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Regenerative braking for an electric vehicle with a high-speed drive at the front axle

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The main contribution of this paper lies in the development of a novel front-to-rear axle brake force distribution strategy for the regenerative braking control of a vehicle with a high-speed electric drive unit at the front axle. The strategy adapts the brake proportioning to provide extended room for energy recuperation of the electric motor when the vehicle drivability and safety requirements permit. In detail, the strategy is adaptive to cornering intensity enabling the range to be further extended in real-world applications. The regenerative braking control features a brake blending control algorithm and a powertrain controller, which are decisive for enhancing the braking performance. Lastly, the regenerative braking control is implemented in the high-fidelity simulation environment *Simcenter Amesim*, where system efficiency and regenerative brake performance are analysed. Results confirm that the designed regenerative braking greatly improves the effectiveness of energy recuperation for a front-wheel driven electric vehicle with a high-speed drive at the front axle. In conclusion, it is shown that it is feasible to use the high-speed drive with the proposed control design for regenerative braking.

1. Introduction

In the past decades, electrically propelled vehicles have been under the spotlight for their sustainable energy potential. One of their key features is their ability to recuperate energy back into the battery through regenerative braking [1]. Research on regenerative brake systems has focused mainly on two areas: optimising energy recuperation efficiency through analysing the brake energy management and improving the blended brake dynamics through cooperative control of the regenerative braking and the hydraulic brakes [2,3].

In brake energy management, there have been many ideas on changing the brake force distribution (BFD) to increase the regeneration potential. However, incorporating the vehicle handling requirements early in the design is usually only limited to the ideal brake curve. That is because the BFD curve is fixed in conventional brake systems. A brake-by-wire system though enables the dynamic manipulation of the BFD. This is useful for increasing the recuperation potential when stability and safety requirements are satisfied. For instance, regenerative braking can be expanded for use during cornering [4,5].

To increase the dynamic brake response and at the same time improve regeneration efficiency, cooperative control of the hydraulic brakes and the electric motor is favourable. The main difficulty of the coordination comes because of flexibilities in the driveshafts, which make smooth torque transfer from the electric motor to the wheels challenging [2]. Finally, regenerative braking and anti-lock braking can be combined to incorporate wheel-slip control in the design, as in [6].

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In this article, a complete regenerative braking control (RBC) is presented for an electric vehicle with a high-speed drive at the front axle. The innovative electric powertrain was designed for the ModulED EU project, and a prototype was built featuring high motor efficiency and augmented power density [7]. The work presented here investigates the challenges and performance of regenerative braking for the high-speed drive with a two-gear transmission mainly in terms of energy recuperation efficiency, limited by vehicle drivability and handling requirements. The backbone of the RBC is a BFD strategy. The BFD strategy considers the vehicle handling–energy maximization trade-off and is made adaptive to the cornering intensity. Furthermore, to support a smooth brake response two control functions are developed: a powertrain controller to suppress oscillations at the driveshafts and a brake blending control algorithm to enhance the braking performance.

Specifically, this article starts with the analysis behind the brake energy management motivated by the driver's habits, which shows how the brake proportioning can both support the driver and increase the driving range. Furthermore, the developed RBC architecture and its key features are presented. Lastly, the results of full-vehicle simulations carried out in the high-fidelity environment *Simcenter Amesim* for various driving cycles with and without regenerative braking are analysed.

2. Brake energy management

2.1 Efficiency and driver's habits

The amount of energy that can be recovered using regenerative braking depends mainly on two factors: driver's habits and the recuperation efficiency of the regenerative braking system. According to the collected data from real-world driving provided by Renault [8], there is a significant potential for energy recovery not only during straight-line braking but also during cornering. In detail, as shown in Figure 1, the energy recuperation potential statistics are presented for various combinations of braking and cornering. On the horizontal axes the longitudinal and lateral acceleration levels are plotted, while on the vertical axis the energy recuperation potential statistics are plotted accordingly.

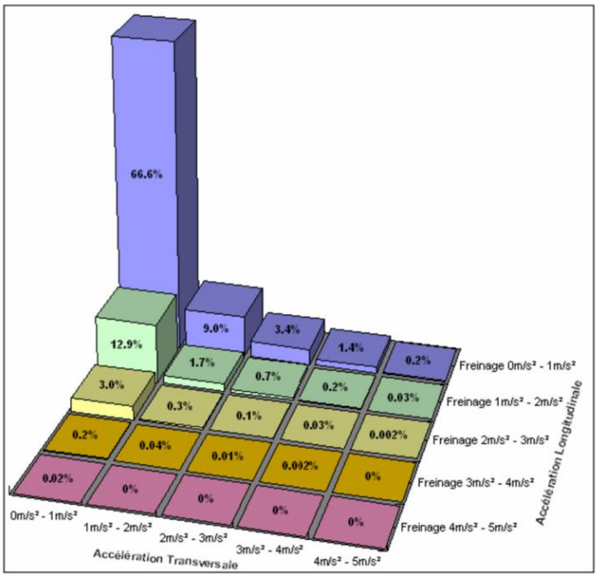


Figure 1: Energy recuperation potential statistics on various braking and cornering levels [8]

From the figure, up to 15.3% of energy can be recuperated for lateral acceleration values in the range 1–3 m/s^2. Above that, the stability control algorithms (ABS, ESC) usually take control as the tire limits are approached. Under these circumstances, safety takes priority over energy recuperation. The main objective of the brake energy management development here is to cover the regenerative braking operating range for combined braking and cornering most efficiently, while driver comfort and safety are maintained.

2.2 Brake force distribution

Increasing the utilization of the front axle increases the available capacity that can be used for regeneration. Increasing the brake torque at the front axle though, reduces vehicle stability and manoeuvrability during cornering [4,5]. Based on this trade-off, a brake force distribution strategy, first proposed in [9], is improved to adapt to the current driving situation.

In a conventional brake system, the BFD is determined by the design of the brake system itself. In a brake-by-wire system though the BFD can be adapted to the current driving conditions. A typical BFD diagram is presented in Figure 2. The ideal- and ECE regulation curves are depicted, which limit the design for best handling and maximum regeneration, respectively. The Conventional, constant brake proportioning curve is also depicted in the diagram. Finally, the proposed "ModulED" BFD strategy is presented. Here, the ModulED curve is made adaptive to the predicted cornering intensity ($a_{yg} = a_y/g$) to consider the combined effects of braking and cornering. Based on the current predicted cornering intensity level, the adaptation moves the [A, B, C] points between a selected fixed position for straight-driving and the Conventional strategy. In detail, a cornering intensity limit is chosen, above which the Conventional strategy is used entirely, while in between, a convex combination of the two strategies (Conventional and straight-driving) is used instead.

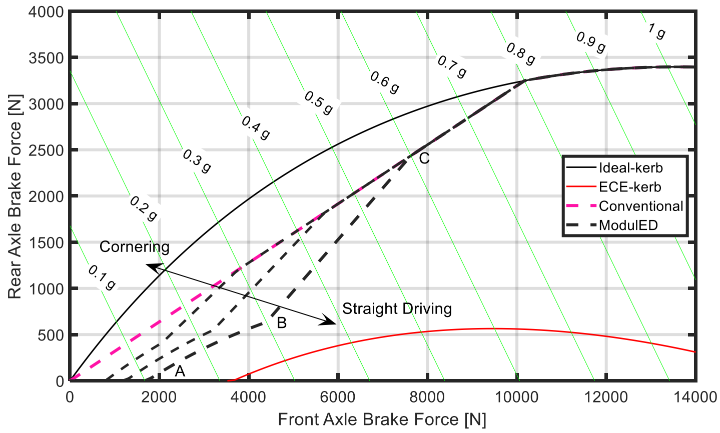


Figure 2: Brake force distribution diagram.

To assess the ideal energy recuperation potential for the various BFD strategies, the energy information from Figure 1 is first extracted. Then, for each strategy the front-to-rear axle brake proportioning is calculated for the same longitudinal and lateral acceleration data points. This ratio is assumed to be equal to the maximum amount of energy that can be recuperated by the electric motor of a front wheel drive vehicle. Therefore, multiplying the brake proportioning with the energy data of each point and summing it up gives the total energy recuperation potential of the strategy. The results are gathered in Table 1.

Table 1. Energy recuperation potential for the various braking strategies

	Conventional	ModulED
Energy recuperation potential	76%	94%

The Conventional strategy has a constant brake proportioning of roughly 76% of the brake torque on the front axle for the showcased vehicle and it is assumed that it maintains drivability in most driving conditions. Therefore, from the energy recuperation potential data [8], an energy value exactly equal to its distribution can be attained. The adaptive ModulED strategy on the other hand achieves higher energy recuperation levels. Specifically, a total of 18 pp (percentage points) more energy can be attained when using the ModulED strategy instead of the Conventional. This number shows the potential energy benefit when the drivability requirements are included in the design. Focusing only on energy recuperation maximization, as when following strictly the ECE curve, cannot give optimal results due to drivability implications with combined braking and cornering.

3. Regenerative brake control

3.1 Adaptive regenerative brake strategy

In Figure 3, a flow chart is presented, which explains the logic behind the complete regenerative brake strategy with adaptive brake force distribution. The brake demand coming from the driver is first split between the front- and the rear axle based on the adaptive ModulED BFD strategy. Here the strategy is only adaptive to cornering intensity, however, it can be made adaptive to different driving conditions in a similar manner. Then, at the front axle, the total front axle demand, T_{afd}, is split between the motor and the hydraulic brakes based on the current speed-dependent motor torque limitations, which translate to the maximum available driveshafts torque that can be provided by the motor, $T_{ds,max}$. The strategy is serial [3], i.e. it is set to always use as much regeneration as possible, while any missing brake torque to fulfil the demand is delivered by the hydraulic brakes.

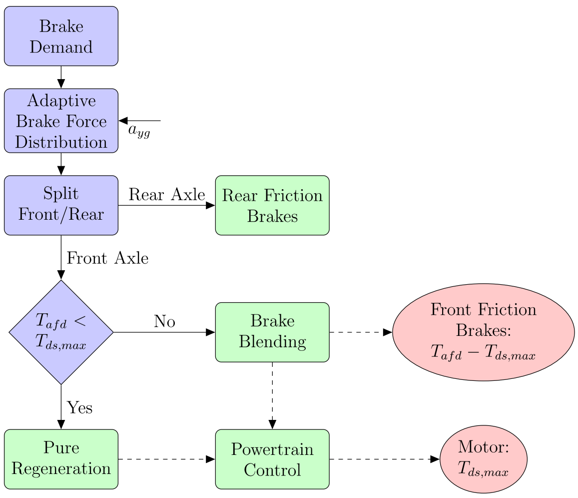


Figure 3: Flow chart of the adaptive regenerative brake strategy

3.2 Powertrain and brake blending control

The longitudinal dynamics of an electric vehicle is examined using a four-DOF nonlinear one-axle vehicle model. The mechanical system of the vehicle comprises three rigid bodies for the body, the front axle, and the electric motor. The tire and motor dynamics are also modelled.

In literature, the stiffness of the driveshafts is commonly reduced to match the first natural frequency of the powertrain, the shuffle [10]. The shuffle's effect is the occurrence of oscillations in the driveshafts when the powertrain applies torque, which in the case of electric drivetrains is important both for acceleration and deceleration. Including this effect into other relevant dynamics, the nonlinear model is first linearized and then reduced for control design, creating a model similar to [11]. The model reduction is done rigorously and gives a model with its gain being adaptive to road conditions, in a similar manner to [12].

To ensure an enhanced braking performance two control algorithms are designed a powertrain controller and a brake blending control algorithm. The powertrain controller is designed to follow a desired driveshafts torque reference model, in a similar manner as in [13]. This controller actively suppresses the occurring oscillations at the driveshafts while ensures a fast and smooth torque transfer from the motor to the wheels. The powertrain controller is based on the simplified model of the powertrain described above. The primary function of the brake blending control is to speed up blended brake response at the front axle and secondary to reduce any significant steady-state error between the demand and the actual delivered front axle brake torque. This is necessary because there are nonlinear variations in the brake response and torque delivered, which mainly occur due to the flexibility of the driveshafts [2]. The coordination of these two systems is essential, mainly for a fast and smooth brake response contributing to increased regeneration efficiency and safety.

4. Vehicle energy efficiency

To assess energy efficiency in detail, a vehicle simulation model is built in *Simcenter Amesim*. The simulation model is comprised of separate models for the vehicle body, nonlinear tires, electric motor, battery and features the control subsystems presented in Sec. 3.2, as well as an automatic gear-shift algorithm for the project's two-speed gearbox. The model's architecture is shown in Figure 4.

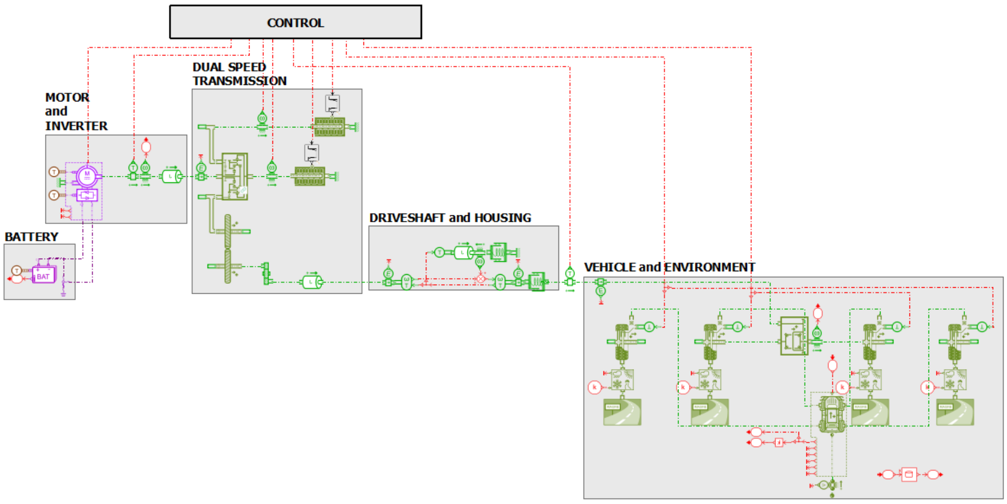


Figure 4: Vehicle model in *Simcenter Amesim*

To evaluate the contribution of regenerative braking on the vehicle's energy efficiency there are two main measures used, namely the energy consumption reduction rate and the driving range extension rate [3]. The energy consumption reduction rate Δ_E is defined as:

$$\Delta_E = \frac{E - E_{reg}}{E} \tag{1}$$

where E_{reg} and E are the net energy consumption with and without regenerative braking, respectively.

In a similar manner the driving range extension rate Δ_S is defined as:

$$\Delta_S = \frac{S_{reg} - S}{S} \tag{2}$$

where S_{reg} and S are the energy consumption with and without regenerative braking, respectively.

4.1 Simulation scenarios

To get a better understanding of how the RBC affects energy recuperation efficiency, several driving cycles are analysed. Specifically, the NEDC, WLTC Class 3, and SFTP-US06 have been chosen as the most suitable for a common electric passenger car.

To evaluate the braking intensity content of a driving cycle, the Relative Negative Acceleration (RNA) measure is used. The RNA is calculated by focusing only on the points of the driving cycle where there is deceleration. In mathematical form this is expressed as (adapted from [14]):

$$a_{RNA} = \frac{\sum v_i a_i^-}{x} \tag{3}$$

where v_i and a_i^- are the velocity and deceleration at each timepoint of deceleration, and x is the total driving cycle distance.

The regeneration efficiency of a driving cycle varies with the BFD strategy [15]. To assess this, the regeneration efficiency is expressed as:

$$\eta_{reg} = \frac{E_e^-}{W_b} \tag{4}$$

where E_e^- is the recuperated energy and W_b is the total braking work. This measure shows in fact how much of the total braking work is recuperated for given driving cycle and BFD strategy.

4.2 Simulation results

A set of results is presented for each driving cycle in Table 2. On the left-hand side, the deceleration intensity content of each driving cycle is given, represented by the RNA and the portion of deceleration that is under 1 m/s^2. On the right-hand side, the efficiency of the two brake strategies is evaluated, through the regeneration efficiency η_{reg}, the energy consumption reduction rate Δ_E, and the driving range extension rate Δ_S measures.

Table 2: Driving cycle results

Cycle dec. content			Efficiency evaluation					
Driving cycle	RNA [m/s^2]	Dec. < 1 m/s^2 [%]	η_{reg} [%]		Δ_E [%]		Δ_S [%]	
			Conv.	ModulED	Conv.	ModulED	Conv.	ModulED
NEDC	0.22	90	73.4	99.5	+21.1	+27.4	+26.8	+37.7
WLTC-C3	0.30	87	73.2	99.1	+20.5	+26.5	+25.8	+36.1
SFTP-US06	0.41	73	74.0	95.4	+20.6	+25.8	+26.0	+34.7

For the ModulED BFD strategy, it is observed that the efficiency measures increase inversely proportional to the deceleration intensity content of the cycle. This can be traced back to the BFD curve since for deceleration levels higher than 1 m/s^2 (point A in Figure 2) the load is gradually switched to the rear to enhance handling. For all driving cycles, the ModulED strategy achieves significant energy efficiency levels, close to the maximum possible. For the Conventional BFD strategy though, there is no such clear trend. Since its brake proportioning is constant, the regeneration efficiency is also relatively constant, changing slightly depending on the energy consumption profile, as it will be shown in the energy consumption analysis later. The ModulED strategy exhibits an overall better efficiency, by recuperating more energy and extending the driving range further than the Conventional. This is in fact evaluated through the regeneration efficiency of the strategy, where the ModulED achieves an average 24.5 pp more than the Conventional. This is translated in an average 5.8 pp less energy consumed or 10 pp driving range extension gain. In Figure 5, the efficiency results from Table 2 are visualized.

Comparing the simulated configuration with the high-speed drive at the front axle and the developed regenerative brake control to the literature [3,15] the results are in favor of the former. This confirms that the high-speed drive can be used successfully for regenerative braking, resulting in very efficient solutions.

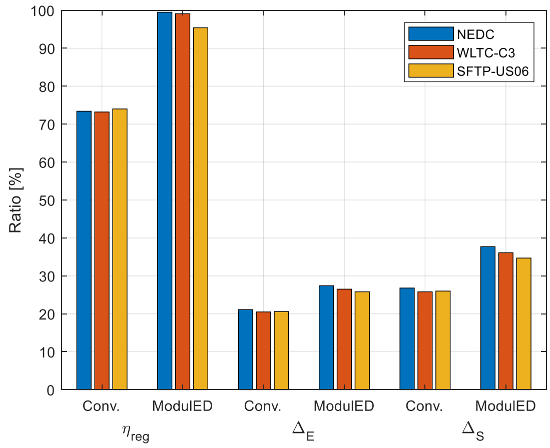
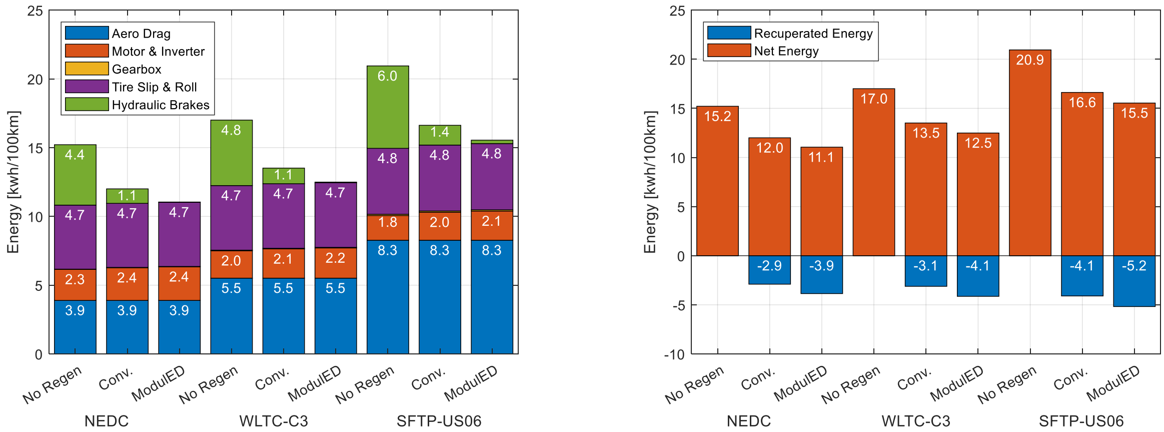


Figure 5: Regeneration efficiency η_{reg}, energy consumption reduction rate Δ_E, and driving range extension rate Δ_S results for the two brake force distribution strategies in each driving cycle



(a) Energy consumption distribution

(b) Total energy

Figure 6: Energy consumption distribution for the various driving cycles and brake force distribution strategies

The analysis of energy consumption for the various driving cycles and BFD strategies is presented in Figure 6. The aerodynamic drag and rolling resistance depend only on the driving cycle and are therefore constant between the various strategies, see Figure 6a. The thermal losses in the motor and inverter though, increase slightly the more the regenerative braking is used. However, the gain reducing the use of the hydraulic brakes is more significant. The energy consumption due to the rolling resistance and slip of the tyres is almost constant between the different driving cycles. A small increase in tire slip is seen in the SFTP-US06 cycle. Reviewing the SFTP-US06 cycle in detail it is observed that the motor and inverter thermal losses are decreasing, but the hydraulic brakes are utilized more for this driving cycle compared to the other two cycles. The combination of these two losses explains mainly why there is a small increase in the efficiency of the Conventional strategy for this cycle. In Figure 6b, an increase in the total energy consumption is observed when regeneration is off. This is traced back to the increased use of the hydraulic brakes. Specifically, there is an inertial resistance at the driveshafts coming from the powertrain when the hydraulic brakes are applied, which is significantly reduced with the use of blended braking.

5. Conclusion

This article focuses on the regenerative brake system of an electric vehicle with a high-speed drive at the front axle. After analysing the trade-off between energy recuperation efficiency and drivability during braking, an adaptive to cornering intensity brake force distribution strategy is proposed to handle it. It is calculated that making the brake force distribution adaptive to cornering can give a recuperation potential up to 18 percentage points relative to conventional, constant brake proportioning. Furthermore, a regenerative brake control algorithm is presented, for increased braking performance and regeneration efficiency, featuring a powertrain controller and a brake blending control algorithm. Conducted full vehicle simulations focus on the energy analysis of various driving cycles. The results show significant energy recuperation gains with the proposed regenerative brake system. In detail, the energy consumption analysis shows that using blended braking benefits the total energy consumption due to inertia effects at the driveshafts. Finally, through this work, it is shown that it is feasible to use the high-speed drive with the proposed control design for regenerative braking.

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