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Arnaud MAS, Frédéric MERIENNE, Andras KEMENY - Lateral control assistance and driver behavior in emergency situations - In: 3rd International Conference on Road Safety and Simulation, Etats-Unis, 2011-09-14 - 3rd International Conference on Road Safety and Simulation - 2011

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LATERAL CONTROL ASSISTANCE AND DRIVER BEHAVIOR IN EMERGENCY SITUATIONS

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Submitted to the 3rd International Conference on Road Safety and Simulation, September 14-16, 2011, Indianapolis, USA

ABSTRACT

Advanced Driver Assistance Systems (ADAS) are designed to help drivers improve driving safety. However, automation modifying the way drivers interact with their vehicle, it is important to avoid negative safety impacts. In particular, the change in drivers' behavior introduced by ADAS in situations they are not designed for, should be carefully examined. We carried out an experiment on a driving simulator to study drivers' reaction in an obstacle avoidance situation, when using a lateral control assistance system. A detailed analysis of the avoidance maneuver is presented. Results show that assisted and non-assisted drivers equally succeeded in avoiding the obstacle. However, further analyses tend to show an influence of the assistance system on drivers' first reaction.

Keywords: driving simulation, advanced driver assistance systems, lane departure warning, lane keeping assistant, obstacle avoidance

INTRODUCTION

Advanced Driver Assistance Systems (ADAS) are designed to help drivers perform certain tasks, in order to improve driving safety. Nevertheless, automation modifies the way drivers interact with their vehicle, and the resulting safety effects can be different from those expected (Evans, 2004).

In several studies, the concept of levels of automation (LOAs) has been developed to categorize the degree of interaction between humans and machines, from fully manual mode to fully automatic mode (Sheridan and Verplanck, 1978; Endsley and Kaber, 1999; Parasuraman et al., 2000). Another classification was proposed for the more specific case of ADAS (Hoc et al., 2009), defining four main cooperation modes: perception mode, mutual control mode, function delegation mode and fully automatic mode.

Human-centered automation aims at finding the most efficient LOA for a given task. Indeed, high LOAs do not necessarily imply a better performance, as the human operator can experience difficulties to take over control when needed (Kaber and Endsley, 2004), mainly because of excessive trust (Parasuraman and Riley, 1997).

Therefore, it is of particular interest to study drivers' behavior with ADAS in situations where these systems do not provide support (Saad, 2006). However, although many studies investigated ADAS failure situations (Ben-Yaacov et al., 2002; Sullivan et al., 2008; Deborne et al., 2008), less attention has been paid to emergency situations ADAS are not designed for.

A few authors studied emergency braking with longitudinal control assistance systems: Koustanaï et al. (2010) observed, on a driving simulator, less collisions with the leading vehicle among drivers using a forward collision warning system than among drivers using no assistance. On the other hand, Nilsson (1995) observed, on a driving simulator and in a similar situation, more collisions with an adaptive cruise control than without assistance. For lateral control assistance systems (LCAS), Hoc et al. (2006) observed, on a real test track, difficulties to take over control in order to avoid an obstacle, while driving with LCAS using function delegation mode, but no clear effect while driving with LCAS using mutual control mode. However, the authors pointed out that, despite a seeming ecological validity, the test track method had too much safety and technical constraints, and that studies on a driving simulator where needed.

Consequently, we used a driving simulator to investigate how drivers using LCAS react in an emergency situation requiring manual lateral control. Since a LOA effect tends to emerge from the presented studies, we compared two different LCAS illustrating two different LOAs. However, the previously described effects refer to a change in drivers' behavior due to previous training with LCAS, but it must be noted that LCAS could also influence drivers' reaction through a disturbance due to LCAS triggering during the emergency situation. Thus, the origin of the observed effects will be examined and discussed.

METHOD

Apparatus

An experiment was conducted on a fixed-base simulator at Renault Technical Center for Simulation (Guyancourt, France). The simulator is composed of a fully instrumented Renault Scenic car, equipped with an automatic gearbox. The visual scene is displayed on a cylindrical screen via three video projectors, providing a 210° horizontal and 35° vertical field of view. The simulation is handled by Oktal SCANeR© II software (www.scanersimulation.com) and MADA, the Renault proprietary vehicle dynamics model.

Two different LCAS were compared, illustrating two different levels of automation. The Lane Departure Warning (LDW) only generates an oscillation on the steering wheel when the vehicle lateral position exceeds 85 cm. The torque applied on the steering wheel is 2 N in the direction of the lane center, and 0.5 N in the direction of the lane departure, with a period of 300 ms (Navarro et al., 2010).

On the contrary, the Lane Keeping Assistant (LKA) actually contributes to the steering task, by applying on the steering wheel a torque inversely proportional to the vehicle lateral position. The maximum torque delivered, when the vehicle is on the lane border, is approximately 2 N. However, the torque delivered by the LKA is not sufficient to steer automatically, and drivers' action on the steering wheel is still necessary.

Both LCAS use two different sub-modes of mutual control mode, as defined by Hoc et al. (2009). LDW uses action suggestion mode, which delivers a warning using haptic modality, whereas LKA uses limit mode, which opposes a resistance to drivers' action and is more intrusive into the control of the vehicle.

Both LCAS were active only above 50 km/h, and were deactivated when the turn signal was activated, to prevent from a negative interference for voluntary lane departures.

In order to distract them and to make them trigger the LCAS, subjects had to perform a distractive task while driving. The distractive task, known as the surrogate reference task (Mattes and Hallén, 2009; Petzoldt et al., 2011), consisted in locating a target circle (190 mm in diameter, 4 mm in thickness) among 65 distracters (150 mm in diameter, 5 mm in thickness) displayed on a side screen. The participants selected the target zone by moving a cursor using a little keyboard. A new task started 15 seconds after the last movement of the cursor. Subjects were asked to perform the new task as fast as possible after it appeared, but to always give the priority to driving safety. Figure 1 illustrates the simulator setup.

Figure 1 Simulator setup, showing the distractive task on the right

Participants

The 27 participants in this experiment (23 men, 4 women) were all employees at Renault. They had a mean age of 36.2 years old (SD = 10), a valid French driving license for 17 years on average (SD = 10.2; min = 3), and were not expert pilots. Their mean annual traveled distance was 18519 km (SD = 13420). All subjects had normal or corrected-to-normal vision.

Procedure

Subjects drove on an itinerary of approximately 14 km on a dual-lane country road. They were instructed to drive naturally, and to respect the traffic law (speed limit was 90 km/h, 70 km/h in curves). Oncoming traffic was present, in order to prompt drivers to stay in their lane.

The experiment consisted in two driving sessions: a familiarization drive and a test drive. Each drive lasted approximately 13 minutes. During the familiarization drive, subjects drove without LCAS, in order to get used to the simulator and the distractive task. Then, they were divided into three groups: Control, LDW and LKA. During the test drive, subjects from Control group remained without LCAS, whereas subjects from LDW and LKA groups used their respective LCAS.

At the end of the test drive, subjects encountered an emergency situation: a truck was parked on the right side of the road. The truck was placed at the end of a curve to the right, and behind a tree row, so that subjects saw it at the last moment. No oncoming traffic was present in this area, to allow subjects to overtake. The event occurred only once in order to keep the surprise effect.

DATA ANALYSIS

Normal Driving

To evaluate the benefits of LCAS, lane keeping was assessed on two different parts of the itinerary: a curve (length = 727 m; curvature radius = 244 m) and a straight line (length = 416 m). The line integral of the lateral position (LILP) of the subject's vehicle along the right lane center was computed for each group. The LILP corresponds to the area between the lane center and the vehicle trajectory along an itinerary, thus representing the quantity of lane departure on this itinerary. One-way analyses of variance (ANOVAs) were performed (or Kruskal-Wallis tests when ANOVA conditions were not satisfied), with group as independent variable, and LILP as dependent variable.

A second analysis was performed on LILP in the curve, in order to investigate if the observed difference was due to a better lane keeping with LCAS, or to subjects from Control group cutting more the curve. LILP was then split into left-LILP (LILP for lateral positions on the left of the lane center) and right-LILP (LILP for lateral positions on the right of the lane center). ANOVAs were similarly performed on left-LILP and right-LILP.

Emergency Situation

Figure 2 represents a typical avoidance maneuver, which we split into three phases. Firstly, drivers reacted quickly by applying a fast correction on the steering wheel to avoid the obstacle (between t0 and t1). Secondly, drivers applied a correction on the steering wheel in the opposite direction (between t1 and t2). Finally, drivers arrived in a straight line, and turned the steering wheel back around the central position and stabilized on the right lane (between t2 and t3). The chosen criterion for steering wheel stabilization was that the steering wheel stayed between -5° and +5° (relatively to the central position) for 2 seconds, starting at t3. Those three steps will be referred as phase 1, phase 2 and phase 3.

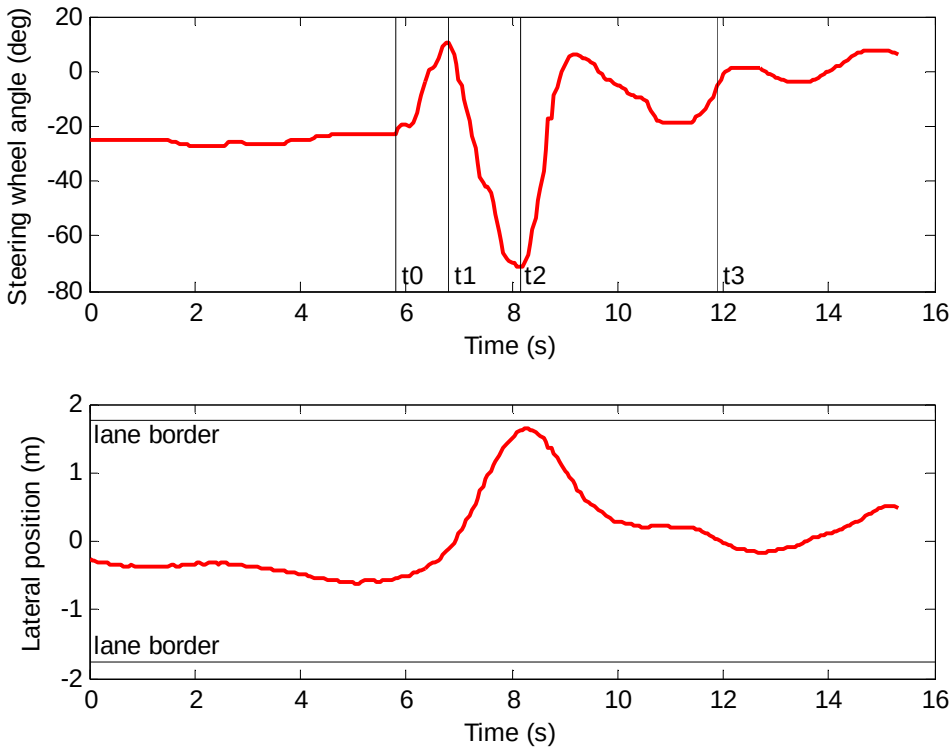

Figure 2 Example of an obstacle avoidance maneuver. Positive values for steering wheel angle and lateral position correspond to steering and lateral deviation to the left.

To better understand the effects of LCAS, the way drivers avoided the obstacle is analyzed, for each group and for each phase. Such a maneuver involves two different control loops. First, drivers react quickly, almost automatically, to the initial situation, using open-loop control. Then, they apply a slower correction depending on the evolution of the environment, using closed-loop control (Michon, 1985). LCAS might influence both control loops, which can be therefore studied separately using the suggested phase splitting. Indeed, we expected that only effects of previous training with LCAS would modify open-loop control, whereas effects of LCAS triggering during the avoidance maneuver would only modify closed-loop control (at $t1$, drivers barely started to deviate from their initial lateral position).

For each phase, we sought to investigate whether subjects adjusted their reaction to the initial situation or to the desired final situation. Therefore, we evaluated the correlation between indicators describing the criticality of the situation at the beginning of the phase, drivers' response, and the goal drivers intended to reach at the end of the phase. This approach is similar to the one proposed by Van Winsum et al. (1999).

During phase 1, the situation was characterized by the obstacle angle, which influences the avoidance maneuver (Fajen and Warren, 2003). It was calculated at $t0$ and $t1$ (and called θ_0 and θ_1, respectively), and corresponds to the direction of the truck in the vehicle frame of reference (see Figure 3). This variable thus defines the level of emergency of the situation: since drivers

had to overtake the truck on the left, a smaller obstacle angle means a more critical situation. Drivers' response to that situation was measured with the steering amplitude δ_1 and the steering duration τ_1. δ_1 corresponds to the difference in steering angle between $t0$ and $t1$, and τ_1 corresponds to the duration of phase 1.

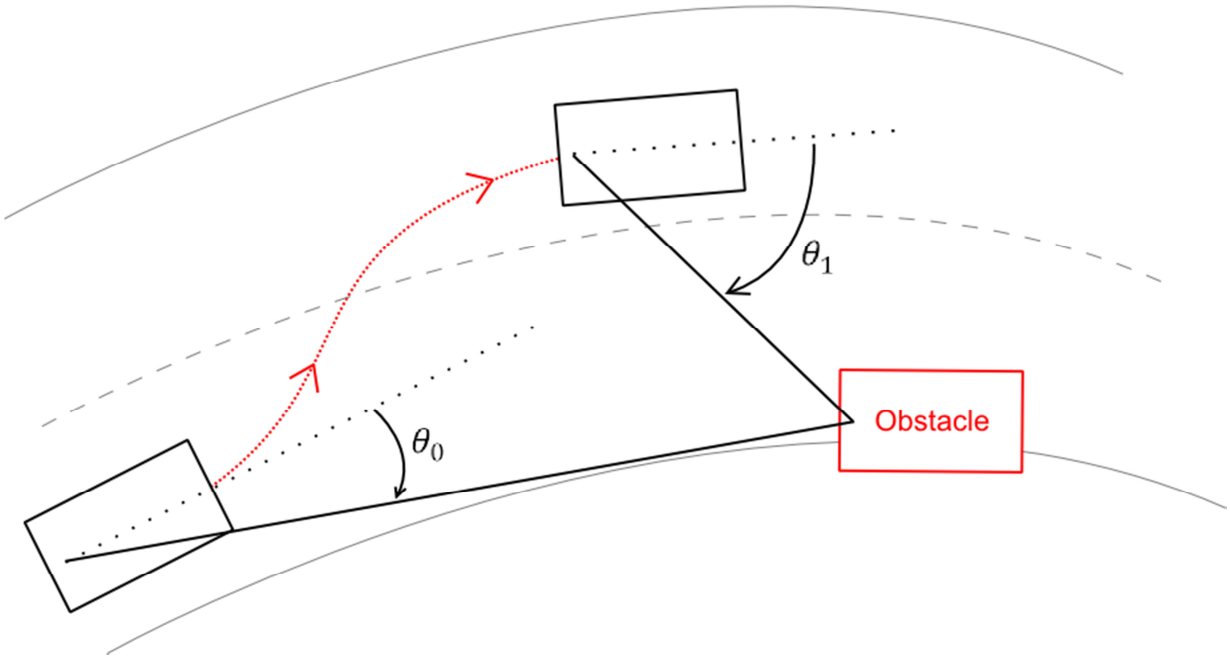

Figure 3 Obstacle angles θ_0 and θ_1. Values are defined with 0 ahead, positive values on the right and negative values on the left.

One-way ANOVAs were performed, with group as independent variable, and δ_1 and τ_1 as dependent variables. Linear regressions were also performed for each group, to explain δ_1 and τ_1 by θ_0, and θ_1 by δ_1 and τ_1.

During phase 2, the situation at $t1$ was characterized by the time to line crossing to the left border of the road (Van Winsum et al., 1999), called TLC_1. Drivers' response was measured with the steering amplitude δ_2 and the steering duration τ_2. The situation at $t2$ was characterized by the lateral position, called LP_2.

One-way ANOVAs were performed, with group as independent variable, and δ_2 and τ_2 as dependent variables. Linear regressions were also performed for each group, to explain δ_2 and τ_2 by TLC_1, and LP_2 by δ_2 and τ_2.

During phase 3, the situation at $t2$ was characterized by the lateral position, called LP_2, and drivers' response with the time to stabilization, called TTS (with the criterion previously described). Thus, TTS corresponds to the duration of phase 3.

A one-way ANOVA was performed, with group as independent variable, and TTS as dependent variable. Linear regressions were also performed for each group, to explain TTS by LP_2.

RESULTS

Groups homogeneity

There were no significant difference of age ($F(2,24) = 0.13$; $p = 0.88$) nor gender ($\chi^2(2) = 0.5$; $p > 0.2$) between groups.

Normal Driving

On the curve, results show no significant effect of the group on the LILP for the familiarization drive ($F(2,24) = 0.09$; $p = 0.92$) and a significant effect for the test drive ($F(2,24) = 3.51$; $p < 0.05$), implying an effect of the presence of LCAS. Post-hoc analysis on the test drive shows that both LDW and LKA groups have a significant different LILP than Control group ($p = 0.04$ and $p = 0.03$, respectively). Those two groups have a smaller LILP than Control group.

There was no significant effect of group on left-LILP ($H(2,27) = 1.85$; $p = 0.4$), nor on right-LILP ($F(2,24) = 1.91$; $p = 0.17$).

On the straight line, there was no significant effect of group on LILP, neither for the familiarization drive ($H(2,27) = 3.52$; $p = 0.17$), nor for the test drive ($H(2,27) = 1.24$; $p = 0.54$).

Emergency Situation

All subjects from all groups succeeded in avoiding the truck. Only one subject from LKA group lost the control of the vehicle after overtaking the truck, and left the road. At $t1$, the peak value of the first steering correction was 4.93° to the left on average (SD = 14.84), and was not significantly different from 0° ($t(26) = 1.73$; $p = 0.1$). Subjects also started to countersteer significantly before the time of their maximal lateral deviation ($t(26) = 28.92$; $p = 0.00$), 1.65 seconds sooner on average (SD = 0.3). θ_0 was 8.23° on average (SD = 1.28).

During phase 1, there was no significant effect of group, neither on δ_1 ($F(2,24) = 0.2$; $p = 0.82$), nor on τ_1 ($F(2,24) = 0.95$; $p = 0.4$).

Table 1 summarizes the regression results on δ_1, which show a significant correlation between θ_0 and δ_1 for LDW and LKA groups, and a significant correlation between δ_1 and θ_1 for Control and LDW groups.

Table 1 Relations between the situation and steering amplitude during phase 1

	Regression of δ_1 on θ_0			Regression of θ_1 on δ_1		
Group	β	p	Adjusted R²	β	p	Adjusted R²
Control	-0.425	0.254	0.064	0.737	0.024	0.477
LDW	-0.790	0.011	0.571	0.743	0.022	0.488
LKA	-0.865	0.003	0.713	-0.501	0.169	0.144

We can see from the sign of β coefficients in Table 1 that for LDW and LKA groups, the more on the left the obstacle at $t0$, the bigger the steering amplitude. Similarly, for Control and LDW groups, the bigger the steering amplitude, the more on the right the obstacle at $t1$.

Table 2 summarizes the regression results on τ_1, which show a significant correlation between θ_0 and τ_1 for Control group.

Table 2 Relations between the situation and steering duration during phase 1

	Regression of τ_1 on θ_0			Regression of $\theta_1$on τ_1		
Group	β	p	Adjusted R²	β	p	Adjusted R²
Control	0.719	0.029	0.449	-0.368	0.330	0.012
LDW	-0.187	0.63	~ 0	0.163	0.674	~ 0
LKA	0.292	0.446	~ 0	0.186	0.631	~ 0

For phase 2, there was no significant effect of group, neither on δ_2 (F(2,24) = 0.58; p = 0.57), nor on τ_2 (F(2,24) = 1.25; p = 0.30).

Table 3 summarizes the regression results on δ_2, which show a significant correlation between TLC_1 and δ_2 for LDW group.

Table 3 Relations between the situation and steering amplitude during phase 2

	Regression of δ_2 on TLC_1			Regression of LP_2 on δ_2		
Group	β	p	Adjusted R²	β	p	Adjusted R²
Control	-0.477	0.195	0.117	-0.628	0.070	0.307
LDW	-0.847	0.004	0.677	0.504	0.166	0.148
LKA	-0.563	0.115	0.212	-0.102	0.794	~ 0

Table 4 summarizes the regression results on τ_2, which show a significant correlation between TLC_1 and τ_2 for all groups.

Table 4 Relations between the situation and steering duration during phase 2

	Regression of τ_2 on TLC_1			Regression of LP_2 on τ_2		
Group	β	p	Adjusted R²	β	p	Adjusted R²
Control	0.814	0.008	0.614	0.117	0.764	~ 0
LDW	0.854	0.003	0.69	-0.660	0.053	0.355
LKA	0.76	0.018	0.517	-0.099	0.800	~ 0

For phase 3, there was no significant effect of group on TTS (F(2,24) = 1.77; p = 0.19). Table 5 summarizes the regression results.

Table 5 Relations between the lateral position and the time to stabilization during phase 3

	Regression of TTS on LP_2		
Group	β	p	Adjusted R²
Control	-0.504	0.167	0.147
LDW	0.214	0.580	~ 0
LKA	0.253	0.511	~ 0

DISCUSSION

Normal Driving

Results showed that the LILP in the curve was significantly smaller for subjects with LDW and LKA. If this difference was only due to the fact that LCAS prevented subjects from cutting the curve, we expected that all the observed difference would reside in right departures only. However, results showed no significant effect of group on right-LILP. This suggests that the difference in lane departure is balanced between left and right lane departure, thus confirming a real lane keeping improvement with LCAS.

Emergency Situation

Globally, subjects easily managed to avoid the truck. They performed a relatively small steering correction, and countersteered quickly. Indeed, the road curvature allowed them to quickly deviate from their trajectory. Unlike overtaking maneuvers, there was no stabilization on the left lane (Younsi et al., 2009), probably because of the larger speed difference between the vehicles.

Given the results for phase 1, it appears that the reaction of subjects from LDW and LKA groups is mostly determined by the obstacle angle at the beginning of the phase, whereas the reaction of subjects from Control and LDW groups is rather determined by the obstacle angle at the end of the phase, after the steering correction. Therefore, it appears that automation induced more reaction and less anticipation for this phase.

Here, the amplitude of obstacle angle values was pretty limited but, in light of these results, it is likely that more extreme values would lead to a bigger steering amplitude, especially for subjects using LKA. This could cause difficulties to recover the control of the vehicle afterwards. In this experiment, one subject from LKA group lost the control of the vehicle. Although it is not significant, we believe that a more critical situation, with a smaller obstacle angle (by placing the truck more on the left, or increasing the road curvature at the emergency location) could emphasize this effect.

On the contrary, the influence of LCAS during phases 2 and 3 appears to be limited. The observed differences mostly manifested themselves during phase 1. Therefore, these findings suggest that LCAS would mostly influence open-loop control, because of previous training with the systems.

CONCLUSION

In this study, we carried out an experiment on a fixed-base driving simulator, on drivers' reaction in an obstacle avoidance maneuver, when driving with LCAS. The results confirmed the efficiency of LCAS in improving lane keeping in curves, but showed that assisted and non-assisted drivers equally succeeded in avoiding the obstacle.

However, a further examination of the avoidance maneuver gave promising results, suggesting an effect of LCAS in the first phase of the maneuver, which is supposed to involve mainly open-

loop control (Michon, 1985). Indeed, when driving with LCAS, subjects' reaction during that phase was determined by the level of emergency of the initial situation (especially for LCAS with high level of automation). On the other hand, when driving with a LCAS with a lower level of automation, or no LCAS at all, subjects' reaction determined the safety outcome of the final situation. These results suggest an safety impact of LCAS with high level of automation, in more critical emergency situations.

Our findings also tend to show that the influence of LCAS in the emergency situation is more probably a change in drivers' behavior due to previous training with LCAS, than a disturbance due to LCAS triggering during the avoidance maneuver.

Future research will focus on creating new emergency scenarios, in order to emphasize the observed trends. It could include more critical situations, and using a moving-base driving simulator, as its importance for steering behavior has been demonstrated (Kemeny and Panerai, 2003). Such scenarios could be useful in the future, to study drivers' reaction in the early stages of ADAS design.

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