1
Introduction

1.1
Motivation

Road fatalities destroy an enormous human potential and also cause serious social and economic consequences. According to the World Health Organization (WHO), 1.25 million road traffic deaths occur every year [1]. Moreover, the risk of a road traffic death varies significantly by region, and there has been little change on this risk factor since 2010 [2]. Whereas, the highest rate is in the African Region (26.6 per 100000 population), the European Region (9.3 per 100000 population) is far below from the global average rate (17.4, dashed line) as it can be seen in Figure 1. Therefore, taking into consideration the grave consequences that road accidents cause on the society, mobility and traffic security, the safety of road vehicles is of paramount importance for the governments and the automotive industry around the globe.

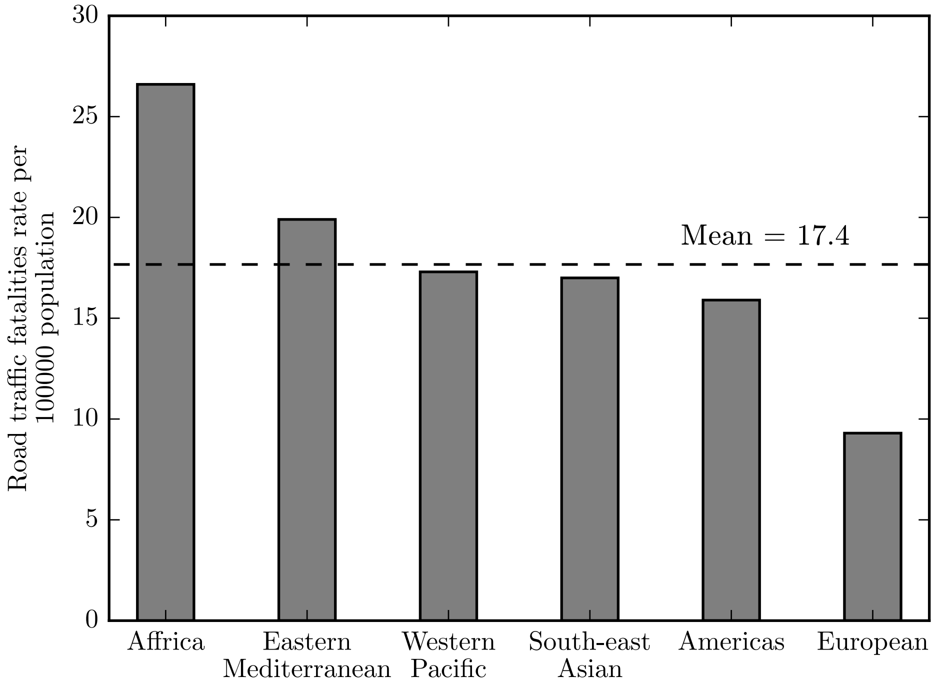

Figure 1: Road fatalities rates around the globe per 100000 population [2].

From the previous statistic, it is clear that the European Region has effective road safety programs. Proof of this is that the European Commission (EC) in its white paper “European transport policy for 2010: time to decide” of 2001 established an ambitious target of halving the number of road fatalities by 2010. This target was almost achieved with an actual reduction of approximate 42%. In 2010, a new objective of the EC for 2020 also aims to halve the number of road deaths between 2010 and 2020 [3], see Figure 2.

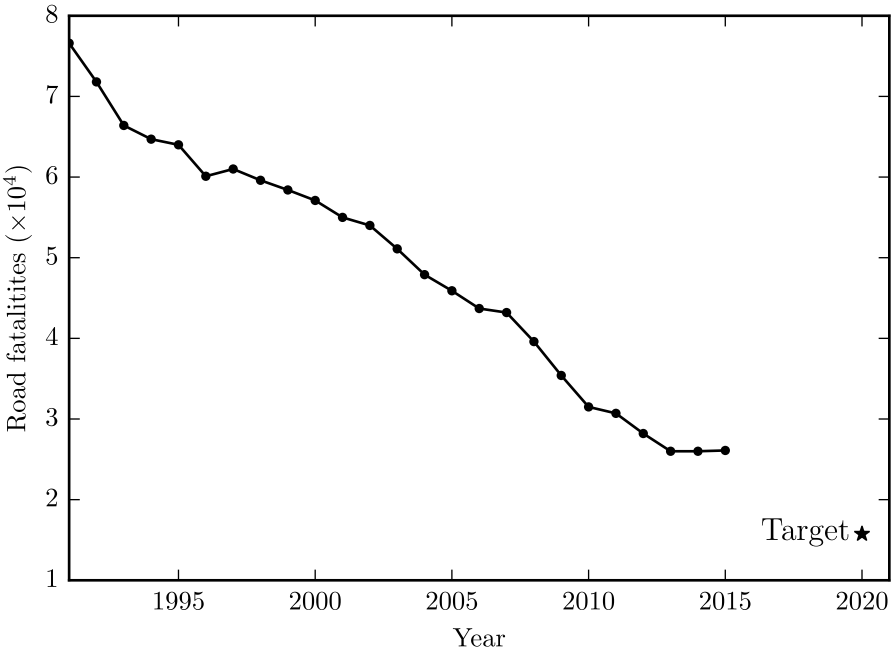

Figure 2: EU road fatalities evolution since 1991 and target for 2020 [3].

Large investments should be made by the governments and industries in order to reduce the number of road fatalities. This is particularly true in the European Union (EU), but not necessarily for the others regions, e.g. Africa and America, as it can be deduced from the statistics presented before. Consequently, effective road safety programs should be applied in all regions, especially in those with high death rates. Furthermore, about 95% of road vehicle accidents are due to human factors [4, 5], e.g. distraction, alcohol-related and over-speed. Therefore, a road safety program should include the following enhancements in:

i. road infrastructure, e.g. better road pavements and traffic signaling,
ii. road regulations, e.g. speed limitation and drastic punishments against drunk drivers.

However, road vehicle accidents are also related when the vehicle is not capable to follow the driver’s commands, e.g. driving in adverses environment conditions (raining or snowing). The reasons for this undesirable behavior involves both, when the vehicle is physically not capable of following an specific trajectory (the tires reached its limits of traction) and when the driver can not apply the suitable commands, e.g. steering and accelerate/braking, to control the vehicle. In consequence, the reduction of road vehicle fatalities also relies on the improvements of vehicle's safety. Then, the road safety program should also consider enhancements on:

iii. the vehicle mechanical design, e.g. improvements on the chassis frame (impact attenuator),

iv. vehicle safety systems that can minimize or prevent accidents, e.g. the Anti-lock Braking System (ABS).

The ABS system was the first active safety device for road vehicles. This system was introduced by Bosch in 1978 to assist drivers during heavy braking and since its introduction, new electronic safety devices were also included on road vehicles. For instance, the Electronic Stability Program (ESP) is capable of reducing in 49% the number of single vehicle accidents (only one vehicle and no other road user is involved) [6]. Consequently, see Figure 3, many companies are fitting its best selling cars with active safety technologies [7].

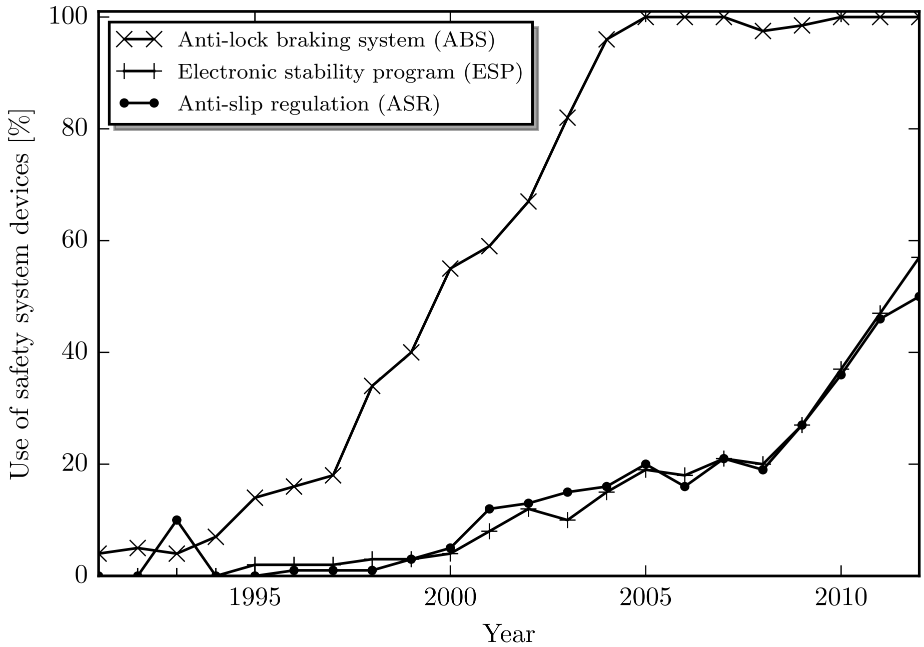

Figure 3: Active safety devices percentage of the top 50 best selling cars [7].

Evidently, the use of active safety devices in road vehicles improves the vehicle's stability and in consequence saves lives. Therefore, modern cars are equipped with many safety systems, e.g. ABS, ESP, Anti-slip Regulation (ASR), Active Front Steering (AFS), Four-wheel Steering (4WS), Tire Pressure Monitoring, Adaptive Cruise Control, Lane Keep Warning and Emergency Brake Assistant. In addition, promising vehicle applications like self-driving cars rely on safety systems due to the necessity to maintain the vehicle as safe as possible during an autonomous driving. Nevertheless, all of this safety devices act mostly independently with their own set of sensors, actuators and objectives. This configuration can introduce performance limitations from unmodeled or unexpected interactions and in the worst case, it may lead to a conflict that becomes a worse scenario to the driver [8], e.g. loss of stability. Therefore, it is important to develop an integrated control structure in order to coordinate the safety system devices of road vehicles. With this integration, between two or more safety systems, an improvement of the vehicle stability can be achieved.

Finally, due to the facts presented above, it is clear that the reduction of road vehicle fatalities constitutes the major motivation and objective of this thesis. Particularly, this aim is addressed in this project with the design of safety system devices and also of an integrated control structure to coordinate these systems in order to improve the vehicle stability in emergency situations.

1.2 Literature review and background

1.2.1 Overview of multibody systems

Multibody systems have proven itself as a well qualified and versatile approach to model and analyze discrete mechanical systems. The first international meeting about this approach was presented at the International Union of Theoretical and Applied Mechanics (IUTAM) symposium in 1977 [9]. Since then, many aspects of multibody systems were treated, e.g. formalism and computational aspect, and therefore; the foundations of this approach were being defined.

Nowadays, multibody systems play an essential role in the development of different engineering systems. Interesting areas of application include vehicle dynamics, rotor-dynamics, biomechanics, robotics and spacecraft. Furthermore, multibody models comprises rigid and/or flexible bodies, joints and massless force elements. Joints are mechanical components that define the relative motions between bodies, e.g. ball and knuckle joints. The force elements are energy transformation components that also connects bodies, e.g. springs, dampers, torsion bars and bushings. This elements can be described using linear and nonlinear relationships or look-up tables. The friction and contact phenomena are also common in mechanical systems and consequently; they may be included in the multibody model [10]. A good example of a multibody system is the quarter car model, see Figure 4. It includes common multibody elements, i.e. rigid bodies (chassis and wheel body), force elements (spring and damper), ideal joints and rigid links.

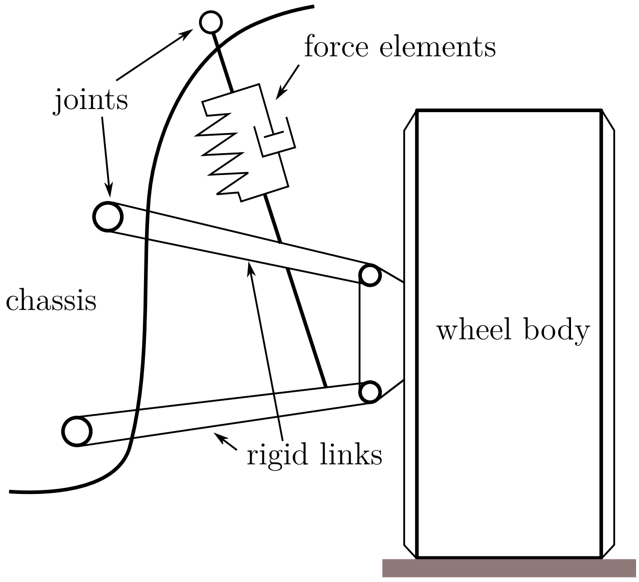

Figure 4: Common elements of a quarter-car model.

Multibody systems are commonly employed in the scientific community and industries for an early stage design of engineering products [11]. Therefore, the multibody approach and particularly multibody softwares, e.g. MSC ADAMS and MBDyn, can be understood as tools to facilitate the transfer of mathematical technology into industry [12]. In particular, multibody models are needed for:

– approximation of a dynamic behavior based on simple models, e.g. using a quarter-car model to analyze the suspension response under random road profiles;
– design and optimization of the performance of a specific part of a mechanical system, e.g. improve the suspension system kinematics for a better alignment during cornering;
– evaluation of the system's performance, e.g. stability analysis, ride comfort, critical velocities;
– forecasting the results of an experimental test in order to assist in the design of test schedules.

Nevertheless, a multibody model should describe the dynamics of the real system with enough fidelity. Consequently, a validation process of the multibody model is an essential step for any application [13, 14, 15, 16]. Generally, this validation is performed by measuring the states of interest through sensors mounted on the real system. Then, this raw sensor data is compared with its pairs obtained using numerical simulations. In addition, it is important to perform a qualitative and quantitative evaluation of both signals, i.e. the raw sensor data and the simulated ones, in order to validate properly the multibody model of the system being studied.

In vehicle dynamics, to investigate handling and ride properties, the multibody approach is commonly applied [33, 17]. Furthermore, because the scope of this thesis involves analysis of the vehicle handling and stability properties, the multibody approach fits perfectly for this type of applications.

1.2.2 The vehicle stability problem

To analyze the stability problem in road vehicles, the understanding of its physical limits is essential. This limitation is defined by the tire-road interaction forces at each tire. In this interaction areas, also called contact patch, forces and torques are produced by the adhesion of the tire rubber to the road, see Figure 5. However, in the investigation of handling and stability properties, longitudinal and lateral forces are of main importance. The longitudinal force is generated by accelerating or braking the vehicle. On the other hand, the lateral forces are produced when an steering action is performed by the driver. In addition, by steering the front wheels, the driver controls the lateral forces at the front axle and therefore, it controls the vehicle's trajectory, e.g. when negotiating a curve.

From a dynamic point of view, the vehicle responds to changes on the tire-road forces through the dynamics of its states. Particularly, two of them, i.e. the yaw rate and sideslip angle, are important for analyzing the vehicle's stability. These two states are commonly studied using the planar vehicle model, often called the "bicycle model". Figure 6 shows the vehicle coordinate system $(x - y - z)$, the yaw rate $(\dot{\psi})$ and the sideslip angle (β). The vehicle axis system is defined by ISO Standard 8855, i.e. with positive x-axis in the forward direction, positive y-axis to the driver's left and positive z-axis up. The yaw rate describes how fast the vehicle's body is rotating around its z-axis. If this state becomes too large and the driver cannot control it, then the vehicle presents an instability condition called "spin out". Therefore, restricting the yaw rate to reasonable values is a critical task for a stability control system.

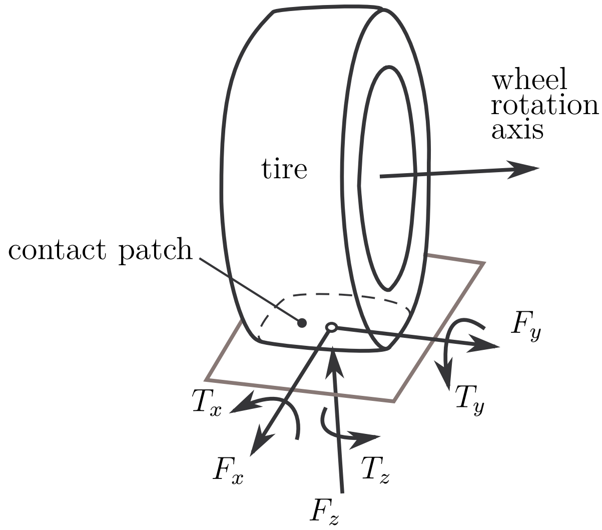

Figure 5: Tire forces and torques in the contact area.

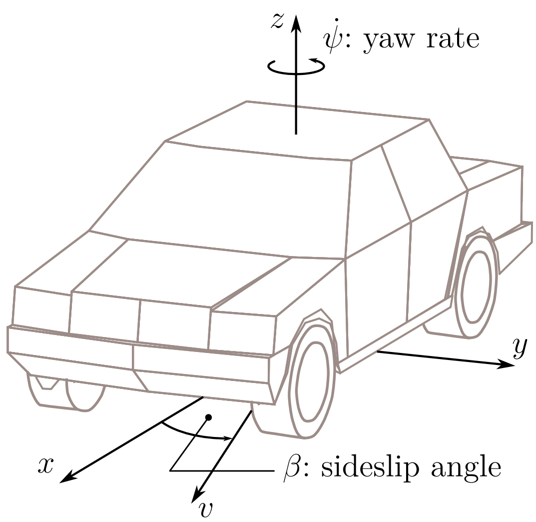

Figure 6: Coordinate system and states of the planar vehicle model.

As a consequence of the yaw rate dynamics, the direction of the vehicle's velocity (v) changes and then, a deviation from the vehicle x-axis is generated, i.e. the sideslip angle (β). In addition, the sideslip angle can be also understood as a measure of how much sideways the vehicle is traveling. Clearly, at high speeds, the sideslip angle should be zero. Nevertheless, traveling at the same speed with a large sideslip would be highly disconcerting. Consequently, keeping this state at moderate values is also a critical task for maintaining the vehicle's stability. In the scope of this thesis, the yaw rate and the sideslip angle are used to analyze and improve the stability of road vehicles in emergency situations.

The wheel body is connected to the chassis through the suspension links and therefore, the vehicle's velocity is imposed to each tire of the vehicle. This, including the yaw rate motion, produces a deformation of the tire rubber and consequently, lateral forces are generated. Actually, this is how these forces are build up in the contact patch. This deformation can be described by the so called tire slip angle (α) as illustrated in Figure 7. In addition, these forces increase with the slip angle until the limits of the tire-road friction. Furthermore, after an steering action is performed (normally on the front wheels), the rear tires also assume a slip angle and produce lateral forces. In stable driving conditions, this force balance and the vehicle reaches an equilibrium state.

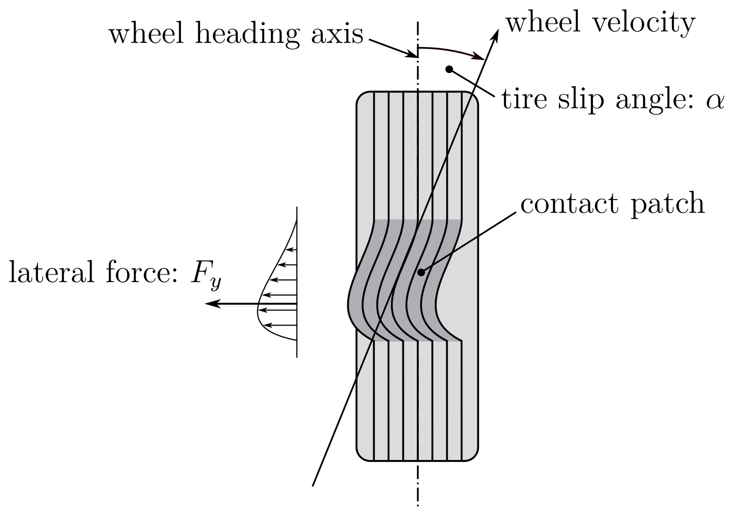

Figure 7: Lateral force and tire deformation at the contact patch.

The equilibrium state depends on the vehicle configuration, driver inputs and environment conditions. The suspension system set up, mass distribution and tire characteristics describe the vehicle configuration. Furthermore, driver inputs like steering, accelerating/braking the vehicle also affect this equilibrium. At some point, this stable state can be lost, e.g. tires begin to slide. If the front tires exceed the tire-road friction limits first, the resulting inability of control these forces is known as "understeer". In this state, the driver cannot control the vehicle's trajectory and then, it follows a path with a lager radius than the driver intends. Conversely, if the rear tires saturate before, the vehicle will turn more than the driver intends. This condition is called "oversteer" and usually results in a vehicle spin. It is also possible that tires at both axles saturate at the same time, this condition is referred as "neutral" and this is characterized by a large sideslip and constant yaw rate.

1.2.3 Stability control systems

The driver abilities are closely related to its comprehension of the vehicle dynamics [18]. In the case of an average driver, its driving skills depends on the understanding of the linear behavior of the vehicle. Therefore, when the vehicle presents an instability condition, i.e. at the limits of understeer/oversteer, the average driver can not recognize this behavior and consequently, will not be able to control the vehicle. Therefore, in these emergency situations, the stability control systems assist the driver in order to maintain the vehicle controllability.

Anti-Lock Braking System (ABS)

This system, introduced by Bosch GmbH in 1978 [19], is the first and most spread active safety device for road vehicles [7, 20]. The ABS should be capable of ensuring that the vehicle retains its handling stability and steerability under heavy braking maneuvers. This is performed by avoiding the wheels from locking up with the increasing, decreasing or maintaining of the braking pressure. By keeping the wheels rolling, the tires are capable to generate lateral forces and therefore, the driver can control the vehicle trajectory by imposing an steering angle. Additionally, the ABS should utilize the maximum available adhesion between the tire and a specific road surface, e.g. dry concrete or wet surface. Figure 8 shows the longitudinal tire force characteristic curve for different surfaces and zones of maximum force.

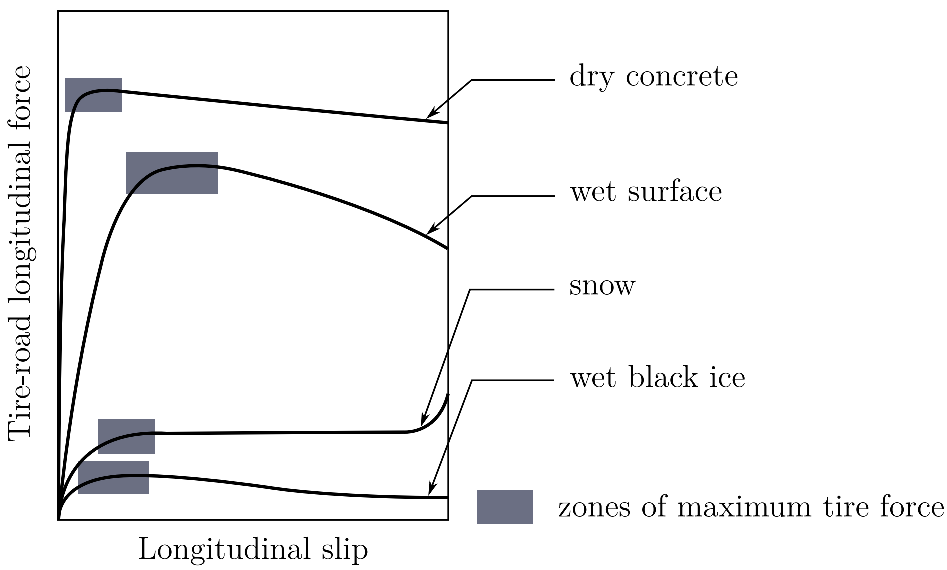

Figure 8: Typical curve of tire longitudinal force in different road surfaces and zones of maximum tire force.

Nowadays, it is very difficult to find details about the ABS algorithms used in practice. Probably, this is due to the high investment made by the automotive companies in this type of system. In the current literature, there are two approaches to model an ABS system, i.e. those based on wheel slip regulation and those based on logic switching using information of the wheel declaration.

For the methods based on wheel slip regulation, an optimal wheel slip value is required, i.e. a slip related to the maximum tire force. The longitudinal slip is employed to characterize the longitudinal tire force as illustrated in the figure above. Details about this tire state will be discussed in Chapter 4. Generally, the maximum longitudinal force, for passenger tires [19], is obtained for longitudinal slip around 0.1 and 0.2. Then, the ABS algorithm controls the actual wheel slip around this reference value. Many control strategies can be found in the literature for this aim, e.g. based on fuzzy logic [21, 22], sliding control [23, 24] and robust control strategies [25, 26]. Nevertheless, this type of ABS model has two drawbacks. Firstly, an accurate method to estimate the longitudinal vehicle speed, needed to compute the wheel slip, is still a complex problem [27, 28, 29]. Lastly, road surface properties, e.g. the coefficient of friction, are not easy to estimate and it can lead to a loss of performance due to the non-optimal wheel slip reference.

In the second class of ABS models, information of the wheel deceleration is employed to switch between control phases [30, 31, 32]. The brake pressure is increased, decreased or held depending of the current phase of the system dynamics. In general words, the control strategy is based on logic switching that depends, commonly, of many parameters that are based on heuristic arguments. Consequently, tuning these parameters might be a difficult task. However, this method has some interesting properties too. For instance, they are robust to changes in the road friction coefficient and they are able to control the wheel slip in a neighborhood of the optimal tire force. This last property is performed without using the wheel slip reference (necessary for the first class of ABS models).

Electronic Stability Program (ESP)

This active safety system was also developed by Bosch GmbH in 1995 [19] and included for the first time, in the Mercedes-Benz S-Class. The ESP is not an independent device, it incorporates the functionality of the ABS and the Traction Control System (TCS) with a stabilization control, in order to compensate the driver's overreactions. This is done by selective braking interventions and/or by reducing the engine power of a specific wheel and thus, generate a compensation moment around the vehicle's vertical axis. This selective braking is determined by the difference of the driver's intended vehicle behavior, inferred using the planar vehicle model, and measurements of the yaw rate and lateral acceleration. Figure 9 shows the ESP braking process under instability conditions, i.e. at the limits of understeer/oversteer. For instance, to avoid too much understeer, the ESP triggers the ABS system to brake the rear inside wheel in order to increase the yaw reaction. On the other hand, to avoid too much oversteer, the ESP brakes the front outside wheel in order to reduce the yaw reaction.

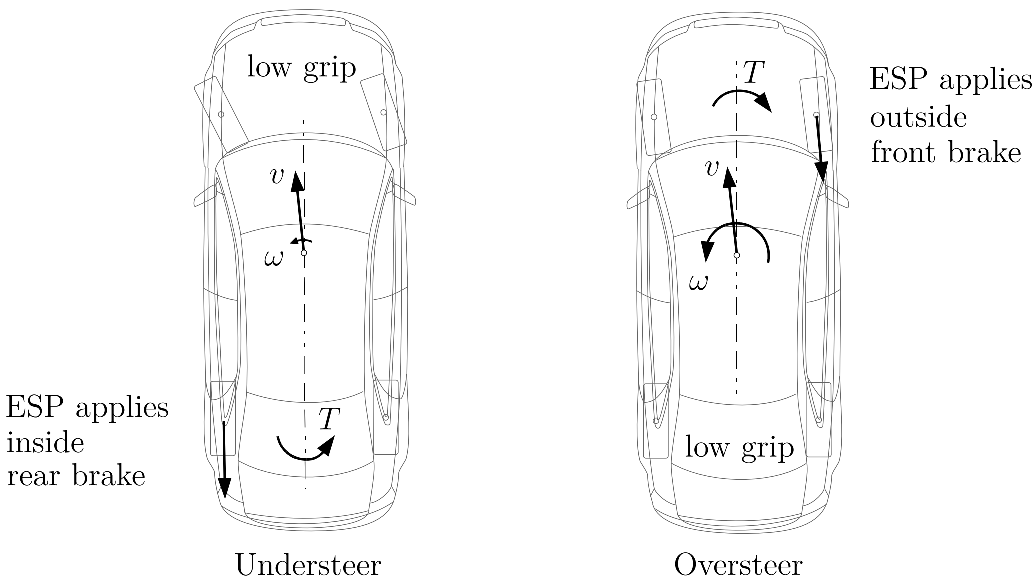

Figure 9: ESP braking concept [33].

In the literature, many authors have proposed methods to improve the vehicle dynamic response under instability conditions as presented before. In [34], Manning and Crolla made an excellent review of the approaches to address this complex problem. The survey of 68 key papers focuses on work done with three control objectives, i.e. yaw rate control, sideslip control and finally, combining both control objectives. In general, Manning and Crolla found that the yaw rate tracking control is dominated by applications of active steering systems, active driveline and suspension [35, 36].

In the case of techniques to control the sideslip angle, Manning and Crolla concluded that the use of differential braking is very common due to its effectiveness in many handling conditions [37, 38]. Finally, they concluded that brake-based systems offer the best solution for pure safety and stability objectives, i.e. tracking of yaw rate or sideslip. However, these type of techniques interfere in the vehicle longitudinal dynamics.

Four-Wheel Steering System (4WS)
The 4WS was introduced by the Japanese manufactures in the late of 1980s, one of the first models was the Nissan R31 Skyline. However, due to the high implementation cost and also for its complex mechanical system, their use has declined. Nowadays, an increasing number of vehicles are equipped with 4WS systems.

This system offers two main advantages. At low speeds, by steering the rear wheel in the opposite direction, the 4WS improves the vehicle's maneuverability because it can perform a smaller turning radius and faster cornering responses. At high speeds, turning the rear wheels in the same direction, the 4WS improves the vehicle's lateral stability. In the literature, a variety of control strategies have been proposed. Most of these techniques rely on the use of feedforward control to command the rear steering angle [39], i.e. the rear steering angle is a function of the handwheel steering angle. In [40, 41], a combination of feedforward and feedback control to command the rear wheel steering angle was proposed. The control objective defined in this work was to track the desired vehicle behavior, i.e. the desired yaw rate and sideslip angle computed using the planar vehicle model.

Active Anti-Roll Bars
The anti-roll bars are fundamental chassis components that influence vehicle's handling and ride properties. Typically, they are designed as elastic torsion bars that connect the wheel carriers of an axle and restrict the lateral inclination [33]. The stiffness of the anti-roll bars on each axle, i.e. front and rear axle, can be adjusted to change the wheel load distribution and therefore, influence the steering behavior. In addition, this chassis component only influences the suspension behavior during opposite wheel travel, i.e. during cornering or when road bumps affect only one side of the vehicle.

The active anti-roll bars are capable of adjust automatically, typically using electromechanical or hydraulic actuators, its stiffness and consequently, can influence conveniently the handling and ride vehicle properties [42, 43, 44].

1.3 Thesis contributions

This thesis describes the design and testing of safety control systems, and of an integrated control structure. This integrated system was developed to coordinate the individual controllers in order to improve the vehicle stability in emergency driving situations. Explicitly, the contributions of this thesis can be divided as follows:

1.3.1
A versatile vehicle simulation package

In this thesis, a fully non-linear and three-dimensional road vehicle model is presented. This model has 14 degrees of freedom (DOF) and it is composed by subsystems, e.g. suspension, tire and chassis. Furthermore, using this vehicle model, a simulation package denominated PyCar is build. In addition, this vehicle software includes a virtual test driver and a three-dimensional environment. The driver model is capable of following a reference trajectory and therefore, it can be used for avoiding maneuvers, e.g. when an obstacle suddenly appears in front of the vehicle. Also, it is possible to create obstacles and different types of road surfaces on the virtual environment. With these features, important road characteristics are available for simulations and consequently, critical scenarios can be emulated, e.g. run-of-road events and brake in μ-split surfaces. Additionally, PyCar has a visualizer that allows the user to see the vehicle bodies motion. This is an important tool that serves as feedback for the development of control strategies and, to gain understanding of the vehicle dynamics and its subsystems. PyCar was employed for different applications that subsequently were presented to the scientific community [45, 46].

1.3.2
Standalone vehicle control systems

In order to improve the vehicle stability in critical driving situations, modern cars are equipped with safety devices. Therefore, in the scope of this thesis, several active safety systems were designed and tested. Specifically, the Anti-Lock Braking System (ABS), the Electronic Stability Program (ESP) and the Four-Wheel Steering System (4WS) are employed. In addition, performance tests were carried out using each of those standalone safety systems to demonstrate their efficiency. In the case of the ABS, maneuvers that involve, full braking in an straight line, in a turn and in a μ-split road surfaces were used. For the ESP and 4WS, a double lane change and run-off-road maneuvers were employed. These safety controllers, together with their respective performance tests, represents a unique set of simulations that proves the importance of safety systems for the stability of road vehicles.

1.3.3
Integrated control system

The safety systems described before enhance a specific dynamic response of the vehicle. The ABS improves the vehicle steerability and stability during heavy breaking scenarios. In the case of the ESP, improvements on the lateral stability at the limits of oversteer or understeer are obtained. The 4WS enhances the vehicle maneuverability at low speeds and its lateral stability at high speeds. However, this independent structure can introduce performance limitations when two or more safety systems actuate at the same time. Therefore, an integrated structure was designed and tested to coordinate these individual controllers and to avoid performance conflicts between them. This integrated system improves the vehicle stability even when two or more active safety system are working simultaneously.

1.4 Thesis outline

As established in this chapter, this thesis presents the modeling, analysis and validation of a road vehicle multibody model. Furthermore, standalone and integrated control application are also performed and analyzed. The remaining chapters are organized as follows:

Chapter 2: Road vehicle modeling
This chapter describes the two vehicle models employed throughout the thesis. The first one, know as bicycle/planar vehicle model, is used for control design. The second model is employed for dynamic analysis and also as a reference vehicle behavior. In the last part of this chapter, the TMeasy tire model is described. Some key features of this tire model are also presented.

Chapter 3: PyCar - A versatile vehicle simulation package
In this chapter, computational aspects of the multibody vehicle model implementation are presented. Then, a validation process of the multibody model is described. Also, a first-order driver model is derived and tested. Finally, some screen-shots of the PyCar visualizer are shown.

Chapter 4: Standalone control application
The modeling and performance testing of the standalone controllers, i.e. the Anti-Lock Braking System (ABS), the Electronic Stability Program (ESP) and the Four-Wheel Steering System (4WS) are described in this chapter.

Chapter 5: Integrated control system
A brief study of the integrated vehicle control system is presented in this chapter. Then, the modeling and testing of the proposed integrated approach is described. Finally, comparisons with the vehicle using the non-integrated

control structure are illustrated and detailed.

Chapter 6: Conclusions

The thesis concludes with a description of the capabilities and limitations of PyCar. Performance analysis of the standalone controllers as well as the integrated control structure were also described in this chapter. Finally, a discussion of including more safety systems is detailed along with possibilities for futures developments of the integrated control architecture.