Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Implementing and studying the effects of a roll stability system in heavy vehicles using a moving simulator

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan i Linköping
av

Ulrika Pettersson

LiTH-ISY-EX--10/4337--SE

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Linköpings universitet
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Titel
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Implementering samt undersökning av nyttoeffekter av ett rollstabiliseringssystem hos tunga fordon i en rörelsesimulator

Implementing and studying the effects of a roll stability system in heavy vehicles using a moving simulator

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Author

Ulrika Pettersson

Sammanfattning
Abstract

This thesis presents the making and the implementation of a roll stability system for a simulator truck. The purpose of the system is to prevent rollover.

The making of the system consists of three parts; calculating the roll angle, calculating a rollover index and constructing the control system. The roll angle was calculated using a one degree of freedom model of the truck with the measured lateral acceleration as input signal. Using the roll angle and the roll rate, a rollover index was calculated. The controller made the truck brake to avoid the impending rollover when the rollover index was at a critical point.

The benefits of the system were measured by conducting a study in which test persons drove the simulator truck both with the stability system switched on and switched off. The scenario in the study was carefully constructed so that it would test the system thoroughly.

The results were not unambiguous, in some situations the roll stability system prevented roll over, but in others it had the opposite effect.

Nyckelord
Keywords

rollover, roll stability, simulator

Abstract

This thesis presents the making and the implementation of a roll stability system for a simulator truck. The purpose of the system is to prevent rollover.

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Sammanfattning

I den här examensarbetesrapporten presenteras ett rollstabiliseringssystem för tunga fordon framtaget på VTIs (Statens väg- och transportforskningsinstitut) begäran. Systemet ska användas i VTIs simulator och det ska förhindra att fordonet välter.

Utvecklingen av systemet kan delas in i tre större områden; beräkning av fordonets rollvinkel, framtagandet av ett rolloverindex samt skapandet av en regulator. Rollvinkeln är framtagen utifrån en lastbilsmodell med en frihestgrad, och skattades utifrån den mätta sidoaccelerationen. Rollhastigheten i sin tur skattades utifrån rollvinkeln. Ett rolloverindex som anger risken för vältning i varje ögonblick räknades fram med hjälp av rollvinkeln och rollhastigheten. Då indexet indikerar att vältning är nära aktiveras ett reglersystem. Detta system bromsar in lastbilen för att minska vältrisken.

Examensarbetet avslutades med en studie utförd i simulatorn där försökspersoner körde både med och utan stabiliseringssytemet inkopplat. Scenariot i studien var speciellt utformat för att testa stabiliseringssystemet. Resultaten var inte entydiga, stabiliseringssystemet hjälpte i vissa situationer men i andra hade det motsatt effekt och fick lastbilen att välta snarare än att förhindra vältningen. Slutligen utvärderades nyttoeffekterna av det framtagna systemet.

Acknowledgments

I would like to thank the Swedish National Road and Transport Research Institute for letting me do this thesis work. It has been interesting and I have learnt a lot.

Thanks to the people at VTI for good times at the breaks and special thanks to everyone at the FTS department for all their help with the simulator.

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Contents

Chapter 1

Introduction

This chapter describes what a roll stability system is and why it is desirable in heavy vehicles. What the goals of this thesis are and what limitations that were made.

1.1 About roll stability systems

Even though rollover accidents are relatively rare it is important to prevent them because they often lead to death once they occur. In 2008 rollover accidents stood for 3.1 % of all large truck accidents in the USA. But as many as 13.5 % of the fatal injuries involving large trucks came from rollover accidents [10]. On top of this, consequences such as traffic stops, environmental risks if the gods are dangerous and economic losses have to be considered at rollovers.

The rollover accidents can be divided into tripped and untripped accidents. When the accident is caused by a curb, ditch, soft soil etc. it is considered tripped and when it is caused by pavement friction it is untripped. Further, strong side winds and incorrectly loaded vehicles can also cause the vehicle to roll over [7]. Only looking at untripped rollovers, as is done in this thesis, most private cars do not need a rollstability system because the risk of rolling over is very small. This is because the center of gravity is close to the ground in relation to the track width. Heavy vehicles like tractor-semitrailers, trucks, busses and even sport utility vehicles have a much higher center of gravity in proportion to their track width. This means that the vehicle is more sensitive to lateral forces that arises in non-straight forward driving and creates a momentum which may overturn the vehicle.

This relation between the track width and the center of gravity is commonly referred to as the Static Stability Factor (SSF) and is track width over two times the hight to the center of gravity. This is an easy but rough and conservative way to estimate the rollover threshold of the vehicle. Therefore it is mostly used to compare different vehicles against each other rather than giving them an exact rollover threshold [9, 11]. Nevertheless, a low SSF means that a sharp turn or a fast lane change could be enough to overturn the vehicle. But the rollover can also come creeping if the roll angle slowly increases over time.

The purpose of the roll stability system is to actively prevent the vehicle from rolling over sideways. This means that when the vehicle is close to rolling over a control system partly takes over the vehicle and stabilizes it. This can be made in different ways, and most often the cause of the impending rollover has to be considered. All methods can not prevent rollovers of all kinds of causes.

The rollover can be caused by side forces that arise for different reasons. One method to prevent this side force induced rollover is to reduce the forward speed of the vehicle. A lower longitudinal velocity implies smaller side forces and this reduces the risk of rolling over. However this only applies if these side forces solely depend on the dynamics of the driving. If the vehicle is affected by other forces as well, for example strong side wind, other methods for preventing rollover have to be used. Here active suspension which leans the vehicle in the direction that reduces the roll angle might be more effective [7].

1.2 Background and goal

At the Swedish National Road and Transport Research Institute it was desired to develop and implement a roll stability system for a truck into their simulator environment. The reason for this was to investigate whether or not this stability system would prevent rollover. The goal is of course to create a stability system that prevents rollover and to conduct a study with real test persons to test the system.

1.3 Limitations

The roll stability system is made for a specific model of truck, which is homogenously loaded and has no semitrailer. The road is flat and dry and there is no wind. Further, only untripped, non-collision incidents are considered. The test persons for the study were mainly friends with driving license for private car, driving license for truck was not required.

1.4 Method

A literature study was conducted to get sufficient knowledge on the area. The used vehicle model for which the system should be made was studied. A model for estimating the position of the truck and the risk of rolling over was made. On basis of this information a control system that reduces the speed of the vehicle when it is close to overturning was implemented in the simulator. A scenario was created to examine the effects of the system. Several pilot studies to improve the system were conducted and finally a study with 24 test drivers followed. The results from the study were analyzed.

Chapter 2

Simulator

This chapter shortly describes the simulator and the kind of truck for which the stability system was developed and the study was conducted in. The VTI Driving Simulator II, also called *Sim*2 was used.

2.1 The truck

The kind of vehicle that is modeled in the simulator in this thesis is a truck without semitrailer. It has three pairs of wheels, one pair at the front and two at the back. The trucks weighs 22, 100 kilos in total, and the mass in the closed truck bed is uniformly distributed. It is approximately seven meters long and three meters high. A similar vehicle can be seen in figure 2.1. The sensor values in this thesis are from the rear body where a rollover usually begins.

Figure 2.1. The kind of vehicle that was modeled in the simulator.

2.2 From the drivers view

When you are driving you are sitting in a Scania production cabin. Inside the cabin there are speakers that give sounds of for example the engine. The road in front of you is a graphic environment that is displayed by three projectors which gives a 120 degree wide view in front of the cabin. The rear-view mirrors are replaced by flat computer screens attached on each side of the cabin. The graphical environment is made at VTI and can be customized to meet most kinds of requirements. The simulator can be seen in figure 2.2.

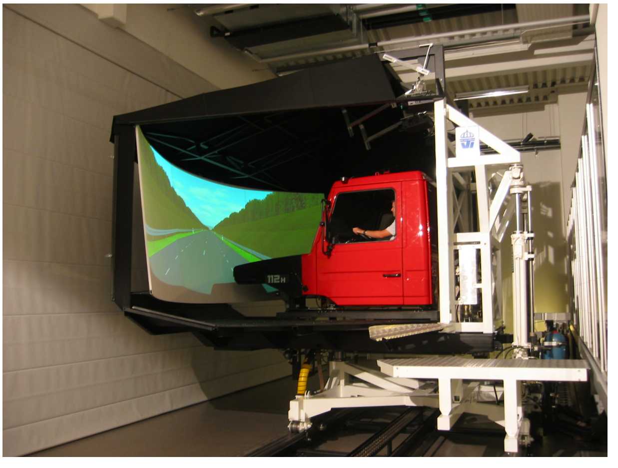

Figure 2.2. The VTI Driving Simulator II.

2.3 Control panel

Outside the simulator the operator has a control panel with five screens that show the same graphics as the driver can see. Three of the screens show the road and the other two show the rear-view mirrors. Through microphones and cameras in the cabin the operator can hear and see the driver in the simulator at all times. The operator can also speak to the driver through a microphone at the control panel when he or she needs to give instructions.

2.4 Moving capacity

The cabin and the screen is attached to a moving base. This moving base can slide sideways at a maximum speed of ±2 m/s and maximal acceleration of ±0.4 g when for example changing lanes. Roll angles up to ±22 degrees can be achieved, this is used to tilt the vehicle in a curve. It can also do pitch movements back and forth when for example accelerating or braking. The pitch angle has a maximum of ± 24 degrees.

On the moving base the cabin is placed on a vibration table which can move ± 5.0 cm vertically and ± 7.5 cm longitudinally. It can also pitch ± 4 degrees and roll ± 7 degrees. These small movements are used to put uneven or bumpy roads into effect.

Chapter 3

Vehicle roll angle estimation

In order to prevent rollover you need to know when you are at risk of rolling over. The current roll angle of the vehicle is a good measure of how high the risk is and in this chapter an estimation of the roll angle will be calculated. The roll rate is obtained as the derivative of the roll angle.

The roll angle can be obtained from the simulator, but most heavy vehicles don't have a roll angle sensor because it is hard and expensive to measure [1, 2, 6]. To make this system as close to reality as possible the roll angle was said to be unknown and needed to be estimated.

3.1 Roll motion equation

In this thesis a one degree of freedom model which represents the roll motion of the vehicle was chosen. It is a robust and sufficient model when driving on flat roads, which is assumed in this thesis [1, 4, 5, 8].

Figure 3.1 shows a schematic drawing of the model. Here the vehicle is driving in a right hand turn and the centrifugal forces that are acting on the wheels have been simplified and are represented by the mass of the truck times the lateral acceleration, ma_y, acting on the center of gravity in this figure.

This force produces a body roll motion making the vehicle lean outwards in the curve. The spring and damping on the wheels with their roll stiffness, K_r, and roll damping, C_r, counteract with the lateral force to keep the truck upright. Also the moment of inertia about the roll axis of the truck, I_x, and the gravity, g, helps from rolling over. By applying Newtons second law turning around the roll center, rc, equation (3.1) is obtained.

$$h_r m a_y \cos\phi + h_r m g \sin\phi - I_x \ddot{\phi} - 2C_r \dot{\phi} - 2K_r \phi = 0 \tag{3.1}$$

This equation is rewritten and simplified assuming the roll angles to be small, the equation seen in (3.2) is obtained.

$$\frac{I_x}{h_r m}\ddot{\phi} + \frac{2C_r}{h_r m}\dot{\phi} + \frac{(2K_r - h_r m g)}{h_r m}\phi = a_y \tag{3.2}$$

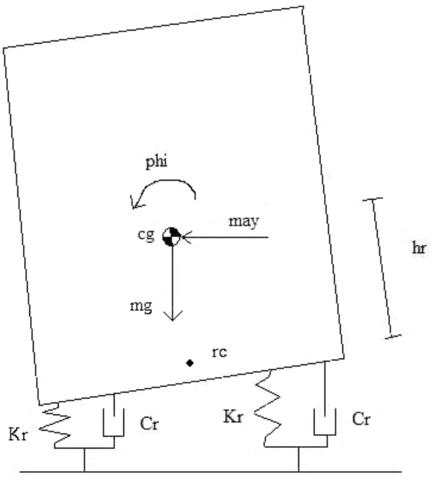

Figure 3.1. Schematic drawing of the truck.

The equation only holds when all wheels have ground contact. ϕ is the roll angle, $\dot{\phi}$ is the roll rate, $\ddot{\phi}$ is the roll acceleration. h_r is the distance between the center of gravity, cg, and the roll center and m is the total mass of the vehicle.

3.2 Obtaining constants

To be able to calculate the roll angle from equation (3.2) the values of the constants have to be found. The roll motion equation is a simple model of the truck compared to the model used in the simulator. Since the simulator model is so detailed the constants corresponding to those in equation (3.2) can not be obtained directly but have to be calculated from sub components. Instead of calculating the individual constants from the simulator model the relation between the variables were chosen to be found in other ways.

3.2.1 Steady state simulation

A steady state turn to estimate the relation between ϕ and a_y was simulated. In a steady state turn the steering wheel position is constant. This means that the lateral acceleration and the roll angle also are constant and that the roll rate, $\dot{\phi}$, and roll acceleration, $\ddot{\phi}$, are zero and can be neglected. The relation between roll angle and lateral acceleration, here referred to as k, can be obtained from the simulation.

In this simulation the steering wheel angle was increased with 0.01 rad every 0.1 seconds, but it was still considered to be steady state. The steering wheel angle was increased until one of the wheels took off from the ground. To know when this occurred the normal force on the ground on all six wheels were measured. A wheel lift was defined as when one of the normal forces reached zero.

Then the roll angle was plotted against the lateral acceleration. A least square method was used to estimate the linear relation referred to as k, see figure 3.2. Only the part of the plot up to the wheel lift was used for this calculation. This simulation was made for several velocities and k was set to the mean value of all the linear relations calculated between roll angle an lateral acceleration.

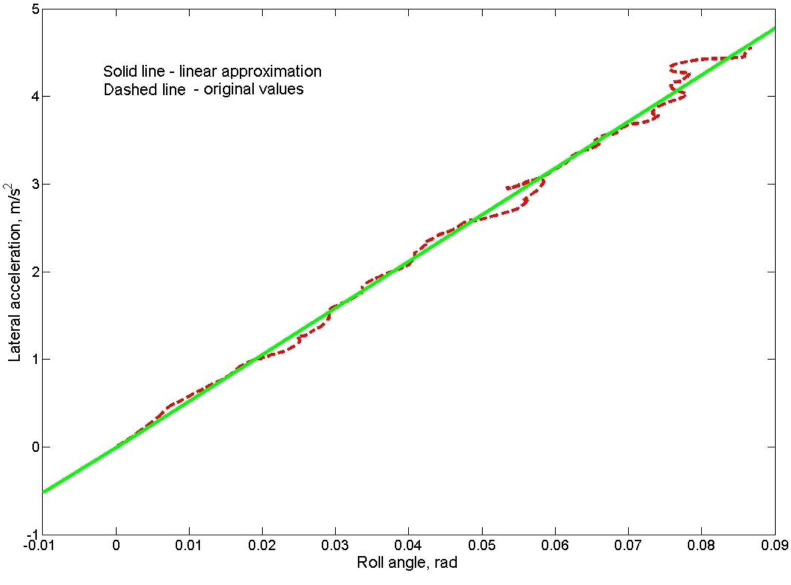

Figure 3.2. Plot of the roll angle against the lateral acceleration from a steady state simulation in 20 m/s and the linear approximation of their relation.

3.2.2 Simplification

By conducting other simulations, such as sinus waves and random driving, where the roll rate and roll acceleration not could be neglected it could be seen that the first and second term in (3.2) did not contribute much at all to the final value of the roll angle. Therefore these two terms were left out of the equation. This decision is also supported by [8] where the same simplification was made.

3.3 The final model

After the simplification of the roll motion equation where the two first terms are neglected the final model that is used to calculate the roll angle is that of equation (3.3). Here k is the relation between the roll angle and the lateral acceleration obtained from the steady state simulations. The lateral acceleration is the measured lateral acceleration from the rear end of the truck modeled in the simulator. The model was validated by comparing the calculated roll angle and the measured rear roll angle of the truck. In figure 3.3 a comparison between the real roll angle and the calculated roll angle is made.

$$\phi = \frac{a_y}{k} \tag{3.3}$$

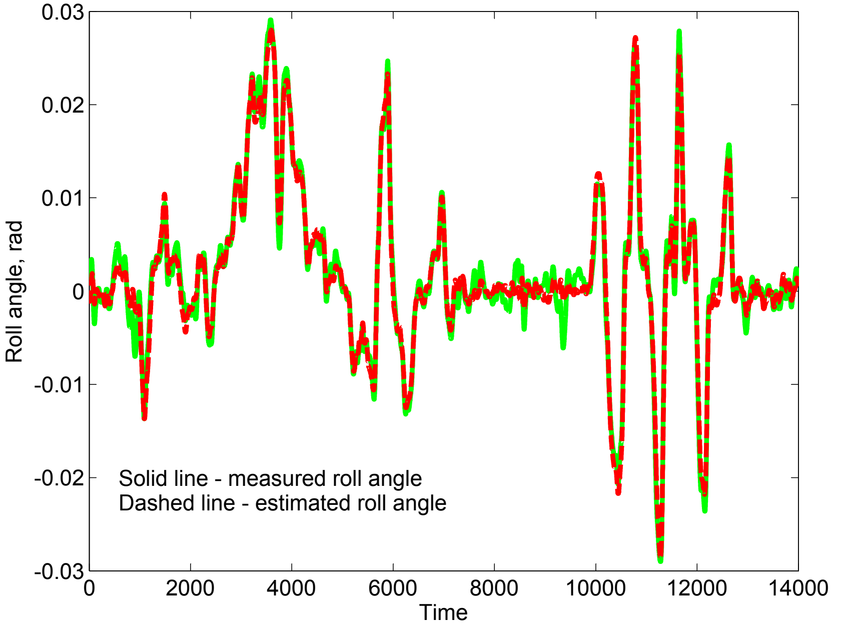

Figure 3.3. Comparison between the estimated roll angle and the sensor measured roll angle.

3.4 Roll rate estimation

The derivative of the calculated roll angle was used as an estimation of the roll rate. As the signal was a bit noisy it was filtered through a first order low pass filter seen in equation (3.4). α is a constant that was tuned.

$$\dot{\phi}_{filtered}(t) = \dot{\phi}_{filtered}(t-1) + \alpha(\dot{\phi}(t) - \dot{\phi}_{filtered}(t-1)) \tag{3.4}$$

In figure 3.4 and 3.5, respectively, the calculated roll rate and the filtered roll rate is compared to the real measured roll rate.

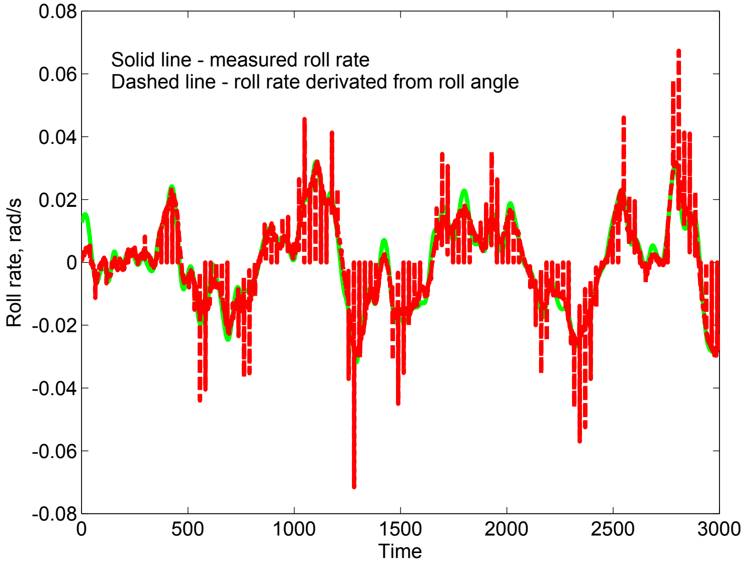

Figure 3.4. The calculated roll rate is compared to the real measured roll rate.

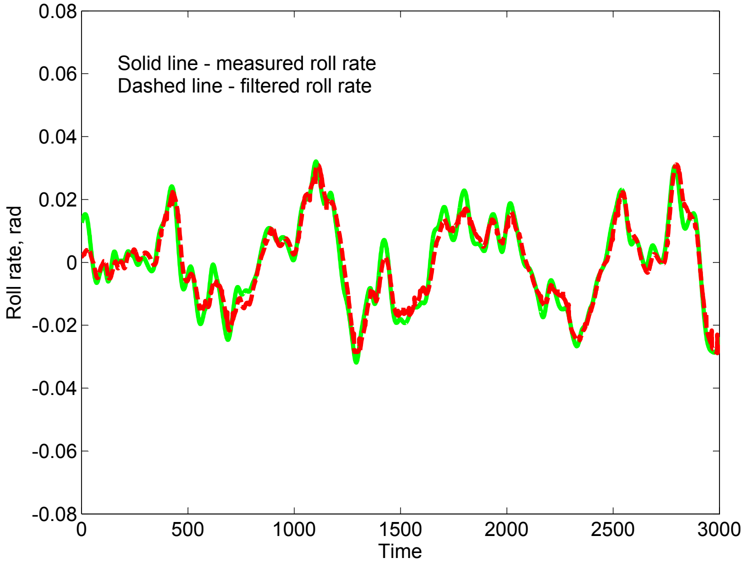

Figure 3.5. The filtered roll rate is compared to the real measured roll rate.

Chapter 4

Rollover index

In this chapter a rollover index which indicates how close the vehicle is from wheel lift off is calculated. Here, wheel lift off is considered equal to rollover. The rollover index is based on the roll angle, roll rate and their thresholds. How the thresholds were found and how the rollover index was formed are presented.

4.1 Roll angle threshold

The roll angle at the moment when the first wheel on either side of the truck lifts off is here referred to as the roll angle threshold, ϕ_{th}. From this point on a rollover is regarded unavoidable and that is why the vehicle has to stay below this roll angle threshold.

To find the roll angle threshold the roll motion equation (3.2) from chapter 3 was used. The same steady state turn where roll rate and roll acceleration were neglected, $\ddot{\phi} = \dot{\phi} = 0$, was studied. Just like before a lift off was defined as when the normal force on any of the six wheels reached zero. The roll angle and the lateral acceleration at wheel lift off is referred to as the roll angle threshold, ϕ_{th}, and the critical lateral acceleration, a_{yc}.

4.2 Roll rate threshold

The roll position of the vehicle in relation to the wheel lift threshold can now be calculated by comparing the roll angle to the roll angle threshold. This is important information when trying to prevent rollover. But even though the position of the vehicle is known, the knowledge of in which direction or how fast it is rolling is lacking.

By looking at the roll rate, this information can be obtained. To be able to use this information to prevent rollover a roll rate threshold, $\dot{\phi}_{th}$, is desired. An exact threshold for the roll rate is hard to establish, because it also depends on the roll angle of the vehicle. Here the roll rate threshold was estimated from the maximum roll rates achieved when performing violent steering wheel movements in the simulator without rolling over. Figure 4.1 shows the result from an automatic simulation of a sinus curve after which the roll rate threshold was tuned.

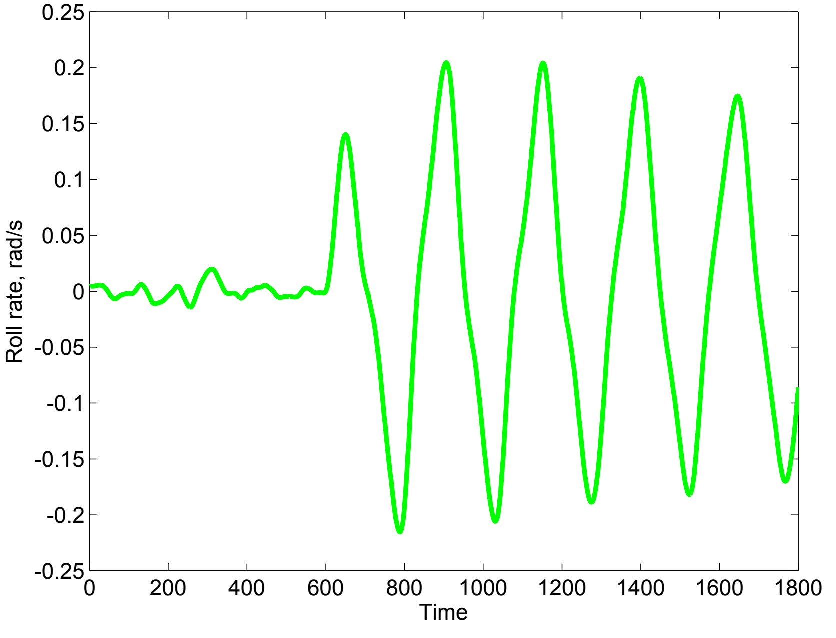

Figure 4.1. The roll rate in a sine curve. The roll rate threshold was tuned after this plot.

4.3 Rollover index

In this section the knowledge of the thresholds are put together to form a rollover index which indicates how close the vehicle is from rolling over. This rollover index, RI, is inspired by the one used in [2, 3, 6] but is changed to suit the conditions in this thesis. For example is the rollover index here a function of the roll angle and roll rate only, not the lateral acceleration as it is in the original version. This is because the only difference between the lateral acceleration and the roll angle in this thesis is a scale factor.

The index is calculated as in equation (4.1) under the condition that the roll angle and roll rate have the same signs, which means that the vehicle is rolling in the same direction as it is leaning. If this condition is not true it means that the vehicle is leaning to one side but is rolling towards the other side. Under these circumstances the rollover index is set to 0, see equation (4.2), because the vehicle is considered to be about to stabilize and reduce it's risk of rolling over.

However, once the rollover index threshold, which will be calculated in the next chapter, is reached the different sign criterion is neglected and RI is calculated according to equation (4.1). This is because the automatic control would be too jerky otherwise.

$$RI = C_1 \frac{|\phi(t)|}{\phi_{th}} + C_2 \frac{|\dot{\phi}(t)|}{\dot{\phi}_{th}} + C_3 \frac{|\phi(t)|}{\sqrt{(\phi(t))^2 + (\dot{\phi}(t))^2}}, \qquad \phi\dot{\phi} \geq 0 \tag{4.1}$$

$$RI = 0, \qquad \phi\dot{\phi} < 0 \tag{4.2}$$

Equation (4.1) needs a closer explanation. The first term expresses the current roll angle in relation to the roll angle threshold. The second term expresses the current roll rate in relation to the roll rate threshold. The last term is combining the roll angle and roll rate to improve the accuracy of how close in time a wheel lift off is.

To understand this last term, take a look at figure 4.2 where the roll angle is plotted against the roll rate. A straight line is drawn between the roll angle and roll rate thresholds. When the vehicle state is in a point near or close to this line the last term of the equation gives some additional information of how far in time a wheel lift is. This last term is equal to cosine of the angle between the roll angle axle and the absolute value of this point in the plane.

This means that the value of this term, just as the other two terms, theoretically varies between 0 and 1. When the roll angle is large, close to it's threshold, and the roll rate is small the time to wheel lift is short. When the roll rate is dangerously large but the roll angle still is small the time to wheel lift is a bit longer.

Finally C_1, C_2 and C_3 are constants which weight the terms, they were tuned when driving in the simulator. The value of the rollover index should be interpreted as that 0 is no danger at all and 1 is overturning. The maximum value of the rollover index is however not 1. This is among other things because the roll rate threshold has been estimated and is not known exactly.

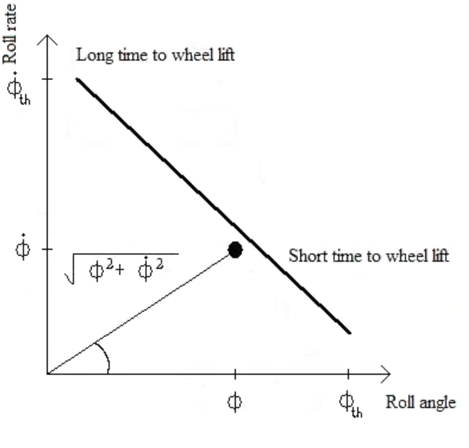

Figure 4.2. Plot between roll angle and roll rate illustrating the expression of the angle between roll angle axle and a absolute value of a point in the plane.

Chapter 5

Control design and strategy

In this chapter the strategy of how to prevent the vehicle from rolling over is presented. The idea is to brake all the wheels reducing the total longitudinal velocity and by that means reducing the lateral acceleration that arise from the forward speed. This means that the side force on the truck reduces and eventually so should the roll angle.

5.1 Method

The idea came while conducting the steady state turns at different longitudinal velocities. The lower the longitudinal velocity the longer before the first wheel lifted. If the velocity was low enough the wheels never lifted. So reducing the velocity of the vehicle by braking should also reduce the roll angle. In the literature braking has also been used as a method for preventing rollover. Some of the arguments for this method is that it is cheep and easy to implement and also the same argument as found while conducting steady state turns; that the forward speed effects the lateral forces on the vehicle which causes it to roll over [6, 14].

Now an appropriate level for the rollover index threshold has to be found. When this threshold is reached the system starts to brake. If the system triggers on too low rollover index it will be braking constantly and the driver will hardly ever have control over the vehicle. But if the braking starts too late the system might not have time to prevent the rollover.

The next question is how hard the braking should be. For example can the braking start at a low rollover index, when the risk of rolling over is relatively low, but not be so fierce at the beginning. Another solution is to start the braking at a higher rollover index, when the vehicle is really close to rolling over, and then brake hard at once. The strategy chosen was something in between these two extremes and by driving the same test over and over again the rollover index threshold and the braking force were tuned. But as will be seen in later chapters, the same method might not be optimal for every driving situation.

5.2 Control strategy

The automatic control is as follows. As the rollover index threshold is exceeded the system is activated. Then it starts braking proportionally to the value of the rollover index. Also the throttle is turned off so that the driver can not give more gas. The braking does not stop until the rollover index drops below its threshold value. All this causes the forward speed of the vehicle to drop and the danger of rolling over reduces.

In equations 5.1 and 5.2 it can be seen how the braking from the system is calculated. RI stands for rollover index and even if that value should be higher than 1 the final brake signal is set to 100, which corresponds to the maximum braking.

$$Brake_{sys} = RI * 100, \qquad RI \geq 0.6 \tag{5.1}$$

$$Brake_{sys} = 0, \qquad RI < 0.6 \tag{5.2}$$

The brake signal from the rollover control is then sent to the brake control of the vehicle which distributes the braking to all six wheel for optimal effects, just as it would when the driver presses down the brake pedal.

5.3 Validation

The control system was tested by driving a sinus curve in 80 km/h with an amplitude of 110 degrees and a frequency of 0.4 both with and without the safety system. In figure 5.1 the results are plotted and it can clearly be seen that the roll angle is lower through the whole sinus when driving with the system.

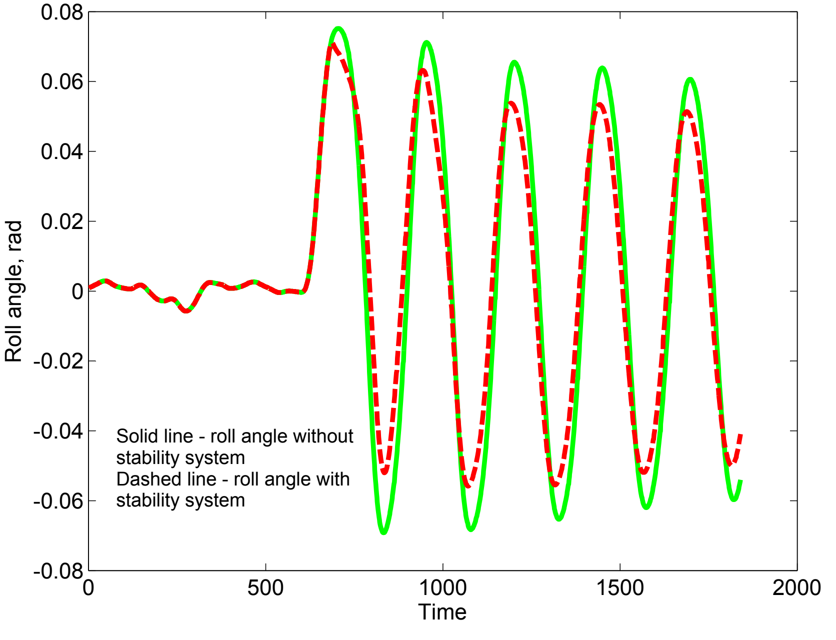

Figure 5.1. Comparing the roll angles from driving in a sinus curve with and without the control system.

Chapter 6

Simulator study

To examine how well the roll stability system would work in real life, a simulator study was conducted. Test persons drove the simulator with the stability system implemented, half of the time it was switched on and the other half it was switched off. A study with test persons is important because even though the system seems to preform well while validating with a robot it is not certain that it is compatible with the drivers. In this chapter the outline of the study and the results from it are presented.

6.1 Design and procedure

How the road and test should be designed and conducted is very important and therefore carefully planned. Situations that trigger the safety system must be included, but yet they can't be too hazardous so that the safety system don't have a chance to prevent the rollover. To reduce the risk of exceeding the simulator threshold for overturning, which would stop the driving, a side force that pushes the vehicle back to upright position just as it is about to turn over was added. This force comes active when the roll angle reaches 0.09 rad. When it does come active the truck is considered to have turned over.

This force is however not always enough to keep the vehicle on the road and sometimes the roll angle becomes too high and the simulator stops abruptly. It is desirable to avoid the simulator from stopping due to rollover because it can effect the drivers further driving behavior. However if the simulator stops due to rollover the test is not aborted. After a few seconds the simulation can continue from the same spot as it stopped and the session is carried on until the end.

6.1.1 The road

The test was conducted on a main country road, with surrounding forest. No other traffic than the truck was on the road. Firstly there was a lightly hilly training road, where the participants could get used to driving the simulator. The speed limit varied from 60 to 80 km/h and there were two obstacles that made the driver do lane changes.

Then the test road started, it was about three km long. It began and ended with a flat, straight road and in the middle the road narrowed into a sharp left hand turn. In the straight parts some cones were placed in different patterns to create different driving situations.

There where two situations on the test road that where designed for testing the roll stability system. There was the sharp, narrow, left hand turn which became tighter and tighter and slowly increased the roll angle and lateral acceleration, but kept the roll rate relatively low. This situation was meant to test if the control system could handel a slowly increasing rollover risk. Then there was a slalom manoeuver with five turns that were made out of the cones. Here the driver had to do big and sudden wheel turns to keep on the road. This lead to high roll rates and the idea was to test how well the system could prevent rollover in fast situations.

6.1.2 The participants

The test persons were mainly friends who had driving license for private car, driving license for truck was not required. They where all in the age group 20 - 30 years old and the distribution between men and women was two thirds to one third.

6.1.3 The procedure

Every person was asked to fill in a form before they where driving. They also got to read instructions of what to do. See Appendix A.

Thereafter they got in to the simulator and started driving. After ten km of training road the test road started and the driver got to practice driving the test road three times in 50 km/h. Thereafter the test road was repeated three times, where the test persons were asked to keep a certain velocity each lap: 60, 70 or 80 km/h. Then the test person was asked to drive three more laps in the same order considering velocity. The roll stability system was turned on either during the first three laps or the last three laps, the test person was kept unaware of which. The order in which the velocities where driven and if the system was on or off were altered from person to person following a scheme that can be seen in Appendix B. This scheme was constructed to get a balanced order that reduces the influence from behavioral effects in the results [15].

When the driving test was over the participants were asked to fill in two more forms. During the test a form was filled in by the operator/test leader. All forms used in the study can be seen in Appendix A.

6.2 Results and analysis

All together there were 24 participants in this study, here the results from the study, both the driving data and the information from the forms, are analyzed. Because of the balanced order all the data can be analyzed together.

6.2.1 Analysis method

The main question is of course whether the system prevented overturns or not. To find this out and to discover other possible effects the results from driving with and without the system were compared for each situation and velocity individually. The number of overturns were compared.

Wilcoxons sign rank test was used to establish a possible difference in number of rollovers. Here a short description of this test follows, for a more detailed description see [12]. The reason for using this test is that the real roll angle values at rollover not are known, they have so called censured values. Here they are given the value 0.1 rad because this is where rollover occurs theoretically, but they can be much higher.

This test uses individual differences between driving with and without the system. The cases where the driver has overturned both with and without the system are removed because there is no known difference between these values. When the driver has overturned either with or without the system the difference is also not know because the angle at rollover is not known. But the difference ought to be big and is given a positive or negative number that is bigger (smaller) than the other differences. The sign depends on whether the overturn was with or without the stability system.

Then the differences are given a rang in ascending order so that the rollover cases get the lowest and highest rang, and then the statistical significance is calculated from there. Normal distribution is not required for Wilcoxons sign rank test. The significance level used here is 5%.

6.2.2 The curve

Here the roll angle and lateral acceleration slowly increases and can after some time become so high that the vehicle finally overturns. The higher the speed the higher the risk of overturning.

Driving in 60 km/h only triggered the system for one driver and no one rolled over. Taking the turn in 70 km/h triggered the system one third of the times with the system turned on. The truck never overturned regardless if the system was on or off. Therefor the data from these two situations can not be used to investigate the effects of the system.

Driving in 80 km/h the stability system triggered every single time and five persons rolled over when the system was turned on and one person when the system was turned off. Wilcoxons sign rank test shows that this is a significant difference. These results and the mean maximal roll angle in every situation can also be seen in table 6.1.

Situation	$\bar{\phi}_{max}$	Overturns	Sign.diff.
60 with	0.0451	0	
60 without	0.0434	0	No
70 with	0.0598	0	
70 without	0.0572	0	No
80 with	0.0836	5	
80 without	0.0750	1	Yes

Table 6.1. Results from the curve.

Handling characteristics in curve

The results from the curve are not what was expected; more people turned over with the system than without it. In figure 6.1 the typical behavior at a rollover in 80 km/h with the system turned on is illustrated. It shows that the roll angle is increasing even though the braking, which should reduce the roll angle, has started. The roll angle keeps increasing until it reaches 0.09 rad and then the side force helps the vehicle back on the road.

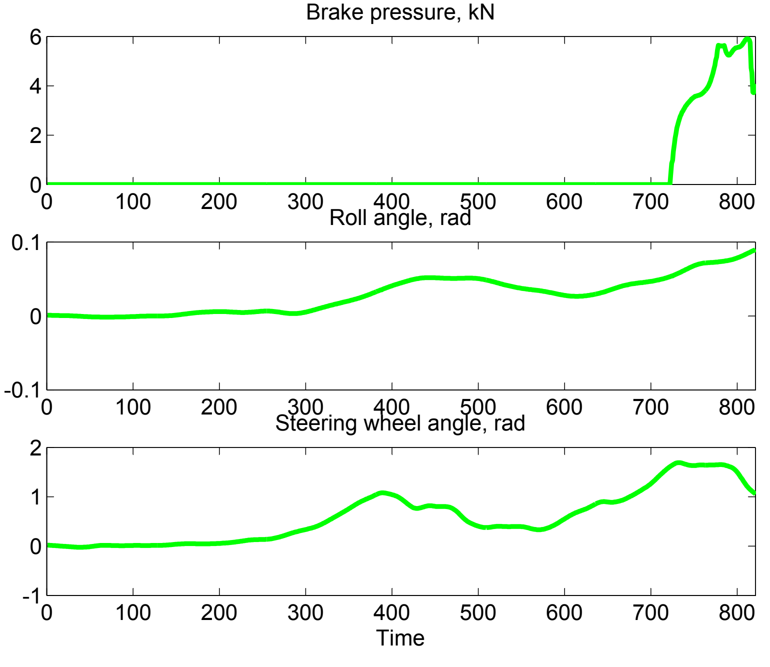

Figure 6.1. Plot from a typical rollover in the curve, showing that the roll angle keeps increasing even though the braking has begun and the steering wheel angle is held constant.

It can also be seen that it is not a higher steering wheel angle that causes the increase in roll angle, in the region where the system is active. Even though the steering wheel angle is held constant or is turned in the opposite direction the roll angle keeps increasing. This implies that it was not the drivers behavior that caused the roll over and the explanation has to be found in the dynamics of the truck.

One possible explanation is that when braking the load suddenly transfers to the front of the truck and the front wheels. The increase in normal force on the front wheels would also increase the lateral forces on the front wheels which may become too large and turn the vehicle over. This would however mean that the roll always begins at the front, but this is not the case.

When the roll stability system reduces the speed in a curve like this it was observed that the vehicle turns slightly inwards to the curve. This behavior can be what turns the vehicle over and it can be explained in two different ways.

The first is that the load transfer to the front of the truck can have another effect than the one mentioned above. When the normal force increases at the front wheels and decreases at the rear wheels the tire forces create a momentum which turns the vehicle inwards in the curve.

Another explanation is the fact that the vehicle is understeer. This would mean that the steer angle required to negotiate a certain curve increases with the lateral force and thus with the longitudinal velocity [13]. Keeping a certain steer angle while driving in 80 km/h and then sudden drop the velocity 10 to 20 km/h makes the steer angle too large for the new lower velocity, the turn becomes too tight and the truck rolls over.

6.2.3 The slalom manoeuvre

In this case the driver is forced to do big and sometimes sudden wheel turns to manage the situation. The higher the speed the more difficult to stay on the road, but also lower velocities can cause problems and make the driver loose control.

Driving in 60 km/h the system triggered two thirds of the time when it was on. No overturns were reported from this situation.

In 70 km/h only a couple of persons managed through the slalom without trigging the safety system. There were two turnovers without the system and none with. Wilcoxons sign rank test showed that this difference was significant.

In 80 km/h there was eight overturns with the system and eleven without it. But the difference was not significant. The results can be seen in table 6.2.

It seems as though the system prevents rollovers when driving in 70 km/h, but not in higher speeds. An explanation to this could be that this slalom manoeuver is to hazardous to drive in 80 km/h. The rollover risk appears quickly and even if the system is turned on it has no chance to prevent the rollover.

Situation	$\overline{\phi}_{max}$	Overturns	Sign.diff.
60 with	0.0551	0	
60 without	0.0544	0	No
70 with	0.0636	0	
70 without	0.0689	2	Yes
80 with	0.0813	8	
80 without	0.0868	11	No

Table 6.2. Results from the slalom manoeuver.

6.2.4 The forms

Here the results from the forms that were filled in during the study are going to be presented and analyzed. The forms as a whole can bee seen in Appendix A.

In table 6.3 some facts about the test persons can bee seen. The group of participants was very homogenous, everyone was between 20 and 30 years of age and fairly unexperienced as drivers. About half of the test persons drives less than 1000 km per year. More variation among the test persons considering age and driving experience both from car and truck might have been desirable. But on the other hand had an experienced truck driver maybe would have acted differently in the driving situations and would not have triggered the system as much as the unexperienced drivers did.

Men/women ratio	2/1
Average age in years	24.6
Average number of years with driving licence for car	6.2
Average km per year behind the wheel	2380
Number of persons with driving licence for truck	0
Number of persons that had driven a simulator before	0

Table 6.3. Facts about the test persons.

In table 6.4 the results from the test leaders form can be seen and in table 6.5 the results from the form regarding specific questions about the study filled in by the test person after driving are presented. The scales on these two questioners went from 1 to 6 and a low number means that the person agrees with the statement.

It seems like the test leader and test person agreed on the performance of the test person as a driver, they drove quite normally. The reason why the test persons did not get the highest grade from the test leader is because they often kept too far to the right, especially in the curve.

The risk of overturning seemed to be experienced as medium high at both the curve and the slalom manoeuver. The fact that there was an extra force pushing

Statement	Result
The test person drives normally on the road	2.0
The test person looks motion sick	5.7

Table 6.4. Results from the test leader form filled in during the driving.

Statement	Result
I drove normally on the road	2.0
There was a great risk of rolling over in the curve	3.3
There was a great risk of rolling over in the slalom manoeuver	3.2
The cones were clearly visible	1.4
It was easy to understand how to drive on the test road	1.0

Table 6.5. Results from the test person form filled in after driving.

the participants back on the road when they were at risk might have made them believe that the risk of overturning was smaller that what it actually was. The last two questions of the test persons form shows that the test road was clear and easy to understand.

The last form that the test persons filled in is concerning the general feeling of the simulator and is a foundation for further improvements of the simulator. Here the scaling is a bit different, it goes from 1 to 7 and a low number means that the person agrees with the statement.

Statement	Result
Driving in the simulator was similar to driving for real	2.7
It was easy to know the position of the vehicle on the road	3.6
The steering of the truck was good	2.5
The brakes were good	3.5
I could keep the desired speed	3.5
I have experience from TV or computer games	3.8
I felt motion sickness during or after driving	5.6

Table 6.6. Results from the test person form from VTI filled in after driving.

The general feeling about the simulator seems to be that it is not quite like driving a real vehicle. This slight above medium grade applies for all major functions in the simulator. To that the test persons have some experience from TV and computer games. All this can have affected the test persons driving behavior, if the driving felt unrealistic they might not have taken the test serious. This also reflects in the experienced risk in the slalom manoeuvre, about half of the test persons turned over but the risk was only considered medium high. The slightly nauseous feeling, which the test persons experienced might also have affected their concentration.

Chapter 7

Conclusion

In this chapter some conclusions from the results and previous analysis are made. The curve and the slalom manoeuvre are treated separately because of the difference in their nature and result. An overall conclusion about the study and system is made and some thoughts on future work finishes off the report.

7.1 The curve

From table 6.1 we can see that the results from the lower speeds, 60 and 70 km/h, don't show any significant difference of driving with system compered to driving without it. In any case are the results from driving in 60 km/h not expected to show any difference as the system hardly ever triggers. Even in 70 km/h the effects of the system does not show, only in one third of the cases the system triggered. This means that the threshold is too high to make a difference in these situations. But on the other hand, as no one rolled over, the system is not really needed in these velocities under the circumstances in this curve and the threshold is right after all. However, nothing can be said about the effects of the system in the lower velocities.

Driving in 80 km/h the effects starts to show, here we can clearly see that the system gives the opposite effect than wanted. The number of rollovers are significantly larger when driving with the system turned on. A typical plot from a turnover suggests that the rollover not is caused by the driver, see figure 6.1. The roll angle increases after the braking has begun despite the fact that the driver keeps a constant steering wheel angle at first and eventually starts to steer back. In chapter 6.2.2 some possible explanations for this behavior are presented and discussed. The force of the braking seems to be too hard, it reduces the longitudinal velocity too quickly and overturns the vehicle rather than preventing it from overturning. This system seems to be wrong for this situation but some kind of system is probably still needed because rollover occurred even without the system turned on.

7.2 The slalom manoeuvre

Also in this particular situation driving in 60 km/h is relatively harmless. The system triggers a little less than half of the time and never overturns. At this velocity no conclusions about the safety system can be drawn.

But this is a riskier situation than the curve, because already in 70 km/h there were a few overturns, and in 80 km/h about 50% of the drives overturned. The number of rollovers are significantly smaller when driving with the system compared to without it in 70 km/h. This is the effect that we were looking for when constructing the safety system and it confirmes that the roll stability system prevents rollovers in this situation and velocity.

In 80 km/h the number of turnovers are also in favour for the system but this difference does not have significance. The conclusion is that it is too hazardous to drive in 80 km/h in this manoeuvre and the safety system simply does not have a chance to prevent rollover.

7.3 The test persons

Looking at the group as a whole there are many factors that speak for their unsuitability in this study. The test persons are young and unexperienced as drivers, neither of them have driving licence for truck. Also did they not experience the simulator as very realistic and they tend to underestimate the risk of rolling over with a truck.

But the reason for the test persons not being able to estimate the danger correctly and the reason for the numerous overturns is just because the fact that they are not truck drivers. This might actually have helped in this study, because with unexperienced drivers the system was tested thoroughly.

7.4 Final conclusions

Summing up the results and conclusions from the different situations and velocities it seems that the system indeed prevents rollover in the slalom manoeuver in 70 km/h. To strengthen this theory the results from the validation are recalled. Here the test was made by a robot and it shows that the roll angle indeed is lower when the system is turned on while driving in a sinus curve.

But in the sharp curve the system has the opposite effect and makes the truck roll over more easily. However, this does not mean that all systems have this effect, with a different tuning this system might be adjusted to prevent rollovers in the curve.

7.5 Future work

The most important improvement that has to be made to the stability system is of course to make it work in steady state resembling situations such as the curve.

The system has to be made smoother so it does not brake too hard and causes the truck to roll over. Some improvements that could be made to this particular system are:

- more precise calculation of the roll angle
- more intelligent braking system
- differential braking where not all wheels brake at the same time
- steer angle control
- active suspensions that tilts the vehicle inwards in curves

Other things that would be interesting to expand the system to handle are:

- uneven roads
- cross wind
- moving loads such as liquids
- bigger vehicles such as tractor semi-trailers

And of course the study could always be sharpened. The test road could be improved by using more realistic driving situations in normal traffic. It would also be interesting to use test persons in wider age group who have driving license for truck.

Appendix A

Forms from the study

Frågeformulär **Fp:**

Innan körningen

Vilken typ av körkort har du?

☐ B	Jag kör cirka	mil/år.
☐ BE	Jag kör cirka	mil/år.
☐ C	Jag kör cirka	mil/år.
☐ CE	Jag kör cirka	mil/år.
☐ D	Jag kör cirka	mil/år.
☐ DE	Jag kör cirka	mil/år.

Hur länge har du haft det/dem?

Har du kört (en liknande) simulator förut? (Även för bil)

Blir du lätt åksjuk?
alltid ☐☐☐☐☐☐ *aldrig* *vet ej* ☐

Frågeformulär Fp:

Efter körningen

Körde du ”*som vanligt*”?
ja, helt ☐☐☐☐☐☐ *nej, inte alls* *vet ej* ☐

Hur stor upplevde du att risken var för att välta i den skarpa kurvan?
mycket stor ☐☐☐☐☐☐ *mycket liten* *vet ej* ☐

Hur stor upplevde du att risken var för att välta i slalombanan?
mycket stor ☐☐☐☐☐☐ *mycket liten* *vet ej* ☐

Hur väl syntes konorna?
mycket väl ☐☐☐☐☐☐ *inte alls* *vet ej* ☐

Hur lätt var det att förstå hur du skulle köra i konbanorna?
mycket lätt ☐☐☐☐☐☐ *mycket svårt* *vet ej* ☐

Övriga synpunkter

Tack för din medverkan!

Testledarnotiser **Fp:**

- Se till att det finns en plastpåse på passagerarsätet
- Be fp fylla i första delen av frågeformuläret

Information till försökspersonen

- Sätet kan ställas in
- Använd säkerhetsbältet
- Automatväxel, bara gas och broms
- Jag hör och ser dig, säg till om det är nåt
- Du hör mig, invänta instruktioner
- Körningen tar cirka 30 minuter och börjar med en övningsväg
- Håll hastigheten hela tiden, följ konbanorna och undvik att köra på konorna
- Nu startar jag igång simulatorn, det kommer att röra på sig lite
- Nu kan du börja på övningsvägen, passa på att ställa frågor under övningsdelen
- Nu får du övningsköra på testbanan, håll 50. (Kör banan i 50 tre gånger utan system)

OBS! RSS är alltid inaktivt i början oavsett vad checkboxen säger!

- *Kör tre varv i 60/70/80 i någon ordning*

Stäng av/ slå på systemet

- *Kör tre varv i 60/70/80 i samma ordning som tidigare*

Frågor att besvara under körning

När är systemet påslaget?

Kör fp normalt på vägen? *helt normalt* □□□□□□ *väldigt konstigt*

Skulle fp ha vält? Var? Hastighet?

Ser fp ut att må illa? *mycket* □□□□□□ *inte alls*

Efter körning

- Fråga allmänt hur det kändes, om det gick bra
- Be fp fylla i de två enkäterna - min egen och den för teknisk utveckling
- Berätta mer om försöket, när systemet var på, om de välte o.s.v.

Deltagarinstruktion

Din uppgift är att köra en modern lastbil i simulator. Försöket tar ungefär 12 minuter. Körningen inleds med en träningsväg varpå testvägen följer.

Träning

Under träningspasset får du vänja dig vid att köra simulatorn. Träningen tar cirka 14 minuter. Du kan under hela träningen ställa frågor till försöksledaren. Träningen består till en början av landsvägskörning med en del hinder bestående av konor. Därefter får du övningsköra på testvägen några gånger. Undvik i möjligaste mån att köra på konorna.

Försöket

Under försöket kommer du att köra på landsväg och det kommer att finnas en hel del hinder bestående av konor. Kör som hindren visar, undvik att köra på konorna och håll hela tiden den angivna hastigheten. Följ de instruktioner som försöksledaren ger.

Allmänt

Lastbilen du kör är automatväxlad. Hastighetsbegränsningen på landsväg är 90 km/h. Din uppgift är att köra som konbanorna visar och hela tiden hålla den angivna hastigheten. Försöksledaren kan under hela försöket se och höra dig i simulatorn. Försöksledaren kommer inte att prata med dig när du kör försöket, förutom då instruktioner ges, men det är viktigt att du säger till så fort någonting inte känns bra. Du kan avbryta försöket när som helst, det gör du genom att tala om för försöksledaren att du vill avsluta försöket. Du ska inte öppna dörren till simulatorn själv.

Sammanfattning

- Håll hela tiden den angivna hastigheten
- Meddela försöksledaren om något inte känns bra
- Öppna inte dörren i simulatorn själv

Simulatorenkät

Fylls i av försöksledaren:
Datum: *Projektnamn:* *FPnr:* *Simulator:*

Följande enkät ligger till grund för vidare utveckling av den tekniska biten på fordonssimulatorn.

Information om dig som förare:

Ålder: ☐ man ☐ kvinna

Hur många mil kör du årligen?
☐ 0 – 1000 ☐ 1000 – 2000 ☐ 2000 – 3000 ☐ över 3000

Utgå från din egen körupplevelse och kryssa i det du anser stämma bäst:

Hur upplevde da att likheten var med att köra på riktigt?
mycket liten ☐☐☐☐☐☐☐ *mycket stor*

Hur upplevde du miljön du körde i?
torftig ☐☐☐☐☐☐☐ *omväxlande*
orealistisk ☐☐☐☐☐☐☐ *realistisk*

Kunde du upptäcka detaljer i miljön i tid?
inte alls ☐☐☐☐☐☐☐ *mycket bra*

Hur upplevde du dina omgivade medtrafikanter?
helt overkliga ☐☐☐☐☐☐☐ *helt verkliga*

Hur väl kände du fordonets placering på vägen?
inte alls ☐☐☐☐☐☐☐ *mycket bra*

Hur upplevde du bilens styrning?
mycket dåligt ☐☐☐☐☐☐☐ *mycket bra*

Hur upplevde du bilens bromsar?
mycket dåligt ☐☐☐☐☐☐☐ *mycket bra*

Hur väl kunde du hålla din önsakde hastighet?
inte alls ☐☐☐☐☐☐☐ *mycket bra*

Vilken vana har du av TV- eller datorspel?
ingen alls ☐☐☐☐☐☐☐ *stor vana*

Upplevde du illamående under körningen?
ingen alls ☐☐☐☐☐☐☐ *mycket*

Slutgiltiga kommentarer:

Vad tycker du är mest angeläget att förbättra på simulatorn?

Övriga kommentarer?

Appendix B

Driving scheme

This driving scheme was followed during the study to achieve a balanced order. It shows if the test person started with or without the roll stability system and in which order the velocities were driven.

1. Started with system 60/70/80
2. Started without system 60/70/80
3. Started with system 60/80/70
4. Started without system 60/80/70
5. Started with system 70/60/80
6. Started without system 70/60/80
7. Started with system 70/80/60
8. Started without system 70/80/60
9. Started with system 80/60/70
10. Started without system 80/60/70
11. Started with system 80/70/60
12. Started without system 80/70/60
13. Started with system 60/70/80
14. Started without system 60/70/80
15. Started with system 60/80/70
16. Started without system 60/80/70
17. Started with system 70/60/80

18. Started without system 70/60/80
19. Started with system 70/80/60
20. Started without system 70/80/60
21. Started with system 80/60/70
22. Started without system 80/60/70
23. Started with system 80/70/60
24. Started without system 80/70/60

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