Thesis for the Degree of Doctor of Philosophy

Decision Making and Control for Automotive Safety

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To my beautiful girls,
Wafaa, Mona and Lina.

Abstract

This thesis proposes a novel automotive safety function that utilizes information about the host vehicle's state and the road ahead to predict and prevent unintended roadway departures. For this purpose predictive threat assessment, decision making and control algorithms are developed. The developed algorithms take into account fundamental limitations in a vehicle's dynamical capabilities while using road information to maintain the vehicle's maneuverability and keep it on the road.

Particular attention is given to the threat assessment problem. A threat assessment algorithm that activates interventions when it can be theoretically guaranteed that it is no longer possible for a driver to avoid departing the road or losing vehicle maneuverability is developed. The algorithm is based on reachability analysis tools for linear systems. An algorithm that recursively estimates the driver's steering behavior as an affine function of the vehicle state is also developed. The explicit representation of the driver's steering behavior is used to form an alternative threat assessment algorithm that, in addition to considering vehicle dynamics, accounts for limitations in the driver's capabilities. Moreover, it is shown how uncertainty in the state, disturbance and parameter estimates can be accounted for in order to maintain the theoretical guarantees of avoiding unnecessary intervention activation also in the presence of uncertainty. In order to maintain such guarantees considering model parameter uncertainty, we derive and prove theoretical results. In addition, a threat assessment algorithm that accounts for the nonlinearities in the system dynamics that are exhibited e.g. during combined braking and steering is developed. For this purpose, we use interval based consistency techniques to solve the threat assessment problem.

The developed methods are validated using simulations, logged experimental data and real-time experiments.

Keywords: Threat Assessment, Decision Making, Active Safety, Semi-Automated Vehicles, Reachability Analysis.

Acknowledgments

I've truly enjoyed my Ph.D. studies and this is much thanks to the people I've worked with. I would like to thank Prof. Jonas Sjöberg for providing invaluable guidance, feedback and encouragement throughout the project. Prof. Paolo Falcone always pushed me to refine every detail, regardless of the associated workload. Thank you for being persistent. Dr. Claes Olsson helped me balance between the academic and industrial objectives of the project. Hans Bäckström helped me set up the experiments. The help from Hans and Claes has been invaluable, thank you for your assistance and commitment. I've also had several additional co-authors throughout the Ph.D. project. Dr. Esteban Gelso, Jonas Nilsson and Andrew Gray, I enjoyed working with all of you and hope that we will get the chance to work together again.

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Finally, I would like to thank my family for bearing with my absence, helping me stay in balance and for reminding me of what is important in life.

Mohammad Ali
Göteborg, August 2012

Contents

II Included papers

Part I

Introductory chapters

Chapter 1

Overview

This chapter briefly introduces and overviews the contents of this thesis.

1.1 Introduction

While the transportation capabilities enabled by road traffic have provided invaluable social and economic benefits, they are also associated with negative consequences. Today more than ever, huge research and development efforts are invested in reducing negative effects like traffic fatalities, gas emissions and traffic congestions. However, at the very core of these efforts is the problem of maintaining an acceptable transportation performance. This is the challenge. In this thesis, this challenge is addressed w.r.t. automotive safety. In particular, the thesis focuses on the problem of preventing roadway departure accidents through automated safety interventions without degrading vehicle performance by excessive interventions, since such degradation is difficult to gain acceptance for.

From a systems and control perspective, theory, methods and algorithms that can be used to predict and prevent traffic accidents while maintaining an acceptable vehicle performance are developed. The developed methods are applied and experimentally validated in applications for prevention of unintended roadway departures that according to [1] account for approximately half of all traffic accidents that result in a fatality or severe injury.

1.1.1 Traffic injuries

In the 2009 global status report on road safety [2], the World Health Organization (WHO) ranked road traffic injuries among the top three causes of death for people 5-44 years old, see Table 1.1. In the same report, the WHO estimates that the global losses due to road traffic injuries are US$ 518 billion and cost governments $1-3\%$ of their gross national product. Road

Age	0 – 4	5 – 14	15 – 29	30 – 44	45 – 69	70+	Total
Rank	14	2	1	3	8	20	10

Table 1.1: Ranking of road traffic injuries among leading causes of death in the world for different age groups, 2004, World Health Organisation [2].

traffic injuries thus constitute a huge problem and consequently, the automotive industry has developed a wide range of vehicle safety systems. When a vehicle crashes, the occupants are protected by *passive safety* systems like e.g. seat belts, airbags and energy absorbing zones that aim to make the accident as harmless as possible. *Active safety* systems on the other hand, can deploy preventive interventions in the stages preceding an accident with the aim of helping the driver to mitigate or avoid the accident.

1.1.2 Active safety benefits

In the last decades, active safety systems have contributed substantially to the reduction of severe injuries and fatalities in traffic [3]. Several studies show that electronic stability control systems efficiently reduce the number of traffic accidents [3–7]. According to [4], such systems reduce fatal run off road crashes by 36% for passenger cars.

For the newer class of active safety systems that utilize external sensors, i.e. sensors providing information of the vehicle's surrounding environment, the market penetration is still low. It is therefore still difficult to make claims about statistically proven benefit. Nonetheless, some indications of the usefulness of such safety systems have been observed. Table 1.2 is extracted from [8]. It compares the insurance claim frequency of the 2010 Volvo XC60, which is the first passenger vehicle to be equipped with a low speed forward collision avoidance system named City Safety® as standard, to other vehicles. We note a significant reduction in insurance claims compared to both other midsize luxury SUVs and other Volvo models not equipped with any collision avoidance system. This indicates that the large difference in insurance claims is likely due to the forward collision avoidance system. Table 1.2 also shows that the reductions are not only in bodily injury claims but also in property and collision claims. Hence, apart from the obvious health benefits that come with safety systems in general, there are also financial benefits.

Eventually, as the degree of active safety technology in vehicles is increased and, as a result, the number of accidents decreases, heavy passive safety systems might no longer be motivated. This will open up the pos-

	vs. other midsize luxury SUVs	vs. other Volvos
Property damage liability	−27%	−19%
Bodily injury liability	−51%	−49%
Collision	−22%	−17%

Table 1.2: Insurance claim frequency for the 2010 Volvo XC60 compared to other midsize luxury SUVs and other Volvo models not equipped with any collision avoidance system. Property damage liability pays for damage an at-fault driver's vehicle does to other peoples property as a result of a crash. Bodily injury liability generally pays for injuries to people involved in the crash other than the insured at-fault driver. Collision pays for damage to the insured vehicle, Insurance Institute for Highway Safety [8].

sibility to noticeably reduce the vehicle's weight and consequently the fuel consumption, hence active safety can also play a role in reducing emissions. Reduced vehicle weight would in turn give even more benefits since the requirements on several other vehicle components like e.g. the brakes will also change leading to more efficient and cheaper cars.

1.2 Thesis outline

The thesis is written as a compilation thesis with two parts. Part I serves as an introduction, provides background information and emphasizes the challenges and contributions of the thesis. The scientific papers that constitute the base of this thesis are appended in Part II.

The rest of Part I is organized as follows: Chapters 2 and 3 provide a deeper insight to the problems tackled in the thesis than what can be found in the appended papers in Part II. In Chapter 2, fundamental limitations in a vehicle's dynamical capabilities are outlined and safety systems that improve the dynamical behavior of the vehicle are mentioned. These limitations are important to understand when designing safety systems that might be forced to operate at the limit of the vehicle's capabilities. In the methods presented in this thesis, such limitations have been accounted for. Chapter 3 discusses trends and challenges of driver assistance systems that, rather than just improving vehicle dynamics, also control the vehicle motion within the surrounding environment. In addition, challenges associated with sharing vehicle control with a driver in such systems are discussed. A summary of the papers appended in Part II is provided in Chapter 4. Finally, Chapter 5 summarizes the contributions of the thesis and briefly outlines directions for future work.

1.3 Publications

This thesis is based on the following appended papers:

Paper 1 M. Ali, P. Falcone, C. Olsson and J. Sjöberg, Predictive Prevention of Loss of Vehicle Control for Roadway Departure Avoidance, *IEEE Transactions on Intelligent Transportation Systems,* In press.

Paper 2 P. Falcone, M. Ali and J. Sjöberg, Predictive Threat Assessment via Reachability Analysis, *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no 4, pp. 1352-1361, 2011.

Paper 3 M. Ali, P. Falcone and J. Sjöberg, Threat Assessment Design under Uncertainty, *Submitted for possible journal publication.*

Paper 4 M. Ali, E. Gelso and J. Sjöberg, Automotive Threat Assessment Design for Combined Braking and Steering Maneuvers, *IEEE Transactions on Vehicular Technology,* Accepted for publication.

In addition to the appended papers, the following related publications have been written within the project:

- M. Ali and J. Sjöberg, Impact of Different Vehicle Models on Threat Assessment in Critical Curve Situations, *International Conference on Enhanced Safety of Vehicles*, June 2009, Stuttgart, Germany.
- M. Ali, C. Olsson and J. Sjöberg, Towards Predictive Yaw Stability Control, *IEEE Intelligent Vehicle Symposium*, June 2009, Xian, China.
- M. Ali, P. Falcone and J. Sjöberg, A Predictive Approach to Roadway Departure Prevention, *IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks*, August 2009, Stockholm, Sweden.
- M. Ali, On Automotive Roadway Departure Prevention, Licentiate Thesis R002/2010, ISSN1403-266X, Chalmers University of Technology, May 2010.
- P. Falcone, M. Ali and J. Sjöberg, Set Based Threat Assessment in Semi-Autonomous Vehicles, *IFAC Symposium on Advances in Automotive Control*, July 2010, Munich, Germany.

- J. Sjöberg, E. Coelingh, M. Ali, M. Brännström and P. Falcone, Driver Models to Increase the Potential of Automotive Active Safety Functions, *European Signal Processing Conference* , August 2010, Aalborg, Denmark.

- J. Nilsson and M. Ali, Sensitivity Analysis and Tuning for Active Safety Systems, *IEEE Intelligent Transportation Systems Conference*, September 2010, Madeira, Portugal.

- M. Ali, P. Falcone and J. Sjöberg, Model-Based Threat Assessment for Lane Guidance Systems, *American Control Conference*, June 2011, San Francisco, USA.

- E. Gelso, M. Ali and J. Sjöberg, Threat assessment for driver assistance systems using interval-based techniques, *IFAC World Congress,* August 2011, Milano, Italy.

- M. Ali, C. Olsson and J. Sjöberg, Real-time Implementation of a Novel Safety Function for Prevention of Loss of Vehicle Control, *IEEE Intelligent Transportation Systems Conference*, October 2011, Washington D.C., USA.

- M. Ali, P. Falcone and J. Sjöberg, Model-Based Threat Assessment in Semi-Autonomous Vehicles with Model Parameter Uncertainties, *IEEE Conference on Decision and Control and European Control Conference*, December 2011, Orlando, USA.

- A. Gray, M. Ali, Y. Gao, K. Hedrick, F. Borrelli, Integrated Threat Assessment and Control Design for Roadway Departure Avoidance, *IEEE Intelligent Transportation Systems Conference*, September 2012, Anchorage, USA.

- A. Gray, M. Ali, Y. Gao, K. Hedrick, F. Borrelli, Semi-Autonomous Vehicle Control for Road Departure and Obstacle Avoidance, *IFAC Symposium on Control in Transportation Systems*, September 2012, Sofia, Bulgaria.

- M. Ali, P. Falcone and J. Sjöberg, Threat Assessment Design under Driver Parameter Uncertainty, *IEEE Conference on Decision and Control*, December 2012, Maui, USA.

The following related patent applications have been written within the project:

- M. Ali, C.Olsson and J. Sjöberg, Method and System for Predictive Yaw Stability Control, European Patent Office, Application no. 09161613.6, Patent pending, June 2009.
- M. Ali and P. Falcone, Method, computer program product, ECU and vehicle, European Patent Office, Application no. 10156390.6, Patent pending, March 2010.
- M. Ali, P. Landfors and M. Bengtsson, Vehicle yaw stability control method and apparatus, European Patent Office, Application no. 12165836.3, Patent pending, April 2012.

Chapter 2

Basic vehicle dynamics

This chapter briefly outlines some important limitations of a vehicle's dynamics. For a more detailed treatment of vehicle dynamics the reader is also referred to any of the numerous textbooks on vehicle dynamics and active safety [9–12].

2.1 Longitudinal dynamics

We start with a simple example showing how a vehicle can behave in the absence of an antilock braking system. Figure 2.1 shows a simulation where high constant brake torque is applied to a vehicle's wheels in order to slow it down. The wheels have much faster dynamics than the vehicle body and as an effect of the high brake torque, the wheels lock while the vehicle is still moving. This is a well known and important characteristic that drivers, at least in Sweden, are exposed to as part of their driving license examination.

2.1.1 Tire forces

In order to understand and explain the behavior observed in Figure 2.1, we study how longitudinal forces are generated at the tire's contact patch. Consider the illustration in Figure 2.2(a) where a torque T_w is applied to a wheel. Due to T_w, the rotational speed of the wheel ω changes and a longitudinal force f_x arises at the contact patch. The force f_x can be described as a function of the so called longitudinal slip, defined as,

$$\kappa = -\frac{v_{xw} - \omega r_w}{v_{xw}}, \tag{2.1}$$

where according to the notation in Figure 2.2(a), v_{xw} denotes the wheel's

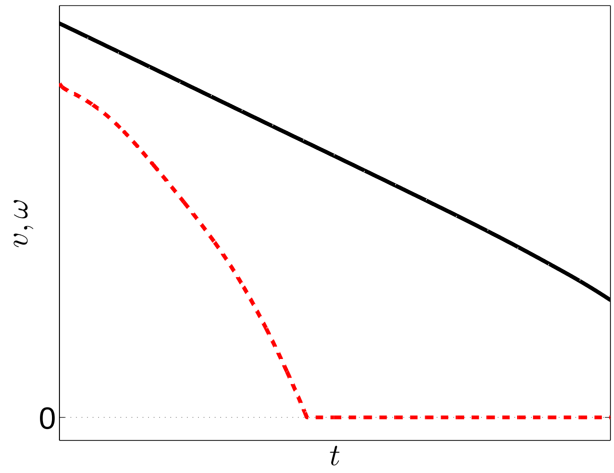


Figure 2.1: A simulation where constant brake torque is applied to a vehicle. The black solid line shows the evolution of the vehicle's speed v while the red dashed line shows the speed at one of the wheels ω. We observe that the wheel locks while the vehicle is still moving

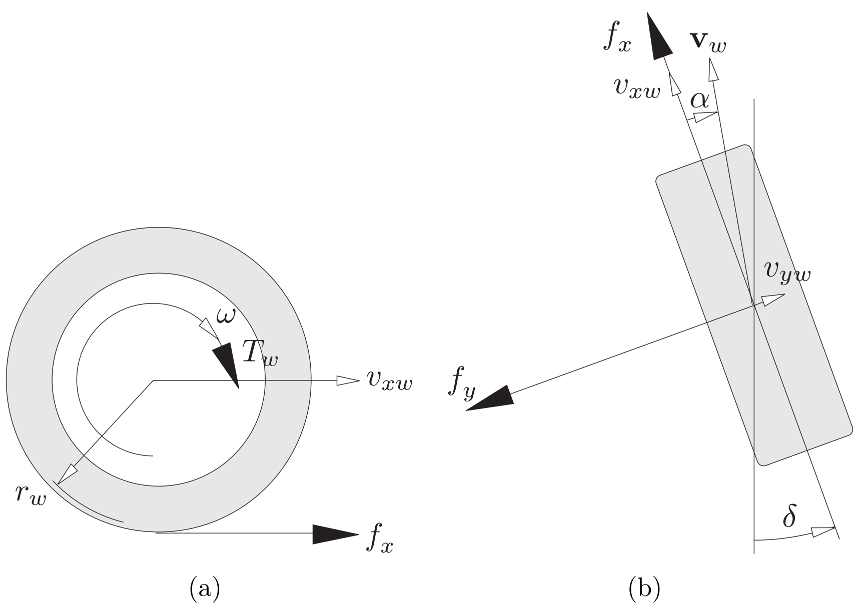


Figure 2.2: Tire modeling notation

longitudinal velocity and r_w the wheel's effective rolling radius. The longitudinal slip reflects the difference between the wheel's peripheral speed and the speed of the wheel in the longitudinal direction. Intuitively, f_x is a monotonic function of the torque T_w, i.e. the larger the magnitude of T_w is, the higher magnitudes of κ and f_x are generated. In general however, this is not always true. Figure 2.3(a) illustrates that, for small slip values, the longitudinal force linearly increases with the slip, then saturates and further starts decreasing for slip values beyond the saturation point. This implies that when a wheel locks, which corresponds to a slip value $\kappa = -1$ (-100%), more braking force can be obtained by letting the wheel start rolling again, i.e. releasing the brakes.

However, maintaining longitudinal force is not the only benefit of limiting the slip. Figure 2.3 also shows a strong coupling between the lateral and the longitudinal forces. The lateral force f_y stems from the relation between the longitudinal and lateral components of the tire's velocity. It can be described as a function of the lateral slip angle α, which is illustrated in Figure 2.2(b) and can be defined as,

$$\tan(\alpha) = \frac{v_{yw}}{v_{xw}}. \tag{2.2}$$

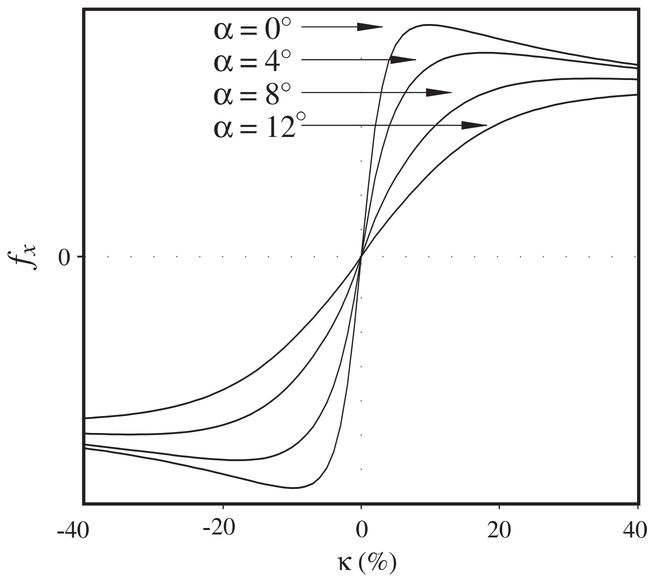
As seen in Figure 2.3(b), the lateral force however also depends on the longitudinal slip κ. The lateral force peak is reduced with increasing longitudinal slip magnitude. As will be explained in the following sections, the availability of lateral force is important for steering the vehicle, hence for high values of longitudinal slip the possibility to steer the vehicle is, in principle, lost. In order to maintain the ability to steer the vehicle also in situations where e.g. powerful deceleration is required, it is therefore important that the slip magnitude is kept at an acceptable level.

2.2 Lateral and yaw dynamics

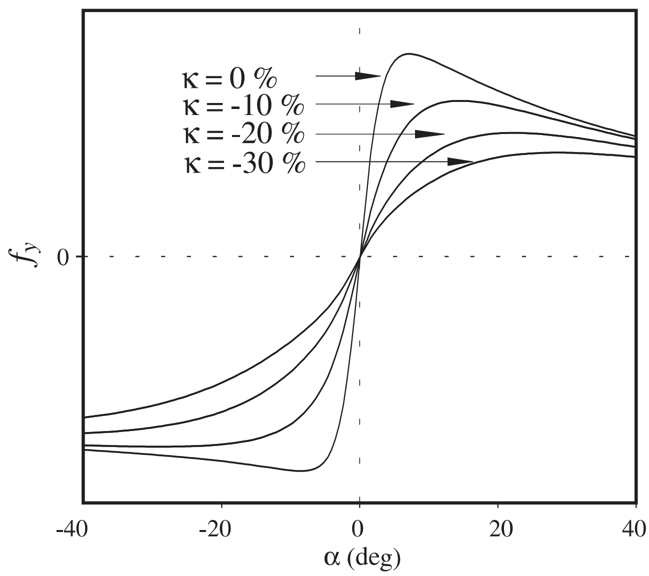
The nonlinearity of the *lateral* tire forces mostly affects the vehicle's highly coupled lateral and yaw dynamics. The following sections describe how limitations imposed by the lateral tire force nonlinearity influences the yaw dynamics.

2.2.1 Yaw dynamics

Through the front steering angle δ, a driver can influence the slip angles (see Figure 2.2(b)) and consequently the lateral forces f_{y_i}. The tire forces induce a moment M_z around a vertical axis centered at the vehicle's center



(a)



(b)

Figure 2.3: Tire forces (a) Longitudinal force as a function of longitudinal slip κ, under the influence of different slip angles α (b) Lateral force as a function of side slip angle α, under the influence of different slip values κ.

of gravity according to the following relation,

$$M_z = F_{yf} l_f - F_{yr} l_r + \Delta M_z^x, \tag{2.3}$$

where the forces F_{yf}, F_{yr} are expressed in the vehicle frame as sums of the lateral forces at the front and rear axles respectively, ΔM_z^x denotes the yaw moment contribution of the longitudinal forces and the rest of the notation is explained in Figure 2.4. Equation (2.3) indicates that F_{yf} contributes

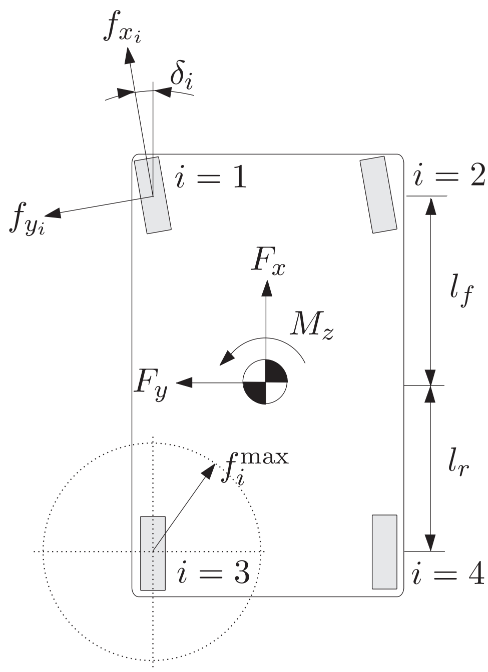


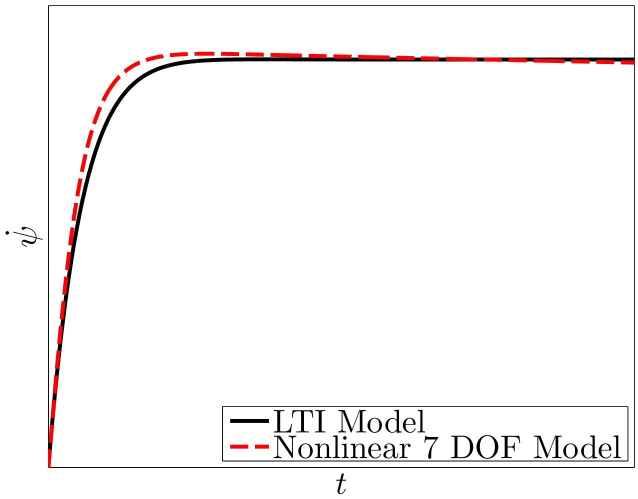
Figure 2.4: Vehicle modeling notation.

positively to the yaw moment and F_{yr} contributes negatively.

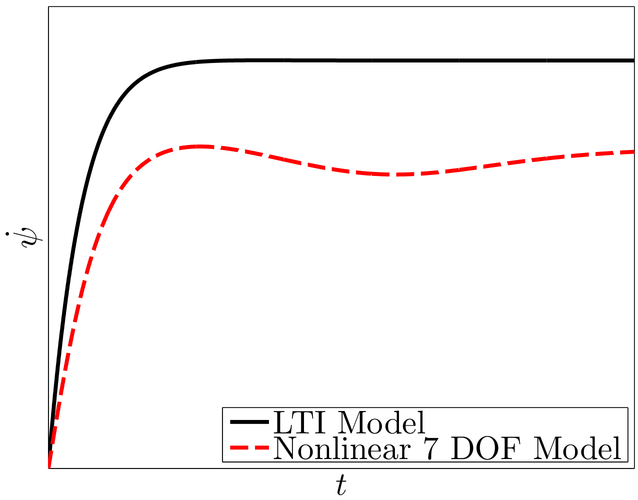
2.2.2 Operation in the nonlinear region

Figure 2.5(a) compares the step responses of a nonlinear and a linearized vehicle model. In the example, the steering angle δ and the yaw rate $\dot{\psi}$, are the input and output signals, respectively. We note that the two models have similar responses. In Figure 2.5(b) the input step has been doubled compared to Figure 2.5(a) from $\delta = 5$ to $\delta = 10$. In this case, there is a clear difference between the two responses.

Figure 2.3(b) shows that, similar to the longitudinal force, the lateral force linearly increases with the slip for small slip values. In normal driving conditions, the slip angles are kept small, i.e. in an operating region where the lateral tire force characteristics can be approximated as linearly



(a)



(b)

Figure 2.5: Yaw rate responses to steps in the steering angle for two vehicle models. The LTI model only considers the lateral and yaw dynamics and has been obtained by linearizing the nonlinear tire characteristics around zero slip, i.e., by using the approximation $f_y(\alpha) \approx \frac{\partial f_y(\alpha,\kappa)}{\partial \alpha}|_{\alpha=0,\kappa=0}\alpha$. In (a), $\delta = 5°$ and in (b), $\delta = 10°$.

related to the slip angle. Most drivers seldom operate outside the linear region. They are familiar with the vehicle's response to a change in the steering angle in this region. However, as soon as the vehicle operates in the nonlinear region of the tires, the vehicle's response changes as shown in Figure 2.5(b). In such situations, a normal driver might not be able to cope with the vehicle's dynamical behavior.

2.2.3 Under- and oversteer

We will refer to yaw rate trajectories obtained using a linearized vehicle model as *nominal* trajectories. In Figure 2.5(b), the yaw rate trajectory obtained with the nonlinear vehicle model has lower magnitude than the *nominal* yaw rate trajectory. This can be explained by considering Figure 2.6 and equation (2.3). Figure 2.6 shows that, in the considered example, the slip angles at the front axle take values in the region where the tires exhibit nonlinear behavior. When the tires at the front axle operate in the

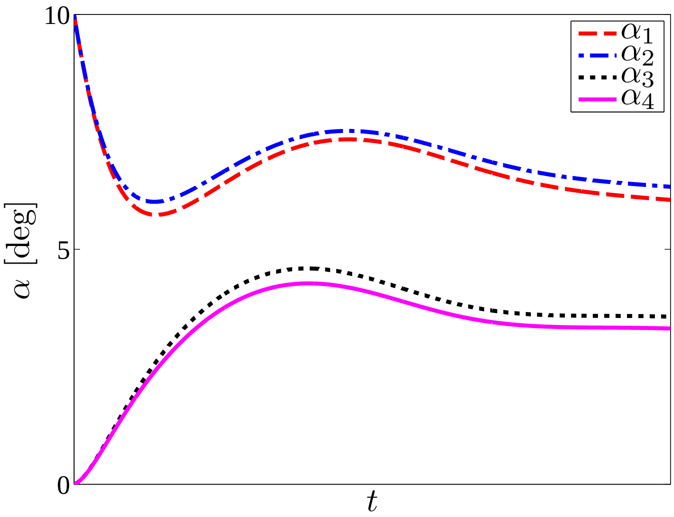


Figure 2.6: Slip angles in the trajectory shown in Figure 2.5(b). The slip angles at the front axle operate in the nonlinear region of the tire characteristics while the rear tires operate in the linear region.

nonlinear region, the front lateral force F_{yf} will be reduced compared to the *nominal* trajectory. From (2.3), we can conclude that such reduction leads to a reduced yaw moment M_z and this is why the vehicle rotates less than in the *nominal* trajectory. We recall that, according to (2.3), the lateral force at the rear axle F_{yr}, on the other hand, counteracts the yaw moment. Reduced lateral force at the rear axle due to operation in the nonlinear region would therefore have the opposite effect, i.e. a higher vehicle rotation would be obtained.

Depending on whether, and of course how far, the front, the rear or both axles are in the nonlinear region, the total effect on the vehicle dynamics will of course be different. In Figure 2.7, two situations that might occur due to tire nonlinearity are illustrated. Compared, again, to a *nominal*

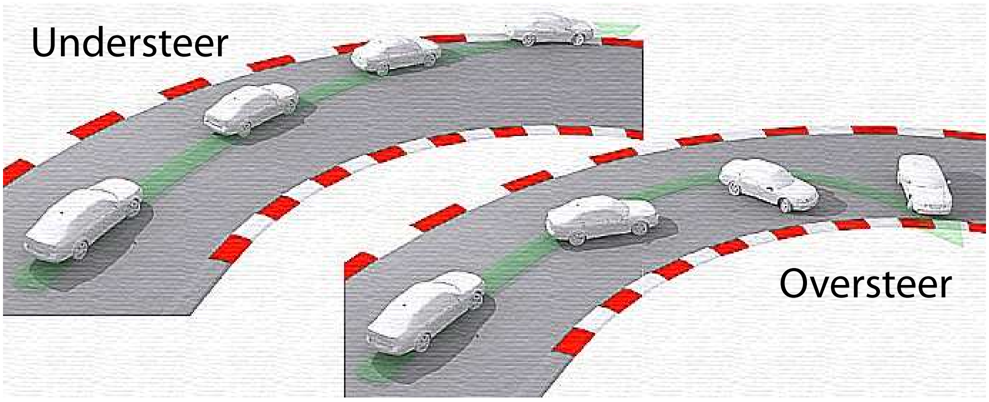


Figure 2.7: Illustration of *under*- and *over*steer

trajectory, the vehicle's rotation is smaller in *understeer*, while in *oversteer* the rotation is larger. We remark that the description of the two terms given here is very simplified but sufficient for this context. A thorough characterization of under- and oversteer can be found in [11].

2.2.4 Yaw moment generation

Powerful under- or oversteer situations can arise quite fast and can hence be difficult to deal with for a driver. As illustrated in Figure 2.7, such situations might even cause a vehicle to leave the road. Next we describe how yaw moment can be generated to counteract under- or oversteer even when the lateral tire forces are saturated.

Let us consider the tire force as a vector, originating at the center of the contact patch and pointing in some direction in the plane as illustrated at the left rear tire in Figure 2.4. The force vector can point in any direction and have varying length as long as it stays inside the dotted ellipse, which represents the limit of attainable force. The size of the ellipse is in general a function of the vertical load. In Figure 2.8, a corresponding *friction* ellipse is shown, this time for the front left tire. For the sake of simple illustration we drop the index i, disregard the vertical force dependance and simply denote the set of attainable force at the front left tire by $\mathcal{P}$.

In order for the force vector to contribute to the yaw moment, it needs to have a non-zero component perpendicular to the diagonal line a drawn

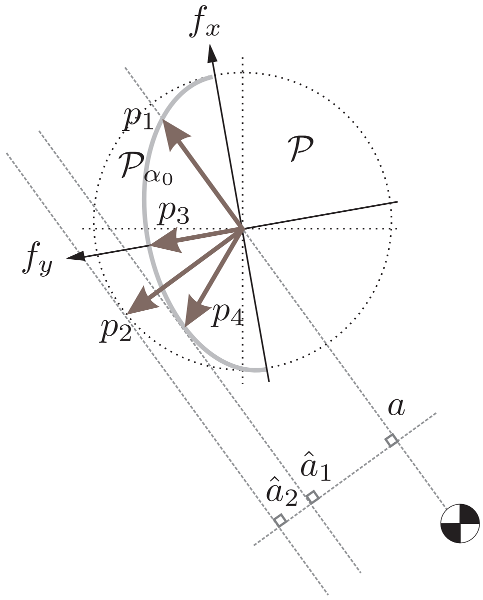


Figure 2.8: Yaw moment generation at the front left tire. The dotted ellipse represents the limit of attainable force and the line a is drawn between the vehicle's center of gravity and the center of the contact patch between tire and road.

between the vehicle's center of gravity and the center of the contact patch. The lines $\hat{a}_1, \hat{a}_2$ are parallel to a. The line $\hat{a}_2$ intersects the set $\mathcal{P}$ at p_2 which gives the largest force component perpendicular to a (in the appropriate direction) and thus maximizes the yaw moment contribution $\forall f(\alpha, \kappa) \in \mathcal{P}$. In addition, we observe that the force vector p_1 gives no contribution to the yaw moment M_z. For the illustrated tire, we note that both p_1 and p_2 have non-zero longitudinal and lateral force components f_x and f_y. It is thus possible to both increase and decrease the yaw moment M_z through f_x in the presence of lateral force f_y.

More precisely, for a given slip angle α_0, the yaw moment contribution can be influenced as follows. Consider the bold ellipsoidal line $\mathcal{P}_{\alpha_0}$, which is defined as $\mathcal{P}_{\alpha_0} = \{f(\alpha, \kappa) \in \mathcal{P} | \alpha = \alpha_0\}$, i.e. the set of attainable forces for a specific slip angle α_0. Depending on the longitudinal slip κ, the force vector will point somewhere on $\mathcal{P}_{\alpha_0}$. For a freely rolling tire, i.e when $\kappa = 0$ a force vector p_3 is obtained. If the wheel is accelerated, positive values of κ are obtained which result in a force vector above p_3. On the other hand, negative κ will give a force vector below p_3. The line $\hat{a}_1$ indicates that the yaw moment contribution is maximized at p_4, $\forall f(\alpha_0, \kappa) \in \mathcal{P}_{\alpha_0}$. As explained in the following section, the possibility to manipulate the yaw moment through braking actuators is utilized in vehicle dynamics control systems to modify vehicles' dynamical behavior in critical situations.

2.3 Vehicle dynamics control

Several active safety systems compensate for and/or counteract limitations imposed by the nonlinear tire characteristics in order to improve the dynamical behavior of the vehicle. Examples of such systems are the antilock braking, traction control, yaw control and roll stability systems.

The antilock braking and traction control systems improve the longitudinal dynamics by limiting the longitudinal slip. The antilock braking for example, identifies excessive longitudinal slip and intervenes by releasing and applying the brakes. Yaw stability control systems instead utilize the brakes to generate additional yaw moment. In Section 2.2.4 we noted that, by utilizing the brakes at individual wheels, a higher yaw moment contribution can sometimes be obtained even if the braking reduces the lateral force (compare e.g. p_3 and p_4). By utilizing this fact, yaw stability control systems can modify the vehicle's dynamical behavior so that it becomes easier to control in limit handling. The underlying idea is that the vehicle's *nominal* behavior in the linear region is considered predictable and thus preferable. In control terms, a yaw control system therefore uses this *nominal* trajectory as reference, sensors measure the vehicle's motion in the body frame and through closed loop control the vehicle's *nominal* behavior can thus be extended a bit into the nonlinear region of the tires. In most commercial yaw control systems, such control is implemented using fuzzy logic schemes to individually modify the yaw moment contribution of each wheel. Typically, the brakes at the inner wheels are used when a vehicle understeers, while the brakes at the outer wheels are utilized in oversteer.

While the available vehicle dynamics control systems are activated only once the vehicle is already operating in the nonlinear tire regions, the threat assessment and control methods developed in Papers 1-4 are predictive and aim at preventing such operation before it occurs. This is beneficial since, once the vehicle is already operating in the nonlinear region, the ability to actuate the vehicle might be significantly reduced.

Chapter 3

Driver assistance systems

In this chapter, Driver Assistance Systems (DAS) are briefly introduced and challenges associated with the subset of DAS that are mainly devoted to increased traffic safety are highlighted.

3.1 Driving automation

Already a century ago, feedback control was utilized to implement a speed control system [13] that partially automated the driving task. At the time, speed control systems utilized a centrifugal governor connected to the engine's throttle valve to control its speed. Nonetheless, while the history of driving automation dates far back, the introduction of external sensors in passenger vehicles, i.e. sensors providing information about the vehicle surroundings, has enabled new possibilities.

3.1.1 Enabling sensors

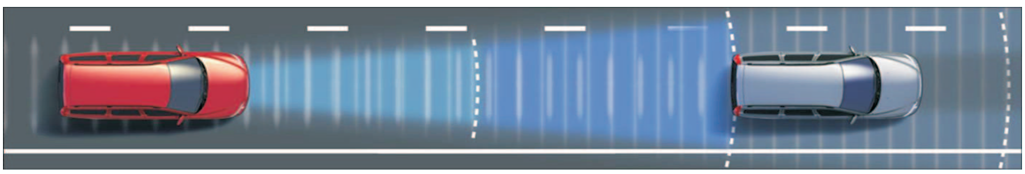


Figure 3.1: Radar measurements providing range and possibly range rate to the preceding vehicle. Such measurements can be used to implement an Adaptive Cruise Control (ACC) system that maintains a constant distance or time gap.

Figure 3.1 illustrates how a radar can be used to measure the distance to a preceding vehicle. Such measurements can be used to extend the functionality of conventional cruise control systems. In addition to maintaining a set speed, Adaptive Cruise Control (ACC) systems can maintain a minimum distance or time gap which is useful if a preceding vehicle that is traveling slower than the set speed is encountered. The same sensor can also be used to avoid or mitigate collisions by automated safety interventions that are activated if the preceding vehicle suddenly stops or significantly reduces its speed. Figure 3.2 shows how external sensors can be mounted in a passenger car. In the illustrated example, a radar is mounted in the front grill of

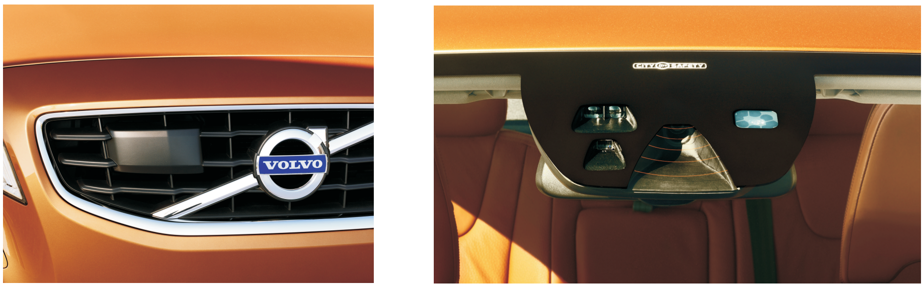


Figure 3.2: Example of how radar, lidar and camera sensors providing information of the surrounding environment can be mounted in a passenger vehicle. These sensors complement each other well, the advantages of the radar are typically the disadvantages of the camera and vice versa [14].

the vehicle and a camera and lidar are mounted in the windscreen window. For ACC and forward collision avoidance applications the benefit of the radar is typically its accurate range and range rate measurements and the camera is useful for classifying that the detected object is e.g. a vehicle that is in the correct lane. The lidar typically provides higher resolution range measurements and is beneficial for low speed applications [15].

As external sensors become cheaper, vehicles' sensing capabilities can be further extended to overview their surroundings not only in the forward direction. As an example, Figure 3.3 illustrates the sensing capabilities of a newly launched passenger car that can detect vehicles, pedestrians and other objects at different locations. In addition, future vehicles are envisioned to communicate with the infrastructure and each other in order to obtain richer information than what is available through external sensors only.

3.1.2 Benefits

Through innovations like electronically controlled brake pressure actuators, electronic fuel injection and electric power steering systems, there are today extensive actuation possibilities in modern passenger cars. The combination of actuation and sensing capabilities has enabled the development of a wide

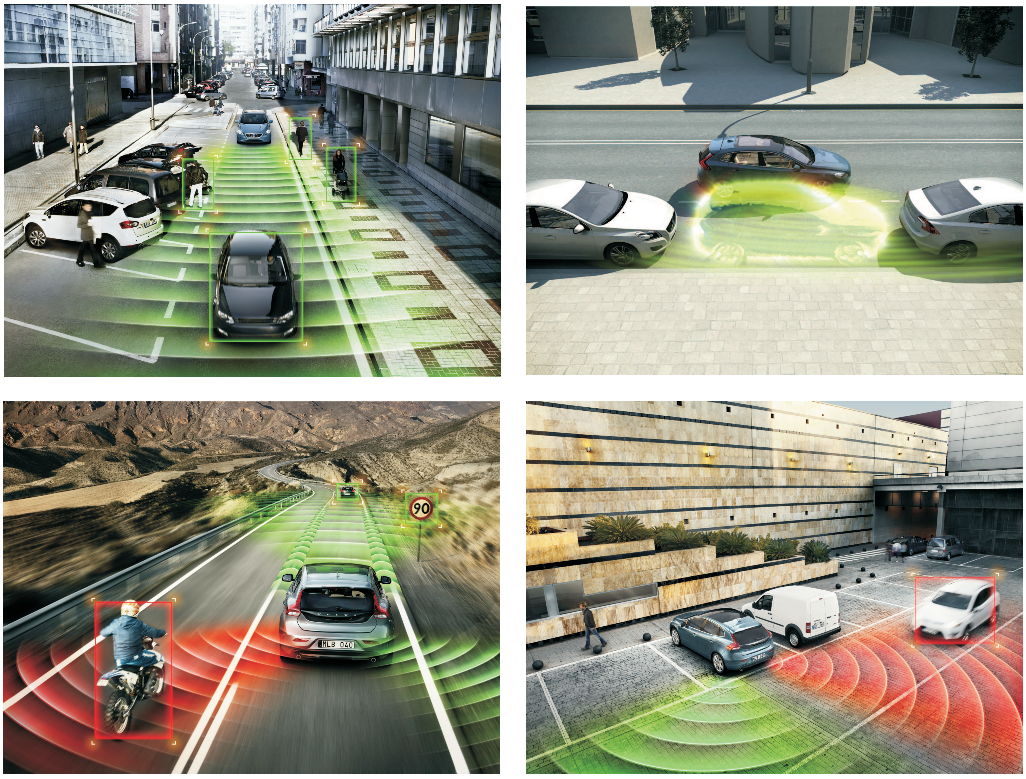


Figure 3.3: Illustration of sensing and detection capabilities of a newly launched passenger vehicle. Future vehicles are expected to have 360° perception and capabilities of communicating with other vehicles and the infrastructure.

range of driving automation features. These, developed and future features provide benefits to vehicle owners and manufacturers.

Automation of the driving task can provide increased convenience for drivers that can utilize time and effort more efficiently. If e.g. the task of following a preceding vehicle is automated in congested traffic, the driver can use the time in the traffic cue for something else. Traffic flow and environmental problems can also be addressed through driving automation. In e.g. the design of ACC systems it is possible to design the vehicle following behavior such that fuel consumption and traffic flow are influenced positively. Driving automation can also influence vehicle safety since, if designed correctly, driving automation features reduce the risk of human error. Finally, for vehicle manufacturers the introduction of driving automation technologies can give a competitive advantage. The potential advantages of automating the driving task are thus many and the development of such technology is today more extensive than ever.

3.2 Challenges with safety systems

Some DAS are specifically devoted to vehicle safety and deploy automated safety interventions only in safety critical situations. Next, we describe some of the challenges associated with such safety systems.

3.2.1 General challenges

Figure 3.4 shows an example of how the architecture of a safety system can typically look like. We observe that several important tasks need to be solved.

The *environment information* and *state estimation and parameter identification* blocks provide estimates of various signals and parameters that the safety system needs in order to operate. Examples of such estimates are velocity, yaw rate, road curvature and road friction. The estimates might in many cases be based on measurements that are not sufficiently accurate. Alternatively the signal of interest might be, not measured at all, but instead estimated based on measurements of other signals. Such measurements need to be processed so that reliable estimates can be obtained. Signal processing and state and parameter estimation are thus important parts of safety systems, see e.g. [16–21] where a wide range of estimation problems are treated.

Other important tasks are addressed in the *threat assessment layer*. The threat assessment layer plays an important role in the interaction with the driver. The *threat assessment* block repeatedly evaluates the threat level in

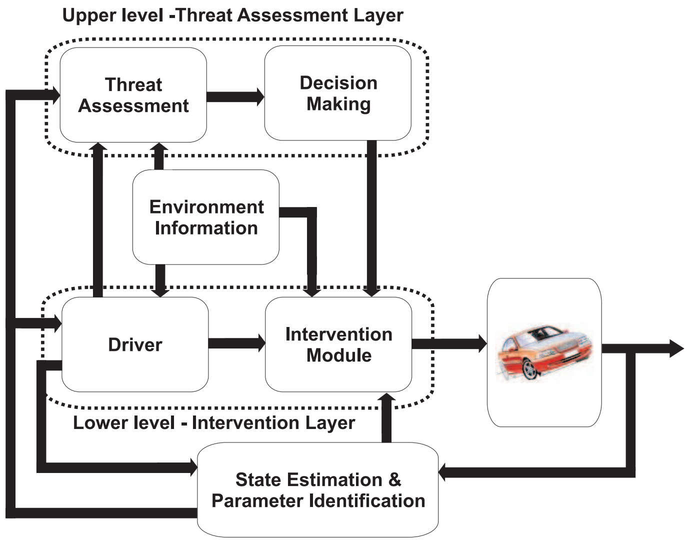


Figure 3.4: Typical safety system architecture.

each situation, this information is then used by the *decision making* block in order to decide whether and how to assist the driver. It is an important challenge to intervene only when the driver is in need of assistance, while interventions should be avoided when they are not necessary. See e.g. [22–29].

Finally, in case of an intervention, the vehicle needs to be controlled towards safe operation. Tasks of the intervention module might involve, both determining a safe trajectory and coordination of the actuators. Various approaches to vehicle path planning and control can be found in e.g. [30–33].

3.2.2 Threat assessment challenges

As vitally important as the sensing and intervention tasks are, this section focuses on challenges associated with the threat assessment layer which is a core part of the work covered in this thesis. The threat assessment layer distinguishes safety systems from other DAS that are generally designed for increased convenience or other purposes. The task of the threat assessment layer is to predict critical situations and maintain safety by deploying safety interventions such as full braking if needed. Essentially, a very high safety level can be maintained if large safety margins are adopted and vehicles are e.g. forced to operate in very low speed. Such degradation of vehicle performance is however difficult to gain acceptance for.

The example situation in Figure 3.5 illustrates the difficulty in maintaining high safety without degrading vehicle performance. The red vehicle is approaching the preceding vehicle in high speed and is, in the illustrated

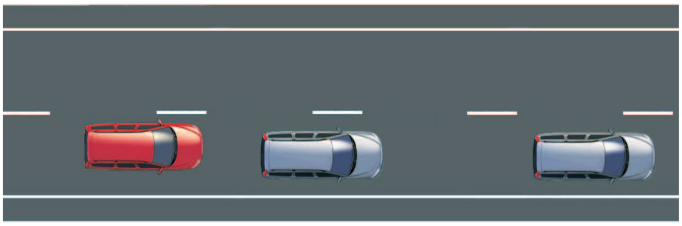


Figure 3.5: The red host vehicle is approaching a preceding vehicle in high speed and is about to turn to the left lane for an overtaking. The red vehicle's speed is such that it can easily avoid the preceding vehicle by steering into the adjacent lane but not by braking.

situation, too close to avoid colliding with it by braking. However, in this situation the driver intends to overtake the preceding vehicle hence the situation is actually not critical. If the red vehicle is equipped with a forward collision avoidance system, there's no need to activate any braking intervention in this situation. In order to avoid nuisance or/and unnecessary degradation of the vehicle's performance, the collision avoidance system thus has to account for the possibility that the driver is intending to steer when evaluating the criticality of the situation. Figure 3.6 shows how this is done in a common algorithm described in [34] where the *time to collision*,

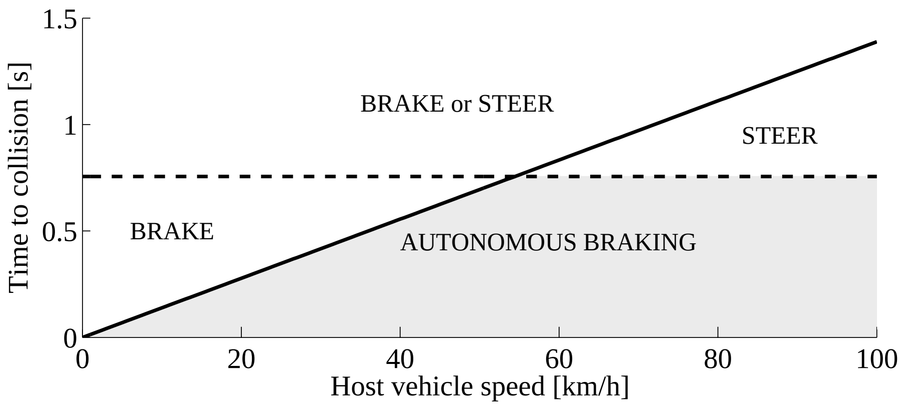


Figure 3.6: Criticality assessment using a common algorithm for forward collision avoidance systems that utilize braking interventions to avoid colliding. In the region below the solid line it is assessed that the driver can no longer brake to avoid colliding. Similarly, it is assessed no longer possible to avoid colliding by steering in the region below the dashed line. The shaded area indicates a region where a forward collision avoidance system that utilizes braking typically intervenes. The graph is extracted from [34].

defined as the time to contact if the velocity remains constant, is used to determine whether braking interventions are activated. We note that, for high speeds, there is a large region where it is possible to avoid a collision by steering but not by braking as in the situation in Figure 3.5. In this region, braking collision avoidance systems generally do not intervene but instead wait until the vehicle is operating in a region corresponding to the shaded one of Figure 3.6 before the brakes are activated. This is a reason why collision avoidance systems that operate in higher speeds are generally incapable of completely avoiding collisions but instead merely mitigate them.

In the situation in Figure 3.5 the driver's actuation or/and control capabilities are not a subset of the capabilities of the safety system that can merely brake. The gap between the capabilities of the driver and the safety system is one contributor to the difficulty in completely avoiding collisions. In the example scenario of Figure 3.5, the availability of a steering actuator might have provided an increased capability of avoiding the object by steering. However, in order to initiate an avoidance maneuver that drives the vehicle out of its lane, it must first be established that the vehicle is driven in to a safe area which is a difficult task and thus an obstacle.

Another contributor to the difficulty in completely avoiding a collision is related to customer acceptance. Even if it can be established that the adjacent lane is safe, in order to avoid a collision, a safety system would have to intervene before collision avoidance is no longer possible. Otherwise the intervention would, by definition, come too late. Many, but not all, drivers keep noticeable safety margins while driving that can be utilized to advance interventions. Determining safety margins that can be accepted by all drivers, while maintaining the ability to avoid collisions is however a serious challenge.

In some scenarios, it might in addition be insufficient to separately steer or brake to avoid a collision. This is typically the case for some roadway departure scenarios that are addressed in this thesis. In e.g. a situation where a vehicle negotiates a curve such that speed needs to be reduced at the same time as the vehicle needs to be steered through the curve, combined braking and steering might be necessary to keep the vehicle from departing the road.

3.3 Driving automation trends

Current convenience DAS such as ACC and lane keeping systems are restricted to operation in fairly simple environments and limited operating conditions. However, research activities have enabled a level of driving automation that goes far beyond the capabilities of current DAS. Prototypes of self driving vehicles have been shown to successfully accomplish complex driving tasks in urban environments [35–37]. In the 2007 DARPA Urban Challenge, vehicles "capable of driving in traffic, performing complex maneuvers such as merging, passing, parking and negotiating intersections" have competed [38]. Such advances have later been further developed and self driving prototypes are currently capable of operating in real traffic [39]. In addition to driving in complex environments, driving at the limit of vehicle handling capabilities is yet another challenge that has attracted interest by researchers. Prototypes have also been demonstrated capable of accomplishing challenging driving tasks, such as double lane changes on slippery surfaces and autonomous cornering at the limit of handling [30,40,41]. Automated driving technologies are thus moving towards a higher capability of operating at the vehicle handling limits.

Similarly we note that, the scope of safety systems is currently also increasing. While early safety systems only warned drivers upon imminent crashes, current collision avoidance systems are capable of autonomously braking to mitigate and sometimes even completely avoid collisions. There are today also safety systems that steer the vehicle back in the lane upon lane crossings to prevent lane departures. Research activities have also demonstrated safety systems that can avoid collisions with other vehicles by steering [28] and systems that are capable of assessing complex scenarios that can occur in e.g. intersections [34]. A wider range of scenarios are thus being considered. The roadway departure prevention applications presented in this thesis also contribute to the extended scope. There are also activities of modeling limitations and detecting degradation in the driver's abilities in order to motivate earlier interventions. This pushes the scope of safety systems to intervene in regions where the vehicle is easier to maneuver. In such regions, less aggressive interventions might be utilized and the difference between vehicle controllers developed for safety systems and controllers for convenience DAS is reduced, enabling potential synergies. The driver estimation and threat assessment algorithms presented in this thesis contribute in this regard. At the same time the research efforts on vehicle control at the limit of handling enables an increased ability of avoiding collisions also in situations where complex, combined steering and possibly differential braking is needed. In such situations, the vehicle is difficult to maneuver.

Given sufficient computational and sensing capabilities, it is possible to exploit research advances to deploy automated driving features capable of handling an increased level of environment complexity and operating closer to the vehicle handling limits. Nonetheless, even though many of the extended technologies have been demonstrated in prototypes, there are limitations and obstacles against their commercial deployment. Series production sensors and computational resources which are generally cheaper than what is used in prototype vehicles do not currently provide sufficient performance for many applications. The automotive industry can influence such limitations through improvements of available sensing capabilities and computational schemes. The scope of DAS is therefore expected to be significantly extended as sensing and computational capabilities become cheaper.

Chapter 4

Summary of included papers

This chapter provides a brief summary of the appended papers. Full versions of the papers are included in Part II.

Paper 1 M. Ali, P. Falcone, C. Olsson and J. Sjöberg, Predictive Prevention of Loss of Vehicle Control for Roadway Departure Avoidance, *IEEE Transactions on Intelligent Transportation Systems,* In press.

In Chapter 2 we showed that vehicle operation in the nonlinear region of the tires is difficult to handle. In Paper 1 we suggest a novel safety function that utilizes information about the host vehicle's state and the road ahead to predict and prevent such operation. In other words, we address the problems considered in Chapter 2 but utilize road information in order to enable the possibility to intervene earlier than a conventional yaw control system.

We consider a complete system with threat assessment, decision making and control via steering and braking. The upper level threat assessment layer detects the risk of vehicle instability within a future time horizon. Once the threat assessment indicates imminent vehicle instability, the decision making block determines an appropriate intervention. We consider two types of control interventions. For the most critical situations, steering and differential braking are coordinated based on Model Predictive Control (MPC) techniques, while in less critical situations the vehicle is simply decelerated.

The decision function is formulated by an optimization problem. It is well suited for making use of several different intervention strategies that might have different advantages and disadvantages. The formulation is also useful for smooth integration of several different safety applications.

The suggested safety function is implemented using the developed methods and validated both experimentally and in simulation. The validation shows that the safety system effectively exploits the preview information in order to issue earlier and less intrusive interventions than a conventional yaw controller.

The thesis author was responsible for the problem formulation, development of algorithms, implementation, verification and writing of the paper.

Paper 2 P. Falcone, M. Ali and J. Sjöberg, Predictive Threat Assessment via Reachability Analysis and Set Invariance Theory, *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no 4, pp. 1352-1361, 2011.

Paper 2 focuses on the threat assessment problem. Roadway departures have varying nature since they can occur both slowly due to e.g. drowsiness or in more dynamic situations due to loss of control. This paper addresses the problem of dealing with several different safety requirements in the same threat assessment algorithm. The requirements on the vehicle's motion are simply defined as a set of constraints on the vehicle states that need to be satisfied over a finite horizon. The stability requirement is specified by constraining the tire slip angles while the vehicle is kept on the road by constraining the vehicle's position in the lane. Using reachability analysis and set theory, a set of *safe states* is then calculated for the vehicle. If the vehicle state is within the set, safety can be guaranteed over a finite horizon, while if the vehicle state fails the set membership condition an intervention can be motivated.

Two approaches are presented in the paper. In one approach, the calculation of *safe states* is based on a vehicle model and is then, the set of states, for which there exists a control signal, that can drive the vehicle safely over a future finite time horizon. In the other approach, we complement the vehicle model with a driver model. In this case the set of *safe states* is, the set of states, from which the autonomous system, formed by combining the vehicle and driver model can be driven safely over the horizon. The mathematical driver model used to predict future constraint violations needs to be adapted to different drivers. We therefore also implement an algorithm for online estimation of the parameters in the driver steering model. The suggested threat assessment methods along with the driver estimation is successfully validated experimentally.

The problem formulation and writing was jointly conducted by the first two authors of the paper. The author of this thesis was responsible for development, implementation and verification of the suggested approaches.

Paper 3 M. Ali, P. Falcone and J. Sjöberg, Threat Assessment Design under Uncertainty, *Submitted for possible journal publication.*

Paper 3 is an extension of the work presented in Paper 2. We consider one of the threat assessment algorithms presented in Paper 2 and show how it can be modified to account for uncertainty. Essentially, there are three sources of uncertainty that are accounted for in different ways. We show how uncertain state estimates, uncertain disturbance estimates and uncertain model parameters can be accounted for. In order to be able to account for model parameter uncertainty without degrading vehicle performance, we derive and prove theoretical results. Moreover, Paper 3 develops alternative, computationally efficient, threat assessment schemes that give equivalent performance as the reachability based approaches but lack the advantages of having an explicit representation of safe sets. For commercial deployment, computational efficiency might have high priority.

We demonstrate the suggested approaches considering uncertainty in the state estimates: lateral velocity, yaw rate, position and orientation in the lane. We also consider uncertain estimates of the road geometry which is treated as a disturbance in the considered approach. The approach to accounting for model parameter uncertainty is demonstrated by considering the uncertainty of the driver model parameters estimates.

The thesis author was responsible for the problem formulation, derivation of proofs, development of algorithms, implementation, verification and writing of the paper.

Paper 4 M. Ali, E. Gelso and J. Sjöberg, Automotive Threat Assessment Design for Combined Braking and Steering Maneuvers, *Accepted for publication in IEEE Transactions on Vehicular Technology.*

Paper 4 also considers the threat assessment problem. In particular we consider the problem of evaluating whether an admissible *combined* steering and braking maneuver exists, that accomplishes the driving task while maintaining the vehicle state within a prescribed subset of the state and input space. Just like in Paper 2, the underlying idea is that, if such a maneuver does not exist, the driver can be deemed incapable of maintaining safety without assistance. By excluding the possible existence of combined maneuvers, the risk for unwanted interventions is even further reduced and autonomous assisting interventions are thus even more motivated.

Although the reachability analysis tools used in Paper 2 are powerful, they are restricted to linear (and piece-wise affine) systems with polyhedral constraints. Dynamical models that simultaneously capture a vehicle's longitudinal and lateral dynamics are however, in general, nonlinear. For systems with nonlinear dynamics and possibly nonlinear, non-convex constraints, reachable sets are more difficult to compute. In Paper 4, we reformulate the threat assessment problem as a constraint satisfaction problem with nonlinear equality constraints. This is a non-convex problem formulation. In solving this problem we resort to interval-based consistency techniques, which can efficiently solve such problems while maintaining theoretical guarantees that false interventions are not activated. We implement and validate the suggested approach experimentally in a roadway departure prevention application.

The thesis author was responsible for the problem formulation, development of algorithms and writing of the paper. It should be noted that the interval based implementations where conducted by the second author of the paper, i.e. not the thesis author.

Chapter 5

Concluding remarks

This chapter summarizes the contributions of the thesis and briefly outlines directions for future work.

5.1 Contributions

This thesis has focused on the problem of improving vehicle safety while maintaining an acceptable vehicle performance. Methods to assess accident threats, determine interventions and control vehicle motion have been developed to improve vehicle safety. In order to avoid degrading vehicle performance through large safety margins, the developed methods have been designed such that interventions can be deployed only when it can be assured that the situation is critical. The following have been considered:

1. A novel safety function that utilizes road preview information to avoid vehicle control loss has been proposed.

2. Threat assessment algorithms have been developed. The algorithms utilize vehicle and mathematical driver models to properly account for limitations in the vehicle's and the driver's capabilities. The algorithms are presented in Papers 1-4.

3. An algorithm for online estimation of a driver model has been implemented. The driver modeling is discussed in Papers 1 and 2 and is used as an integrated part of the threat assessment algorithms.

4. The threat assessment has been extended to account for uncertainties in the state and disturbance estimates as well as system parameters like the driver model parameters. In Paper 3, theory and threat assessment algorithms are developed to handle such uncertainty.

5. The threat assessment methods have been modified to account for nonlinear system dynamics. In Papers 1 and 4 nonlinear dynamics are accounted for. Moreover, in Paper 4 nonlinear dynamics are included while maintaining theoretical guarantees that false threat detections are avoided.

6. A novel framework for decision making in general automotive accident avoidance systems has been developed. The framework enables the integration of a wide range of control strategies ranging from completely autonomous coordination of braking and steering to previously developed control schemes implemented in e.g. onboard yaw control systems. The decision making framework is discussed in Paper 1.

7. Intervention/control strategies for automated coordination of both steering and braking have been implemented and evaluated. The intervention strategies are presented in Paper 1.

8. All the methods presented in the thesis have been experimentally validated.

The work presented in this thesis has implications within:

Roadway departure prevention Essentially, unwanted roadway departures occur either in highly dynamical situations where limitations in the vehicle dynamics reduce the driver's ability to keep the vehicle on the road or in situations where the driver slowly strays off the road due to drowsiness or distraction. Traditionally, vehicle dynamics limitations have been addressed by the vehicle dynamics control systems mentioned in Chapter 2 while safety systems that utilize external sensors like *lane departure warning* or *lane keeping aid* have focused on keeping the vehicle within the road borders. In the appended papers, several methods for detecting that a vehicle is about to depart the road are presented. These methods, are useful in both highly dynamical situations and when the driver strays off the road due to drowsiness or distraction. As illustrated in Figure 5.1 the scope of these methods covers scenarios addressed by both vehicle dynamics control systems and newer active safety systems that utilize external sensors.

Driver interaction The methods presented in the appended papers influence driver interaction in several ways. The computation and availability of safe sets is useful for threat assessment as shown in Papers 2 and 3. The method for computing such sets influences the interaction between the resulting safety system and the driver. In Paper 2

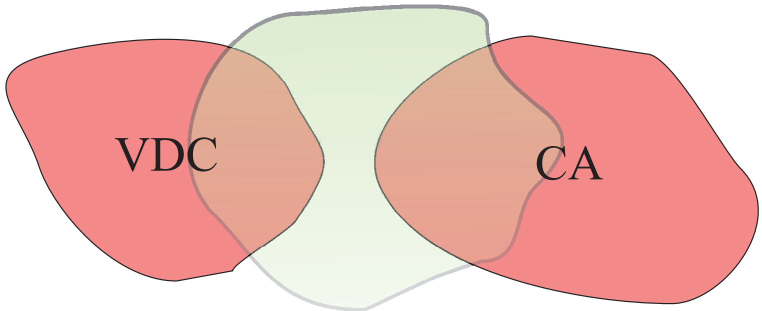


Figure 5.1: The set labeled VDC illustrates the scope of vehicle dynamics control systems and the set labeled CA illustrates the scope of current collision avoidance systems that utilize external sensors. The work in this thesis utilizes information provided by external sensors to both control the vehicle's dynamical behavior and for collision avoidance.

we observed that the use of a model of the driver's steering behavior in the threat assessment design is one way to influence the driver interaction. While the use of vehicle models facilitates incorporating vehicle physical limitations, the driver modeling presented in the appended papers is valuable in order to account for driver limitations. By incorporating a driver model in the threat assessment, the calculated threat level and consequently the initiation of interventions is based not only on vehicle dynamics limitations but also on the driver's abilities. This facilitates proper timing of interventions and thus the interaction with the driver. Specially as the model is adapted to each driver through driver parameter estimation.

The computation of safe sets is also associated with uncertainty. There are several sources of uncertainty that need to be accounted for differently depending on how they appear in the mathematical equations. In Paper 3 we show how uncertainty in estimates of the states, disturbances and model parameters can be accounted for such that the resulting threat assessment algorithms are theoretically guaranteed to avoid false and missed threat detections, respectively. Naturally, a safety system designed to theoretically guarantee safety interacts with the driver in a different way than a system that is designed to only intervene when there is an accident threat. Paper 3 provides a foundation for designing both kinds of systems. In a commercial application where customer acceptance is vital, it might be preferred to delay interventions until an accident threat is theoretically guaranteed at the cost of risking to miss interventions. However, once an intervention has been activated, the criteria for deactivating it might be different from the activation criteria. The purpose of the intervention is to improve safety and it is therefore reasonable to keep it active until safety can be assured. Both threat assessment algorithms that avoid false and missed threat detections are thus applicable in safety systems where the interaction with the driver is important.

Intervention design The availability of safe sets is not only useful for threat assessment. Safe sets can be used to influence the interaction with the driver also in the intervention design. In particular, the intervention can be designed such that it steers the vehicle back into a safe set. As an example we show how this can be done using Model Predictive Control (MPC) which has been used by interventions in Paper 1. In MPC, the control signal is determined at each time sample by solving an optimization problem. The optimization problem can have the form,

$$\begin{aligned}
& & \min_{\text{Controls}} \; J, & \quad (5.1a)\\
& s.t. & \text{System dynamics}, & \quad (5.1b)\\
& & \text{Safety requirements}, & \quad (5.1c)\\
& & \text{Actuator limitations}, & \quad (5.1d)\\
& & \text{Initial conditions}, & \quad (5.1e)
\end{aligned}$$

where J is a performance index that can involve tracking errors and corrective control action. The minimization of the performance index J is typically subject to constraints like (5.1b) that prescribe the system dynamics, safety requirements (5.1c) which in roadway departure applications can be that the vehicle remains on the road, actuator limitations (5.1d) to ensure that the computed control signal can be applied and (5.1e) that simply states that the predicted evolution of the vehicle state using (5.1b) is initialized at the current vehicle state. At each time step, the computed control signal is applied to the plant, the constraint (5.1e) is updated using new measurements of the vehicle state and the optimization problem is then solved again over a shifted horizon to utilize the updated information. It is possible to augment the optimization problem with additional terminal constraints that prescribe a region of the state space to which the state must evolve at the end of the prediction horizon. By prescribing that the vehicle evolves to a safe set, it is possible to design interventions that are not only capable of avoiding accident threats but also steer the vehicle operation towards a region where the driver is capable of taking back control.

Safety verification The threat assessment methods developed in this thesis have focused on evaluating the driver's abilities of avoiding accidents. Vehicle and driver models have been used to perform safety verifications for the driver controlled vehicle. Equivalently, such verifications might also be performed for driving modes where the vehicle control is partially or completely automated as long as models of the vehicle behavior in such modes are available. The methods presented in this thesis are thus also useful when the driving task is automated.

Extensions to other applications An obvious strength of the methods presented in the appended papers is that they are model based. By utilizing a vehicle model and constraining it to operate in a stable operating region, we can e.g. systematically handle fundamental vehicle limitations discussed in Chapter 2. Even though we demonstrate the methodology in roadway departure prevention applications there is actually no reason to restrict the methods to such applications.

System integration The suggested threat assessment methodology enables integrated design of several different active safety features in the same threat assessment algorithm. Since the safety requirements are simply defined as a set of constraints, this enables a wide range of requirements to be taken into account simultaneously.

Nonetheless, while there are benefits with integrated threat assessment design it is sometimes desirable to integrate existing safety features that already have separate threat assessment and intervention controllers. The decision making presented in Paper 1 enables such integration. It is e.g. possible to utilize the capabilities of the already existing onboard yaw control system in situations when those are known to perform well while other more advanced control strategies can be adopted in other situations.

5.2 Directions for future research

Further development of the roadway departure prevention applications towards industrialization is one possible direction for future work. This involves modifications of code for real-time execution and extensive testing of the algorithms' performance in real world scenarios.

Another direction is to further improve performance and extend the scope of the developed threat assessment methods. This can be achieved by modifying the models that have been used to account for a wider range of scenarios. Some example scenarios to which the scope might be extended

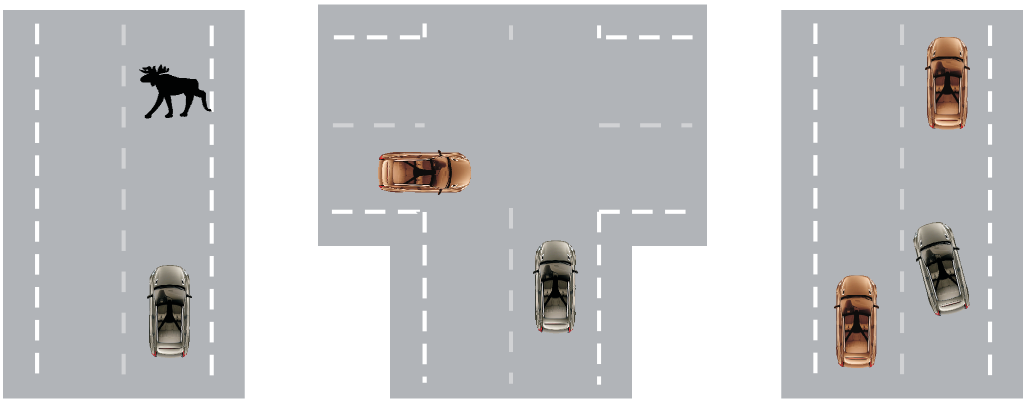


Figure 5.2: Examples of traffic scenarios that might lead to accidents.

are shown in Figure 5.2. The two leftmost pictures illustrate situations where there's a risk of colliding with an animal that's blocking the road, and another vehicle in the crossing path, respectively. The longitudinal vehicle dynamics can be well described as a linear system and it is possible to formulate the *admissible* paths using linear inequalities if the state space is chosen carefully. For these scenarios it is therefore straightforward to modify the threat assessment methods presented in Paper 2 to evaluate whether braking is necessary. Uncertainty in estimates of the state, disturbance and model parameters can then be handled as demonstrated in Paper 3.

The rightmost picture in Figure 5.2 instead illustrates a situation where it might be necessary to consider combined acceleration and steering maneuvers to evaluate the criticality of the situation with good performance. In such case it is more difficult to describe the vehicle dynamics well with a linear model. For accident situations where the system dynamics exhibit nonlinear behavior and/or the admissible states are difficult to represent as convex sets, the methods in Paper 4 might be more useful.

Extending the scope can thus be performed by utilizing the methods that have been proposed in this thesis and adjusting the modeling to account for a wider range of accident scenarios. In this regard, the modeling of drivers' behavior is particularly challenging. The driver model considered in this thesis provides reliable predictions on e.g. highways or country roads, when there is no other vehicles involved. It does not take into account e.g interaction with preceding vehicles, speed adjustment in curves or more complex behavior in e.g. traffic intersections. Further modeling and estimation of driver behavior to account for, in particular, drivers' longitudinal behavior would be valuable, both for increasing performance in the roadway departure scenarios considered in this thesis and also for extending the scope to more general situations. For some scenarios it might be sufficient to start simple with decoupled models of drivers' steering and acceleration behaviors. A good start is to evaluate the numerous virtual driver model structures in the literature [42], by means of system identification methods and large data sets, to determine how well they describe the driving behavior of actual drivers.

An additional challenge is that, even if it is possible to find model structures that can be used to describe drivers' behavior well, the parameters of such models will vary for different drivers and driving situations. Introducing adaptivity, through online estimation of driver model parameters is one way of addressing this problem. Nonetheless, sufficient excitation of the driver's behavior which is necessary to account for a wide range of situations might be difficult, specially for situations that rarely occur. Hence, even though the introduction of adaptivity is expected to have a high potential of improving performance by advancing interventions for individual drivers, it is also associated with limitations that need to be carefully considered.

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Part II

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