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Fault Isolation in the Hydraulic Circuit of an ABS: A Real-World Reference Problem for Diagnosis

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Abstract

We present requirements and success criteria for the real-world problem of (off-board) diagnosis of the hydraulic circuit of an anti-lock braking system. The primary problems to be addressed are quite fundamental: First, it is practically impossible to predict the dynamic behavior of this controlled automotive system as it depends on a number of unknown context conditions. Second, there are no direct measurements of the actual behavior available. Instead, the only available input are a number of temporally unspecified and inherently vague symptoms such as "vehicle is yawing to the right". Both problem dimensions might be considered a real challenge for model-based prediction and consistency checking techniques. A number of diagnostic scenarios for the system have been selected based on existing failure mode and effects analysis (FMEA) documents. Their practical relevance is confirmed by experts in the domain.

Description of the Application Domain

Purpose

The anti-lock braking system (ABS) [Bosch 95, 96] is a safety add-on to the regular braking system of a car. Its purpose is to prevent the wheels from locking up and, thus, to maintain steerability and stability of the car during braking.

Structure and Components

An ABS is composed of an electronic control unit (ECU), wheel speed sensors and hydraulic pressure modulators. The hydraulic part consists of two symmetric subsystems, each one operating on a pair of (typically diagonally opposite) wheels. As shown in Figure 1, the hydraulic circuit of each diagonal comprises

- four valves,
- two brake cylinders,
- a return pump element,
- an accumulator chamber,
- a damper with throttle.

The pump elements of the two diagonals share one common drive motor. The hydraulic circuit is connected to the master cylinder that transforms a force acting on the brake pedal into increased pressure. To ensure that the pressure in the brake cylinders is never higher than the actual pressure in the master cylinder, the inlet valves have built-in non-return valves.

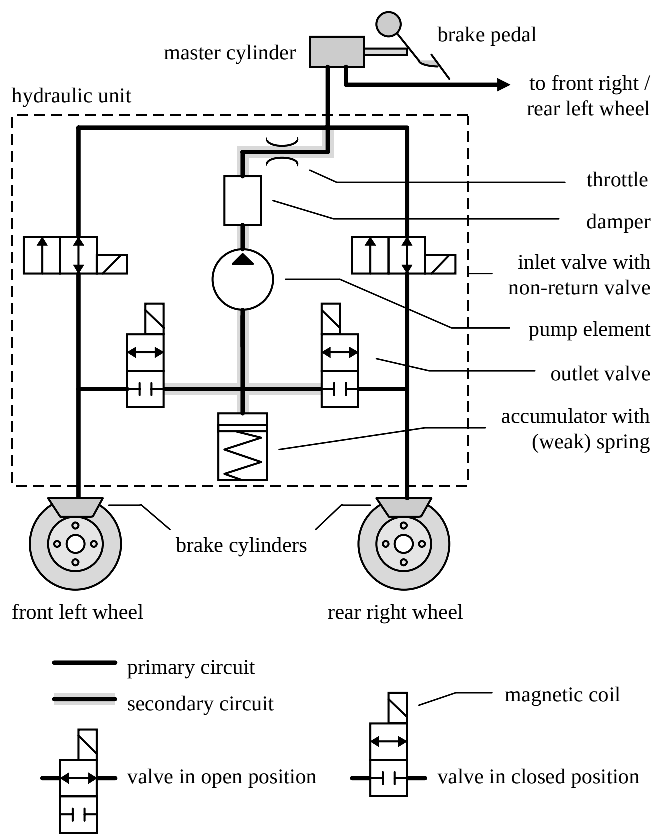

Figure 1: Hydraulic circuit of the ABS (diagonal distribution pattern)

Behavior and Control

The ABS achieves its function by governing the valves and pump elements inside the hydraulic circuit to reduce or increase the pressure exerted on the wheel brake cylinders. The rotational speed of the wheels is measured and serves as an input to the electronic control unit. It estimates the vehicle speed based on the different wheel speed signals. From this reference speed and the individual wheel speeds the ECU calculates the brake slip for each wheel. By combining this value with the (de-)acceleration of the wheel, it determines whether a wheel has a tendency to lock up. If this is the case, the control unit energizes the valves which control the brake pressure in the respective brake cylinders.

If the ABS is inactive, the braking system acts in the regular manner, maintaining the pressure on the brake cylinders while the pedal is pushed. In this mode, only the so-called primary circuit (see Figure 1) is active with the outlet valves closed. If the ABS is activated, reduction of pressure on the brake cylinders is accomplished by involving components of the secondary circuit.

The control of the pressure in the brake cylinders is achieved by stepping through different operation modes, as shown in Figure 2:

- **pressure-buildup**: for each wheel an increase in pressure is achieved by an open inlet valve and a closed outlet valve as in the regular braking mode (Figure 2a).
- **pressure-holding**: the inlet valve is closed (Figure 2b).
- **pressure-reduction**: the outlet valve is opened, and the accumulator fills quickly. Also, the return pump starts immediately to transport the fluid back towards the main cylinder (Figure 2c).

If necessary, the brake pressure is then increased again to ensure that the wheel is not under-braked, and the next cycle may start.

- **pulsed pressure-buildup**: in some cases it might be useful to quickly interleave pressure-holding and buildup mode (the inlet valve receives a pulsed signal), to achieve a more smoothly raise of pressure.

The finite state machine shown in Figure 3 models in more detail the modes of the ABS control and the transition conditions which lead from one state to another. The essential condition is given by the wheel acceleration a, which is computed from the measured wheel speed v_w, and thresholds $a_1 < 0 < a_2 < a_3$. Additional variables are the vehicle speed v_{veh} and the pedal position s_{ped}, with thresholds v_0 and s_0, respectively, which serve as termination conditions to switch off the ABS control (because the driver stopped braking or the vehicle speed has been reduced appropriately). In fact, this is still a simplified description of ABS control. Note also, that the above-mentioned parameters are not available under workshop conditions, nor would they be particularly useful for diagnosis, as the behavior of the control loop depends to a large extent on (unknown) exogenous parameters. Among these parameters are the adhesion between tire and road (which in turn depends on road surface, wheel load, tire condition, etc.), out-of-roundness or differences in the circumferences of the wheels, and variations in the driver's brake pedal actuation causing differences in the pressure input to the master cylinder.

The ECU is also equipped with built-in monitoring capabilities and produces error codes if it detects implausible signals. That is, it performs fault detection and a weak form of fault localization. However, this holds only for the electrical parts of the system (sensors and actuators). The reason is that there are simply no sensors in the hydraulic circuit, e.g. for pressure. The only exception is a sensor indicating that the brake fluid level has dropped below a critical threshold, which is of no help for immediate detection of misbehaviors and irrelevant for fault localization.

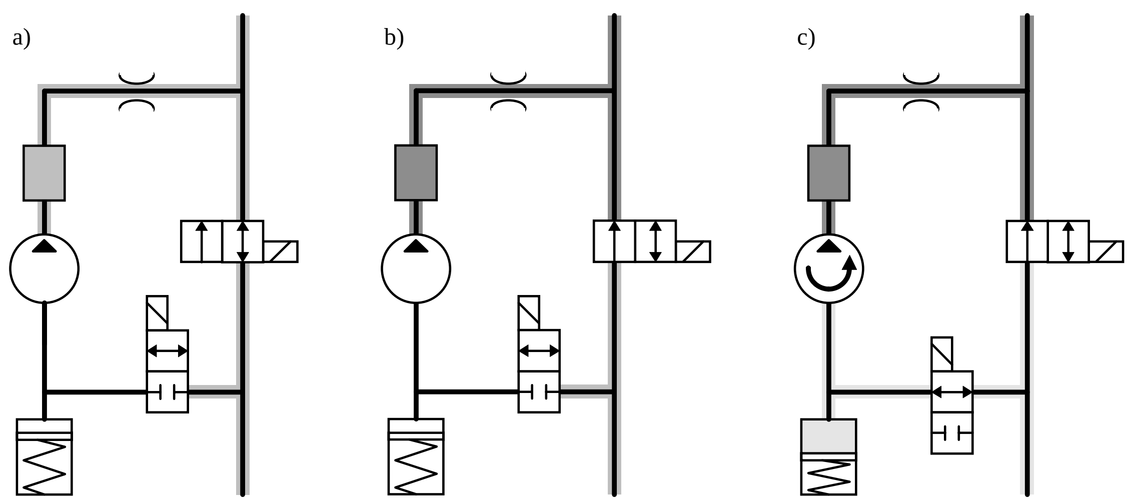

Figure 2: Operation modes of the ABS: a) pressure-buildup, b) pressure-holding and c) pressure-reduction

Diagnosis Problem

Diagnostic Tasks

The task is to support both detection and localization of faults in the hydraulic circuit under workshop conditions. Usually, off-board diagnosis in the garage starts by reading information off the ECU with a handheld tester. It is generally assumed that the ECU and its software are functioning correctly. For the problem addressed here, it is also assumed that there are no faults present in the electrical circuit. Refer to [Struss et al. 95] for results in diagnosing electrical faults of the ABS. If there are no error codes present in the ECU, diagnosis has to rely on manual observations and tests. As was already stated, no ECU monitoring is performed and therefore no error codes exist for the hydraulic circuit. Additionally, there exist no specific test-benches or analyzers that check the function of the entire ABS. Instead, information about pressures inside of the hydraulic circuit can only be obtained indirectly from observing the (de-)acceleration of the wheels. However, it is not realistic that the driver or even a mechanic can exactly measure wheel acceleration or deceleration. As a result, diagnosis of the hydraulic subsystem has two major sources of information:

- **Symptoms reported by the driver**. Except for a lit control lamp, all a driver can perceive is some unexpected behavior of the vehicle w.r.t. braking and steering. For instance, typical observations are that a wheel tends to lock up (indicating a too high pressure in the respective brake cylinder) or that the brake pedal is too soft (as a result of an unusually low pressure in the master cylinder).
- **Tests** under defined operation modes **in the workshop**. With the same tool that is used to read off the error codes of the ECU, each operation mode of the ABS can be activated individually. The test, e.g. for the pressure-holding phase, consists of pushing the brake pedal while the pressure-holding mode is activated and checking if the respective wheel can still be moved freely, indicating that the system could indeed maintain the low brake cylinder pressure.

A list of the available observations and tests for the system, together with rough classifications of the ease to obtain them, is given in the appendix.

Diagnostic Scenarios

A typical diagnosis scenario which we will use for illustration is that while braking,

- the car is yawing to the right, and
- the brake pedal feels somewhat harder than normal.

We assume that the first symptom can be refined to

- under-braking at the left-hand and
- over-braking at the right-hand side.

The symptoms are taken from a failure mode and effects analysis (FMEA) for the ABS. This analysis is carried out during the design of a system and lists a number of possible component faults such as clogged or enlarged valve profiles, valves stuck open or punctured, a defective pump element or air included in the circuit, together with their (potential) effects (e.g. the symptoms stated above).
The observations above describe failure effects the FMEA lists for a clogged left inlet valve. Given these symptoms and assuming that they occur during the pressure-buildup phase, it is actually possible to isolate the left inlet valve as

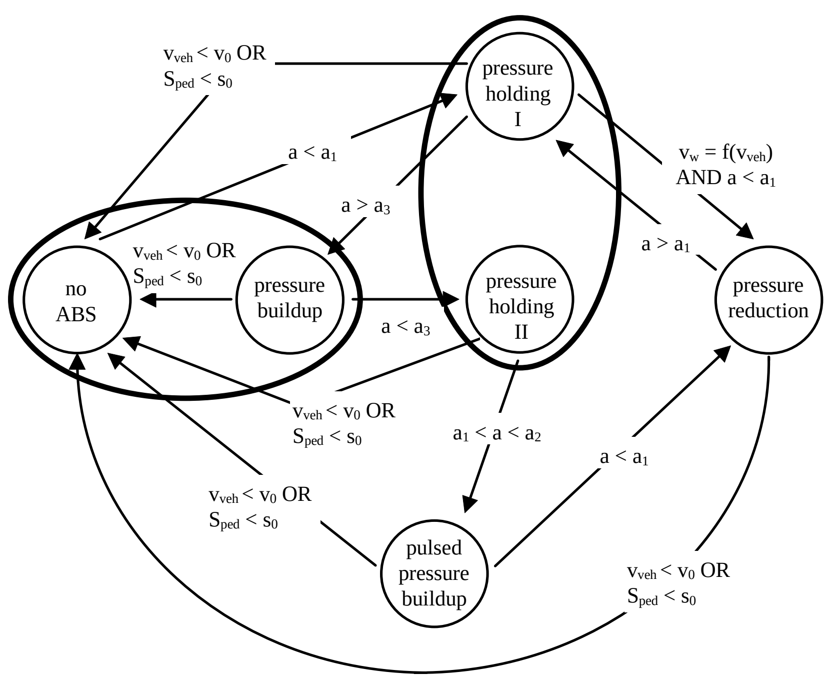

Figure 3: States and transition conditions of the ECU

the only possible single fault (see [Struss et al. 97]).

For each of the diagnostic scenarios described below, the success criteria is whether the respective failure cause occurs in the set of diagnostic candidates generated, and how well it can be isolated. Clearly, an ancillary condition is that this should be based on the most easily available observations.

A list of the diagnosis scenarios can be found in the appendix. The symptoms listed for each scenario can up to now be regarded as spanning the space of possible observations. If the ABS hydraulic circuit should indeed be selected as a reference problem, we will provide for concrete test cases, i.e. complete descriptions fixing the set of observations.

Diagnostic Problem Dimensions

We emphasize that observations like the ones mentioned above

- are **qualitative** in nature,
- are **sparse**, and only **indirect**, and
- have an **unspecified temporal extent**.

For instance, under-braking is a phenomenon that characterizes the behavior of a wheel over the entire period of braking, not even related to a particular phase. Only under the described testing conditions in the workshop, observations can be associated with the operation mode of the test. But even then, no detailed temporal aspects can be measured. From the system description in the above section we also know that

- there are **no sensors** in the hydraulic circuit and
- **contextual influences** on which the behavior of the system depends, such as road conditions, are also **not measurable**.

These facts contrast with two main properties of the device's behavior:

- It is a **dynamic** system, working in different operation modes.
- It is a **controlled** system, where complex control unit behavior determines the current operation mode in response to contextual influences.

In summary, the proposed problem is an instance of a fairly large class of diagnostic problems that are up to now far from being solved:

- The complexity of the system lies in the **dynamics** and the **control loops**.
- The principal characteristics of the diagnosis problem are determined by **limitations in observability**: environmental influences to the control are unknown or can only be characterized qualitatively, whereas the system behavior itself is only observable indirectly and at a temporal granularity much coarser than a single control cycle.

In the domain of automotive systems, more instances of this problem class can be identified. One further example is the electronic diesel control (EDC) [Bosch 96], a subsystem which controls the time of injection and the fuel quantity injected for diesel engines.

The question is whether solving this problem can be a challenging goal for automated diagnosis. The answer may lie in human problem solving behavior. A human observer who is familiar with the components of the circuit and has a basic understanding of the functionality of an ABS as given in the above section, is able to come up with reasonable diagnostic hypotheses. For instance, based on the symptoms of our example scenario, she might conclude:

Under-braking on the left-hand side indicates insufficient pressure. This could be due to a clogged inlet valve or an open outlet valve. The former would also explain why too high pressure remains in the master cylinder (hence the hard pedal) and in the primary circuit of the right-hand wheel (possibly causing over-braking). So, this seems to be a plausible diagnosis.

The crucial question is what techniques are required to perform this kind of reasoning in an automated diagnosis system.

Previous Approaches to the Problem

In [Struss et al. 97] these problems are tried to tackle by applying models that capture qualitative deviations of variables and parameters from nominal behavior. These models are used in a state-based diagnosis framework, i.e. only the observed states are checked for consistency with the model, and no simulation of the dynamic behavior is required [Dressler 96, Malik and Struss 96, Struss 97]. The crucial step in making the approach work is to exploit basic constraints on continuity for complementing the directly obtained observations by information about derivatives. For a number of scenarios in the pressure-buildup phase, this approach turned out to be quite successful. However, a number of fairly strong assumptions had to be made to make diagnosis work, in particular, to compensate for the unspecified temporal scope of the observations. For instance, one of those assumptions stating that the occurrence of symptoms is synchronized, is inadequate as soon as multiple faults are taken into consideration.

Previous work in [Struss et al. 95] reports on results in model-based automation of the generation of diagnosis guidelines for the electrical circuit and speed sensors of the ABS.

Acknowledgments

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Appendices

Parameters

Some typical figures have been collected to give a feeling of the orders of magnitude of the hydraulic circuit's parameters:

- **volume**: The accumulator can hold about 2-3 cm^3, each brake cylinder about 1 cm^3 of brake fluid.
- **pressure**: Braking pressure reaches up to 2000 N/cm^2 in buildup mode. Brake fluid is almost incompressible, and hardly reduces its volume even in this case.
- **control speed**: Switching of the valves takes some 10^{-3} seconds. Due to the characteristics of the brake fluid, spread of the pressure pulses is also in this range. About 5-10 control cycles are performed each second, depending mainly on the friction coefficient of the wheel.
- **control duration**: The maximal retardation of a wheel that can be achieved (i.e. with optimal brake coefficient) is about 12 m/s^2. Under these conditions, e.g. during emergency braking at 100 km/h, the ABS is active for about 8 sec. until reaching the termination threshold $v_0 \approx 5$ km/h.

The pressure-modulation components of the circuit are not distributed over the car, but are combined in a rather compact (ca. 1.5 dm^3) and lightweight (ca. 2.5 kg) unit interposed between the pipes of the ordinary braking system.
If the ABS hydraulic circuit should be selected as reference problem, we should be able to make more detailed data available, e.g. concerning parameters of the control automata in Figure 3.

Observations

a) Driver symptoms

Vehicle behavior (Table 1): Symptoms related to vehicle behavior are the most indirect and temporally integrated ones, as they are the result of the combination of individual wheel behavior. The wheel behavior itself can be characterized in terms of rotational speed and brake slip (the higher the brake slip, the less forces can be transmitted between the wheel and the road) during braking. Note that in the upwards direction of this list, the symptoms are increasingly combined and temporally integrated. Downwards, they are increasingly specific and therefore more difficult to observe.

Brake pedal behavior (Table 2): Symptoms perceivable at the brake pedal are an indication for the pressure in the master cylinder and manifest itself mechanically in terms of the distance the pedal moves, its speed, and the force that is required to push it.

Noises and sounds: An additional symptom can be increased noises and sounds during governing due to dried-out active components or very high pressure/flow at certain points in the circuit.

Observation	Description
reduced steerability	loss of lateral guiding force at front wheels due to a too high brake slip
reduced driving stability	loss of lateral guiding force at rear wheels due to a too high brake slip
yawing moment	turning motion around the vertical axis of the vehicle due to vastly differing braking forces at opposite wheels
under-braking at one side	too low braking force is applied at one side of the vehicle
over-braking at one side	too high braking force is applied at one side of the vehicle
under-braking of a wheel	too low braking force is applied at one wheel, its adhesion between tire and road is (temporarily) not used optimally
over-braking of a wheel	too high braking force is applied at one wheel, its brake slip is (temporarily) too high
lock-up of a wheel	wheel stops rotating

Table 1: Observations related to vehicle behavior

Observation	Description
pedal "soft"	given nominal force, the pedal moves a greater distance than normally
pedal "hard"	given nominal force, the pedal moves a shorter distance than normally
pedal "blunted"	further pressure build-up is restricted to an unusual low threshold
increased backlash	pulsations from the ABS control through the pedal, e.g. as a result of ineffective damping

Table 2: Observations related to the brake pedal

In the presented order, the classes of driver symptoms are more and more difficult to observe. The driver symptoms may also be greatly intensified (or even only be noticeable) under specific context conditions. They can be mainly characterized by the friction coefficients of wheels and steering actions. A split of the friction coefficients (e.g. if one side of the car is on a slippery surface and the other on dry asphalt) aggravates symptoms which affect the yawing moment. A rapid change of friction coefficients (e.g. when driving over patches of ice or snow) requires rapid matching of braking force, thus aggravating failures where the pressure increase or decrease rate is affected. Finally, deteriorated steerability will show up most intensely during cornering.

b) Tests in the workshop

Reproduction of driver symptoms: The first point to notice is that driver symptoms can be reproduced in the workshops (by experienced technicians) with higher accuracy and reliability.

Test of individual operation modes: The possible actions to test the hydraulic circuit in the workshop are

- activation of an operation mode with handheld tester
- pushing or releasing the brake pedal
- lifting up the car and testing if a wheel can be moved freely or is blocked.

Using this set of actions, it is tried to determine whether the ABS is functioning correctly. E.g. the test for the pressure-holding phase consists in pushing the brake pedal while the pressure-holding mode is activated, and checking if the respective wheel can still be moved freely. This indicates that the system could indeed maintain the previously low brake cylinder pressure.
The complete test sequence for the front left (FL) valves of the hydraulic circuit (taken from a repair manual for the ABS) is as follows:

1. lift up the FL wheel until it can be moved freely
2. activate the pressure-holding phase for the FL valves
3. push the brake pedal and keep it this way
4. test if the FL wheel can be rotated freely
5. if yes: proceed; otherwise: fault detected
6. activate the pressure-buildup phase for the FL valves and keep the brake pedal pushed.
7. test if the FL wheel can still be rotated freely
8. if yes: proceed; otherwise: fault detected
9. activate the pressure-reduction phase for the FL valves and keep the brake pedal pushed.
10. test if the FL wheel can still be rotated freely
11. if yes: proceed; otherwise: fault detected

This test can be likewise performed for all four wheels. It is especially suited as a means to detect permutations of the hydraulic connectors. To make the description of the possible tests complete, the pump motor can be activated by the handheld tester for some seconds. It is audible if it is running or not.
In the presented order, the observations are increasingly costly. Especially the tests of individual operation modes are expensive.

No.	Failure cause	Description of failure effect	Symptoms
1	inlet valve: partially occluded	pressure increase rate is too low, therefore pressure buildup is delayed	• under-braking of the respective wheel (temporary) • hard brake pedal • over-braking of other wheels possible • car yawing in extreme cases
2	inlet valve: stuck open or punctured	pressure holding is not possible	• over-braking of the respective wheel (due to the pressure in master cylinder) • if accumulator is already full, over-braking of diagonally opposite wheel possible • both wheels of the diagonal lock up in extreme cases
3	outlet valve: stuck open or punctured	pressure holding is not possible	• under-braking of the respective wheel • accumulator gets filled, which in turn can affect pressure reduction at diagonally opposite wheel (over-braking) • pedal has to be moved a greater distance until sufficient braking force is available
4	pump element: internal leakage	low pressure level in the secondary circuit cannot be achieved	• pressure-buildup: pedal soft, under-braking of respective diagonally opposite wheels possible • pressure-reduction: depending on leakage size: respective wheels over-brake or lock up
5	accumulator: spring broken	accumulator is permanently filled	• pressure-reduction too slow • over-braking of the respective diagonally opposite wheels at the beginning of pressure-reduction phase, lock-up in extreme cases • increased pulsations at pedal
6	hydraulic circuit not properly vented	air bubbles in primary circuit	• under-braking of the affected diagonally opposite wheels • brake pedal soft
7	hydraulic connectors to the wheel brake cylinders permuted	pressure is applied at the wrong wheels	• depending on the actual configuration: combinations of under/over-braking and locking possible

Table 3: Failure causes, failure effects and symptoms in the scenarios for the hydraulic circuit

Scenarios

Table 3 shows seven relevant failure scenarios for the hydraulic circuit. They were selected based on a FMEA of the system. The guiding criteria which led to this selection were on the one hand the estimated probabilities of occurrence (as stated in the FMEA), and on the other hand concrete experience of workshop technicians. In addition to this list, leaks of the device are also relevant in practice. However, most likely, leaks trigger the switch for the level of brake fluid and activate a warning lamp before affecting the functionality of the ABS.

Additional Features and Scalability

The hydraulic circuit we presented here is not meant to be specific for a certain ABS or passenger car version. It can rather be regarded as a basic pattern for a variety of systems, whose actual configuration depends upon the brake force distribution concept, the type of vehicle drive concerned, costs factor, etc. For this reason, first, for each ABS version there exists a number of variants which differ w.r.t.

- vehicle mounting position: horizontal, vertical
- pump motor version: small, large (two pump delivery rates)
- brake circuit configuration: X distribution pattern (diagonal distribution pattern), II distribution pattern (front axle/rear axle split)
- accumulator sizes.

Second, the basic functionality of the ABS as presented can be enriched by additional features, each of which have also an impact on diagnosis of the device. Some of these features are e.g.

- **select low (SL) control:** [Bosch 96 pp. 659] Select low is a different control principle which, instead of individually controlling the brake pressure for each wheel, applies the same (lowest) brake pressure level to both wheels of an axle. This reduces the yawing moment and improves steerability at the expense of stopping distances. A typical configuration is that the front wheels are controlled individually, while the rear axle is governed by select low. Consequently, for modeling, the simplifying assumption that wheels operate independently from each other is violated.

- **yaw moment buildup delay (GMA)**: [Bosch 96 pp. 630] This add-on uses a yaw moment sensor to measure the actual turning motion around the vertical axis of the vehicle. GMA delays the pressure buildup in the wheel brake cylinder of the front wheel with the lower braking slip. That is, this wheel is intentionally under-braked at first to give the driver time for reacting steering maneuvers. Besides that wheels are then again not controlled independently of each other, this feature entails the additional complication that a measured parameter of vehicle behavior is fed back into the control loop.

- **traction control (ASR)** and **vehicle dynamics control (VDC)**: [Bosch 96 pp. 574, 633] While ABS avoids braking slip by modulating the given brake pressure, ASR and VDC likewise hold the acceleration slip within acceptable levels by applying additional brake force. The standard ABS hydraulic circuit is expanded by two additional valves which allow for active buildup of pressure in the master cylinder through the return pump elements. VDC is a more advanced concept: An auxiliary pre-charge hydraulic pump supports and speeds up pressure buildup. As a next step, most recent systems even replace the mechanical connection between the brake pedal and the master cylinder by an electrical connection which activates the charge pump. Consequently, observations at the brake pedal are blinded out. However, for these systems, an additional test for active pressure-buildup exists:

  1. lift up the car until the respective wheel can be moved freely. Do not push the brake pedal during the test
  2. trigger the active pressure-buildup mode
  3. test if the respective wheel is blocked
  4. if yes: proceed; otherwise: fault detected

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