Effects of experience and electronic stability control on low friction collision avoidance in a truck driving simulator

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Effects of experience and electronic stability control on low friction collision avoidance in a truck driving simulator

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Abstract

Two experiments were carried out in a moving-base simulator, in which truck drivers of varying experience levels encountered a rear-end collision scenario on a low-friction road surface, with and without an electronic stability control (ESC) system. In the first experiment, the drivers experienced one instance of the rear-end scenario unexpectedly, and then several instances of a version of the scenario adapted for repeated collision avoidance. In the second experiment, the unexpected rear-end scenario concluded a stretch of driving otherwise unrelated to the study presented here. Across both experiments, novice drivers were found to collide more often than experienced drivers in the unexpected scenario. This result was found to be attributable mainly to longer steering reaction times of the novice drivers, possibly caused by lower expectancy for steering avoidance. The paradigm for repeated collision avoidance was able to reproduce the type of steering avoidance situation for which critical losses of control were observed in the unexpected scenario and, here, ESC was found to reliably reduce skidding and control loss. However, it remains unclear to what extent the results regarding ESC benefits in repeated avoidance are generalisable to unexpected situations. The approach of collecting data by appending one unexpected scenario to the end of an otherwise unrelated experiment was found useful, albeit with some caveats.

Keywords: driving experience, electronic stability control, trucks, collisions, driver behaviour, driving simulation

1. Introduction

Starting in 2014, electronic stability control (ESC) systems will be mandatory for all new heavy trucks in Europe (European Commission, 2011). One part of the upcoming ESC requirement is the inclusion of a yaw stability control (YSC) system, counteracting instabilities in the yaw plane, such as skidding on a low-friction road surface. YSC systems are designed to continuously monitor the vehicle's yaw rate, comparing it to a desired rate estimated from current steering wheel angle and speed. If the difference between the two becomes too large due to vehicle understeer or oversteer, the YSC system applies individual wheel brakes in a controlled manner so as to achieve appropriate yaw motion. Another required part of ESC systems is roll stability control (RSC), reducing vehicle speed when high lateral accelerations put the vehicle at a risk of roll-over.

For passenger cars, comparisons of crash statistics between ESC-equipped vehicles and non-ESC equipped vehicles have provided solid evidence that ESC prevents about 40% of control-loss crashes (Høye, 2011). For heavy trucks, however, such studies are not available, partially due to the currently limited deployment of ESC in trucks (Woodrooffe et al., 2009).

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Awaiting a possible impact of increased market penetration rates, other methods have been applied to estimate potential safety benefits of heavy truck ESC. Kharrazi and Thomson (2008) studied a U.S. in-depth database of 1,070 truck crashes and found that 18.7% of these involved loss of yaw or roll control, and could thus be targeted by ESC. Woodrooffe et al. (2009) combined a study of the same database with hardware-in-the-loop simulation and other methods, and were thus able to predict a prevention of around 4,700 out of an ESC-targeted annual U.S. crash population of around 11,000 (just over the 40% prevention ratio reported for passenger cars by Høye, 2011). Furthermore, tests with predetermined manoeuvres, specified in terms of exact control inputs or vehicle paths, have been carried out to provide verification of stability improvements of truck ESC, both in real vehicles driven by test drivers or steering robots (Laine et al., 2008) and in computer simulation (Kharrazi and Thomson, 2008; McNaull et al., 2010).

These previous research efforts provide important insights into the potential benefits of truck ESC, but one important factor, covered implicitly in the passenger car studies reviewed by Høye (2011), has to a large extent been left unaddressed: The actual behaviour of real drivers in the targeted critical situations, with and without ESC. In real traffic, drivers' control behaviour in an ESC-relevant situation can be expected to exhibit considerable between-driver *variability*, some of which will be due to limited *expectancy* for and limited *experience* of urgent manoeuvring. For example, limitations in expectancy and driving experience are both known to be associated with longer reaction times to hazards in a traffic scene (Deery, 1999; Green, 2000), and both factors may also influence the type of manoeuvring adopted by drivers in response to hazards, from highly controlled behaviours to non-reactions or overreactions (Malaterre et al., 1988; Hollnagel and Woods, 2005). Tests involving steering robots or skilled test drivers seem to hold limited validity in emulating these phenomena. In theory, driver models applied in computer simulation could be more successful in this respect, but so far available models generally lack proper validation (Markkula et al., in press).

A possible means of bridging this gap is the use of driving simulator studies. Although not free from validity concerns (e.g. in terms of fidelity of driver and vehicle behaviour to their real-traffic counterparts), simulator studies allow observation of ordinary drivers reacting to (reasonably) unexpected simulated critical situations. Papelis, Watson, Mazzae, and colleagues (Papelis et al., 2004; Mazzae et al., 2005; Watson et al., 2006; Papelis et al., 2010) conducted a series of large simulator studies on passenger car driving in unexpected scenarios designed to create vehicle instability, and consistently found that ESC reduced crash risk significantly. Dela et al. (2009) carried out a small pilot study of simulator-based testing of truck ESC, but found no effects of ESC. They argued that this could be due to their limited sample size.

In this paper, a simulator study will be presented that builds upon the study of Dela et al. (2009). The study presented here was focused on YSC specifically, in collision avoidance on a low-friction surface. This type of situation was adopted due to its presence in accident statistics (Kharrazi and Thomson, 2008, attribute 11% of truck control loss crashes to avoidance manoeuvres), in combination with the ample room it leaves for behavioural variability, implying that it could leverage well the specific advantages of simulator-based testing. Furthermore, due to the suspected impact of experience on avoidance behaviour, both novice and experienced drivers were included.

The overall aims were to study the effect of experience on when and how drivers responded to the situation, as well as the combined effects of experience and YSC on subjective and objective measures of situation outcome. Specifically, with regards to the YSC system, it was hypothesised that drivers would experience less severe skidding, and lower frequencies of full control loss, when the system was present. Furthermore, it was an aim of the study to clarify whether YSC would be equally helpful for drivers of both experience groups. In theory, if a driver's control strategies for critical manoeuvring, supposedly shaped by experience, differ from the YSC system's model of driver intentions, situations could arise where system and driver are pursuing slightly different goals. In order to investigate whether any detrimental mismatches of that kind could occur for either of the experience groups, interaction effects were hypothesised between experience and YSC presence, for measures of control effort and for situation outcome. With regards to other possible effects of driving experience on collision avoidance behaviour in this type of scenario, little was known beforehand, and therefore a more exploratory analysis approach was adopted.

Furthermore, two methodological devices were incorporated in the study, both aiming at more cost-

Table 1: *Parameters for the three versions of the critical lead vehicle braking scenario.*

Parameter	Unexpected	Repeated	Catch trial
R_x	1.15	1.15	1.15
T_{cut}	0.9 s	0.9 s	0.9 s
v_{cut}	5.4 km/h	5.4 km/h	5.4 km/h
T_b	1.5 s	1.5 s	1.5 s
d_b	0.35g	0.45g	0.45g
μ_1	0.7	0.7	0.7
μ_2	0.25	0.25	0.25
v_3	-	-	45 km/h
a_{acc}	-	-	0.3g

efficient collection of a larger data set for statistical analysis: (a) an *instruction-based* paradigm[1] for repeated collision avoidance, and (b) appending an unexpected critical scenario to the end of another simulator experiment. With regards to (a), it was hypothesised that the use of instructions would allow repeated reproduction of the type of steering avoidance situations that occur naturally in an unexpected scenario. With regards to both (a) and (b), exploratory analyses were carried out to clarify any impact these methodologies had on participant behaviour and situation outcome (effects of repetition, and of differing experiences prior to an unexpected situation, respectively).

The remainder of the text will be organized as follows: First, the adopted methods will be described, in terms of the conducted simulator experiments and the subsequent statistical analysis of obtained data. Then, results will be presented, followed by a discussion. Finally, some general conclusions will be provided.

2. Method

2.1. Simulator experiments

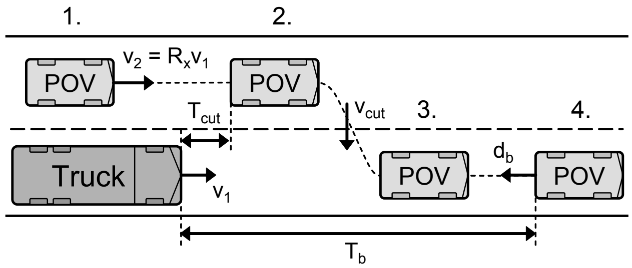
2.1.1. Simulated avoidance scenario

The simulated collision avoidance scenario was an adaptation of a scenario originally proposed by Engström et al. (2010); see Figure 1 for an illustration. The adapted scenario took place on a divided highway with 80 km/h speed limit, with two lanes in the truck's direction of travel. A passenger car, here referred to as the *principal other vehicle* (POV), overtook the truck at longitudinal speed $v_2 = R_x v_1$ proportional to the truck's current longitudinal speed v_1. Then, at a time headway of T_{cut} with respect to the truck, the POV changed into the truck's lane, at lateral speed v_{cut}, and continued ahead at longitudinal speed v_2. Then, for no apparent reason, at time headway T_b, the POV applied braking with a longitudinal deceleration d_b. Prior to this deceleration, the POV's longitudinal speed was set, from one simulation time step to the next, to the truck's speed v_1. This was done to ensure that as soon as POV brake lights were turned on, time headway would start decreasing below T_b. Before the start of the scenario, road friction was at a value μ_1, corresponding to dry asphalt. During the scenario, a lower value μ_2 was set, to emulate a wet or icy road surface. The visual representation of the road scene did not change, however, so the drivers had no indication that friction had been reduced.

As indicated in Table 1, this scenario was parameterised in three different versions, an *unexpected avoidance* version, a *repeated avoidance* version, and a *catch trial* version. In the first two versions, braking alone was not enough to avoid collision with the POV (i.e. steering was needed). In the catch trial version, however, POV deceleration ended at longitudinal speed v_3, and was followed by a longitudinal acceleration a_{acc}, such that the truck driver could avoid a collision by braking only.

The aim of the unexpected avoidance version of the scenario was to elicit *ESC-relevant manoeuvring* from unexpecting drivers, for as many as possible of the participants. ESC-relevant manoeuvring is here defined

[1] Here, an instruction-based paradigm is one in which drivers are given some prior instructions on how to behave in response to the simulated scenarios.



(a)

(b)

Figure 1: *(a) Schematic illustration of the simulated avoidance scenario. After Engström et al. (2010). (b) A still from the recorded video data, showing the winter environment in which the simulated avoidance scenario took place, and a driver engaged in steering avoidance.*

as manoeuvring that triggers an ESC yaw control intervention, or would have triggered such an intervention, had the ESC system been active[2]. For this to occur in practice in the avoidance scenario studied here, a steering avoidance manoeuvre of some severity is typically needed (as opposed to e.g. braking only, or a moderate steering manoeuvre). A pilot study was carried out: In a fixed-base driving simulator, twenty-five professional truck drivers experienced, at the end of another simulator experiment, one of six scenario parameter combinations varying T_b and d_b. The parameter combination for which the highest frequency of severe steering avoidance was observed is the one adopted here.

The aim of the repeated avoidance and catch trial versions (used together as described in the next Subsection) was to recreate in repeated avoidance roughly the same lateral avoidance situation as in unexpected avoidance, in terms of vehicle speeds, headway, and time to collision at the time of steering initiation. To this end, values for d_b and v_3 were chosen based on results of simulations with a simple driver–vehicle model, assuming reaction times to unexpected stimuli as observed in the pilot study, and to expected stimuli as suggested by Green (2000).

[2]Specifically, a manoeuvre is considered ESC-relevant if the difference between the actual yaw rate of the truck and the driver's desired yaw rate (calculated based on vehicle speed and steering wheel angle) exceeds a certain threshold value at any point during the manoeuvre. This is a simplified version of the triggering criterion of the actual ESC system used in this study, but in preliminary tests it was found that this method predicted reliably whether or not a given manoeuvre would trigger an ESC yaw control intervention.

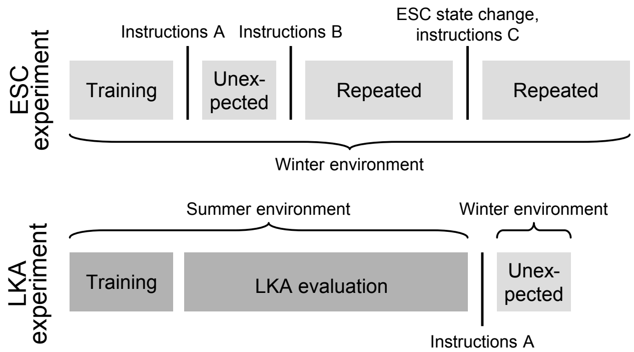


Figure 2: *An overview of the experimental procedure used in this study. Further details are provided in the text.*

2.1.2. Experimental procedure

An overview of the experimental procedure is provided in Figure 2. Data were collected from two simulator experiments, here referred to as the *ESC experiment* and the *lane keeping assistance (LKA) experiment*. Both experiments started with standard procedures for obtaining subject consent. However, nothing was said to the subjects regarding ESC or critical situations, in order to limit expectancy of such situations as much as possible.

The ESC experiment started with a ten-minute training drive, on the same two-lane highway as in the avoidance scenario described above. Inspired by Jamson and Smith (2003) and McGehee et al. (2004), the training drive included both steady state driving, with surrounding (overtaking) traffic, as well as five decelerations to full stop from 80 km/h, and six lane changes.

Unexpected avoidance: Next, subjects were instructed that their first task was now to drive normally at 80 km/h until instructed otherwise, and that this part of the experiment would last less than ten minutes ("instructions A"in Figure 2). After about four minutes of driving, including four overtaking vehicles and one lane change induced by a roadwork site, the unexpected avoidance scenario occurred. At this point, half of the subjects had the ESC system present, and half did not. This division was also balanced across experience groups (see section 2.1.4). However, all subjects had an anti-lock braking system (ABS). After the scenario, the subjects were asked to assess the severity of the resulting situation.

Repeated avoidance: Next, some information and instructions were provided ("instructions B" in Figure 2). Subjects were informed of the presence of ABS and the presence or absence of ESC (explained as an "anti-skid system")[3]. They were also informed that in the following, overtaking cars would sometimes brake in front of them, and that in a majority of cases braking alone would be sufficient to avoid collision (the catch trial scenario), but that sometimes it would not (the repeated avoidance scenario). In the latter cases, drivers were instructed to apply evasive steering. In a first block, subjects experienced a randomised sequence of 18 events: four overtaking vehicles, eight instances of the catch trial scenario, and six instances of the repeated avoidance scenario. Each repeated avoidance scenario was followed by the subjects assessing situation severity. After completion of this block, the ESC state was changed from off to on or vice versa. Subjects were informed of this change ("instructions C" in Figure 2), and finally experienced another block, identical to the first one except for the randomized order of scenarios.

The main purpose of the LKA experiment (described in more detail by Johansson et al., 2012) was to study a lane keeping assistance function, providing warnings or steering torque control interventions in the case of lane excursions without prior turn indication. Here, the training drive and the main experiment (together about 30 minutes total driving time) took place on a rural road in a summer setting. During the experiment, drivers carried out a visual-manual secondary task, and vehicle dynamics was manipulated so

[3]The argument behind informing on the presence or absence of the ESC system was that not doing so could introduce additional variance in subject behaviour, if some drivers were able to notice system presence and some were not.

Table 2: *Summary data on the subjects included in the experiments of this study.* License *refers to license for heavy truck with trailer. Kilometers driven refers to driving with heavy truck.*

Experi-ment	Experi-ence	N	Gender		Age			Years w. license			10^3 km driven/year		
			M	F	Av.	S.D.	Range	Av.	S.D.	Range	Av.	S.D.	Range
ESC	Low	12	9	3	22	6	18-35	0.6	1.0	0-3	20	35	0-100
	High	12	12	0	46	9	32-60	22	10	6-40	60	46	4-150
LKA	Low	8	7	1	21	7	18-37	0	0	0	14	39	0-110
	High	16	16	0	45	10	28-61	20	13	4-43	96	32	45-160

as to generate lane excursions, thus allowing drivers to experience and subjectively assess the LKA system. At the end of the experiment, the simulated truck was moved to the winter driving environment used in the ESC experiment, drivers were provided with the same initial instructions as the ESC experiment drivers, and then experienced an identical unexpected avoidance block.

2.1.3. Driving simulator

The *VTI Driving Simulator II* in Linköping, Sweden, was used for both the ESC and LKA experiments. It consists of a truck cabin and a visual system mounted on a motion platform. The visual system provides a 105° forward field of view, and rear view mirrors are emulated using LCD displays. The motion platform provides linear motion of ± 3.5 m (in this study used to emulate lateral movement of the simulated truck), as well as pitch and roll motion.

Vehicle dynamics were emulated using a Volvo in-house model of a six-wheeled rigid truck with a wheel base of 6.2 m, from first to last axle. The brake control system, including ABS and ESC, was emulated by an exact software-in-the-loop integration of the software used in actual Volvo trucks. The resulting simulated vehicle dynamics during low-friction manoeuvring were subjectively judged as acceptable by experienced test drivers, and inspection of data recorded from the simulator indicated a qualitative match between the simulated truck's behaviour and that of its real life counterpart in similar manoeuvres (Markkula et al., 2011). Limited quantitative validation was obtained by verifying that the simulated vehicle's yaw rate response to a step steering input on a high-friction road surface reproduced closely that of the real truck. Furthermore, the sound of air release from the pneumatic brake chambers was emulated, to provide auditory feedback on ongoing ABS and ESC interventions.

To ensure safety of subjects, the simulation was aborted whenever the there was a risk of the motion platform reaching the physical endpoints of lateral motion. In practice, this meant that full road departures could not be observed; see further Section 2.2.2.

2.1.4. Subjects

Table 2 provides summary data on the subjects involved in this study, separately for the two experiments and the two experience groups. Low-experience drivers were recruited mainly from a local driving school. They had a license to drive a heavy truck, and had just recently or was just about to obtain a license to drive a heavy truck with a trailer. High-experience drivers were recruited from local hauler companies.

The ESC experiment involved 24 subjects, divided equally into the two experience groups. The LKA experiment also had 24 subjects, originally divided into three experience groups *low*, *medium* and *high*, where the two latter groups taken together corresponded to the *high* group of the ESC study. For the purposes of this study, the *medium* and *high* groups of the LKA study were thus merged into one group, denoted *high*.

2.2. Experimental design

2.2.1. Independent variables

The independent variables considered in this study were: (a) *Driving experience*, with conditions *low* and *high*, defined as in Table 2. (b) *ESC state*, with conditions *on* and *off*. (c) *Test setting*, with conditions *unexpected*, *repeated* (both referring to the ESC experiment) and *unexpected after LKA* (referring to the LKA experiment). (d) *Repetition*, with conditions *1* through *12*, or *1* through *6*, when analysing repetitions with ESC state on and off separately.

2.2.2. Dependent variables

As mentioned above, after each avoidance event, both in the unexpected and repeated test settings, subjects were asked to rate the resulting severity of the event, on a scale from one to ten (from *"there was no danger at all"* to *"there was a serious accident"*). The severity of the situation in terms of vehicle stability was also quantified objectively, using the measure *maximum body slip angle* (defined as the maximum deviation between the direction of the truck's front and the truck's direction of motion, see Figure 5 for an illustration), as well as the binary measures *ESC-relevant manoeuvring occurred* (see Section 2.1.1 for a definition) and *full control loss occurred*.

Full control loss was defined as occurring whenever either or both of the following occurred: (1) loss of directional control, or (2) road departure beyond either road shoulder. For determining loss of directional control, the algorithm proposed by Papelis (2006) was adopted. This algorithm reports loss of directional control whenever the maximum body slip angle exceeds 45 degrees, the terminal yaw angle compared to the road at simulator safety system intervention (see Section 2.1.3) exceeds 45 degrees, or the terminal yaw rate exceeds 20 degrees per second[4]. This algorithm was tuned for passenger cars, but its judgments correlated very well with our subjective judgments of loss of directional control also for this data set. As previously mentioned, road departure could not be observed directly, since the simulators safety system aborted simulation before full road departure occurred. For four instances of repeated on-road avoidance, the safety system intervened without directional control loss being reported by the algorithm of Papelis (2006). Based on inspection of video logs and terminal lateral position, yaw angle and yaw rate data, it was subjectively judged that road departure beyond a road shoulder would have occurred in three out of these four instances, had the simulation not been aborted. The fourth case was less certain, and was therefore not classified as a full control loss.

To capture the steering effort applied in vehicle stabilisation, the measure *steering wheel reversal rate* was calculated, using the implementation proposed by Markkula and Engström (2006), with *gap sizes* 5° and 20°. This measure took into account steering data recorded from the point of reaching the POV (defined as the truck's front longitudinally reaching the rear of the POV, with or without collision), to whichever occurred first of: (a) the truck travelling 100 m after reaching the POV, (b) the truck's speed falling below five km/h, or (c) full control loss.

In addition to the above-mentioned dependent measures, motivated by the specific hypotheses defined in Section 1, additional objective measures were defined to allow a more detailed, exploratory study of the braking and steering control applied by the drivers in response to the collision situation.

Brake reaction time was calculated as the time from POV brake light onset to the first instant with a non-zero depression of the truck's brake pedal (signal confirmed to be noise-free, in this respect). Similarly, *steering reaction time* was calculated as the time from POV brake light onset to the moment of *steering initiation*, defined as the first instant with an absolute steering wheel angle exceeding 15°. Drivers who did not reach this threshold value were classified as non-steering[5]. Furthermore, to obtain a quantitative description of the situation at first steering, the measures *longitudinal speed at steering initiation* and *time to collision (TTC) at steering initiation* were calculated. Throughout this paper, TTC is defined as headway distance divided by relative speed (i.e. accelerations are disregarded). Evasive braking behaviour before reaching the POV was quantified using the measures *maximum brake pedal position* and *maximum brake pedal speed*, and to quantify the initial leftward evasive steering (all steering drivers evaded to the left), the measures *maximum leftward steering wheel angle* and *maximum leftward rate of steering* were calculated, also using only data from before reaching the POV. The severity of the collision situation was quantified using the measure *minimum TTC* (defined as TTC at the instant just before the truck steered clear of the POV, laterally), as well as the binary measure *collision occurred*.

[4] Papelis (2006) also included criteria based on excessive yaw angles at reaching zero speed, and detection of the vehicle traveling backwards, but such outcomes did not occur in this study.

[5] The 15° threshold was adopted based on the observation that the smallest maximum steering wheel angle applied by any driver who was able to avoid collision with the POV was 17°. More elaborate algorithms for identifying the time of steering initiation were also tested, but yielded similar results as those reported further below for the 15° threshold approach, therefore preferred here for its simplicity.

2.3. Statistical analysis

For all dependent variables except the binary variables, general linear model (GLM) analysis of variance (ANOVA) was used to test for effects of the independent variables. For the dependent measures which were meaningful only in cases where the subjects applied evasive steering (steering reaction time, and the measures quantifying the situation at steering initiation), non-steering events were treated as missing values, with listwise deletion. The data from the two unexpected avoidance settings were analysed using between-subjects ANOVA, with a full factorial model *test setting* (only including levels *unexpected* and *unexpected after LKA*) × *experience* × *ESC state*. The repeated avoidance data were analysed using mixed design ANOVA, with a full factorial model *experience* × *ESC state* × *repetition*. To compare the unexpected and repeated test settings, per-driver averages of the repeated avoidance data were taken, and mixed design ANOVA *experience* × *test setting* (only including levels *unexpected* and *repeated*) was carried out[6].

To analyse binary dependent variables (such as *collision occurred*, or *full control loss occurred*), two types of tests were used: For the unexpected avoidance data, χ^2 tests (replaced with Fisher's exact test when expected frequency in any cell was below 5) were carried out for each independent variable separately. For the repeated avoidance data, binary variables were transformed to continuous variables by taking averages, per driver and ESC state, yielding measures such as *control loss frequency*. Mixed design ANOVA *experience* × *ESC state* was then carried out on these measures.

When there were indications that ANOVA assumptions were not met (Shapiro-Wilks test of normality, Levene's test of variance homogeneity, and Mauchly's test of sphericity), the ANOVAs were replaced by non-parametric tests (the Mann-Whitney test for between-subject factors, Friedman's ANOVA for the twelve-level *repetition* factor, and the Wilcoxon signed-rank test for the other, two-level, within-subject factors). In general, non-parametric testing was applied to the same data sets as would have been used for the ANOVAs. However, in one specific case (the analysis of the effect of ESC state on max body slip in the repeated avoidance data), averaging per driver and ESC state, such as outlined above for binary variables, was applied in order to be able to apply the Wilcoxon signed-rank test.

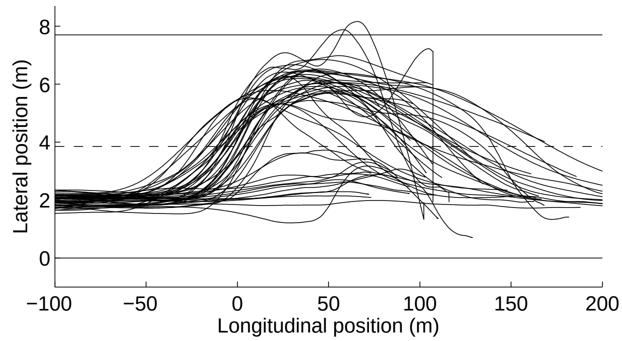
It should be noted that the statistical modelling and testing described above served the dual purpose of analysis outlined in Section 1: (a) testing a number of specific hypotheses, and (b) exploring other effects of the independent variables on driver behaviour and situation outcome. Due to the large number of statistical tests carried out, there is a clear risk of committing Type I errors if one interprets results solely in terms of statistical significances (here, $p < 0.05$ or lower). In response to this concern, the significance testing was complemented with calculation of effect sizes, in terms of Pearson's correlation coefficient r (as recommended by Field, 2009, here possible to apply for all of the independent variables except repetition, since it had more than two levels), and special care will also be taken when discussing the results in Section 4.

3. Results

Overall, 48 instances of unexpected collision avoidance were recorded, and $24 \times 2 \times 6 - 1 = 287$ instances of repeated avoidance (in one case, the repeated avoidance scenario was terminated prematurely, due to an unintended effect of the scenario programming). Figure 3 shows the obtained vehicle trajectories.

In what follows, notation with regards to statistical testing is to be interpreted as follows: F-values refer to GLM ANOVAs, U-values refer to Mann-Whitney tests, T-values to Wilcoxon signed-rank tests, and χ^2-values refer to χ^2 tests if not otherwise indicated (in some cases, they refer to Friedman ANOVAs). In all figures showing bar charts, error bars show 95% confidence intervals, calculated under the assumption of a normal sampling distribution.

[6]The averaging approach reduces the power of the statistical testing, but was preferred over adoption of more elaborate statistical methods, which would be required in order to handle the major difference in sample size between unexpected and repeated test settings in the original data set.



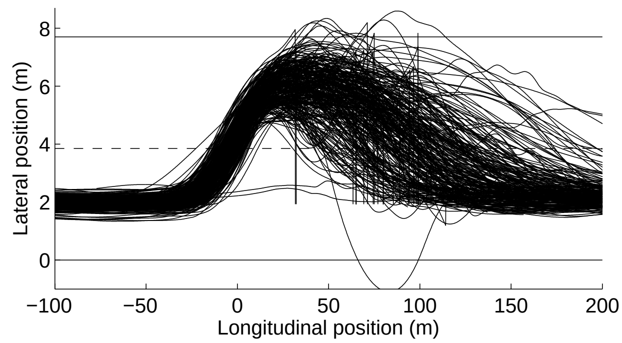


Figure 3: *Recorded vehicle trajectories for unexpected (top panel) and repeated (bottom panel) collision avoidance. Horizontal lines indicate lane boundaries. Longitudinal position zero corresponds to the point where the truck front reached the rear of the lead vehicle.*

3.1. Unexpected collision avoidance

The unexpected scenario gave a varied range of behavioural responses and situation outcomes. 11 drivers out of the 48 (23%) did not apply evasive steering (i.e. had maximum steering wheel deflections below 15°; see Section 2.2.2). In all these cases, the drivers collided with the POV. The timing, magnitude, and outcome of the evasive steering behaviour applied by the remaining 37 drivers is illustrated in Figure 4. In total, collision occurred for 25 of the 48 drivers (52%). ESC-relevant manoeuvring was observed for nine of the drivers (19%) and, out of these, three experienced full control loss (one with ESC inactive, two with ESC active). A more detailed view of control behaviour and the resulting vehicle trajectories is provided in Figure 5, for three drivers: One who did not steer, one who successfully avoided the near-collision situation, and one who experienced full control loss.

Figure 6 illustrates the main results regarding driving experience in the unexpected scenario, separated into the data collected from the ESC and LKA experiments: Experienced drivers had significantly shorter brake reaction times ($U = 163.0$, $z = -1.99$, $p < 0.05$, $r = 0.29$; Figure 6a), and applied significantly less braking, in terms of maximum brake pedal position ($F(1, 40) = 5.82$, $p < 0.025$, $r = 0.36$; not shown in figure; averages were 80% and 59% of maximum brake pedal position, for low and high experience drivers, respectively). Regarding whether or not evasive steering was applied, there was no statistically significant effect of experience (Fisher's exact test, $p > 0.05$, $r = 0.14$; Figure 6b), but among the drivers who did attempt steering, the reaction times to steering were significantly shorter for experienced drivers ($F(1, 29) = 10.10$, $p < 0.01$, $r = 0.51$; Figure 6c; the lower number of degrees of freedom in this specific test is due to the exclusion of non-steering drivers, see Section 2.3). Furthermore, the overall frequency of collisions was significantly lower among experienced drivers than among inexperienced drivers ($\chi^2(1) = 10.71$, $p < 0.01$, $r = 0.47$; Figure 6d).

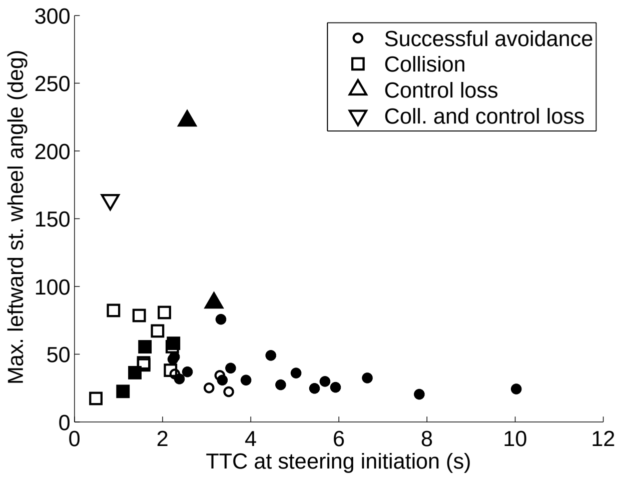


Figure 4: *Outcome of the unexpected scenario, for drivers who attempted steering, as a function of when and how steering was applied. (For all drivers who did not attempt steering, the outcome was a collision.) Filled and empty symbols denote drivers from the high and low experience groups, respectively.*

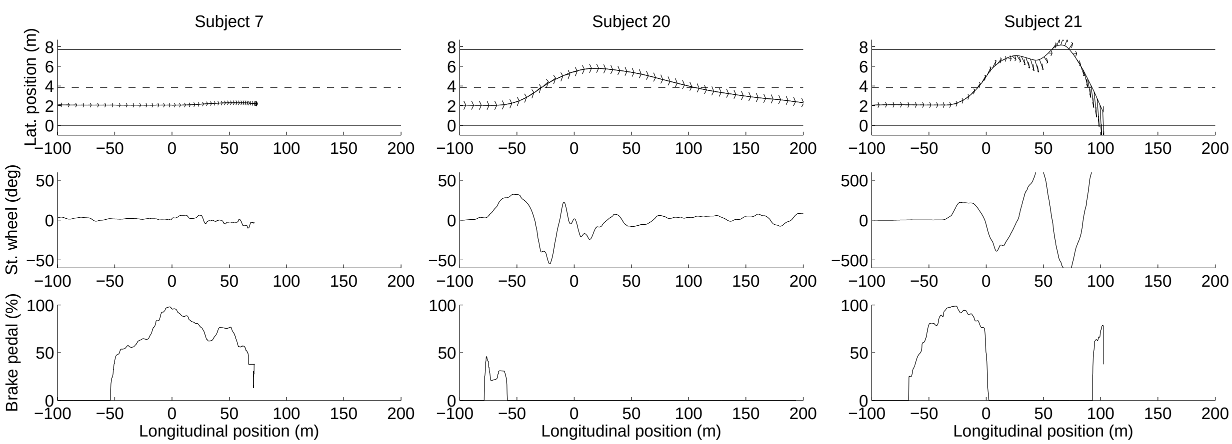


Figure 5: *Recorded vehicle trajectories (top panels), steering input (middle panels, note the variations in scale), and brake input (bottom panels), for three selected drivers in the unexpected avoidance scenario. In the top panels, horizontal lines indicate lane boundaries, and the arrows along the trajectories show momentary direction of the truck's front (i.e. indicate skidding, or* body slip, *when pointing away from the trajectory). Subject 7 collided with the lead vehicle at longitudinal position zero (corresponding, for all drivers, to the point where the front of the truck reached the rear of the lead vehicle), subject 20 managed a successful collision avoidance, and subject 21 reached full control loss (see the text for definition) at about 100 m longitudinal position.*

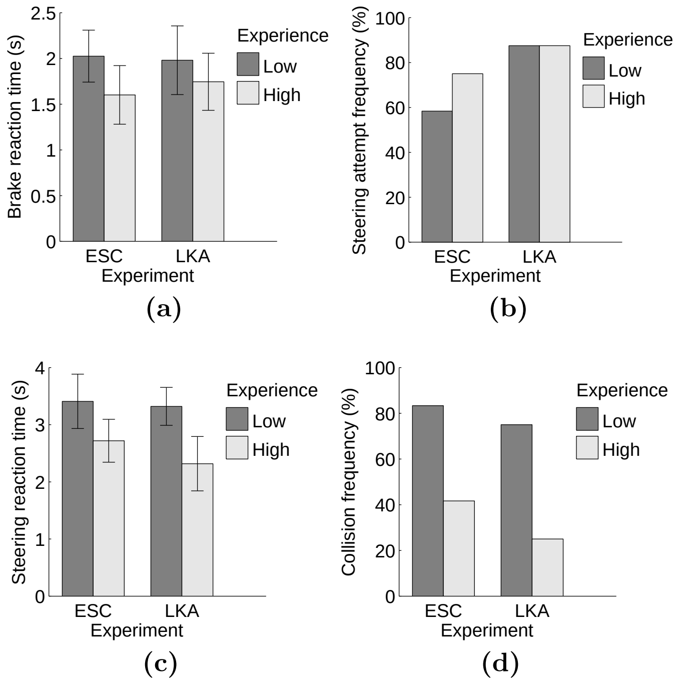


Figure 6: *Effects of driving experience on avoidance reactions and collisions in the unexpected avoidance scenario, observed in the two experiments involved in this study.*

None of the differences between the ESC and LKA experiments shown in Figure 6 were statistically significant, providing some motivation for analysing the two data sets together with respect to the dependent variables shown in the figure; this issue will be discussed further in Subsection 4.3.1. However, there were also some statistically significant effects, illustrated in Figure 7: The LKA experiment drivers used significantly lower brake pedal speeds ($F(1, 40) = 31.92$, $p < 0.001$, $r = 0.67$; Figure 7a), had significantly higher minimum TTCs ($U = 192.0$, $z = -1.98$, $p < 0.05$, $r = 0.29$; Figure 7b), and rated the severity of the situation significantly lower than the ESC experiment drivers ($U = 140.5$, $z = -3.10$, $p < 0.01$, $r = 0.48$; Figure 7c).

In the unexpected scenario, no statistically significant effects of the state of the ESC system were observed on any of the dependent measures. However, for steering wheel reversal rate, there was a significant interaction between ESC state and driving experience: For inexperienced drivers, average reversal rates were lower with the ESC system active than without, whereas for experienced drivers the opposite was observed, both for 20° gap size ($F(1, 40) = 4.32$, $p < 0.05$; shown in Figure 7d) and 5° gap size.

3.2. Repeated collision avoidance

Steering avoidance attempts were observed in 285 out of the 287 instances of repeated avoidance (99%), and ESC-relevant manoeuvring (as defined in Subsection 2.1.1) occurred in 217 of 287 instances (76%). Here, some significant effects of the ESC system could be observed, see Figure 8. With ESC active, the maximum body slip angle was reduced ($T = 57$, $p < 0.01$, $r = 0.38$; analysis included averaging over repetitions, as described in Section 2.3; Figure 8a), and so was the per-driver frequency of full control loss ($T = 0$, $p < 0.001$, $r = 0.45$; Figure 8b). These analyses were carried out non-parametrically, due to violations of ANOVA assumptions, and therefore the hypothesised interactions for these measures, between ESC state and driver experience (see Section 1) could not be tested directly. Instead, additional non-parametric testing was carried out for the two experience groups separately. In this analysis, the effect of ESC on maximum

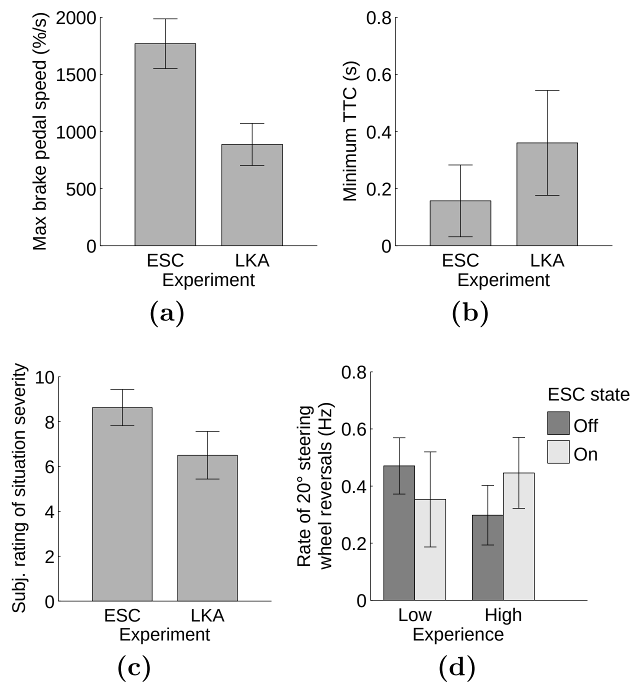


Figure 7: *(a)–(c): Effects of experiment on behaviour and outcome in the unexpected collision avoidance scenario. (d) An interaction effect, of driving experience and ESC state, on large steering wheel reversals in the stabilisation phase of unexpected collision avoidance.*

body slip angle was found significant for inexperienced ($T = 11$, $p < 0.05$, $r = 0.45$) but not for experienced drivers ($T = 18$, $p > 0.05$, $r = 0.34$), whereas the effect on control loss frequency was significant for both experience groups ($T = 0$, $p < 0.05$, in both cases; $r = 0.45$ and $r = 0.46$ for low and high experience, respectively). There were no significant interactions of ESC state and driving experience for any of the other dependent measures, e.g. the interaction effect for steering wheel reversal rate observed for the unexpected scenario was not observed for the repeated scenario.

Figure 9 illustrates the main findings regarding similarities and differences between unexpected and repeated avoidance behaviour. In terms of braking, there were clear differences. The average brake reaction time was significantly lower in the repeated setting than in the unexpected setting ($F(1, 22) = 98.79$, $p < 0.001$, $r = 0.90$; Figure 9a), and the maximum brake pedal position was significantly higher in the repeated setting ($T = 36$, $p < 0.01$, $r = 0.47$; shown in Figure 9b). However, the near-collision situation facing drivers at the moment of steering initiation was not significantly different between unexpected and repeated settings, in terms of longitudinal speed ($F(1, 14) = 1.54$, $p > 0.05$, $r = 0.31$; Figure 9c) or TTC ($F(1, 14) = 0.52$, $p > 0.05$, $r = 0.19$; Figure 9d)).

In the repeated avoidance data, there were some effects of repetition itself. The maximum brake pedal position gradually increased over repetitions (Friedman ANOVA $\chi^2(11) = 32.61$, $p < 0.01$; Figure 10a). Likewise, the significant effects of repetition on brake reaction time (Friedman ANOVA $\chi^2(11) = 55.77$, $p < 0.001$; Figure 10b) and subjectively perceived situation severity (Friedman ANOVA $\chi^2(11) = 55.77$, $p < 0.001$; Figure 10c) could possibly be interpreted as gradual trends, but the significant effect of repetition on the 20° steering wheel reversal rate (Friedman ANOVA $\chi^2(11) = 24.47$, $p < 0.025$; Figure 10d) was less clearly gradual in nature. There were no significant effects of repetition on the objective measures quantifying situation outcome severity.

4. Discussion

The main results of this study are (a) the effects of driving experience in the unexpected scenario, and (b) the effects of ESC state, especially in the repeated scenario. Below, these two matters are discussed separately. Furthermore, a brief discussion regarding methodological aspects is given. For the reasons outlined in Subsection 2.3, the discussion will not rely solely on levels of statistical significance, and especially so for the more exploratory statistical analyses.

4.1. Impact of driving experience on unexpected avoidance

As illustrated in Figure 6d, in the unexpected critical scenario of this study, the inexperienced drivers were significantly less successful than the experienced drivers at avoiding collision with the POV. Below, possible explanations for this finding are discussed.

4.1.1. Differences in reaction times

First of all, the inexperienced drivers had significantly longer brake reaction times (Figure 6a). This medium sized effect ($r = 0.29$; the denominations of effect sizes proposed by Cohen, 1988, are adopted here) aligns well with previous empirical results. Novice drivers have repeatedly been found to be slower than more experienced drivers at detecting and responding to hazards in a traffic scene, and it has been proposed that this may, for example, be due to a poorer ability of context-sensitive anticipation of possible hazards, and less efficient visual scanning strategies (see e.g. Deery, 1999; Scialfa et al., 2011).

However, in the unexpected critical scenario of this study, braking alone was not sufficient to avoid a collision, regardless of brake reaction time. Successful crash avoidance thus depended crucially on the use of evasive steering. Despite the fact that there was ample margin for safe steering avoidance (e.g. as illustrated by subject 20 in Figure 5), 52% of drivers failed to apply steering successfully. Also these results are in line with previous observations, from both accident studies and controlled experiments (Adams, 1994; Lechner and van Elslande, 1997), and it has been suggested that this type of reluctance or inability to apply required evasive steering may be due to drivers' limited experience of severe lateral manoeuvring, or to perceived added risks of rapidly leaving one's own lane.

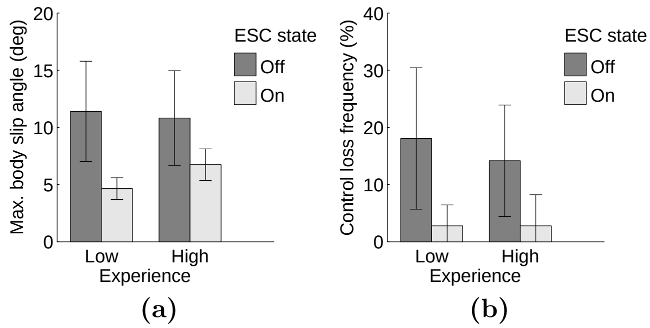


Figure 8: *Effects of ESC state on skidding and control loss in the repeated avoidance scenario. It may be noted that the control loss frequency data was significantly non-normal, which is evident here from the confidence intervals of Panel (b) extending below zero. As mentioned in the text, confidence interval calculations assumed normality, but the statistical analyses did not.*

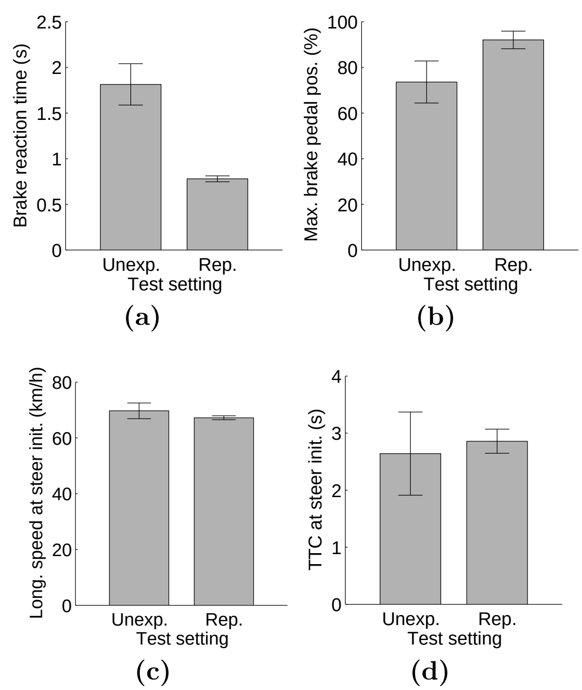


Figure 9: *Comparison of unexpected and repeated avoidance. Note that the averaging approach described in Subsection 2.3 reduces the contribution of intra-driver variance to the total variability in the repeated avoidance setting, something that affects the confidence intervals shown here.*

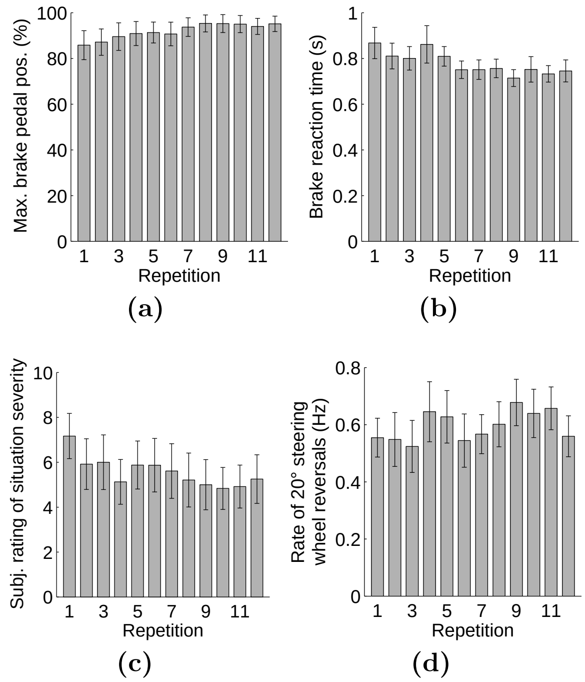


Figure 10: *Effects of repetition on braking behaviour and skidding in the repeated avoidance scenario.*

Overall, Figure 4 suggests that the main reason for failed steering avoidance in this study was that initiation of steering occurred *too late*. In a rear-end collision situation, there will typically be a point in time after which steering avoidance is no longer possible, for the given vehicle on the given road surface. Here, Figure 4 shows clear indications of such a limit being present at a TTC of around two seconds: All drivers initiating steering at a TTC below this limit collided with the POV, regardless of the amount of steering applied, and all drivers initiating steering earlier were able to avoid collision.

Thus, if a late steering initiation is the main cause of collisions in the unexpected scenario, the large effect ($r = 0.51$) of experience on steering reaction time, with later steering responses for inexperienced drivers (Figure 6c), may be considered a satisfactory explanation for the more frequent collisions suffered by these drivers.

4.1.2. Alternative explanations

Two alternative explanations could be that (a) in a given situation, inexperienced drivers apply smaller steering magnitudes than experienced drivers, such that steering is more often insufficient to avoid the collision, or (b) experienced drivers are more prone than inexperienced drivers to attempt a steering manoeuvre at all. However, none of these explanations seem to be clearly supported by the recorded data.

With regards to (a), there were no significant effects of experience on maximum steering magnitudes or rates; in the unexpected scenario the average maximum steering magnitudes were actually slightly higher for inexperienced drivers than for experienced drivers. Furthermore, any between-driver differences regarding whether or not sufficient steering was applied should have been visible in Figure 4, as regions of TTC at steering initiation within which some drivers avoided collision, whereas other drivers applied less steering and did not avoid collision. In other words, there should not have been such a sharp limit of TTC beyond which all drivers collided.

With regards to (b), the frequency of attempted steering was indeed lower for inexperienced than for experienced drivers (70% versus 82%; Figure 6b), but this small effect ($r = 0.14$) was not statistically

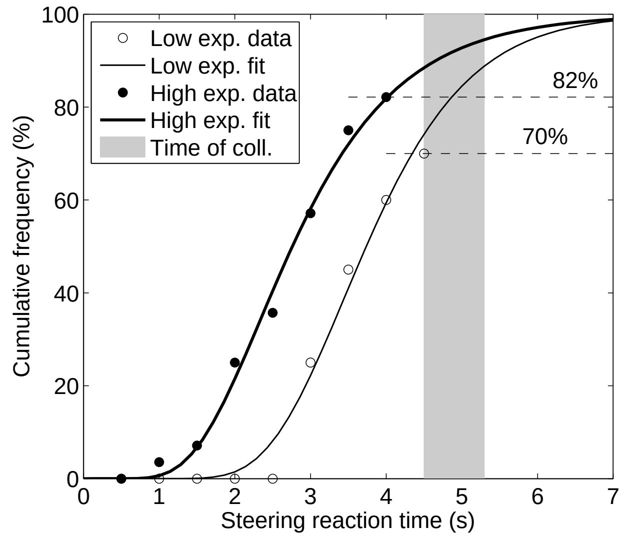


Figure 11: *Least-squares fit of log-normal cumulative distribution functions to cumulative steering reaction time data for the drivers who attempted steering in the unexpected scenario (70% and 82% of low and high experience drivers, respectively). The shaded region shows the range of time after lead vehicle brake initiation within which all observed collisions occurred.*

significant. In any case, further analysis suggests that this alternative explanation can to some extent be reconciled with the proposed explanation in terms of reaction times: Figure 11 suggests that both the obtained steering reaction time data *and* the observed frequencies of non-steering can be interpreted as due to the same log-normal distributions of steering reaction time (one for each experience group), cut off at the point where collision occurred. According to this interpretation, the non-steering drivers should not be understood as drivers who would *never* apply steering avoidance, but instead as drivers with a long enough steering reaction time for collision to occur before steering initiation.

4.1.3. Mechanisms governing steering reaction times

An obvious follow-up question is to determine what causes the longer steering reaction times of inexperienced drivers. Considering the previous empirical work, cited above, on the effects of experience on hazard perception times, and on steering avoidance failures in collision situations, three partially related mechanisms could be suggested: (a) The experienced drivers were better at anticipating that the overtaking POV could generate a situation that could require steering; (b) after braking had been initiated, experienced drivers needed a shorter time to grasp that the decelerating POV still remained a hazard, for example due to previous experience of similar situations; (c) with experience, drivers had become more prone to and comfortable with the use of steering, or steering and braking, as their first response to a collision conflict, rather than braking only.

All three of these proposed mechanisms can, to some extent, be understood as experienced drivers having more *experience* and greater *expectancy* of steering collision avoidance. A formulation in terms of expectancy fits well with the findings by Green (2000), that typical brake reaction times range from 0.7 s for fully expected stimuli, up to about 1.5 s for surprise events, steering reactions being a few tenths of a second faster, overall. The long brake reaction times observed in the unexpected scenario of this study (2.0 s and 1.7 s for inexperienced and experienced drivers, respectively), thus seem to suggest that in both experience groups, the drivers were not at all expecting the POV to apply deceleration after overtaking. On the other hand, the average times between braking initiation and steering initiation (1.4 s and 0.8 s for inexperienced and experienced drivers, respectively), could be interpreted as the inexperienced drivers also being surprised that there was a need to apply steering in addition to braking, whereas the experienced drivers were not.

However, it should be pointed out that the very specific reaction time values proposed by Green (2000) have been criticized (Summala, 2000), and probably rightfully so.

4.2. Impact of ESC on avoidance

4.2.1. Unexpected avoidance

In addition to the clear division of the x axis, into colliding and non-colliding drivers, Figure 4 also suggests a division along the y axis: All three drivers applying a maximum steering wheel angle of about 100° or greater experienced full loss of yaw control, whereas the other drivers, who applied smaller evasive steering magnitudes, did not experience yaw control loss. Thus, as could be expected, yaw instability seems closely correlated with heavy steering.

In total, including the three drivers experiencing control loss, 9 drivers out of 48 (19%) applied ESC-relevant manoeuvring (i.e. manoeuvring such that an ESC intervention was triggered, or would have been triggered, had the ESC system been active). This is comparable to what was obtained by Dela et al. (2009), and suggests that simulator-based testing of truck ESC by means of unexpected scenarios remains problematic, in the sense that experiments may need to involve a large number of drivers in order for any effects of ESC to be measurable.

4.2.2. Repeated avoidance

Since the limitation just mentioned was anticipated, the instruction-based, repeated avoidance scenario test setting was also included in the study. In the repeated avoidance setting, the frequency of ESC-relevant manoeuvring was markedly higher (76%) and, here, results indicate that the ESC system did provide the type of benefits it is designed to provide: Reductions of skidding (in terms of maximum body slip angle; $r = 0.38$; Figure 8a), and of control loss frequency ($r = 0.45$; Figure 8b).

As mentioned in Section 1, one prior hypothesis was that driving experience could have an impact on the usefulness of ESC. The results provide some indications in the direction of experienced drivers having slightly less use of ESC, but inconclusively so: (a) the significant interaction in the unexpected avoidance data, between experience and ESC state, for large steering wheel reversals, could be interpreted as the experienced drivers needing to apply greater steering effort when ESC was present, whereas the opposite seemed to occur for inexperienced drivers. However, this interaction was *not* observed in the repeated avoidance data, despite the higher frequency of ESC interventions. (b) Comparing averages, the reductions of skidding and control loss due to ESC in the repeated scenario were smaller for experienced drivers. Furthermore, as mentioned in Subsection 3.2, when analysing the experience groups separately and non-parametrically, the reduction in skidding was statistically significant only for inexperienced drivers. However, the Pearson correlation coefficient still indicated a medium-sized effect for the experienced drivers ($r = 0.34$), so the lack of significance could to some extent be attributable to the reductions in test power associated with non-parametric testing and smaller sample sizes. Also, the reductions in control loss frequency were statistically significant for both experience groups separately. Overall, it is possible that these findings are caused by the experienced drivers' control behaviour being less in line with the ESC system's model of driver intentions, something which could be due either to some highly developed driver control strategies, but just as well to a tendency of applying excessive countersteering during skidding. Further analysis of these matters is needed, but is beyond the scope of this paper.

4.2.3. Comparing unexpected and repeated avoidance

Given the seemingly higher face validity of the unexpected scenario, due to its higher degree of realism, it is relevant to try to understand why this scenario did not generate observations of ESC benefits, whereas the repeated scenario did. The limited size of the sample of ESC-relevant unexpected avoidance manoeuvring may be hypothesized to be one contributing factor (such that increasing the experiment size could, in theory, lead to observations of ESC benefits also for the unexpected scenario), but whether or not this really is the case cannot be concluded from the data and analyses presented here.

Another possible factor to consider is that the repeated avoidance scenario seems to have been more successful at placing drivers in situations with a real risk of loss of yaw control. There were no statistically

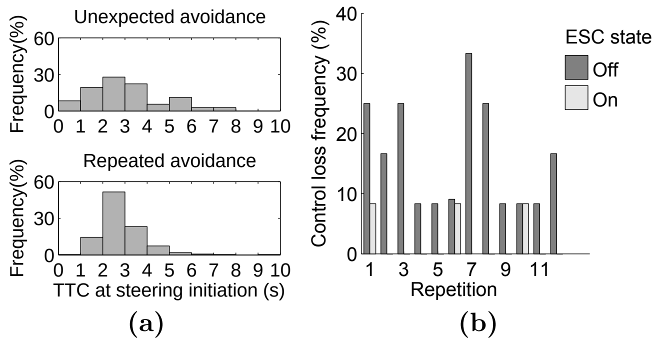


Figure 12: *(a) Distributions of TTC at steering initiation, for the unexpected and repeated avoidance scenarios. (b) Frequency of control loss in the repeated avoidance scenario, per repetition and ESC state.*

significant differences between the unexpected and repeated scenarios on the generated steering avoidance situations (in terms of speed and TTC at steering initiation; Figures 9c and d). However, a closer look at the data, such as in Figure 12a, indicates that the steering avoidance situations in the repeated scenario were a narrowed-down subset of the steering avoidance situations occurring in the unexpected scenario. Specifically, Figure 12a and, to some extent, also Figure 3 suggest that the repeated scenario eliminated the latest and earliest of the unexpected steering attempts, and instead had drivers more frequently initiating steering from around a TTC of two to three seconds. According to Figure 4, this was a type of situation from which collision could be avoided, but not without risk of losing yaw control, something that could explain the higher frequency of ESC-relevant manoeuvring in the repeated avoidance scenario, in turn yielding a larger effective sample for the study of ESC effects.

The above argument could be taken to imply that, if the experiment size were increased, the ESC benefits observed for the repeated avoidance in the present study should be guaranteed to appear also in the unexpected scenario, for unexpected steering attempts starting from a TTC of two to three seconds. However, for this to be the case, it would also be required that driver control behaviour *after* initiation of steering from a given steering avoidance situation, be the same in unexpected and repeated avoidance, something that cannot be conclusively stated based on the analyses presented here. On the contrary, as touched upon above in this paper, Hollnagel and Woods (2005) suggested that differences in the expectancy for, and previous experience of, a control task could lead to qualitatively different *control modes* being employed. If so, it seems possible that transitions between control modes could occur in the transition between unexpected and repeated collision avoidance. Further analysis or discussion of these aspects fall outside the scope of this paper.

A completely different type of explanation for why ESC benefits were only observed in the repeated scenario could be that drivers had to *learn* how to drive with the system, before being able to enjoy its benefits. The idea behind ESC is clearly not that any such learning and adaptation should be needed, and previous research can be taken to suggest that ESC reduces control loss even for drivers who are not aware of the system's presence in their vehicle (Høye, 2011). Nevertheless, the possibility deserves brief attention: If learning effects were the cause of ESC benefits in the repeated avoidance scenario, this should have been observable as improvements over repetitions in situation outcome measures, and more markedly for repetitions with ESC activated. However, no interaction effects of that kind were observed. Figure 12b shows the frequency of control loss as a function of repetition and ESC state and, if anything, it suggests that repetition led to improvements for driving *without* ESC, in other words the opposite of what this hypothesis would predict[7].

[7] Note that repetitions 1 and 7, at which peaks of control loss frequency for ESC off are discernible in Figure 12b, correspond

4.3. Methodological aspects

4.3.1. Appending a critical scenario to another experiment

The specific observed differences between unexpected avoidance occurring at the beginning of the ESC experiment, as compared to at the end of the LKA experiment (Figure 7), could be interpreted in terms of prior experience of the winter environment in which the unexpected scenario took place. The ESC experiment drivers had driven for ten minutes in this winter environment, including five decelerations to full stop (during which road friction was still good), before starting the four-minute drive that ended with the unexpected scenario. The LKA drivers, on the other hand, were moved directly to this four-minute drive from a thirty-minute experiment in summer surroundings. It could be hypothesised that this may have generated, among LKA experiment drivers, a heightened expectancy for difficult traffic situations in general, and for low-friction road conditions in particular. Such an interpretation seems to be supported by the observations of more careful brake application (Figure 7a), as well as an earlier steering avoidance, measured as shorter steering reaction times (Figure 6c; a difference which was not statistically significant) and as higher minimum TTCs (Figure 7b; significant). The lower severity ratings provided by LKA drivers (Figure 7c) could be understood as resulting from the higher minimum TTCs.

As mentioned in Subsection 3.1, the analyses of effects of experience on reaction times and collision outcome were carried out on the full data set of recordings from both experiments, since for these dependent variables there were no significant effects of experiment (nor any interactions between experiment and experience). Furthermore, a closer look at Figure 6c indicates that the lower steering reaction times in the LKA experiment were due mainly to the experienced drivers, and the data for minimum TTC exhibit a similar pattern. This observation could be interpreted as the experienced drivers of the LKA experiment being more sensitised than the low-experience LKA drivers, by the above-mentioned change from summer to winter environment. In other words, the observed differences in driver behaviour between the two experiments can be nicely integrated with the explanatory model sketched in Subsection 4.1.3 above, as the experienced LKA drivers being able to add also the change of environment to the set of circumstances on which they based their higher expectancy for a possible need of steering avoidance manoeuvring.

4.3.2. Repeated, instruction-based collision avoidance

The differences between repeated and unexpected scenarios in terms of braking (Figures 9a and b), and to some extent also the effects on braking of repetition itself (Figures 10a and b) suggest, as expected, that the adopted paradigm for repeated avoidance is not suitable for the study of braking behaviour. However, as discussed above, for the purposes of this study it proved useful, by frequently generating a type of steering avoidance situation highly relevant to the evaluation of ESC. Furthermore, the other observed effects of repetition (Figures 10c and d) did not seem to have any major impact on this evaluation.

As has been discussed above, this type of repeated avoidance testing has lower face validity than testing with unexpected scenarios. However, it could be argued that the validity is higher than for methods involving predefined control inputs or tracks to follow (such as described in Section 1), precisely since here, drivers are free to adopt whichever escape paths and control strategies they prefer, something that arguably could make behaviour more similar to behaviour in real traffic.

One final aspect to be noted is that, compared to an unexpected scenario, the repeated avoidance paradigm alters the distribution of responses to the rear-end situation, yielding more frequent steering responses (here, 99% versus 77%), and a more narrow distribution of steering response times (see Figure 12a). Therefore, care will need to be taken in any comparison of ESC benefit figures, such as control loss reduction ratios, from this type of paradigm with figures from studies based on unexpected avoidance paradigms or on accident statistics.

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to the subjects' very first repetitions without ESC, since half of the drivers began the experiment with ESC off, and the rest had ESC turned off before repetition 7.

5. Conclusions

In the unexpected lead vehicle braking scenario of this study, the most striking effect of experience was that inexperienced drivers collided considerably more often than experienced drivers, and in general, the results suggest that this was caused mainly by inexperienced drivers having longer reaction times to steering initiation. Furthermore, the obtained data seem to provide some support for the hypothesis that these differences in steering reaction times could be due to experienced drivers having a greater expectancy for steering avoidance in this type of situation.

The range of behavioural responses observed in the unexpected scenario was wide, and the type of yaw instabilities targeted by the ESC yaw control system occurred only for a small subset of behaviours. The consequent limitation in effective sample size could be one reason for the lack of effects of ESC in the unexpected avoidance data.

However, the instruction-based paradigm for repeated avoidance was able to frequently reproduce the type of steering avoidance situations for which losses of yaw control were observed in the unexpected scenario. In repeated steering avoidance starting from this, less variable, range of initial conditions, statistically significant benefits of ESC were observed, in terms of reductions of skidding and control loss. These benefits did not seem to be attributable to learning effects. There were some indications of experienced drivers gaining slightly smaller benefits from the system, but the reductions of control loss were statistically significant for both experience groups separately. In summary, it seems that the ESC system reliably improved the stability of the drivers' repeated avoidance manoeuvring. However, given the possibility of subtle differences in driver control behaviour between unexpected and repeated collision avoidance, the present analyses do not allow any precise predictions of the extent to which these repeated-avoidance benefits of ESC could be present also in unexpected avoidance.

In addition to the repeated avoidance approach to increase sample sizes, the approach of appending one critical situation to the very end of another simulator experiment was evaluated, and in this specific study it was found useful. However, the obtained results also highlight that whenever systematic variations are introduced in what drivers experience in the simulator prior to a situation under study, it is recommendable to carefully control for any effects of these variations on the drivers' behavioural responses.

6. Acknowledgments

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