4
Vehicle standalone control systems

In this section, an overview of the main safety systems for road vehicles is presented. The focus of this section is the modeling and requirements of these systems as well as their performance analysis. Moreover, for all the simulations presented in this section, a full-size car was employed. Characteristic parameters of this type of vehicles are summarized in Table 8. In addition, this type of vehicles has an understeer steering tendency and becomes more understeer at high lateral acceleration in order to improve the vehicle's stability at the limits, see Appendix B.2. For simulations that considers on- and off-road surfaces, these areas are characterized by coefficients of friction of $\mu = 1.0$ and $\mu = 0.4$ respectively and the road is located 5 cm above the off-road area.

Table 8: Full-size vehicle: overall characteristic parameters.

Parameter	**Value**	**Units**
Mass	2127.8	kg
Inertia at COG	$\begin{bmatrix} 585.9 & 0.0 & 2.4 \\ 0.0 & 3086.4 & 0.0 \\ 2.4 & 0.0 & 3358.3 \end{bmatrix}$	$kg \times m^2$
Wheel base ratio	$l_f/l_r = 1.50/1.40$	m
Height of COG	0.55	m
Track width	front: 1.53, rear: 1.52	m

4.1
Antilock braking system - ABS

As detailed in the Subsection 1.2.3, the ABS system is the most spread and first active safety device for road vehicles [7, 19]. A simple closed-loop control scheme for commercial ABS systems is illustrated in Fig. 27. In general, the ABS device involve many components, e.g. the wheel speed sensors, the electronic control unit (ECU), the hydraulic modulator and the caliper assembly. Each of them plays an essential role in order to prevent the wheels to lock up during heavy braking scenarios.

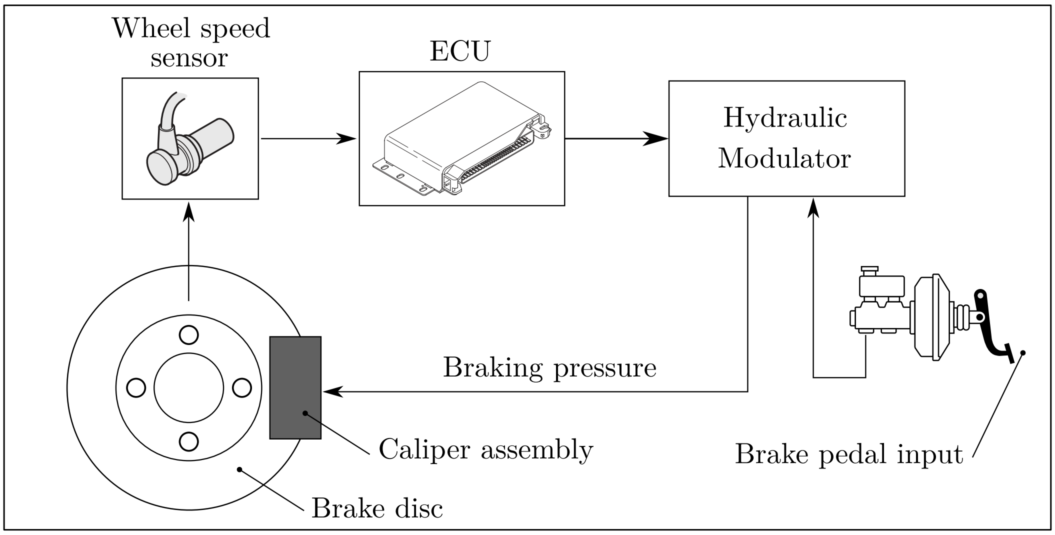


Figure 27: A simple closed-loop scheme of a commercial ABS system.

Wheel speed sensor – It measures the angular velocity of the wheel and pass the electrical signal to the ECU. This information is used to compute the degree of slip between the tire and the road contact area, i.e. detect if the wheel is about to lock up.

Electronic control unit (ECU) – This electronic component calculate the degree of slip and use this information to compute the required control signal through the ABS algorithm. Then, the ECU send this signal to the hydraulic modulator in order to increase, hold or decrease the braking torque of a specific wheel.

Hydraulic modulator – Components of a commercial hydraulic modulator are shown in Fig. 28. This hydraulic system is a set of solenoids that can open and close the brake line between the master cylinder (3) and the caliper assembly (5). In this system is where the braking pressure is built, distributed and regulated according to the degree of slip computed by the ECU. In normal driving conditions, the solenoid valves are set to `pressure application`, i.e. the inlet valve (4) is opened and the outlet valve (6) is closed. Then, under braking, a rise on the brake pressure is achieved due to the direct connection between the master cylinder (3) and the caliper assembly (5). Moreover, if the ECU detects an increassing on the degree of slip (risk of locking increases), the valves are set to `maintain pressure`, i.e. the inlet (4) and the outlet (6) valves are closed and therefore; the pressure is maintained on the brake line. Finally, if a reduction of the braking pressure is necessary, the valves are set to `release pressure`, i.e. the inlet valve is still closed and the outlet valve is opened and the pressure is released to the return bump (8) and the accumulator

(7).

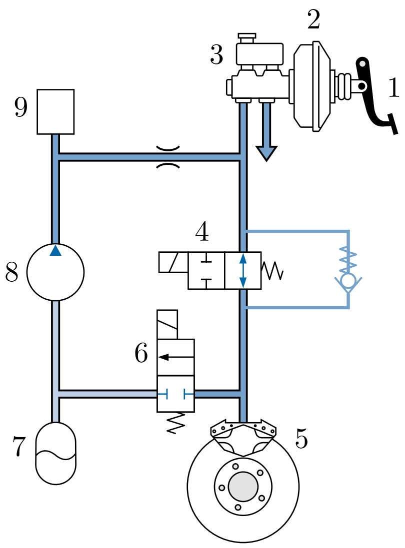
Schematic of a Hydraulic Modulator	**Common components**
	1. Brake pedal 2. Brake booster 3. Master cylinder and reservoir 4. Inlet valve 5. Caliper assembly 6. Outlet valve 7. Brake-fluid accumulator 8. Return pump 9. Damping chamber

Figure 28: Schematic of a Hydraulic modulator with 2/2 solenoid valves of a Bosch GmbH ABS system [19].

4.1.1 Requirements

A commercial ABS system must meet a reasonable number of requirements under braking and in all types of road surfaces. The most important one is related to the handling stability and steerability [19, 70]. In a car equipped with the ABS system, it should be possible for the driver to control the vehicle under unfavorable braking conditions, e.g. slippery road surfaces. These unfavorable conditions can be summarized as follows:

- Low grip road surfaces – use the maximum possible grip to generated the braking force, e.g. slippery road surfaces or black ice,
- Changes in road surfaces grip (split areas) – the system should be adapted rapidly to the changes in the road adhesion properties, e.g. μ-split areas.

4.1.2 Control design

The control strategy for an ABS model need to take into account the requirements detailed above. In the scope of this thesis, a simple ON-OFF switch control strategy was employed. However, this type of controllers produce unrealistic effects because the brake pressure/torque is performing at very high frequencies. Therefore, a delay effect need to be considered in order to obtain practical results. This is done by including the dynamics that arise from the hydraulic components. The hydraulic model employed for the ABS system is a second-order model as depicted in Figure 29.

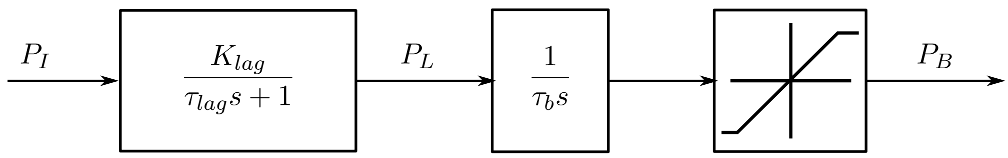


Figure 29: Hydraulic model.

In the hydraulic model presented above, P_I represents the input pressure commanded by the controller, P_L is the pressure after the hydraulic line, i.e. the pressure after overcoming the inertia and resistance of the hydraulic line, and lastly, P_B represents the braking pressure, this pressure is built up through an integrator (hydraulic capacitor). In addition, it is a good practice to include a saturation to limit the pressure output.

Additionally to the hydraulic dynamic presented before, the ABS model design process also consider a single wheel dynamics as illustrated in Figure 30.

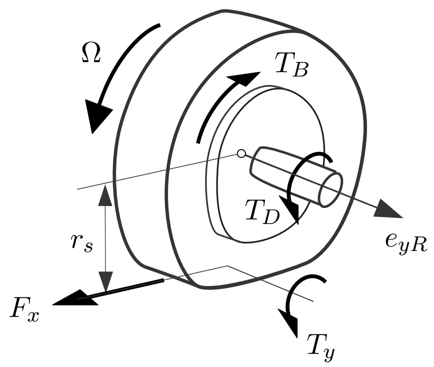


Figure 30: Wheel dynamics.

The dynamics of the wheel rotation is governed by the following equation

$$\Theta\dot{\Omega} = T_D - T_B - r_s F_x + T_y \tag{4-1}$$

where Θ is the wheel inertial around its rotation axis e_{yR}, T_D is the driving torque, T_B is the braking torque, F_x is the longitudinal force at the contact area, r_s is the static tire radius, and T_y is the rolling resistance. In addition, T_y is usually small in comparison to the other terms and consequently, it can be neglected [33].

Considering a braking scenario, i.e. $T_D = 0$, and also employing the TMeasy model (described in Section 2) to calculate the longitudinal tire force F_x, the time derivative of the wheel angular velocity $\dot{\Omega}$ can be defined as follows

$$\dot{\Omega} = \frac{-T_B - r_s F_x}{\Theta}. \tag{4-2}$$

and the longitudinal acceleration of the wheel is obtained via

$$\dot{v}_x = \frac{F_x}{m_w} \tag{4-3}$$

where m_W represent the mass of the wheel. Finally, the equations (4-2) and (4-3) describe the wheel dynamics in pure braking scenarios.

The ABS algorithm consider a slip reference that depends of the tire and the road condition. This longitudinal slip is defined via

$$s_x = -\frac{(v_x - \Omega r_D)}{|\Omega| r_D} \tag{4-4}$$

In general, for passenger tires, the reference slip is between 0.10 and 0.20. Considering this reference slip value, it is possible to define the ABS algorithm as follows

$$\dot{u} = \begin{cases} \dot{u}_{min} & \text{if} \quad s_x > s_{x,\text{ref}} \\ \dot{u}_{max} & \text{if} \quad s_x < s_{x,\text{ref}} \end{cases} \tag{4-5}$$

where u represent the pressure input defined by the driver's brake action and $\dot{u}$ its variation, $\dot{u}_{min}$ and $\dot{u}_{max}$ are the minimum and maximum pressure rate respectively.

Finally, considering the hydraulic and the wheel dynamics as well as the ABS ON-OFF algorithm, the ABS control structure can be depicted as shown in Figure 31. Furthermore, the brake efficiency γ_b is also considered within the ABS control loop. This parameter, that represents the gain between the braking pressure and torque, is drastically depending on the temperature on the brake disc [31]. However, for the sake of simplification, a constant brake efficiency is assumed.

In order to show the effects of considering the hydraulic model, simulations including and neglecting this dynamics were realized. The simulation is performed using a single wheel with a initial longitudinal speed of 80 km/h and then it is fully braked at $t = 0.05\,s$. In addition, it is considered a road surface

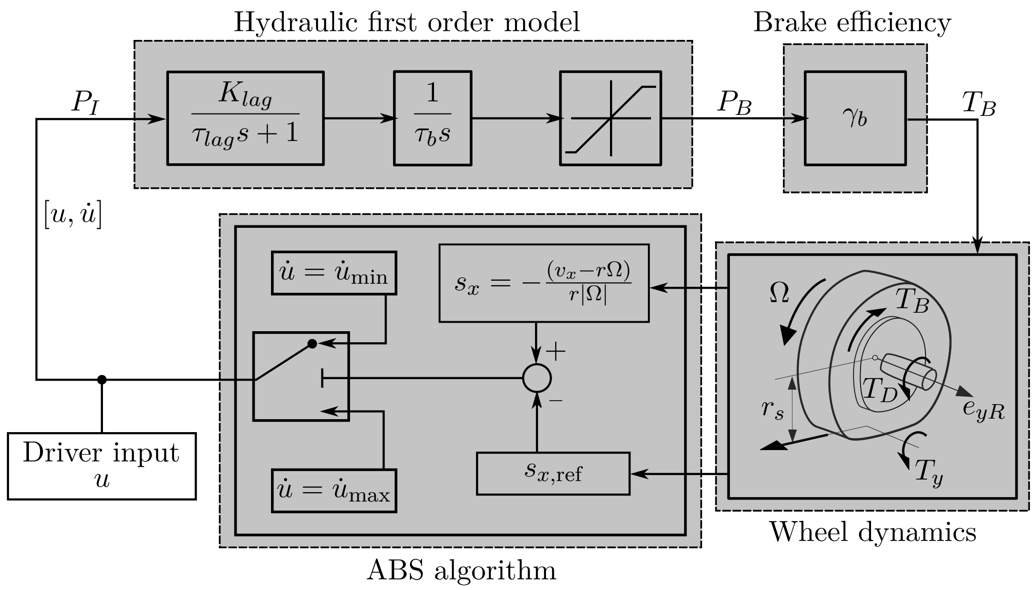


Figure 31: ABS control loop structure.

with coefficient of friction $\mu = 1.0$. The parameters of the ABS controller are defined in Table 9 and the parameters of the wheel and hydraulic model used in these simulations are summarized in Table 10.

Table 9: ABS model parameters.

ABS parameters			
Parameter	**Symbol**	**Value**	**Unit**
Reference slip	$s_{x,\mathrm{ref}}$	0.1	-
Minimum pressure rate	$\dot{u}_{min}$	-500	bar/s
Maximum pressure rate	$\dot{u}_{max}$	+400	bar/s

Table 10: Wheel and hydraulic parameters.

Wheel			
Parameter	**Symbol**	**Value**	**Unit**
Mass	m	350	kg
z-axis inertia	Θ	1.2	$kg \times m^2$
Static radius	r_s	0.3	m
Hydraulic line			
Gain	K_{lag}	0.689	bar
Delay	τ_{lag}	0.01	s
Build-up delay	τ_b	1.0	s
Maximum brake pressure	$P_{B,max}$	103.42	bar
Brake efficiency	γ	30	N.m/bar

As can be seen in Figure 32, the hydraulic model introduce a delay effect in building up the braking pressure. This can be noticed between $t = 0\,s$ and $t = 0.5\,s$ in every plot of this figure, i.e. the braking torque, the longitudinal slip, the speeds and the normalized longitudinal acceleration. Moreover, by including the hydraulic dynamics the braking torque varies at moderate frequencies, i.e. more practical results, as can be seen in the top left plot of the same figure. The longitudinal slip is controlled by the ABS algorithm around the reference value ($s_{x,\text{ref}} = 0.1$) as can be noticed in the bottom left plot. The longitudinal acceleration is normalized and with the proposed ABS algorithm, the maximum available deceleration is achieved, i.e. $a_{max} = \pm\mu g$ with $\mu = 1.0$, as shown in the bottom right plot. Finally, it can be noticed that the wheel does not lock during braking as shown in the top left plot. This is demonstrated by the oscillation of the wheel circumferential speed during the braking maneuver.

4.1.3 Performance tests

Braking in a straight line – this maneuver is one of the most common tests to analyze the brake system performance. Therefore, performing this maneuver with two full-size cars (parameters summarized in Table 8), the effectiveness of the ABS model described before is proved. For this simulation, an initial vehicle speed of 90 km/h and a full braking at $t = 6\,s$ are considered. Furthermore, the vehicle equipped with the ABS model is defined as ABS-ON and the one without the ABS model is denominated as ABS-OFF.

With the ABS-OFF, all wheels are locking instantly as we can see in the upper plot (dashed lines) of Figure 33. On the other hand, with the ABS-ON, the wheels are still rolling (same plot, solid line) and then, it results in a controlled longitudinal slip $s_{x1} \approx -0.1$, see bottom plot (solid lines) of Figure 33. In addition, with the ABS-ON, the vehicle is reaching decelerations up to $\frac{\dot{v}_x}{g} = 1.0$, bottom right plot (solid line) of Figure 34, which is the limit imposed by the coefficient of friction of the road ($\mu = 1.0$). Finally, the braking distance achieved by the vehicle equipped with the ABS model proposed in this thesis, i.e. ABS-ON, is shorter than the distance achieved by the vehicle without ABS, as can be seen in the multi-frame shots of Figure 33.

The states of the hydraulic system are shown in the top plots of Figure 34. As can be noticed, both states, i.e. the input (controlled) u and the output (braking) pressure P_b, varies at moderate frequencies. It can be concluded that, by considering the hydraulic system into the control loop of the ABS model, realistic results can be achieved.

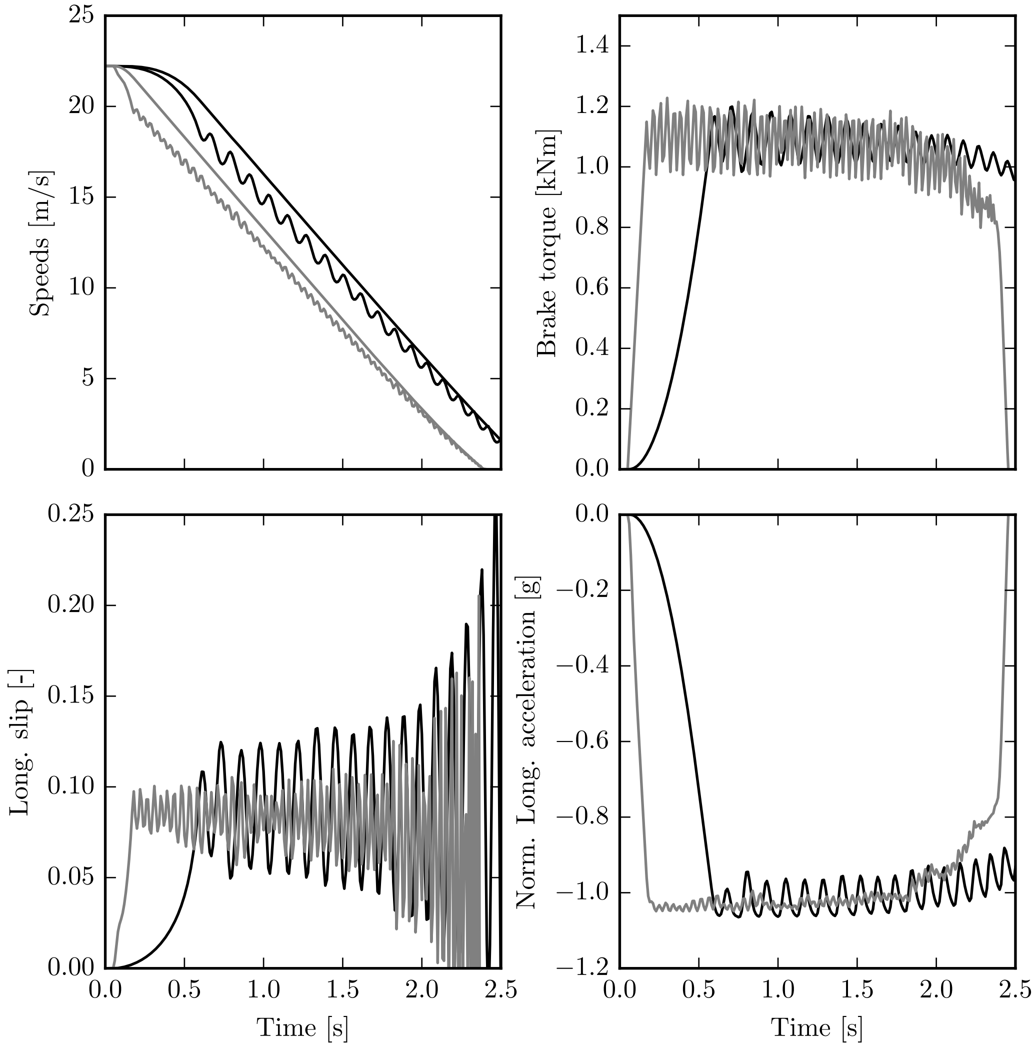


Figure 32: Single wheel states during braking: with hydraulic dynamics (black line) and without hydraulic dynamics (gray line).

Braking in a curve – this last maneuver was built in order to prove the gain in stability using the ABS model. In this simulation, the vehicle is driving in a straight line and at $t = 5.7\,s$ a steering wheel of 30^o is applied and then, at $t = 6.0\,s$, the brakes are triggered. With the ABS-OFF, the wheels are locked by the braking torque. Therefore, the vehicle follows a straight trajectory because the front wheels are not capable to generate lateral forces. In the case of ABS-ON, the vehicle follows the driver's intentions because the front wheels are not locked completely and then, it can generate lateral forces. These results are shown on the multi-frame shots of the trajectories in Figure 35.

Finally, it can be concluded that, the ABS model described before improve the handling stability and steerability of road vehicles.

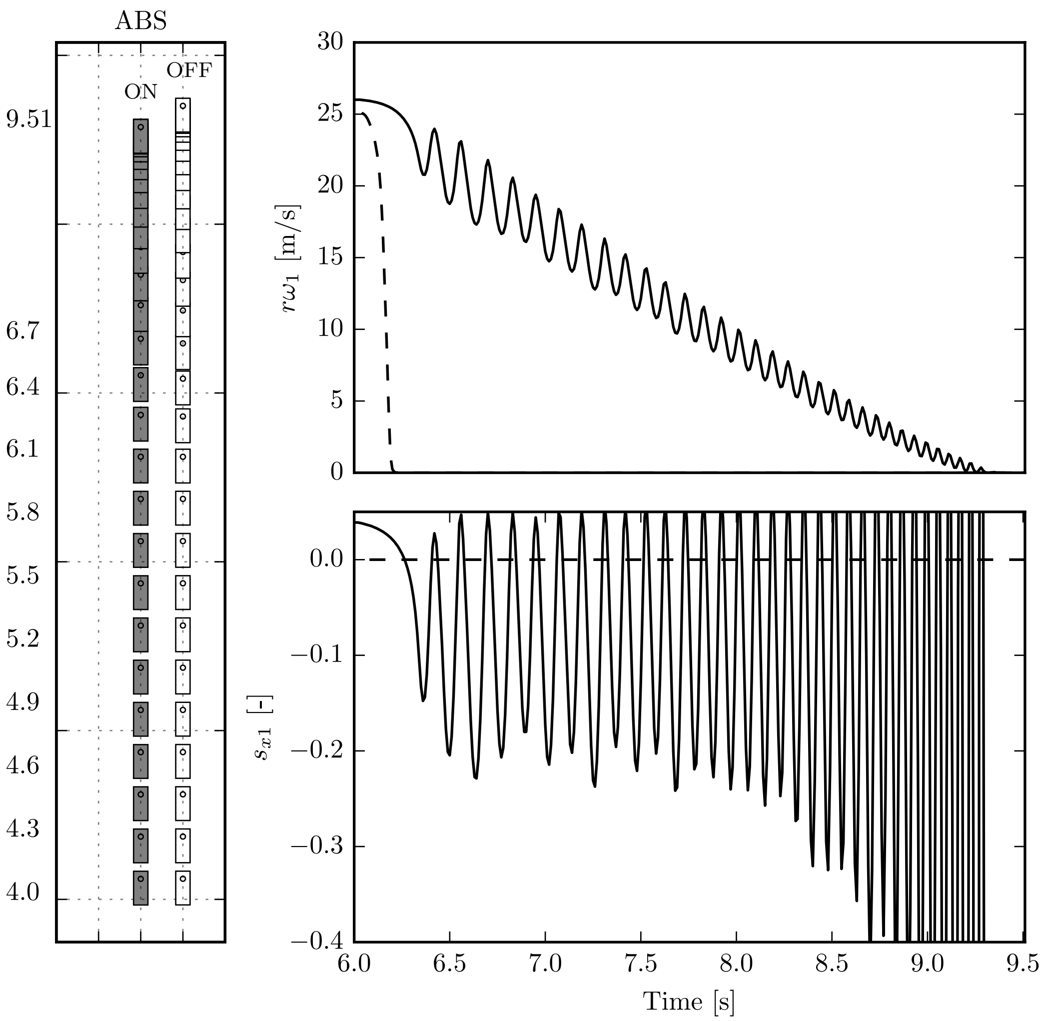


Figure 33: Braking in a straight line test: solid line (–): ABS-ON, dashed line (- -) ABS-OFF. **Top plot:** circumferential speeds of front left wheel. **Bottom plot:** longitudinal slip of the same wheel. **Multi-frame shots:** trajectory of both vehicles.

4.2 Electronic stability program - ESP

In demanding driving situations, e.g. to avoid an obstacle that suddenly appears in front of the vehicle, see Fig. 36, an average driver will perform sharp steering maneuvers. Due to this panic reaction, fast changes on the steering wheel are performed, e.g. first a right-turn ($\dot{\delta}_w < 0$) and quickly a left-turn ($\dot{\delta}_w > 0$), see phase 1 and 2 of Fig. 36. After avoiding the obstacle, the driver try to back to the road and again, fast changes on the steering wheel are imposed (phase 3 and 4). Generally, at this point, the vehicle reach its physical limits due to the changes on the road surface properties (run-off-road), the vehicle's velocity and the steering wheel angle. Therefore, the

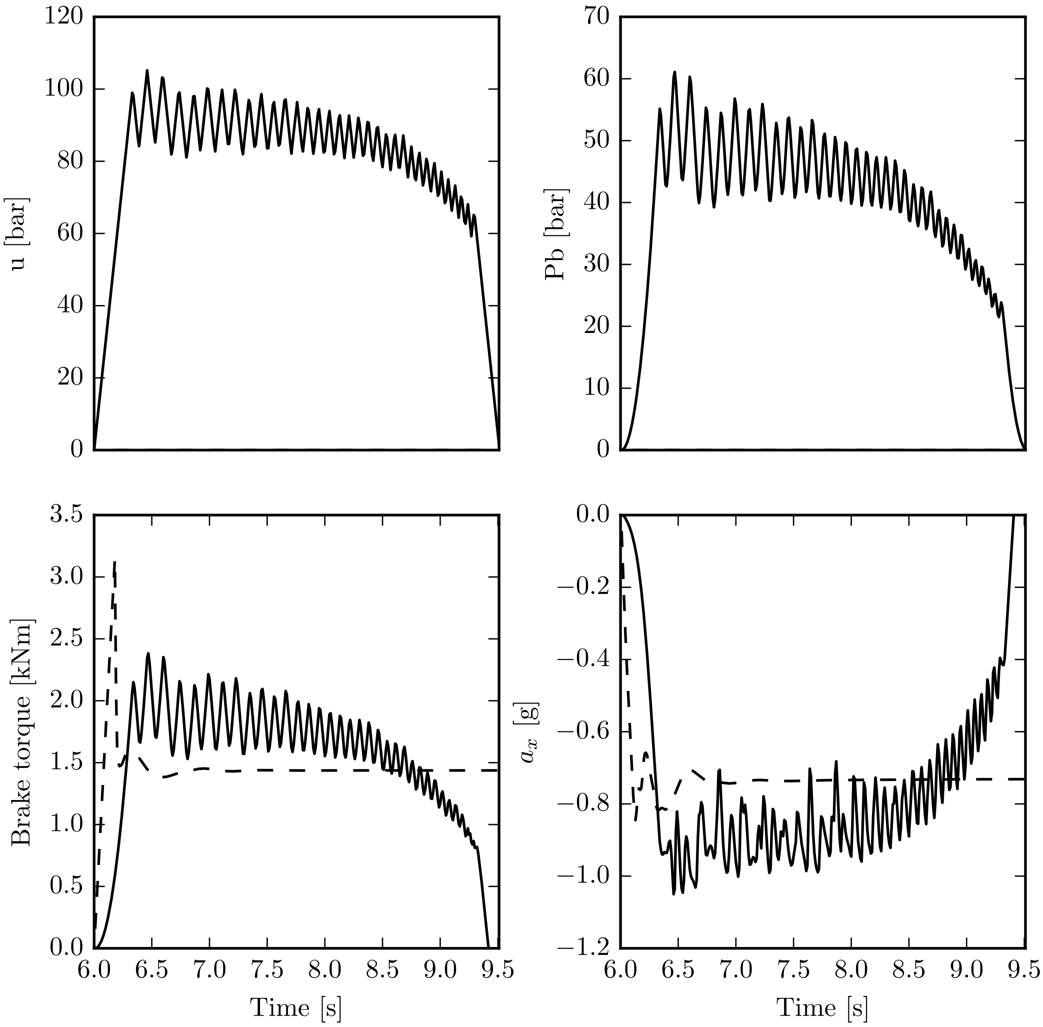


Figure 34: Braking in a straight line test: solid line (–): ABS-ON, dashed line (- -) ABS-OFF. **Top:** input u and output pressure P_b of the hydraulic system. **Bottom:** brake torque and normalized longitudinal acceleration.

vehicle become uncontrollable (phase 5) and consequently; it start to skidding and breakaway. In addition, this instability condition is characterized by a large sideslip angle ($\beta > 1$), i.e. large deviation of the vehicle's longitudinal axis x from its velocity v.

In order to improve vehicle handling and stability in demanding scenarios, as described above, a control device to assist the driver is essential. This active safety system was 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/or of the traction control system (TCS) with a stabilization control, in order to compensate the driver's overreactions. This is done by a selective braking interventions and/or by reducing the engine power of a specific wheel and thus, generate a

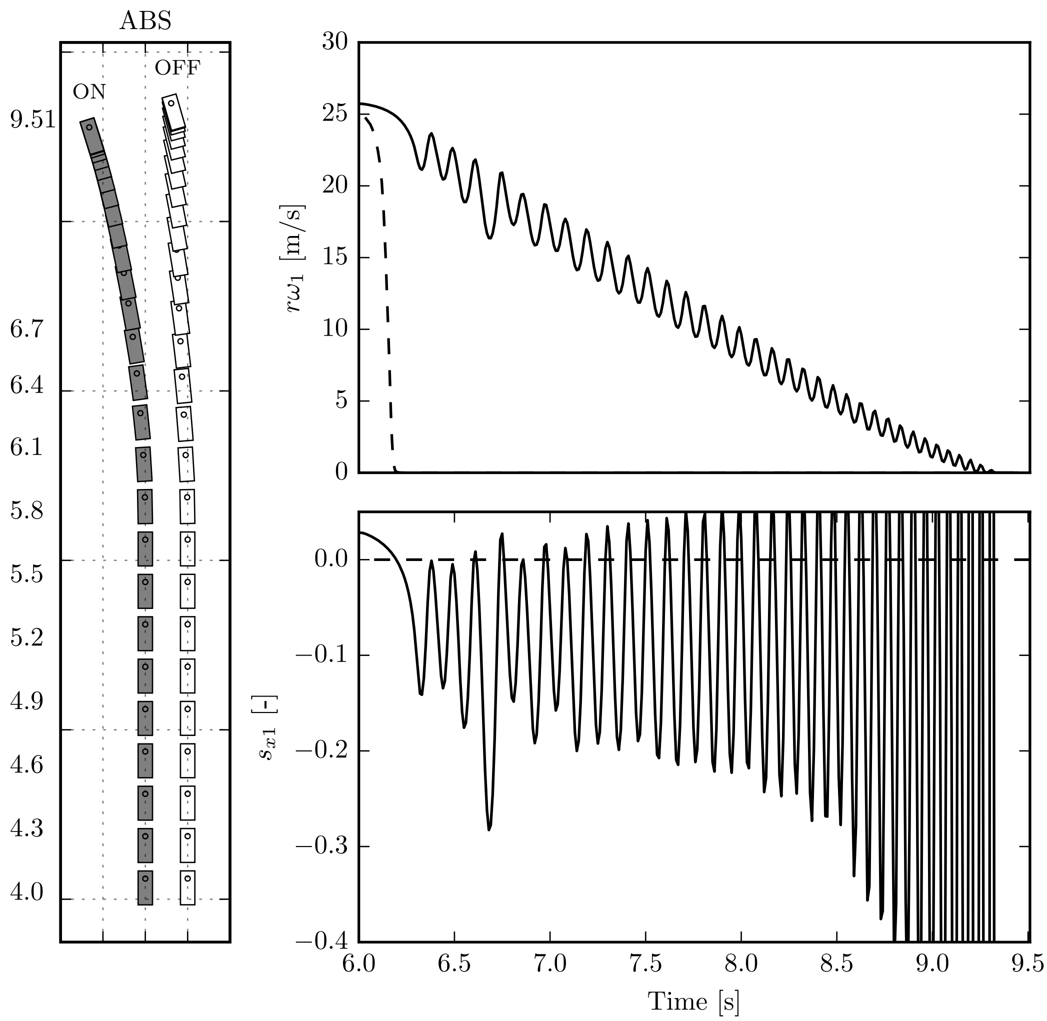


Figure 35: Braking in a curve test: solid line (–): ABS-ON, dashed line (- -) ABS-OFF. **Top plot:** circumferential speeds of front left wheel. **Bottom plot:** longitudinal slip of the same wheel. **Multi-frame shots:** trajectory of both vehicles.

compensation moment around the vehicle's vertical axis. The ESP system use information of the current state of the vehicle in order to compute, trough a mathematical procedure (algorithm), the control signal (selective braking). These informations are obtained by sensors, e.g. the steering angle, wheel speeds, yaw rate and lateral acceleration sensors. As mentioned before, the ESP is a closed-loop system that incorporates the functionality of the ABS and the TCS. Therefore, some actuators and sensors of the ABS system are also used by the ESP. Fig. 37 displays the common components of a commercial Bosch ESP® technology.

4.2.1

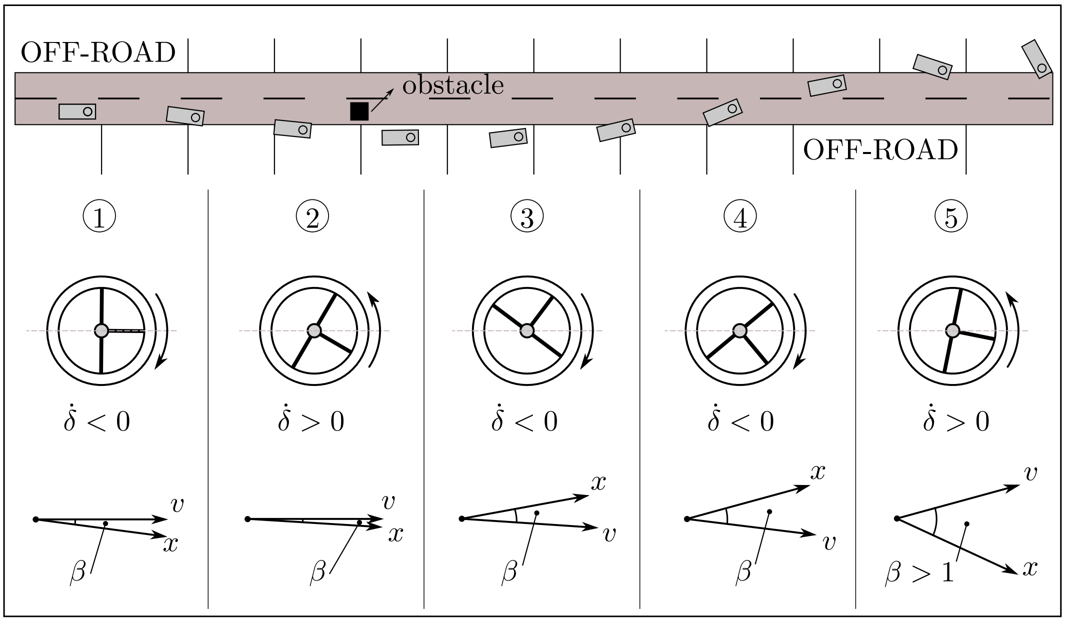


Figure 36: Lateral dynamic response of a road vehicle during an avoiding maneuver at high speeds [45].

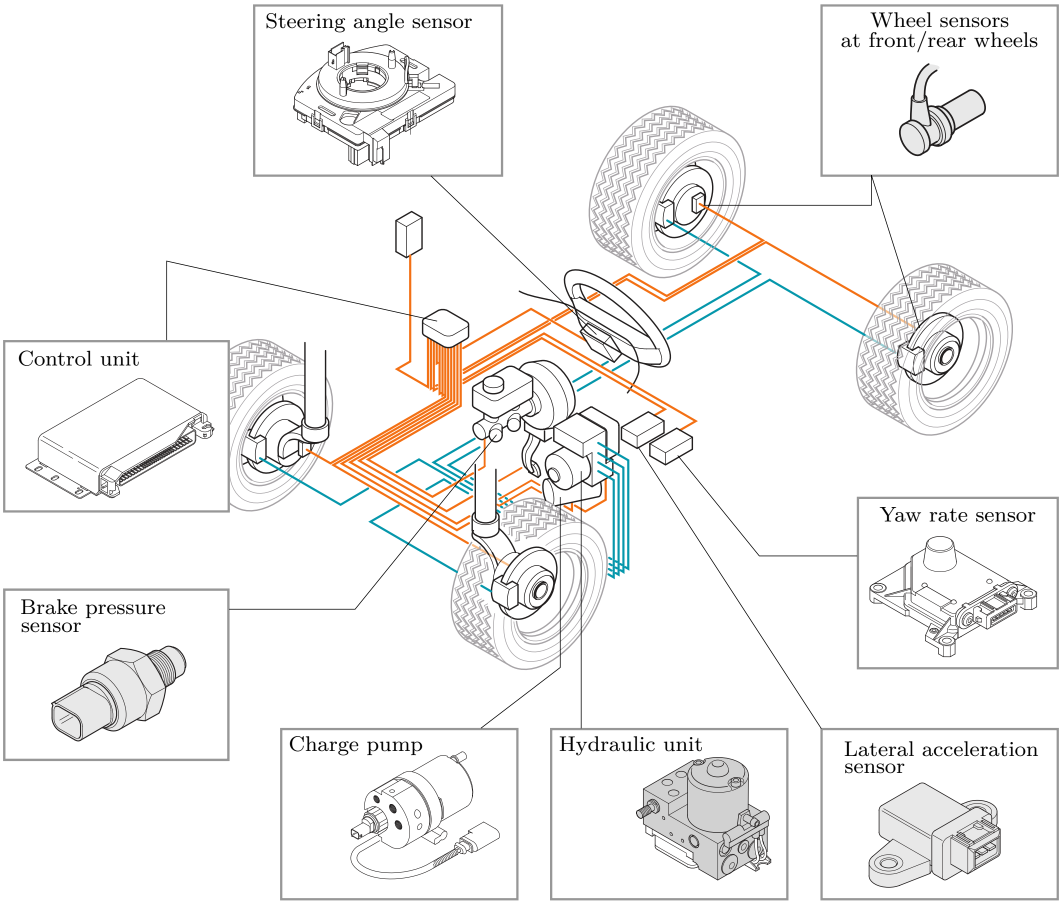


Figure 37: Common components of a commercial Bosch ESP® [66].

Requirements

A commercial ESP system must meet a number of requirements in order to have a reasonable performance in a diversity of demanding driving situations.

These requirements can be summarized as follows:

- Increase the vehicle stability at the limits of traction, e.g. when the vehicle performs a drastic maneuver (avoid an obstacle at high speeds), to diminish or avoid the danger of skidding and/or breakaway,
- Improve the directional vehicle stability, i.e. the ESP should assist the driver in maintain the vehicle under control in critical driving scenarios.

4.2.2
Control design

An ESP model need to consider the requirements detailed above. In order to define the current state of the vehicle, a comparison with the simple handling model defined in Equation (2-19) was performed. The states of this model are the desired ones. Then, by considering the difference between the desired yaw rate $\dot{\psi}_d$ and the actual one $\dot{\psi}$, the vehicle tendency is estimated and therefore, a braking torque is applied to a selected wheel. The ESP control process is illustrated in Figure 38.

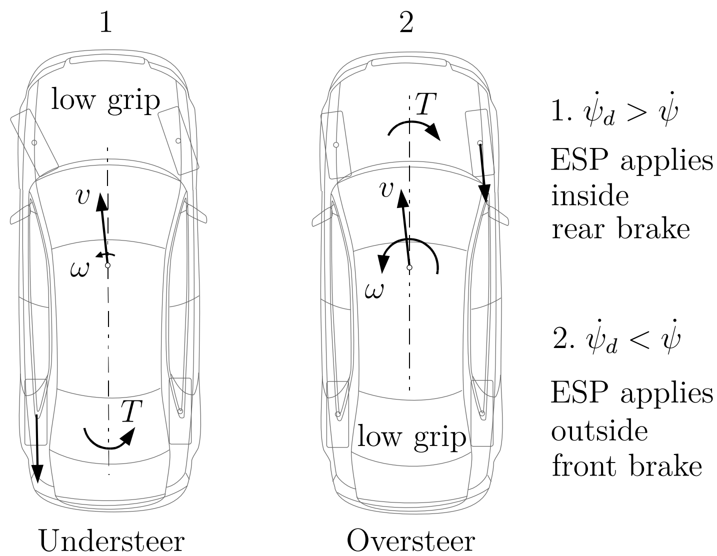


Figure 38: ESP braking concept.

4.2.3
Performance test

In Figure 39, two simulations are compared. The solid black line indicates the results of an avoidance maneuver with ESP-ON, the gray line considers the same maneuver with ESP-OFF. At the beginning of the avoidance maneuver $t \approx 4\,s$, an understeer tendency is estimated by the ESP algorithm and in consequence, the ESP triggers the ABS system to brake the rear right wheel as can be seen in the bottom right plot of Figure 40. After that, the vehicle goes off-road and then the driver tries to maintain the vehicle as close as possible to the road surface. During this maneuver, the driver applied a steering angle at approximately $t = 5$ to avoid the obstacle, at this time the ESP brakes the rear left wheel in order to maintain the vehicle stable as can be seen on the bottom left plot of Figure 40. After this scenario, the driver tries to back to the road and again, the ESP brakes the front right wheel at $t \approx 5.9$ in order to maintain the vehicle stable, see top right plot of Figure 40. Also, during all the avoiding maneuver, the yaw rate and the lateral acceleration, see top and bottom plots of Figure 39 are maintained in a safe range on the vehicle equipped with the ESP model proposed in this thesis. Finally, ESP assisted the driver to maintain the desired path as indicated by the multi-frame shot at the very left of Figure 39.

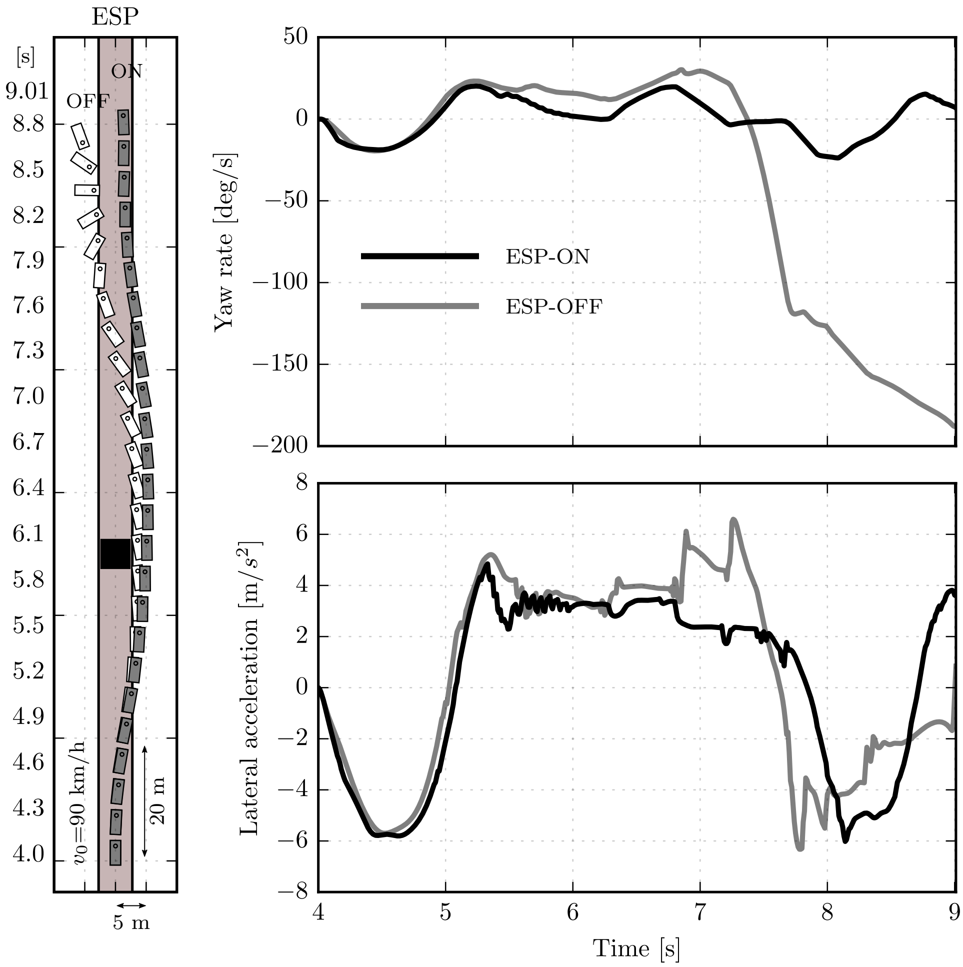


Figure 39: Trajectory and main states of a full-size vehicle during an avoiding maneuver. **Top:** yaw rate. **Bottom**: lateral acceleration. ESP-ON (black line), ESP-OFF (gray line).

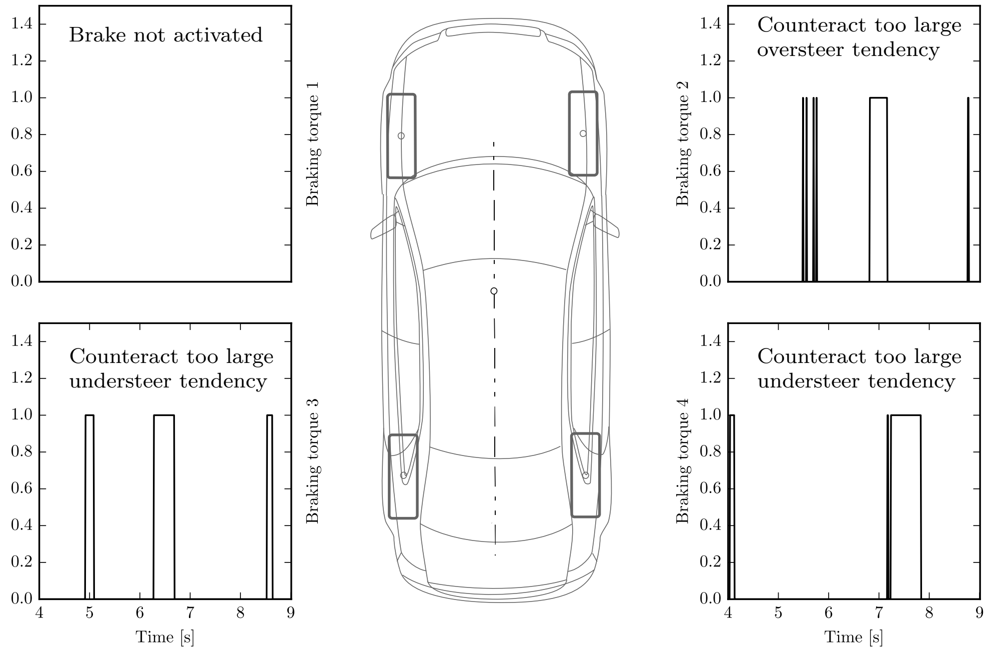


Figure 40: ESP braking activations during avoiding maneuver. **1:** front left. **2:** front right. **3:** rear left. **4:** rear right.

4.3 Four-wheel steering system - 4WS

The 4WS was introduced by Nissan in its Skyline model in the late of 1985. The main advantages of this system are the improvements on the maneuverability at low speeds and the vehicle's lateral stability at high speeds.

4.3.1 Control design

In [39], it is concluded that a simple feed-forward control can improve the vehicle lateral stability. This controller monitors the front steering angle δ_f, and depending of this value and also of the vehicle speed a rear wheel angle is imposed δ_r. In this work, a value of $\delta_f \approx 11.5°$ for the steering wheel angle was chosen, see Figure 41.

4.3.2 Performance test

The same avoiding maneuver performed before was applied to test the performance of the feed-forward 4WS model proposed here.

In Figure 42, results from a simulation of the vehicle with 4WS and without 4WS is shown. During all the avoiding maneuver, the yaw rate and the lateral acceleration, see top and bottom plots of Figure 42 are maintained

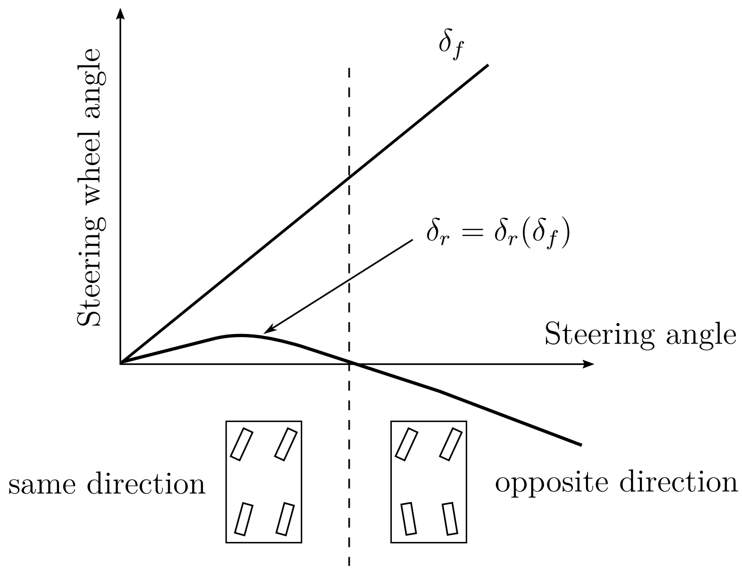


Figure 41: Proposed feed-forward control law.

in a safe range on the vehicle equipped with the 4WS model proposed in this thesis. Finally, 4WS assisted the driver to maintain the desired path as indicated by the multi-frame shot at the very left of Figure 42.

Figure 43, shows the rear steering activations performed by the 4WS system. As can be seen, the rear wheels were steered in the same direction of the front wheels. This is because the front steering angles are small and in addition, the vehicle is traveling at high speed ($v \approx 90$ km/h). Finally, it can be concluded that, a simple feed-forward controller can improve the vehicle lateral stability. However, this system was only tested in this particular scenario. In consequence, a more advance 4WS should be considered for further works.

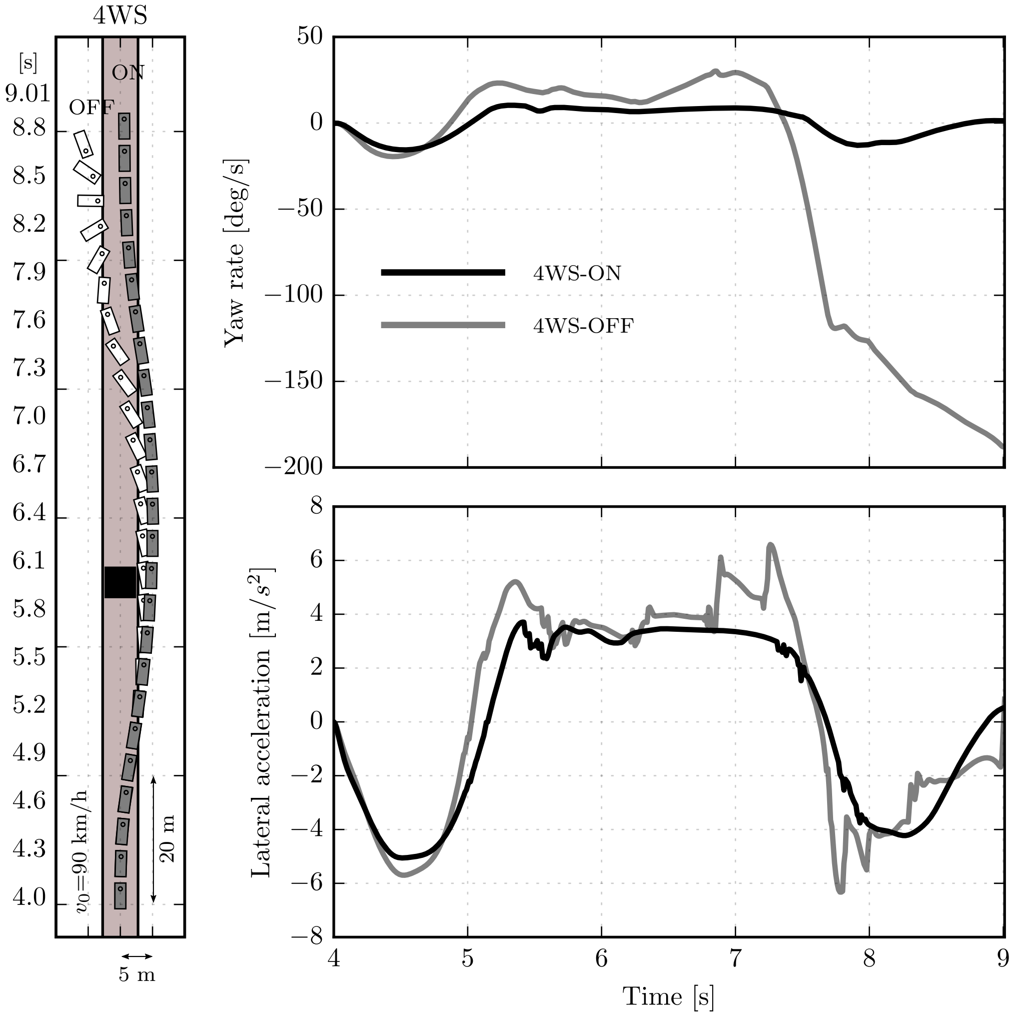


Figure 42: Trajectory and main states of a full-size vehicle during an avoiding maneuver. **Top:** yaw rate. **Bottom**: lateral acceleration. 4WS-ON (black line), 4WS-OFF (gray line).

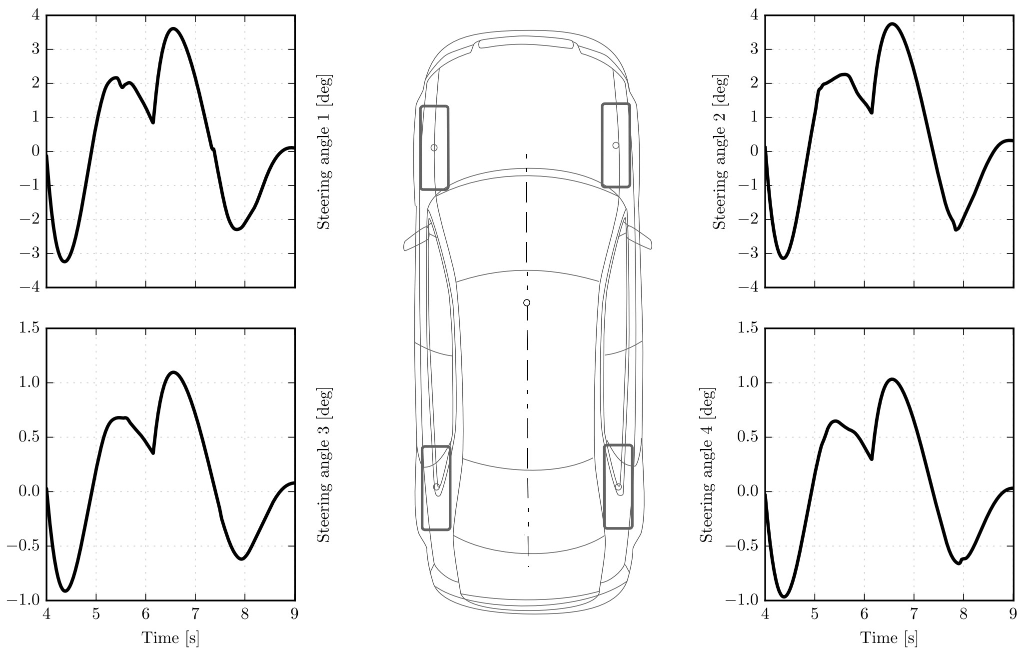


Figure 43: 4WS rear steering activations during the avoiding maneuver. **1:** front left. **2:** front right. **3:** rear left. **4:** rear right.