Final report AFFECT
(FFI Dnr 2015-04817, Aktiv styrkraftsåterkoppling för tunga fordon steg 2)

Project within: Fordons- och trafiksäkerhet
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1 Executive summary

Traffic accidents constitute one of the leading global causes of death. Deadly traffic accidents occur, even in countries that have implemented far-reaching countermeasures, at a rate that cannot be tolerated. Improved safety of heavy trucks is an important remedy, as these vehicles are involved in a large part of all fatal accidents. Human error forms the leading cause of these accidents. Yet, the human ability to handle unstructured elements is unparalleled. The focus of this project was is to develop a method for controlling the longitudinal and directional motion of the truck combination.

The method combines the strength in human flexibility and a computer's ability to act fast in structured situations. Furthermore, the method is derived from observations of how drivers behave in normal and critical situations. This approach is defined as driver-centred vehicle motion control, where primarily steering and braking are coordinated.

The most important common conclusions drawn from these studies are the following. Steering wheel torque can be used as a means of changing driver behaviour. Yet, this requires that the action of the torque coincides with the cognitive objectives of the driver. A consequence of this is that the applied torque must change slowly in order to have a potential effect on the motion. Differential braking proves to be a much more effective approach when fast directional changes are required. This calls for a combination of differential braking and slowly varying steering wheel torque guidance, which is how the developed method operates. The control method has been implemented and evaluated in three studies and reported in a PhD thesis. Additionally, experiments in a real vehicle was made to verify the actuation with today's steering and brake systems. Also, a study on angle-overlay steering systems was added after the PhD thesis.

2 Background

Going back to 1997 the Riksdag (Parliament) in Sweden adopted a long-term vision of zero fatalities and severely wounded in traffic. Most common accidents, involving heavy vehicles, that are causing fatalities or severely injured victims, are: Oncoming collisions with a car or another HGV (~32% of victims). Based on the findings of AFFECT step 1 (FFI-project 2012-00938) and that of other researchers, it is clear that a quick lateral avoidance manoeuvre, to prevent an oncoming collision, requires more than only steering torque feedback; also other autonomous intervention countermeasures are needed to avoid overexcited driver reflex action.

Controllable steering assistance systems are now emerging into heavy vehicles, e.g. Volvo Dynamic Steering. In combination with wheel-individually controllable brakes and emerging environment sensing systems, the vehicles then have hardware equipment to take a steps in coordination of actuators for new safety functions.

3 Objective

The project had the objective to develop knowledge useful for development of a novel driver-centred vehicle motion control, coordinating steering, braking and propulsion are coordinated.

4 Project realization

The project was run as a research project with main contribution from one PhD student, Kristoffer Tagesson. The student had a strong support for test vehicles and simulation models from both companies, Volvo GTT and Sentient.

5 Results and deliverables

Kristoffer Tagesson graduated as PhD in mid 2017. Concepts for steering control and coordination was developed and presented in several publications, including a PhD thesis [1].

Additionally, experiments in a real vehicle was made to verify the actuation, see 5.1.

Further on, a study on angle-overlay steering systems was added after the PhD thesis. See 5.2.

5.1 Verification of actuation of lateral avoidance in real vehicle

Tests with tractor and semi-trailer on AstaZero test track where performed. The steering and brake coordinator developed during the project was used to do a quick and small ($\approx 0.5\ m$) lateral displacement of the vehicle. The purpose was to verify that the vehicle actuation used in simulator tests in [6]. The test showed that the actuation works.

5.2 Investigation of active angle-overlay for Steer-by-wire functionality in Heavy Vehicles

During the project it became evident that control of the vehicle during avoidance scenarios such as a lane change can be significantly enhanced if the driver can be taken out of the loop. Such scenarios require quite high angular rates of the front axle steering, and a driver with the hands on the steering wheel is thus a limiting factor. This is especially true during low-mu conditions. So called "Steer-by-Wire" (SbW) systems have entered the passenger car segment lately on a limited basis, but are today not represented among heavy trucks. Such systems allows for disconnecting the driver, but are by today not foreseeable for series production in the near future. Another suitable technology are differential angle actuators that have been introduced to passenger cars around the millennium shift and can today be found in the majority of high end and mid-sized vehicle. The following characterises a differential angle actuator:

1. With an angle overlay system, the driver can be disconnected up to a certain steering wheel/road wheel angular speed

2. A mechanical steering column and mechanical connection is always present.

3. There is no engaging/disengaging member such as a safety clutch in SbW systems with mechanical backup.

The research question was therefore if a differential angle actuator could be used in order to provide SbW-like functionality within the framework of heavy vehicles of today. What made the investigation of particular interest is the following:

1. Many heavy trucks have indirect steering due to legal requirements for the case of loss of hydraulic assist. The driver though desires direct steering for day-to-day usage. With the differential angle actuator, the driver can have a "virtual" direct steering which becomes "indirect" during fall-back, and thus fulfils legal requirements.

2. There a various suppliers available with solutions that are proven in practice, i.e. little new development is required.

3. A safety system, such as an "autonomous avoidance function" can be sold as a bundle with a comfort functions (see [1]), where the comfort functions is the primary object of interest for the buyer. Market penetration of safety systems is therefore likely to increase, as these are part of the functional bundle. The same happened in the passenger car segment.

There are today two types of angle overlay systems present on the marked, namely planetary gears or harmonic drives. Both provide constant meshing of gear teeth but use different gear types. In both cases an electric motor is present to produce a differential angle between steering wheel and road wheel. The differential angle between the shafts of the actuator is proportional to the differential angle of the electric motor. The gain or amplification of the actuator can be decided by choosing the physical gear ratios of te planetary gear or the harmonic drive The research question thus became:

- **Research Question:** Can a standard differential actuator be used in order to provide SbW-like functionality for a heavy truck, and in particular, is the provided maximum angular rate sufficient for autonomous avoidance manoeuvres?

In order to answer the research question a number of activities have been conducted.

Collecting relevant data for a double lane change on low-mu: During the winter test 2016, a Volvo FH 4x2 tractor running bobtail was used in a double lane change manoeuvre with and without driver. During these scenarios, quite substantial steering wheel angle rates were required, and it becomes evident that the driver with the hands on the wheel can be a limiting factor in an autonomous manoeuvre. Another aspect worth mentioning is that the hydraulic power steering was operated close to its flow limit.

Test rig with truck steering system and differential angle actuator: A test rig has been built where a passenger car differential angle actuator has been connected to the upper part of a trucks steering system. The passenger car system came from an Audi A7, and had to be modified. The electronic control unit did not allow for a control as required for a truck (which was expected), so a new controller was developed including 3-phase control of the brushless DC motor. The main task of the differential angle controller has been to disconnect the driver during the autonomous lane change, i.e. the road wheel angle had to be changed without interference from the driver. The collected data from the winter test has been used in the test rig.

Result of sub-project

Using the test rig together with the data from the winter it was able to answer the research question of this sub-project with "**yes**": It is possible to use a standard differential angle actuator for the scenarios from the winter test 2017 in Kiruna. Generally speaking, a typical passenger car servo system has a catch up limit of approximately 900 deg/s, while a truck

steering peaks at approximately 600 deg/s. The differential angle actuator used in this project peaks at approximately 650 deg/s if the motor controller applies field weakening control for the three phase currents of the motor.

6 Dissemination and publications

6.1 Publications by the PhD student

All publications from the PhD student Kristoffer Tagesson can be found at https://research.chalmers.se/person/kristoft. Here, also publications from the FFI-project 2012-00938 are contained, with links to full-text versions. A subset of this are the publications from present project:

[1] Kristoffer K D Tagesson, Driver-centred Motion Control of Heavy Trucks, Doktorsavhandling, 2017

[2] Kristoffer K D Tagesson, D. Cole, Advanced emergency braking under split friction conditions and the influence of a destabilising steering wheel torque, Vehicle System Dynamics. Vol. 55 (7), p. 970-994, Artikel i vetenskaplig tidskrift, 2017

[3] Andrea Sinigaglia, Kristoffer K D Tagesson, Paolo Falcone et al, Coordination of motion actuators in heavy vehicles using Model Predictive Control Allocation, IEEE Intelligent Vehicles Symposium, Proceedings. Vol. 2016-August, p. 590-596, Paper i proceeding, 2016

[4] Kristoffer K D Tagesson, Björn Eriksson, Johan Hultén et al, Improving directional stability control in a heavy truck by combining braking and steering action,

[5] International Symposium on Heavy Vehicle Transport Technology (HVTT14), Konferensbidrag (offentliggjort, men ej förlagsutgivet), 2016

[6] Kristoffer K D Tagesson, Leo Laine, Bengt J H Jacobson, Combining Coordination of Motion Actuators with Driver Steering Interaction, Traffic Injury Prevention. Vol. 16 (Supp 1), p. 18-24, Artikel i vetenskaplig tidskrift, 2015

6.2 Other publications from project

[7] Syarifah Siregar, A New Design of Human-Machine Interaction for Steering Articulated Truck Combinations, MSc thesis, https://research.chalmers.se/publication/216073 , 2015

[8] Andrea Sinigaglia, Actuators Coordination of Heavy Vehicles using Model Predictive Control Allocation, https://upcommons.upc.edu/handle/2117/83028, 2015

[9] Patrick Volz, Analysis of Potential in Asymmetric Braking for Autonomous Applications, MSc thesis, http://studentarbeten.chalmers.se/publication/254938-analysis-of-potential-in-asymmetric-braking-for-autonomous-applications , 2018

7 Conclusions

Development of driver-centred motion control for heavy trucks is an important step towards improved traffic safety. This has been the focus of this thesis. Driver behaviour has been analysed and has resulted in several conclusions. These conclusions have formed the basis of a longitudinal and directional control method that has been proposed. This method has thereafter been implemented and tested in three applications that all represent important traffic safety problems. For the first application a demonstration of split friction braking, when considering that the driver's level of attention can vary, has been performed. Directional stability control has been the focus of the second application, where the developed method

was compared to the ESC system that was fitted to the truck. The third application has focused on oncoming collision avoidance.

The first question that has been analysed with respect to driver behaviour is whether it is possible to affect a driver with overlaid steering wheel torque. This has led to the conclusion that only slowly changing torque guidance can be expected to have an effect upon the motion of the vehicle, when assuming that the magnitude is kept below reasonable limits. Typical human cognitive delay (~0.2 s) can be used as a limit to define what slowly means.

Yet, a slowly changing steering wheel torque contribution can only have an effect upon the motion of the vehicle when the cognitive objectives of the driver coincide with the guidance. This was for instance demonstrated in a driving simulator experiment run by Melman et al.[1] where subjects supported by an LKA function hit far less cones that had been put on the sides of the lane. In order to be able to fully utilise prior art in the field of steering, and to be able to transfer steering torque functions between vehicle types, it is important to establish an understanding of how steering wheel torque should scale as vehicle dimensions change. It can be concluded that some tuning will always be required when functions are e.g. transferred from cars to trucks. It is however possible to start by using two simple general rules, describing how to scale functions and results when important dimensions change. Firstly, a driver perceives force rather than torque. Secondly, yaw rate gain is the primary property that a driver perceives as the response variable of a vehicle.

The number of heavy trucks that are equipped with AEBS will grow in number in the coming years, as fleets are renewed and as more countries enact laws. Also, the number of scenarios targeted by AEBS will grow. All in all this will make it more likely that AEBS will activate more often on split friction. Similarly to a front tyre blow out, this will cause the vehicle to decelerate with an acting yaw torque disturbance. As trucks have positive steering offset at ground this will furthermore lead to a destabilising steering wheel torque disturbance. It has been found that the magnitude and rate at which the torque is applied will limit its effect upon the motion of the vehicle, when the driver is gripping onto the steering wheel. For an incapacitated driver the effect can be a lot higher. With respect to the ability of drivers to handle a yaw disturbance it has been found that the limits that were developed by Neukum et al.[2], where above a failure can be considered as dangerous, are also relevant for trucks.

The performed studies further proved that differential braking can be used as a tool to override a driver, in particular when fast directional movements are required. The developed motion controller has therefore been designed to combine differential braking and steering wheel torque guidance. The rate at which the torque guidance should be allowed to change can be set by a parameter. The method further demonstrates the benefits that can be achieved when steering and braking are commonly coordinated.

The three applications that have been demonstrated show that it is enough to build only one method for motion control and still achieve good performance. When more and more higher layer functions are to be introduced, e.g. as new sensors are available, it is not only convenient to have this type of hierarchical control design as a foundation, it will most likely even become a necessity. A unique operating system cannot come with every application that is to be installed. That would drive a huge cost and limit the growth of innovations. The driving simulator study that has been run on the topic of oncoming collision avoidance represents a

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[1] T. Melman, J. deWinter, and D. Abbink, "Does haptic steering guidance instigate speeding? a driving simulator study into causes and remedies", Accident Analysis & Prevention, vol. 98, pp. 372–387, 2017.
[2] A. Neukum, E. Ufer, J. Paulig, and H. Kruger, "Controllability of superposition steering system failures", Steering tech, 2008.

clear example that it is possible for a human driver and a computer to share the control of a vehicle; also in the lateral direction. Moreover, when starting to consider further use cases where the developed motion controller can be applied it is apparent that an immense safety benefit could be elicited. Some examples of potential benefits include: i) collisions caused by unintentional lane departures where the driver is incapacitated or distracted, ii) collisions with unprotected road users, iii) collisions at intersections, iv) run off road accidents, v) collisions with animals, and vi) accidents caused by a jack-knife.