A PILOT EVALUATION OF USING LARGE MOVEMENT DRIVING SIMULATOR EXPERIMENTS TO STUDY DRIVER BEHAVIOUR INFLUENCE ON ACTIVE SAFETY SYSTEMS FOR COMMERCIAL HEAVY VEHICLES

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The evaluation of active safety functions like Electronic Stability Control (ESC) is of increasing importance, driven by legislation, to commercial heavy vehicle producers and to society as a whole to predict the potential benefits of the systems. Direct testing in real traffic with normal drivers of those functions are most often infeasible due to cost, repeatability and safety. This paper presents an attempt to explore the possibility of using large scale moving based driving simulators to evaluate functions like ESC. This is conducted through a simulator experiment where the subject drivers have been provoked in driving scenarios to ESC interventions. The experiment indicates the possibility of using driving simulators for evaluation purposes. This implies that studies of the benefits can be performed with higher accuracy regarding repeatability and evaluation testing of active safety functions can be made more cost efficient and without jeopardizing safety of involved driver and other road-users.

Keywords: Driver Behaviour, Simulator Experiments, Active Safety Systems, Electronic Stability Control, Yaw Stability, Roll Stability, Commercial Heavy Vehicles

1. INTRODUCTION

The overall purpose for any active safety system introduced in public road vehicles is to reduce the risks of accident from occurring during driving in traffic. The first step in this direction was done in the 1970s by introducing anti-lock braking systems (ABS) for road vehicles, resulting in safer braking/steering manoeuvres. After this, the ABS wheel speed sensors were also used to avoid skidding during traction, and then the traction control system (TCS) was introduced. The next natural step in active safety development was to design the Yaw Stability Controller (YSC) which assists when the driver’s desired vehicle path is diverting too much from the vehicle’s actual path.

The YSC performs a correcting planar moment realised by individual wheel braking interventions. Commercial heavy vehicle combinations are prone to have high centre of gravity during laden conditions which makes them sensitive for roll over accidents when negotiating curvy driving paths. This lead to the development of the Roll Stability Controller (RSC). The RSC ensures that the driver’s desired path is not too sharply curved for the actual vehicle speed. If so, the RSC will reduce the positive powertrain torque and additionally apply wheel braking for the whole vehicle combination to reduce the vehicle speed to an acceptable level for the actual curvature. The YSC and RSC are commonly named as part of Electronic Stability Control (ESC) and the development started as early as in the 1980s. In short, all the active safety systems mentioned above are taken

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1 Desired path: Defined by steering wheel input and vehicle speed.
2 Actual path: Measured by yaw rate and lateral acceleration sensors
3 Certain passenger cars have high centre of gravity such as Sport Utility Vehicles (SUV)s which also was a reason for the RSC development.
4 Vehicle Combination: Towing truck/tractor and connected trailer(s).
for granted in today’s road vehicles. The ESC system will therefore naturally be a legal demand on new commercial heavy vehicles within the EU by the year 2014 \cite{1}. New active safety functions are introduced, such as Collision Avoidance Systems (CAS), Intelligent Speed Adaptation (ISA), which uses GPS and map databases to set hard constraints on vehicle speed limit, Automatic Steering Systems (AS), Adaptive Cruise Control (ACC), and Collision Warning Systems (CWS). The list of new active safety systems is not getting shorter and when the road vehicle’s motion control completely reaches x-by-wire \cite{6} technology it will require that the automotive industry intensifies the discussion on which design philosophies should be used when introducing additional driving automation functions into the vehicles. Ultimately, how should a virtual co-driver interact with a human driver? In \cite{5}, two main design philosophies for driving automation were discussed: hard versus soft automation, which depends on whether the control system or the driver has the ultimate authority. The design philosophies originate from the two main aircraft manufacturers: Airbus, with its hard automation and Boeing with its soft automation approach. Airbus, which was first to introduce fly-by-wire aircraft, uses hard automation philosophy in the belief that the automation technology exists to prevent the pilot from unintentionally exceeding the safety limits, pre-defined performance envelope, of the aircraft. Boeing uses soft automation to instead aid pilots which gives the pilots full authority to override the control system, and therefore the full performance envelope of the aircraft still is at hand for the pilot. Both philosophies have benefits and drawbacks. Soft automation allows better judgement of a human to avoid critical situation to becoming worse, however, hard automation, if programmed correctly and also including all possible options, would never have allowed the situation to become critical. In road vehicles ABS, ESC with YSC and RSC, ISA, and CAS are examples of hard automation systems. Soft automation examples are ACC, AS, and CWS systems. In this study the focus has been to study hard automation systems, and specifically the ESC system for commercial heavy vehicles. When hard automation is selected as a design philosophy it demands that the active safety function is robust enough to perform as desired for a variance of drivers with different skill levels and for different events in the environment. Figure 1 illustrates how driver, vehicle system, and environment can be seen as a complete system. The overall control loop is that the driver influences the vehicle, the vehicle influences the environment, and finally the environment influences the driver, see Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Illustration of how the driver, the control system with hard automation, the vehicle, and the environment can be seen as a complete system. Note that the steering wheel input from the driver is usually still seen as a direct input to steering actuators and cannot be overruled by the control system.}
\end{figure}

The driver has the control over acceleration-, brake- and steer inputs as long as the vehicle control system and its preprogrammed safety limits are not exceeded. When the preprogrammed performance envelope is exceeded for, e.g. yaw stability, the YSC system takes over the ultimate authority of acceleration- and brake input and re-coordinates the brake and powertrain actuators as it finds necessary due to the situation at hand. In today’s vehicle systems, the driver still has the ultimate authority over the steering wheel input, as illustrated in Figure 1 as a straight line cutting through the vehicle’s control system and going directly to the motion actuator block. The

\footnote{The legal demand was for commercial vehicles was postponed from year 2011 to 2014 \cite{2}, \cite{3}, \cite{4}.}

\footnote{All vehicle’s motion actuators are electronically controlled.}
actual motion is then realised within the chassis/tyre block. This block also represents the true performance envelope of the vehicle, shown in Figure 1 as a friction ellipse with lateral force limits due to the roll stability limits.

To be able to perform an in-depth evaluation of an active safety function it is necessary to include a variance of real drivers in the study and also include a realistic traffic environment. It is not ethical nor safe to perform stimulated experiments to induce critical situations in real traffic. Therefore, large movement simulator experiments have the potential to be a viable tool to evaluate future active safety systems for public road vehicles. The work presented in this article was conducted to understand what issues need to be addressed for the successful use of driving simulator experiments when used in product development of future active safety systems. In the pilot evaluation presented in this paper, following question was used for guiding the experimental design and analysis of the results:

Can road simulator experiments on commercial heavy vehicles and professional drivers be used to evaluate active safety systems with a hard automation design philosophy such as the ESC?

The adopted approach for answering this question is to break it down into smaller questions which all need to be answered positively:

• Can virtual driving scenarios be created that are capable, at least in a majority of cases, of provoking driver behaviour so that the situation develops into an ESC intervention?
• Can the driving scenarios trigger ESC interventions if they are repeated more than once per driver? (Important in order to keep the size of simulator experiments within reasonable limits.)
• Can the vehicle dynamics model, ESC system, and simulator platform be tuned in so that the ESC system is capable of producing the same type of control improvements in the simulated situations as it does in a real vehicle?
• Can a method for obtaining subjective feedback be devised from simulator test drivers on how they perceive ESC interventions in situations of varying criticality, in terms of usefulness, acceptance, etc.?

The first three questions address if the driver, environment, and simulator can be set up so that objective studies can be performed on the hard automation system. The fourth question addresses subjective aspects. When designing an active safety system, its objective effects on driving is one important factor, but also the driver’s subjective impressions of the system need to be considered. If a system induces a positive objective safety effect, this should preferably not be at the expense of driver acceptance and appreciation of vehicle behaviour. This is of course especially important for systems which the driver can him/herself inactivate.

The outline of the paper is as follows, Section 1.1 will give a background on relevant public material on using large movement simulator experiments for ESC performance evaluation. Section 2 will discuss how the experiments were set up and what experimental design was used. In Section 3 the results on ESC and its activation are given. Finally, a discussion and concluding remarks are given in Section 4.

1.1. BACKGROUND

It has been previously shown that driver expectancy for safety critical situations has a significant effect on driver behaviour and performance in these situations. In [6] it is stated that in real traffic, most rear-end crashes occur due to unexpected events. Based on a meta analysis of a large number of data sets it is shown that driver expectation is the most important factor influencing driver brake reaction times to traffic events [7]. According to analysis in [7], reaction times1 to expected events are about 0.7-0.75s. For unexpected but common events, such as lead vehicle brake lights activating, reaction times increase to about 1.25s. For surprise events, such as an object suddenly moving into the driver’s path, reaction times are about 1.5s. The expectancy phenomenon has an impact on the study of critical situations in controlled experiments, in the sense that repeated exposure to critical events will increase driver expectancy critical events, thus inducing a learning effect, altering the behaviour of drivers as the experiment progresses. For example, in a study at the NADS driving simulator, [8], it was shown that responses at the second exposure to a lead vehicle braking event were on an average 430ms faster than responses at the first exposure. These effects mentioned here are important to take into account when designing the driving scenarios for specific simulator experiments.

One of the public state of the art large movement simulators is the National Advanced Driving Simulator(NADS) which is located at Iowa University of Technology. The system consist of a large dome which can hold an entire car, tractor or truck cab. It can produce large longitudinal and lateral motions in a area of 19.5 times 19.5m by a so called X/Y table. The dome is mounted on a six degree freedom motion hexapod, which allows 330 degrees of yaw motion, in addition to high frequency vibration actuators. In Göteborg, Sweden, a new large movement simulator is planned

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1 reaction time: time from event occurring to driver’s foot reaching brake pedal.
The graphics are computed in standard PCs and a central PC is supervising the sound, motion and
with 3 smaller screens replacing the rear view mirror and the 2 side mirrors of the truck cabin. The
scenarios and experimental design for when the new VTI simulator in Göteborg is up and running.

A successful simulator experiment on how ESC in passenger cars can assist the driving perform-
ance was conducted at NADS [10], [11]. The study used different driving scenarios to trigger
critical situations where ESC would take over control and compared the outcomes of the scenarios
when ESC was permanently switched off and on. Six scenarios were studied for sensitivity and
redundancy: both left and right curves with decreasing radius of curvature, strong turbulent wind
gusts from both left and right side, a road incursion from the right, and a road incursion without
a lead vehicle. From a sensitivity and redundancy analysis, three scenarios were selected in the
main study: the left curve with decreasing radius of curvature, the wind gust from the right, and the
road incursion without a lead vehicle. A total of 120 drivers completed the experiment. The study
sample included 40 participants from each of the age groups: 18-25, 30-40, and 55-65. The gender
was divided equally. Five independent variables were included in the experimental design: 1. ESC
presence was assigned to half of the drivers. The other half had the ESC permanently switched
off. 2. Drivers were each assigned to one of two different vehicle and ESC models. 3. Each driver
experienced the three scenarios in the following order: incursion which aimed on a double lane
change manoeuvre, the closing curve, and finally the wind gust. 4. Three age groups were used.
5. The gender was equally distributed. The dependent measure was ‘loss of control’ defined as
‘Participants departed road beyond shoulder while oriented away from road with high rotational
velocity. If vehicle came to rest, does not count as loss of control, even when beyond the shoulder.’
The results showed that in total 27.9 percent experienced loss of control during the scenarios if
ESC was permanently switched off and only 3.4 percent if the ESC was permanently switched
on [10]. The results show that there is a clear benefit to having ESC assist the driver in a loss of
control situation. However, from an experimental design point of view, the report is not discussing
if the drivers became more careful or sensitive after experiencing the first scenario compared to the
following ones. Additionally, the study [10] was conducted on passenger cars with an average pop-
ulation of car drivers. The study presented in this article, includes heavy commercial truck drivers
which have several times more driving hours per week than an average passenger car driver and
are therefore considered as highly experienced drivers which can affect the outcome of the results.

2. EXPERIMENTAL SETUP

2.1. Apparatus

The driving simulator study was conducted at the Swedish National Road and Transport Research
Institute (VTI) facility in Linköping, Sweden. The simulator used, the SIM II, is one of two large
scale motion base driving simulators at VTI Linköping. The simulator SIM II, see Figure 2, is
exclusively dedicated for heavy vehicle driving simulations.

The SIM II consists of a modified SCANIA truck cabin, mounted on a shake table with 4 degrees
of motion freedom and a motion system with 2 degrees of freedom. The cabin, including the motion
system, the shake table and a 120° screen constitutes the dome that is completely covered. The
dome is attached to a linear motion system with one degree of freedom. The complete simulator
has the following mechanical motion capabilities:

- Motion system
- Pitch angle of ±24°
- Roll angle of ±22°
- Maximum amplitude of ±3.5m
- Maximum speed of ±2.0m/s
- Maximum acceleration of ±0.4g
- Vibration table
- Vertical movement of ±5.0cm
- Longitudinal movement of ±7.5cm
- Roll angle of ±7°
- Pitch angle of ±4°

The graphics are presented to the driver on the 120° front projection screen with 3 projectors and
with 3 smaller screens replacing the rear view mirror and the 2 side mirrors of the truck cabin.
The graphics are computed in standard PCs and a central PC is supervising the sound, motion and
graphics so that they are synchronized. The simulator has a linear motion of ±3.5m in the lateral direction. This degree of freedom is used to simulate the lateral forces on the driver when driving within the lane. This implies that the movement within the lane is represented by a position of the linear movement of the moving base (a scaled position) and enables a very realistic sensation on rural/highway roads. The cabin is tilted to simulate longer durations of lateral forces, for example in cornering situations. Longitudinal forces are simulated analogously, i.e. by pitching the cabin and the dome.

2.2. Vehicle modelling and Software in the Loop

The vehicle system, as illustrated in Figure 1, contains of three parts: 1. The motion control system, 2. Motion actuators, and 3. Chassis/tyre. All three parts were modelled within matlab/simulink and then compiled to the realtime target computer. Here, the studied motion control system is the Electronic Brake System (EBS) which includes the ESC. The used EBS is found in production of commercial Volvo trucks and was included as a Software In the Loop within the matlab/simulink system model. Models of the motion actuators such as the pneumatic brakes were also included with the necessary Anti-lock Brake System control. Simplified models of the powertrain’s engine, retarder, and an automatic manual transmission were also included. The chassis and suspension were modelled within matlab’s Simmechanics toolbox. The chassis of a 6 wheeled truck with one tag axle was modelled as a weak chassis frame with warping effects. Axle loads were set to 7.7, 11, and 7.1 metric tonnes. The average height of centre of gravity was set to 1.5m. The actual wheelbase between first and last axle was 6.2m. The cabin was modelled as a rigid body with pitch, roll, and heave capabilities. The tyres were modelled with combined slip by magic formula and with dynamic relaxation. The vehicle model included also a non-physical, i.e. not existing in real vehicles, virtual roll-over protection function which prohibits the normal forces of the tyres to go below a certain limit. The force feedback to the driver’s steering wheel was also included. Sound effects such as the activation of brakes, ABS activation on front axle, and of the powertrain were also included in the cabin’s loud speakers. Tuning of the vehicle system to feel realistic was conducted in the Sim II simulator with assistance by two of Volvo’s professional test drivers.

2.3. Scenario Description

The design of driving scenarios is a key issue for any simulator experiments to succeed. In this study it is important that the scenarios induce a majority of truck drivers to repeatedly have situations where yaw- or/and roll- instability occurs. The following four driving scenarios were evaluated: a) ‘parked car accelerates in same direction as the truck’, b) ‘the truck negotiates a closing curve’, c) ‘a moose crosses the road’, and d) ‘double overtaking and a parked car accelerates into the same lane as the truck and makes a full stop’, see Figure 3.

Scenario b) is only a road geometrical condition with the sole purpose of inducing roll instability due to the fact that the truck driver negotiates the closing curve with too high initial speed. The scenarios a), c), and d) are more complex and try mainly to induce yaw instability.

The choice of the moose scenario over the two scenarios with hidden parked cars entering the truck’s lane was made based on a small preliminary experiment. In the preliminary experiment, three professional truck drivers experienced all of the four implemented driving scenarios. The
order of scenario occurrence was varied so that the first scenario occurring (least driver expectancy) was one of the three yaw-oriented scenarios, a different one for each of the three drivers. It was observed in this preliminary experiment that the professional drivers changed into the opposing lane while passing the parked vehicle behind which the hidden parked car was waiting. When oncoming traffic made it impossible to change lanes, the drivers slowed down to let the oncoming traffic pass first. When an overtaking vehicle was present and tried to drive with a short headway in front of the truck, in order to hide the stationary vehicles, see (d in Figure 3, the professional drivers would slow down to get a larger headway. Due to these risk averse driving strategies, it was concluded that out of the yaw-oriented driving scenarios, the moose scenario, with its high degree of unpredictability, was the scenario best suited for inducing yaw instability events. The moose scenario was tuned in by tuning the triggering of Time To Collision (TTC) and by reducing the road/tyre friction to as low as 0.26. This also reduced the combination of both yaw and roll instability occurring in the same scenario.

2.4. Experimental Design

To address the questions formulated in Section 1, a 16 subject experiment was designed for studying the effects of ESC presence in critical situations. To cover both roll and yaw instability, the closing curve and moose scenarios, see b and c in Figure 3, were included in the experiment. Due to the limitation to 16 test subjects, a within group design was preferred, i.e. an experimental design where all test subjects would drive both with and without ESC activated, experiencing both driving scenarios with both conditions.
2.4.1. Independent Variables

The independent variables considered in this study are listed below.

ESC state
All drivers drove two test drives, one with the ESC system activated, where the ESC system will perform stabilizing interventions when certain criteria are met. The other test drive was with the ESC system inactivated.

Driving scenario
In each ESC state condition (activated and inactivated), the drivers experienced both the moose and the curve driving scenarios.

Scenario repetition
This independent variable refers to the repetition of the individual driving scenario. E.g. the first time a subject experiences the moose scenario, this is considered the first repetition of that scenario for that driver. In the same driver’s second test drive, the driver would then experience a second repetition of the same scenario.

Driving environment
Before providing subjective feedback on individual scenario instances after test driving, drivers were shown a recorded copy of the road scene as it had been shown to them during the simulated driving. As a further support for the subjects’ memory, a visually discernible difference was desired between first and second test drive. This was implemented by adding a very slight fog to the rendering of the simulated road scene. The main visual effect of this was that it changed the blue sky into a cloudy sky, but it did in practice also reduce the sight distance for the drivers from “‘infinite’” distance to 2.5 km. It was judged that this reduction in sight distance should not have an impact on driver behaviour. In addition, Complete balancing of condition order was done to avoid any systematic order effects.

2.4.2. Dependent Measures

A number of dependent measures, both objective and subjective, were defined to study. Objective measures defined and studied, per scenario instance, included:

Potential loss of control
The vehicle was defined to reach a state of ‘potential loss of control’ when a control intervention from the ESC system would have been triggered if the ESC was activated. During test drives with ESC inactivated, it was not possible to read from the ESC system whether an intervention would have been triggered had the ESC system been activated. Therefore, two dependent measures were defined roughly emulating the triggering criteria of yaw and roll stability control interventions of the ESC system. They will be referred to here as ‘potential loss of yaw control’ and ‘potential loss of roll control’, and were based on if actual sensor values exceeded a static reference band. For yaw this reference band was set to static estimated yaw control reference band set to $\pm 4$ degrees/second around the driver’s estimated desired yaw angle velocity. For roll an absolute value of the lateral acceleration larger than 2.7 m/s$^2$ was used. These measures were used both in the ESC activated and the ESC inactivated conditions, to objectively determine whether a given scenario instance was considered to have reached a state of potential control loss.

Loss of control
The vehicle said to reach a state of ‘loss of yaw control’ when more than two seconds of uninterrupted time was spent outside the yaw control reference band. ‘Loss of roll control’ was defined to have occurred if the virtual roll-over protection was activated (see Section 2.2).

Driver action
Driver action, quantified as maximum values of brake pedal depression and steering wheel angle during the scenario instance.

Vehicle speed
Vehicle speed at various locations during the scenario instance.

Subjective dependent measures, per scenario instance, included:

Driver ratings
Driver ratings of the perceived realism of simulated driving, criticality of scenario, level of control experienced during scenarios, own driving performance, truck operation, in terms of steering and braking function, steering wheel feeling, grip on road. The driver’s acceptance ratings for the behaviour of the truck, were according to the nine-item van der Laan scale [12]. Additionally, driver

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1 In other words: Half of the drivers drove with ESC activated in the first drive. Of this half, half drove in the clear sky environment in the first test drive. Of this half, half experienced the moose scenario before the curve scenario in the first test drive. Of this half, half experienced the moose scenario before the curve scenario also in the second test drive. Altogether this yields 16 combinations, so that in practice there was a unique condition ordering for each subject.
ratings of the extent to which they could recall the scenario.

Experimenter rating
Experimenter rating of the extent to which the driver could correctly recall the scenario, supported by a number of control questions.

2.4.3. Participants

16 professional truck drivers were recruited as test subjects. All were male. Average age was 42 years, standard deviation 11 years. Average time since acquiring truck driving license was 21 years, standard deviation 11 years. Average distance of truck driving per year was 77000 km, standard deviation 40000 km. Nine of the drivers did mostly long haul driving, four mostly distribution driving, and three mostly some other type of driving. The test drivers were paid 1000 SEK each for their participation in the study.

2.4.4. Procedure

When meeting each test driver, the experimenter first provided an introductory description of the experiment. The test drivers were informed that the purpose of the experiment was to develop methods for using driving simulators as a tool in safety research and development, and to fine tune the systems in the simulator. The ESC system was not mentioned nor that critical situations would be occurring during the simulated driving. The drivers were further informed that they would be driving one practice test drive, and then two test drives of about 30 minutes each.

After filling out a background data form and a consent form, a 5-10 minute practice test drive followed. The purpose of this was to get the test drivers accustomed to the simulated driving. During the practice drive, the drivers were all instructed to carry out the same set of simple manoeuvres, including lane changes and braking to a full stop. After the practice drive, the drivers verbally answered a first set of questions on simulator realism and vehicle behaviour.

Then followed the two test drives. The timing of critical scenarios during driving was not the same in both test drives. The general driving environment was a two-lane rural road. Between critical scenarios, there were both curves which were not sharp curves, and parked vehicles by the side of the road from behind which mooses did not appear. The purpose of this was to lower driver expectancy of the critical scenarios, if possible.

After the two test drives, the drivers verbally answered a full set of questions on realism, scenario criticality, perceived control etc, as described above. This was done per scenario instance, and to support the memory of the drivers each scenario was reviewed by watching a video recording of the road scene as it had been visible to the driver during the scenario.

Finally, the drivers were asked if they had noted any differences between the two test drives. They were then informed of the fact that an ESC system had been present in one of the two test drives, and asked whether they had noticed any ESC interventions. If so, a set of questions on their experience of the ESC interventions were asked.

2.4.5. Analysis

Objective and subjective dependent measures were compiled and analysed statistically, to find any effects of independent variables. For each of the two driving scenarios, the main procedure was the following:

- First, for each dependent measure, a two-way ANOVA test was carried out with factors **Scenario repetition** and **Driving environment** was made. In this analysis, all scenario instances were included.
- Next, a further analysis was made, only including the scenario instances where potential yaw or roll control loss had occurred. Also in this analysis two-way ANOVAs were carried out for each dependent measure, but now with factors **ESC state** and **Scenario repetition**. In the analysis of the effect of **ESC state**, it was not considered correct to include scenarios where ESC was not (supposed to be) activated.

3. RESULTS

3.1. Effects of Experimental Design

Table 1 shows some selected results for the two driving scenarios. Below, further results are presented for each scenario, followed by some results on ESC control interventions. Finally, results concerning the test drivers’ subjective impressions are presented.

3.1.1. Roll oriented scenario (curve)

As noted in Table 1, the state of ‘potential loss of roll control’ was reached in nine out of the 32 instances of the curve scenario (two instances per driver). Full ‘loss of roll control’ was never
Table 1. Selected observations of the 16 test subjects, grouped by Driving scenario and ESC state condition.

<table>
<thead>
<tr>
<th>Roll oriented scenario (curve)</th>
<th>Yaw oriented scenario (moose)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential loss of roll control</td>
<td>Potential loss of yaw control</td>
</tr>
<tr>
<td>Loss of roll control</td>
<td>Loss of yaw control</td>
</tr>
<tr>
<td>ESC inactivated</td>
<td>ESC activated</td>
</tr>
<tr>
<td>4 (25%)</td>
<td>3 (19%)</td>
</tr>
<tr>
<td>0 (0%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>3 (19%)</td>
<td>4 (25%)</td>
</tr>
<tr>
<td>ESC activated</td>
<td>ESC inactivated</td>
</tr>
<tr>
<td>5 (31%)</td>
<td>4 (25%)</td>
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<tr>
<td>0 (0%)</td>
<td>0 (0%)</td>
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<tr>
<td>4 (25%)</td>
<td>4 (25%)</td>
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<tr>
<td>Total</td>
<td>Total</td>
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<tr>
<td>9 (28%)</td>
<td>7 (22%)</td>
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<tr>
<td>0 (0%)</td>
<td>2 (6%)</td>
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<tr>
<td>7 (22%)</td>
<td>8 (25%)</td>
</tr>
</tbody>
</table>

reached. In all of the five cases with potential loss of roll control when ESC state was activated, rollover protection interventions were indeed triggered. Among the eleven instances of curve driving with ESC activated without potential loss of roll control, it occurred twice that roll-over protection interventions were generated, this due to the rough definition of 'potential loss or roll control' when compared with the real ESC thresholds and triggering events. 'Potential loss of yaw control' occurred twice, both in cases where also potential loss of roll control occurred, but no yaw control interventions were triggered during curve driving.

Statistical analysis of the entire set of curve scenario instances (two-way ANOVA for factors Scenario repetition and Driving environment) revealed no statistically significant effects ($p \leq 0.05$). Trends were noted as follows: Maximum brake pedal position lower on second repetition ($p = 0.06$). Speed before curve was higher in the cloudy environment ($p = 0.07$).

Further analysis of the nine cases with potential roll control loss (two-way ANOVA for factors ESC state and Scenario repetition) also did not reveal any statistically significant effects. Trends were noted as follows: Maximum brake pedal position lower on second repetition ($p = 0.10$). Time outside yaw control reference band higher on the second repetition ($p = 0.10$).

3.1.2. Yaw oriented scenario (moose)

As noted in Table 1, the state of 'potential loss of yaw control' was reached in seven out of the 32 instances of the moose scenario. Full 'loss of yaw control' was reached in two cases, both when ESC was inactive. In all of the four cases with potential loss of yaw control when ESC state was active, yaw control interventions were indeed triggered, and these were the only occurrences of yaw control interventions in this scenario.

Statistical analysis of the entire set of moose scenario instances (two-way ANOVA for factors Scenario repetition and Driving environment) revealed statistically significant effects as follows: Speed at moose crossing lower on the second repetition ($p = 0.01$). Speed before moose crossing lower on the second repetition ($p = 0.02$) and in the cloudy environment ($p = 0.02$). See Figure 4 for an illustration.

Further analysis of the seven cases with potential yaw control loss (two-way ANOVA for factors ESC state and Scenario repetition) did not reveal any statistically significant ($p \leq 0.05$) effects. A trend was noted as follows: Speed at moose crossing lower in the second repetition ($p = 0.09$).

The observed difference in proportion to the of potential loss of yaw control leading to full loss of yaw control, between ESC state conditions (two out of three of potential instabilities leading to full instabilities with ESC inactive, and zero out of four with ESC active), is not statistically significant (Fisher’s exact test, $p = 0.14$).

3.2. Roll Stability Control Activation

In total it was 9 of 16 test drivers that had 'potential loss of roll control', see Table 1. Here test results from one of these 9, test driver number six, is shown when the driver negotiates the closing curve scenario with the ESC system is activated, see Figure 5. Just before the curve starts, see Steering Wheel Angle (SWA) input in Figure 5 at about 180m in longitudinal distance, the driver
releases his gas pedal. The driver seems to underestimate the sharpness of the curve because the driver starts to press gently the gas pedal again during the curve. This results in that the entrance speed which this curve is negotiated with is too high. The lateral acceleration exceeds 2.7 m/s$^2$ at the longitudinal distance of about 240m. For about 50m the lateral acceleration is well beyond 2.7 m/s$^2$.

After a while the driver steers sharply back and then again steers so that the lateral acceleration is exceeded for a second time at longitudinal position of about 310m to 325m. In lateral position it can be seen that the vehicle comes quite close to the right side of the lane. Interesting is that the driver never applies the brakes despite the fact that the driver obviously feels the need to reduce the steer angle input during the manoeuvre. When test driver number six negotiates the curve for the second time with the ESC inactivated, the driver applies braking during the start of the curve up until the sharpest part has been reached, which gave a safe entrance speed for the curve at hand and balanced the lateral acceleration just below 2.7 m/s$^2$. The ESC inactivated plots have been omitted from this article.

### 3.3. Yaw Stability Control Activation

For the moose scenario seven situations had a 'potential loss of yaw control', two situations had a 'loss of yaw control', and eight collisions with the moose occurred, see Table 1. Here test results are shown for test driver number six with the ESC activated who had a 'potential loss of yaw control' in the moose scenario, see Figure 6. The test driver applies hard braking at longitudinal distance from about 50m to 100m, see Figure 6. This reduced the speed of the vehicle, still the driver succeeds to steer so rapidly that his actual yaw rate comes outside the statical reference band three times when driver compensate for the first turnings. At longitudinal distances 120m, 145m, and 170m the actual yaw rate is outside the statical reference band, yaw intervention could be expected. It is interesting to note that due to the excessive usage of steering the driver also triggers real roll interventions at about 110m and 160m in longitudinal distance. When test driver number six negotiates the moose scenario with ESC inactivated, the driver brakes similar to what is shown in Figure 6, with the major difference being that the driver does not try to avoid the moose by steering and instead allows the truck to hit the moose. The ESC inactivated plots have been omitted from this article.

### 3.4. Subjective Results

On an average, the drivers rated the realism of the simulated driving as 3.5 out of 5 (In comparison with real driving; 1 being not at all satisfactory, and 5 very satisfactory) after the first training round, and as 3.4 out of 5 after the full experiment. Corresponding standard deviations were 0.6 and 0.7, respectively.

A number of significant effects of *Scenario repetition* on subjective measures were noted. The test drivers’ perceived level of criticality of situations was lower for the second repetition of both
Figure 6. Results from moose crossing the road for test drive number six with ESC activated. Only statical reference bands are included, no dynamical bands from ESC are included for simplicity.

Table 2. Driver subjective impressions of situation criticality, grouped by driving scenario and Scenario repetition condition. Rating scale was from 1 (not critical at all) to 5 (very critical).

<table>
<thead>
<tr>
<th>Scenario repetition</th>
<th>Roll oriented scenario (curve)</th>
<th>Yaw oriented scenario (moose)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First repetition</td>
<td>2.6</td>
<td>3.9</td>
</tr>
<tr>
<td>Second repetition</td>
<td>1.7</td>
<td>3</td>
</tr>
</tbody>
</table>

the curve scenario ($p = 0.02$) and the moose scenario ($p = 0.05$). See Table 2 for reported estimates of criticality. Furthermore, the drivers perceived the behaviour of the truck as more ‘nice’ (as opposed to ‘annoying’) on the second repetition, for both curve ($p = 0.03$) and moose ($p = 0.04$) scenarios. A similar result was also obtained for the acceptance dimension ‘pleasant’ (as opposed to ‘unpleasant’) for the curve scenario ($p = 0.03$). There were not however significant effects (or clear trends) of scenario repetition on the overall van der Laan ratings of Usefulness and Satisfaction.

10 out of 16 drivers spontaneously reported that they suspected that the moose scenario could reoccur in the second test drive, and the corresponding figure for the curve scenarios was 8 out of 16. This was in response to a question on any differences, in general, experienced between first and second repetition, not a specific question on suspicion of repeated scenarios.

There were no significant effects or clear trends of Scenario repetition on the extent to which drivers reported that they could recollect individual scenarios. However, there was a statistically significant ($p = 0.04$) reduction in experimenter judgement of test driver memory, between the first and second repetitions of the curve scenario. I.e. the experimenters judged that the drivers found it more difficult to remember the second instance of the curve scenario.

Only one out of the 16 drivers reported that he had noticed an ESC intervention. He reported that it was the sound of the pneumatic brakes that had made him notice the intervention. This driver did not provide any specific further comments on the ESC intervention as such.

4. DISCUSSION AND CONCLUDING REMARKS

This pilot evaluation of using large movement driving simulator experiments as a development tool for active safety systems for commercial heavy vehicles have given some insight on what has to be addressed for successful experiments to be conducted when systems like ESC with hard automation design philosophy are evaluated. This study was conducted with professional truck drivers that must be taken for highly skilled drivers which most likely makes it harder to design realistic driving scenarios where the driver has a ‘loss of control’ situation compared to passenger car drivers used in similar ESC simulator experiments. Used ‘potential yaw/roll control loss’ static reference bands emulated fairly well the actual ESC interventions on the level of scenario instances, although not the exact timing with the real ESC interventions.

Revisiting the questions from Section 1, the first question addressed if the test scenarios could develop ESC intervention situations in the majority of the tests. Overall, the subjective criticality estimates are rather low, see Table 2, and ‘potential loss of control’ was reached only in 28% of curve situations and 22% of moose situations. In future experiments, the scenarios should be tuned
more aggressively. The second question if the scenarios can be repeated, the studies here show that there is a very clear effect of scenario repetition on subjective measures, although objectively the only significant effect is the reduction in speed in moose scenarios. These results together could be interpreted as suggesting that if scenarios are tuned more aggressively, to become more critical, one can expect a clearer effect of scenario repetition also on objective situation criticality. Question three about the vehicle system model and the realism of driving a vehicle was ranked 3.5 of 5, which can be seen as satisfying results, however one motion that is highly important for this type of driving situation is the longitudinal acceleration during braking which is not transmitted to the driver more than by a pitching motion in the used Sim II simulator. The realism will most likely be improved in the new simulator which planned to be built in 2010 in Göteborg which has a X/Y table which will allow better feeling for driver when braking. This will most likely also increase the awareness of ESC and its interventions for the drivers, which was only observed by one driver in this study. Finally question four about subjective results from questions answered by the drivers gave valuable input, and sometimes statistically significant results as well.

Additionally, the effect of the driving environment on speed in the moose scenario was highly unexpected. It can be seen in Figure 4 that the effect seems to be due mainly to lower speed in the first repetition, which could indicate that drivers, potentially unconsciously reacted to the cloudy weather by reducing speed. This finding suggests that great care needs to be taken if varying driving environment - in this case it is questionable whether the benefit of potential memory support was large enough.

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References