

The Electronic Wedge Brake - EWB

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Siemens AG, Siemens VDO Automotive, Body and Chassis Electronics, SV C BC AX

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ABSTRACT

Future driver assistance systems will not only monitor the current traffic situation, but actively assist the driver in emergencies. Autonomous intervention in vehicle dynamics will increasingly help keep the vehicle under control, even in difficult operating situations. A rapid and intelligent braking system is one of the foundations for advancing the next generation of driver assistance systems. Siemens VDO sees its electronic wedge brake (EWB) brake-by-wire technology as the answer to future vehicle chassis safety, weight, reliability, and space requirements.

In early 2005, Siemens VDO Automotive AG acquired the innovative company eStop to enter the automotive brake market with the EWB. The EWB is a self-reinforcing electromechanical wedge brake, which operates around the point of maximum self-reinforcement, in order to minimize actuation forces to levels that can be supported by 12V vehicle electrical systems. Previous papers published by eStop addressed the basic design, modeling and control aspects of this concept. This paper focuses on the progress with the latest prototype and some basic test results from this prototype, robustness testing, vehicle implementation and development of higher level brake functions.

INTRODUCTION

Particularly in the automobile sector, there is an increasing trend towards replacing existing hydraulic or pneumatic brake systems with 'drive-by-wire' solutions. While mechatronics, i.e. intelligent, controllable electromechanical actuators, are already in use in many automotive and non-automotive areas, there are particularly strict requirements for purely electromechanical braking systems which require complex development processes. These are highly safety critical systems, which must provide both excellent control quality and sophisticated fail-safe behaviour. The challenge is to achieve a high power density in the wheel brake actuators.

In early 2005, Siemens VDO Automotive AG acquired the innovative company eStop to enter the automotive brake market with the electronic wedge brake technology. Previous publications from eStop ([1],[2],[3])

have shown that the EWB concept can produce the high dynamics and high braking torque which are required in modern braking systems by using the standard 12V power supply system. This was first proved by testing the first prototype on an automated dynamometer which simulated the inertia and braking energy of a passenger vehicle.

The next step was then to produce a prototype which was capable of producing full braking power as well as providing the majority of functionalities expected in a future brake by wire system. This paper represents the environment used in the testing of this prototype, as well as the results from these tests which include demonstrations of wedge brake specific functions and more advanced braking functions.

WEDGE BRAKE OVERVIEW

THE BETA PROTOTYPE

The third EWB prototype, also known as the 'beta', was developed in 2004-2005. It was the first EWB prototype to show the full functionality of an automotive wheel brake. The basic principle of the brake heart mechanism and the dual motor activation for backlash prevention remains the same as that of the alpha prototype, which is described in more detail in [3].

This prototype was designed to be mounted on a brake disk inside a wheel, and to be used in test vehicles running in real environments. As a result, the 'beta' is a more compact and robust design than the alpha. There are also extra functionalities, including automatic pad wear adjustment and self-release, an important part of the safety concept.

The prototype design and a high temperature test with optimized heat dissipation can be seen in Figure 1.

The 'beta' prototype was used to produce the test results in this paper.



Figure 1: Beta prototype with full functionality, wedge bearing in detail (left), and high temperature test with optimized heat dissipation (right)

CHANGE TO NORMAL FORCE CONTROL

One difference between the test results shown in this report and those from the 2004 SAE publication ([3]) is that the outermost control loop has changed from moment control to force control. However, the structure of this controller loop (see Figure 2) has remained almost identical with that of moment control, and the earlier results are still valid as verification of the EWB concept.

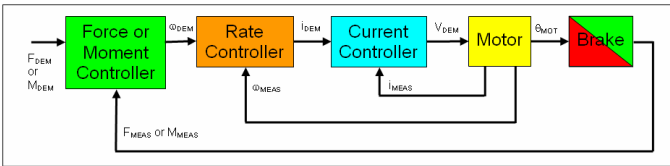


Figure 2: Wedge controller cascaded structure

The reason behind the change from brake torque control to normal force control is the lack of availability of automotive grade torque sensors suitable for this application. Automotive grade force sensors are, however, available in suitable specifications.

The lack of a suitable torque sensor was clearly observed during early testing with the trailer – it proved to be difficult to measure only the desired component of the torque. The flexibility of the caliper structure (possibly excited by unevenness in brake torque) and the motion of the vehicle suspension produce additional effects which make the signal from the chosen torque sensor unreliable.

TESTING EQUIPMENT

The testing equipment that was used to generate the test results in the later section will be briefly described here.

AUTOMATED DYNAMOMETER

The Seefeld site has in house a 160kW machine, capable of simulating a passenger car up to a weight of approximately 1600kg. This set up is described in more detail in [3].

MOBILE QUARTER VEHICLE TEST RIG

Free configuration of all relevant chassis parameters such as toe, camber, caster, suspension and shock absorber characteristics is made possible by a specially developed mobile quarter vehicle test rig. This test rig allows the wheel contact forces and slip angle to be set independently during tests of the controller. In these tests the main emphasis is laid on the high level of reproducibility of the driving situation, which can be set precisely for extreme values. One example is the lifting of a tire on the inside of a curve in conjunction with a high tire slip angle. The trailer represented the first chance to test the EWB under realistic environmental conditions and to test the interaction of the ABS algorithm with real tire dynamics. Figure 3 shows the completed test trailer (left) and wheel suspension (right).



Figure 3: Mobile quarter vehicle test rig

TEST VEHICLE

The test vehicles are equipped with a rapid prototyping environment as shown in Figure 4. The control electronics is implemented in a dSPACE AutoBox, whereas the power electronics and signal conditioning for the individual brake actuators are run on so called E-Box platforms. A conventional hydraulic brake and electrical parking brake on the rear axle are retained as a back up solution. A brake disk with an EWB system/ hydraulic back up can be seen in Figure 5.

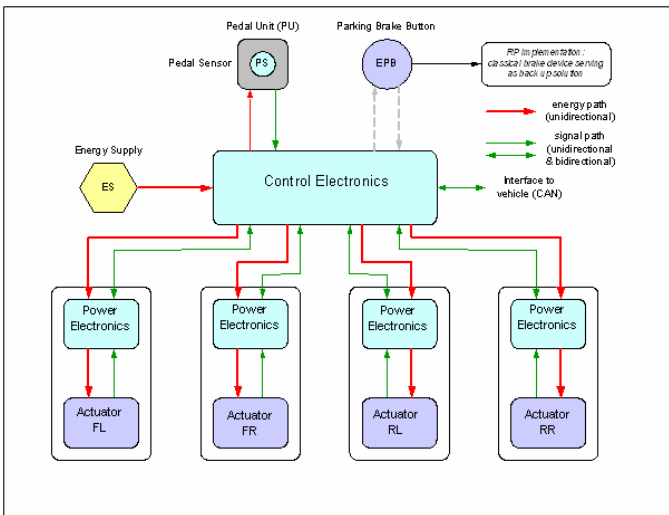


Figure 4: Vehicle set up in a Rapid Prototyping Environment

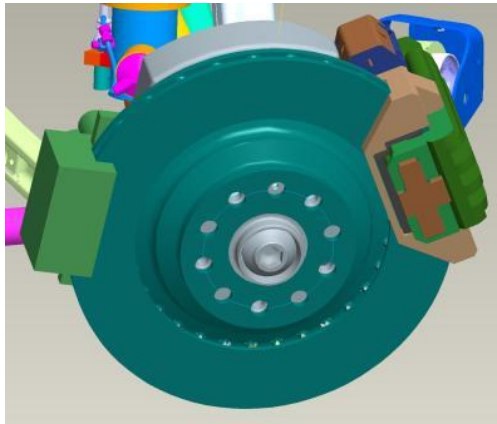


Figure 5: Test vehicle installation of EWB (caliper on the right) with hydraulic back up (on the left)

TESTING METHODOLOGY

VIRTUAL REFERENCE VEHICLE FOR TEST LOAD CALCULATIONS

In order to get a classification of the test results taken with respect to a real vehicle application a reference vehicle was defined and a basic sample calculation was conducted. This is necessary to get a feeling for the capability of the state-of-the-art EWB prototype and the test equipment.

The reference vehicle was defined as a "Golf class" (B-segment) vehicle with a total mass of 2,085kg. From the defined data, values such as those in Table 1 were calculated. These define the parameters in the test scenarios. Hence for the experiments with the mobile quarter vehicle test rig the wheel load was set to approx. 7000N, equivalent to the front wheel of a B-segment vehicle with a 1 g deceleration demand.

Specification	Value	Unit
Dynamic wheel load – front axle	70%	
Wheel load – front axle	14325	N
Braking force – front axle	14325	N
Braking torque – one front wheel	2278	Nm
Normal force at wheel brake – front wheel (at $\mu_{\min}$)	37961	N

Table 1: Selected reference vehicle specifications

TEST RESULTS

The test results are divided into categories to illustrate the various aspects of EWB requirements and performance.

RESPONSE DURING BRAKING

High Dynamics Response

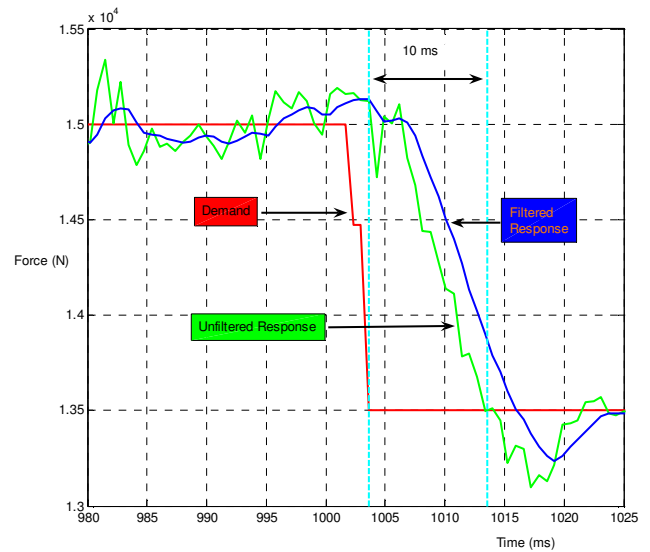


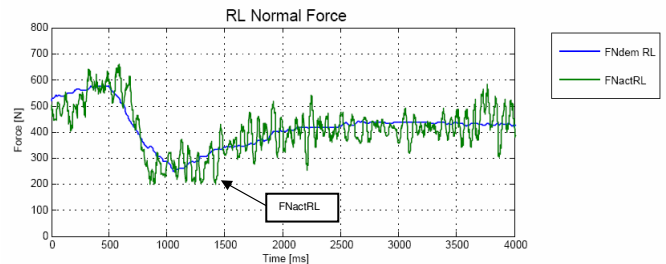
Figure 6: Step Response, Dynamometer, Tuned Controller

The result shown in Figure 6 demonstrates what can be achieved by tuning up the controller. This means that the controller gains are adjusted such that some stability margin is sacrificed for improved response speed. The red line shows the signal that was actually applied to the brake, which is held for two sample times of the recording frequency.

This demonstrates that the brake can reduce forces at a rate appropriate for a modern ABS system. The unfiltered force, which is what acts on the wheel, is reduced by 10% in approximately 10 ms, with a small overshoot.

FINE CONTROLLABILITY

One of the advantages of an electromechanical brake system compared to an electrohydraulic one is the ability to control braking forces with high accuracy, even for small inputs. This is important for braking comfort as well as certain additional functionality, such as disk wiping and drying, and soft stop.



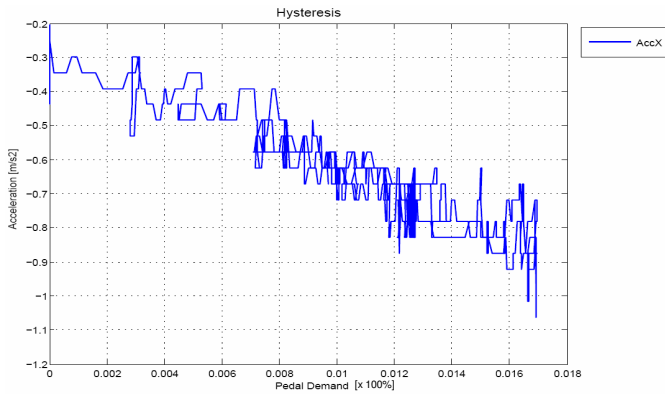


Figure 7: Light Braking, Test Vehicle

The plot in Figure 7 shows an instance of a very small demand from the driver to make a very gentle stop. It can be seen that, despite the force sensor noise, the force tracks the demand very well even at this low level. In particular, it can be seen that the vehicle deceleration response to the pedal demand is linear and shows no significant hysteresis or dead-band.

ROBUSTNESS

Tests have been performed to ensure that the design and control of the wedge brake are able to handle reasonable levels of hardware damage and imperfections. Here, two simulated situations are shown – a disk with a severe abrasion and thickness change on a part of the disk, and a disk that has been rusted on all but the area covered by the caliper.

Varying μ and Thickness Change on Disk (Damaged Disk)

A segment of a brake disk was manipulated to investigate the combined effect of increased roughness and change in thickness on the controller response. The damage inflicted on the disk is shown in Figure 8 below.



Figure 8: Manipulated disk with deep grooves after heavy braking

The dynamometer test result in Figure 9 illustrates the effect of the damage on the normal force produced by the brake.

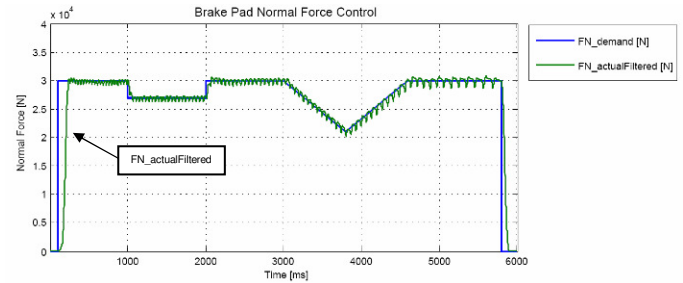


Figure 9: Damaged Disk, General Test Profile

With the degree of damage done to the disk, it is not a bad thing if the driver feels the effect, but it is important that the general control of the brake is not affected. This is demonstrated in the figure above: The controller is not unduly disturbed by the damaged disk, and stable control is maintained. There is evidence of the disturbance once every revolution of the wheel but otherwise the response is very similar to that with an undamaged disk.

Rusted Disk

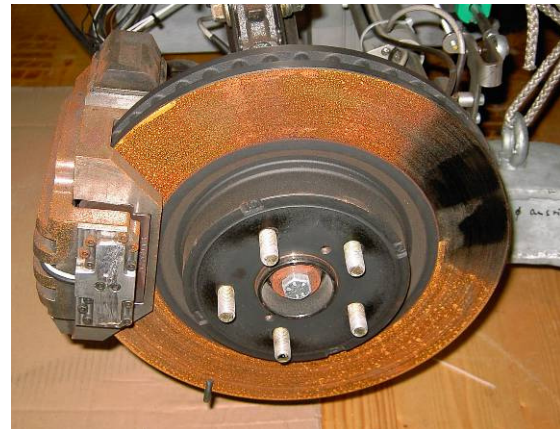


Figure 10: Rusted Disk

A disk was deliberately left to rust and then mounted on the trailer. This is illustrated in Figure 10 above, which shows the condition between tests after a few brake applications. The clean spot on the disk corresponds to the brake caliper location during the rusting process.

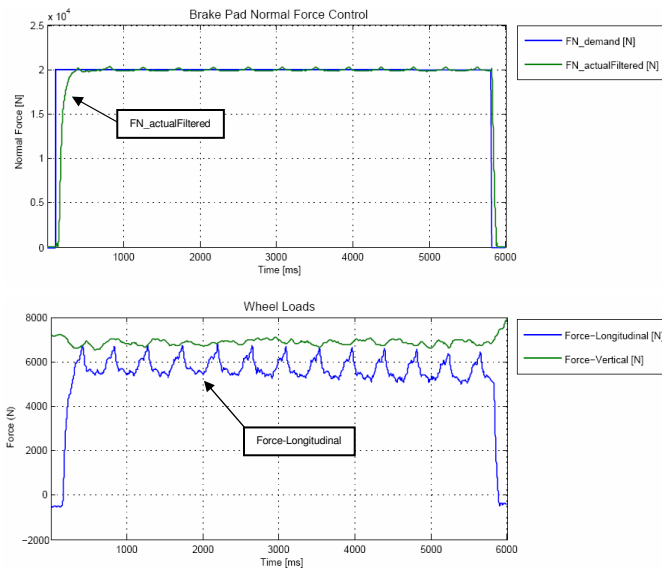


Figure 11: Rusty Disk, Trailer

The result from trailer testing in Figure 11 shows that the normal force is well controlled despite the damage to the disk. There are small fluctuations in the force as the pads contact the clean area of the disk but the position of the motors is relatively constant. In contrast, the longitudinal force measured at the wheel shows very distinct peaks once per revolution, representing a change of approximately 10% in the braking moment. This is the result both of a slightly larger normal force and a significant change in the coefficient of friction between the rusted and clean areas.

The fact that the controller is not unduly disturbed by the rusted disk, and that the driver would receive some feedback that maintenance is required, is a good initial result.

WEDGE SPECIFIC FUNCTIONS

From the previous test results, it has been established that the wedge brake is able to handle the normal braking situations. However, for many, there remain questions regarding whether the EWB can adequately handle situations where the direction of self-reinforcement changes.

Overview

Before looking at the test results, it is useful to briefly explain the algorithms used to handle the special braking situations. A few representative situations are listed below.

Vehicle stationary on any road gradient - the self-reinforcement property of the wedge is still valid even when the wheel is not rotating, as long as the wedge is in the correct direction. In order to ensure that the vehicle does not roll away under any external forces in either forward or backward directions, either the front or rear brake wedges are placed to get self-reinforcement in the

forward direction, while the other brake wedges are placed for self-reinforcement in the reverse direction.

Coming to a stop – the brake system must be ready to brake in the reverse direction as soon as the vehicle comes to a stop. This is necessary, for example, on an uphill slope where the vehicle is braked to a stop. This is achieved by changing the direction of two of the wedges just before the vehicle stops. During the wedge direction change the brake will produce reduced braking force (down to zero) for a short time. This is compensated by increased brake force on the other brakes, and the vehicle deceleration is kept constant.

Rolling away from a stop – this is the opposite of the case where the vehicle comes to a stop. Two of the wedges change direction shortly after the vehicle begins to move, so that all four wedges are set in the correct direction for the direction of vehicle motion.

The following test results show how the EWB system handles the wedge specific complications in these situations.

Vehicle Moves from a Stop under Braking

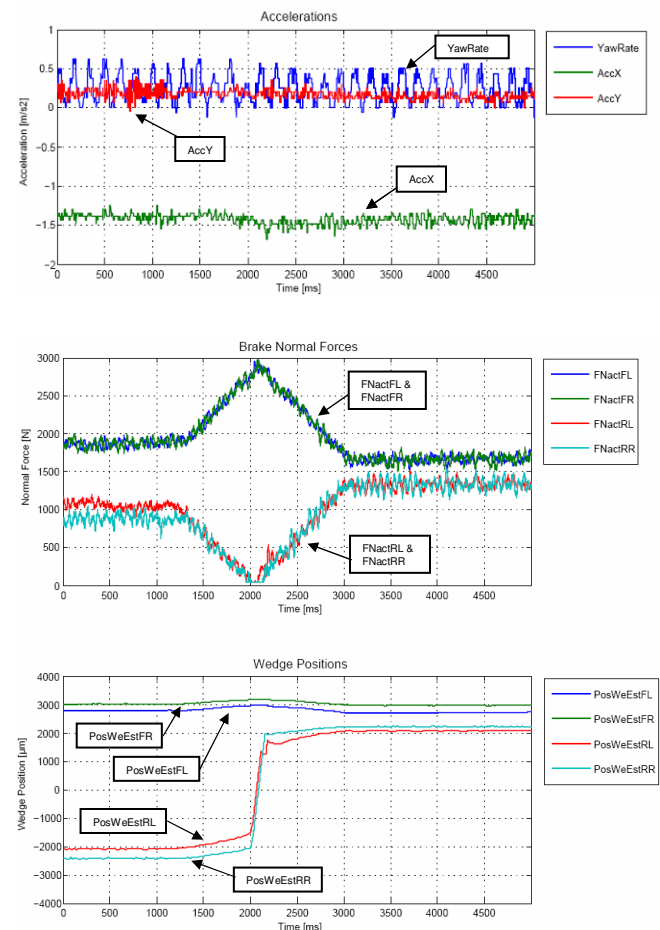


Figure 12: Vehicle moving off from stop

The measurement in Figure 12 shows a situation where the vehicle is allowed to roll forwards downhill from a standstill but the driver maintains a small brake demand. Before rolling and at very low speeds (in the period between 0 and 1000 ms), the wedge actuators are split into two groups where the front wedges are commanded forwards and the rear ones backwards. This is a robust solution to hold the vehicle on the brakes independently of the external forces (hill slope, trailer, wind, local slope, edge under the wheels, loading the vehicle, etc.). Once rolling, the wedge directions have to be controlled into the direction of travel in order to provide maximum brake performance, should it be required. The transient process is done in a smart, controlled way so as not to cause any recognizable effect on the total brake performance. The wedge direction change is done by first decreasing the rear brake demand, then switching the command direction, and finally increasing the demand back to the original level. During the transient, the front brakes are controlled to maintain a constant total brake force. This process is shown on the fourth panel. The V-shaped ramp and the compensation on the front wheels are demonstrated well. On the third panel, the longitudinal acceleration signal (given by the line AccX at approximately -1.5 m/s^2) shows no steps, holes or any visible effect of manipulating the brake force distribution, proving that the smooth wedge direction transient is feasible.

Vehicle Stopping

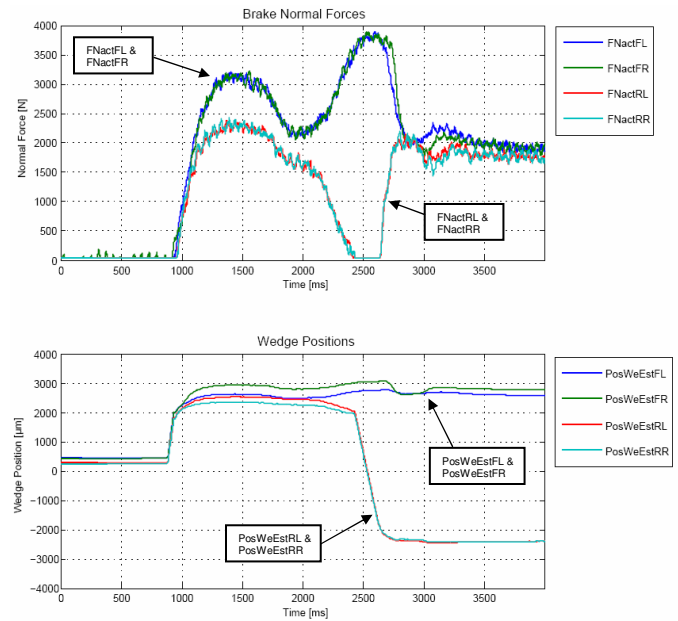
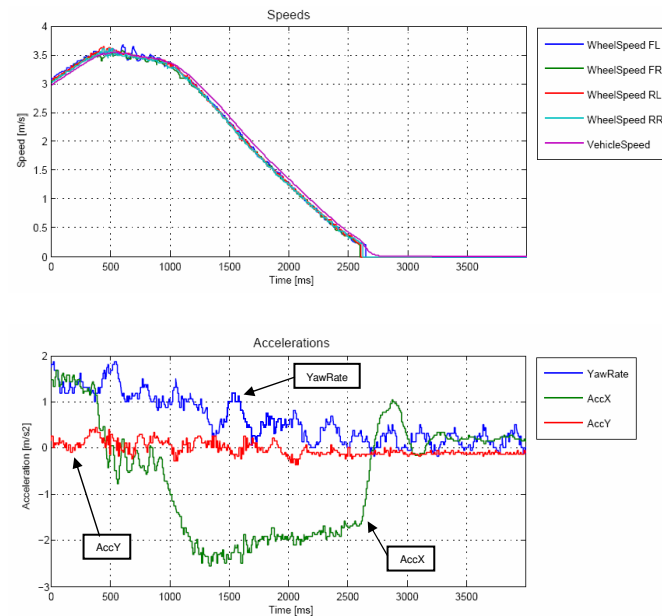


Figure 13: Vehicle stopping

These results in Figure 13 show the stopping process in more detail. A wedge direction change is necessary at the moment of stopping. Shortly after stopping the proper brake performance has to be available to keep the vehicle from rolling away in both directions. Such a wedge direction transient is shown on the 4th panel. The decrease of rear brake force is compensated by the increasing front brake force, so that there is no evidence for the switch in the longitudinal acceleration curve. As soon as the vehicle stops, the demand is increased further because it does not affect the vehicle's motion anymore. These functions are controlled in one block in the wedge management module of the central brake controller.

On stopping, there is an overshoot in the longitudinal acceleration (see panel 2) before it settles down to the stationary value. This is not wedge brake specific, but is rather a function of the suspension. A result recorded when the same test vehicle was braked to a stop using its hydraulic brakes showed similar oscillations. The best way to prevent this is to implement the soft-stop function.

Stopping on a Slope

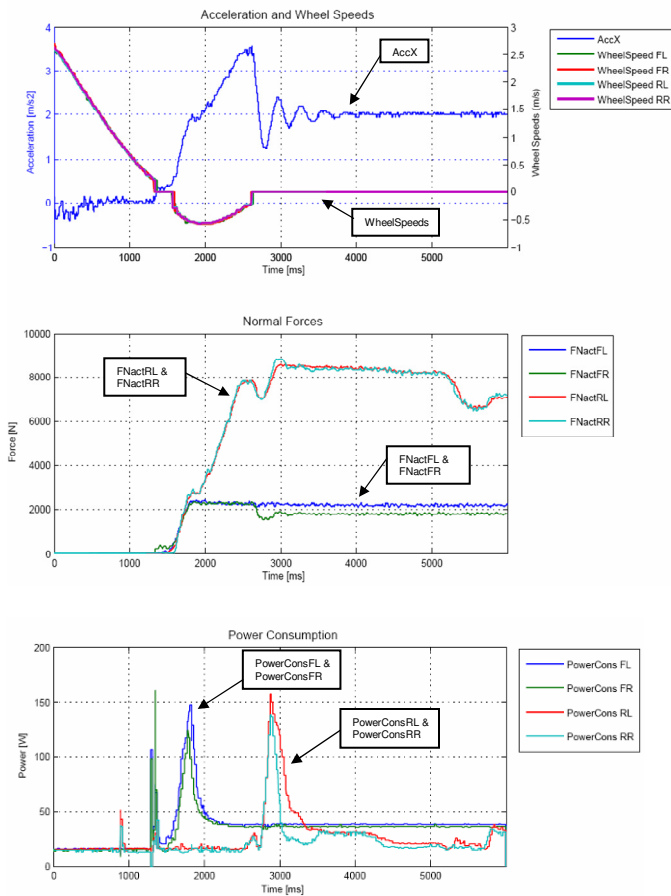


Figure 14: Transients on stop; steep hill

In this test the car was allowed to roll uphill and come to a halt forwards without application of the brakes, then deliberately allowed to roll backwards, and then stopped with the brake pedal. It occurs on an uphill slope of about 12 degrees, as can be seen from the steady state accelerometer signal.

The results here demonstrate that the vehicle can be held on a reasonable slope without an increase over the normal power consumption, and that the EWB can still take advantage of the self-reinforcement effect by putting front and rear wedges in opposite directions. The current implementation is that the front wedges are set to produce self-reinforcement when the vehicle is traveling forwards, while the rear wedges in the opposite direction.

When the vehicle first stops (ca. 1,500ms), the front brakes lose self-reinforcement due to the uphill gradient and can no longer follow the desired demand. However, intelligent current limit is applied to reduce the power consumption, as can be seen from the relatively smooth fall in the measured power on these brakes.

The rear brakes still have self-reinforcement even after stopping, because the uphill slope provides an external force on the system. As a result they provide a much higher force than the front brakes and yet require less power. The only exception is during the transition on the

second stop (ca. 2,700ms), where the suspension dynamics interact with the system, reducing the self-reinforcement and resulting in a temporary increase in the brake power consumption.

OTHER VEHICLE LEVEL FUNCTIONS

ABS

The EWB forms part of a vehicle dynamics control system. One of the benchmarks for the performance of the system is the requirement to match or out-perform the state-of-the-art ABS. While some basic criteria were defined for simulations and dyno tests, the performance of the EWB under ABS control has now been validated in the test vehicle.

Early Test Using the Trailer

This operation of a single EWB unit under ABS control is demonstrated by this test result (Figure 15) from the test trailer. All other test results shown are recorded from the test vehicle.

In this test, the trailer began braking on a dry asphalt surface, and then during the braking the surface changed to a wet surface with lower friction. While this test is interesting from an ABS controller point of view, it is also possible to see that the wedge controller was able to precisely follow the normal force demand from the ABS controller. It confirms that the dynamics and controllability of the wedge brake is sufficient for high fidelity, high bandwidth vehicle dynamics control applications.

A high brake demand (40kN) is applied to the wheel, such that the ABS takes control of the brake even on the high friction surface. At about 2,100ms into the measurement, the tire transitions onto the low friction surface (time marked by chained line) and the ABS reduces the demand as a locking intention is observed. The jump can clearly be seen in the longitudinal force measurement, which also shows that the ABS copes with the transition relatively cleanly.

It can be seen that the average power is approximately 60W despite constant ABS activity. The power peaks at about 400 ms and 2200 ms are caused by reactions to increased wheel slip, which leads to large sudden changes in the demanded brake force, requiring fast actuator movements. It should be noted that the 60W measurement is equivalent to a current measurement that is close to the lower limit of the current sensor's dynamic range. Later measurements show that the EWB draws approximately 20W per wheel brake when a steady brake torque is requested.

The standard normal force controller was used to produce this measurement.

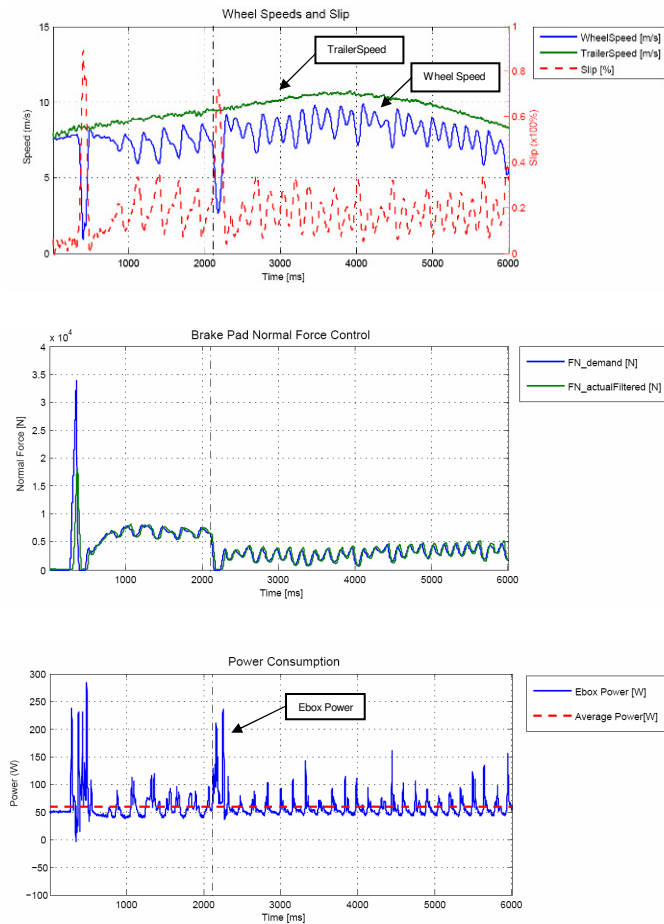


Figure 15: ABS with μ jump, trailer

High Friction Braking on Asphalt

After verifying the operation of ABS control of a single wheel, tests were done on the test vehicle and some more advanced algorithms were developed for the central chassis controller to ensure that the brake functions of all the brakes on the vehicle are coordinated.

The measurement in Figure 16 shows a braking situation on a high grip asphalt surface. For clarity, only the data from the left hand side wheels are shown. The right hand side wheels showed very similar behavior. The ABS controller used here has been more extensively tuned than the version used on the trailer, and it is clear that the system now provides better control of wheel slip and vehicle deceleration. The first panel shows that the wheel speeds are well controlled during the entire braking maneuver. The differences between the wheel speeds and reference vehicle speed remain below about 3 m/s, whereas in earlier tests, there were much larger initial drops in wheel speed when ABS was first activated.

From panel 2, one can also see that the vehicle deceleration remained constant throughout the braking. From panel 3, one can see that the braking forces reduced slightly from the beginning to the end of the braking, and that the wheels no longer locked towards the end of the recording. This is caused by an increase in μ between the road and the tyres as the braking

maneuver progressed. Because of this, later in the braking period the demanded brake force no longer caused the wheels to lock up, leading to an end to the ABS activity. At the end of the braking, one can see on panel 3 that the rear brake normal force reduces to zero – this is the process of wedge direction switching for holding the stationary vehicle, and when ABS is active, the switching process occurs after the vehicle has stopped.

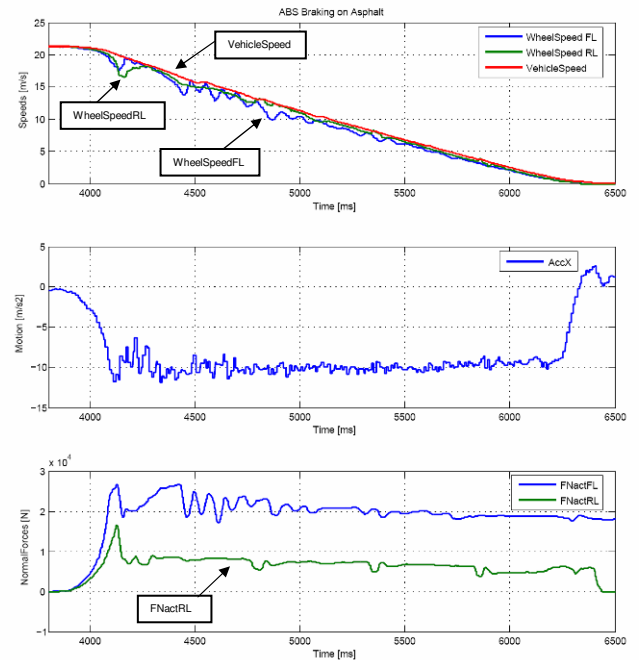


Figure 16: ABS on asphalt

μ-split Braking

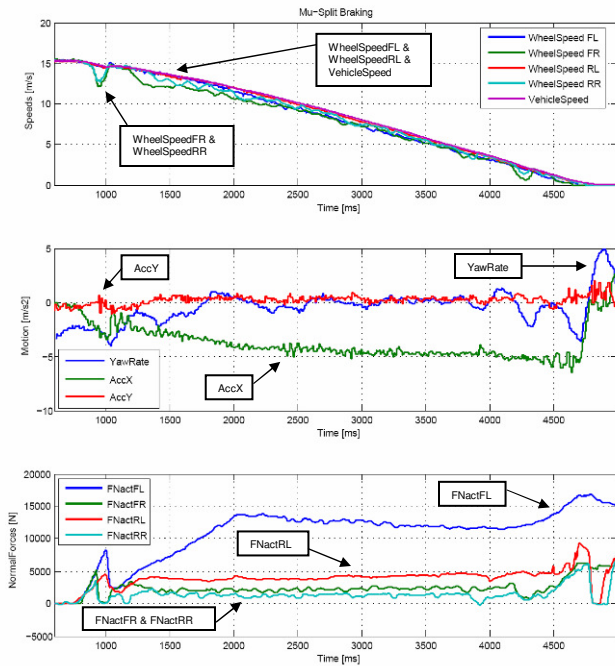


Figure 17: ABS on μ-split surface

The measurement in Figure 17 shows a typical ABS μ-split braking, where one side of the vehicle is braking on a low-friction surface and the other on high-friction. This situation needs special handling in the ABS control software. If the slip controllers are totally independent, the vehicle generates strongly asymmetric brake forces which cannot be compensated through steering inputs. If the axles use the so-called select-low controller method, they limit the brake force for both wheels to that on the low side of the vehicle. In this case, controllability is excellent, but the stopping distance is not acceptable.

The state of the art solution is to allow a limited brake force difference between the low and high side of each axle, such that the difference is gradually increased from a small value to the maximum allowed level using a ramp function. This allows the driver to compensate for the resulting yaw moment using the steering system. This yaw moment handling method is implemented in the ABS logic, as is shown in the measurement. The low side brake forces make the usual loop-like dynamic slip control, while the high side forces are increased with a ramp and limited to a level which represents the best compromise between stopping distance and directional stability.

Braking on a Low-Friction Surface

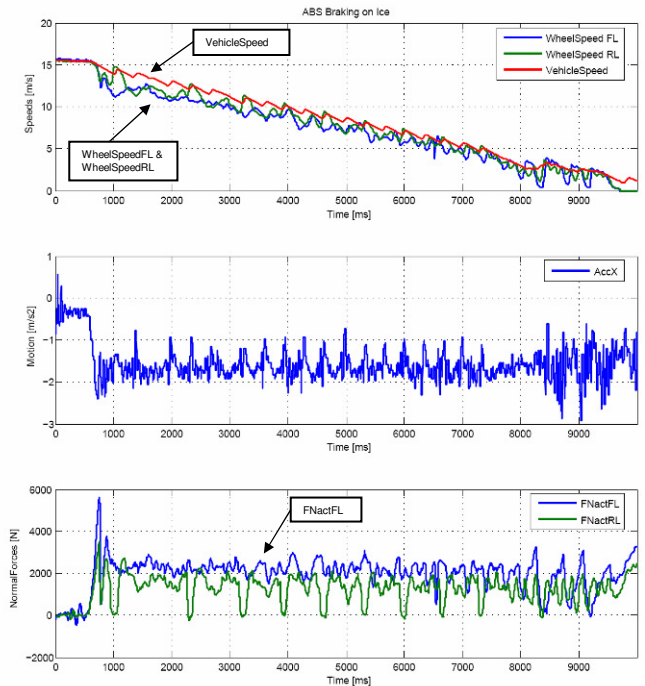


Figure 18: ABS on ice

The measurement in Figure 18 shows ABS operation on a low μ surface. Looking at panel 2, the deceleration with the ABS in operation is about 1.8 m/s^2 . One can see that the deceleration remains steady and shows that the ABS and wedge brake controller function accurately even at lower μ and force levels. One feature shown here is the wheel speed recalibration algorithm. As shown in panel 3, the brake clamping force on the rear wheel reduces to zero periodically, in order to gain an up-to-date measurement of the vehicle speed. The updating can be seen in panel 1, where the estimated vehicle speed behaves in a slightly jagged manner. The improved vehicle reference speed accuracy enables better slip calculations and therefore more accurate ABS control.

Soft Stop Function

In the case shown in Figure 19 the brake demand is reduced without driver intervention as the vehicle comes to a halt. The function is only enabled when the speed is below approximately 1.5 m/s , there is no ABS activity and the brake demand is in the comfort range so that the effect on stopping distance is zero in critical cases. It can be seen that there is no overshoot in the longitudinal acceleration as the vehicle halts (second panel). The 3rd panel shows that the normal forces on the rear brakes decrease to zero at about 3,000 ms – this is when the vehicle comes to a stop and the wedge direction change occurs at the rear wheels.

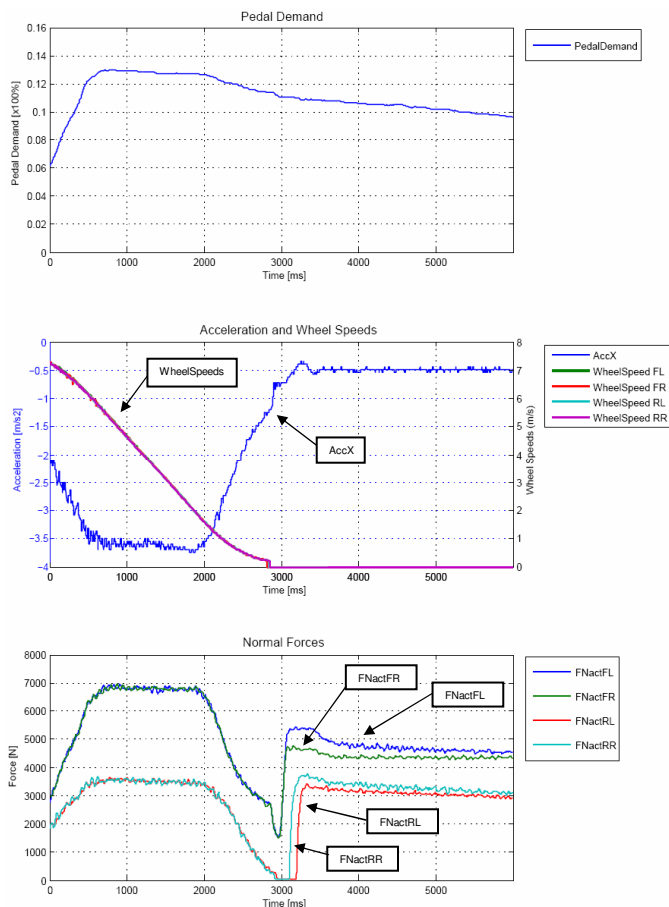


Figure 19: Soft Stop Function

PROGRAM STATUS

While the development of the basic wedge controller on the beta prototype is close to complete, testing with this prototype continues to progress in a variety of set ups and conditions, in order to test and validate higher level functions.

The next generation of hardware is being developed in parallel. This will be a concept that is much closer to production reality, not just regarding functionality but also packaging and cost. This will necessitate some further testing of the basic wedge functions, but the basic behavior will remain the same.

CONCLUSION

Brake-by-wire will enter the market at the end of this decade as well as integrated chassis control will be established, and ADAS functions will be in the vehicles using the by-wire technology. Our development will take these aspects into account. The braking functions will be AUTOSAR compliant and there will be an optimized

functional architecture with modular structure and interfaces to braking, steering and suspension. This concept uses an open architecture so the EWB will be an essential sub-system of integrated chassis control, managed either by the OEM or by Siemens VDO.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

EWB	Electronic Wedge Brake
EPB	Electric Parking Brake
μ	friction coefficient
F_N / normal force	brake caliper clamp force
ABS	anti-lock braking system
ADAS	advanced driver assistance system
AUTOSAR	Automotive Open System Architecture
OEM	Original Equipment Manufacturer