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Tracking and threat assessment for automotive collision avoidance

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Tracking and threat assessment for automotive collision avoidance

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To Anna

Abstract

This thesis is concerned with automotive active safety, and a central theme is a new safety function called Emergency Lane Assist (ELA). Automotive safety is often categorised into *passive* and *active* safety, where passive safety is concerned with reducing the effects of accidents and active safety aims at avoiding them. ELA detects lane departure manoeuvres that are likely to result in a collision and prevents them by applying a steering wheel torque. The ELA concept is based on traffic accident statistics, *i.e.*, it is designed to give maximum safety based on information about real life traffic accidents.

The ELA function puts tough requirements on the accuracy of the information from the sensors, in particular the road shape and the position of surrounding objects, and on robust threat assessment. Several signal processing methods have been developed and evaluated in order to improve the accuracy of the sensor information, and these improvements are also analysed in how they relate to the ELA requirements. Different threat assessment methods are also studied, and a common element in both the signal processing and the threat assessment is that they are based on driver behaviour models, *i.e.*, they utilise the fact that depending on the traffic situation, drivers are more likely to behave in certain ways than others.

Most of the methods are general and can be, and hopefully also will be, applied also in other safety systems, in particular when a complete picture of the vehicle surroundings is considered, including information about road and lane shape together with the position of vehicles and infrastructure.

All methods in the thesis have been evaluated on authentic sensor data from actual and relevant traffic environments.

Acknowledgments

Working as a PhD student in industry is a little bit like tight-rope walking. Balance is required! On one hand, the problem chosen to study has to be relevant to the company, and stay relevant throughout the PhD project. On the other hand, it has to be academically interesting, the “squiggle level” (krumelurnivån) has to be sufficiently high as my previous manager Robert Hansson used to call it, and it has to be suitable for the tools that one’s academic institution provides.

Many people have helped me stay in balance. My supervisors Fredrik Gustafsson at Linköping University and Jochen Pohl at Volvo Car Corporation have provided fantastic guidance and inspiration throughout the project and I hope I shall have the opportunity to keep working with both of you. I also want to thank Robert Hansson, my manager during the first half of the project, for recruiting me and for excellent motivation and guidance. I thank Jonas Ekmark, who became my manager during the second half of the project and who has provided constant support and guidance, and for maintaining the creative environment in our group at Volvo Cars. I also express my sincere gratitude towards Volvo Car Corporation and the PhD program committee for running the Volvo Cars PhD program. It is a fantastic opportunity for the students in the program and it supports the long-term development of the company. I would also like thank Lennart Ljung for allowing me to join the Automatic Control group in Linköping, the most ambitious and inspiring group of people imaginable.

Thomas Schön has been my co-author in two of the papers, and I have really enjoyed working with him. Thanks also to Jonas Jansson who has always found the time for many interesting discussions. Another co-author is Lars Petersson at NICTA in Canberra, Australia, with whom it was a privilege to work; thanks to him and Niklas Pettersson, also at NICTA, for looking after me when I was lost and lonely in Canberra. In addition I would like to thank Lena Westervall at Volvo Cars for her excellent help with developing and tuning the demonstrator.

The last two years have been funded by Intelligent Vehicle Safety Systems (IVSS), for which I am very grateful.

Balance between life and work is also important, and in order to keep this balance, my family and friends have been everything. Thanks to all for constantly supporting me. And last but certainly not least, thanks to Anna for putting up with all my travels and for being a wonderful person. She always helps me put my life in perspective by taking me kayaking, ice skating or mushrooming, although persuasion is sometimes required.

Linköping, January 2007
Andreas Eidehall

Contents

Part I

Introduction

1

Overview

In 2005, Folksam, a major Swedish insurance company, that also carry out research, released their report “Hur säker är bilen 2005” (How safe is the car 2005). Among many other things, they state that during slippery road conditions the contribution of an anti-skid system, often referred to as ESP or DSTC, to safety in a car is as high as that of the safety belt (Folksam, 2005). In such conditions, an anti-skid system cuts the risk of being killed or seriously injured by half. For researchers in automotive active safety this is an encouraging result, which shows that as passive safety systems reach a high level of maturity active safety systems have a huge potential.

This thesis is devoted to active safety research from a control and signal processing perspective. Active safety, as opposed to passive safety, aims at preventing accidents *before* they occur. A typical example is the anti-skid system referred to above, which tries to keep the driver in control when the vehicle is about loose grip, and thus hopefully avoid being involved in an accident. The thesis deals with three distinct but connected areas within the active safety field.

First, reducing the number of traffic accidents is extremely important. For instance, in the European Union nearly 40,000 people are killed in traffic accidents every year as a result of traffic accidents(European Road Federation, 2004). However, how to design new safety functions to reduce these numbers in the most efficient way is often unclear. The first part of the thesis tries to provide a structured approach to this problem. It compares different, possible, safety function designs and estimates which has the highest potential safety benefit.

Second, most current and future active safety functions will have certain parts in common. They involve some kind of sensor to measure physical properties and they involve some kind of signal processing in order to translate the measured properties to information about the traffic situation and the vehicle state. Furthermore, a decision mechanism to determine *when* to activate the response and a control unit to decide *what* to do in the case of a response are typically also required. While early active safety systems, *e.g.*, the anti-skid system, mostly measure internal properties of the host vehicle, such as wheel speeds, steering wheel angle and yaw rate, currently-emerging and future safety systems will also include information about surrounding vehicles, the shape of the road and the position of the host vehicle in relation to the road. The main part of the thesis deals with signal processing in this context. Information from external sensors, *i.e.*, sensors measuring positions of surrounding objects and the shape of the road, is merged with information from internal sensors, measuring velocity, yaw rate etc. in order to estimate a complete picture of the surrounding traffic environment.

Third, active safety functions in general need a decision module, *i.e.*, the function needs to decide if and when to intervene or warn the driver. This is typically done by computing a threat level based on the available information, and then comparing this to a threshold. In the ESP case, the threat level computation is based on internal vehicle signals, but in many currently-emerging and future active safety systems, the threat level may be based on the position of surrounding vehicles relative to the host vehicle and relative to the lane. This topic is also addressed in the thesis.

1.1 Publications

This thesis is based on the following publications:

P1 Eidehall, A., Pohl, J., Gustafsson, F. and Ekmark, J. “A new approach to lane guidance systems”. In *Proceedings of the IEEE Intelligent Transportation Systems 2005*, pages 108-112, Vienna, Austria. This is the first presentation of the ELA safety function.

P2 Eidehall, A. “Lane game”. In *Traffic Technology International 2005 Annual Review*, pages 40-42. This is a popular science version of P1.

P3 Eidehall, A., Pohl, J., Gustafsson, F. and Ekmark, J. “Towards autonomous collision avoidance by steering”. Accepted for publication in *IEEE Transactions on Intelligent Transportation Systems*, 2006. This is an extended version of P1 which also includes the development of the ELA concept based on accident statistics. It is included in the thesis as **Paper A**.

P4 Eidehall, A. and Gustafsson, F. “Combined road prediction and target tracking in collision avoidance”. In *Proceedings of the IEEE Intelligent Vehicles Symposium 2004*, pages 619-624, Parma, Italy. This is the first implementation of the integrated filter for road shape and object tracking.

P5 Eidehall, A., Pohl, J. and Gustafsson, F. “Joint road geometry estimation and vehicle tracking”. Provisionally accepted for publication in *Control Engineering Practice*, 2006. This is an extended version of P4 which is a more mature implementation and also includes a more thorough analysis of the performance. It is included in the thesis as **Paper B**.

P6 Schön, T. B., Eidehall, A. and Gustafsson, F. “Lane Departure Detection for Improved Road Geometry Estimation”. In *Proceedings of the IEEE Intelligent Vehicles Symposium 2006*, pages 546-551, Tokyo, Japan. This paper shows how a Kalman filter model can be adapted online according to changes in the behaviour of the tracked vehicles. It is included in the thesis as **Paper C**.

P7 Eidehall, A. and Petersson, L. “Threat assessment of general road scenes using Monte Carlo sampling”. In *Proceedings of the IEEE Intelligent Transportation Systems 2006*, pages 1173-1178, Toronto, Canada. This is a threat assessment algorithm for long term predictions based on stochastic driver models.

P8 Eidehall, A. and Petersson, L. “Statistical threat assessment of general road scenes using Monte Carlo sampling”. *Submitted to IEEE Transactions on Intelligent Transportation Systems*, 2006. This is an extended version of P7 which also includes evaluation on authentic sensor data. It is included in the thesis as **Paper D**.

P9 Eidehall, A., Schön, T. B. and Gustafsson F. “The Marginalised Particle Filter for Automotive Tracking Applications”. In *Proceedings of the IEEE Intelligent Vehicles Symposium 2005*, pages 369-374, Las Vegas, USA. This shows how the marginalised particle filter can be used in the combined road shape/object tracking filter. It is included in the thesis as **Paper E**.

P10 Eidehall, A. and Gustafsson, F. “Obtaining reference road geometry parameters from recorded sensor data”. In *Proceedings of the IEEE Intelligent Vehicles Symposium 2006*, pages 256-260, Tokyo, Japan. This paper presents a method to obtain ground truth data that can be used for filter tuning. It is included in the thesis as **Paper F**.

1.2 The scientific contribution of the thesis

The main contributions of the thesis are:

- The development of the new safety function Emergency Lane Assist (ELA), including an assessment method for the potential benefit of new safety functions. The ELA safety function has also been evaluated in simulations, in artificial scenarios on a test track and with authentic traffic data. This function is discussed mainly in Paper A.

- Derivation and evaluation of different geometric models in an integrated filter for combined road shape estimation and target tracking. The derivation is presented in Paper B but integrated road and object tracking in general is also discussed in Papers E and C.

- A demonstration of how change detection can be used to detect lane changes of leading vehicles. This is then used to improve the accuracy of the lane shape estimate in the integrated filter. This is presented in Paper C

- A demonstration of how a marginalised particle filter can be used instead of the extended Kalman filter in the integrated filter, which is based on a nonlinear model. This is presented in Paper E.
- A method to obtain true road geometry parameters from recorded sensor data. This can be used as a reference for filter tuning and does not require extra sensors or other hardware. This is presented in Paper F.
- A statistical threat assessment method based on vehicle dynamics and a stochastic driver behaviour model. Using this, more accurate and longer predictions can be made. It also considers interactions between objects in the road scene. This is presented in paper D.
- A dynamic vehicle model that can be used in curved, road-aligned coordinates, *i.e.*, a coordinate system that is shaped according to the road shape. Using this model, threat assessment can be done in the road-aligned coordinates directly. Previously, road-aligned coordinates has only been used for tracking applications. This is also presented in paper D.

2

Trends in automotive active safety

2.1 Active safety functions

This section gives a brief overview and some of the milestones of the development of active safety functions that have become available on the market during the last few decades. The overview starts with the ABS system which was introduced in 1978, which can be claimed to be the first electronic active safety system, *i.e.*, its goal is to help the driver *avoid* accidents, and then moves on towards more modern systems. A problem is that it is often unclear when a safety system was actually introduced on the market. For instance, it is often announced that a certain system will be introduced on a certain model, but then the introduction is then delayed. Furthermore, systems are often launched on different markers at different times. Here, the goal has been to find the first year that a system was introduced, regardless of which market.

ABS (Anti-lock Braking System, 1978) ABS prevents the wheels from locking and will maintain the steering ability of the vehicle during hard braking. During bad road conditions, ABS will also reduce the stopping distance. The system measures the velocity of all four wheels, and if one of the sensors reports an abnormal deceleration (higher than a physically reasonable value) it concludes that the wheel is about to lock, and the pressure in the braking system is reduced. The German automotive supplier Bosch actually has a patent from 1936 for a "mechanism to prevent locking of the wheels of a motor vehicle". The first ABS prototype was tested in 1970, but reliability of the electronics was too low and it was not before 1978 that the first system was put into production, manufactured by Bosch. Since 1978, ABS technology has been developed further, Figure 2.1 shows that the physical size of the system has been reduced significantly.

Traction control (1985) The functioning of the traction control system is very similar to that of the ABS. The system prevents the wheels from slipping during acceleration

Figure 2.1: 1978 and 2001 ABS unit. The 2001 system is much more compact. Photo: Bosch

by using the same velocity sensors as the ABS. If a vehicle starts to slip, the engine power is reduced in order to maintain lateral control of the vehicle. The first traction control system was launched in 1985 and was also a Bosch system.

Stability control (1995) Again, Bosch was first with their stability control system ESP (Electronic Stability Program) in 1995. While slightly different configurations exist, a stability control system basically measures the yaw rate of the vehicle, i.e., the rotation in the ground plane, and compares it with the desired trajectory. If the deviation is greater than a certain threshold, the system will activate the brakes on one side of the vehicle to correct this.

Adaptive Cruise Control (1998) While sources differ on this, Jones (2001) claims that in May 1998 Toyota became the first to introduce an Adaptive Cruise Control (ACC). ACC uses a forward looking sensor, usually radar or laser, to monitor the distance to leading vehicles. If the cruise control is active and time gap to the leading vehicle falls below a certain threshold, the vehicle's ACC system will automatically brake in order to maintain distance. ACC is often not considered a safety system in isolation: it usually comes bundled with a forward collision warning. In Europe, government restrictions typically limit the permitted braking rate to 3.0 or 3.5 m/s^2. If the vehicle detects that a higher deceleration is required to avoid colliding with the leading vehicle, an audible warning is given to the driver.

Forward collision mitigation (2003) Forward collision mitigation refers to systems that will try to reduce the impact speed by applying the brakes when a collision with the leading vehicle appears to be unavoidable. While many car manufacturers have announced short-term availability of such systems, there are only a few manufacturers that currently sell them. Honda has sold a Collision Mitigation System (CMS) since 2003. Most systems have a similar functionality when it comes to the intervention strategy. They use increasing warning levels as the threat approaches. Hondas system, for example, uses the following technique:

Primary warning When there is a risk of collision with the vehicle ahead or if the distance between the vehicles has become too close, an alarm sounds, and the message "BRAKE" appears on the multi-information display in the instrument panel, prompting the driver to take preventative action.

Secondary warning If the distance between the two vehicles continues to diminish, CMS applies light braking, and the seat belts are retracted gently two or three times, providing the driver with a tactile warning. At this point, if the driver applies the brakes, the system interprets this action as emergency braking, and activates the brake assist function to reduce impact speed.

Collision damage reduction If the system determines that a collision is unavoidable, the seat belt pretensioners are activated with enough force to compensate for seat belt slack or baggy clothing. The CMS also activates the brakes forcefully, at approximately 6 m/s^2, to further reduce the speed of impact.

The system was presented by Kodaka and Gayko (2004). It has not been revealed how many systems are actually sold, but it was mentioned that customer acceptance of the system has been quite low. For example, it seems that the false alarm rate, especially for aggressive drivers, has been high.

Figure 2.2: The Volvo Blind Spot Information System (BLIS). Photo: Volvo Car Corporation.

Lane Guidance System (2003) Lane guidance system refers to systems that try to help the driver stay in the lane. Systems typically use an audible warning or a steering-wheel torque to alert the driver if the vehicle is approaching the lane markings. The steering-wheel torque used by some of the proposed systems will automatically steer the vehicle back into the centre of the lane, thus working almost like an autopilot. In Japan, Honda has been selling their Honda Intelligent Driver Support

(HIDS), which includes the Lane Keeping Assist System (LKAS), since 2003. The system combines an audible warning and steering-wheel torque. However, Honda's idea is that the driver should be kept in the loop at all times. Therefore, the system only supplies 80% of the required torque, the remaining 20% has to be provided by the driver. Their system has been approved by the Japanese Ministry of Land, Infrastructure and Transport and is permitted on expressways in Japan. Ishida and Gayko (2004) provides further details.

A rather recent idea is to try to mimic the sounds and vibrations that are generated by rumble strips, *i.e.*, the grooved lane markings that are sometimes used on motorways to indicate lane departure. A lane guidance system like this has recently been put into production by Citroën (Citroën, 2005). This system differs from the Lane guidance system discussed earlier which uses a camera mounted in the windscreen. The system from Citroën uses dedicated infrared sensors mounted in front of the front wheels, looking straight down. This construction makes the system very robust, but at the same time it cannot measure the distance to the line, nor can it distinguish between lane markers and, for example zebra crossings.

Blind-spot warning (2005) The general idea behind a blind-spot warning system is to lower the risk of lane change accidents by warning the driver about vehicles in the blind spot. There are different techniques for achieving this but usually ocular vision or radar is used. Blind-spot warning systems have been announced several times in the past by different car manufacturers, but it was not until 2005 that Volvo released their Blind Spot Information System (BLIS) and became the first to actually put the system on the market. Figure 2.2 shows a BLIS camera.

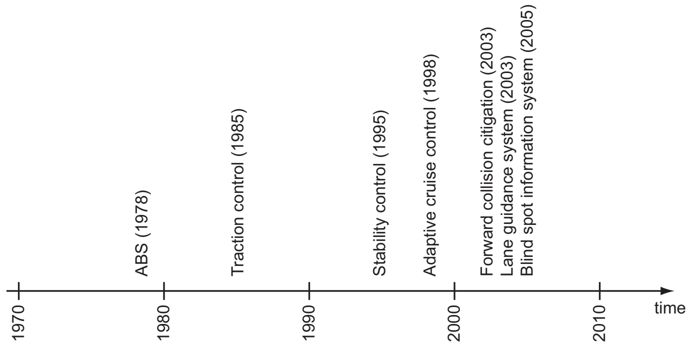


Figure 2.3: *Milestones in the development of active safety systems during the last few decades.*

The market introduction years for these active safety systems are also illustrated in Figure 2.3.

Blind-spot related accident

Collision with a faster moving vehicle

Collision with a slower moving vehicle

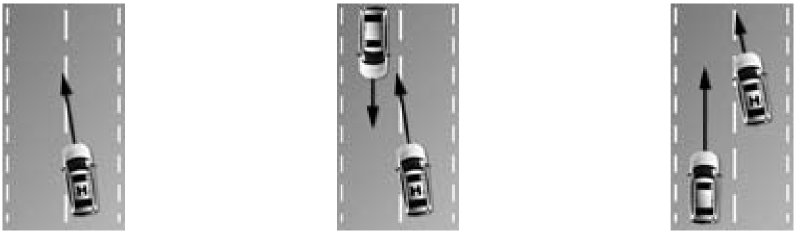
Figure 3.3: *This is an example of how lane change related accidents can be divided into subcategories. H indicate the host vehicle,* i.e., *the vehicle to be equipped with the safety function.*

3.2 Emergency Lane Assist

The result of the evaluation method is a new active safety function called Emergency Lane Assist (ELA). ELA is similar to traditional lane guidance systems in that it tries to prevent lane departure by applying a steering wheel torque in the opposite direction. Such systems typically use a camera mounted in the windscreen to monitor lane markings. Then, as the vehicle is about to cross the lane markings, a steering-wheel torque is applied or the driver is alerted by an audible signal. The difference is that ELA only prevents *dangerous* lane departure manoeuvres. This is achieved by also monitoring traffic in adjacent lanes. If there is no traffic in adjacent lanes, the lane markings can be crossed without intervention. But if a lane departure manoeuvre is commenced in such a way that a collision is likely, for instance with an oncoming vehicle or a faster moving vehicle approaching from behind, then a steering-wheel intervention will be initiated. The function also includes some logic for determining if the departure manoeuvre is intentional or not. Figure 3.4 shows a few examples of ELA behaviour. ELA addresses several important accident categories, of which the most dangerous is accident with an oncoming vehicle. But there are also many accidents on motorways, in particular in Germany, where vehicles change lanes in order to overtake, and are hit from behind by a vehicle in the “faster lane”. ELA is presented in detail in Paper A that is entitled “Towards autonomous collision avoidance by steering”. This refers to the fact that it is actually a practicable step towards automatic steering intervention for collision avoidance.

3.3 Tracking

In order to realise the ELA function, rather accurate information about the host vehicle surroundings is needed. First, in order to determine when a lane change is commenced, and to be able to steer back into the original lane, the position and orientation of the host



No ELA intervention since there is no threat in the adjacent lane.

ELA intervention.

ELA intervention.

Figure 3.4: *Examples of the behaviour of the ELA function.*

vehicle in relation to the lane is needed. Second, the position of surrounding objects is also needed in order to determine wether a commenced lane change is likely to result in a collision or not. Third, the lateral position of other objects in relation to the lane is also needed. The purpose of this is to determine which objects are actually occupying the lane that the host vehicle is about to enter. Consider an example where we assume that the intervention takes two seconds to carry out, *i.e.*, it takes two seconds to get the host vehicle back safely into the original lane. If the host vehicle is travelling at 90 km/h and there is an oncoming vehicle travelling at the same speed, then the two vehicles approach each other at 50 m/s. If we need to initiate the intervention two seconds before the collision, then the decision must be made when the distance to the oncoming vehicle is 100 m. Thus, vehicles need to be assigned to the correct lane when 100 metres away, which is dependent on knowing both the position of the object and the shape of the road. Figure 3.5 illustrates how the leading vehicle lane assignment is dependent on the current estimate of road radius.

It was noticed early on that the position estimate of tracked vehicles, which is based on radar measurements, and also the positioning of the host vehicle in relation to the lane, which is based on a camera and image processing, was sufficiently accurate. However, the positioning of tracked vehicles in relation to the lane has been a great challenge, primarily due to the difficult task of road shape estimation. The conclusion was that this needed improvement.

The first step is to develop some sort of quality measure in order to be able to evaluate potential improvement methods. Such a quality measure is typically based on comparing estimated values, in this case, of the parameters describing the road shape with reference or "true" values, or with another estimate where the error is significantly lower. For instance, the reference data could come from a better sensor; it could be extracted from a detailed map; or it could be obtained from the local road authorities. Another solution is presented in Paper F, which consists of an algorithm for computing a reference value of the road shape parameters based on recorded sensor data. Since an enormous amount

Figure 3.5: *Lane assignment of leading vehicles is dependent on road shape estimation. Which lane the leading vehicle is assigned to depends on the current road radius estimate.*

of such data is usually already available, this is a faster and cheaper method than the alternatives mentioned earlier. It uses recorded sensor data in order to recreate the actual shape of the road that was driven, and by being able to access the entire data set, *i.e.*, also future sensor measurements, a rather accurate value of the parameters describing the road shape can be obtained. This reference data can then be used in various ways. For instance, the mean error of different estimation methods can be computed and compared. Statistical properties, *e.g.*, standard deviation, can also be obtained.

When quantifying the requirements for estimation error, it can be found, for instance, that in order to assign a leading vehicle 100 metres away to the correct lane, an error in the road *curvature* estimate of $5 \cdot 10^{-4}$ (1/m) or less is needed, where the curvature is defined as one divided by the road radius. Using the proposed method for obtaining ground truth data, this requirement can easily be verified. Figure 3.6 shows how the errors in the vision system curvature estimate can be distributed. In this case, the error is above the requirement for about 7.5 percent of the time. Note that this is an unusually good result. The vision system is very sensitive to changed visibility conditions, and is affected by weather, hills and slopes which reduce the visibility, and also by the conditions of the lane markings. In the case of very worn lane markings, the performance can be significantly reduced.

Paper B discusses how the accuracy of this parameter can be increased. The first natural step is to include more information. In the vehicle we have access to yaw rate and velocity, for instance, and the camera also provides lateral position in the lane. This is a much more accurate signal than the lane geometry information. However, in order to use this information a model is needed to relates the new information to the lane shape parameters.

The lane shape is described by two states: c_0 is the local lane curvature around the host vehicle, *i.e.*, one divided by the road radius, and c_1 which is the clothoid parameter, defined as the distance derivative (the change rate) of c_0. Paper B also includes a parameter W denoting lane width, but it is not essential here and has been excluded. The host

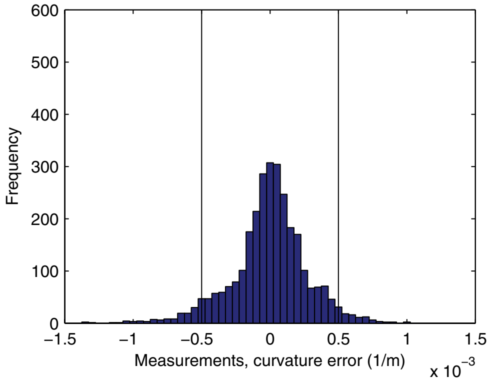


Figure 3.6: *Error distribution in the vision system. The error level* $5 \cdot 10^{-4}$ *is a requirement for making correct lane assignments at long distances. Here, the error is higher than the requirement 7.5 percent of the time.*

state in relation to the lane is described by y_{off} and Ψ_{rel}, where y_{off} is the lateral position measured from the centre of the lane, and Ψ_{rel} is the heading angle in relation to the lane markings. For a summary of these parameters, see Figure 3.7. A model relating these parameters can then be written:

$$\dot{y}_{\text{off}} = v\Psi_{\text{rel}} \tag{3.1a}$$

$$\dot{\Psi}_{\text{rel}} = \dot{\Psi}_{\text{abs}} - vc_0 \tag{3.1b}$$

$$\dot{c}_0 = vc_1 \tag{3.1c}$$

$$\dot{c}_1 = 0 \tag{3.1d}$$

where v is the velocity and $\dot{\Psi}_{\text{abs}}$ is the measured yaw rate of the host vehicle. This model is derived and discussed more in detail in the paper. The states y_{off}, Ψ_{rel} and c_0 are directly measurable. It is interesting to note that using this model, the state c_0 is observable from y_{off} and Ψ_{rel} only. This suggests that to include these measurements should improve the accuracy of c_0. The improvement can be seen in Fig, 3.8, where the same data sequence as in Figure 3.6 is processed with a Kalman filter based on the new model. The time that the error is higher than the requirement is reduced to 4.5 percent.

Is it possible to include even more information to achieve further improvement? One idea that was raised by Dellaert and Thorpe (1997) and Zomotor and Franke (1997), for example, is to include the motion of surrounding vehicles to support the estimate. The idea is rather brilliant and relates to the way that humans drive. The assumption is that other vehicles are very likely to keep following their current lane, and since their position can be measured accurately using the radar, this assumption can be used to support the road shape estimate. This is very similar to how drivers behave during reduced visibility, *e.g.*, fog or darkness, where the tail lights of leading vehicles can be seen more clearly than the lane markings at long distances. If a leading vehicle starts to move left it is natural to assume that the it is entering a curve to the left. Note that it is important not to

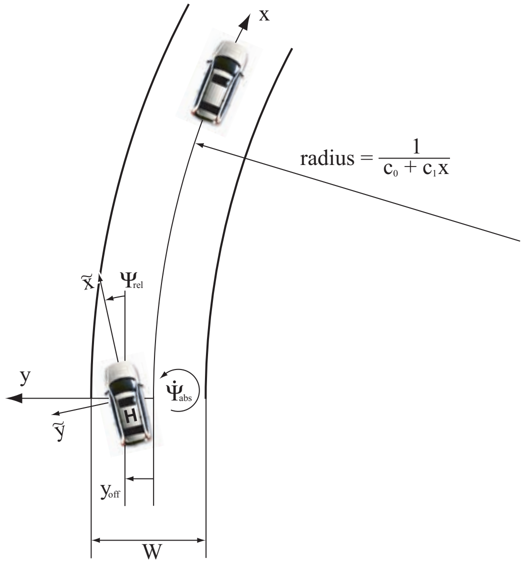


Figure 3.7: *y_{off} and Ψ_{rel} are the host vehicle states while c_0 and c_1 describe the shape of the road.*

rely too much on this assumption. The best solution is to say that it is *highly probable* that the car is entering a curve, but also remain open to the alternative that the car is changing lanes or exiting the road. In order to achieve this model (3.1), above, needs to be related to the motion of surrounding vehicles. Paper B discusses different methods of doing this. The common feature of these methods is that they use a curved, road-aligned coordinate system and that the motion of tracked vehicles is modelled in these coordinates. The road-aligned coordinates are denoted (x, y) and are also shown in Figure 3.7. The model describing the lateral motion of tracked vehicles then simply becomes

$$\dot{y} = 0, \tag{3.2}$$

where y is the lateral position of the tracked vehicle in the lane, which simply says that vehicles will keep following the road, *i.e.*, not move laterally. This is then related to the road shape states c_0 and c_1 via a measurement equation. The simplest one used in Paper B is

$$\tilde{y} = y - y_{\text{off}} - \Psi_{\text{rel}} x + c_0 x^2/2 + c_1 x^3/6. \tag{3.3}$$

This is a Taylor expansion of an exact geometric model that includes trigonometric formulas; the distance to the vehicle is x and $\tilde{y}$ is the lateral position in relation to the *host* vehicle (see Figure 3.7) in which the sensors are positioned.

Here, if x is used as a state in the filter, then the model becomes nonlinear and the standard Kalman filter cannot be used. The other, more complex methods/models discussed in Paper B are also nonlinear. The most common choice in such cases is the *extended*

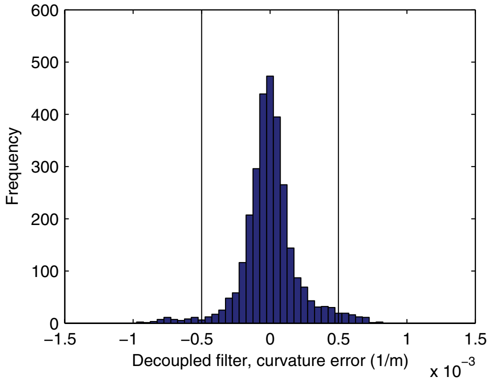


Figure 3.8: *Error distribution after initial filtering. The error level* $5 \cdot 10^{-4}$ *is a requirement for making correct lane assignments at long distances. The time that the error is higher than the requirement is reduced to 4.5 percent.*

Kalman filter (EKF), and this is what has been used mainly in this work. Other alternatives include the *particle filter* (PF) and the *unscented Kalman filter* (UKF). Paper E investigates how a marginalised particle filter (MPF), which is a special version of the Particle Filter in which a linear substructure of the problem is utilised to get a more efficient implementation, can be applied to this problem. The outcome is that slightly better results than the EKF can be obtained, but at much higher computational cost. The conclusion from Paper E is that the MPF is probably not worth the extra computational cost today, but it might be needed in the future in order to include other types of information that are "more nonlinear". For instance, information from a map database. A thorough investigation of the MPF is given by Schön (2006). The unscented Kalman filter is suitable for this application but its performance has not been investigated so far. Since the improvement of the MPF over the EKF was not that high, the UKF can not be expected to give much improvement either.

The result of using EKF can be seen in Fig, 3.9. The time that the error is higher than the requirement is reduced to 1.5 percent. One of the main prerequisites of this method is, of course, that there is a leading vehicle. As soon as there are no vehicles around, the performance drops to the level indicated in Figure 3.8.

3.4 Change detection

The last step is dependent on the assumption that vehicles keep following their lane. The degree to which we want to rely on this assumption can be determined in the design of the Kalman filter. Since vehicles actually do change lanes and exit the road, the choice has to be a compromise. On one hand, if we rely too much on it, every lane change and road exit will be misinterpreted as a curve entry. On the other hand, if we rely too little on it, the benefit of including surrounding vehicles into the filter will be gone. When implementing

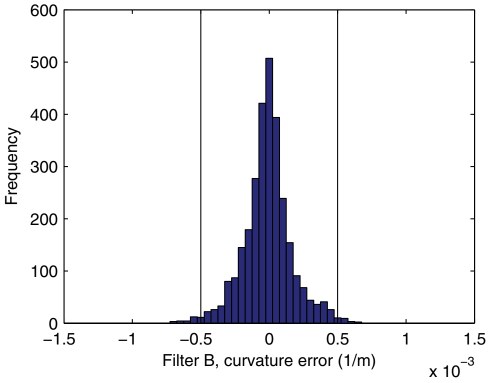


Figure 3.9: *Error distribution when including information from the motion of surrounding vehicles. The error level* $5 \cdot 10^{-4}$ *is a requirement for making correct lane assignments at long distances. The time that the error is higher than the requirement is now reduced to 1.5 percent.*

the filter, (3.2) is discretised and then stochastic, white process noise with variance Q_{lat} is added. A low Q_{lat} then corresponds to relying on (3.2) very strongly, *i.e.*, there is a strong connection between the motion of surrounding vehicles and road model, while a high value of Q_{lat} relaxes the connection.

Paper C investigates whether Q_{lat} can be changed automatically as the traffic situation changes. More specifically, if a lane departure or road exit of a leading vehicle could be detected, Q_{lat} could be raised temporarily. In that case, there would be no need to compromise and Q_{lat} could be kept very low when the assumption that surrounding vehicles follow their lane is valid. The goal is then that the filter performance will be improved further.

There are different approaches to achieve this. Paper C analyses a method called the CUSUM test (from CUmulative SUM). The CUSUM test is designed to detect changes in the filter residuals that are connected to lateral movement. The test is designed in order to alarm when a lane change or departure is taking place and then raise Q_{lat} temporarily. An example is shown in Figure 3.10. Being able to keep Q_{lat} low gives advantages during curve entry and exit. The key is then to detect when vehicles deviate from the “typical” behaviour, otherwise the performance of the filter will deteriorate. This is what happens just after time 4270 s in Figure 3.10. A leading vehicle lane change to the right makes the filter believe that it is entering a curve to the right. In Paper C it is demonstrated how this can be detected and used in order, temporarily, to raise Q_{lat} during such events.

It is clear that this method gives better performance during curve entry and exit, but how the average, long term performance is affected is not yet fully investigated. In order to make a detector robust, there has to be a delay before an alarm can be triggered, and in this case, it means that the performance will be slightly degraded during these delays. Whether this is acceptable compared to the benefit that the detector can give in curves probably depends on the application.

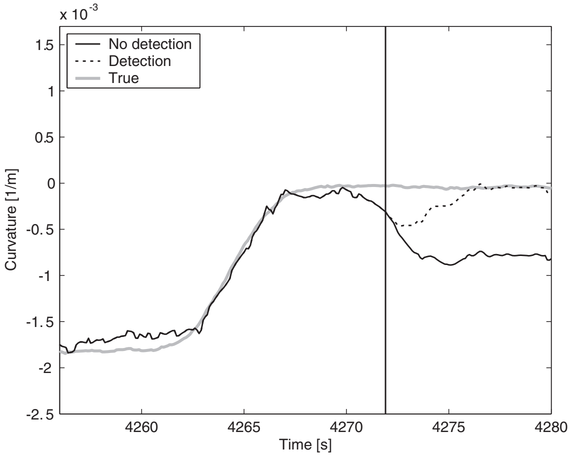


Figure 3.10: *Being able to keep Q_{lat} low gives advantages during curve entries and exits. This works as long as leading vehicles do not deviate from the lane, which occurs just after time 4270 s. The vertical line shows when the CUSUM algorithm detects this and adapts the model.*

3.5 Threat assessment

Active safety functions, such as Emergency Lane Assist (ELA), needs a decision unit that decides if and when to warn the driver or intervene. As discussed in the overview, such a decision is typically based on computing a threat level and if the threat is higher than a predefined threshold, a warning or an intervention is activated. In ELA and other emerging active safety functions, this threat is typically based on the surrounding traffic situation, rather than internal vehicle signals.

In order to evaluate the ELA concept, Paper A introduces a rather simple decision module. As was discussed in Section 3.2, the function aims at preventing dangerous lane departures. Three things needs to be checked before an intervention can be triggered. First, we need to check that a lane departure manoeuvre is in progress. This can be done by studying the lateral motion of the host vehicle in relation to the lane.

Second, potential conflicts with other vehicles if the lane change is completed need to be found. This is done by predicting the positions of other vehicles to the time when the host vehicle is expected to enter the adjacent lane. This prediction is the most difficult step, since the prediction time is very long: typically around two to three seconds but sometimes more. The road-aligned coordinates (x, y) in Figure 3.7 that were discussed above simplify these predictions significantly. Predicting vehicles movement in a straight line within the road coordinates means that they will also follow the road in curves. But despite this fact, a lot of things can happen in two or three seconds. Other drivers may decide to change lane, brake in order to avoid an obstacle, etc. Other methods of prediction are addressed later in this section.

Third, when it has been established that a lane change has been commenced and is instead of global, cartesian coordinates. First of all, the motion model can be greatly simplified. The assumption that cars will stay in their lane can be simply expressed as $\dot{y} = 0$ where y denotes lateral position in the road coordinates. In a Cartesian or polar coordinate system, a higher order system would have to be used and would still only describe a more primitive shape, see Figure 3.15.

This also relates to predicting future positions of other vehicles. With the $\dot{y} = 0$ motion model, vehicles are predicted to follow straight lines, which in RAC means that they will follow the road. Prediction with a higher order model can be difficult since many people tend to wander slightly when driving. This means that a prediction, say 50 or 100 metres ahead will often be outside the road. This is illustrated to the right in Figure 3.15.

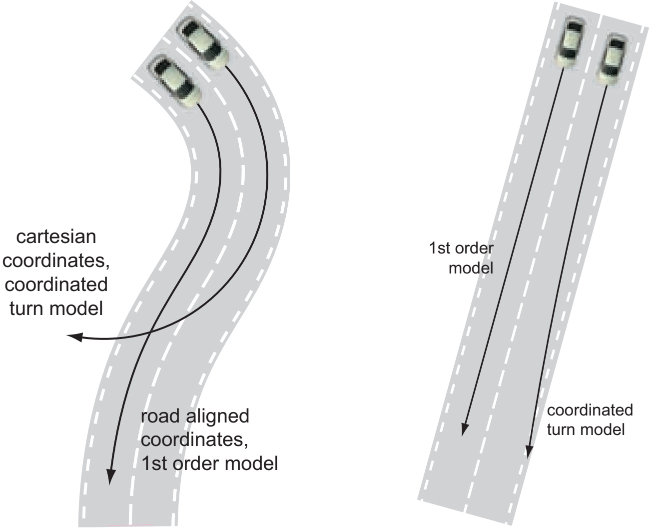


Figure 3.15: Left: Comparison between a road-aligned coordinate system with a low order motion model and a Cartesian coordinate system with a higher order motion model. In order to illustrate this difference, the curvature and clothoid parameters of this road have been exaggerated. Right: Prediction with a higher order motion model can be difficult since most people tend to wander slightly when driving.

Also, since all positions are already given in the road coordinates, it is easier to design automotive applications. For instance, Adaptive Cruise Control (ACC) controls the speed of the host vehicle based on the distance to and speed of the leading vehicle. Using RAC, leading vehicles can be found simply as vehicles with y-coordinate close to zero. They will be in the same lane as the host vehicle, also in curves. Similarly, the ELA function is also dependent on the lane position of surrounding vehicles. Specifically, vehicles that are occupying the adjacent lanes need to be found. With RAC, this can be done by simply defining an interval in the y-coordinate.

In the statistical threat assessment algorithm in Paper D, RAC also gives several advantages. First, in the driver-behaviour model discussed above, it was noted that vehicles are very likely to keep following the road, *i.e.*, manoeuvres that behave in this way should be given a high probability. For a specific manoeuvre, this is implemented by measuring the average distance to the intended path and then computing the probability based on that. In RAC, this simply means computing the lateral distance to a straight line, which is easier than measuring the distance to a circle or a clothoid segment. Second, the road edges, shown for example in Figure 3.14, can always be modelled as straight lines. This means that all objects in the algorithm can be modelled as polygons. In a Cartesian coordinate system, a new object class with circular shapes would have to introduced, or the road borders have to be approximated with straight segments.

One of the things that need to be considered before implementing decision algorithms based on curved coordinates is the change in the dynamics. There are certain limitations in the way that a vehicle can manoeuvre, caused, for example, by tire-to-road friction or limited engine power, which puts boundaries on the forces that can be exerted on the vehicle. These are then translated to accelerations via Newton's law. However, Newton's law cannot be applied directly in a non-Cartesian coordinate system, which is why Paper D derives modified dynamic equations. It turns out that these modifications can be implemented as a simple offset to the ordinary dynamic relationships. Using these modifications, all threat measures that are normally used in fixed Cartesian coordinates can be translated directly into the RAC.

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