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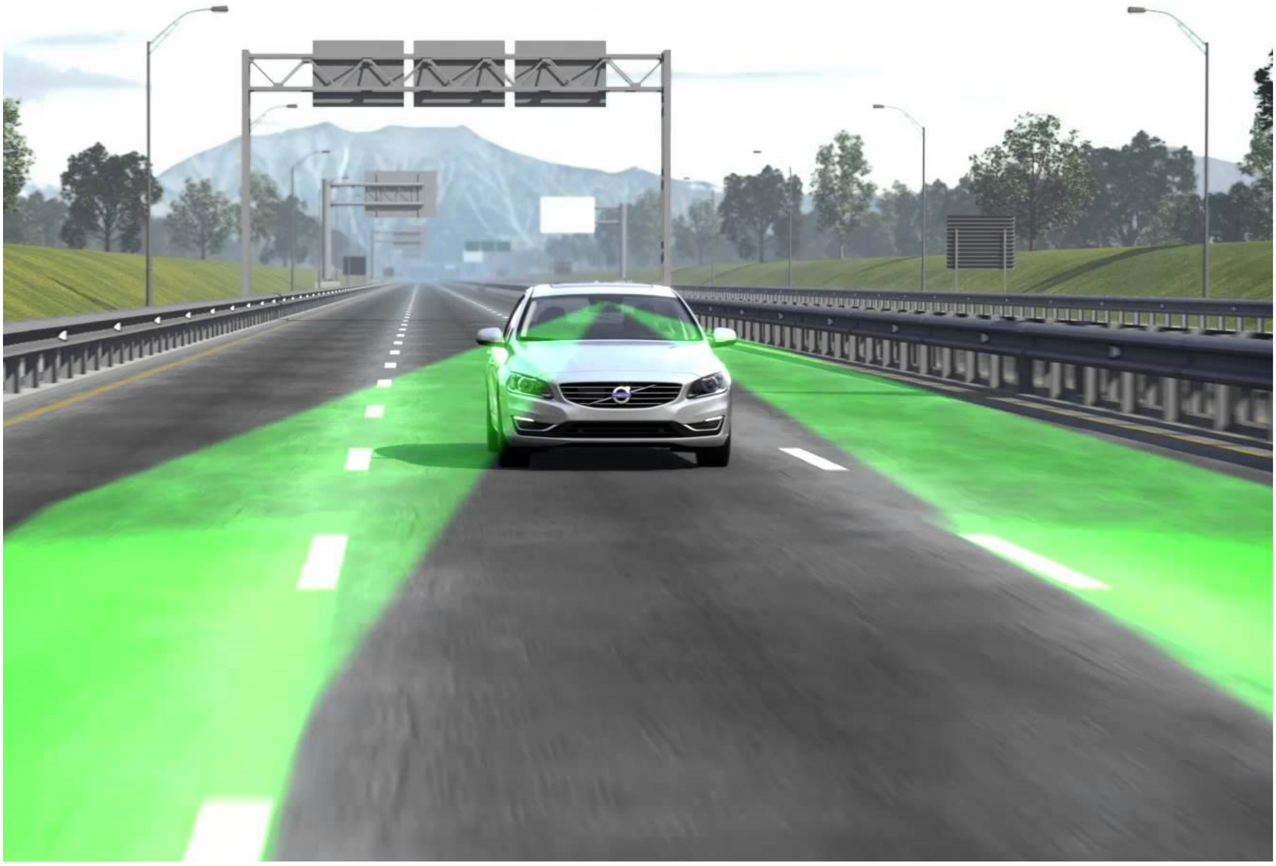

Driver response to a lane-departure prevention system

Based on real-world traffic data

Master's thesis in Applied Physics

LINUS LILJEBLAD

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2015

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An illustration of a lane-departure prevention system. Reproduced from Volvo Car Corporation.

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Abstract

Today, there are commercially available cars with some kind of *lane-departure prevention* system, with the purpose of stopping the driver from unintentionally crossing the lane marker. The latest versions of the system does not only warn the driver, but is actually trying to steer the car back on the right track when the driver fails to steer the car sufficiently. The systems applies torque on the steering rack which then translates into the wheel as well as the steering wheel and effects both the driver and the car. The driver's reaction to this kind of intervention has been studied before in experiments but never investigated in real-world traffic data.

This thesis describes a methodology to understand driver response to a lane-departure prevention system based on an analysis of real-world traffic data. As far as the author is aware, this type of analysis has never been done before, and therefore it constitutes an important part of the understanding of driver behaviour. The purpose was to develop a methodology that could describe the drivers reaction when external torque from the lane-departure prevention system was applied.

The study show that it was possible to give a rather good description of how the driver reacts to an externally applied torque. A reaction was noticeable for almost every intervention when only looking at the torques in the system, but a distinct visible reaction was only noticeable in 11.6 % and 19.1 % of the initial (0 s–0.5 s) and whole intervention respectively. The difference in applied torque between the driver and the lane-departure prevention system also showed that the driver tends to take more control over the steering wheel when the duration of intervention was longer than 0.5 second, than when the intervention was shorter or in the initial phase of a longer intervention. The study further show that it was possible to describe and understand the movement of the steering wheel by analysing the steering wheel angle and its rate. Finally, the fraction of the driver reaction with respect to the other torques in the system that effects the steering could be calculated and analysed.

Keywords: Driver response, lane-departure prevention system

Preface

The study for this thesis was conducted at Volvo Cars Safety Center, and within the Traffic Safety Data Analysis group at Torslanda, Gothenburg. The supervisors at Volvo Cars were Magdalena Lindman and Bo Svanberg, and from Chalmers University of Technology was Ola Benderius supervisor as well as examiner. The thesis was written at the Department of Applied Mechanics, in the Division of Vehicle Engineering and Autonomous Systems (VEAS), at Chalmers University of Technology as a part of the author's masters studies within the master Applied Physics.

Acknowledgements

First, I would like to thank my supervisors Ola Benderius, Magdalena Lindman and Bo Svanberg who has supported and guided me during this whole process of working with the research and writings of this thesis. Thank you for the time and effort you have invested in me. Without you, this had not been possible.

Secondly, I would also like to thank the rest of the Traffic Safety Data Analysis group at Volvo Cars Safety Centre, for taking me in as a part of your team, and a special thanks goes to Tobias Karlsson who has answered all my question regarding everything and especially programming issues. Thank you for your patience.

My last and final thanks goes to my wife Therese, who loves me despite my nerdiness and the times I have disappeared into the cave of technical stuff and science. Thank you for believing in me during all these years at Chalmers, and for never giving up hope of me finishing, even though the road has been demanding and bumpy.

Contents

1 Introduction

When buying a car today there is a lot to think about, such as image, design, price, comfort, horse powers and fuel consumption, to name a few. One thing, that many people emphasise when buying a car, is the *safety* aspect, cause if disaster strikes, that is what counts. When thinking about safety one could say that "It is not the speed that kills you, it is the sudden stop" [1]. With this being said, a lot of time, thought and money has been invested in car safety that has focused on making that 'sudden stop' not quite so sudden. Deformation zones, safety belts and airbags are nowadays standard functions in every car sold. The passive safety has been the biggest part of the safety work being done in the car industry and those safety precautions has a long history of saving lives. Today, the technical innovations in computer science and sensors technology makes it possible to stop the accident from ever happening. This active safety strategy is focusing on helping the driver to make better decisions when driving, and if needed, sometimes provide either braking or steering interventions. Active safety has in general saved a lot of lives with systems such as *electronic stability control*, [2] and the field is growing rapidly with a lot of new safety feature constantly developed.

Run-off-road (RoR), is one type of crash that causes serious injuries due to high crash severity [3], or in worst cases fatality [4]. The RoR crashes was accounted for 70 % of the total number of *single-vehicle crashes* (SVC), fatal traffic accident in US between 1991 to 2007 [5]. The crash type is defined as to when the car initially departs the road before running into, or hitting, another object. Also included are rollovers and undercarriage damage crashes. The impact object could be a ditch, embankment, tree, shrubbery, rocks, and all kind of static or moving objects. There are a lot of reasons as to why these crashes occur, and a numerous of explanations has been seen to why the cars departs from the road [3], even though over 95 % can be related to driver performance [4].

Many car brands, e.i. Audi, BMW, Ford, Mercedes, Toyota and Volvo Cars, have solutions to the lane-departure problem such as different lane departure warning and lane keeping aid systems [6, 7, 8, 9, 10, 11]. Different ideas on how to actually prevent the driver from drifting or steering of the road, gives rise to different implementations. This means that a system called *Lane keeping aid* or *Lane keeping assist* in one brand could act quite different from another brand, due to different torque implementations. So despite strong resemblance in names for the safety function, they could be perceived differently. The latest versions of these kind of systems applies both torque, to steer the car back on track again, and some sort of sound or haptic warning to alert the driver if the car is about to depart from the lane.

The different implementation means that the driver is going to response and react differently. The interaction between human and machine is crucial to understand in order to develop a function that cooperate with the driver in the best possible way. Experiment has showed that driver tend to react to applied torque with applying a torque in the opposite direction [12, 13]. This driver response has never been analysed in real world data, as far as the author is aware. The aim of this thesis is therefore to develop a methodology for analysing the driver response to a *lane-departure prevention* (LDP) system, based on real-world traffic data. The methodology should be able to evaluate and describe the driver response to an LPD intervention and whether or not the driver reacts by applying torque in the opposite direction with respect to the LDP system. The thesis should also show if the analysis methodology is relevant for RoR crashes by comparing the real-world traffic data with the RoR crash data.

1.1 Problem description

The overall purpose of this study is to create a methodology for evaluating driver response in real world traffic (i.e. not in an experimental situation) for an LDP system that effects the steering of the car. The aim is to describe the reaction and behaviour of the driver with respect to the LDP system. The driver response was investigated via an analysis of the real world data from a *field operational test* (FOT), sample. A driver could in principal react to an intervention in one of the three following ways: (i) fully relaxed or taking the hand of the steering wheel and by doing so letting the LDP system control the steering entirely, (ii) flex the muscles to some degree but still letting the LDP effect the steering, and (iii) fully flex the muscles and completely overtake the applied torque, to have control over the steering. If the reaction falls into the third category one may argue that the system still gives some kind of warning to the driver, whom consciously or unconsciously could contribute to the desired effect of the system.

The main research question; *What is the driver response to an LDP intervention?* was addressed by the following approach;

1. The driver response to an LDP interventions were analysed by using FOT data from cars with an LDP system.
2. Key measurements of the driver response was developed and applied to the FOT data.
3. The relevance of the FOT data was investigated by comparing LDP interventions and real world crashes from a crash data base.

The scope is the physical aspect of the driver response, and not about the cognitive or emotional reaction. In the experimental studies made previous to this thesis, the driver has been subjected to distraction and intervention on straight roads. Therefore, were the pre-crash scenarios filtered so that only crashes and event occurring on straight road were analysed. Even though no comparison was done in this study between experimental data and real world data, this would be of help for later comparison.

2 Background

This chapter will go through general background to how the driver response is originated and the steering arrangement in a car. This will later serve as the framework for the study and the analysis.

2.1 Driver's response to external torques

In order to do an analysis of the driver response a basic understanding of the human anatomy in regard to the neuromuscular system and reflexes is needed. These are fundamental building blocks when it comes to grasping how and why drivers reacts the way they do to an intervention. The following sections describes the fundamental parts of the neuromuscular system and their relation to the driver response, and a basic description of how the muscles work together. For more detailed presentation of the system, see [12].

The main components that controls the reflexes and movement of the limbs, are the muscles, spinal cord and brain. The full complexity of the system is not addressed in this study but merely an attempt to understand the basic reactions to externally applied torque on the steering wheel. A schematic view of the relationship between the brain, spinal cord and muscles can be seen in Fig. 2.1.

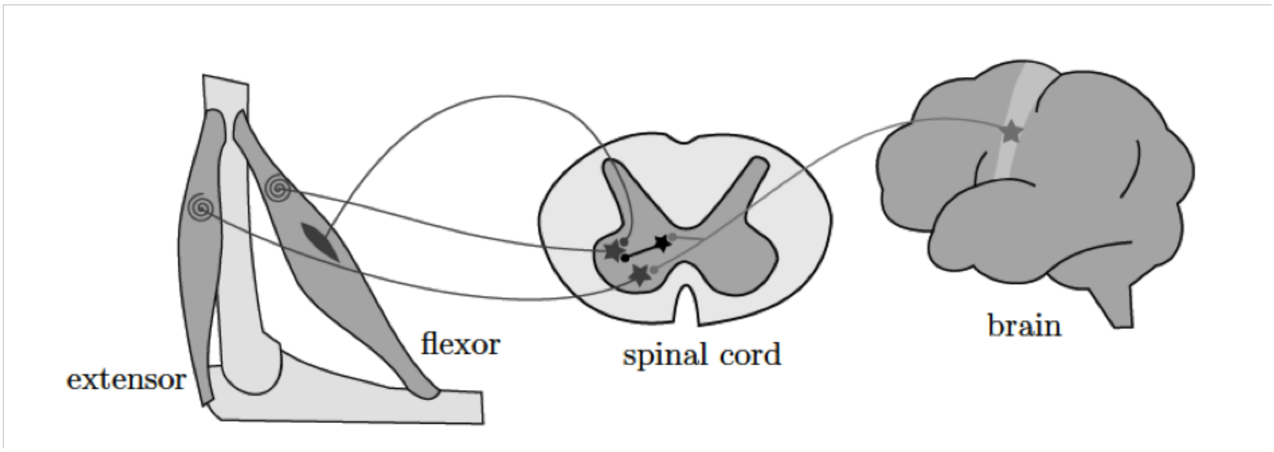

Figure 2.1: A schematic view of the relationship between the muscles, spinal cord and brain. Here the *bicep* and *triceps* muscles of the upper arm is illustrated as the *flexor* and *extensor* of the *antagonistic* muscle pair. Reproduced from [12].

When turning the steering wheel, the turning itself is not, as one could imagine, originated from a torque request from the brain but rather from an angle, or more precise, distance request. According to this theory [12], the steering could be seen as a reaching aspect which originates from the consciousness of the brain. The upper body, responsible for the turning of the steering wheel, is acting to meet the distance it needs to move to achieve the angle change. The *reaching-pattern* is fairly constant despite the distance the arms has to travel, hence making the time of a steering action quite uniform and could be separated from other types of movement.

The muscles are typically arranged in *antagonist pairs*, since a muscles can not push, but only pull joints, they work together in those pairs to create a movement, e.g. the *bicep* and *triceps* muscles, as seen to the left in Fig. 2.1. The forearm, for example, is lifted up when the bicep is contracted, *agonist*, whiles the triceps acts with a counter contraction, *antagonist*, to slow the lifting down until it comes to a stop. This interaction between the muscles is a highly complex cooperation and can consist of more muscles intervening, *synergistic muscles group*, than the main pair. The muscles are, in this type of movement, never contracted at the same time, but are activated in sequence after one another with an update frequency of 30 Hz–60 Hz, which causes a smooth motion. The naming convention, *flexor* and *extensor*, is given to the muscles depending on whether they increase or decrease the angle of the joint when and where they are activated, and the agonist refers to the muscles that initiates the movement and the antagonist, the one slowing it down.

When the brain instead of moving the limb wants to keep it steady, the muscles are activated at the same time so that they both pull at the joint in a *co-contraction*. A co-contraction is a way of removing unwanted movement in the steering wheel, and the response time for this type of action is around 200 ms and it normally originates from the unconscious part of the brain. The action makes the joint more stable and stops the angle from changing, but also more insensitive in regard to its fine motor skills.

The *stretch reflex* is yet another way the neuromuscular system can react, and arises when the length of the muscle is changed due to an applied external force. The muscle then sends a signal to the spinal cord which responds by sending an activation pulse to the muscle. Via contraction, the muscle then applies torque in the opposite direction, see Fig. 2.1. These reflexes are an unconsciously activated collaboration between the muscles and the spinal cord, and they are in general fast, around 50 ms.

A typically reaction pattern to a externally applied torque on the steering wheel, is then initiated by the stretch reflex which makes a first short counter reaction after about 50 ms. When 200 ms has passed, the unconscious co-contraction from the brain is initiated, and stabilise the arms and slows down the angle change. After this, the conscious part of the brain may take a decision to change the angle to its original position or to a new one, with the reaching-pattern. One could argue that this reaction is due to years of driving a car, but it has been showed that the reaction is rather fundamental and seems to be hard-wired in the neuromuscular system, when the same effect on applied torque was demonstrated in 12-years old drivers as well as their driving parents [12].

2.2 Steering of a car

The steering is more complex and has more variables and parts than presented here, but this section gives an adequate description at the level needed. There are basically three parts that contributes with torque to the steering of a car: (i) driver, (ii) *electrical power assistance* (EPAS) motor, and (iii) aligning. The EPAS motor is in general responsible for facilitating steering by adding torque on the steering rack, see Fig. 2.3, which reduces the amount of torque the driver has to apply. In Fig. 2.2 to 2.4, there are sketches of a steering arrangement presented with notation on where the signals are measured and where the torques originates.

Starting from the ground up, the first variables to take into account are depending on the dynamic and geometry of the wheels on the car. Here, there are a lot of factors one could take in consideration, e.g. suspension, friction, the weight of the chassis and so forth, but in this study only the *aligning torque* (T_a), in Fig. 2.2 was considered. The torque has the name due to its tendency to self align the car when there is a difference in heading of the car and the wheel, see Fig. 2.2. In the case when the wheel has another direction than the car, the torque wants to reduce the *slidslip angle* (Θ) by turning the wheel straight again. The *trail distance* (d_t), comes the elasticity and dynamics of the wheel, *pneumatic trail* (d_{pt}), as well as the geometrical, *mechanical trail* (d_{mt}). The T_a comes from the offset, d_t, between the centre of the wheel to where the *trail force* (F_t), effect the tire, see Fig. 2.2, and is depending on the Θ. The d_t and T_a can then be written as

$$d_t = d_{mt} + d_{pt} \tag{2.1}$$

$$T_a = F_t d_t. \tag{2.2}$$

For more information on how the *trail force* or *pneumatic trail* is calculated see literature on vehicle dynamics (e.g. [14]).

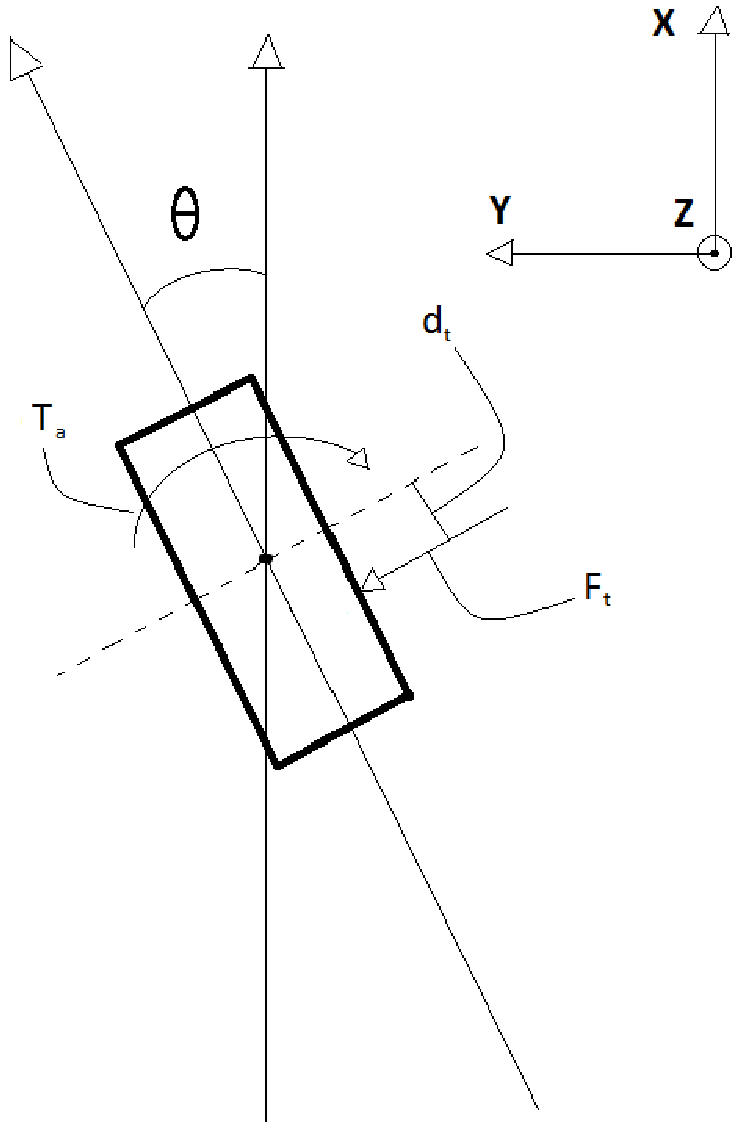

Figure 2.2: Sketch over the origin of the T_a, seen from a top view over a front wheel. The T_a originates from the distance d_t to the F_t. The car is travelling in the x-direction and the wheel is pointing in an offset direction with an angle Θ.

In Fig. 2.3, is a full overview of the steering arrangement as approximated in this study presented. In the figure are also the *steering rack*, *steering column*, *steering wheel*, and EPAS motor presented in a schematic way. When the T_a wants to turn the wheel, it effects the steering rack with an *aligning force* (F_a), that in turn effect the steering column and steering wheel, see Fig. 2.3. Since every part in the steering are connected mechanically, all movement and force applied will effect the whole system so that it always is in equilibrium. The *net torque* (T_n), is the summation of the applied torque in the steering arrangement, that translates into rotation of the steering wheel. The connection between the T_n in the steering arrangement and the *rotation acceleration* ($\ddot{\delta}$), of the steering wheel can be written as

$$J\ddot{\delta} = T_n \tag{2.3}$$

where J is the *moment of inertia*, for the whole steering arrangement.

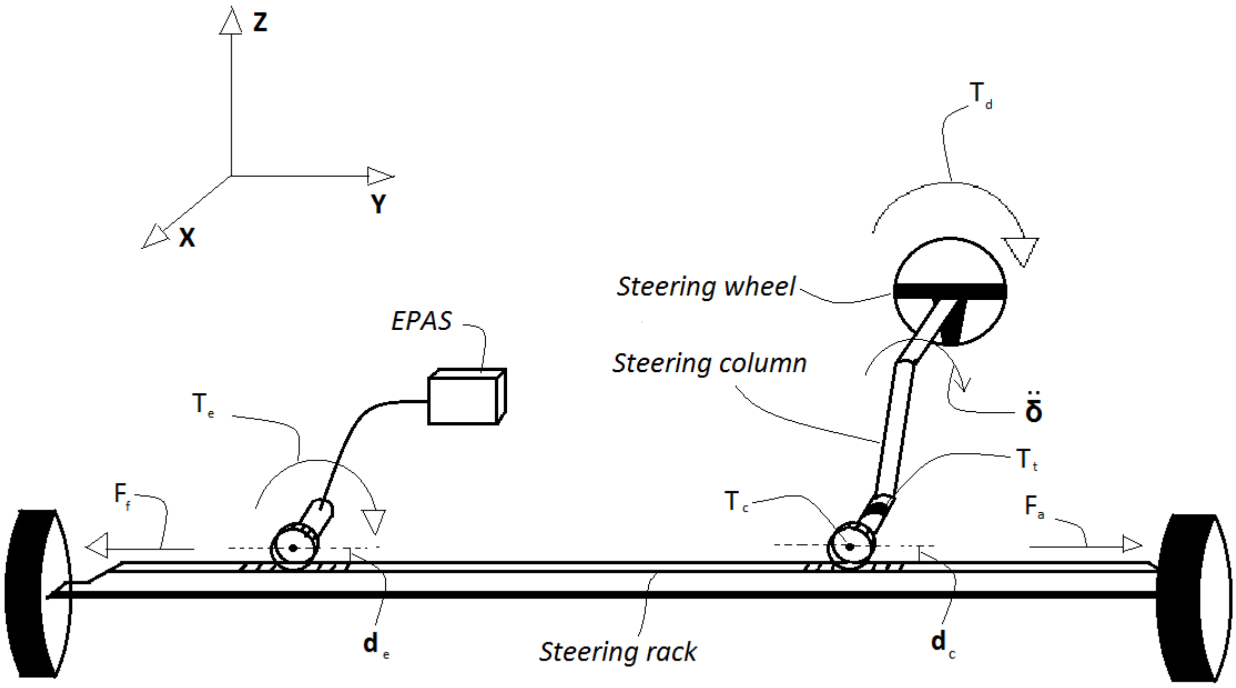

Figure 2.3: Sketch over the whole steering arrangement with the EPAS, steering rack, steering column, steering wheel, and all the torques T, distances d, and forces F that exist in the system of interest.

The *combined torque* (T_c), in Fig. 2.3, gathers the torques and forces from the steering rack into one combined torque that effects the steering column. The *friction force* (F_f), comes from within the arrangement and between the road and the tire. Both the F_f and the F_a are the respectively total forces from both wheel on the sides of the steering rack. The distance to the applied *EPAS torque* (T_e) and the calculated T_c from the steering rack is given by the distances d_e and d_c respectively. In the figure is also the *driver torque* (T_d), marked out as applied to the steering wheel. The T_n from the system could then be written as

$$T_n = T_d + T_c \tag{2.4}$$

where the T_c is written as

$$T_c = d_c \left(\frac{T_e}{d_e} - F_a + F_f \right). \tag{2.5}$$

From these equations, a final equation for the whole steering arrangement can be written as

$$J\ddot{\delta} = T_d + d_c \left(\frac{T_e}{d_e} - F_a + F_f \right). \tag{2.6}$$

When the LDP system is activated, the EPAS torque, T_e, can be divided into two components. One for the general *assistance torque* (T_{ass}) and one for the *LDP torque* (T_{ldp}). The actual torque from the LDP that effects the driver is the *intervention torque* (T_i), which is equivalent to the torque that the driver needs to apply to the steering wheel to get the same output on the steering rack as the LDP system do. Since the geometry is known in the system, it acts as a torque interface factor between the two torques, and the T_i could be calculated as

$$T_i = \frac{d_c}{d_e} T_{ldp}. \tag{2.7}$$

The movement equation for the whole system is then finally written as

$$J\ddot{\delta} = T_d + T_i + \frac{d_c}{d_e} T_{ass} - d_c F_a + d_c F_f = T_d + T_i + T_o \tag{2.8}$$

where *other torques* (T_o), is the combination of the assistance, aligning, and friction torques.

The *torsion bar torque* (T_t), as seen in Fig. 2.3, measures the overlap between the *upper* and *lower* part of the steering arrangement. The last figure, Fig. 2.4, displays an *free-body sketch*, and represent the whole steering arrangement as a stiff rod with a cut, where the T_t is measured.

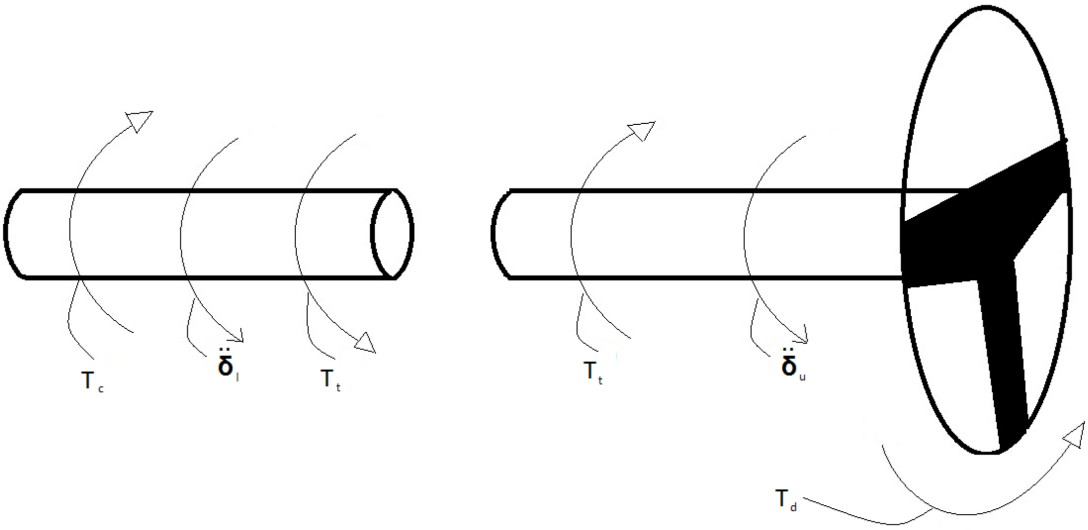

Figure 2.4: The *free-body* sketch as an approximation of the steering arrangement, with all the torques and movement terms.

The $\ddot{\delta}$ can be split into the upper and lower part in the free-body sketch. With the approximation that the torsion bar was stiff, the relationship between the $\ddot{\delta}$ could be written as

$$\ddot{\delta}_l \approx \ddot{\delta_u}. \tag{2.9}$$

The moment of inertia was also split between the upper, J_u, and lower, J_l part. Thus the equation could be written as

$$J = J_l + J_u. \tag{2.10}$$

From the free-body sketch the equations can be written as

$$J_u\ddot{\delta} = T_d - T_t \tag{2.11}$$

$$J_l\ddot{\delta} = T_t - T_c = T_t - T_i - T_o. \tag{2.12}$$

Finally one may note that

$$T_d = T_t + J_u\ddot{\delta} \tag{2.13}$$

$$T_o = T_t - T_i - J_l\ddot{\delta}. \tag{2.14}$$

3 Method

This chapter explains the LDP system, the different data sets and the important definition of an intervention and a straight road. The analysis method used in the study is also described in the end of the chapter.

3.1 The used LDP system

For the purpose of this study, a commercially available LDP system from the *Volvo Car Corporation* (VCC), referred to as *lane keeping aid* (LKA), was used. The system was first introduced in the Volvo V40 models from 2012. The predecessor to the LKA system was called *lane departure warning* (LDW), and gave an haptic and audible warning if the car crossed a lane marker. Today the LKA function applies a torque to the steering rack in order to steer the car back into a safe trajectory. If the applied torque is insufficient, and the car proceeds over the lane mark, a haptic warning in the steering wheel lets the driver know that the car left the lane. Today's LKA function has three different settings that let the driver can choose from: full function with both LKA torque and haptic warning, only LKA torque or only haptic warning.

The system used as an example in this thesis was the second generation of LKA and can be found in 2014 years S/V60 models. LKA was primarily intended to be used on freeways and highways between the speeds of $65\,\mathrm{km\,h^{-1}}$–$200\,\mathrm{km\,h^{-1}}$ [11]. The system also had restraints on maximum strength and rate for which the system could apply torque to the steering. A couple of factors can turn the system off e.g. activated direction indicators, no hands on the steering wheel or poor lane markings [11].

For the analysis carried out in this work, the driver torque, T_d; the intervention torque, T_i; and other torques, T_o are used. The intervention torque is known due to on-line measurements, and the driver and other torques are calculated according to Eqs. 2.13 and 2.14 based on the fact that the torsion bar torque, T_t, is known. The moments of inertia, J_u and J_l, is not known but approximated as $0.035\,\mathrm{kg\,m}$ and $0.107\,\mathrm{kg\,m}$ respectively [15].

3.2 FOT data

The FOT data from the on-going *Eyes on road project* [16] includes both *controller area network* (CAN), data and video samples from naturalistic driving and GPS signals. CAN data are signals that exist on a local network inside a car and monitors almost every electrical feature of a car. This makes it possible to manually validate the analysis based on the CAN data, by looking at the video while checking the signals. The FOT data was recorded in the period of 22 May 2014 to 28 April 2015 and covered ten company cars of the V60 model from 2014, who were equipped with CAN recorders and five cameras that captured the forward, back, driver, eye movement and foot placement. The total driving time covered over 4300 hours divided over roughly 14300 trips. The data was re-sampled from 40 Hz–60 Hz into 10 Hz to be compatible with the existing FOT analysis programs at VCC.

The FOT data contained 14348 trips and within them 4437 had LDP interventions according to the definitions (in Sect. 3.4). From the 4437 trips, the total number of interventions were 27059. Of the 27059 interventions, 12552 that occurred on a straight road, constituting the main data sample for the study.

3.3 Crash data

The real-world crash data from *Volvo Cars Statistical Accident Database* (VCTAD), was used to analyse RoR crashes. VCTAD contains Volvo passenger vehicles in Sweden in which the repair cost due to a crash exceeds a specified level. Inspectors from Volvia (If P&C Insurance), the company in which all new Volvo passenger cars are insured, identify the crashes. Photos and technical details of the cars are sent to *Volvo Cars' Accident Research Team*. A detailed questionnaire is sent to the owner of the car to gather information about the crash, the car and the occupants. With the approval of the occupants, medical records are sent for (when applicable) and coded by a physician within *Volvo's Traffic Accident Research Team*. Injuries are coded according to the *Abbreviated injury scale* (AIS), [17]. The limit of repair cost criterion is currently 4500 euro, a level chosen to cover traffic accidents of severity ranges where it is possible for occupant injuries to arise. This level has been adjusted over the years to reflect and keep the impact severity for different crash modes stable [18]. The data set that was analysed contained over 8,000 car crashes with recent Volvo car models from accident years 2002-2013, and had over 2,200 RoR crashes. A total number of 1085 RoR crashes with no traction loss was found, and of those were a random sample of 416 cases digitalised. Filtering of crashes on straight road gave 280 crashes out of the 416, which made the total number of crashes analysed 280.

With the information given from the drivers, generic simulations of the accidents was performed by using approximated locations and positions from the description in the questionnaire, to find the place of the crash. When the geometry of the road is defined, a simulation that gives lateral speed, the road departure angle in respect the the lane markers and the initial distance to the same, can be made. Together, the simulation and the questionnaire gives good knowledge about how the impact of speed, road departure angle and various distances correlate with the crash severity. The variable longitudinal speed was given in the questionnaire by the driver and the rest of the variables were calculated from the reconstructed simulations.

3.4 Definition of an intervention

The definition of an intervention was based on a signal that measures the LDP torque applied by the EPAS motor. This signal, which was only non-zero when LDP was activated, measures the strength of the applied torque. The duration was calculated as the time from the first non-zero values to the last, and in order to be counted as an independent intervention it was needed to be separated in time with at least 0.2 s from another intervention. The strength of an intervention was set to the max torque during the whole event. The torque rate was calculated as the first coefficient in a linear approximation between the closest values less than 25% and the closest value greater than 75% of the max torque. If the intervention was short, the 25% or 75% could in principle be the starting or max strength of the intervention.

Both a strength and a duration limit were implemented to filter the signal and diminish the effects of noise. The strength and duration were equivalent to the limit on which the LDP true/false state signal displays an ongoing intervention to the driver in the dashboard. An intervention was hence defined as when the applied torque from the LDP signal had two succeeding values that were greater than 0.5 N m, in other word, when the torque was larger than 0.5 N m for 0.2 s.

The LDP system should be active between speeds of $65\,\mathrm{km\,h^{-1}}$–$200\,\mathrm{km\,h^{-1}}$ [11], but from a pre-study done before the main study in this thesis, the discovery of interventions in lower speeds than $65\,\mathrm{km\,h^{-1}}$ was found. Another discovery in the pre-study was that sometimes the LDP torque was unrealistically high due to signal logging errors during service of the car in a workshop when the car had zero speed. Therefore, was the event trigger set to vehicle speed above $50\,\mathrm{km\,h^{-1}}$ and hence solved both issues.

One other factor that effected the analysis of the driver response was lane change due to overtakes, or other situations when the driver willingly crossed a lane marker. The driver behaviour was though to not be the same as to when a driver by mistake gets to close to the lane marker and the system applies torque. Therefore, was the event also filtered so that only interventions with no lane marker crossings 5 s before or 2.5 s after the intervention was accounted for. This time limit, 7.5 s, was set by looking at overtakes in the FOT data and estimating them to be around 7.5 s long on average. This also means, that there are no haptic warnings included either in the interventions, but only driver reaction to torque applied on the steering wheel.

All signals are standard CAN signal from production cars from Volvo, and all sensors are from the internal sensor system within those cars. The signals that was needed for the analysis are listed in Table 6.1. In summary, an intervention was defined as to when:

1. The LDP torque signal was larger than 0.5 N m for at least 0.2 s
2. The interventions were at least 0.2 s apart
3. The speed of the car was above $50\,\mathrm{km\,h^{-1}}$
4. There were no lane marker crossing 5.0 s before or 2.5 s after the intervention

Table 3.1: Signals analysed.

Signal	Short description
LDP torque	Applied LDP torque from the EPAS motor
Time	One time step was 0.1 s
Speed	Longitudinal speed of the vehicle
Lane change left	Gave a value when crossing a lane
Lane change right	Gave a value when crossing a lane
Torsion bar torque	Absolute value of the torque in the torsion bar
Torsion bar torque sign	Sign of the torsion bar torque
Steering angle	Angle of the steering wheel
Steering angle rate	First derivative, rate, of the steering wheel angle change
Steering angle acceleration	Second derivative, acceleration, of the steering wheel angle change
X-coordinates	The x-coordinates from the GPS in the car
Y-coordinates	The y-coordinates from the GPS in the car
Yaw rate	Yaw rate of the car. Calculated from the centre of gravity in the car
Right lane offset	Distance to the right lane marker from the car
Left lane offset	Distance to the left lane marker from the car
Road curvature	Estimated road curvature from the sensors in the car

3.5 Definition of a straight road

The definition of a straight road was complex, since there are no formal definition of what a straight road is. In the crash data, the driver themselves marks in the questionnaire if the accident happen in a curve or on a straight road with only the drivers subjective definition as guideline. The limits of the radius used for comparison between the data sets was therefore chosen after reviewing 20 event in the FOT data and estimating the radius during interventions when the curvature was perceived as straight or not. The subjective definition was set that corresponded to a *good* curve radius according to the *Swedish national road association* [19]. The limits was as follow, for 50 km h^{-1}–70 km h^{-1} it was set to 850 m, for 70 km h^{-1}–90 km h^{-1} it was set to 1500 m, for 90 km h^{-1}–110 km h^{-1} it was set to 2000 m and finally for curves on road with higher speed limit than 110 km h^{-1}, 2800 m. All curves with radius over the specified limits, was considered as straight roads in the FOT data. The length of the radius was mostly affected of two main variables, the speed limit of the road and the lateral gradient.

3.6 Analysis methods

A descriptive analysis was done on both the FOT and crash data to be able to compare to two data sets. This contained descriptive statistics with respect to five variable deemed important for the evaluation of the FOT in regard to the crash data, and the possible overlap between them, as well as how they relate to each other. The five variables were, longitudinal and lateral speed, radius of the road, road departure angle (measured with respect to the crossing of the first lane marker) and initial distance to the lane marker. It has been shown that speed and radius are critical parameters and affects crash rate and crash type [20]. The road departure angle and initial distance to the lane markers are also important since they describe the relationship between the car and the lane in which it travels.

A signal analysis of the FOT data was used for the methodology of evaluating and analysing the driver response, to find the important signals from a driver response perspective. The signal analysis included a understanding of the origination of the signals and how they were measured and what strong and weak sides they had. The driver response was analysed with the two different approaches below.

1. Different torques in the steering system.

2. The steering wheel angle, rate of angle change.

4 Result

This chapter includes result from both the investigation of the driver response during an LDP interventions and the development of the key measurement as indicators of the driver response, as well as the result from the comparison of the FOT and crash data.

4.1 Driver response

The first approach was to look on the torques in the steering system, by combining the T_d and the T_i in different ways. In order to evaluate if the driver response should be counted as a distinct reaction in regard to the intervention a measurement called *difference in torque rate* were calculated, for a detailed description of this measurement, see Sec. 4.2. To this measurement a limit of $10.0\,\mathrm{N\,m\,s^{-1}}$ were set as the definition of an intervention, in the figures below the *difference in torque rate* value are stated.

In Fig. 4.1 to 4.3, are the four signals: (i) other torque, T_o (assistance torque, aligning torque and friction forces of the steering rack), (ii) intervention torque, T_i, (iii) driver torque, T_d, and (iv) net torque, T_n (the sum of all torques acting on the steering arrangement). The three example showed in this section should not be seen as representatives for the whole data sets but merely an attempt to show how the signals could be understood. For all plots in this section the intervention start at 5 s, and the signals are shown 0.2 s before and after the intervention.

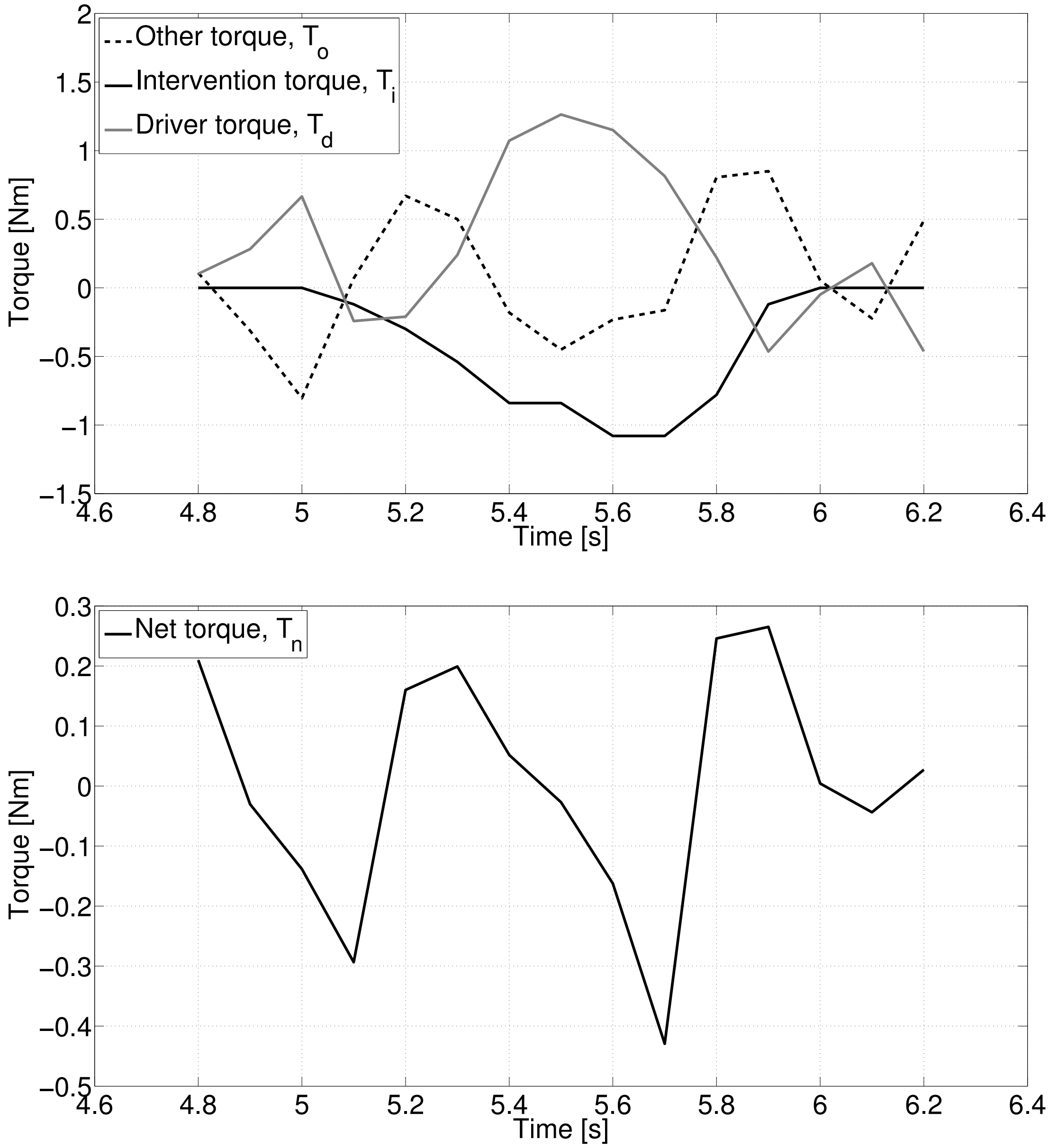

Figure 4.1: The other torque, intervention torque, driver torque, and net torque during an intervention. The intervention starts at 5.0 s and ends at 6.0 s, and the event has the DIT rate of $13.5\,\mathrm{N\,m\,s^{-1}}$.

In Fig. 4.1 one can see that there are two distinct movement happening. The first one is the response in the other torque to the driver's torque from something that happen before the intervention starts, and the second one is from the intervention itself. If one disregard the initial movement, the net torque starts to increase and change after 300 ms–400 ms after the activation of the LDP system. The interventions torque was around 0.5 N m when the change in the net torque started. The DIT rate was high enough for this event to be considered as a distinct driver reaction and one can see that the driver applies torque in the opposite direction compared to the LDP system.

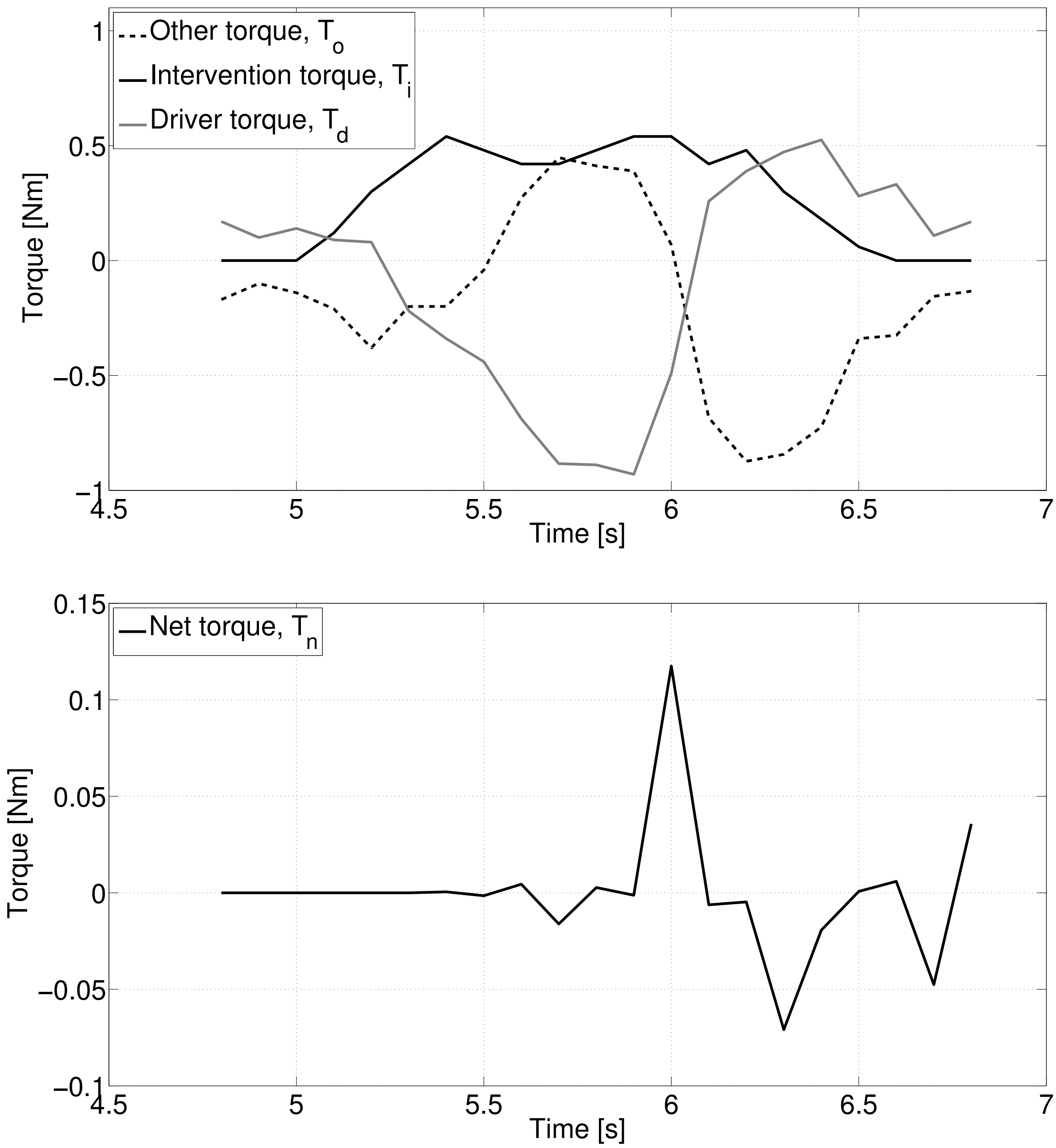

Figure 4.2: The other torque, intervention torque, driver torque, and net torque during an intervention. The intervention starts at 5.0 s and ends at 6.6 s, and the event has the DIT rate of $8.7\,\mathrm{N\,m\,s^{-1}}$..

In Fig. 4.2 the other torque responds more to driver than the interventions torque. The torques are overall weaker with DIT rate of 8.7 N m compared to the signals in Fig. 4.1. The net torque are also weaker and the driver's reaction cancels out the effect of the interventions torque until 500 ms. After that the net torque starts to change, even though between small values. Again the net torque starts to change when the intervention torque reaches values around 0.5 N m.

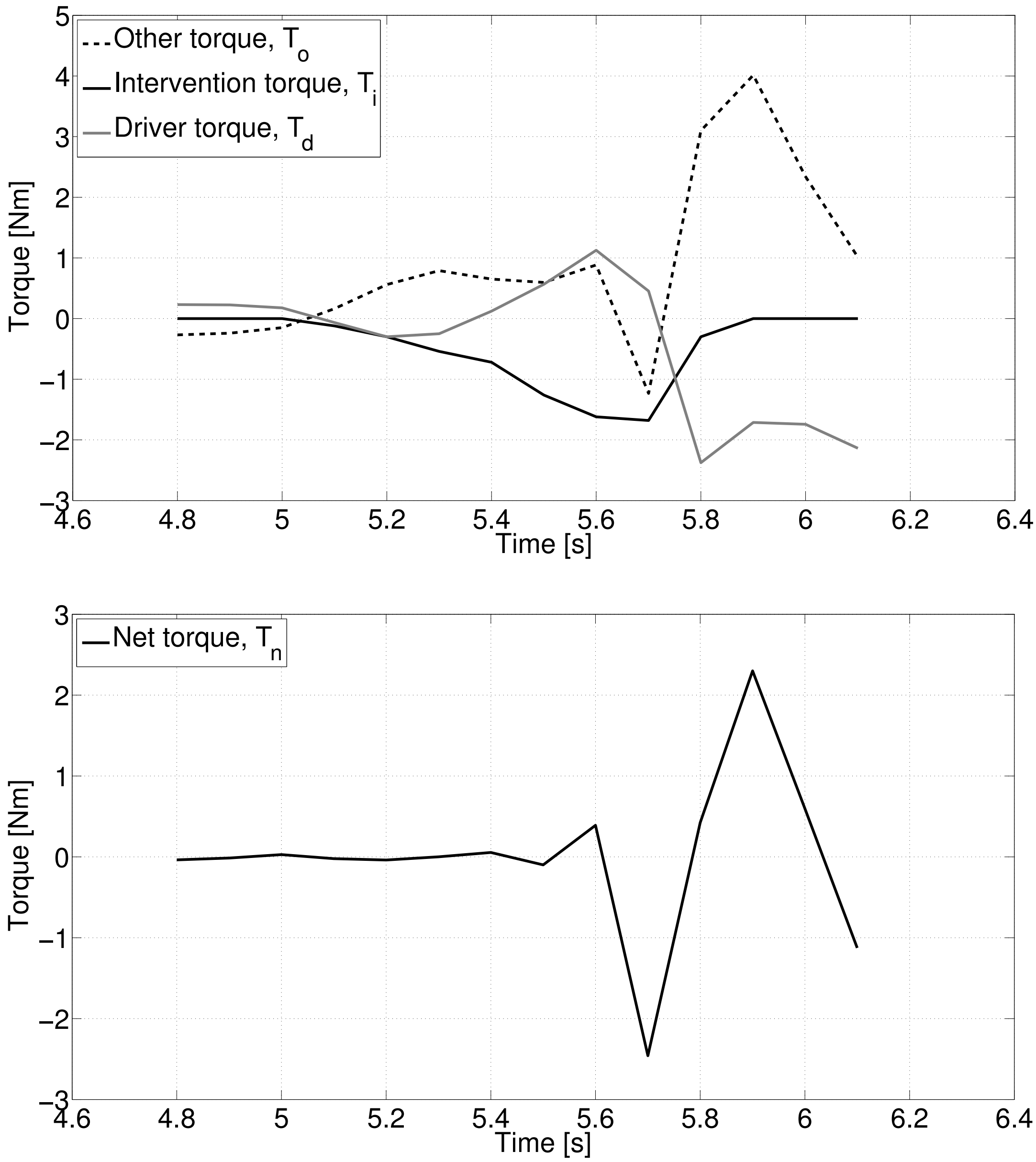

Figure 4.3: The other torque, intervention torque, driver torque, and net torque during an intervention. The intervention starts at 5.0 s and ends at 5.9 s, and the event has the DIT rate of $42.0\,\mathrm{N\,m\,s^{-1}}$.

In Fig. 4.3 which has a very high DIT rate, the net torque starts changing significantly after 600 ms. In this case the intervention torque reaches a value around 1.5 N m before the net torque starts to change. Here, the driver reaction was also more in regard to the intervention torque.

This first approach, investigating the torques, show that one can see when and how strong the driver react by measuring and calculation the applied torques in the system.

In the second approach, an analysis of the steering wheel behaviour during an intervention was analysed by looking at the steering wheel angle and its rate. The examples of the same events as with the torques are presented in Fig. 4.4 to 4.6. The lagging of the rate changes compared to the absolute value of the angle, arises most likely from the filters and the re-sampling from 40 Hz to 10 Hz, that are applied on the steering wheel angle signal by the FOT analysis programs at VCC, before it is plotted here.

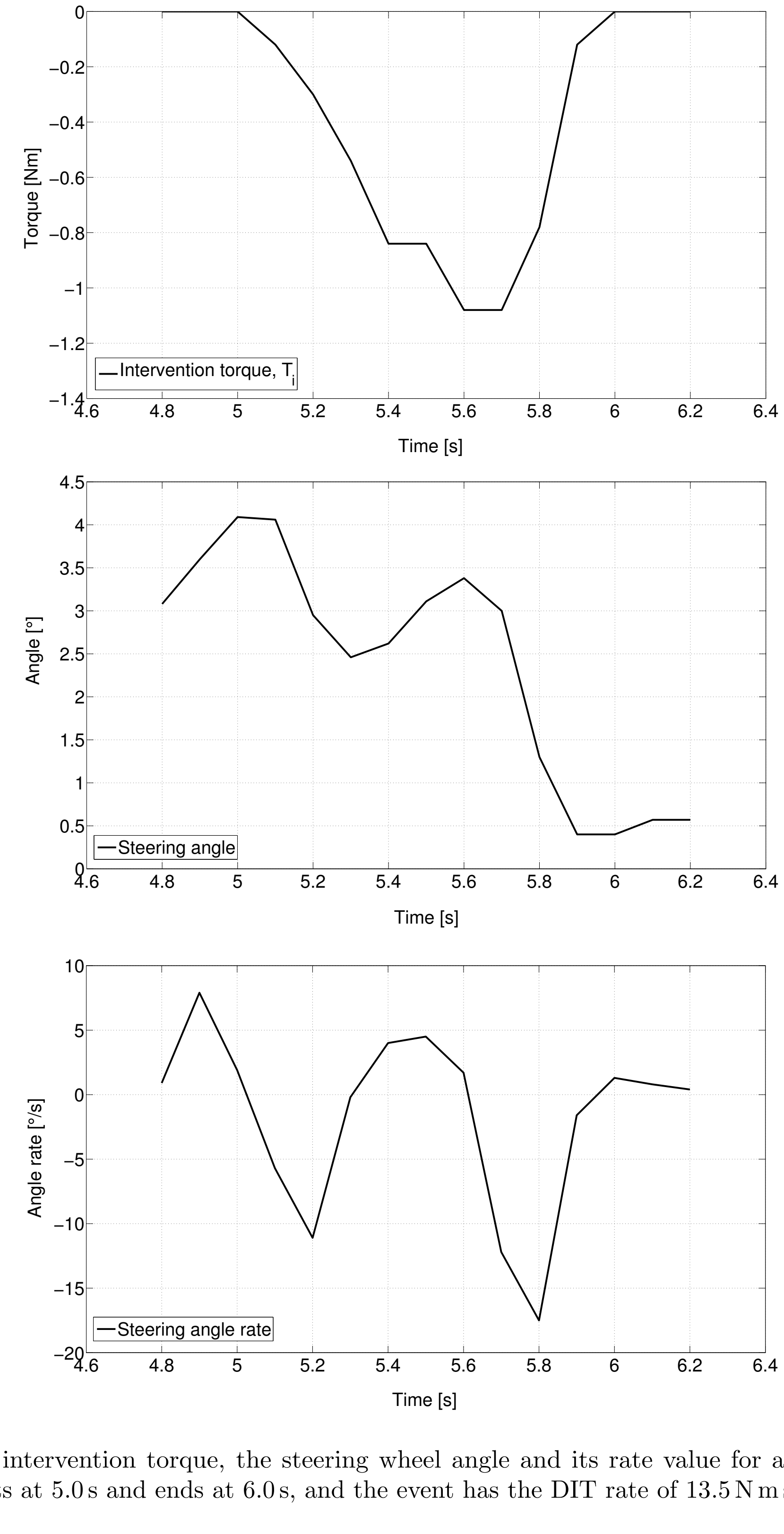

Figure 4.4: The intervention torque, the steering wheel angle and its rate value for an intervention. The intervention starts at 5.0 s and ends at 6.0 s, and the event has the DIT rate of $13.5\,\mathrm{N\,m\,s^{-1}}$.

In Fig. 4.4 the change in movement of the steering wheel angle start after 300 ms, when the net torque was changing sign in Fig. 4.1. If one does not take into account the initial reaction, but only look at what the LDP causes, a distinct change can be seen at around 5.6 s instead when looking at the rate. The absolute steering angle levels out after the response between 5.6 s–5.9 s, and the angle change during that time was around 3°.

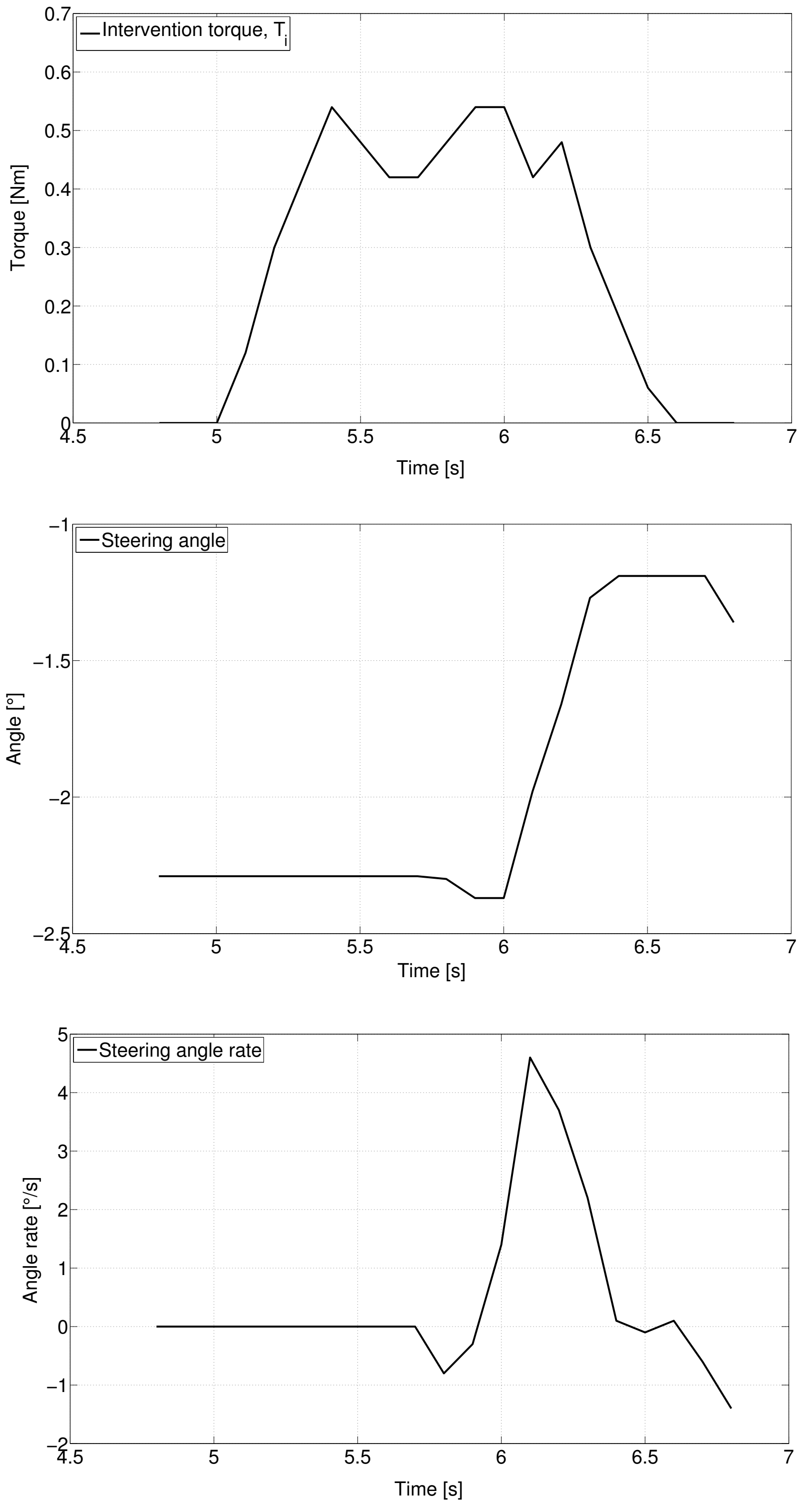

Figure 4.5: The intervention torque, the steering wheel angle and its rate value for an intervention. The intervention starts at 5.0 s and ends at 6.6 s, and the event has the DIT rate of $8.7\,\mathrm{N\,m\,s^{-1}}$.

In Fig. 4.5 the change of movement in the steering angle also starts after around 600 ms. The steering angle was changed between $-2.25°$–$-1.75°$ in the time between 5.6 s–6.4 s.

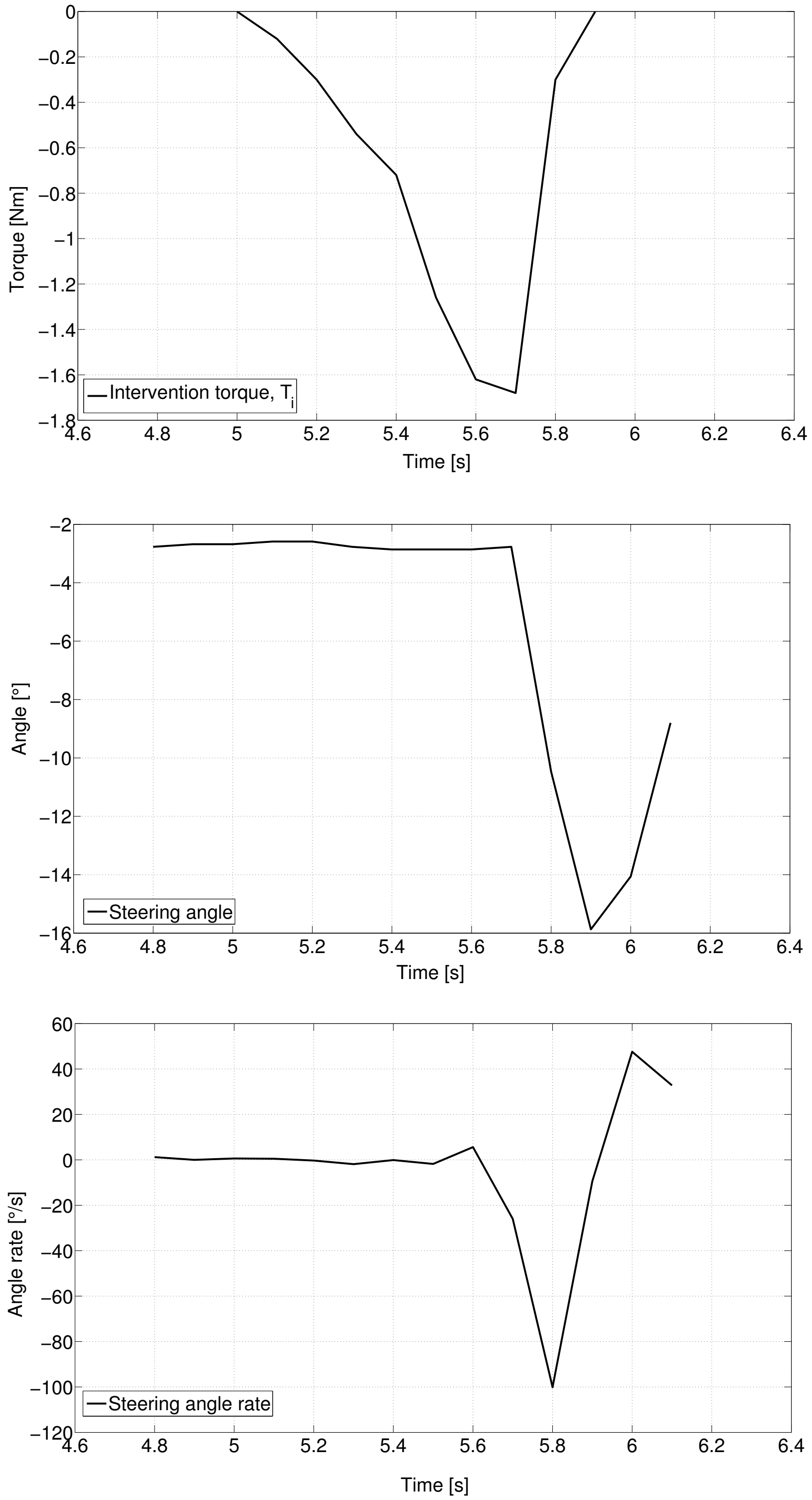

Figure 4.6: The intervention torque, the steering wheel angle and its rate value for an intervention. The intervention starts at 5.0 s and ends at 5.9 s, and the event has the DIT rate of $42.0\,\mathrm{N\,m\,s^{-1}}$.

In Fig. 4.6 the change in steering angle rate starts after 600 ms. Until then, the torques was at equilibrium in the steering arrangement and the steering wheel angle does not change its angle despite the large DIT rate in the example. The large change in steering angle, $-16°$–$-9°$, after the initial movement, $-16°$–$-9°$, also show that the initial reaction was to strong and had to be corrected as seen after 5.9 s when its goes back to $-9°$ again.

The second approach with the steering angle and its rate gave further insight of how the reaction from the driver was with respect to the LDP intervention.

4.2 Key measurements

Three key measurements were developed and derived from the understanding of sec.4.1. The results is presented as line histograms over the initial (0 s–0.5 s) phase and the whole interventions for every measurements. If an intervention were shorter then 0.5 s, the whole event was used for both calculations, hence it had the same value for both the initial and whole event. In the section that follows are the measurements listed in a enumeration with their respective equation and histogram over the result. The axis in all figures shows percent of intervention on the y-axis and normalised value on the x-axis.

1. *Difference in torque rate* (DITR). This measurement shows the difference in applied torque by the driver/LDP by taking the first derivative of it, see 4.1. When the DITR is close to zero, the LDP and the driver wants to turn the steering wheel in the same direction since the difference between them is small. A large value for the measurement on the other hand, inclines that the LDP and the driver wants to turn the steering wheel in different direction, hence a driver reaction. Therefore, by taking the max value of this measurement over an intervention describes how much the driver reacts, and one may see how common it is with this type of reaction and how strong it is. In Fig. 4.7, the distribution of the DITR measurement is presented for the initial and whole intervention. This measurement where the result of an experimental approach where the measurements where calculated first and then when looking at the videos, it matched well. The limit was set to 10.0 N m s^{-1} after reviewing 50 videos of drivers and finding that limit corresponds well to a distinct visible driver reaction that did not look like the surrounding ordinary steering in the video sequence.

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$$DITR = max(|\frac{d}{dt}(T_d - T_i)|) \tag{4.1}$$

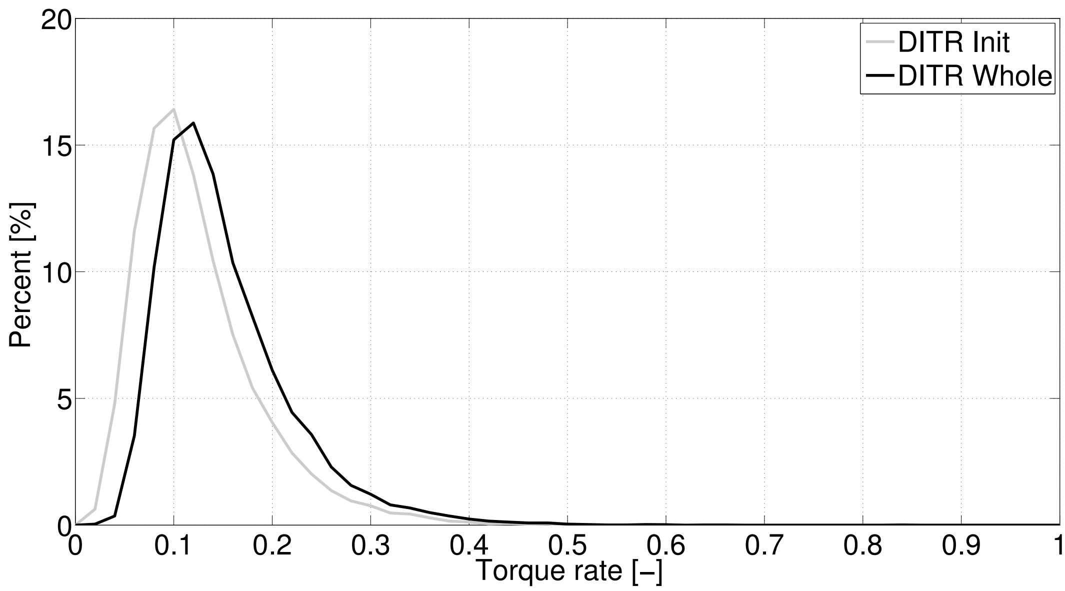

Figure 4.7: Driver reaction to the interventions in form of the DITR measurement for the initial phase and whole event.

The limit of 10.0 N m was at 0.2 in Fig. 4.7. The DITR for the whole event causes the share over the limit to increase from 11.6 % to 19.1 % compared to the inital phase. This means that for the whole intervention, the driver had stronger reactions to the LDP interventions than in the initial phase. The figure also show that for the majority of the interventions, the driver does not react in a distinct visible way.

2. *Difference in torque output* (DITO). This measurement describes the relationship between the LDP and driver torque applied. It is the difference over the integral for the two applied torques. If the sign is positive, the driver is the strongest part of the two, and vise versa if the sign is negative, see Eqs. 4.2. The measurement only describe which agent that applies the most torque, and not the direction of them. In Fig. 4.8, the distribution of the DITO measurement is presented for the initial and whole intervention.

$$DITO = |\int (T_d)dt| - |\int (T_i)dt| \tag{4.2}$$

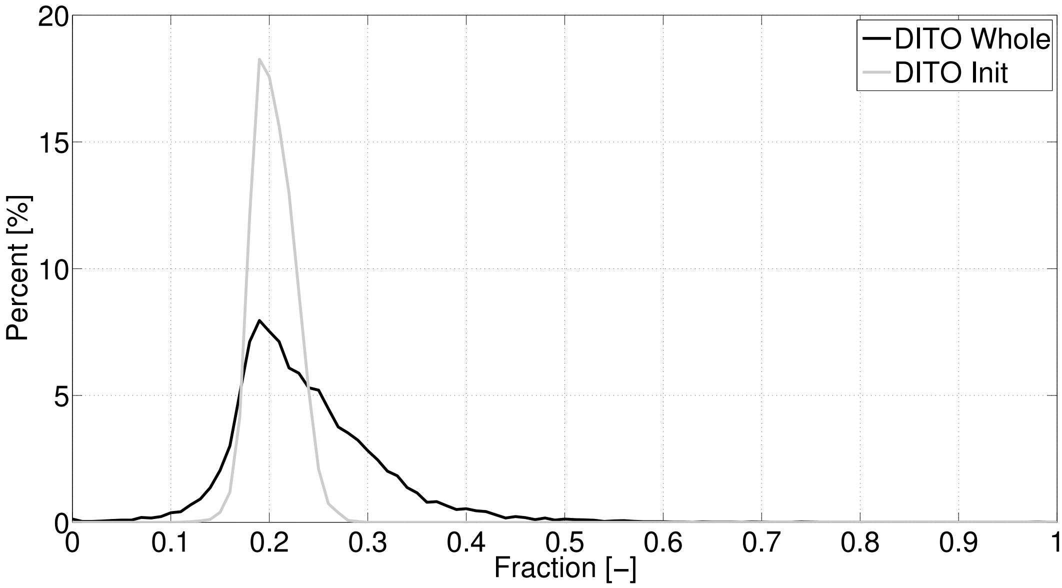

Figure 4.8: Driver reaction to the interventions in form of the DITO measurement for the initial phase and whole event.

The DITO was distributed around zero, at 0.2 in the figure, and the drivers part of the DITO changes over time from 55.0 % to 66.2 %. This means that for initial phase the LDP system had more impact on the steering compared to the whole intervention, and also that the driver applied more torque compared to the LDP system after 0.5 s than before. Furher it shows that in both the initial phase and for the whole intervention the driver applied more torque than the LDP system and hence contributes more to the steering than the LDP system in general.

3. *Driver portion* (DP). This measurement is the ratio between the applied torque from the driver and the LDP system, see 4.3. DP is, in other word, the ratios between the two torques that effects the steering wheel in the system from an external perspective since all other torque arise as a result of the driver and intervention torque. In Fig. 4.9, the distribution of the DP measurement is presented for the initial and whole intervention.

$$DP = \frac{|\int T_d dt|}{|\int T_i dt|} \tag{4.3}$$

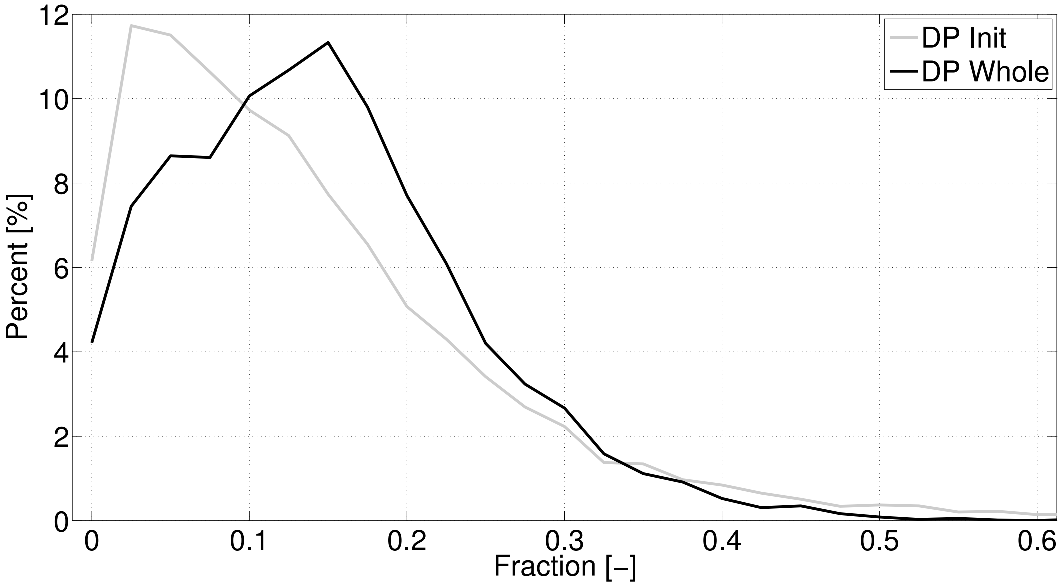

Figure 4.9: Driver reaction to the interventions in form of the DP measurement for the initial phase and whole event.

The fraction 0.1 was where the shift at 100 % occured. This means that values over 0.1 in the figure represent interventions where the driver had applied more torque than the LDP system in the steering arrangement. In regard to the total strength of the torques applied on the steering system, the applied torque from the driver makes up for 55.0 % during the initial phase and 66.2 % for the whole intervention. This indicate that the actual turning of the steering wheel is more due to torque originating from the driver than from the LDP system.

4.3 Comparison of the FOT and crash data

A descriptive statistical analysis was made in order to find out how representative the FOT data was with respect to the crash data. The analysis was done by analysing variables of interest for pre-crash scenarios regarding RoR crashes. The variables that were used to compare the FOT and crash data sets were: (i) speed, (ii) radius of the road, (iii) initial distance to lane marker, (iv) road departure angle, and (v) lateral speed. The result from the comparison is presented in Fig. 4.10 - 4.14.

The variables were defined as below in order to make a comparison between two FOT and crash data. For every definition follows the comparison result as a histogram over the two data sets, starting with the FOT data on top in every picture, and the crash data below. Since this analysis only makes a comparison of the different data, the values of the x-axle are normalised between 0 and 1. All figure uses the same indexing on the x-axle for both the FOT and crash data, so the two data sets can be compared visually, the y-axle then present the percentage of a certain value. The number of events analysed in the FOT data was 12552, and in the crash data 280.

1. The *longitudinal speed* of the car, (from here on denoted as *speed*), was measured as the actual speed when the system was activated in the FOT data and taken from the questionnaire in the crash data. The speed in the crash data was approximated from the simulation of the crashes and hence the drivers own perceived notion of speed at the crash.

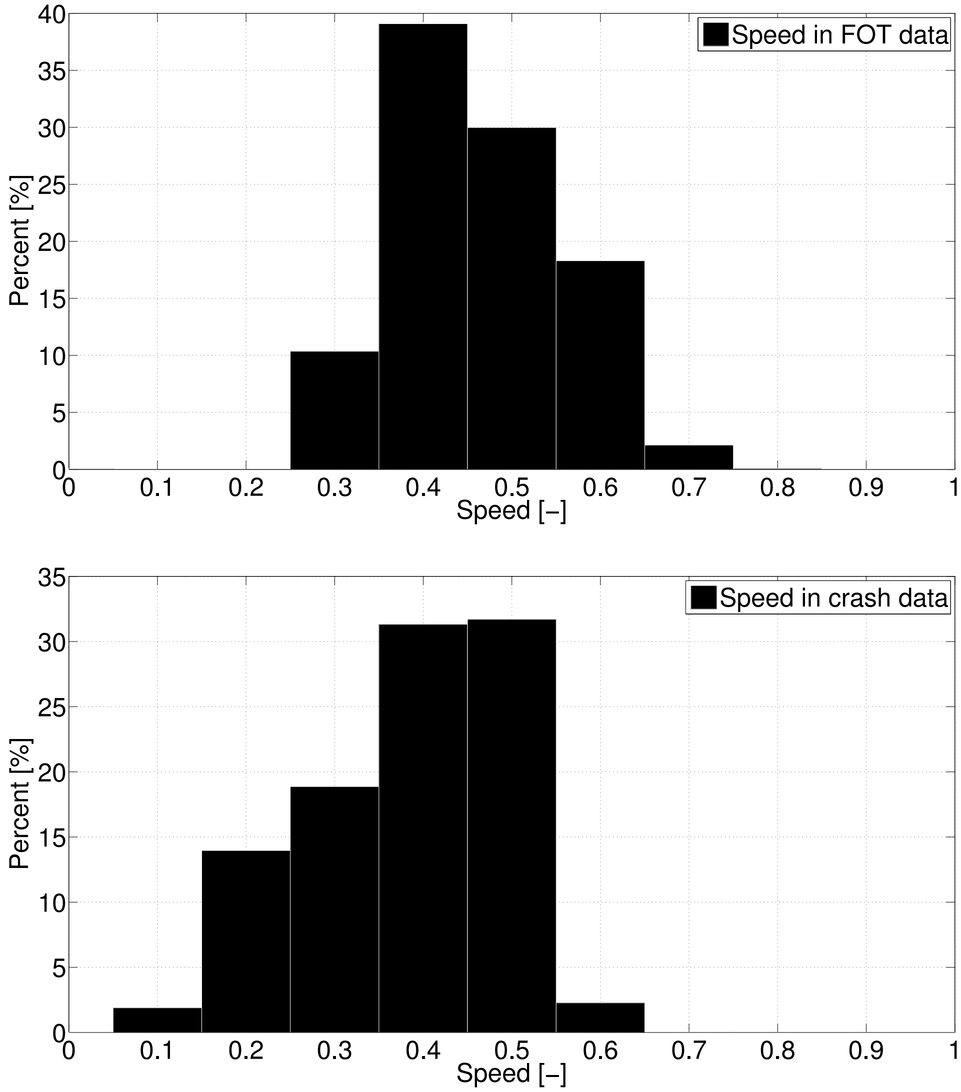

Figure 4.10: Vehicle speed in the FOT and crash data.

The speed in the FOT data are in general higher than in the crash data, but the overlap is quite good around 0.4–0.5 on the x-axis. For the lower speeds (below $50\,\mathrm{km\,h^{-1}}$), 0–0.2, the FOT data does not have any intervention and therefore there are no events below 0.3 on the x-axis. The distribution around 0.6 also differs between the two data sets.

2. The *radius* of the road in the FOT data was calculated as the inverse of a curvature signal logged in the CAN data. For the crash data the radius of the road was calculated by using a simple three point mathematical algorithm that calculates the radius of a circle if all three point lie on the boundary, arc, of the circle. After calculating the radius for every point in time during the whole intervention, and for one second before and after, the median radius value in each time period was used to determine if the event took place right before, during or after a curve. If any of the three time periods had to small of a radius (according to the definition of a straight road in sec. 3.5), the event was categorised as being in a curve. The crash data was analysed in the same way but with the coordinates from the digitalised and simulated data.

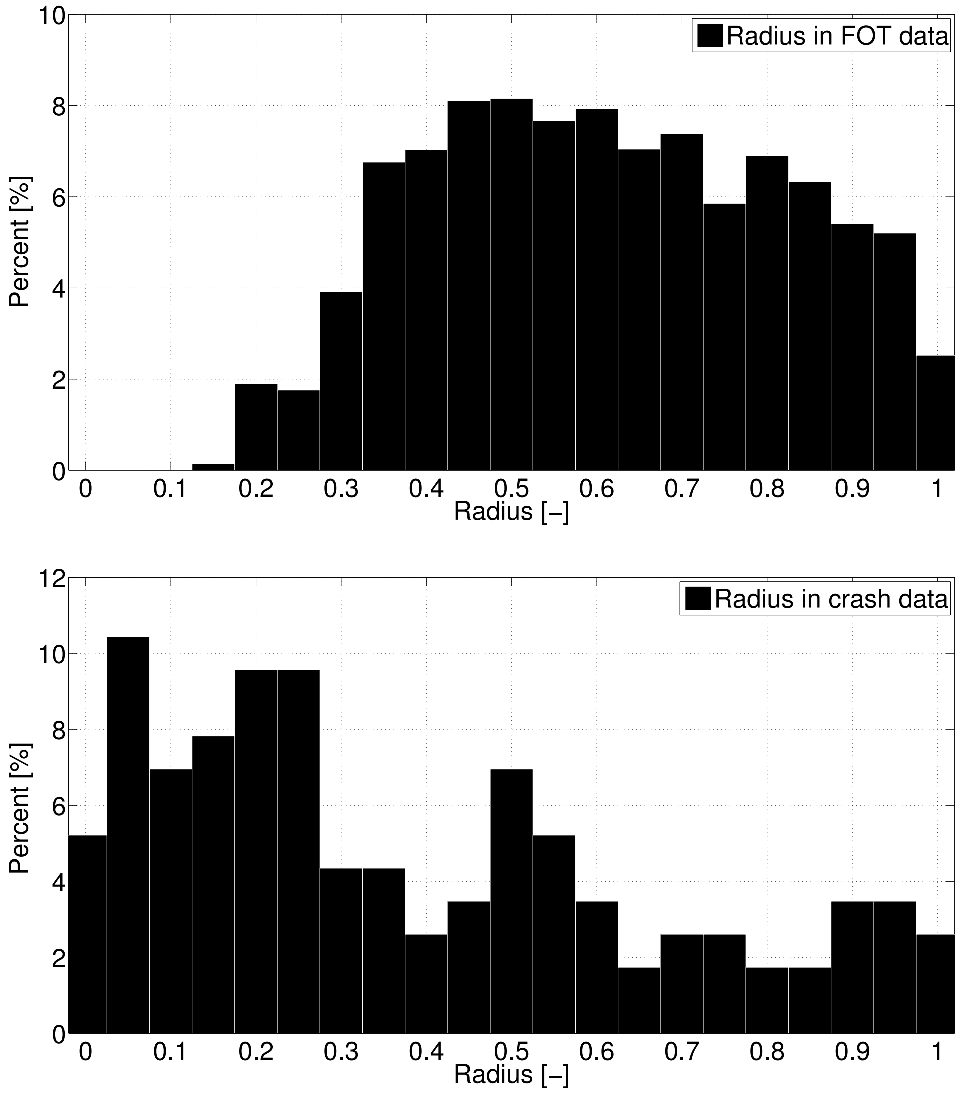

Figure 4.11: A subset of the radius of the road when the road has been defined as straight in the FOT and crash data. Both histograms contain roughly half of its total number of input value since they were too large radius to be included.

About half of the crashes displayed in the figure happens on roads with small radius, below 1500 m or 0.3 in the histogram, but those small radius only constitutes about 4 % in the FOT data. In the FOT data the radius are in general larger than in the crash data as seen in the figure above.

3. The *initial distance* was defined as the absolute value of the distance between the centre of the car and the lane marker, and was measured from the time step before the intervention in the FOT data and from the the start of simulation in the crash data. In the crash data, this means half of the width of the lane that the car was driving in.

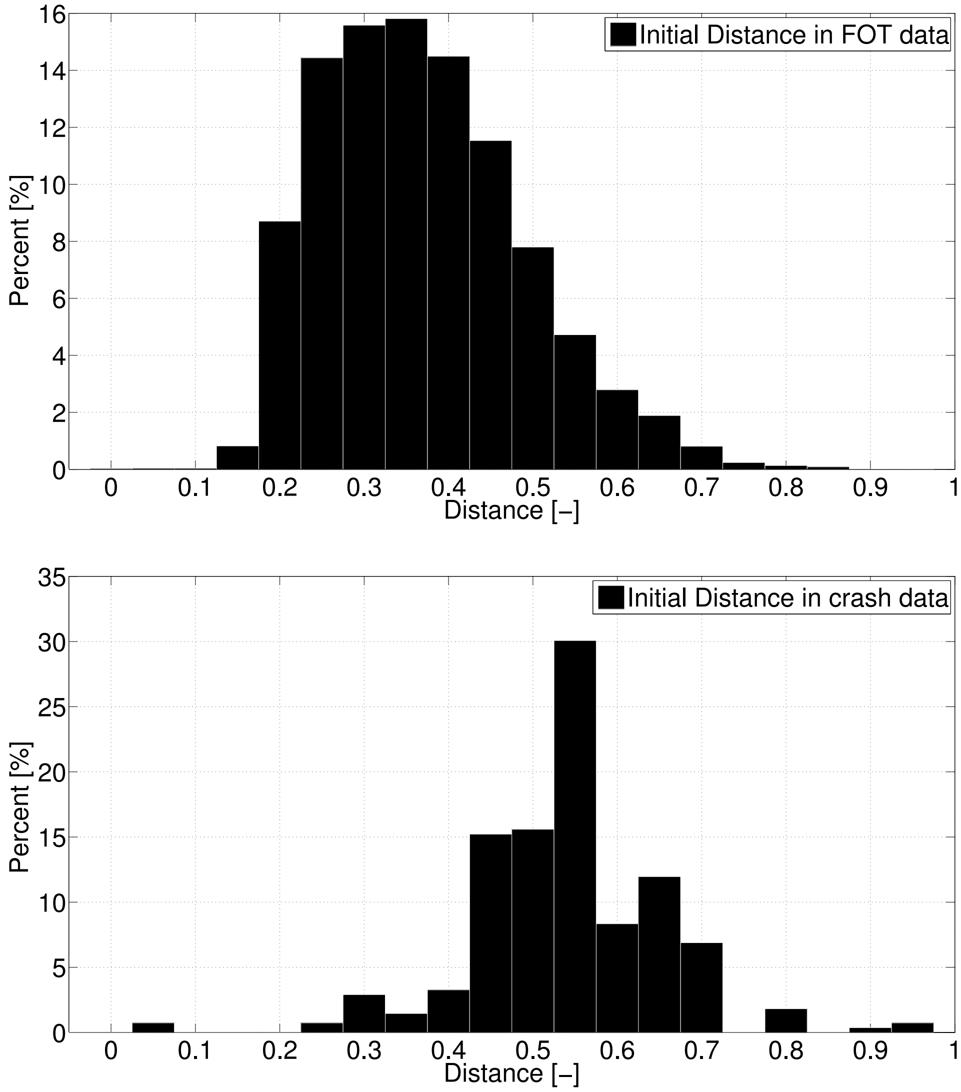

Figure 4.12: Median distance to the lane marker the second before activation, on the side where LDP was activated or crash occurred, in the FOT and crash data.

The initial distance to the lane marker are smaller in the FOT data compared to the crash data as seen in the figure. The FOT data and the crash data covers in principle the same range of distances but have different distribution.

4. The *road departure angle* (RDA), was defined as the angle between the trajectory of the car and the lane marker about to be crossed. In the FOT data it was assumed that the lane markers are parallel to the cars longitudinal trajectory. The angle was calculated by averaging over the two last time steps and its position changes before the LDP activation. The averaging was due to stability and robustness reasons. The RDA in the crash data was calculated in a similar way, but here all angles are known thanks to the simulation, and only the last time step is taken into account. To find the equivalent RDA in the crash as in the FOT data, the variable were calculated when it reached a certain distance to the lane. This distance was the average distance to the lane marker the time step before activation in the FOT data, namely 1.25 m. So the RDA in the crash data was the angle between the car and the lane marker when the centre of the car was 1.25 m from the lane marker.

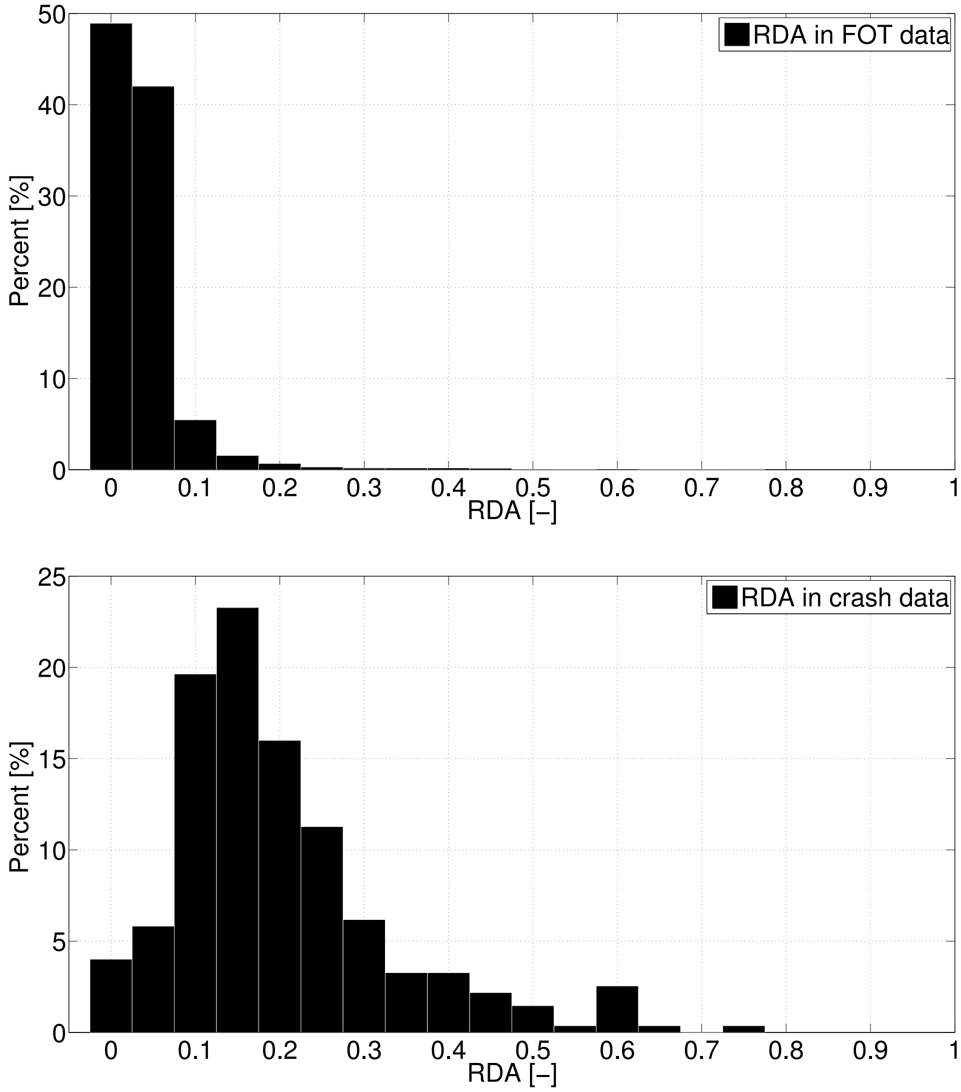

Figure 4.13: RDA in the FOT and crash data.

The data sets differs in range of the angle from 0–0.2 in the FOT data to 0–0.8 in the crash data, so the FOT data only covers a portion of the crashes. Even though the FOT data covers about 70 % of the crash data, it does not match in distribution either.

5. The *lateral speed* was calculated by the difference in distance from the car to the lane marker over the last time steps. In the FOT data, the lateral speed were calculated over the two time steps right before the intervention. To find the equivalent lateral speed in the crash data as in the FOT data, the variable were calculated when it reached the same distance to the lane marker as in the case with the RDA, namely 1.25 m. This distance was the average distance to the lane marker the time step before activation in the FOT data.

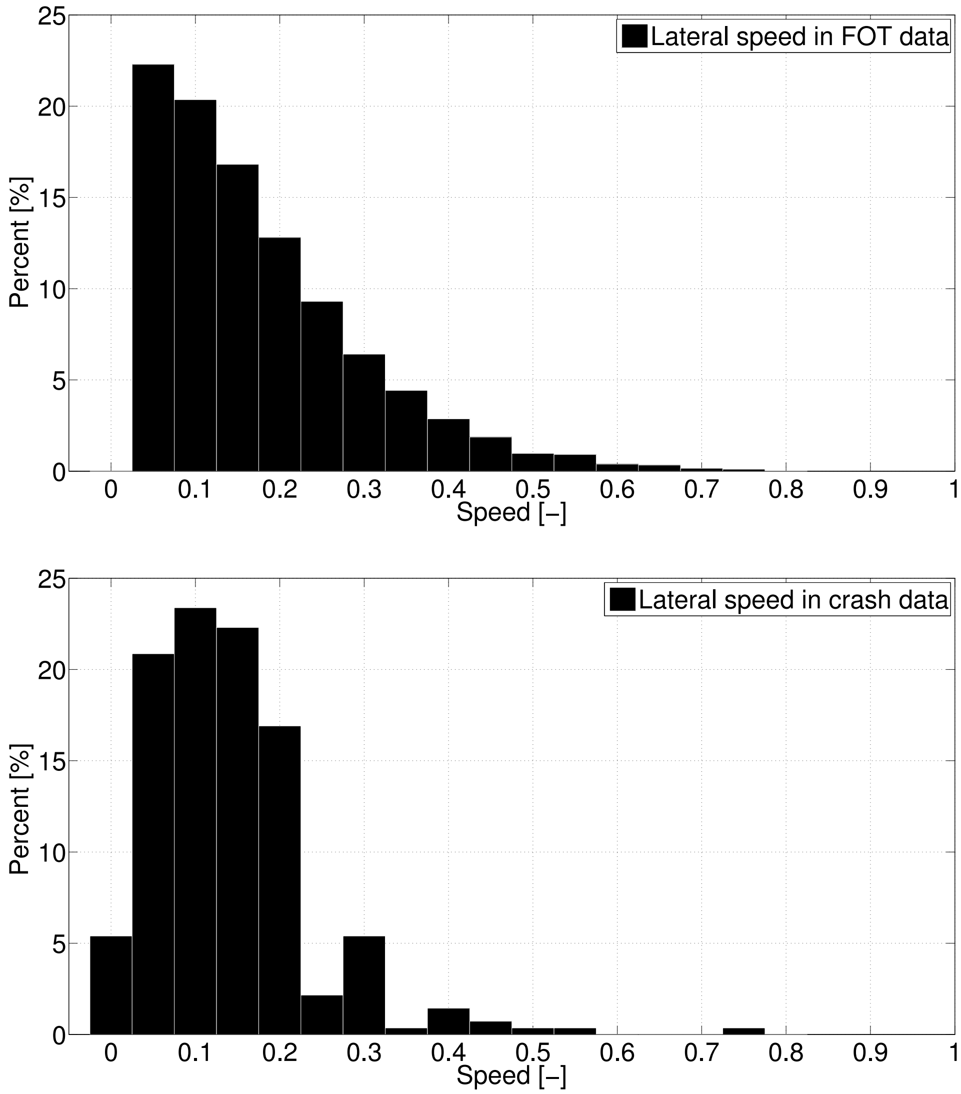

Figure 4.14: Lateral speed in the FOT and crash data.

The range of the values of the data was comparable but the percentage and hence the shape of the distribution was not as close. The distribution between 0.05–0.2 are alike but the for low speed, around 0.0 in the histograms, and high speed, above 0.25 the different becomes larger.

In the quantitative comparison of the FOT and crash data set, it was found that for the distribution of speed and radius of the road, the two data sets where alike for higher values but not for lower. The range of values in the initial distance as well as the lateral speed in the two data sets were also alike but differed in their distribution. The RDA neither had the same range of values or the same distribution of the same in the different data sets.

5 Discussion

This study developed a methodology for analysing the driver response to an intervention by a lane-departure departure prevention system. In conclusion, the CAN signals analysed could be combined to understand the whole picture of the driver response. The combination of the torques and steering wheel angle change, gave an insight of the strength and rate of the torque applied by the driver as well at how those torques effected the steering wheel. The comparison of the FOT and crash data also showed that the two data sets had some differences but also many things in common. They often ranged over the same order of magnitude for the values but there were often big changes in the distribution over the same. In the sections that follows, the driver response as well as the comparison are discussed.

5.1 A method for analysing the driver response

This first approach, investigating the torques, show that it was possible see when and how strong the driver react by measuring and calculation the applied torques in the system. It is interesting to see that even though the driver response was hard to distinguish only by looking at the videos from trips where the DITR were low, it was clearly a reaction in the sense that the driver was compensating for the LDP torque. This was expected to be seen in the torque values due to the fact that the driver is always trying to parry for noise and vibration from the road, see Sect. 2.1. Small intervention can be seen as road noise with respect to driver reactions. The driver response was thus comparable with ordinary steering patterns when the interventions are small and they become more distinctly different from ordinary driving behaviour when the DITR was larger. Interesting to note was that the net torque does not make any big changes until around 0.6 s in the two last example, see Fig. 4.2 and 4.3. This was probably due to the time it takes for the LDP system to ramp up the torque needed to be noticeable by the muscles, and when that time has passed and the muscles has had time to react, that long periods might well have passed. Since the DITR also was defined as for the whole intervention, the large difference could also arise after the initial phase of the intervention. In the first figure though, Fig. 4.1, the net torque moves before 0.6 s which could be explained by a reaction to an earlier steering before the intervention started.

The second approach, analysing the steering angle and its rate, gave further insight of how the reaction from the driver was with respect to the LDP intervention. Here it was also noticeable that the angle rate does not make any big changes either until around 0.6 s in the two last example above, despite the large different in the DIT rate, see Fig. 4.5 and 4.6. In the first figure though, Fig. 4.4, the angle moves before 0.6 s. The strength of the DITR does not seem to effect the turning of the steering wheel either, since both Fig. 4.5 and 4.6 displays the same behaviour. In Fig. 4.4 to 4.6 there was a lagging between the start of angle rate change and the absolute value of the angle. This was probably due to that the rate was calculated before the down sampling of the signal, and after the some filter were applied for processing the signals. One could have used derivatives straight on the absolute angle signal to get a rate that did not lag but the decision was made to use the existing signal since it otherwise had the risk of including other errors.

The special case when the driver does not hold its hands on the steering wheel, it is hard to talk about a driver reaction even if the DITR shows a high value. The value should in general be lower than when the driver applies torque in the opposite direction but it could still in theory be calculated as a driver reaction even though the driver did not hold the steering wheel. This is something that could be addressed in future studies by filtering out the case with no driver torque. In this study they was included in the analysis but they should be a very small portion of the total number of intervention.

DITO that was derived from the torque approach further gives insight about the relationship between the driver and LDP torque applied in the system. The DITO describes if the driver applies more torque than the LDP, and by this effects the steering wheel. If DITO was negative, the LDP was effecting the steering wheel and the driver was either steering along or applies to small amount of torque to actually adding torque to the steering wheel. The DP variable describes how big part of the steering that actually comes from the driver. This gives insight about how strong the applied torque is compared with the other torques in the system.

The comparison between the initial phase and whole intervention could be improved by looking at each time step instead of only two time periods. This could give a deeper insight on when the driver reaction start and a more detailed description on it. For all the key measurement, the time impact should also be taken into consideration so that they can not be tampered with by increasing the length of the intervention. Also a correlation study in regard to the key measurements and the LDP torque strength, rate and duration could be interesting to investigate.

It was hard to distinguish specific steering wheel behaviour for the LDP intervention as indicated by the results. The steering wheel angle acceleration was changing quite rapidly and there was nothing specific about the signal around the LDP intervention that does not show in the rest of the trip. This was especially true when the DITR was small and the reaction of the LDP torque was filtered by the driver as road noise. When the DITR was higher, it could sometimes be seen that the steering wheel angle acceleration was higher during the LDP intervention compared to the surroundings. The fact that the acceleration changed so fast made it hard to see the real peaks in the signals due to the low sampling frequency. This could have been possible to solve by interpolation between the point before and after a suspected missed peak. If this technique was used it might be possible to define an reaction or counter steering by some distinct pattern in that signal. A future development of the driver response methodology could be to interpolate between the time steps, or by a reversed sampling processing obtain better approximation of the peak values. The measured based on the rate of the steering angle suffered from the same kind problem even if it was not as severe.

The definition of a reaction as a response to the intervention is a complex matter. In the study, the limits set to the DITR that defines a reaction was chosen from manually viewing 40-50 trips with different values on the DITR. The decision to set the limit to $10.0\,\mathrm{N\,m\,s^{-1}}$ was based on a subjective analysis of when a distinct reaction from the driver could be seen or not. The limit is therefore arbitrary, and up to the analyst to define since there is no formal definition. For this study, the aim was not to evaluate the safety benefit of the LDP system but to develop a methodology to evaluate driver steering response to interventions. The subjective definition is not a problem for this study, since the methodology could be used regardless of the values of the definition. The measurement originates from experimental study when trying to find a good way of detecting the driver reaction in regard to the intervention. A more direct approach could have been to investigate the driver torque, and to try to find a limit for the driver reaction that way also, and it might be a more theoretical correct way of approaching the issue. There were attempts to make the analysis based on the driver torque, but it was tricky to find a good reference point to which normal driving behaviour could be distinguish. By only investigating the driver torque itself, the relationship between the intervention torque was also lost and the driver reaction would then be seen as merely and reaction to the all the torques originating from below the torsion bar, and not specific to the intervention torque.

The uncertainties that affect the outcome of the exact torque applied from the driver and its accuracy, was the unknown variables throughout the steering arrangement. The steering column is for example distorted when torque is applied to it, and this was approximated as a rigid structure in this study. This would have an affect on the result when the rotation of the steering wheel rapid changed direction. The slip angle from the tires and the complexity within the aligning torque all the way up to the steering wheel was also something that was a blunt approximation. The steering model can seem like a oversimplification of a rather complex steering system and to make a more accurate analysis, more variable could be taken into account. The methodology for evaluating the driver response could however be applicable in both this approximation or a more advanced, the real difference would rather be in the way to analyse the output data from this analysis methodology.

One measurement could be implemented is a new measurement place in the steering system after the EPAS motor, providing the torque the EPAS motor actually applied on the steering rack. This would contribute to a better understanding of the steering system and the driver response could be understood to a higher degree of certainty. Then the only real uncertainty would be the distortion of the steering column which affects the steering angle and its derivatives. One could also simulate the *driver in loop* (DIL), factor from the simulation model of the system, this is a possible area for further studies of the topic in this report. This could provide an interesting variable of how much the driver reacts under an intervention, since the DIL ramps down the intervention with a function that takes the torque applied on the steering wheel into consideration. A preliminary study of this was performed at Volvo Cars in the summer of 2014. With these two measurements, a quite accurate model of the applied torques should be reasonable to develop, even though a full scale driver model demands that almost every unknown variable and uncertain variable is eradicated. The driver response model would then give a deeper understanding on how to develop new safety function that does not evoke an evasive reaction from the driver, or dealing with them in a better way.

How the specific signals were measured and with what sensor type, was not deemed important since they are unique for every car model and for the method it was only a matter of implementation. In an experimental setup, this would have been more important, but as for the method it is something that the different users of the method themselves need to implement in a sufficient way.

One major drawback with the FOT data used is that it was re-sampled from 40 Hz–60 Hz, depending on the signals, into 10 Hz in order to be compatible with the FOT analysis software used in this work that are used to analyse the trips. If it would have been able to analyse the 40 Hz–60 Hz data instead, one could have been able to see a much more detailed resolution, especially on the initial driver response. This is due to the high speed of the neuromuscular processes in the spinal cord that operates at around 50 ms or 20 Hz. To accurately capture this, a sampling frequency at around 60 Hz is needed, according to the Nyquist criterion. With this higher sample frequency, not just the slower cognitive reflexes that lies around 200 ms–300 ms or 5 Hz, but also those initial response that now disappears into the general noise of the sampling [12] might be possible to detect. It is hard to say whether or not these short and weak signals actually would be noticed or if they would get lost in all the other unknown factors in the steering. In this FOT data there are uncertainties due to low resolution which is something to look into in future research.

5.2 The validation of data comparison

In the quantitative comparison of the FOT and crash data set, it was found that for the distribution of speed and radius of the road, the two data sets were alike for higher values but not for lower. The range of values in the initial distance as well as the lateral speed in the two data sets were also alike but differed in their distribution. The RDA neither had the same range of values or the same distribution of the same in the different data sets.

The Fig. 4.10, shows the speed differs somewhat between the FOT and crash data. The fact that the two data set has different definitions on speed makes this variable hard to compare. One thing that one may say though, is that there are crashes happening in lower speed then what the LDP system is designed to handle. This also affects the radius distribution of the road since higher speed requires larger radius which is seen in the FOT data compared to the crash data. The radius of the road in Fig. 4.11, shows that the roads with radius over 1500 m are as equally distributed in both data sets. The difference under 1500 m is probably due to the speed limit set on the LDP system.

In Fig. 4.12, the initial distance to the lane marker are quite different. This is due to how the both distances are measured. The first being an actual distance measured from sensors in the car, and later being the measured distance at the start of the crash simulation, so essentially in the middle of a car lane. The crash data initial distances then only shows half the width of the lane where the car was travelling. The median distance to the lane marker in the FOT data is 1.25 m which then is a little bit shorter then in the crash data.

The interesting RDA variable seen in Fig. 4.13, is bigger in the crash data compared to the FOT data. This could be due to two things, first, the crash data is simulated with the run-off-road trajectory as a second degree polynomial. The approximation may give steeper RDA then in the real traffic data, i.e the FOT data. Secondly, the RDA is measured when the simulated car is 1.25 m away from the lane marker since it is the median and mean distance to the lane marker in the LDP interventions, which could give a slightly higher bias towards higher RDA compared to the FOT data since none of the smaller RDA then counted.

The last comparison by the lateral speed in Fig. 4.14, shows to have a small difference as well. This could also be due to the same reasons as with the RDA hence they both are measured when the distance to the lane marker is the same. The curve is not so smooth in the crash data as in the FOT data, and this may be due to that all lateral speeds are taken at the same distance to the road and with the same trajectory approximation, which then should produce a smaller variation in the data than in real traffic data.

One may also make a more general remark, and that is that the FOT data was filtered so that no events when the car had crossed any lane markers were included in order to avoid response not solely to torque applied. This also gives at hand that no event where the car drifts over the lane marker and then back again are counted for, and these would probably have had larger RDA and higher lateral speed since the LDP system did not stop them. For future comparison this filtering could be altered so that all event are accounted for by setting limit on for example the distance to the lane markers instead of the lane crossing.

The crash data has given the experts in safety a very good insight of what the environment looked like in regard to crash sites and road geometry. Nevertheless, no one can, only by observation, fully understand the self-perceived experience of the pre-crash scenario. There are, however, some interesting new features in new cars that offers new possibilities to log and save data that can be used to make reconstruction. *event data recorder* (EDR), is today a data collecting unit in new car models in alignment with US law and around the world which record crash information [21]. By adding signals that could be stored here, with for example, the coordinates of the last 10 s before a crash and the trajectory of the car, one could gain more information on pre-crash scenarios from real world traffic data. With the added signals the EDR would more objective data about the driver reaction and responses to circumstance around the car crash.

The conclusion was that the two data sets has some similarities but they were not a perfect match. The differences in the two data sets comes manly from the different speed restrictions they had when one count crashes that occurs in all speed and the FOT data only roughly account for speed between $65\,\mathrm{km\,h^{-1}}$–$200\,\mathrm{km\,h^{-1}}$. The filtering of events could also come into play for mainly the RDA and lateral speed, and also the fact that they were calculated as to the median distance to the road when the FOT data had interventions, gives rise to a somewhat bias statistical references in the crash data. The FOT data does not capture the RoR crashes as a whole, but they might be more alike in real life than what could be shown by this comparison.

No qualitative comparison of the interventions in the FOT and crash data was performed. So the true positives in the FOT data is unknown.

6 Conclusion

A methodology for evaluation of driver steering response to a lane-departure prevention system was developed based on an analysis of FOT data. The methodology was validated by analysing video recordings of LDP interventions. Key measurement regarding the relationship between the driver and the LDP system was also developed and applied on the FOT data. In previous experiment the intervention torque were stronger and applied with higher rate than in the FOT data. This study shows that in the real-world data, the interventions were in the majority of the events small and did not cause any significant visible driver reaction when looking at the video from the events, even though a reaction could be seen when looking at the signals. The similarities in pre-crash scenarios of the interventions in the FOT and crash data were also considered vast enough to conclude that the FOT data captures some of the higher speed crashes in the crash data, but not the whole set.

Table 6.1: Key measurements.

Measurement	Short description	Outcome
DITR	*Difference in torque rate.* Defined the driver reaction. Limited to 10.0 $\mathrm{N\,m\,s^{-1}}$.	11.6 % was initially larger, and 19.1 % for the whole intervention.
DITO	*Difference in torque output.* Measures if the driver of the LDP system applied the most torque during the intervention.	In 55.0 % of the initial phase was the driver strongest, and in 66.2 % for the whole intervention.
DP	*Driver portion.* Measures the portion of torque the driver applies to the steering wheel with respect to the LDP system.	In 55.0 % of the inial phase of the event did the driver apply more torque, and for the whole event the numbers were 66.2 %

6.1 Future work

Suggestions for future work and research.

1. Higher sampling frequency of the FOT data would give interesting detail information about the first initial response. As of now, this is not possible due to to the low sampling rate, especially after the re-sampling into 10 Hz data.
2. Correlation study between the different key measurements and the LDP system would be interesting. To understand their relationship and what affects the driver reaction and in what way.
3. A study of the DIL factor in the FOT data set could be done. This may give insight as to when the driver reactions actually start and the effect of the driver on the LDP system.
4. A complete steering arrangement where, for example, the torsion of the steering column is considered. This would help to give a more accurate and precise description of the reactions.

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