Functional Potential by Crosslinking Domains – Optimized Recuperation for the SpeedE Research Vehicle

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Summary

The Institute for Automotive Engineering (ika) of RWTH Aachen University is currently developing, constructing and implementing the research vehicle SpeedE as an open innovation platform for research and industry. The conflict between efficiency, safety and driving experience is one the most difficult challenges in automotive development. Crosslinking different domains inside a vehicle seems to be an adequate way to at least partly solve this conflict. To illustrate this procedure on the example of a brake-by-wire system, this paper will firstly introduce the research vehicle SpeedE and its different domains. The different sensors and actors will be presented to show the functional potential by crosslinking them. As an example an optimized recuperation strategy will be inspected. It will be shown that, by intelligently using the full potential of the vehicle, the efficiency can be improved without adding further components and therefore keeping the weight, costs and complexity to a minimum.

1 Introduction of the SpeedE Research Vehicle

The Institute for Automotive Engineering (ika) of RWTH Aachen University, is currently developing, constructing and implementing the research vehicle SpeedE (see Figure 1) as an open innovation platform for research and industry. The goal of the concept vehicle is to create a distinct added value to an electric vehicle, leading from electromobility to E-Motion. The vehicle concept was developed in conjunction with the renowned Department of Transportation Design at Hochschule Pforzheim University, with the intent of combining design and technology in a new approach at an earlier stage of development. Financial support for this project is offered by the foundation Hans Hermann Voss-Stiftung. [1]

Fig. 1: SpeedE Rolling Chassis at Aachen Colloquium 2014

SpeedE is an all-electric vehicle that features drive-by-wire, brake-by-wire and wheel individual steer-by-wire functionalities. The Body is designed as an extremely stiff aluminum space frame structure developed in house. The structure of the spaceframe is validated by numerical analysis throughout the complete development process in order to ensure body stiffness at sportscar level and excellent structural performance even in harsh crash load cases. The driver's seat is located in central position; additionally two rear passenger seats can be integrated.

The whole project was started mid 2011, some of the key milestones are listed in Figure 2.

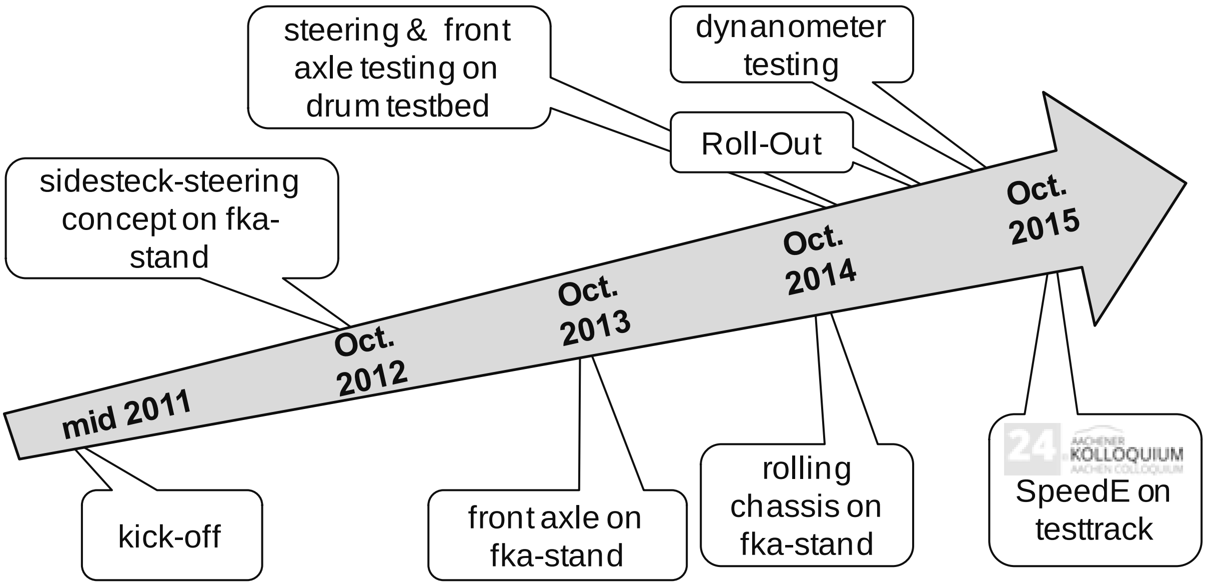

Fig. 2: SpeedE Development Timeline

Instead of a conventional steering wheel, control of the vehicle can be achieved via the use of two sidesticks as depicted in Figure 3. The sidesticks are mounted stationary. The driver can adjust his seat as well as the pedals in order to achieve a comfortable driving position. Besides the new control system by using active sidesticks new interior design possibilities are created. The front axle's steer-by-wire system is not only able to steer each wheel individually, but also to achieve steering angles of up to 90°. The central core of the steering system is made up of two electric motors in combination with harmonic drive reduction gears integrated in the upper control arms of a double wishbone suspension, which is accompanied by a replacement of the outer ball joints of the upper control arm by cardan joints and an elimination of the tie rods. Using an electric rear axle with twin motors, torque vectoring is possible. This allows outstanding maneuvering possibilities. A turning circle with the rear, inside wheel set as the center of rotation can be achieved. [2].

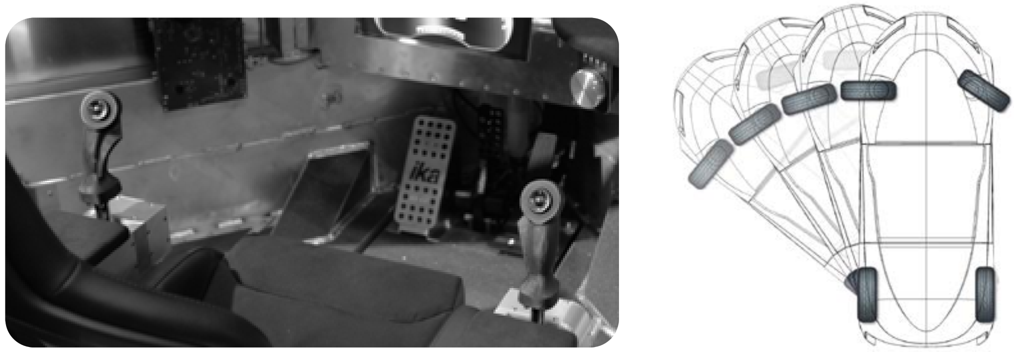

Fig. 3: Steering via sidesticks, high maneuverability

The all electric drive train as depicted in Figure 4 mainly consists of two electric motors that each drive one rear wheel, allowing above mentioned torque vectoring functionalities not only while parking but also while cornering at higher speeds. The maximum power of each motor is around 100 kW. The maximum battery power is 160 kW, thus maximum engine power can only be used while torque vectoring. The battery being located behind the seats leads to a rear axle load percentage of about 60 %, allowing the transfer of high wheel forces during driving. Maximum engine torque is 220 Nm up to a motor speed of 3,600 rpm (corresponding to about 80 km/h). Above 3,600 rpm the engine torque decreases, down to about 60 Nm at 11,000 rpm.

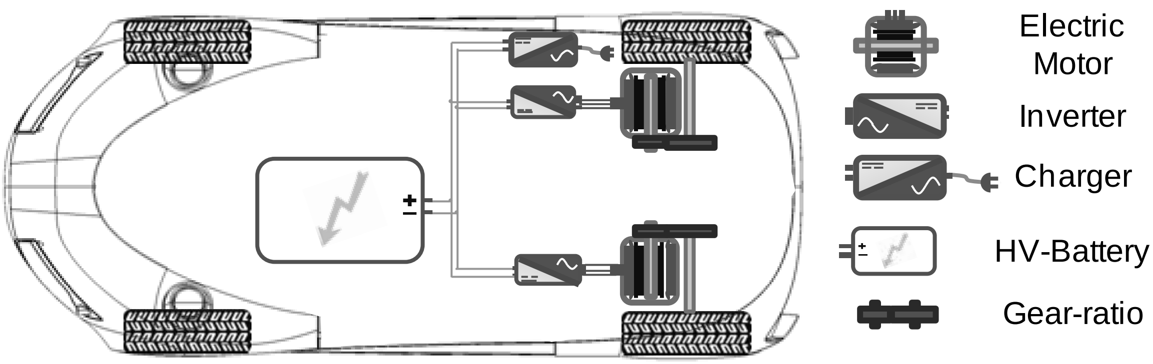

Fig. 4: SpeedE Drive Train Topology

One special feature of SpeedE research vehicle that is involving different vehicle-domains is the safety concept for the steering system in conjunction with the drive train. As it is a complete steer-by-wire system, safety measures have to be implemented, especially for the case of one steering actuator malfunctioning. To keep the vehicle weight to a minimum, hardware redundancy, like for example used in aviation steer-by-wire systems, is not an option. Also costs are negatively influenced by adding further components. Therefore other approaches had to be looked at. Firstly safety goals have to be defined intelligently by keeping the solution space as wide as possible. The main safety goal should not be that the steering actuators never fail but that if one of the steering actuators fails, the vehicle can still be navigated to a safe standstill, even by a non professional driver. Instead of developing a domain centered safety system, crosslinking the different domains has been inspected to take advantage of the capabilities of other domain's components in order to avoid redundancies. Using simulation, it can be shown that in the case of faulty steering actions by one actuator this can be compensated by correctional steering of the second actuator and torque vectoring actions by the electric motors. Due to these interventions the vehicle can be navigated to a safe standstill as demanded earlier. Although this solution is more complex on the functional side than a redundant steering actuator, this cross-domain measure is very efficient from the point of size, weight and costs. [3]

Another important feature is the brake-by-wire system, optimized for driving safety and energy efficiency. Using a combination of regenerative braking and electro hydraulic actuators all four wheels can be individually braked depending on the current driving situation. The braking system will be further inspected in chapter three of this paper.

2 Vehicle Domains - Sensors and Actors

In this chapter the different sensors and actors of the SpeedE research vehicle as well as the communication structure will be presented. Knowing the functionality of the different components is needed as a basis to understand the brake-by-wire system presented in chapter three of this paper. Sensors are components that only deliver information about the current state of the vehicle to the control algorithms. Actors on the other hand are additionally able to undertake actions as demanded by the control algorithms. Components that are not necessary for the control algorithms of the brake-by-wire system are out of scope of this document.

2.1 Communication Structure and Development Platform

In Figure 5 the communication structure inside SpeedE research vehicle is illustrated. The different communication methods using CAN, FlexRay, digital, serial and analog connections can be seen. Control algorithms are designed by using Matlab/Simulink. The whole system is running on a dSPACE Micro Autobox II.

The steering actuators as well as the sidesticks are communicating by using the FlexRay protocol. Furthermore all four CAN-Channels offered by the Autobox are used. The High-Voltage CAN is connecting the components from the drive train domain, such as the electric motors / inverters, the battery, battery charger and 12V DC/DC Converter. The Brake CAN is connecting four electro hydraulic actuators with the control algorithms that will be presented in detail later on. The HMI CAN is controlling the lights, gear choice, an accelerometer and will be extended to control a display in the near future. The last CAN (marked as Steering CAN) has been controlling the steering actuators and sidesticks before those components had been upgraded to FlexRay. For now only the 48V-Battery is left on this CAN. Besides CAN and FlexRay there are serial, analog and digital inputs and outputs being used. The serial input is connected to a GPS sensor, delivering information about the current position and velocity. The analog input is connected to the driving-pedal and information of the wheel speeds is gained by using the digital inputs.

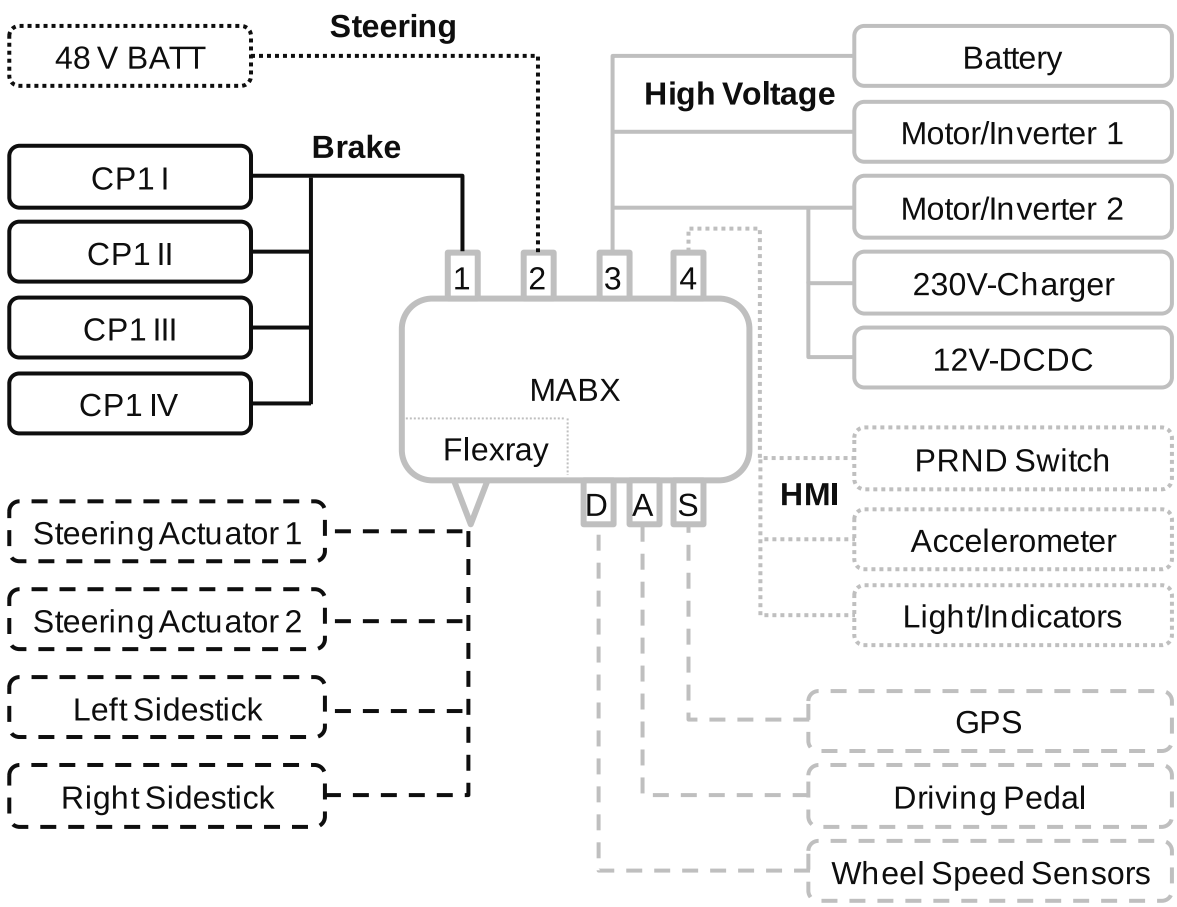

Fig. 5: Communication Structure SpeedE

There are further components connected, for example those of the cooling system; however since they are not relevant for the topic of this paper they will not be shown.

2.2 Actors and Sensors

Sidesticks:

Main functionality of the two sidesticks (left and right, see Figure 6 below) is to steer the vehicle. Besides that the driver can demand a deceleration by using the recuperation-trigger of each sidestick. Furthermore there are five different buttons on each stick that can be used for various functions, like for example activating the indicators, the lights or the horn.

Based on the driver's hand-force the sidestick-controller determines the steering demand. The drivers hand force is converted to the steering angle of a single track model. In multiple steps this angle is converted into the individual steering angles for each wheel. As a feedback for the driver, the calculated wheel angles are lead back to the sidesticks that adjust their position in coherence with the actual wheel angle. At the time this paper was written there are no feedback methods for the recuperation trigger, therefore the brake system is completely decoupled.

Brake Actuators / Brake System:

Inside the SpeedE research vehicle four wheel-individual electro hydraulic actuators, as pictured in Figure 6, by FTE automotive are used. Inside the actuator an electric motor moves a piston over a spindle to generate hydraulic pressure. Since the component actuation is not part of the recuperation logics it shall be described shortly. Depending on the brake force demand the control algorithm firstly determines a pressure demand. In the next step the target position of the spindle is calculated in order to reach the wanted pressure. The position is controlled via a PID-Controller. Communication between the control strategy on the dSPACE Autobox and the actuator is running via CAN. For functional safety the spindle has not been build self locking. In the case of a failure or missing power supply the actuator will therefore not generate any pressure.

Fig. 6: Sidesticks and Electro Hydraulic Actuator

Secondly a conventional hydraulic braking system is installed. This system can be seen as a safety measure to guarantee a fallback system if any of the X-by-wire systems fails in this prototype vehicle. The conventional brake system mainly consists of a brake pedal acting on a balance beam, brake lines and its own brake caliper. Brake disks are used by both brake systems. The brake circuit layout is X-distribution, so diagonal wheels are combined in one circuit. Brake force distribution can be adjusted by the balance beam, there are no further components like for example a brake booster.

GPS-Sensor:

The SpeedE research vehicle is fitted with a Navilock MD6 GPS sensor. Main functionality at the moment is to deliver additional information about the velocity. In the future the information might be used for example for navigation purposes or other systems.

Accelerometer:

The SpeedE research vehicle is fitted with an accelerometer delivering real time information about the current lateral and longitudinal acceleration as well as the yawrate. This information is crucial for the correct determination of the current dynamic state of the vehicle.

Wheel Speed Sensors:

Each individual wheel is fitted with a wheel speed sensor. The information about the different wheel speeds is used to estimate the vehicle velocity or detect slipping wheels.

2.3 Drive Train Components

Battery:

The SpeedE research vehicle features a Li-Ion Battery of the type EVB1-400-40 constructed by Brusa. Nominal voltage is 400 V, with voltage while operation ranging between 324 V and 448 V. As seen from the type designation capacity per cell is 40 Ah, leading to an energy content of 16 kWh. Total number of cells is 108. The maximum discharge power is 160 kW (400 A), continuous discharge power is 80 kW (200 A). Charging can be achieved with up to 32 kW (80 A). Total weight of the battery is around 145 kg. Control and communication of the battery is achieved via CAN. Important information for the recuperation logics are the maximum allowed charging current, the battery voltage, state of charge and temperature.

Motors:

The SpeedE features two hybrid synchronous motors by Brusa combined in one unit. Propulsion is wheel individual with each motor delivering up to 100 kW of peak-power. Peak torque is around 220 Nm; maximum engine speed is 12000 rpm. The ratio between wheel and motor is at 5.5 leading to a wheel torque of more than 1200 Nm. The motors are directly controlled by the inverters.

Inverters:

The inverters are, as well as the motors and the battery, constructed by Brusa (type: DMC524) to guarantee optimal functionality under all circumstances. Efficiency is around 97 %, maximum power at 105 kW and the continuous power is at 79 kW (225 A). The operation range is between 120 V and 450 V, therefore surpassing the battery limits. As with the battery, control is achieved via the use of the High-Voltage CAN. Recuperation can be achieved by sending a negative torque demand. Additionally the control algorithms determine the maximum permitted motor and generator currents. Depending on the state of the battery those limits have to be adapted dynamically so the maximum battery charging current is not exceeded.

3 Optimized Recuperation for SpeedE

Inside this chapter the recuperation algorithms for SpeedE research vehicle shall be presented. Firstly it is shown why an optimized recuperation is required. In the next step existing brake systems for electric vehicles are presented as well as the corresponding limitations. In the main part the focus is shifted completely to SpeedE and its brake system in combination with the newly developed control algorithms.

3.1 Reasons for Optimized Recuperation

Due to the limited energy content of the battery in pure electric vehicles, efficiency and therefore range are major issues. As a result, one objective has to be the minimization of energy consumption. In comparison to conventional vehicles, the kinetic energy of the moving vehicle can be partly recuperated under deceleration. To maximize energy efficiency recuperation should be as high as possible under all circumstances, therefore as much energy as possible needs to be recuperated.

In Figure 7 the relative improvement in energy consumption as a function of the maximum regenerative deceleration compared to no recuperation is shown. Depending on the driving cycle the potential of the recuperation changes. As soon as the maximum cycle deceleration can be achieved by pure regenerative braking, no further improvement is possible. When looking at the WLTP and the AC1 (Aachen Cycle, real drive) an improvement of beyond 5 % can be achieved if the recuperation systems allows a deceleration of at least ~1.7 m/s². The potential is even higher if looking at a drive on a racetrack (NBR). Due to many hard deceleration, the relative improvement in energy consumption is continuously increasing right here.

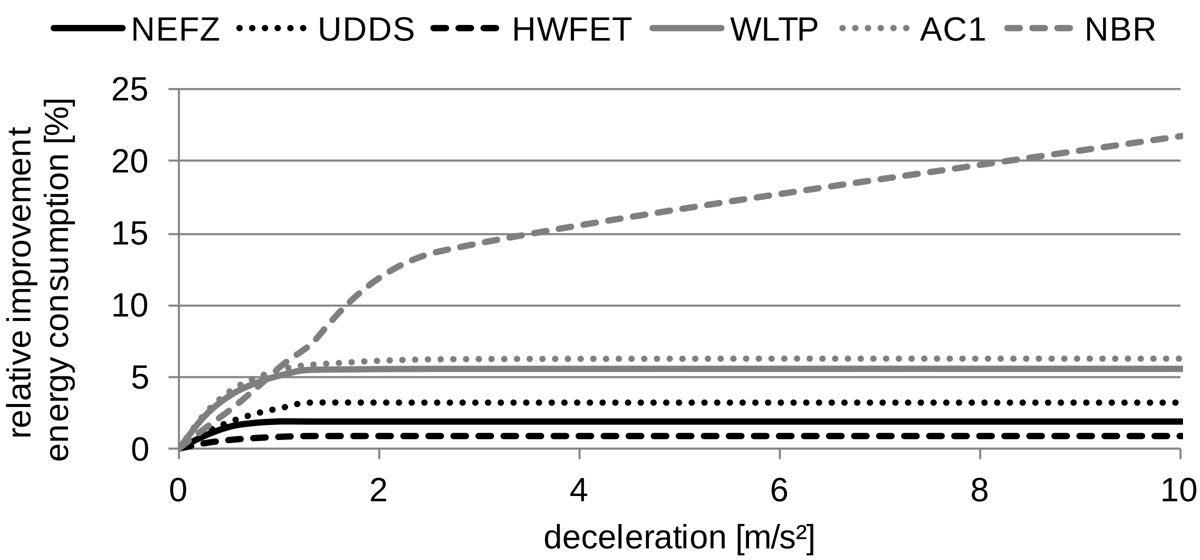

Fig. 7: regenerative deceleration vs. energy consumption

The above shown results have been achieved by using a simulation model for longitudinal dynamics in Matlab/Simulink with component data resembling the SpeedE vehicle. For generating the results it has been assumed that decelerations up to 10 m/s² can be achieved by the electric recuperation system. It can clearly be seen that for maximizing energy efficiency the regenerative torque should be as high as possible. Studies have shown that 80 % of all deceleration are below 3 m/s². Nevertheless also deceleration above this value, even though they are less likely to appear, should be taken into consideration. [4]

3.2 Brake Systems for Electric Vehicles

Basically there are different approaches to realize brake systems for electric vehicles using regenerative braking as well as hydraulic braking. Firstly there is the possibility to emulate the behavior of a conventional engine and its drag torque. Secondly there is the parallel recuperative brake system and thirdly the combined or serial recuperative brake system [5]. Unfortunately nomenclature is not used consistently by different persons.

As soon as the driver steps of the driving pedal in conventional vehicle the drag torque of the engine is clearly noticeable due to a small deceleration. So the first recuperation approach for hybrid or electric vehicles is to emulate the ICEs drag torque by running the electric motor in generator mode, demanding a small torque only. Recuperation is therefore not affected by the driver stepping on the brake pedal and limited to a small amount.

The parallel brake system consists of a conventional hydraulic brake system actuated by the driver operating the brake. On top of the hydraulic brake force a small regenerative brake force is added, unnoticeable for the driver. Regenerative braking is usually limited to 0.1 m/s². Therefore this system is mainly suitable for mild hybrids. The parallel brake system is easy and cheap to realize, nevertheless regenerative-efficiency is limited. In comparison to the friction-torque-emulation the recuperation is only active when the driver is actively braking the vehicle. When the driver only releases the driving pedal the vehicle is coasting. [5]

To increase the efficiency due to higher regenerative decelerations the serial or combined brake system can be used. It features a situation-depended brake blending between the electric motor-generator-unit and the hydraulic brake. To realize this brake pedal and brake actuation need to be decoupled. The control algorithms then decide on the brake force distribution. Figure 8 (top left) shows the basic principle of brake blending. During very low velocities a recuperation of the electric motors is not possible, thus the electro hydraulic brake actuators lead to a deceleration. With increasing velocity recuperation can be increased, the brake actuators can therefore be turned off. When exceeding the motors base speed, the maximum available torque decreases. To compensate this loss in wheel-brake-force the actuators brake pressure gets gradually increased to keep the deceleration at a constant level.

This example of course only illustrates decelerations which correspond exactly to the maximum generator torque of the vehicle. In the case of higher decelerations, the electro hydraulic brake actuators have to be active during the whole braking maneuver (bottom right). In the case of lower decelerations the use of the brake actuators and the generator can be further reduced (bottom left).

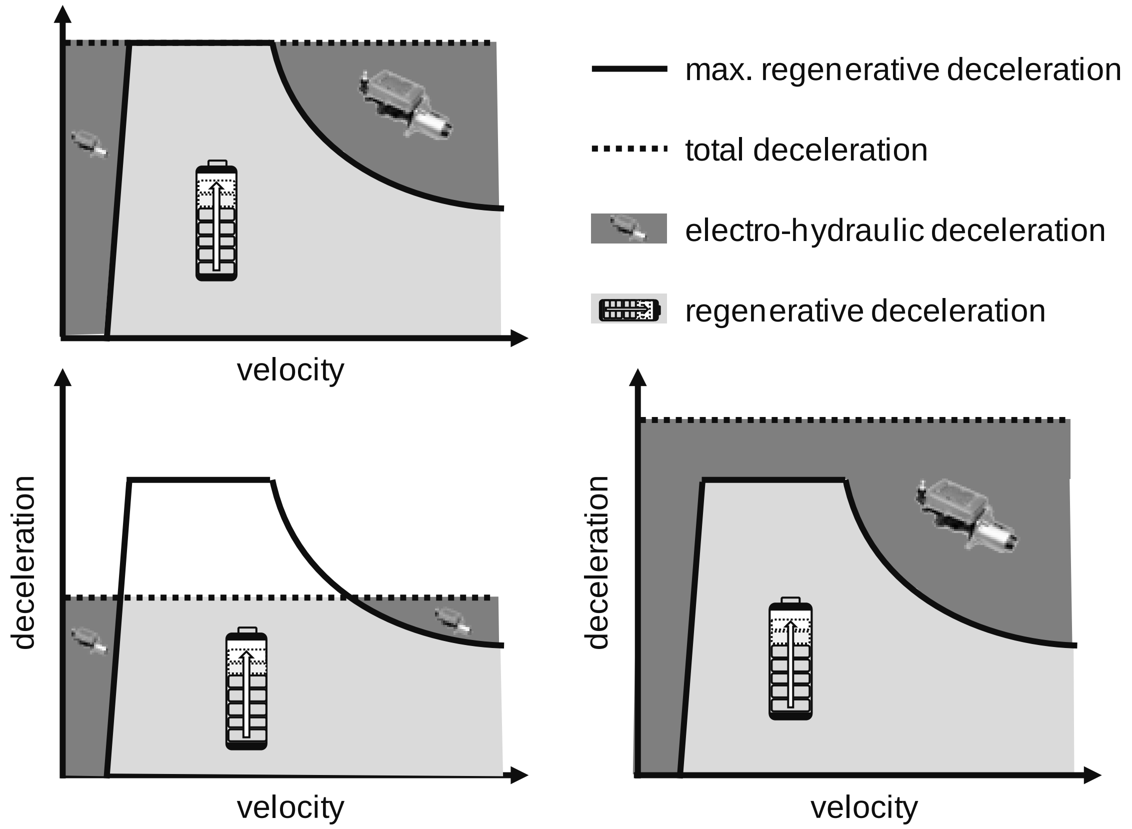

Fig. 8: Brake Blending

3.3 Limitations for the Brake System

There are different limitations and requirements regarding the brake system. The following requirements can be listed and prioritized [6]:

- stability of the vehicle
- reach of the demanded deceleration
- maximum recuperation efficiency
- ideal brake force distribution during recuperation

The highest priority is to keep the vehicle stable under all possible driving situations. If for example due to a low coefficient of friction the demanded deceleration cannot be reached this has to be accepted. The control algorithm is not allowed to further increase the wheel brake force if stability could be affected. Second priority is to reach the demanded deceleration to satisfy the driver. Only after that maximum recuperation efficiency can be looked at. To maximize recuperation efficiency it has to be deviated from the ideal brake force distribution towards more brake force on the rear axle in the example of the SpeedE research vehicle and its rear wheel drive layout.

While trying to reach the above mentioned requirements, the following boundaries or limitations have to be considered:

- maximum regenerative torque / power
- maximum battery charging current
- battery state of charge
- component temperatures
- coefficient of friction
- vehicle velocity / electric motor speed

Depending on the current velocity of the vehicle the duty point of the electric motor can be determined. Based on the duty point the maximum available braking torque from the electric motor can be derived. Further the maximum braking torque can be influenced by the temperature of the electric motor and inverter. When exceeding certain temperatures, the engine power and therefore also the engine torque are being derated. Another influence is the state of charge of the battery. In case of an almost fully charged battery the maximum charging current is limited. As a result the maximum regenerative torque also has to be limited, so battery current limits are not exceeded. The last but also very important limitation is the coefficient of friction between road and tire. If the coefficient of friction decreases certain decelerations might be possible when braking all four wheel but not when braking the two rear wheels only.

The most demanding maneuver is braking under cornering. During this situation the wheels have to transfer longitudinal and lateral forces at the same time. Studies have inspected the maximum possible recuperation for real wheel drive vehicles while cornering. It has been shown, that decelerations above 2 m/s² lead to clearly noticeable vehicle reactions by the means of an increased yaw angle. By switching to an ideal brake force distribution under these circumstances vehicle stability can be regained. Very high regenerative braking can therefore only be achieved for vehicles with front or all wheel drive. Nevertheless using brake torque vectoring the recuperation potential can be increased for rear wheel drive vehicles. Another study has inspected the influence of brake torque vectoring while constantly cornering with 72 km/h on a 100 m radius. It has been shown that an equally distributed regenerative braking can only be used up to 1 m/s² while using torque vectoring the deceleration can be increased up to 3 m/s². [7] [8]

3.4 SpeedE Brake System Concept

After introducing the main features of the SpeedE research vehicle the focus shall now be shifted to the recuperation and braking system. Inside the vehicle two different braking systems are installed. Firstly a brake by wire system which shall be further investigated inside this chapter. Secondly a conventional hydraulic braking system as already presented in chapter 2 as mechanical fallback solution. After completing the application of the different X-by-wire systems and all necessary safety measurements the conventional hydraulic system can be removed, again to avoid hardware redundancy as mentioned before.

The brake-by-wire system is made up of the following hardware components:

- four wheel-individual brake actuators
- two electric motors on the rear axle
- actuation by the driver via two sidestick recuperation triggers

From the software perspective a control system in Matlab/Simulink is running on the dSPACE Autobox, managing the brake-by-wire system. Depending on the actual driving situation as well as the vehicle status the control logic decides on the brake force distribution. By using the recuperation trigger the driver is able to demand a certain deceleration. For small decelerations and a partly discharged battery these can be implemented as fully recuperative by using the rear wheels electric motors. During higher decelerations or while the battery is fully charged, the deceleration cannot be reached by only using the electric motors. Thus the brake actuators have to be used additionally. Thanks to the use of the sidesticks triggers, the functionality of the brake-by-wire system is fully decoupled. As a result the control algorithms can be designed completely universal and modular. The system is basically reactionless, but depending on the used actuators every wanted information mechanism can be implemented.

In Figure 9 the basic control concept of the SpeedE brake system can be regarded. Starting with the input signals the control algorithm stepwise determines all necessary output signals in five main subsystems. The whole system is implemented modular, so that it could be easily adapted for other vehicles as well. The first and last blocks solely have the purpose to convert data into the correct format. The three blocks in the middle do all the necessary calculations with predefined input and output data format. An example for the output data mapping is the already described control of the electro hydraulic brake actuators, see Chapter 2.2.

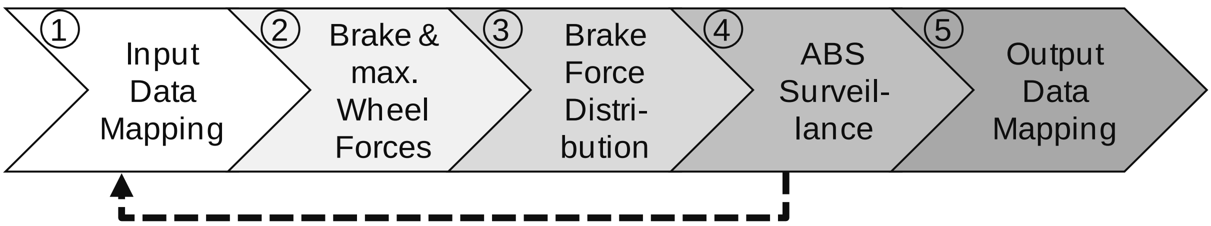

Fig. 9: Brake System Concept

Firstly the different input data gets prepared for further calculations. The following data is considered:

- recuperation trigger percentage (left/right)
- gear (PRND)
- wheel speeds
- steering angle at the front wheels
- battery state (state of charge, max. charging power, temperature)
- vehicle weight, wheelbase
- electric motor characteristics (speed/torque map, temperature)

Since steering is achieved via the use of two sidesticks, the driver can operate two recuperation triggers, both delivering a signal range from 0-100 %. For the first application it has been decided, to use the maximum of those two values to determine the drivers brake force demand. Based on the individual wheel speeds and the signals from the GPS sensor, the velocity of the vehicle is estimated. Based on the velocity and the signals from the accelerometer the longitudinal deceleration is estimated. Furthermore slipping wheels, as detected by the later on described ABS surveillance, are eliminated from the calculation of the reference speed.

The second block determines the maximum transferable wheel forces as well as the needed brake forces to obtain the demanded deceleration. To calculate the dynamic axle loads both longitudinal as also lateral influences are considered. Firstly the static axle load is calculated as a function of the vehicle weight and the location of the center of gravity. In further steps corrections according to the current driving situations are added. Major influences are inclines or declines, dynamic shifts in axle load under acceleration or deceleration and also aerodynamic lift forces. After having calculated the axle loads for the current driving situation, the individual wheel loads have to be determined. While driving in a straight line the weight distribution between left and right side is assumed to be equal. Having the information about the current lateral acceleration one last correction is added to consider the shift in wheel load between the inside and outside wheels under cornering. Having calculated the individual wheel loads and estimated the coefficient of friction the transferable wheel forces can be calculated. Using the single track model the front and rear axle side forces while cornering are estimated. The maximum wheel force in longitudinal direction is estimated by looking at the axle load and the actual side force using the friction circle. For cornering maneuvers the rear wheels brake force can be additionally limited to non noticeable yaw-influences.

The actual brake force demand is calculated by taking all major resistances into account. These are the rolling resistance, drag resistance, climbing resistance and acceleration resistance for the demanded situation. As a result the wheel brake force is determined.

Furthermore the maximum regenerative braking force is calculated inside the second model block. Main influences are of course the engine maps, especially the maximum regenerative torque at the current engine speed and also the maximum battery charging current. Minor influences are reductions in regenerative braking close to a standstill, when the battery is fully charged or when exceeding the batteries or motor/inverter temperature limits.

The main block in die middle of the figure calculates the brake force distribution. To maximize the efficiency the existing regenerative brake torque should be fully utilized, leading to a strongly rear axle orientated brake force distribution. Therefore in the first step the maximum regenerative brake force is calculated. Limitations might be on the one hand the maximum regenerative brake force due to maximum engine torque. On the other hand the maximum transferable wheel force for the rear axle has to be considered as well as theoretical brake-torque-vectoring. Based on this information the minimum of the two forces can be chosen. The result will be transferred as regenerative braking force. If the total demand for brake force has not been reached by pure regenerative braking the electro hydraulic actuators also have to contribute. Therefore the remaining brake force demand is determined and afterwards distributed to the four actuators. Firstly only the actuators for the front wheels will be activated until an ideal brake force distribution is reached. If the total brake force demand still cannot be reached all four actuators will further increase braking pressure while trying to keep to the ideal brake force distribution. Figure 10 illustrates the brake force distribution depending on the actual deceleration z of the vehicle.

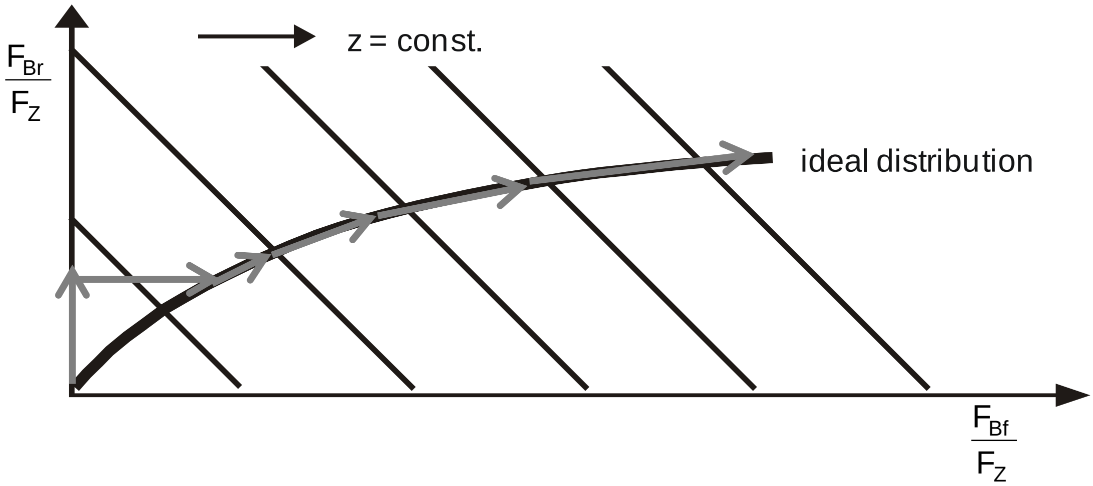

Fig. 10: Schematics Brake Force Distribution

To increase the driving safety there is an ABS functionality integrated into the control algorithms. Therefore the individual wheel deceleration as well as the wheel slip is being monitored. When exceeding certain boundaries, a further brake force increase on a wheel has to be prevented and the actual brake force is being held constant. Simultaneously the ABS control for this wheel gets activated and transmitted to the data preparation block to exclude this wheel from the vehicle velocity estimation. If the wheel-slip further increases under constant braking force, the brake force will be decreased. As soon as the wheel slip drops below a certain limit again, the wheels brake force can be increased again. This methodology is not only applied to the electro-hydraulic brake actuators as already know from conventional vehicles but also to the regenerative brake force from the electric motors.

In the last block the calculated wheel brake forces are being transferred into the correct sizes to send to the actuators. The regenerative braking can be achieved by sending a negative torque demand to the electric motors, hydraulic braking is achieved by sending the correct target position to the spindle actuator.

4 Summary and Outlook

After introducing the SpeedE research vehicle with its different domains, important sensors and actors have been presented. Brake strategies for electric vehicles have been shown as well as the need to optimize the recuperation strategy for maximum efficiency. The combination of recuperation by the electric motors and electro hydraulic brake actuators on the hardware side has been illustrated as well as the needed control algorithms. Up to the deadline of this paper measurements with the optimized recuperation strategy could not be finished but will hopefully be presented during Aachen Colloquium.

Further potential on the safety side could be the integration of ESP functionalities using recuperation and the brake actuators. Looking at energy efficiency predictive brake strategies using information from driver assistance systems could be implemented. Last but not least further vehicle dynamics functions could be implement, not only using torque vectoring but also selective braking of wheels.

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