste à des perturbations extérieures. Enfin, il semble que les conducteurs sont capables de gérer un stress soudain et de courte durée. L'expérimentation a été réalisée sur le simulateur de conduite dynamique ULTIMATE développé au Centre Technique de Simulation de RENAULT. Le simulateur s'est vu doté d'un nouveau restituteur d'effort pour le volant, offrant des performances dynamiques supérieures au précédent restituteur. L'installation et la validation de ce nouveau matériel sera présentée dans de plus amples détails.

Le comportement des conducteurs a été étudié au travers de questionnaires afin d'évaluer la production de stress lors des différentes situations. La détection et/ou la reconnaissance d'objets dans la scène virtuelle procure des indices quant aux effets sur l'attention visuelle du conducteur de la défaillance du système d'assistance. Dans le but de quantifier la performance de conduite, des indicateurs tels que le Steering Reversal Rate, le Steering Entropy et le Time-to-Line-Crossing ont été utilisés. Malgré que l'évènement soit inattendu, tous les conducteurs ont réussi à terminer leur tâche de conduite sans quitter la route. Les résultats montrent une augmentation du stress lorsque cet évènement apparaît. Remarquons aussi l'altération de l'attention visuelle des conducteurs de part leur difficulté à reconnaître les objets de l'environnement. Cette étude suggère que les simulateurs de conduite à hautes performances autorisent l'évaluation des effets sur la performance de conduite d'évènements critiques en termes de sécurité.

Introduction

In order to improve drivers' safety, car manufacturers have developed a wide range of Driving Assistance Systems (DAS) such as ABS, ESP… The understanding by the drivers of the behavior of these systems is a major challenge that designers have to cope with. A DAS can for instance change the perceived car dynamics and create a discrepancy between the observed and expected car behavior for the drivers. In particular, in case of system failure, we may wonder how the drivers will react to it. In this paper, we study the effect of an unexpected behavior of an electrical power steering system, during a common driving task. The system considered reduces efforts needed to turn the steering wheel during cornering maneuvers; failure of such system produces a sudden and permanent loss of steering assistance and makes the steering wheel more difficult to turn.

Questions

In such a situation we can expect different reactions from the driver. Immediately after the event occurrence the driver can manage the torque feedback increase and continue his driving task, or can be unable to stabilize the steering wheel and drive off the road.

The possible management of this event arises a question on the driver control properties. In fact, different control strategies may allow successfully carry out the steering task. The natural robustness of the driver neuromuscular system may be sufficient to deal with a perturbation. Pick & Cole [1] measured an increase of muscle stiffness and arm impedance during change lane maneuvers. Drivers may also update the internal representation [2] of the steering wheel dynamics. Toffin et al [3] highlighted the driver's ability to adapt different steering wheel force feedback. They studied different steering wheel control laws which were modified on straight road segments in order to avoid the necessity of the driver to deal with sudden torque changes at the steering wheel. It was observed that subjects were able to maintain their level of performance in cornering maneuvers and could adapt immediately to such events. In our experiment we were interested in the overall capacity of the drivers to deal with steering wheel assistance system failure thus also with increased of torque feedback occurring while driving in a curve.

The surprise effect and the possible generated stress could also modify the driver control performance. Nevertheless, Matthews mentioned in [4] that a sudden stress due to a brief and unexpected event may be quickly regulated. This stress can be more important as the difficulty of the situation understanding increases and alters the driver performance. Westman suggests in [5] that strategies used to regulate the stress may induce an increase of the mental workload. Such a variation of the mental workload can reduce the size of the functional visual field size (which allows particularly the detection and recognition of objects) [6]. Then, the stress produced by the unexpected event can impair the driver task in terms of visual performance reduction.

Materials

Simulator

The experiment was conducted on the ULTIMATE dynamic driving simulator developed by the Technical Centre for Simulation (CTS) of RENAULT in the framework of a European research project (Eureka # 1493 consortium: RENAULT (leader), SEOS Ltd., Rexroth-Hydraudyne, CNRS-LPPA). A cylindrical screen made of three single-chip DLP projectors creates a 150°x40° field of view for the front view. Two LCD screens replace rear view mirrors. An XY rails motion system coupled with a Hydraudyne 6-DOF hexapod platform generates the movement. The simulator is running under the modular software SCANeR© II developed initially by the CTS and in cooperation since 2005 with OKTAL, which manages each subsystem, generates the traffic, records experimental data. The validation of the simulator performances is achieved at different levels, from basic platform dynamics, real-time vehicle model accuracy to subjective vehicle tests [7].

Electrical power steering

In order to provide a high performance torque rendering device for the steering wheel, a benchmarking of different Electric Power Steering systems (EPS) was conducted at the CTS in cooperation with other services. The aim of the study was to identify their performances in comparison with the current device fitting ULTIMATE. The performance characterisation of the different competing EPS was achieved through two axes of study. On one hand, dynamical performances were identified through objective criteria and on the other hand, the perceived torque rendering was measured.

The characterisation of the EPS dynamics was performed through the study of their response to different test signals:

- Torque steps from 0 to 2, 4, 6, 8 and 10 Nm to measure the device torque rise time response.
- Torque steps from 2, 4, 6, 8 and 10 to 0 Nm to measure the device torque descent time response.
- Sinusoidal signals to identify bandwidth and phase diagrams.
- The resolution and noise level on angle position and speed measures were also quantified (see table 1).

For these tests, two EPS were considered: A and B. The A system is an open calculator which means it can be directly torque controlled via the CAN network. The B system had to be modified by the CTS to allow the torque control feature.

EPS device	Steering wheel angle [°]	Noise level on the angle [°]	Steering wheel angle speed resolution [°/s]	Noise level on the angle speed [°/s]
A	0.1	0	0.3	0.3
B	0.1	0.1	2	2

Table 1: Steering wheel angle position and speed measures

Moreover a subjective evaluation of the EPS is accomplished by Renault expert drivers, assessing the following criteria: dead zone around zero, the simulated steering limits. The device chosen for ULTIMATE is the system A, which was rated 7/10 at the subjective evaluation, according to a RENAULT steering wheel customer evaluation scoring grid. Such score guarantees that the device satisfies the customers' requirements of vehicle performances defined by vehicle engineering. The EPS was integrated in the simulator in early 2007 (see figure 1).

Method

Subjects

Ten drivers took part in the experiment (age 23 to 28). They were not accustomed with simulators but working at RENAULT. They also carried a driver's license for more than two years.

Figure 1: EPS fitted in ULTIMATE

Training session

In order to get accustomed with both the simulator and the itinerary they had to follow, drivers had to achieve two different 5 minutes sessions. During the first one, they had to drive on a open area. They were requested to make at different speed both right and left turns and slalom (approximately 1Hz frequency and 30° amplitude for the steering wheel movements). We expected subjects to discover the dynamical behavior of the simulated car and of the steering wheel. A second session was dedicated to learn the itinerary, the test curve and the environment.

Task

Subjects had to perform a double task: to drive at 70 km/h as naturally as possible, and to look out for objects in the environment. The environment was a rural highway with oncoming traffic (see figure 2). The studied curve had a 100 m radius. Each driving session lasts 5 minutes. Subjects are thus asked to drive normally, and they have to look out for a “hidden” bicycle in the environment.

Figure 2: Visual environment before the steering event, showing the hidden cyclist (red circle).

During the experiment, cyclists had a random position for each of the five sessions. But in each possible position, cyclists were equally distinguishable to the driver. The unexpected steering critical event is a sudden increase of the torque feedback during a cornering maneuver simulating a loss of electrical power assistance. The nominal torque level is 3 Nm during the curve and reaches 6 Nm when assistance is altered. The event occurs once, during the 4th trial and before passing the third truck on the right side of the road. The torque increased persists until the end of the trial. The torque feedback recovers its previous level for the 5th and last trial.

Data collection
Data from the simulation are collected using SCANeR© II and sampled at 20Hz.

Objective indicators
In order to quantify the driving performance, we chose the following criteria:
- **Lateral deviation**, a basic lane keeping indicator [8].
- **Time-to-Line-Crossing** (TLC) through the SCANeR© II built-in function also provides cues on changes on the driver safety margins [9].
- **Steering Wheel Reversal Rat**e [8] and **Steering Entropy** [10], to quantify the alteration of the primary driving task. These task indicators are suited for long and multiple task contexts but their relevance for short duration driving with critical event is not yet established.

These indicators are computed from the position where the event occurs in the 4th trial to the end of the curve.

Subjective indicators
The study of subjective indicators was based on a questionnaire (table 1) filled by the subjects at the end of each session included the following topics:
- **Stress** perceived by the subjects.
- Quality of the **objects detection**.
- **Situation understanding** for the session during which the unexpected event occured.

We used the phi-square test [11] to assess the correlation between the quality of object detection and the unexpected event. This test allows quantifying independence between two variables regardless to limited numbers of subjects. The stress levels gathered through a questionnaire during the sessions with versus without the unexpected event are compared using a Wilcoxon Mann Whitney test (U test). This test is a non parametric statistic test that allows us to compare the mean values of two groups.

Stress perceived by the subjects
*Did you easily manage to drive the vehicle on the simulator?**
Did you think to drive a real car? *
Which was the level of stress generated by the driving situation? *
Quality of the objects detection
Did you see an object near one of the truck?
If “Yes”: **-** *Can you recognize it?*
- *Near which truck was it?*
Situation understanding
What did happen?
Did you feel something different with the steering wheel?
What did you think during that event?
Did you feel in a dangerous situation?

Table 2: List of questions asked to subjects

* Subject had to give a grade on a scale from 0 to 7.

Results

Lateral deviation

During all trials, every subject succeeded to keep his or her vehicle inside their lane. The steering event systematically increases the mean lateral position value during the curve without affecting the standard deviation. However, the levels of standard deviation values are high and similar to their mean values, close to 30cm. For the subject 2, we notice a variation of the lateral position of 1m on the left side of the lane at the event onset.

TLC

We measured the range of TLC values and the number of its oscillations for nominal driving of each subject and compared with the values from the altered condition. All subjects (except one) showed similar TLC profiles during different driving conditions (figure 3). We noticed for the subject 2 a sudden decrease of its TLC (a variation from 1.28s to 0.6s) when the steering assistance was removed. He succeeded in 2 seconds to recover a “normal” TLC profile.

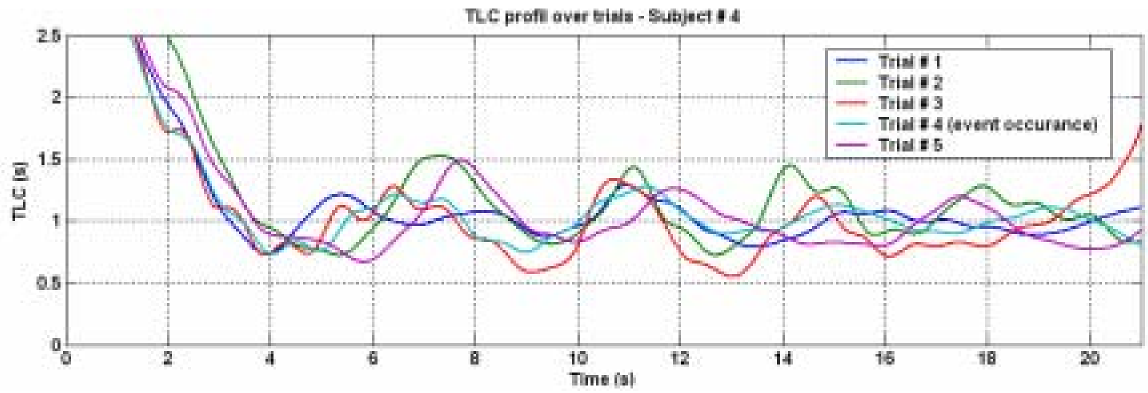

Figure 3: Typical TLC profiles over trials – (Subject # 4)

Steering Entropy

The Steering Entropy was computed as described in [10] for each subject and trial. It is based on a prediction algorithm. The predicted steering wheel angle is compared with subjects' experimental measures. The Steering Entropy H_p is defined as:

$$H_p = -\sum_{i=1}^{m} p_i \cdot \log_m p_i$$

Equation 1: Steering Entropy formula, p_i is the probability of prediction errors falling into one of the m bins (9 in the present study).

We present the mean Steering Entropy over subjects for each trial. The first trial is used as a baseline for the computation of the steering entropy of the other trials. We notice an increase of the Steering Entropy during the 4th trial where the unexpected event occurs.

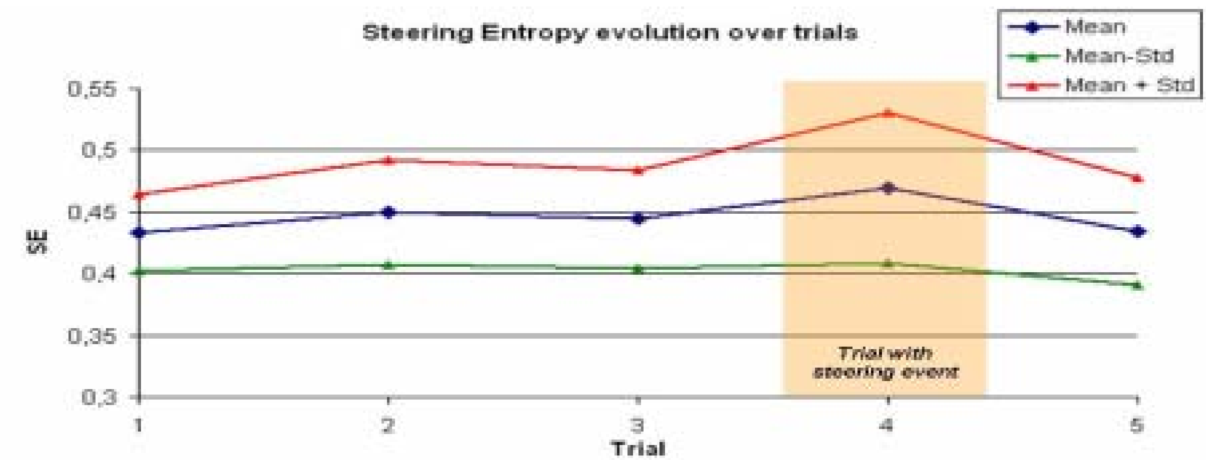

Figure 4: Mean SE over subjects per trial

Steering Reversal Rate

We computed the Steering Reversal Rate for each subject and trial, counting the number of steering wheel direction changes over than a considered threshold (2°). Subjects maintained the indicator during the 4th trial at the same level than during the others (mean 0.2 change/s, standard deviation 0.03 change/s). Then the occurrence of the event is systematically followed by a decrease of the steering wheel angle (mean 9.52 degrees, standard deviation 2.31 degrees).

Questionnaires - Stress perceived by the subjects

No subject reported any difficulty to drive the simulator (mean value 5.7 on a scale level from 0 to 7 over the subjects, maximum grade 7 meaning "no difficulty encountered") and no one suffered from simulator sickness. During nominal trials, no stress was reported (mean value 1.3 on a scale level from 0 to 7 over the subjects, maximum grade 7 meaning "no stress during the driving session"). The comparison of the means of stress level was done using a U test and revealed that the increase is statically relevant (p= 0.00018) using a threshold of 5% (p=0.05).

Questionnaires - Quality objects detection

In nominal sessions, the displayed cyclist in the visual environment was seen more easily than in altered session. The phi-square test shows that the link between the kind of session and the cyclist detection is “intermediate”. The couple “altered session” and “no object detection at all” contributes the most to the phi-square (i.e. there is more “no object detection” during this trial).

Questionnaires - Situation understanding

Although all subjects had the same steering wheel event, only one didn’t feel in danger at all, another was worried about hitting the cyclist, or two other considered that the situation could have been dangerous on a real car, but not on a simulator. In addition, even all subjects felt the increase of steering wheel force feedback, only one has combined it with an EPS failure.

Discussion

In this paper, we studied the effects of steering assistance loss during a cornering manoeuvre.

Objective indicators. The effects of the unexpected event do not seem to affect the Time-to-Line-Crossing and the Steering Reversal Rate: they do not appear to be suitable indicators for characterizing the driver adaptation process. The event occurrence systematically increases the mean value of lateral deviation: subjects shift on the left side of the road. This can be interpreted as a choice to increase their safety margin from road border. The Steering Entropy seems to increase during the altered session. It can be interpreted as a modification of the mental workload allocated to the both tasks. This modification can be due to the sensorimotor adaptation process.
Subjective indicators. The unexpected event increased the level of stress perceived by the subjects but no one decided to stop the vehicle, they all continued their task. The event also seems to reduce the visual performance of the subjects. They tended to link the event with an experienced situation. The only subject who correlated the event with a failure of the EPS had already faced it in a real vehicle. Then, no subject felt in danger during the steering assistance loss. They reported that they knew they were in a simulator and thus safe.

The experiment was conducted with a limited numbers of drivers: all tendencies observed above will require experiments with a higher number of subjects.

The effects of an unexpected event on the driver performance can be partly appraised with objective and subjective criteria. Nevertheless, they are limited as to the understanding of the driver adaptation processes. Numerical models of the driver control attempt to describe the involved processes in the driving task. Modelling the driver behaviour for cornering manoeuvres such as lane changing has been extensively investigated. The lateral control task is often considered as a multi level control inspired from tracking tasks such as described in [12]: a pursuit level [13-14] producing open loop-motor commands according to a desired movement and a compensatory loop [15] working like a closed-loop controller, correcting errors on the movement and using feedback sensory cues (cf. figure 5).

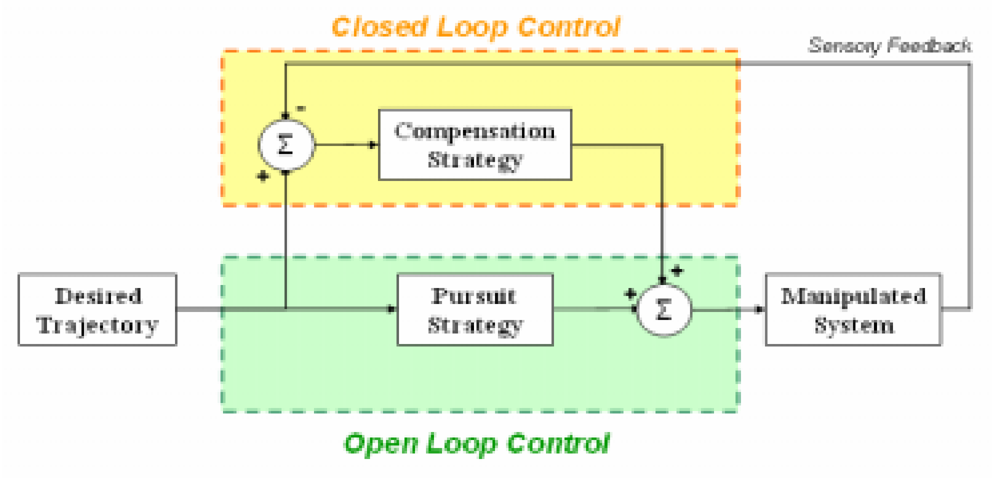

Figure 5: General tracking model architecture

For both levels of lateral control, compensation and anticipation, it is generally assumed that the driver behaviour is already fully learnt, for instance with an adaptive internal model of the vehicle dynamics [16]. Adaptation can occur at a lower control level through for e.g. a muscle stiffening loop [17] which allows a better control of the steering wheel position.

Future work includes developing a new driver model presenting a real time adaptation capability of both levels of control with following characteristics:

- High gain adaptive control theory [18] to describe the increase of arm impedance.
- Extraction of information about the varying vehicle dynamics during driving.

The present study does not allow to determine the origin of driver adaptation which is maybe due to exclusively pursuit or compensation levels or both of them. A way to detect adaptation of the pursuit level and then the building/update of an internal model is made through the observation of an adaptation after-effect [19] which will be the aim of our future experiments.

Conclusion

This study confirms the previously observed plasticity of the human control in driving. Furthermore, in our experiment subjects succeeded to perform their driving task in spite of the occurrence of unexpected steering wheel control law change during cornering manoeuvres. Drivers' ability to face critical events seems to be fast and efficient, as it is shown by the corresponding Time-to-Line-Crossing and Steering Reversal Rates. The increase of Steering Entropy reveals changes in subject's mental workload allocation, which suggests an increase of stress and/or the execution of subsequent adaptation processes. This adaptation capability is to be further studied to a better integration in vehicle engineering. Future work includes the design of a new driver model, inspired from adaptive control theory with real time adaptive mechanisms.

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