EVS26
Los Angeles, California, May 6-9, 2012

Braking Systems of electric and hybrid electric Vehicles under ergonomic Aspects

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Abstract

The amount of electric and hybrid electric vehicles in development or offered on the market is strictly increasing. To make such vehicles more efficient and to extend the range a common method is energy recuperation during braking. So electric and hybrid electric vehicles often are equipped with regenerative braking systems, which usually consist of a electric system and a friction brake. The layout and the interaction of both parts are very different and depend on several points, such as power train architecture, level of recuperation and so on.

A main focus of this paper is the quality of Human-Machine-Interface (HMI) of vehicles with regenerative braking systems. The aim of HMI is to give a feeling of authenticity and safety and it also should enable intuitive brake actuation. Because of enabled brake blending, many vehicles have a decoupled braking system as friction brake, whose pedal feeling often is described as “synthetic”.

This paper in a first step shows a benchmark of vehicles with regenerative braking systems with different layout. So the pedal and brake characteristics of coupled and decoupled braking systems are analyzed. In a further step the results of the benchmark are validated with test drives in a special built up research vehicle with variable pedal and brake characteristic. Based on these steps recommendations for layout of regenerative braking systems from the HMI point of view are given.

Keywords: BEV, braking, EV, series HEV, regenerative braking

1 Introduction

The amount of electric and hybrid electric vehicles in development or offered on the market is strictly increasing. Reasons therefore are stronger requirements for CO_2 emission and decreasing oil resources. A common problem of vehicles with an electric powertrain is the short range of kilometers that can be driven. To make such vehicles more efficient a common method is energy recuperation during braking. Therefore the architecture of braking systems has to change.

A main focus of the development of regenerative braking systems is the quality of the Human-Machine-Interface (HMI). The aim of the HMI is to give a feeling of authenticity and safety; it also should enable an intuitive brake actuation, so that brake situations and actuations have to be reproducible. From this point of view modern and future braking system concepts show relevant characteristics, which have to be identified and

rated. Topics as pedal and brake feeling, braking dynamics, artefacts out of interaction between electrical and mechanical friction brake or effect and feeling of fails-safe mode are set to focus of current research and development activities.
There is an actual demand on the field of systematic analysis of such specific and pedal feeling relevant features. Therefore methods for precisely automated and reproducible data acquisition of specific vehicle dynamics coupled with driver behaviour and its validation are necessary.

2 Regenerative braking systems

2.1 Recuperation

Conventional mechanical friction brakes reduce vehicle velocity by converting kinetic energy into thermal energy that usually is not used further. The principle of energy recuperation during braking is changing kinetic energy to another form of energy, which is in parts used for running the vehicle. This paper focuses on electromechanical energy conversion, the most common form. An electromechanical transducer that is coupled to the power train is running in generator mode and generates the braking torque depending on its rotational speed. Because of the limited power of the generator, its applied braking torque is limited, too. Therefore and to compensate the special characteristic of the generator in addition a conventional friction brake is necessary. A possible interaction between the two parts of the regenerative braking system is called brake blending (see Figure 1).

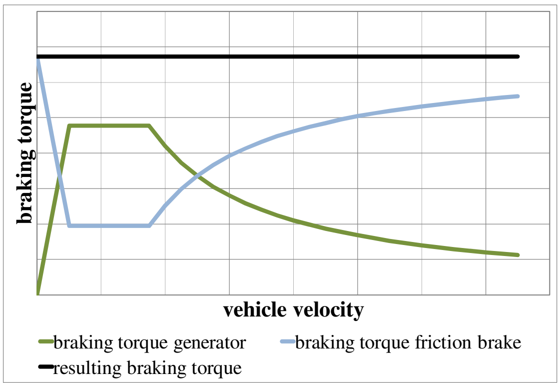

Figure 1: Brake blending – parts of braking torque for a constant resulting braking torque

With an assumption of 70% to 75% efficiency for generative-driven and motor-driven mode of the electrical machine incl. charging and discharging the battery, the total efficiency is about 50% to 55%. The NEDC offers approximately 1400 kJ braking energy during recuperation for vehicles with a gross vehicle weight of 1500 kg. The available energy for driving out of recuperation amounts circa 700 kJ. That corresponds to about 0.5 l/km [3], [4], [5].

2.2 Braking systems

Two different basic types of braking systems are available on market within hybrid electric and electric vehicles: coupled hydraulic braking system and decoupled brake-by-wire systems (see Figure 2 and Figure 3).

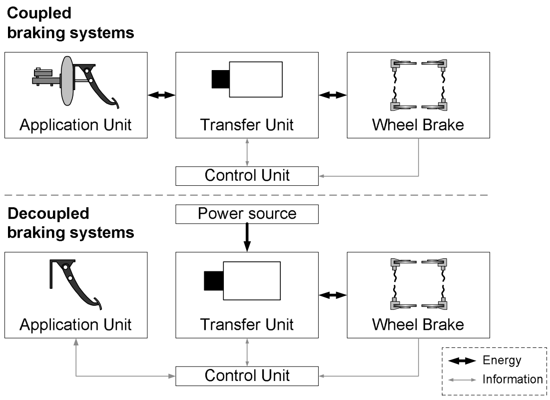

Figure 2: Principle of coupled and decoupled braking systems, based on [1]

Decoupled braking systems have no direct energetic connection between application unit and wheel brake. The braking torque is calculated by the control unit, based on detected driver command and set by interaction of power source, transfer unit and wheel brake. So the brake-by-wire system is, in contrast to coupled braking systems, able to adapt the braking torque of the friction brake to the wheel torque generated by the generator. Depending on architecture of power train different brake-by-wire systems are used (see Figure 3).
The layout of coupled braking systems does not enable brake blending because of mechanical connection between application unit and wheel brake. Mechanical initial travel extension in the master brake cylinder allows regenerative braking until initial travel is crossed and the friction brake is actuated. So within the range of initial travel the pedal travel – deceleration characteristic depends on vehicle velocity.
ESC systems enable an electronic extension of initial travel. Though ESC systems reduce brake pressure during low and moderate brake actuation when the generator offers braking torque. Figure 3 shows the different layout possibilities of regenerative braking systems.

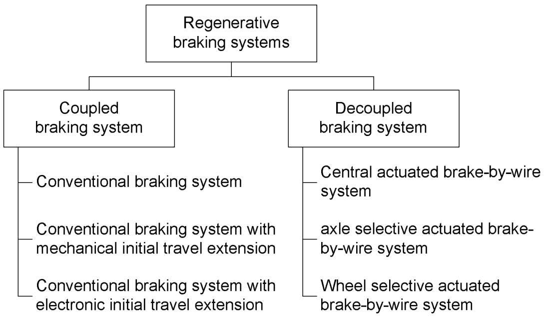

Figure 3: Layout of regenerative braking systems

The non existing energetic connection between application unit and wheel brake of brake-by-wire systems causes some differences in brake and brake pedal feeling and in fail safe mode compared to coupled braking systems. To give the driver a feeling of authenticity and safety and to guarantee an intuitive brake actuation, brake-by-wire systems need a pedal simulator, an additional assembly that should create the common brake pedal feeling. Such simulators can be classified into dry and wet concepts. Dry simulators only use mechanical elements, such as springs and elastomers. Wet concepts are built up with mechanical and hydraulic components.
Fail-safe concepts of brake-by-wire systems look different, depending on the system layout. The most common architectures are based on hydraulic braking systems. So fail-safe mode usually is based on build up of an energetic connection between application unit and wheel brake (e.g. by switching a valve). Depending on layout of the braking system, it is different if front and rear axle or only front axle is actuated within fail-safe mode. Electromechanical braking systems need other more difficult fails-safe concepts. But such systems are not considered in this paper.

3 Analysis of vehicles with regenerative braking systems

The following passages bring some characteristics into focus that are typical for the analysed braking system concepts.

3.1 Analysed vehicles

Within the research activities two electric vehicles, two hybrid electric vehicles and one electric vehicle with range extender were analysed.

Table 1 and Figure 4 give an overview about the spectrum of analysed vehicles. All vehicles convert kinetic to electric energy during recuperation.

Table 1: Comparison of power train and braking systems of analysed vehicles

Vehicle	**Power Train**	**Braking system**	**Brake blending**	**Fail-safe**
Vehicle 1	mild *hybrid* rear-wheel-driven	central actuated brake-by-wire system with active booster and dry simulaor	available, not axle selective	mechanical connection between application unit and all wheel brakes
Vehicle 2	strong *hybrid* variable 4-wheel-driven	electrohydraulic brake-by-wire system with wet simulator	available, wheel selective	hydraulic connection between application unit and wheel brakes at front axle
Vehicle 3	*electric* vehicle front-wheel-driven	conventional coupled hydraulic	not available	conventional
Vehicle 4	*electric* vehicle rear-wheel-driven	conventional coupled hydraulic	not available	conventional
Vehicle 5	*electric* vehicle with range extender front-wheel-driven	electrohydraulic brake-by-wire system with wet simulator	available, wheel selective	hydraulic connection between application unit and wheel brakes at front axle

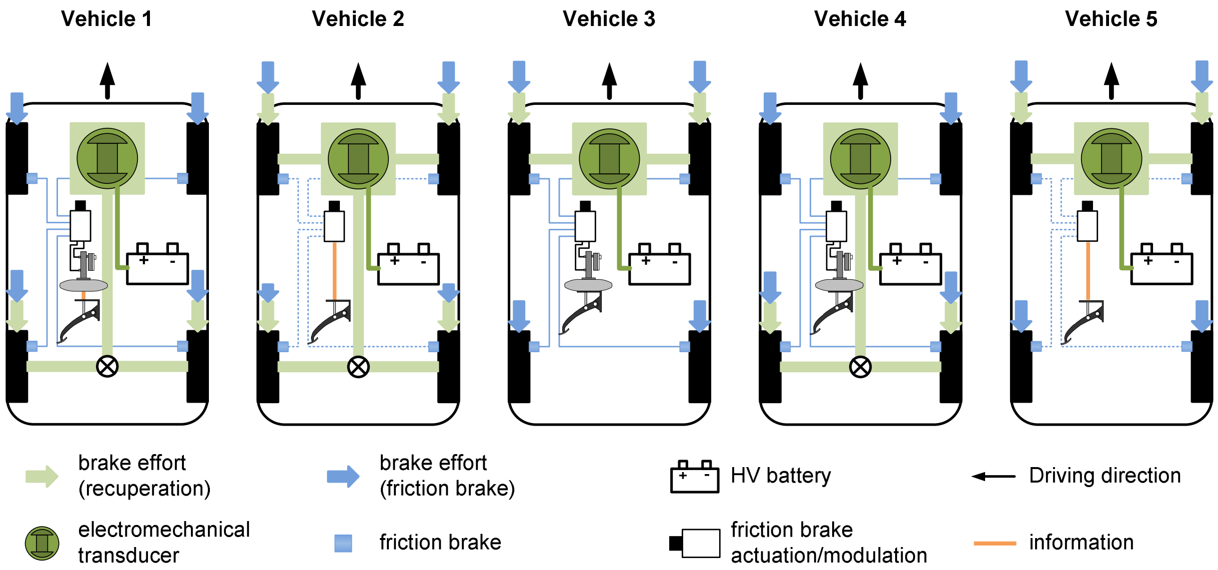

Figure 4: Comparison of power train and braking systems of analysed vehicles

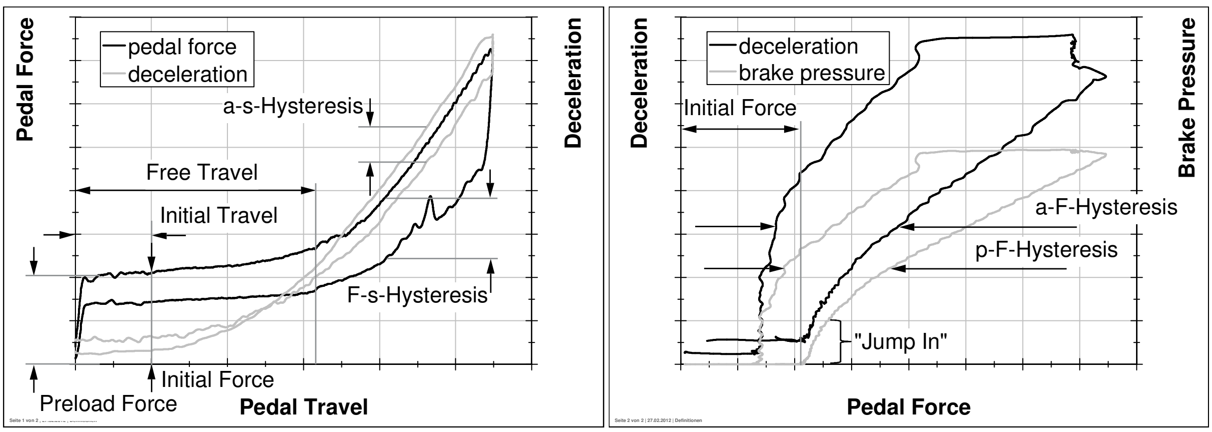

Figure 5: Definition of brake pedal and brake characteristic [6]

3.2 Test concept

To guarantee reproducible and automated measurements, a servo-hydraulic pedal actuator (“Brake Robot”) was used. This Robot offers different methods of pedal actuation, such as a series of ramps or oscillating movements in driving and stationary mode.

A uniform definition of pedal travel and pedal force (see Figure 5) combined with standardized and automated pedal actuation enable a comparable and effective evaluation. Pedal travel is defined as the secant of the circular path done by boundary point of tangent from pedal pivot to pedal pad. Pedal force is the effective force that appears rectangular in this boundary point. [7]

3.3 HMI of analysed braking systems

Figure 6 compares the brake pedal characteristics of all five analysed vehicles. Pedal application is a ramp with a speed of 0.005 m/s until about a deceleration of 8 m/s² is reached.

Vehicle 3 and 4 show a typical characteristic of conventional braking systems. The free travel with a small dF/ds gradient is followed by a progression with a large dF/ds gradient at the end. So the curve is accurately divided into two parts.

Characteristic 5 is a good reproduction of such a conventional one with two clearly separated parts.

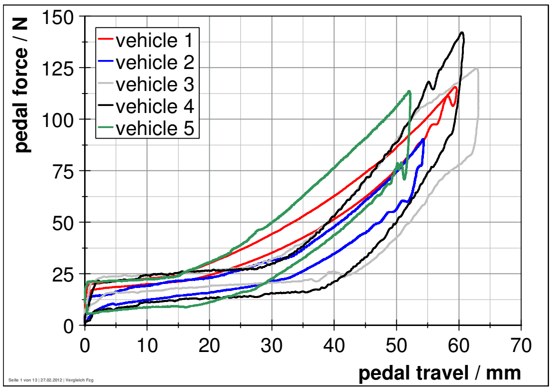

Figure 6: Pedal force against pedal travel at quasi-static pedal application

In contrast curves of vehicle 1 and 2 look different. Here the free travel is not defined so exact. Vehicle 1 with the dry pedal simulator has a very harmonic characteristic. The second vehicle has two separate parts in its characteristic, but the gradient of free travel is high because of a very small preload force in comparison with the preload force of the other characteristics. Because of the small preload force it is difficult for the driver to find intuitional the brake pedal in case of moving his foot from gas to brake pedal.
Regarding the hysteresis, the dry simulator of vehicle 1 offers the smallest one. Indeed Figure 6 only shows the static hysteresis but characteristic 1 also has the smallest dynamic hysteresis. Hysteresis in a defined range is essential to for realizing a stable pedal [6], [7].
In Figure 7 the brake characteristics of the benchmark vehicles are plotted. The test procedure is the same as described at beginning of chapter 3.3.

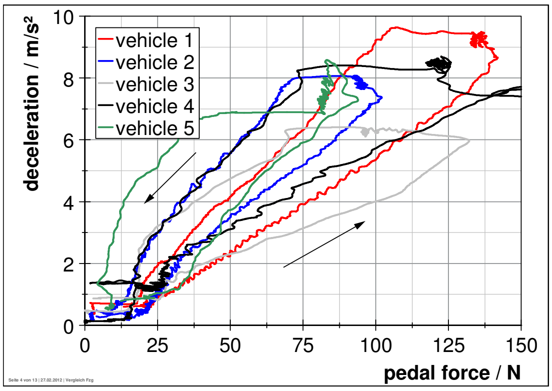

Figure 7: Deceleration against pedal force at quasi-static pedal application

“Jump in” and pedal force at maximum deceleration are important within the a-F characteristic. Jump in is a large da/dF gradient at beginning of the pedal application that leads to a high braking effect followed by a degressive progress of the curve. This range corresponds to the free travel but from another point of view. In coupled braking systems the jump in is caused by the booster. Especially at low vehicle velocity and in ranges of low deceleration (e.g. parking) this part of the characteristic is very important for the driver to dose deceleration [6]. Pedal force at maximum of deceleration accounts for the safety feeling of the driver. If it is too high, reaching maximum deceleration is not comfortable, but if it is too small, brake effect all over the application range becomes too large and it is difficult do dose deceleration.
Vehicle 2 features the only brake-by-wire system that simulates the jump in. The characteristics of vehicles 1 and 5 do not offer such a a-F characteristic. Contrariwise braking system 1 also has a very poor braking effect all over brake actuation. A consequence out of the small da/dF gradient of characteristic 1 is a comparable high pedal force within low and moderate deceleration.
Figure 8 shows the p-s characteristic. Conventional braking systems, as vehicle 3 and 4, typically do not have a hysteresis. In contrast curves of the brake-by-wire vehicle show a large hysteresis. But as it is shown in the following passage, this hysteresis is not caused by friction and damping effects of brake components. Rather the reason for this hysteresis can be found in poor time delay between pedal and brake actuation caused by latency periods of control units.

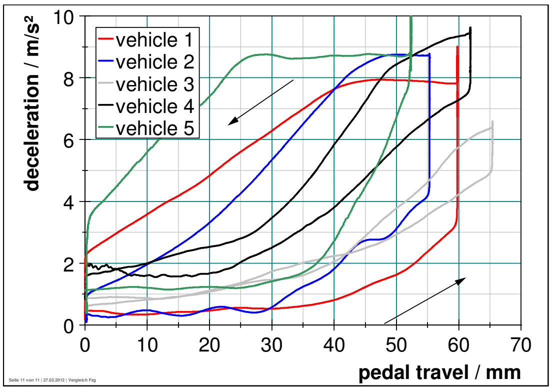

Figure 8: Deceleration against pedal travel at pedal speed of 0.2 m/s

3.4 Analysis of brake dynamics

For analysis of system dynamics of a real braking system with on-road tests it is not possible to use a deceleration step. So another input function has to be realized, such as a ramp. For getting the correct system response without influence of any driver

assist system such as Brake Assist, the ratio of the ramp is limited. The following test procedure is a pedal travel controlled application. The set point corresponds to a deceleration of about 8 m/s². Measurement starts at a vehicle velocity of 130 km/h. Dynamic pedal application speed of the ramp is defined by 0.05 m/s, 0.1 m/s and 0.2 m/s.
Reference of the measurement in application direction is a pedal application with pedal velocity of 0.005 m/s. Because of the slow pedal velocity, time delay between pedal and brake actuation only has a very small influence on the p-s characteristic. To analyze the brake dynamic of faster pedal applications, the reference is scaled with a factor that scaled pedal velocity of reference and original pedal velocity are the same. So scaled reference brake actuation becomes the set point. For evaluation time delay t_1 at deceleration $a_1 = 1$ m/s² and time delay t_2 at deceleration $a_2 = 6$ m/s² is analyzed (see Figure 9).
Table 2 gives a summary about reached dynamics of the benchmarked braking systems.

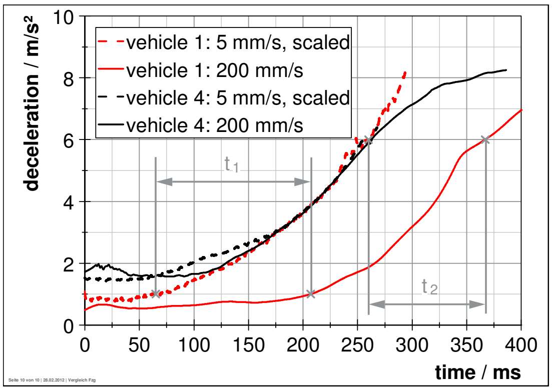

Figure 9: Time response at fast pedal application

When releasing brake, response-time is the time measured from beginning of moving backward the pedal until deceleration decreased 10% in value.
Figure 9 shows exemplary dynamics of a decoupled (vehicle 1) and a conventional coupled (vehicle 4) braking system. All analysed brake-by-wire systems have a poor time response in comparison to the conventional braking systems in both directions: application and release (see Table 2). So the often called advantage that decoupled braking systems are more dynamic than coupled braking systems (see [1], [8]) is rebutted in analyzed vehicles.

Table 2: time response of dynamic brake application

	Vehicle 1	**Vehicle 2**	**Vehicle 3**	**Vehicle 4**	**Vehicle 5**
pedal velocity: 0.05 m/s					
t_1 / *ms (1 m/s²)*	136	126	3	-	-
t_2 / *ms (6 m/s²)*	113	306	28	1	-81
pedal velocity: 0.1 m/s					
t_1 / *ms (1 m/s²)*	144	77	9	-	-
t_2 / *ms (6 m/s²)*	105	210	33	5	29
pedal velocity: 0.2 m/s					
t_1 / *ms (1 m/s²)*	140	77	9	-	-
t_2 / *ms (6 m/s²)*	110	109	74	6	26
pedal velocity: -0.2 m/s					
$T_{90,rel}$ / *ms*	127	96	39	75	154

3.5 Recuperation and brake blending

Test procedure is a pedal travel controlled application, with a set point that corresponds to a deceleration of 2 m/s² out of a vehicle velocity of 85 km/h. Pedal application speed is 0.1 m/s until vehicle deceleration reached 2 m/s², then a constant pedal travel is kept. The illustrated current is measured between power electronics and high voltage battery in each case.
Different braking system and power train architectures (see Figure 4) lead to different characteristics during brake actuation. In Figure 10 the braking process of vehicles 2 and 5 are shown. Both vehicles are equipped with brake-by-wire systems and so they enable brake blending (see

Table 1). Therefore deceleration difference between braking in drive mode “D” and “N” is nearly zero in each case. But because in power train of vehicle 2 there is placed an E-CVT transmission between electric generator and wheels is variable. So it is possible to configure the operating point of the electric transducer in a point of maximum recuperation with constant high current.
In vehicle 5 generator is directly connected to front wheels with a constant transmission. So during braking process the recuperated current decreases. But the ratio of regenerative braking in vehicle 5 is higher than in vehicle 2. As result within low deceleration (e.g. 2 m/s²) brake pressure can be reduced to 0 bar (see Figure 10, right).

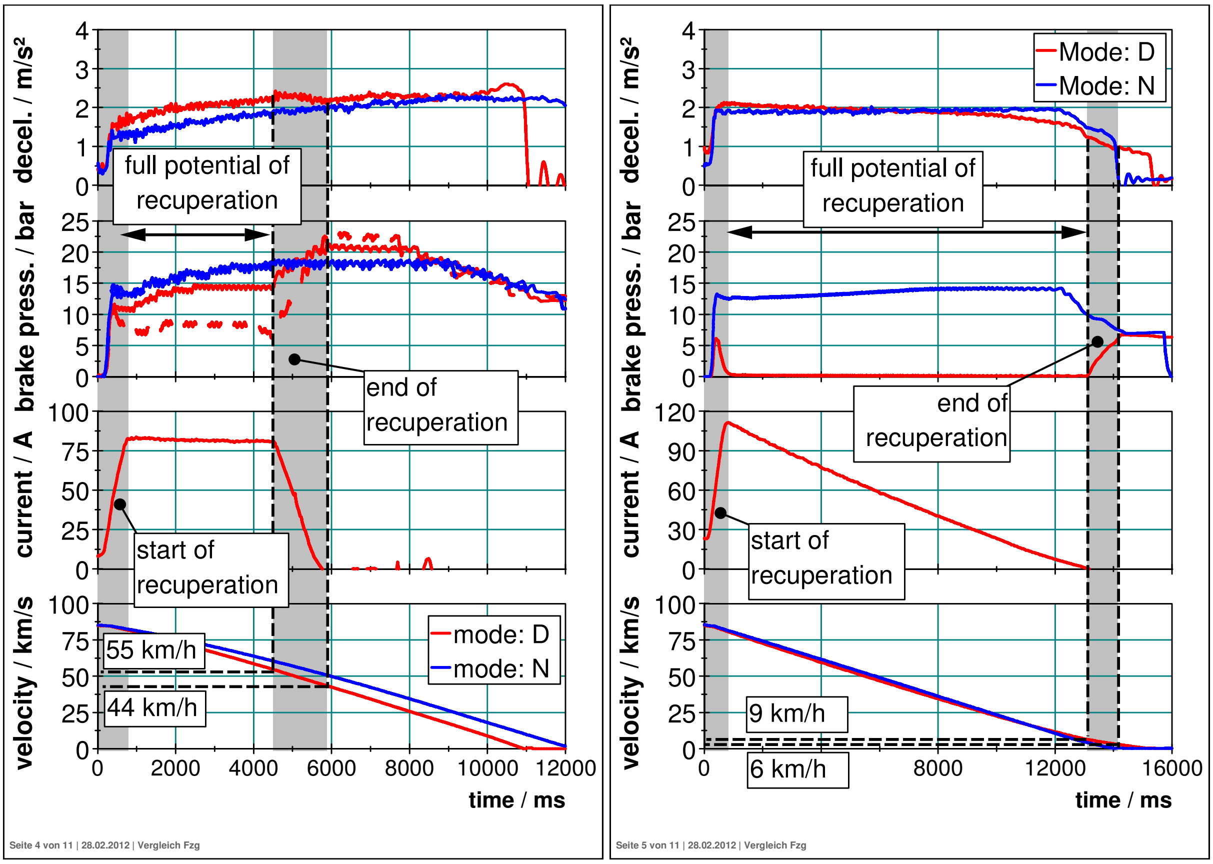

Figure 10: Regenerative braking of decoupled braking system with brake blending. Left: vehicle 2, Right: vehicle 5

Regarding the measurements of regenerative braking with conventional coupled braking system of the electric vehicle 4 in Figure 11, some elementary differences become articulate. As it is shown, no brake blending is possible. So brake pressure is independent of driving mode. In consequence a constant pedal application does not lead to a constant deceleration. The ratio of regenerative brake is added to the brake torque of friction brake. During full potential of recuperation the generator torque is constant. That causes a constant deceleration until about 20 km/h. The deceleration part generated by electric transducer is about 1.75 m/s². Because of a direct connection of the generator to the rear wheels, the current decreases with a constant gradient. After end of recuperation deceleration only is generated by friction brake (running-resistance is neglected). Since the brake pressure remains constant, deceleration decreases 1.75 m/s² in value.

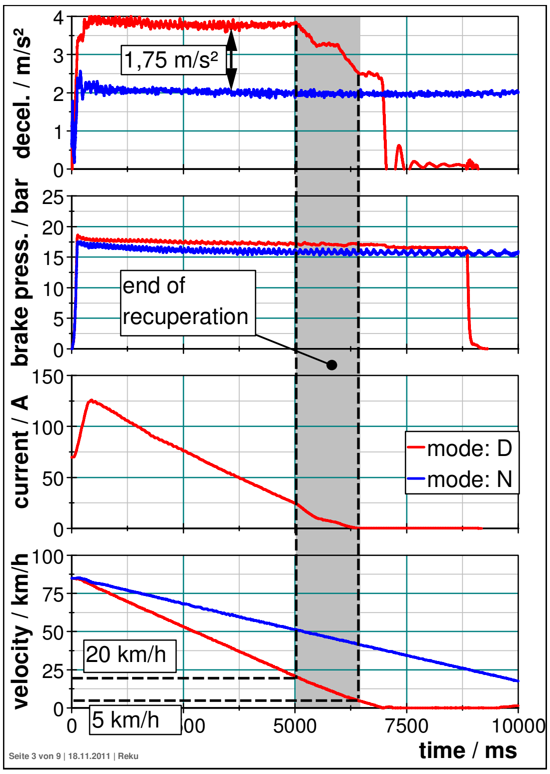

Figure 11: Regenerative braking of coupled braking system of vehicle 4

3.6 Fail-safe concepts

Brake-by-wire systems generally require the same requirements to emergency braking system as conventional braking systems. But the realization is something different. In all analysed vehicles, fail-safe concept is implemented with a direct mechanical or hydraulic connection from application unit to wheel brake (see

Table 1). According to [2] with a pedal force of 500 N at least 2.44 m/s² have to be reached in fail-safe mode.

Figure 12 gives an overview about the p-F characteristic of stationary brake-by-wire vehicles.

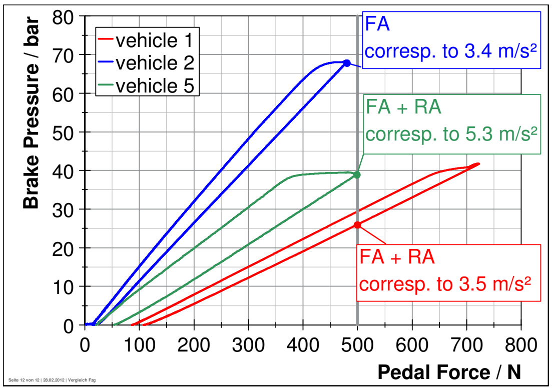

Figure 12: Brake pressure in fail-safe mode, stationary vehicle

In vehicles 1 and 5 the driver actuates front and rear wheel brakes. In contrast in vehicle 2 application unit only is connected to front axle in fail-safe mode. That is the reason for the higher dp/dF gradient. Corresponding deceleration values are identified out of brake actuation of driving vehicle in drive mode "N". So the relationship between brake pressure and deceleration could be identified and effects caused by generator are eliminated.

4 Test drives for gaining perceptual thresholds of drivers

Based on the braking characteristics of artificially imprinted events or interference effects (disturbances) in the manner of additional brake torque were simulated in the context of this base investigations, as can occur in coupled regenerative braking systems. The severity of these interference effects has been varied with regard to alteration time and change level. This allowed statements about which disturbances are just not perceptible for the driver. As a starting point the accepted very good pedal and braking characteristics of a midsize car with a conventional non-regenerative braking system was selected.

In Figure 13 for each variant, the mean values of evaluation are shown for all test persons. It confirms the expectation that in addition to the pure amount of disturbance (|z|) even the time when the disturbance reaches its full amount (dz / dt, alteration time) has an influence on whether this is perceived by humans or not. Furthermore, the sign of the disorder is relevant (sign (z)). To quantify the perceptual thresholds it is not enough to indicate only the amount of potential disturbance.

interpretation	1=very disturbing
	4=not noticeably

„low" deceleration (ca. 1 m/s²)

change level \ alteration time	5.0 s	2.0 s	1.0 s	0.5 s	0.1 s
+100 % (+1,0 m/s²)	3.0	2.4	2.0	2.3	1.3
+50 % (+0,5 m/s²)	3.1	2.9	2.7	2.7	2.0
+25 % (+0,25 m/s²)	3.7	3.6	3.3	3.3	3.3
+10 % (+0,1 m/s²)	3.7	4.0	4.0	3.8	3.8
0% (+/- 0,0 m/s²)			3.9		
-25 % (-0,25 m/s²)	3.8	3.8	3.5	3.3	2.8
-50 % (-0,5 m/s²)	3.7	3.4	2.9	2.6	2.4

„moderate" deceleration (ca. 3 m/s²)

change level \ alteration time	5.0 s	2.0 s	1.0 s	0.5 s	0.1 s
+50 % (+1,5 m/s²)	2.6	1.9	1.5	1.5	1.0
+25 % (+0,75 m/s²)	3.5	2.5	2.5	2.5	1.9
+10 % (+0,3 m/s²)	3.8	3.5	3.7	3.7	3.7
0% (+/- 0,0 m/s²)			3.9		
-25 % (-0,75 m/s²)	4.0	3.3	3.0	2.5	2.0
-50 % (-1,5 m/s²)	3.5	2.6	2.8	2.1	1.8

Figure 13: Evaluation – averaged over all probands

The larger the amount of disturbance and the larger the gradient is, the sooner and more strongly this variant is evaluated as a nuisance. Large disturbance amplitudes are still acceptable if the duration of the alteration time of the disturbance is long enough. The driver then compensates the disorder - perhaps unconsciously - more easy. Overall, the resulting changes in the vehicle deceleration, which are easy tolerated by the probands are very low (up to b = ± 0.3 m/s ²). It is expected that a disturbance in the vehicle deceleration which occurs very close to the time the vehicle is stationary, is masked partly by the vehicle body pitching. It would be permissible stronger disturbances in this case.

A disturbance in the form of increase in vehicle deceleration is irritating to the driver and leads to severe over-braking of the vehicle if the disturbance is too strong. The reason for this may be found in the inertial force self-excitation of the "braking leg" (see also [7]). If the driver already depresses the brake pedal while the vehicle performs a jump-like increase of the deceleration, the inertia of the musculoskeletal system leads to that the driver realizes an abrupt increase in pedal force. The result is a further increase of vehicle deceleration. This effect is self-reinforcing and is obviously difficult to compensate by the driver. A disturbance in the form of a decrease of the vehicle deceleration affects also tends irritating, but can be well compensated by the driver.

Generally, the imprintings of the interference effects occur as slowly as possible. It should be noted that abrupt changes with an alteration time near t=0.5 s, should be avoided.

5 Conclusion

In summary the studies showed, which disturbances caused by regenerative braking process are noticeable by the driver. The level of the driver's toleration is depending on amplitude and the gradient of the additional deceleration. The perceptual threshold of disturbances in vehicle deceleration lies in a range of about ± 0.3 m/s². Mentionable is the fact that this threshold seems to be independent of the initial deceleration level. Furthermore deceleration increasing leads to over-braking, that only can be controlled poorly by the driver. Decreasing deceleration is disturbing, too, but can be controlled better. So, depending on recuperation level and its characteristic, brake-by-wire systems are recommended, especially within vehicles with high recuperation potential, as vehicle 2 or 4. Finally the decision actually is a compromise inside the goal conflict of a good pedal feeling, tolerated disturbances interference effects of brake blending and costs. But for vehicles with high recuperation level a brake-by-wire system is advisable.

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