Automatic Emergency Steering with Distracted Drivers: Effects of Intervention Design

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***Abstract*—Driver inattention is reported to be one of the most prominent contributing factors to crashes. Modern vehicles feature sensor equipment able to detect an imminent collision, potentially permitting advanced driver assistance systems (ADAS) to cope for such human error. Steering interventions, however, make high demands on the human-machine-interaction. Unlike in autonomous emergency braking, conflicting driver input cannot be omitted. Three different ADAS configurations for an automatic emergency steering intervention with small lateral offset were tested against an unassisted baseline condition in a driving experiment with distracted drivers. The results suggest an influence of feedback modalities and actuator choice.**

Keywords*—*ADAS; active safety; human-machine-interaction; obstacle avoidance; steering intervention;

I. INTRODUCTION

A large number of road traffic accidents are attributed to driver inattention. In a naturalistic driving study with 100 cars, for example, Klauer and colleagues report driver inattention to have been a contributing factor to 78% of all observed crashes [1]. The risk posed by driver inattention can potentially be mitigated by machine vision in modern vehicles, acting as a second pair of eyes able to perceive and interpret the traffic situation. If an imminent crash is overlooked by its driver, the vehicle can act as a safety net and intervene via an advanced driver assistance system (ADAS), either warning the driver of the threat or temporarily taking control of the vehicle in order to resolve the situation autonomously.

One of two ways to avoid a collision with an obstacle in the vehicle's path is reducing the vehicle's speed relative to the obstacle to zero. ADAS able to perform such a maneuver – emergency braking – in the driver's stead are state of the art. For an emergency braking intervention it is, in simplified terms, sufficient to know the vehicle is approaching a relevant obstacle at critical relative speed, in order to trigger the system's intervention. In the course of the intervention, conflicting driver input can easily be ignored by decoupling the accelerator. Such systems are available for a variety of vehicles from different manufacturers. European law, for example, even considers them mandatory equipment on newly licensed heavy goods and large passenger vehicles [2].

The second collision avoidance strategy is steering out of the obstacle's path. While shortest braking distance scales quadratically with relative speed, shortest steering distance on the other hand scales linearly with relative speed. Therefore, for each set of parameters (maximum longitudinal deceleration, maximum lateral acceleration, required lateral offset) a certain threshold speed exists, above which successful collision avoidance by steering can be accomplished in a shorter distance than by braking (see e.g. [3]), rendering some collisions avoidable that would, by braking alone, be unavoidable. This is especially true when considering a combined braking and steering maneuver that provides even greater collision avoidance potential. As emergency braking may be accompanied by other disadvantages, e.g. blocking traffic flow, braking exclusively is not necessarily the best action if other options are available. The optimal strategy (in terms of most probable successful collision avoidance with the least adverse side effects such as risk of secondary collision or impact on traffic flow) is dependent on the individual traffic situation. Factors include obstacle width and lateral movement, relative closing speed, other obstacles (e.g. oncoming traffic) and available evasion space, as well as surface conditions. Combined with the finding of several studies, e.g. those reviewed in [4], that drivers tend to react to an imminent crash most frequently by braking only, even in scenarios that favor a steering maneuver, these facts make obvious the potential contribution of an emergency steering ADAS to road safety.

Collision avoidance ADAS with emergency steering have been under development for over a decade (e.g. [5]) but have so far not taken the plunge onto public roads. This is mostly due to the challenges such systems face. For the decision on whether and how to intervene, for example, it is no longer sufficient to know merely that the vehicle is closing in on a relevant obstacle at critical relative speed. Instead, it is necessary to analyze the vehicle's entire surroundings in detail, including all other objects and their predicted trajectories, in order to identify available evasion space and determine a viable evasive trajectory. A combined emergency steering and braking intervention, moreover, obviously makes highest demands with regard to vehicle dynamics control. As an additional challenge, an ADAS steering intervention must compete or cooperate with the driver with regard to lateral vehicle control, whose potentially conflicting input cannot be omitted with conventional steering systems where decoupling of the steering wheel is not possible. When developing such an emergency steering ADAS, it is therefore of paramount importance to choose an intervention design that yields the most favorable human-machine-interaction possible.

II. BACKGROUND

In order to address the issue of human-machine-interaction adequately, ADAS testing and development must be

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accompanied by user studies [6] which must feature relevant test scenarios. For an emergency steering ADAS, one of the most probable types of intervention scenario involves a distracted driver. At the same time, this constitutes a worst-case scenario for the human-machine-interaction, because, while a distracted driver does have influence on the control loop on the one hand, he is, on the other hand, less likely to react adequately to unfolding events. Any torque applied to the steering wheel by the driver during an automatic steering intervention is noise that can potentially cause the vehicle to over- or understeer the desired trajectory.

Most experiments with automatic emergency steering, e.g. [7] and [8], report considerable resistance of drivers against the steering intervention, reducing its effectiveness. Some possible reasons are reviewed in [9], one of which is the hypothesis that drivers support themselves against the steering wheel, thus holding it in place, especially during deceleration when inertia is pulling them forward. This effect would therefore be expected to be especially severe with a combined steering and braking assistance. Braking in addition to steering, however, appears advantageous for several reasons. In case of unsuccessful collision avoidance, the performed deceleration mitigates the collision. Due to inertia pressing the front wheels harder onto the road during deceleration, the wheel contact force is increased, allowing for more dynamic steering. Moreover, braking provides additional time to establish the required lateral offset and also to better observe how the situation develops, in case not all involved obstacles are stationary.

Another hypothetical explanation for drivers' initial resistance to automatic steering interventions is a corrective reflex. In normal traffic, sudden steering wheel torque not applied by the driver usually originates from strong gusts of wind or potholes against which drivers have learned to take action immediately by holding the steering wheel in place. A torque applied by an automatic steering intervention may trigger the same unreflected reaction. This issue would be expected to be even more severe with distracted drivers who are more likely to initially mistake the steering intervention for an unwanted externally caused steering perturbance. This aggravation could be mitigated if the driver were alerted to the imminent danger. Auditory cues are often neglected in favor of visual cues in this context (e.g. [10]) on the grounds of their being unable to convey direct behavioral recommendations as effectively as the latter. Since inattentive drivers that require warnings, however, are often also visually distracted, acoustic signals can prove more effective at gaining their attention, since they can be perceived from any direction.

Conflicting driver input could, of course, most easily be dealt with by taking the driver out of the control loop. This could be effectively accomplished (though not by conventional steering systems) either by applying torque of a strength the driver is unable to compete with, or by decoupling the steering wheel. In this case, however, the driver is bereft of control over the vehicle, which naturally does not comply with controllability standards (see [11]). The trade-off between system effectiveness and system controllability is a dilemma in active safety ADAS development that requires creative approaches to solve. One such approach could be the use of additional steering actuators, for example unilateral braking, to induce part of the required yaw. In this case, drivers' tendency to hold the steering wheel in place would have less impact on the effect of the steering intervention, while drivers are still given feedback about the steering intervention via the steering wheel of which they retain full control and full ability to countersteer.

III. RESEARCH QUESTIONS

The experiment reported in this paper focused on the effect of different collision avoidance ADAS configurations for automatic emergency steering with small lateral offset. It was devised to assess whether a steering torque overlay steering intervention can generally be effective in a scenario with low time to collision, small required lateral offset and visually distracted drivers. Furthermore, the experiment aimed to assess the influence of the different ADAS configurations on the human-machine-interaction in said scenario, i.e. the possible effect of an additional auditory cue, and the possible effect of the use of unilateral braking as an additional steering actuator. Although the presented experiment was mainly aimed at system benefit in a justified intervention scenario, another important aspect is the reaction of drivers to unjustified system interventions. Therefore an additional scenario was included in order to collect rudimentary data on system detriment in case of a false positive activation.

IV. METHOD

A. Driving scenarios

The experiment featured two driving scenarios: one with a suddenly appearing obstacle (true positive, justified system intervention) and a false alarm scenario without an obstacle (false positive, unjustified system intervention).

1) True positive scenario

The road consisted of two lanes of 3.1 meters width separated by a lane marking of 0.1 meters width. Signs with a simple main clause each (printed in small characters such that the signs were only readable once they were past the A-pillar from drivers' point of view) were placed approximately every 45m along the left side of the road in a 45° angle and were used to visually distract the drivers (Fig. 1). A single traffic cone was placed on the center road marking preceding each of the signs by 2 meters in order to ensure that subjects stay in their lane while reading the signs. In a straight section of the road, 16 meters behind one of the signs, CAPLOS (compressed air powered lateral obstacle simulator, a machine built to simulate suddenly appearing obstacles) was positioned behind cover at the right side of the road, ready to move a photorealistic but safely crashable dummy car into the subject car's lane (Fig. 2 and 3). The dummy car's movement into the road was first visibly noticable at a time-to-collision (TTC) of 1.2 seconds, at which point the system intervention – if applicable – was requested. The dummy car's final position protruded 0.6 meters into the subject car's lane. The opposing lane was empty.

Fig. 1. Exemplary sign for visual distraction at the left side of the road

Fig. 2. Approaching CAPLOS, obstacle fully withdrawn

Fig. 3. Approaching CAPLOS, obstacle fully extended

2) False positive scenario

The road consisted of two lanes of 3.1 meters width seperated by a lane marking of 0.1 meters width. In a straight section of the road, a system intervention was triggered for no apparent reason. Both lanes were empty.

B. Experimental Design and Measurement Units

The experiment used a full factorial 5 (system intervention in true positive scenario) x 3 (system intervention in false positive scenario) between-subjects design.

The five system intervention groups in the true positive scenario consisted of the three different automatic steering interventions A, B, and C (see (IV.C)), a haptic steering recommendation (the results for which will not be covered in this paper and have therefore been excluded from analysis) and a control condition without ADAS assistance. The three system intervention groups in the false positive scenario were the three different automatic steering interventions A, B, and C.

In the true positive scenario, the following measures were assessed for each test subject:

- perceived criticality of the situation (ratings on the scale for criticality assessment of traffic and driving scenarios [12], Fig. 4),
- primary collision (whether a collision with the obstacle occurred),
- lateral safety distance (whether a lateral offset of at least 0.5 meters to the obstacle's final position was established before passing the obstacle),
- longitudinal safety distance (remaining longitudinal distance in meters to the obstacle when lateral safety distance was established),
- opposing lane intrusion (whether the subject car's left rear wheel crossed the lane separation markings during any part of the maneuver),
- hypothetical secondary collision (whether any part of the subject car intruded more than 0.55 meters into the opposing lane, hypothetically colliding with an oncoming standard passenger car of 2 meters width driving in the center of its lane), and
- deviation from ideal trajectory (mean of the absolute values of the lateral deviation from an ideal trajectory at each measurement point).

Fig. 4. Scale for criticality assessment [12]

In the false positive scenario, the following measures were assessed for each test subject:

- perceived impact on driving task (ratings on the interference impact scale [13]),
- lateral offset (maximum lateral offset to the left from the point of intervention onset),
- lane departure (whether any part of the subject car crossed the lane separation markings), and
- intense braking (whether a longitudinal deceleration of at least 7 meters per square second occurred).

Statistical analysis of differences between the experimental groups was performed using the Kruskal-Wallis-test for subjects' ordinally-scaled ratings (perceived criticality of the situation, perceived impact on driving task), the Pearson-χ^2 test for frequencies (primary collision, lateral safety distance, opposing lane intrusion, hypothetical secondary collision, lane departure, intense braking), and a one-way analysis of variance (ANOVA) for ratio-scaled data (longitudinal safety distance, deviation from ideal trajectory, lateral offset).

C. Test Setup and Data Recording

The test vehicle was an instrumented Audi A7 Sportback. Vehicle position was tracked with a high precision inertial measurement unit (IMU) fed with GPS and dGPS correction data. Data were recorded at a frequency of 25 frames per second for camera data, 100 Hertz for IMU data, and 50 Hertz for vehicle data.

Three different ADAS setups for an automatic collision avoidance were tested in the experiment. All steering interventions aimed to guide the vehicle to a target lateral position 0.6m left of the lane center (leaving 0.09 meters to the left before entering the opposing lane as well as 0.09 meters to the right before violating the 0.5 meters lateral safety distance to the obstacle) on a vehicle dynamics optimized trajectory. All system interventions included the projection of the same visual cue into the windshield throughout the collision avoidance scenario.

- System A: automatic steering was realized via adaptive steering torque overlay. The entire intervention was accompanied by automatic braking with an approximate deceleration of 3 meters per square second.
- System B: automatic steering was realized via adaptive steering torque overlay. The entire intervention was accompanied by automatic braking with an approximate deceleration of 3 meters per square second. Additionally, an auditory cue (high pitch continuous tone) was presented.
- System C: automatic steering was realized in part via adaptive steering torque overlay and in part via unilateral braking. Only the first 0.2s were accompanied by a fixed bilateral automatic braking with an approximate deceleration of 3 meters per square second. Additionally, an audio cue (high pitch continuous tone) was presented.

D. Procedure

Test subjects first filled in a questionnaire on basic demographical information as well as driving experience and habits. They were then instructed to perform a series of basic driving maneuvers (cautious as well as strong acceleration, cautious as well as strong deceleration, steering at low and high speeds, driving through a constricted opening) in order to familiarize themselves with the handling and physical dimensions of the test vehicle. Test subjects were then reminded of the alleged experimental purpose (i.e. assessing at which distance road signs with a certain character height can be deciphered from a car moving at a certain speed) and read out aloud as many words of every sentence on the signs at the left side of the road as possible, while passing by. They were further instructed to keep a constant speed of 50 kilometers per hour and generally act as they would in normal traffic. Test subjects were then confronted with the true positive scenario described in (IV.A). Once the scenario was resolved, subjects were informed of the true purpose of the experiment and asked to fill out questionnaires on the experienced situation. Subjects were then informed of an alleged error in data recording with regard to speed and vehicle position. They were asked to keep a speed of 50 kilometers per hour and drive in the center of their lane while the experimenter would monitor the recorded data for errors. Test subjects were then confronted with the false positive scenario as described in (IV.A) and subsequently asked to fill out another questionnaire on the experienced situation.

E. Subjects

Only data sets of distracted test subjects (those whose gaze was averted to the left for at least the entire time span from the requesting of the dummy obstacle to the requesting of the system intervention) were included in the analysis. These were the data of 56 test subjects between the ages of 19 and 78 years (M=27.8; SD=12.0) with mileage between 1,000 and 100,000 kilometers in the past 12 months (M=27,710; SD=22,774) and an estimated total mileage between 9,000 and 2,000,000 kilometers (M=201,598; SD=304,640). 45 of these test subjects were male, 51 were right-handed.

The experimental groups were matched with regard to mileage in the past 12 months, total mileage, and age. One of the groups (steering recommendation, n=10) was excluded from analysis in the true positive scenario for the purposes of this paper, see (IV.B).

V. RESULTS

A. True positive scenario

An overview over the results for the true positive scenario is given in Table I.

1) Perceived criticality

The observed ratings spanned across the entire range of the scale from 0 to 10. 80% of all test subjects rated the experienced situation as dangerous or uncontrollable (ratings of 7 and higher). The median value was 8. Results did not differ significantly between the experimental groups, H(3, N=46) = 2.28, p = .52.

TABLE I. TRUE POSITIVE SCENARIO RESULTS SUMMARY

Dependent variable (reported value)	***System***				***p-val***
	None	***A***	***B***	***C***	
Perceived criticality (median)	8	8	8	7.5	.52
Primary collision (relative frequency)	0	0	0	0	1.00
Lat. safety distance (relative frequency)	75%	75%	100%	92%	.14
Long. safety distance (mean)	1.22m	3.29m	4.54m	4.54m	.001
Oppos. lane intrusion (relative frequency)	67%	33%	70%	58%	.27
Hypothetical secondary collision (relative frequency)	25%	0%	20%	8%	.26
Deviation from ideal trajectory (mean)	0.23m	0.16m	0.15m	0.15m	.001

2) Primary collisions

No primary collisions were observed in any experimental condition.

3) Lateral safety distance

Lateral safety distance was most frequently established with system B (n=10, 100%), followed by system C (n=12, 92%), and finally system A (n=12, 75%) and the unassisted control group (n=12, 75%). The observed effect was statistically not significant, $\chi^2(3, N=46) = 4.02$, $p = .14$.

4) Longitudinal safety distance

Longitudinal safety distance was longest with systems B (n=10, M=4.54m, SD=1.28m) and C (n=11, M=4.54m, SD=1.22m), followed by system A (n=9, M=3.29m, SD=1.49m), and finally the unassisted control group (n=9, M=2.24, SD=1.28). The effect was statistically significant $F(3,35) = 6.81$, $p = .001$. Bonferroni post-hoc tests revealed a significant difference of longitudinal safety distance between the control group and the system B and system C groups.

5) Opposing lane intrusion

Opposing lane intrusion was most frequent in the system B group (n=10, 70%), followed by the control group (n=12, 67%), then the system C group (n=12, 58%), and finally the system A group (n=12, 33%). The observed effect was statistically not significant, $\chi^2(3, N=46) = 3.88$, $p = .27$. It is to be noted that the opposing lane was empty and thus no harm resulted from entering the opposing lane. It is to be expected that lane intrusion would be less common in a scenario with a compelling reason to stay within the drivers' own lane, for example due to oncoming traffic.

6) Hypothetical secondary collision

Hypothetical secondary collision was most frequent in the control group (n=12, 25%), followed by the system B group (n=10, 20%), then the system C group (n=12, 8%), and finally the system A group (n=12, 0%). The observed effect was statistically not significant, $\chi^2(3, N=46) = 3.97$, $p = .26$. Again it is to be noted that the opposing lane was empty (see (V.A.5)).

7) Deviation from ideal trajectory

Deviation from ideal trajectory was largest in the control group (n=12, M=0.23m, SD=0.05m), followed by the system A group (n=12, M=0.16m, SD=0.05m), and finally the system B (n=12, M=0.15m, SD=0.06m) and system C groups (n=12, M=0.15, SD=0.05). The effect was statistically significant $F(3,42) = 6.20$, $p = .001$. Bonferroni adjusted post-hoc tests revealed a significant difference of deviation from ideal trajectory between the control group and the system A, B, and C groups.

B. False positive scenario

It is to be noted that the entire road, including the opposing lane, was devoid of any obstacles. There was, therefore, no apparent necessity for drivers to avert the steering intervention's effects.

1) Perceived impact on driving task

The observed ratings spanned from 1 to 8. Only 5% of all test subjects rated the impact of the unjustified steering intervention as dangerous or uncontrollable (ratings of 7 and higher). The median value was 3.5. Results did not differ significantly between the experimental groups, $H(3, N=56) = 3.98$, $p = .14$.

2) Lateral offset

Lateral offset was largest for the system A group (n=23, M=0.59m, SD=0.20m), followed by the system B group (n=18, M=0.52m, SD=0.15m), and finally the system C group (n=15, M=0.48m, SD=0.11m). The effect was statistically not significant $F(2,53) = 2.42$, $p = .10$.

3) Lane departure

Lane departure was only observed in the system A group (n=23, 13%), not in the system B or C groups. The observed effect was statistically not significant, $\chi^2(2, N=56) = 4.55$, $p = .10$.

4) Intense braking

Intense braking was observed most frequently in the system B group (n=18, 11%), followed by the system A group (n=23, 9%), and finally the system C group (n=15, 0%). The observed effect was statistically not significant, $\chi^2(2, N=56) = 1.67$, $p = .55$.

VI. DISCUSSION

The results of the study indicate that all three ADAS configurations for automatic emergency steering proved successful. Though unassisted drivers were able to avoid the collision as well, assisted drivers established a lateral safety distance more frequently and earlier (allowing for the hypothesis, that they would be more successful than unassisted drivers at avoiding collisions in scenarios with lower times-to-collision or larger obstacle width), and deviated less from an ideal trajectory.

An interesting finding of the reported study is the behavior of unassisted drivers in the control group. Based upon results of other collision avoidance studies (see [4] for an overview of early research) a higher collision rate was expected (especially because subjects were visually distracted), yet not observed. All test subjects in the control group showed a braking (stepping on the brake pedal) as well as a steering reaction (steering at least 5° to the left, lowest observed maximum was 9.4°) before passing the obstacle. This may be due to a variety of factors in which the chosen driving situation differs from those of many other studies on the same topic. For example low time-to-collision when the obstacle first appears in combination with the obstacle moving laterally to the subject car. There have been indications in previous research (to be published) that steering reactions become more likely, the later and faster obstacles appear from the side, possibly evoking an unreflected rather than a reflected steering reaction. Also, the small required lateral offset could have influenced driver behavior (possibly making more obvious to test subjects the possibility to avoid the collision by steering). The results certainly warrant further research to investigate the exact influence of every parameter of the traffic situation (obstacle movement direction, obstacle movement speed and acceleration/deceleration, required lateral offset, time-to-collision when obstacle appears, and possibly also driving speed and other variables).

A second interesting finding of the reported study is the effect of the auditory cue. Though observed differences lack statistical significance for the small sample size, the resulting trajectories show that more and earlier lateral offset resulted with system B than with system A (which only differ with regard to the auditory cue). This is because drivers put up less resistance against the steering intervention with system B, reducing its effectiveness less, or even apply an additional torque to the left in surplus of the steering intervention, overshooting the desired trajectory respectively. At the same time, lateral offset caused by the steering intervention in the false positive scenario was less with system B than with system A. These results seem to imply that an auditory cue has the precious ability to enhance the human-machine-interaction in a manner that allows both for a higher effectivity of justified as well as better controllability of unjustified steering interventions, which are usually detrimentally influenced by most other factors. Though it can be argued that this effect may be smaller or even nonexistent for visually not distracted drivers, the probability that an automatic steering intervention is required is much higher for visually distracted drivers and the auditory cue should therefore be considered a valuable tool.

A third noteworthy finding lies in the results for system C. Less automatic braking and less steering at the steering wheel have yielded the same benefits as system B, while slightly fewer adverse side effects have been observed, i.e. less frequent overshooting of the desired trajectory far into the opposing lane, and less frequent intense braking in reaction to a false alarm steering intervention. Future research should be aimed at isolating the factors responsible for each effect in order to assess whether automatic braking is more detrimental than beneficial in an emergency steering situation. And it should be assessed whether decoupling of the driver from part of the steering intervention by using other actuators in addition to electronic power steering is able to increase the effect of a justified intervention more than it decreases the controllability of an unjustified intervention, unlike previous attempts of decoupling the driver by the means of steer-by-wire steering systems (see e.g. [9]). More studies, in general, should focus on the human-machine-interaction of combined steering and braking for automatic collision avoidance.

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