Chapter 1
Introduction to Active Braking Control Systems

1.1 Introduction

It can be certainly acknowledged that skidding has been a problem for as long as wheeled vehicles have existed. A 1952 paper by A.C. Gunsaulus of Goodyear Aircraft Corporation [28] defines skidding as simply the “unwanted sideways movement [of an automotive vehicle] not planned by the driver... Its prime cause is a combination of a lessened grip of the tyre on the road coupled with a sideways force that is greater than the tyre’s grip. Its effect is usually a partial or, it may be, a total loss of control of the vehicle by the driver.”

In road vehicles, the unwanted skidding phenomenon can be prevented by means of active braking control systems.

As a matter of fact, most modern road vehicles are equipped with electronic ABS. ABS can greatly improve the safety of a vehicle in extreme circumstances, since it can maximise the longitudinal tyre–road friction while keeping large lateral (directional) forces that ensure vehicle driveability. The use of automatic braking control systems has also been extended to electronic stability control (ESC) systems (see, *e.g.*, [27, 39, 45, 88]).

The design of automatic braking control systems is clearly highly dependent on the braking system characteristics and actuator performance. As is well known, standard ABS systems for wheeled vehicles equipped with traditional hydraulic actuators mainly use rule-based control logics (see, *e.g.*, [124]).

On the other hand, recent technological advances in actuators have led to both electro-hydraulic and electro-mechanical braking systems, which enable a continuous modulation of the braking torque, thereby allowing us to formulate active braking control as a classical regulation problem (see, *e.g.*, [15, 23, 41, 90]). In the field of automatic braking control, a large number of methods and approaches have been proposed in the last decade, ranging from classical regulation loops, to sliding-mode, fuzzy-neural, or hybrid architectures (see, *e.g.*, [15, 38, 39, 53, 54, 59, 60, 95, 101, 122]).

This chapter will provide an overview of ABS systems, both in terms of their historical development and of the results in this field available in the scientific literature. Further, the main features of the brake systems considered in this book are discussed and their mathematical description is provided. Finally, the chapter offers a brief discussion on recent evolutions in active chassis control systems which involve the braking controllers as subsystems to achieve the so-called global chassis control (GCC).

1.2 ABS Systems: a Historical Perspective

The current hydraulic ABS systems were conceived from systems developed for trains in the early 1900s. In particular, the first patents in the field (*An Improved Safety Device for Preventing the Jamming of the Running Wheels of Automobiles when Braking*) dates back to 1932, while a similar result was reported in a U.S. patent (*Apparatus for Preventing Wheel Sliding*) issued in 1936.

Nevertheless, none of these early devices could react quickly enough to the wheels locking to lessen the stopping distance or to provide greater vehicle control in a panic situation. The problem of skidding wheels gained new prominence during the Second World War with the success of air warfare. After the war, several aircraft producers and their subcontractors began to work on designing an anti-skid device for aircraft brakes. In 1947, the first use of anti-lock brakes on airplanes was on B-47 bombers to avoid tyre blowout on dry concrete and spin-outs on icy runways. Mechanical skid prevention devices appeared on both military and commercial planes in the early 1950s.

The first automotive use of ABS was in 1954 on a limited number of Lincoln cars which were equipped with an ABS from a French aircraft. In 1965, Jensen FF offered a mechanical ABS system developed by Dunlop. In the late 1960s, Ford, Chrysler and Cadillac offered ABS on their top-end models. These very first systems used analogue computers and vacuum-actuated modulators. Since the vacuum actuated modulators cycled very slowly, the actual vehicle stopping distance significantly increased, even though the level of safety improved and the lateral stability of the vehicle increased.

In Japan, Nissan and Toyota announced the development of an electronic ABS system, while in Germany a joint-venture between Telefunken and Bendix was trying to put an ABS system called Tekline on the market. However, the electronic design tools were not reliable yet and the analogue circuits still suffered large interferences coming from the car, which were due to large working temperature variations, humidity and most of all vibrations. These problems caused many industrial projects to fail, and legal concerns then literally put the development on hold in the U.S., while the European companies took the lead in the next 10–20 years.

In fact, in 1978 Bosch announced its *anti-blockier system* (from which the ABS acronym was coined) and this started the spread of the ABS technology in the automotive field; the modern age of ABS had begun.

By 1985, Mercedes, BMW and Audi had introduced Bosch ABS systems and Ford introduced its first Teves system. By the late 1980s, ABS systems were offered on many high-priced luxury and sports cars. Today, braking systems on most passenger cars and many light-duty vehicles have become complex, computer-controlled systems. Since the mid 1980s, vehicle manufacturers have introduced dozens of different anti-lock braking systems. These systems differ in their hardware configurations as well as in their control strategy.

Today, 50 years after their first appearance on a commercial car, these active braking control systems have become standard on all passenger cars.

Notwithstanding this historical development full of significant evolutions, the research and development of new technologies and new control strategies is far from complete. Every step forward either in braking force actuation technology and/or in the available sensors asks for a significant re-design of the main control algorithms. In particular, the forthcoming advent of EMBs and of wheel-hub electric motors with high boosting capabilities will probably be the next revolution in active braking control.

1.3 The Actuators: Main Technologies and Functional Description

The ABS available on most passenger cars are equipped with hydraulic actuators (HAB: hydraulic actuated brakes) with discrete dynamics. Such systems are depicted in Figure 1.1.

In these systems the pressure exerted by the driver on the pedal is transmitted to the hydraulic system *via* a build valve (see also Figure 1.1), which communicates with the brake cylinder. Moreover, the hydraulic system has a second valve, the dump valve (again see Figure 1.1), which can discharge the pressure and which is connected to a low pressure accumulator. A pump completes the overall system. The braking force acts on the wheel cylinder, which transmits it to the pads and, finally, to the brake discs.

According to its physical characteristics, the HAB actuator is only capable of providing three different control actions. *Increase* the brake pressure: in this case the build valve is open and the dump one closed. *Hold* the brake pressure: in this case both valves are closed, and *decrease* the brake pressure: in this case the build valve is closed and the dump one open.

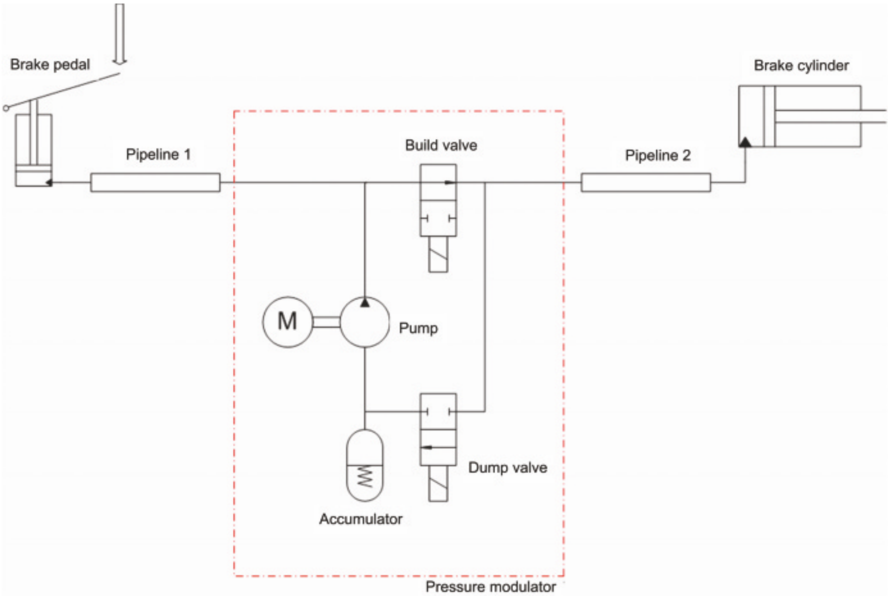

Figure 1.1 Hydraulic braking system

In dealing with this type of actuator for braking control design a static brake pad friction model is assumed, *i.e.*, the braking torque T_b is computed from the measured brake pressure p_b as

$$T_b = r_d \, \nu \, A \, p_b, \tag{1.1}$$

where r_d is the brake disc radius, ν is the (constant) brake pad friction coefficient and A is the brake piston area. Note that the brake pads friction coefficient is in general not perfectly constant over the brake life, as it varies mainly due to brake usage. However, the variation of the braking dynamic behaviour is, in general, compensated for by the servo-control loop, which regulates the brake pressure. Therefore, we assume that the braking pressure p_b considered for the conversion is the one provided as output by the servo-control of the braking system, which copes with the system uncertainties so that a constant coefficient ν can be used.

Note further that the increase and decrease pressure actions are physically limited by the actuator rate limit k, which defines the actuator performance. According to this description, the braking torque dynamics for the HAB actuator will be described as

$$\frac{\mathrm{dT_b}}{\mathrm{dt}} = u, \tag{1.2}$$

with $u = \{-k, 0, k\}$. According to the value of the control variable u, we model the three possible actuator actions, *i.e.*, $u = -k$ corresponds to the *decrease* control action, $u = 0$ corresponds to the *hold* control action and $u = k$ corresponds to the *increase* control action. The rate limit $k \in \mathbb{R}^+$ is a known parameter. Its nominal value in this book will be set to $5\,\mathrm{kN/s}$.

Note that, in some industrial braking systems, the rate at which the brake pressure increases or decreases is not perfectly constant, mainly due to the (unknown) pressure difference between each wheel brake cylinder and the main brake cylinder [124]. Nonetheless, the assumption of either a *fixed* or a *user-selectable* (within physical limits) actuator rate limit has been used in several works on rule-based ABS, as for example in [26, 49, 74]. In the control design approach discussed in this book a constant actuator rate limit is employed, which is considered to be equal for the increase and the decrease control action, in order to simplify the notation.

The HAB are characterised by a long life-cycle and high reliability, and this is the main motivation which has up to now prevented the new generation of braking systems (electro-hydraulic and electro-mechanical) to enter the mass production.

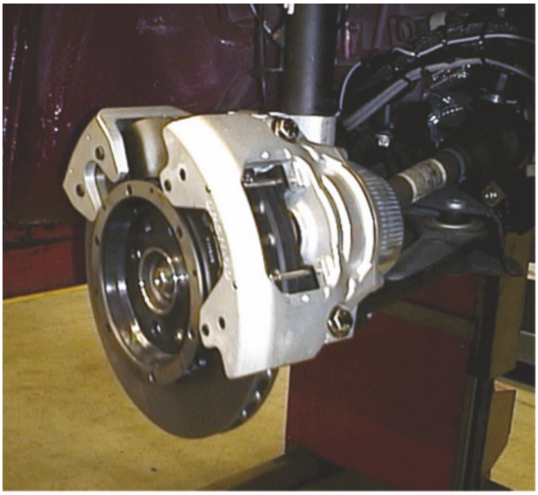

Figure 1.2 Electro-mechanical brake (courtesy of Brembo S.p.A.)

On the other hand, the disadvantage of HAB is related to ergonomic issues: with these brakes, in fact, the driver feels pressure vibrations on the brake pedal when the ABS is activated, due to the large pressure gradient in the hydraulic circuit. In fact, the HAB are wired to the brake pedal, hence their action cannot bypass that of the driver, but it is superimposed onto it.

The new generation of braking control systems will be based on either electro-hydraulic or electro-mechanical brakes; the latter will be the technology employed in upcoming *brake-by-wire* (BBW) systems.

In EHBs, a force feedback is provided at the brake pedal (so as to have the drivers feel the pressure they are exerting) and an electric signal measured *via* a position sensor is transmitted to a hydraulic unit endowed with an electronic control unit (ECU), physically connected to the *caliper* (*i.e.,* the system made of the external brake body). The EMBs are characterised by a completely *dry* electrical component system that replaces conventional actuators with electric motor-driven units (see also Figure 1.2).

Table 1.1 Comparison of braking systems actuators

	HAB	**EHB**	**EMB**
Technology	Hydraulic	Electro-hydraulic	Electro-mechanical
Force Modulation	Discrete (on/off)	Continuous	Continuous
Ergonomics	Pedal vibrations	No vibrations	No vibrations
Environmental Issues	Toxic oils	Toxic oils	No oil

With respect to the traditional brakes based on solenoid valves, the main potential benefits of EMBs are the following:

- they allow an *accurate continuous adjustment of the braking force*;
- no disturbances (pressure vibrations) are present on the brake pedal, even if the ABS system is active;
- the integration with the other active control systems is easier thanks to the electronic interface;
- there is a pollution reduction, as the toxic hydraulic oils are completely removed.

A final concise comparison between the different actuators is given in Table 1.1. It is now worth describing the main characteristics for the EMB and introducing its servo-controller basic features.

A typical EMB is shown in Figure 1.3. As can be seen, the main components of such a braking system are the following:

- an electric brushless motor;
- a planetary gear;
- a reversible ball screw;
- a piston, integral with the ball screw;
- two brake pads;
- a brake disc;
- the brake external body, called *caliper*, to which the motor and the external pad are fixed; and
- a force and/or a position sensor.

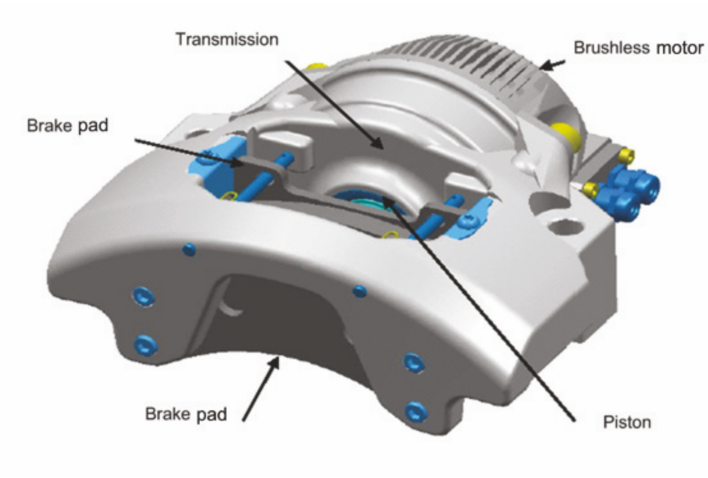

Figure 1.3 Components of a typical EMB

When a braking force is requested by the driver, an electric signal is transmitted to the motor control unit, which feeds the motor with an electric current. The motor generates a traction torque which, *via* the planetary gear and the ball screw, is scaled and converted into a linear force that moves the piston and the pad until contact with the brake disc is established.

When the pads are in contact with the disc, the piston is shifted again and this induces a deformation of the brake external body, which allows the external pad to keep contact with the disc and actuate the brake force.

When no more force is requested, the brake system must go back to the initial position; this is mainly achieved by exploiting the ball screw reversibility.

Clearly, the EMB is a highly uncertain system, mainly due to the asymmetrical friction characteristics in the pads and piston motion, the high variability of the disc-pad friction coefficient, the temperature drifts and the ageing of the brake pads.

Hence, to obtain acceptable braking performance, the EMB must be equipped with a servo-control, which counteracts all the above–mentioned sources of uncertainty and ensures repeatability of the braking manoeuvre.

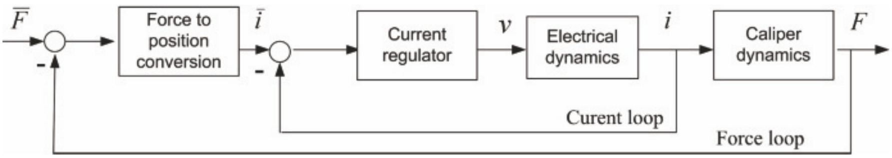

Figure 1.4 Block diagram of the EMB servo-control

This book will not directly deal with the EMB servo-control design. Hence, we only present the servo control structure, depicted in Figure 1.4, which will be needed in the next chapters.

As shown in Figure 1.4, the caliper control is usually composed of two different control loops, namely:

- a current loop, which regulates the electrical dynamics of the motor; and
- a force loop, which regulates the brake action when pads and disc are in contact.

Note that some EMBs are equipped with a position sensor (an incremental encoder placed on the electric motor shaft) instead of a force sensor (a load cell placed between the piston and the internal pad), and in this case the external loop is a position control loop. In the most sophisticated EMBs, however, there are both the position and the force sensor. These brakes are thus endowed with three nested control loops, where the position one is mostly devoted to controlling the so-called *in air* braking phase, *i.e.*, the pads and piston motion until contact with the brake disc is established. With this architecture, often the position control loop is kept active only until the force sensor measures a non-null braking force. From then on, the force loop takes care of regulating the braking force and it manages the overall manoeuvre.

In this book, a proportionality relation between braking force and braking torque is assumed, namely

$$T_b = \kappa_b F_b, \tag{1.3}$$

where F_b is the braking force and $\kappa_b \in \mathbb{R}^+$ is the proportionality constant.

For our purposes, unless otherwise stated, the servo-controlled EMB will be considered, and its closed-loop dynamics will be described as a first-order system with delay with transfer function

$$G_{\text{caliper}}(s) = \frac{\omega_{\text{act}}}{s + \omega_{\text{act}}} e^{-s\tau}, \tag{1.4}$$

with $\omega_{\text{act}} = 70$ rad/s and $\tau = 10$ ms.

Note that the delay accounts for both that possibly due to the actuator dynamics and for that due to the signal transmission introduced by the networked vehicle architecture, which manages the data transmission. Of course, the real value of the pure delay must be carefully established in any practical situation. Finally, note that the EMB, as any actuator, has physical limits which determine a saturation of the admissible braking torque values. Such a saturation must be taken into account when implementing the braking control algorithms. The lower bound on the braking torque is of course equal to 0, whereas the upper bound is braking-system dependent and must be carefully evaluated.

1.4 The X-by-wire Approach

In a vehicle, there are three main human-machine-interfaces (HMIs), which ensure the interaction between the driver and the vehicle: the steering wheel, the accelerator pedal and the braking pedal. These are usually linked to the respective physical actuators *via* mechanical or hydraulic connections.

In the *x-by-wire* (XBW) approach the links between each HMI and the vehicle are replaced by an electronic digital link. The x usually stands for the actuator of interest, thus either steer, brake, or throttle. Sometimes, in the case of the traction subsystem, the locution *drive-by-wire* is used.

There are different motivations leading automotive original equipment manufacturers (OEMs) toward XBW. A frank discussion on XBW technology cannot be but twofold: on the one hand it undeniably offers significant improvements and potentials for performance advancements; on the other, especially when tailored to safety critical vehicle systems (such as the braking system), it still has to prove its ability of providing the same safety standards of hydraulic braking circuits. As for the potential benefits of a full XBW system (those specific to the EMB have been already introduced above), we can mention the following [55]:

- Improved ride and handling. By-wire computer control of chassis dynamics allows steering, braking, and suspension to work together.
- Enhanced stability control. Sensors and controllers work together to detect and correct abnormal yaw moments that could result in spin-outs or rollovers.
- Easier integration of additional safety systems. By-wire technology provides the communication link necessary to enable automated safety systems like lane keeping and collision avoidance.
- Increased modularity. Fully functional by-wire modules reduce OEM assembly time and cost.
- Improved driver interface. The elimination of mechanical connections to the steering column gives OEMs more flexibility in designing the driver interface with regard to location, type, feel, and performance.
- Enhanced passive safety. An x-by-wire cockpit can simplify and improve occupant restraint management.
- Added flexibility. Vehicle designers will have more flexibility in the placement of hardware under the hood and in the interior to support alternative powertrains, enhance styling and improve interior functionality.
- Deployment time reduction. OEMs will be able to use a laptop computer to perform soft tuning capabilities instead of manually adjusting mechanical components.

Nonetheless, these systems must fulfill several requirements. Specifically, for brake-by-wire systems, these are the following [32]:

- Safety: after an arbitrary fault, the system must be available in a satisfying manner, *e.g.*, the brakes have to work with an adequate braking force.

- Reliability: the reliability of a by-wire system must be at least as high as that of a comparable mechanical system.
- Availability: it must be at least as high as that of the braking systems currently in use.
- Maintainability: the time interval over which the system is maintainable must be at least as long as that of the braking systems currently in use.
- Lifetime: it must be at least as long as that of the braking systems currently in use.
- Cost: it must be no more (or only slightly more) expensive than conventional braking systems.
- Compartment: it must be small enough for easy integration of the components.
- Legal aspects: they must be fulfilled, *i.e.*, to be considered safe, a brake system must provide performance within specific tolerance levels.

Finally, it is worth noting that an important principle behind by-wire systems in general is the *physical redundancy* of the system. In fact, to comply with the safety standards, it is necessary to provide at least a double redundancy of the main hardware components, so as to be able to recover from a failure.

1.5 State-of-the-art in Active Braking Control Design

The control systems evolution in the automotive field is well described by Figure 1.5 (see [55]). One may notice that since electronics has been integrated into vehicles, the advances in the development of active vehicle control systems has been inextricably linked to advances in sensors and actuators technology.

Hence, also the results available in the scientific literature are unavoidably dependent on the brake system under consideration. As a matter of fact, standard ABS systems for wheeled vehicles equipped with traditional hydraulic actuators use rule-based control logics (see, *e.g.*, [124]), as they have to deal with the on/off dynamics of the HAB system (see also Figure 1.1). On the other hand, as discussed in Section 1.3, EHB and EMB enable a continuous modulation of the braking torque, thereby allowing active braking control to be formulated as a classical regulation problem (see, *e.g.*, [15, 23, 41, 90]). In braking control systems, two output variables are usually considered for regulation purposes: wheel deceleration and wheel longitudinal slip. These output variables have characteristics which are somehow complementary.

Wheel deceleration is the controlled output traditionally used in ABS, since it can be easily measured with a simple wheel encoder (see also Appendix B); however, the dynamics of a classical regulation loop on the wheel deceleration critically depend on the road conditions. Henceforth, deceleration-based control strategies inherently require the online estimation

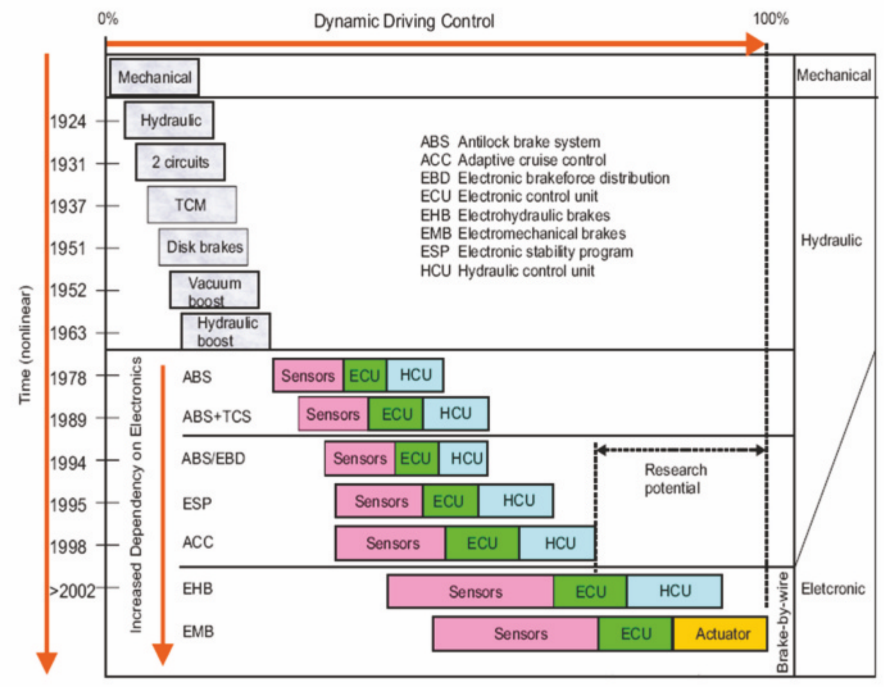

Figure 1.5 Evolution of braking systems [55, 77]

of the road characteristics; moreover, deceleration control usually is not implemented as a classical regulation loop, but heuristic threshold-based rules are used (see, *e.g.*, [88, 124]).

On the other hand, a regulation loop on the wheel longitudinal slip is simpler and dynamically robust. However, the wheel slip measurement is particularly critical since it requires the estimation of the longitudinal speed of the vehicle body, which cannot be directly measured (see Chapter 5 for a detailed treatment of this issue).

As a matter of fact, the current trend in braking control is to move from threshold-based control rules mainly based on the wheel deceleration to genuine slip control (see, *e.g.*, [15, 40, 41, 100, 131]). Slip control is particularly attractive since it can be straightforwardly and seamlessly extended from ABS to TCS and ESC applications. The challenge is to alleviate the high sensitivity of slip control to poor slip measurements, which is particularly critical at low speed and around low-slip set-points.

Moreover, to regulate the wheel slip the knowledge of vehicle speed is necessary, so that a lot of research efforts have been devoted to devise reliable and low-cost filtering and estimation algorithms. As a matter of fact, the vehicle speed can be directly measured (by means of laser beams) only for testing and for prototyping purposes. In commercial cars it must be estimated by indirect measurements, *e.g.*, by using longitudinal accelerometers or some filtering and identification tools — see, *e.g.*, [37,48,85,119] and the references cited therein. In Chapter 5 a speed estimation algorithm will be described, together with a detailed analysis of the state of the art in this specific field.

Another active research field inherently linked to active braking control systems design is that focused on the estimation of the tyre–road friction characteristics, (see, *e.g.*, [12, 24, 29, 65, 69, 92, 118, 127, 129]).

This topic will be thoroughly discussed in Chapter 8, where, together with a specific approach to the problem, we also provide some insights on the results available in the scientific literature.

1.6 Recent Evolutions: Brake-based Global Chassis Control

Traditionally, all the active control systems on board of the vehicle, such as suspension, steering and braking control systems, are designed and implemented independently from each other, and each of them is studied so as to solve *local* problems. This is due to the fact that approaching the control design for a MIMO system, of which a vehicle is a quite complex example, by local decoupled SISO loops makes the problem easier and guarantees acceptable yet suboptimal performance in the case where the couplings are weak enough. The significant work carried out with this approach has allowed the development of reliable and effective solutions for the control of the single subsystems, both comfort and safety-oriented (see, for example, the developments in active and semi-active suspensions, steering, braking and traction control systems).

Relying on these advancements, the research focus is moving toward solutions that envisage communication and coordination between the different local control systems, which comprise sensors, controllers and actuators, so as to pursue global safety and performance objectives which involve all the chassis dynamics and can aim at achieving some optimality features.

Of course, such an approach may lead to conflicting or inappropriate control objectives. As such, research efforts are being devoted to devising sound control methodologies in order to orchestrate the collaboration among these subsystems. These new control approaches are being developed within what is called global chassis control (GCC), see, *e.g.*, [3, 52, 81, 132]. Note that, however, the price to pay when working toward GCC in comparison to the traditional subsystem approach is a centralised controller of significant complexity.

While different approaches are being developed, the underlying idea is to control the global vehicle dynamical behaviour and to consider the vehicle as an object (characterised by a certain position and orientation in the space) that moves in a constrained space and can react to the different working situations *via* constrained and heterogeneous actuators.

Several solutions to active chassis stability control have been proposed in the scientific literature, whose common aim is to actively modify the vehicle dynamics by generating suitable yaw moments to restore vehicle stability when dangerous manoeuvres occur, see, *e.g.*, [1, 17, 18].

In the field of active vehicle dynamics control systems tailored to enhance both stability and handling, most of the available solutions are brake-based, see, *e.g.*, [94]; these approaches try to enhance both vehicle performance and stability during curves by imposing — *via* differential braking — an understeering or over-steering behaviour on the vehicle.

Examples of brake-based approaches can be found in [20, 25]. In [20], the overall control problem is formulated as a tracking problem, where the trajectory is specified as a desired yaw rate and longitudinal acceleration profile, which must be tracked while stabilising the roll and pitch motion. The coordination policy for the two actuators is achieved by solving a constrained optimisation problem. A similar problem within the context of autonomous vehicles is tackled in [25], where the model predictive control approach is used to design control laws acting on active front steering, active braking and active differentials aimed at ensuring that the vehicle follows a given path by controlling the front steering angle, brakes and traction at the four wheels independently, while fulfilling both physical and design constraints. Further examples are presented in [30, 121], where the problem of actuator coordination, in these cases active steering and braking, is setup as based on a dynamic control allocation approach. Specifically, [121] proposes a yaw stabilisation scheme composed of a high level module which deals with the vehicle motion control objective, *i.e.*, the computation of the yaw rate reference and the related tracking problem, and a low level module which handles the braking control for each wheel. The link between the two is ensured by an allocation module which generates the longitudinal wheel slip reference for the braking controller commands and front wheel steering angle corrections. The optimal use of the available control variables is obtained as the solution of a real-time optmisation problem.

An alternative to brake-based solutions is provided by the use of a new generation of torque biasing devices in the vehicle driveline, which can be controlled to actively distribute the driving torque between front and rear axle to improve stability and performance. On-demand torque redirection from front to rear axle can be achieved either *via* electronically-controlled differentials or *via* electronically-controlled central transfer cases, [73, 80]. These torque-biasing devices allow tuning the torque distribution so as to actively change the vehicle configuration and to make it closer to a full front-wheel-drive to pursue safety objectives, or to a four-wheel-drive to optimise performance *via* a more balanced torque distribution to the four wheels.

It is worth pointing out that the GCC has also opened the way to achieving the capability of altering, *via* an electronic control system, the car behaviour, which is in principle dictated from its mechanical layout.

From a broader viewpoint, we believe that the GCC research area will provide a first enabling key for the design a new generation of vehicles, where the driver's preferences and inclinations will be sensed by appropriate control systems and mapped onto specific control systems settings which will enable the vehicle dynamic behaviour which is closest to the driver preferences. Of course, such online vehicle personalisation must be performed while always guaranteeing and enforcing active safety.

In this challenging scenario, braking systems appear to be a strategic subsystem to employ for different control objectives and this motivates us to describe in this book different solutions to the braking control problem which offer specific advantages and may be selected also according to higher level control goals.

1.7 Summary

In this chapter the active braking control problem was introduced and discussed, starting from an historical perspective. Further, the available brake technologies were presented, with specific emphasis on the hydraulic and electro-mechanical brakes, which will be those considered in the design of the control approaches presented in this book. Moreover, the context of XBW has been outlined, highlighting its differences with respect to the current technology and its potential benefits.

Finally, a perspective on the future evolution of braking systems within the context of GCC systems has been provided, to motivate the fact that a thorough understanding of braking control offers the way to tackle and solve new and complex control problems.

Further, a new interesting stream of research both in braking control systems and brake-based GCC systems will be initiated by the new challenges posed by (fully or partially) electric vehicles and actuators. In this context, in fact, energy management and optimisation issues must be considered explicitly also in the control design phase, and the link between the two is one of the new research issues, which will deserve lot of attention in the near future.