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Driver Response to Automatic Braking under Split Friction Conditions

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At normal pedal braking on split-µ a driver can actively steer or adjust brake level to control lateral drift. The same driver response and thus lateral deviation cannot be assumed when brakes are automatically triggered by a collision mitigation system, since the driver can be expected as less attentive. To quantify lateral deviation in this scenario a test was run at 50 km/h with 12 unaware drivers in a heavy truck. Brakes were configured to emulate automatic braking on split-µ. Results show that the produced maximum lateral deviation from the original direction was 0.25 m on average. Two drivers deviated by 0.5 m. This can be compared to 2.2 m which was reached when steering was held fixed.

Topics/Active safety and driver assistance systems, Driver modelling

1. INTRODUCTION

A road section with significantly different level of friction between left and right vehicle sides is said to have split friction or split-µ. Common reasons for split-µ are: oil spillage, uneven ice coating, and one-sided aquaplaning. When cruising or accelerating slowly the driver may not even notice the effect, but when braking hard in an emergency situation the effect from unbalanced braking forces may cause serious rotation of the vehicle towards the side of high friction. For trucks towing one or more trailer this can also lead to jack-knife [1].

At the event of modest rotation the driver can steer and balance uneven braking forces. However if the driver is surprised by the situation and thus unprepared it is likely that substantial lateral deviation from ego lane can occur before the driver has responded. This can result in run of road or collision with oncoming traffic. Fig. 1 provides an example of this where a truck ends up in the opposite lane.

Furthermore a hypothesis is that when braking is activated by an advanced emergency braking system, AEBS, automatically the surprise would become even bigger. And thus also produce bigger lateral deviation and higher risk of jack-knifing. One can also note the similarity to front tyre blow-outs that yearly leads to some fatal accidents e.g. see [2]. In [3] a truck simulator study was performed where the left front tyre exploded. It was observed that driver behaviour very much depended on if the blow out came as a surprise or not. Hence it is important to include the effect from surprise also when investigating automatic braking under split friction conditions.

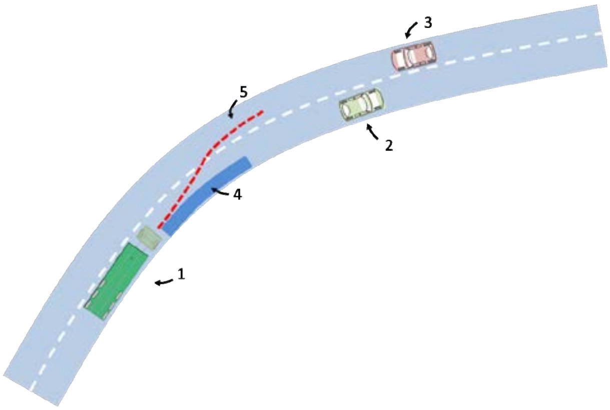

Fig. 1 An example with a truck (1) that brakes because of a stationary car (2). A patch of one-sided low friction (4) causes the truck to yaw and move sideways (5). When adding an oncoming car (3) into the scene an accident is imminent.

The split friction braking scenario has been a well-known hazard for decades and many innovations have been presented to reduce the effects [4]. Some have been proven more effective than others. E.g. brake pressure limiting approaches are already used on many vehicles, but have the effect of reducing brake performance. There are also legal requirements for split-µ braking that limits the allowed lateral deviation, under certain conditions [5]. The aim of this paper is to study if these legal requirements together with commonly used functionality are enough, on split-µ, when AEBS is introduced and soon mandatory on heavy trucks in Europe [6]. Or if there is a need of further supporting the driver.

In order to understand the severity in automatic braking under split friction conditions it is important to know how a driver reacts. For this reason a test was set up exposing drivers to a rather sudden situation, where the truck pulls sideways during automatic braking.

In section 2 the arrangement of the experiment is described, results follow in section 3 and finally section 4 present some conclusions. Notations and properties used, especially sign conventions, are compliant with ISO 8855 [8].

2. METHOD

The test was run with a 9 ton solo tractor on a test track where 12 drivers were exposed to sudden automatic braking. Research results were obtained through informed consent. Brakes were controlled to emulate split-µ conditions on an even test-track. The drivers were not aware of the true purpose of the test in order to preserve the effect from surprise. The test was carefully designed to guarantee safety.

Only professional drivers, normally driving durability tests of trucks, took part. The average age was 42, the oldest driver was 60 and the youngest 27. Only one driver had experience from pure brake or handling tests. Drivers were told that the intension of the test was to record normal positioning in lane and that they should run back and forth inside a straight lane for 300 m. Cruise control was set to 50 km/h. After running back and forth for 5 minutes, without any intervention, an operator fired of automatic braking as described. After the first unexpected intervention two repeated runs were made at the same speed, followed by two more at 70 km/h.

2.1 Vehicle and Track

A 6×2 Volvo FH pusher tractor was used in the experiment having the pusher axle lifted. Since the test was set up for the first time it was run without any trailers to ensure safety. The same goes with the selection of speed. It was low initially to guarantee safety. For more details on the vehicle used see Table 1.

The test was run on a test track in Sweden during two days in December. Temperature was 3-8°C. The track was slightly wet, but it did not rain. No other vehicle was nearby; therefore cones were put in the adjacent lanes creating a sense of danger. Fig. 2 provides an illustration of the set-up.

Table 1 Vehicle System Parameters

Description	**Value**	**Unit**
Wheelbase, distance between front and drive axle	4.1	m
Vehicle width, to outer wheel side	2.25	m
Front axle vertical load	58470	N
Pusher axle vertical load (lifted)	0	N
Drive axle vertical load	29430	N
Overall steering ratio	23.2	-
Steering wheel radius, measured from centre to rim edge	0.225	m
Wheel effective radius	0.5	m

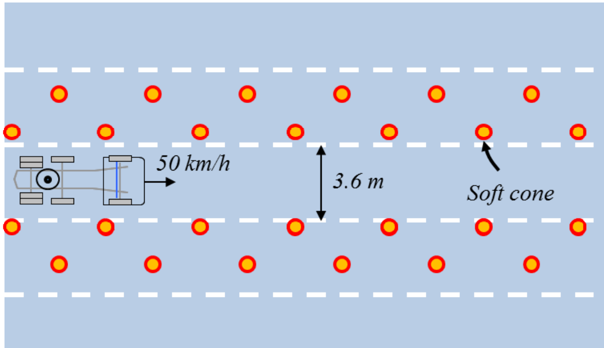

Fig. 2 The test was run at 50 km/h using cruise control. Soft cones were used to create a sense of danger.

2.2 Brake Controller

In [6] requirements implicitly say that an AEBS system shall be capable of performing deceleration by at least 2.2 m/s^2 during the emergency braking phase. Also stated is that "the AEBS shall be designed to minimise the generation of collision warning signals and to avoid autonomous braking in situations where the driver would not recognise an impending forward collision", i.e. nuisance should be avoided. In practise this means that the automatic emergency braking phase would have to be triggered closer to the imminent collision. In [9] normal braking behaviour of drivers in cars is analysed. At 80 km/h and time to collision, TTC, at 2.7 s it is a 75% chance that a driver would treat the required brake action as hard, in order not to collide with a moving target vehicle. In [10] a study on truck driver deceleration behaviour was made. At 80 km/h it was observed that normal braking does occur as late as TTC 3.9 s. This is based on 10000 normal brake interventions from euroFOT data. With the combined findings in [9] and [10] and the requirement regarding nuisance in [6] an AEBS should at least be capable of decelerating at 3.5 m/s^2 during the emergency braking phase. Here assuming that brake initiation is delayed until TTC 4.0 s and that the brake system has a delay of 0.2 s from brake request until full deceleration is reached (this delay was verified on used truck). Therefore as target deceleration 3.5 m/s^2 was used in a brake controller.

The controller consisted of a feedforward and a feedback part. The feedforward part was constant and the feedback part was a PI controller with integrator saturation and delayed initiation.

The sum of the feedforward part and the PI controller was fed into a static allocation function. The proportion between left and right brake torque was fix and set to 4. This value was derived from real split-μ testing, using normal factory brake system settings. In this mode the tractor was compliant with [5] since it had a brake pressure limiting function setting allowed difference between left and right brake pressure. The relation between front and rear brake pressure was set according to static normal loads. A linear relation was assumed between brake pressure and brake force. In Fig. 3 a block diagram of the controller is shown. All properties included are listed in Table 2.

In case the driver pressed the brake pedal a select high pressure routine was used per wheel. If the driver pressed the accelerator pedal the test was aborted.

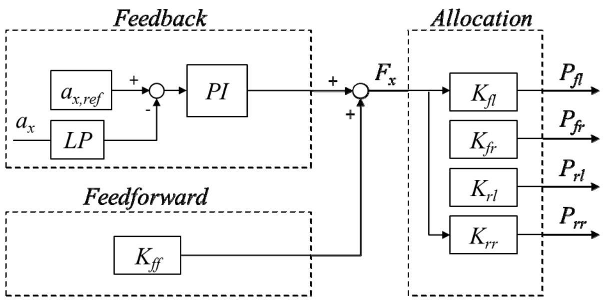

Fig. 3 Block diagram of brake controller

3. RESULTS

All 12 trajectories relating to the very first exposure of automatic braking interventions are shown in Fig. 4. All lines have been rotated and moved so that (0, 0) m correspond to where the operator activated the automatic braking, i.e. brake onset. The stopping distance, counting from brake onset, ranges from 30.2 m to 33.3 m. Two drivers instinctively deactivated the intervention by pressing the accelerator pedal. This corresponds to the two trajectories that continue to travel even after 35 m. The mean maximum lateral deviation was 0.25±0.07 m, using 95% confidence level. Two drivers deviated by 0.5 m. The open loop response produced by locking the steering wheel, StW, is also shown. It deviates by 2.2 m at standstill.

Corresponding time series are shown in Fig. 5. Looking at the speed curves it can again be seen that two drivers instinctively deactivated the intervention by pressing the accelerator pedal. The second subfigure shows StW angle relative change, calculated as:

$$\Delta\delta_H(t) = \delta_H(t) - \delta_H(0) \qquad (1)$$

where $\delta_H(t)$ is StW angle at time t. After 0.6 s, on average, drivers started steering. Some drivers responded with a smooth and steady movement of the steering wheel, whereas others oscillated widely.

The negative scrub radius, which acts destabilizing, can be observed in the StW torque plot. Around -2.5 Nm of the disturbance reached the driver.

As seen in the last subfigure yaw rate starts building up after 0.3 s and also the response shows a one period sine wave. Corresponding frequency, 0.5 Hz, happens to match the resonance frequency of several truck combination types, see [7]. This highlights the importance of extending the study for multi-unit truck combinations.

Table 2 Brake Control Parameters

	Notation	Value	Unit
Feedback			
Measured longitudinal acceleration	a_x	-	m/s^2
First order low pass filter with time constant 0.2 s	LP	-	-
Target longitudinal acceleration	$a_{x,ref}$	-3.5	m/s^2
PI saturation		6000	N
P-gain		4000	N/m/s^2
I-gain		20000	N/m/s
Integrator saturation		2000	N
PI activation time		1.5	s
PI error linear ramp up duration		0.5	s
Feedforward			
Braking force	K_{ff}	-18000	N
Allocation			
Total longitudinal force	F_x	-	N
Allocation constant	K_{fl}	-2.04×10^{-4}	Bar/N
Allocation constant	K_{fr}	-5.10×10^{-5}	Bar/N
Allocation constant	K_{rl}	-6.79×10^{-5}	Bar/N
Allocation constant	K_{rr}	-1.70×10^{-5}	Bar/N
Brake pressure (front/rear left/right)	$P_{fl/fr/rl/rr}$	-	Bar

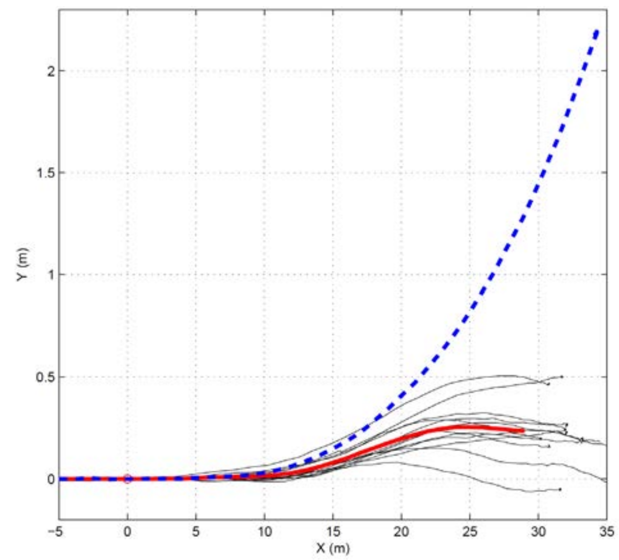

Fig. 4 Position of tractor rear axle during unexpected brake intervention, starting at (0, 0) m. One black solid curve per driver, thick solid red is average of all drivers, dashed thick blue is reference run with fixed steering. Lines have been moved and rotated to get zero offset and heading at beginning.

Continuing with the repeated runs, Fig. 6 and 7 give all trajectories and time series from the repeated runs. Four runs have been filtered out since the drivers pressed the accelerator pedal early on during the exposure. The average maximum lateral deviation observed is 0.13±0.03 m, again using 95% confidence level. There seems to be a reduction in lateral deviation, as drivers become aware of the true purpose of the test. To investigate this further a paired t-test was performed on the StW response. Fig. 8 show average change in StW angle from both the initial runs and the repeated runs. Also shown is the average difference between these runs per driver. Since each driver conducted only one initial run and two repeated runs the comparison is made between the initial run and the average of the repeated runs. In the four cases where runs are excluded only one repeated run is used. The difference between the lines indicate that there is a difference in reaction time between the runs. This is also clearly confirmed with the t-test which show a significant difference after 0.5 s, run with 95% confidence level and 11 degrees of freedom. Looking at the time where the on average -5 deg is passed the difference is about 0.1 s.

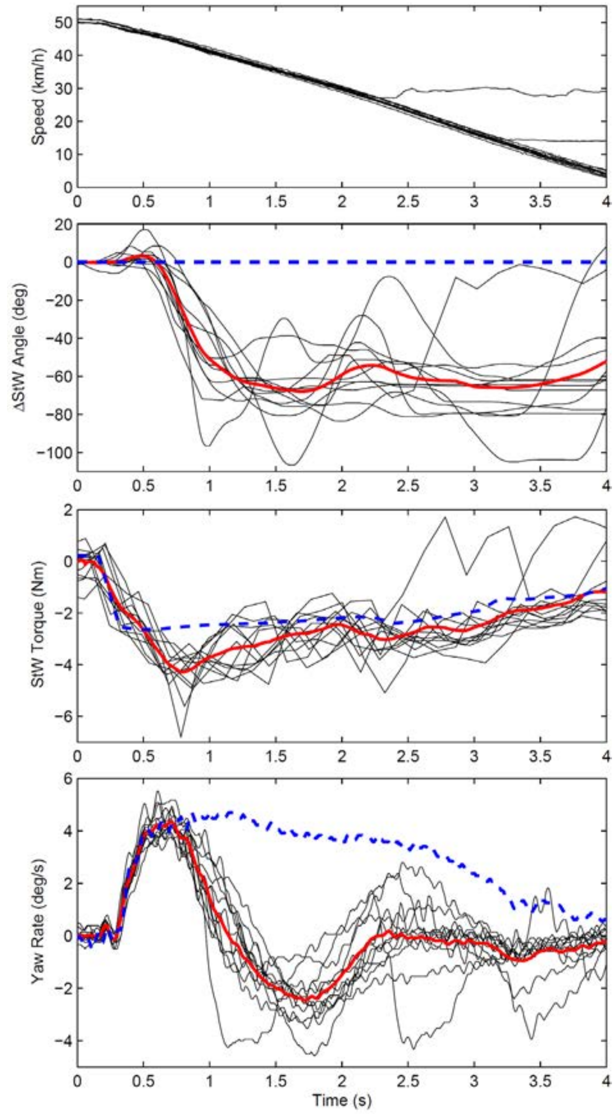

Fig. 5 Response to unexpected brake intervention, starting at time 0 s. Line styles same as in Fig. 4.

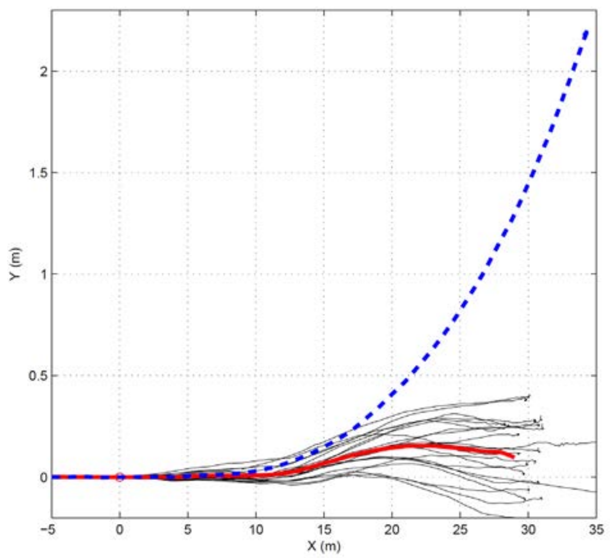

Fig. 6 Position of tractor rear axle during repeated brake intervention. For line styles see Fig 4.

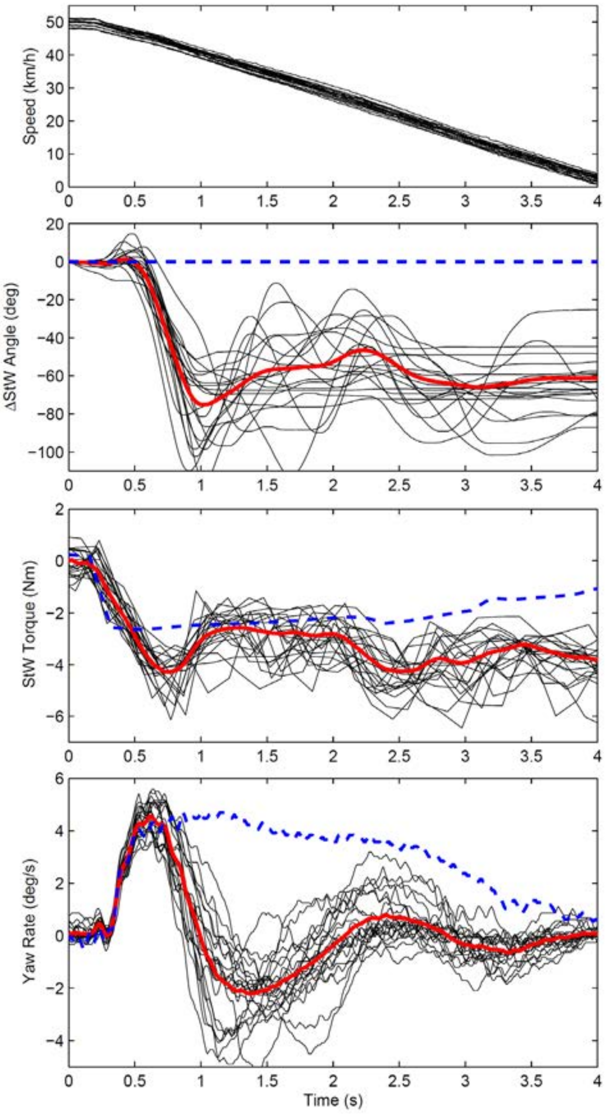

Fig. 7 Response to repeated brake intervention, starting at time 0 s. Line styles same as in Fig. 4.

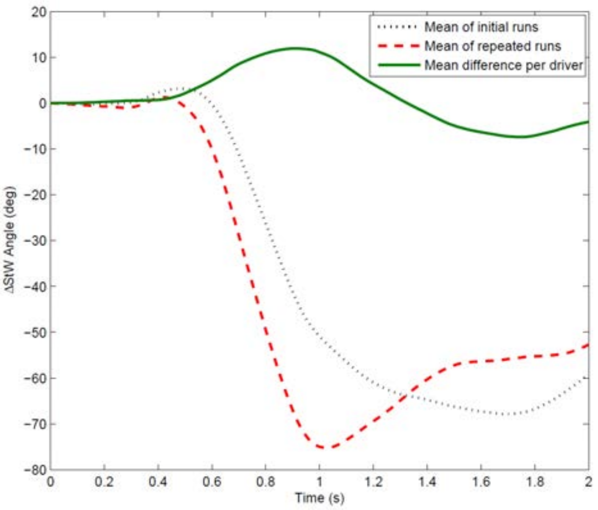

Fig. 8 Mean value of change in StW angle from the first initial runs and from the repeated runs. Also shown is the average difference between the initial run and the repeated runs.

For the repeated runs done at 70 km/h the lateral deviation observed was at a similar level as in the repeated runs done at 50 km/h. The average maximum lateral deviation observed was 0.10±0.04 m, using 95% confidence level. The reaction time, before reaching a StW angle of -5 deg, was again lowered.

4. CONCLUSION

The combination of split-µ and automatic brake intervention has been tested in a truck with 12 unaware drivers. Even though drivers were unaware of brake intervention they were still all aware of being part of a study and consequently more observant than normal. The lateral deviation observed was higher in the first runs, when drivers were unaware, compared to repeated runs. An identified reason for this was shorter reaction time. Measured levels suggest that the risk of collision, due to lateral deviation, is low for an alert driver. For a distracted driver more support might be required. This was motivated by the runs where steering was held locked. As was obvious from the repeated runs a driver which knows what will come is more effective in reducing lateral deviation. This underlines the fact that the warning phase, which is already an important part of AEBS, should not be underestimated.

Also beneficial would be a low value, or even negative value, of scrub radius since this limits the destabilising StW torque which has to be taken care of by the driver. Using even more sophisticated approaches for StW torque, like overlay torque guidance, might even improve the results further. This is however not obvious.

Angle overlay, steer-by-wire or rear axle steer systems are other ways of reducing lateral deviation even further, e.g. see [4]. These also have the potential of reducing the stopping distance, when combined with brake controls. Stopping distance is obviously important when AEBS has activated due to risk of collision.

No major difference in lateral deviation was observed when increasing speed from 50 km/h to 70 km/h. Drivers did however show shorter reaction time in this case, most likely since it was the last part of the test.

Finally said, the yaw rate frequency matched, in most runs, the resonance frequency of several truck combinations. It is however not clear whether drivers respond in the same way when having trailers connected. Therefore additional tests, including trailers running at a higher speed, are of importance to completely be able to investigate the combination of automatic braking on split friction.

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