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INVESTIGATION OF REGENERATIVE AND ANTI-LOCK BRAKING INTERACTION

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ABSTRACT−The use of a regenerative braking mode can reduce overall vehicle energy usage for most of the most common drive cycles. However, a number of technical issues restrict the use of regenerative braking for all possible braking situations. These issues are concerned with two key limitations. The first is related to physical limitations of the applied regenerative braking system, e.g. Electric Motor (E-Motor) power limits; energy storage device capacity and vehicle load transfer etc. The second limitation results from the potentially detrimental interaction between regenerative braking and the Anti-locking Braking System (ABS). The first type of limitation can, to some extent, be alleviated by suitable choice of hardware and, as a consequence, will not be discussed further in this paper. The second type of limitation concerns the regenerative braking strategies during an ABS event. Some of the regenerative braking strategies designed and investigated within the Low Carbon Vehicle Technology Project (LCVTP) will be described and analyzed in this paper. A comparison of competing strategies is made and conclusions are drawn together with suggestions for further research. The work has been progressed as a part of a major research programme; namely the LCVTP, which has been conducted within an extensive industrial and academic partnership, mutually funded by the European Regional Development Found and Advantage West Midlands.

KEY WORDS : Braking system, Regenerative braking, Anti-lock braking system, Braking strategies, Brakes blending

1. INTRODUCTION

The operation of Hybrid and Electric Vehicles (H/EVs) differs significantly from the operation of conventional vehicles that are driven purely by means of an Internal Combustion Engine (ICE). However, the vehicle attributes controlled by the driver should remain familiar and should only be changed in a minimal way (Zhang *et al*., 2010). This requirement demands the use of sophisticated control systems, which will need to be developed for the propulsion system. The reduction of the overall vehicle energy consumption requires the use of maximum regenerative braking for all braking manoeuvres. This also requires the use of a regenerative braking mode during the intervention of the Anti-locking Braking System (ABS) (Peng *et al*., 2008). Inappropriate use of regenerative braking can, however, lead to vehicle instability and reduce handling behaviour, especially during lateral manoeuvres. This prompted the development and investigation of regenerative braking strategies during ABS events and the subsequent proposal of a braking control strategy, which is presented in this paper.

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1.1. Regenerative Braking Strategies during Abs Event

In order to ensure maximum energy recovery, the interaction of the regenerative braking control and the ABS has been investigated. This has been done on the premise and *a priori* assumption that interaction of the braking control systems is technically possible. This allows the regeneration of energy over the braking activity, which greatly exceeds the deceleration level of *0.1 g*, which corresponds to the situation when, even for low mu surfaces, the vehicle is still free of ABS intervention. In this paper, the following strategies are taken into account:

- Termination of regenerative braking during an ABS event (without any blending phase).

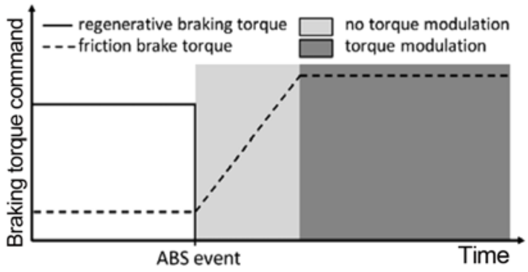

Figure 1. Regenerative and friction brake torque trace for the first strategy upon occurrence of ABS event.

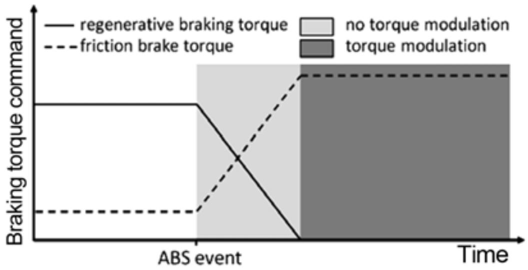

Figure 2. Regenerative and friction brake torque trace for the second strategy upon occurrence of ABS event.

- Ramp down regenerative braking to zero with friction torque blending (only friction torque modulation for ABS purposes).
- Torque maintained at the same level or ramped down to a variable residual level (only friction torque modulation for ABS purposes).

In this study the regenerative braking can start to operate ahead of the friction brakes (parallel braking strategy). All of the investigated regenerative braking control strategies operate in open loop control.

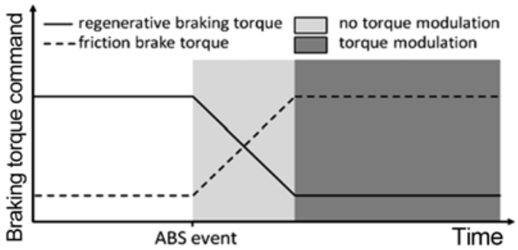

Figure 3. Regenerative and friction brake torque trace for the third strategy upon the occurrence of ABS event.

1.1.1. Termination of regenerative braking during ABS event

The first strategy for regenerative braking control during an ABS event has been introduced without a blending phase between the regenerative braking and the friction braking, see Figure 1. In the case of an ABS event, the regenerative braking torque is instantly reduced to zero (reduction in torque demand). In order to fulfil the braking torque deficit caused by the sudden regenerative braking torque reduction, the friction brakes are activated. The ABS functions (i.e. torque modulation) are implemented with use being made of friction/hydraulic brakes. At the onset of an ABS event the regenerative braking torque is reduced to zero and the friction brakes take over the responsibility for the vehicle deceleration. It is worth noting that in the first instance the ABS intervention cannot be performed on the friction brakes as the available friction brake torque is too low for correct modulation (i.e. the braking torque modulation for ABS purposes). The range denoted with the use of a light grey background in Figure 1 is described as – no torque modulation (for ABS purposes). Upon reaching the targeted torque using the friction brakes the modulation of the friction torque can be performed, this is shown as a dark grey background in the Figure 1.

1.1.2. Ramp down regenerative braking to zero with friction torque blending

In order to improve the characteristics of the first strategy, which is connected with the momentary lack of braking torque, the second strategy is introduced. In this strategy, upon the occurrence of an ABS event the regenerative braking torque is ramped down to zero, see Figure 2. This enables the friction torque to compensate the gradually reduced regenerative braking torque. Similarly to the first strategy the ABS torque modulation is performed with the use of friction/hydraulic brakes. This strategy presents a greater energy recovery level than the first strategy at the expense of severe increase of ABS operation.

1.1.3. Ramp down regenerative braking to a variable residual level

The next strategy is similar to the second but instead of reducing the regenerative braking torque to zero the regenerative braking torque is reduced to a variable residual level, see Figure 3. The introduced residual level of regenerative braking torque ensures that the greatest amount of energy is recovered among the three strategies considered. Due to the non-zero regenerative braking torque level, the friction brakes supply additional torque in order to meet the driver's deceleration request. In this case the ABS braking torque modulation is realised via the foundation brakes (or friction brakes). A vehicle that makes use of this strategy will, theoretically, be prone to frequent use of ABS, as a part of the braking torque will be out of the range of ABS control.

2. DESCRIPTION OF THE SIMULATION PLATFORM

The simulation platform comprises three commercially available software products that are suitable for simulation of different system domains, namely: MATLAB/Simulink,

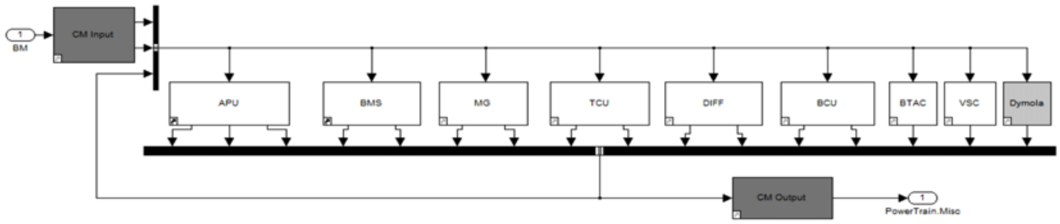

Figure 4. Vehicle controller model interactions.

Dymola, and IPG CarMaker, extended from WARPSTAR 2+ (Cheng *et al*., 2010).

2.1. Driveline Architecture

The generic simulation platform designed within this study supports the simulation of a wide range of H/EV architectures. However, for the purpose of this paper only the Series Hybrid Vehicle with Rear Axle Regenerative Braking capability has been considered.

2.2. Model Integration

In order to meet the simulation model requirements a new simulation platform has been designed. The general plant simulation has been embedded within a MATLAB/Simulink environment with some system models performed using Dymola (Cheng *et al*., 2010). Moreover the simulation platform has been extended by making use of the IPG CarMaker vehicle dynamics environment.

The following control systems and plant models have been developed:

- MATLAB/Simulink: general models integration platform, Brake Torque Apportionment Controller (BTAC), Electronic Brake-force Distribution Model (EBD), Anti-lock Braking System Model (ABS).
- Dymola: drive line, E-Motors, hydraulic brake circuit, friction brake, Internal Combustion Engine (ICE), battery, power electronics.
- IPG CarMaker: road features and environment, vehicle dynamics, suspension model, driver model, tyre model.

Figure 4 presents the model interactions for an E-Motor simulated vehicle configuration. In Figure 4 the white boxes represent the vehicle controllers, such as the Auxiliary Power Unit (APU), Battery Management System (BMS), Moto-Generator (MG), Traction Control Unit (TCU), Differential (DIFF), Brake Control Unit (BCU), Brake Torque Apportionment Controller (BTAC), and Vehicle Supervisory Controller (VSC). The light grey box represents the Dymola precompiled plant model (Dymola), and the dark grey boxes represent the IPG Car Maker interface (CM Input and CM Output).

2.3. Detailed Model Parameters

Vehicle Model – In this paper the vehicle has been modelled in the IPG CarMaker environment, see Figure 5. The vehicle model was created with the assumption of rigid body dynamics and on the basis of the parameters presented in Table 1.

Table 1. Vehicle parameters.

Unloaded weight	1796 [kg]
Wheelbase	3032 [mm]
Wheel size front	19/45/245 [inch./%/mm]
Wheel size rear	19/40/275 [inch./%/mm]
Main body	rigid body
Turning circle	12.3 [m]
Drag coefficient	0.29 [-]
Vehicle length	5122 [mm]
Vehicle width	2110 [mm]
Vehicle height	1448 [mm]

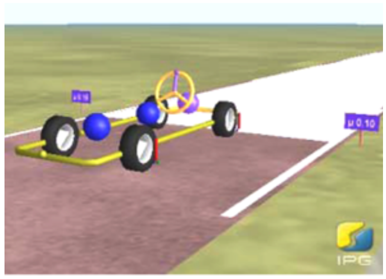

Figure 5. CarMaker's basic vehicle representation for low mu surface braking manoeuvre.

Two different sizes of tyre have been used, see Table 1. The tyre model has been created using the Magic Formula MF-Tyre 5.2, version number 6 (Pacejka, 2002). The models include the tyre relaxation behaviour. For the closed-loop drive simulations – vehicle-handling simulations the IPG Driver has been used. The driver has been described using a maximum Longitudinal Acceleration/ Deceleration equal to *1.0 g* and a maximum Lateral Acceleration equal to *1.0 g*.

Regenerative Braking Model and Control – The Regenerative Braking capability has been assumed to be dynamic in terms of torque delivery and can be represented by a 1st order dynamic system with a time constant $\tau = 0.01s$. The E-Motor has been modelled using Dymola software. The E-Motor has been fitted to a rear differential through a three-

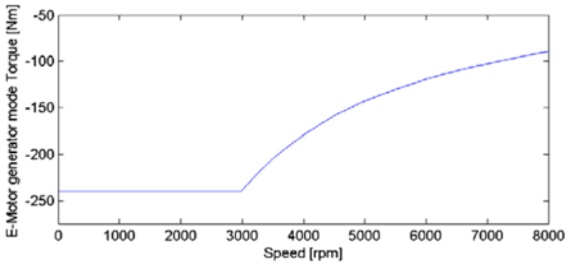

Figure 6. Peak torque characteristic for E-Motor in generator mode.

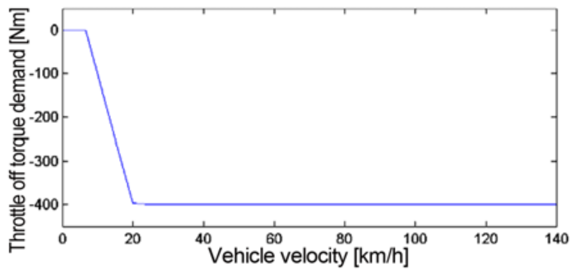

Figure 7. Throttle-off characteristic as a function of vehicle velocity replicated by the E-Motor.

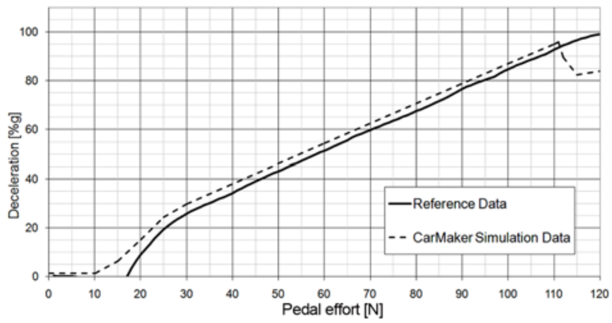

Figure 8. Vehicle deceleration vs. pedal effort for the simulation model and the reference data from the road tests.

speed gearbox. The characteristic of the braking torque of an E-Motor operating in generator mode is presented in Figure 6.

For regenerative and friction brakes control, the Brake Torque Apportionment Controller (BTAC) has been designed. The detailed operation of this controller is not given here; however, the main functions of the BTAC are to:

- determine the driver braking torque demand from the brake pedal position,
- determine the braking torque between the axles with regard to load transfer and current adhesion conditions (Electronic Brake-force Distribution – EBD functionality),
- blend the regenerative braking torque with the foundation brakes.

Friction Brake Model – The model of the friction brakes has been performed with the use of Dymola software. The main virtue of this approach is the use of physically derived model variables (Breuer and Bill, 2008).

Driveline Model – The driveline model has been created using the Dymola software. The driveline architecture has been assumed as an electrically driven rear axle. The vehicle model has also been equipped with an Internal Combustion Range Extender Unit. The driveline model also includes shaft compliance along with a typical friction model and values for bearing resistance. The stated model/values were provided by OEMs and as they are covered by intellectual property rights these will be not presented in this paper. It should also be noted that left and right driveline shafts (between differential and wheels) are of different lengths due to the vehicle setup. The driveline model characteristics (open differential, bearings with friction) and setup (different lengths of axial drive shafts) result in an asymmetry in torque delivery into the separate wheels.

The Vehicle Supervisory Controller (VSC) used in this simulation has been equipped with 'throttle-off' functionality. In this case the throttle-off condition has been simulated via activation of the E-Motor. The activation function for the additional E-Motor braking torque is presented in Figure 7.

2.4. Vehicle Model and Braking System Validation

The vehicle model has been parameterised using values from a given vehicle manufacturer. The hydraulic braking system model has been validated in two ways. First, the characteristics of the parts in the braking system, e.g. booster, have been measured and used for friction brakes system modelling under the Dymola software. An additional validation data set has subsequently been used to ensure model integrity. Secondly, the vehicle model with the brakes model was correlated with empirical deceleration performance of a standard vehicle equipped with a conventional braking system. The vehicle deceleration results versus pedal effort for the created vehicle model, as well as reference data, are presented in Figure 8.

3. SIMULATION RESULTS

The proposed regenerative braking strategies have been tested against specific braking manoeuvres and the simulation results are presented in this section. On this basis conclusions concerning the regenerative braking operation during braking manoeuvres for a rear wheel regenerative braking vehicle with E-Motor fitted via an open differential will be formulated.

3.1. Results for Single Braking on High Mu Surface

The first simulation within this study has been performed for a single braking manoeuvre on a high mu surface. The simulation parameters are presented in Table 2. The parameters for this test have been chosen in such a way that

Table 2. Single braking on high Mu surface manoeuvre parameters.

Initial speed, v_1	27.7 [m/s]
Mu coefficient of the surface, μ	1.0 [-]
Normalized brake pedal position	0.75 [-]
Time range for full brake pedal application	0.5 [s]

the manoeuvre requires a light ABS intervention. The numerical results for this test and the proposed regenerative braking strategies are shown in Table 3.

In the following sections the results of the investigated braking strategies are presented in pairs. The initial comparison considers the first regenerative braking strategy with the throttle-off braking approach and these are presented in Figure 9. The left column of the graphs presents the simulation results for the chosen manoeuvre with only throttle-off E-Motor torque generation. The throttle-off torque characteristic has been presented in Figure 7 and has been introduced in order to simulate the internal combustion engine throttle-off braking in the case of acceleration pedal lift off. The E-Motor torque after reaching the steady state torque level (for *t=29.50s*) is gradually reduced to zero for a vehicle velocity lower than *5.5 m/s* (starting from the point *t=31.25s*). The first part of the throttle-off torque trace is a result of the driver pedal application time and the dynamic E-Motor torque response. The second part of the throttle-off torque trace directly follows the assumed throttle-off torque characteristic presented in Figure 7. The right column of graphs in Figure 9 shows the results for the same braking manoeuvre with use of the first proposed regenerative braking strategy (termination of the regenerative braking during an ABS event). The regenerative braking torque on the rear axle is generated together with friction brakes torque on the front axle. When the regenerative braking torque reaches an inflection point, after which the increase of the torque is drastically reduced (due to the E-Motor power limitation, see Figure 6), the rear axle friction brakes are activated in order to meet the driver deceleration request. From *t=29.10s* the ABS system starts to operate (after detection of the excessive rear wheel slip). For this situation the control system terminates the regenerative braking torque. In the present case the regenerative braking torque is reduced to the throttle-off torque level. The numerical results of this, as well as, the other strategies are presented in Table 3.

Figure 9 also presents some oscillations in the deceleration profile that are recorded for zero vehicle velocity. The deceleration oscillations are in phase with the friction torque trace. The reason for this phenomenon can be due to oscillations in the vehicle pitch, which is recorded by the acceleration sensor, located at the centre of gravity. Furthermore, the origin of the torque oscillations is considered to be connected with the driveline shaft compliance introduced into the model. It should be noted that the simulation results presented in Figure 9 are for the high deceleration braking test (up to *1 g*). In this case the decelerations and applied braking torque are significant enough to force the system to operate in the nonlinear region (shaft compliance, tyre model, etc.).

In this study the regenerative braking torque source is a device, which is uncontrolled for ABS purposes. For the

Table 3. Manoeuvre energy potential for different regenerative braking strategies during an ABS event.

Initial speed, v1	27.7 [m/s]				
Mu coefficient of the surface	1.0 [-]				
Bake pedal position	0.75 [-]				
Regenerative braking strategy during an ABS event	Throttle-off only	Termination of re-gen	Ramp down re-gen to zero	Ramp down re-gen to residual level (250 Nm)	Ramp down re-gen to residual level (500 Nm)
Dissipated energy - Friction brakes, Front axle [Wh]	111.1	114.5	122.0	120.5	117.5
Dissipated energy - Friction brakes, Rear axle [Wh]	83.6	74.4	57.5	56.0	54.4
Restored energy - Regenerative braking, Rear axle [Wh]	20.7	25.8 (+25%)	35.2 (+70%)	37.1 (79%)	41.2 (99%)
Peak power - Friction brake, Front axle [kWh]	241.0	245.7	245.7	245.7	245.7
Peak power - Friction brake, Rear axle [kWh]	184.2	179.9	122.8	124.2	124.2
Peak power - Regenerative braking, Rear axle [kWh]	40.9	78.0	78.0	78.0	78.0
Maximal wheel slip [%]	7.5	6.7	5.0	4.8	5.7
Braking distance [m]	48.2	48.0 (-0.5%)	51.7 (+7%)	51.0 (+6%)	49.9 (+4%)

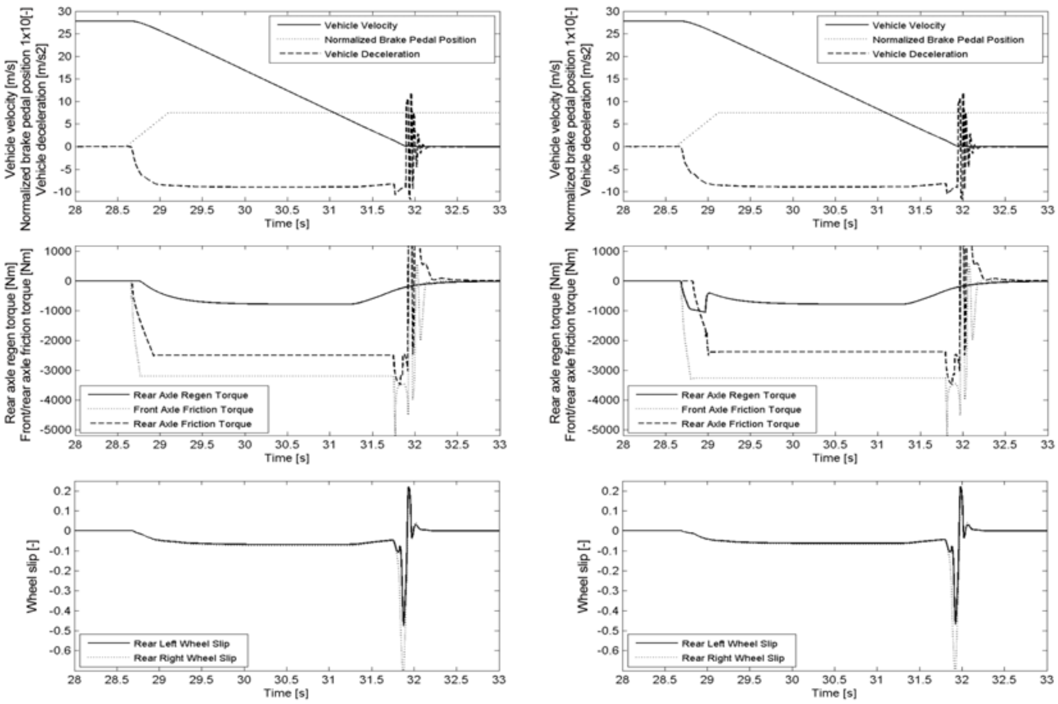

Figure 9. Simulation results for single braking manoeuvre on the high mu surface (μ=1.0). Left graphs – results for throttle-off regenerative braking, right graphs – results for the first regenerative braking strategy (termination of regenerative braking during an ABS event).

tested manoeuvre the recorded slip level is within the acceptable range, which does not cause vehicle instability events. The use of throttle-off regenerative braking only for the given set-up and braking parameters results in *48.2 m* vehicle stop with *20.7 Wh* restored energy. In the case of the first proposed regenerative braking strategy the restored energy increases by *25*% (to *25.8 Wh*) together with a *0.5*% shorter braking distance. This result is an unexpected benefit from the use of regenerative braking. This observation also indicates the positive influence of an uncontrolled (via ABS) braking torque in braking distance. The second and third (with regenerative level during an ABS event of *250 Nm* and *500 Nm*) strategies regenerate even more energy; +*70*%, +*79*%, and +*99*% respectively (in comparison to the throttle-off regenerative braking only). The main difference between the first regenerative braking strategy and the other investigated strategies is the increase of the braking distance in a range from *4*% to *7*%, see Table 3.

3.2. Results for Single Braking on Low Mu Surface

The simulation results for braking on the high mu surface indicate approximate properties of the regenerative braking strategies. For a deeper understanding and comparison of the proposed strategies the low mu surface braking manoeuvre is now investigated. The test parameters are presented in Table 4. This test allows an investigation of the braking strategies and their influence on the vehicle dynamics.

Table 4. Simulation manoeuvres parameters.

Initial speed, v_1	27.7 [m/s]
Mu coefficient of the surface, μ	0.3 [-]
Normalized brake pedal position	0.3 [-]
Time range for full brake pedal application	0.5 [s]

The four sets of graphs presented in Figures 10 and 11 show the results for the regenerative braking strategies (including the two cases for strategy three). The left graphs in Figure 10 present the results for the braking activity on the low mu surface ($\mu=0.3$) for the first regenerative braking strategy. It can be observed from the regenerative braking torque trace, where for $t=29.0s$ the regenerative braking torque is terminated due to occurrence of an ABS event. In this test it may also be observed that the rear right wheel slip at the level of *12*% is higher than the slip for the rear left wheel *5*%, with both being recorded for the first part of the braking manoeuvre until the regenerative braking is terminated. The right column of the graphs in Figure 10 presents the results for the second regenerative braking strategy for the same braking manoeuvre. In this strategy the regenerative braking torque is gradually reduced to zero (to the throttle-off torque level). This causes, however, severe ABS operation as the rear right wheel reaches *40*% slip for $t=30.5s$.

Figure 11 presents the two cases for the third

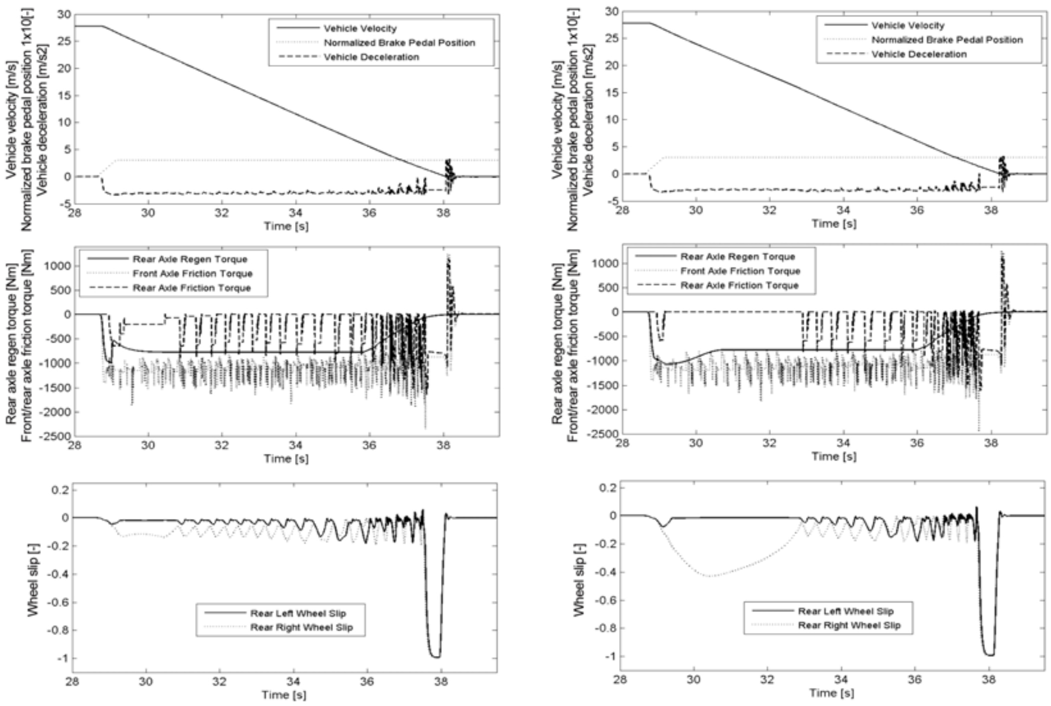

Figure 10. Simulation results for single braking manoeuvre on the low mu surface (μ=0.3). Left graphs – results for the first regenerative braking strategy, right graphs – results for the second regenerative braking strategy. Regenerative braking switch off 6.7 m/s.

regenerative braking strategy. The left graphs show the simulation results, where the regenerative braking residual level is established at the level of *250 Nm*, the right graphs being *500 Nm*. Both sets of graphs are in the main very similar. The greater residual torque results in a higher and earlier occurring wheel slip for the right wheel, with the *500 Nm* residual level resulting in *76.8*% slip for *t=30.1s*, whereas the *250 Nm* residual level results in *74.5*% wheel slip for *t=31.0s*, see Figure 11.

An analysis of the numerical results of the tests highlights some very interesting observations, see Table 5. The application of the first regenerative braking strategy on the low mu surface increases the restored energy by *4*% in comparison to the throttle-off only regenerative braking, with *0.5*% greater braking distance. The second proposed regenerative braking strategy gives a *10*% increase of restored energy at the expense of *3*% greater braking distance. The third regenerative braking strategy, however, decreases the restored energy level by *7*% for a *250 Nm* residual level and by *12*% for a *500 Nm* level, together with an increase of the braking distance by over *6*% for both cases. This situation has arisen as a result of the applied braking torque being too excessive, which is out of the range of ABS control. In both cases a single wheel slip greatly exceeded *70*% during the regenerative braking and grows even higher for the second part of the test, see Figure 11. This limits the braking force that can be transmitted by the tyre to the road (increasing the braking distance) and reduces the restored energy gain over the braking manoeuvre.

The low mu surface simulations also revealed a very interesting behaviour, which concerns one wheel slip higher than the other. This phenomenon can be observed for all strategies. However, for the third regenerative braking strategy the difference between one axle (rear axle) wheels slip is significant. A deeper analysis of these phenomena reveals that this is directly connected with the mechanical means of the regenerative braking torque delivery. The simulated power train set-up uses an E-Motor fitted with a rear axial differential via a three speed gearbox. The use of the open differential during the regenerative braking manoeuvre causes an unequal lateral torque distribution. For a situation when the ABS reduces the friction brake torque close to the zero level, the regenerative braking torque plays a major role in terms of wheel slip. The initial asymmetric torque delivery is caused by the natural asymmetry in the vehicle. Such asymmetry causes an initial difference in the wheel slip for left and right wheels. This difference will increase, as the torque delivered by the E-Motor will naturally follow the path of least resistance. On this basis the torque will be received by the wheel exhibiting the higher wheel slip.

The higher slip of the wheel causes an additional problem in terms of regenerative and friction brakes blending. For both simulations, shown in Figure 11, the regenerative braking torque has been drastically reduced,

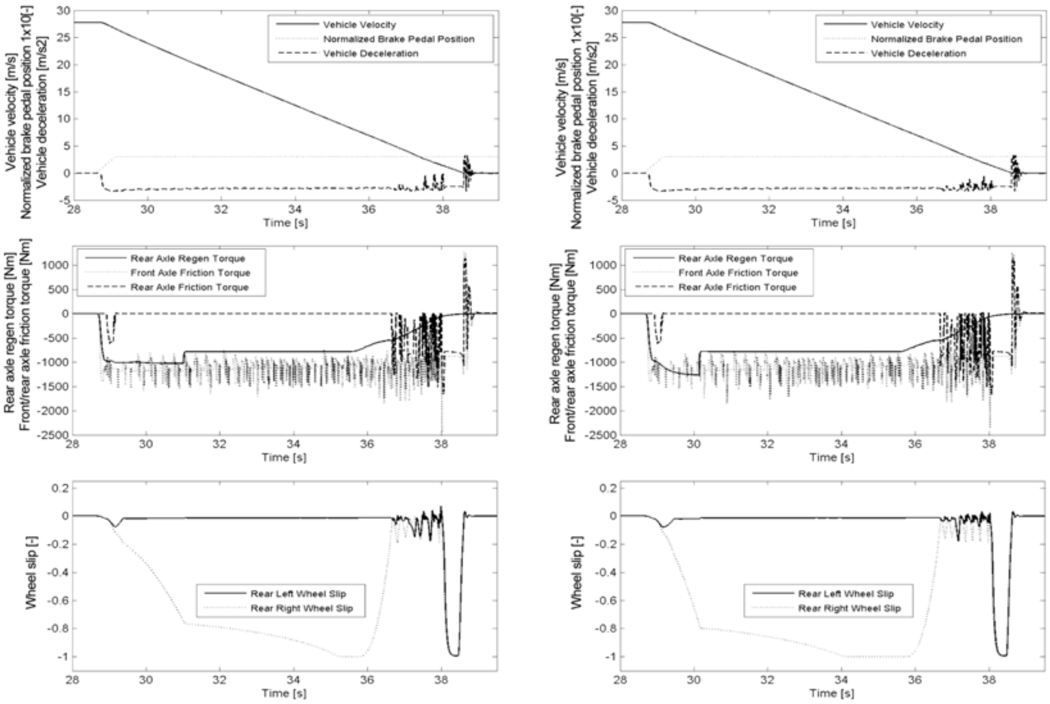

Figure 11. Simulation results for single braking manoeuvre on the low mu surface (μ=0.3). Left graphs – results for the third regenerative braking strategy with regenerative braking torque during an ABS event on the level of 250 Nm, right graphs – results for the third regenerative braking strategy with regenerative braking torque during an ABS event on the level of 500 Nm. Regenerative braking switch off 6.7 m/s.

particularly in the case of the higher wheel slip (one wheel nearly locked). This results in the sudden regenerative braking torque decrease for *t=31.0s* for the left column of graphs (first regenerative braking strategy) and *t=30.1s* for the right column of graphs. Based on the observations regarding backward wheel rotation, a regenerative braking

Table 5. Manoeuvre energy potential for different regenerative braking strategies during an ABS event.

Initial speed, v_1	27.7 [m/s]				
Mu coefficient of the surface, μ	0.30 [-]				
Bake pedal position	0.30 [-]				
Regenerative braking strategy during an ABS event	Throttle-off only	Termination of re-gen	Ramp down re-gen to zero	Ramp down re-gen to residual level (250 Nm)	Ramp down re-gen to residual level (500 Nm)
Dissipated energy - Friction brakes, Front axle [Wh]	101.2	102.0	104.9	107.6	108.0
Dissipated energy - Friction brakes, Rear axle [Wh]	25.4	21.6	9.3	3.8	3.6
Restored energy - Regenerative braking, Rear axle [Wh]	68.5	71.5 (+4%)	75.3 (+10%)	63.9 (-7%)	60.0 (-12%)
Peak power - Friction brake, Front axle [kWh]	109.3	129.6	107.9	107.7	109.8
Peak power - Friction brake, Rear axle [kWh]	84.6	55.9	42.8	44.2	43.9
Peak power - Regenerative braking, Rear axle [kWh]	50.7	78.0	78.0	78.0	78.0
Maximal wheel slip [%]	17.7	13.7	42.9	74.5	76.8
Braking distance [m]	128.6	129.1 (+0.5%)	132.7 (+3%)	136.5 (+6%)	136.8 (+6%)

Table 6. Initial conditions for split mu braking.

Initial speed, v_1	50 [m/s]
Left side Mu coefficient of the surface, μ_1	1.0 [-]
Right side Mu coefficient of the surface, μ_2	0.3 [-]
Normalized brake pedal position	0.15[-]

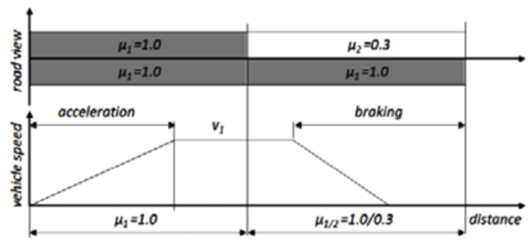

Figure 12. Upper graph presents the road plan view with friction coefficient details; lower graph depicts vehicle velocity profile of the manoeuvre with respect to driver action.

torque cancellation has been conveniently introduced into the simulations (noting that this would require further development in practice). This introduces individual wheel speed control in order to prevent the backward wheel rotation caused by the negative regenerative braking torque.

Figures 10 and 11 present sudden friction torque changes (especially for the front axle). The origin of these changes is directly connected with the ABS operation for tests on the low mu surface. It can be observed that the frequency of the torque changes correspond to typical ABS operational frequency i.e. up to 10 Hz. Similar oscillations have been recorded for the rear wheels friction brakes. In this case the oscillations present are lower in frequency due to the lower wheel slip for the rear axle.

3.3. Split Mu Surface Single Braking Test

The next simulation has been performed for the split mu surface braking manoeuvre (Metz and Scheibe 2009). The particular test track characteristic is presented in Figure 12, and the test parameters are presented in Table 6.

Figure 13 presents the simulation results for the first and the second regenerative braking strategies. For both strategies an excessive single wheel slip has been recorded. In both cases the ABS system starts to operate from *t=29.1s* introducing the regenerative braking strategies during an ABS event. It should be noted that during an ABS event the throttle-off torque is continuously supplied by the E-Motor. The decrease of the friction braking torque (hydraulic pressure reduction) causes the higher left wheel slip. The increase of the friction brakes torque results in the regaining of the tyre grip (slip reduction) by the wheel.

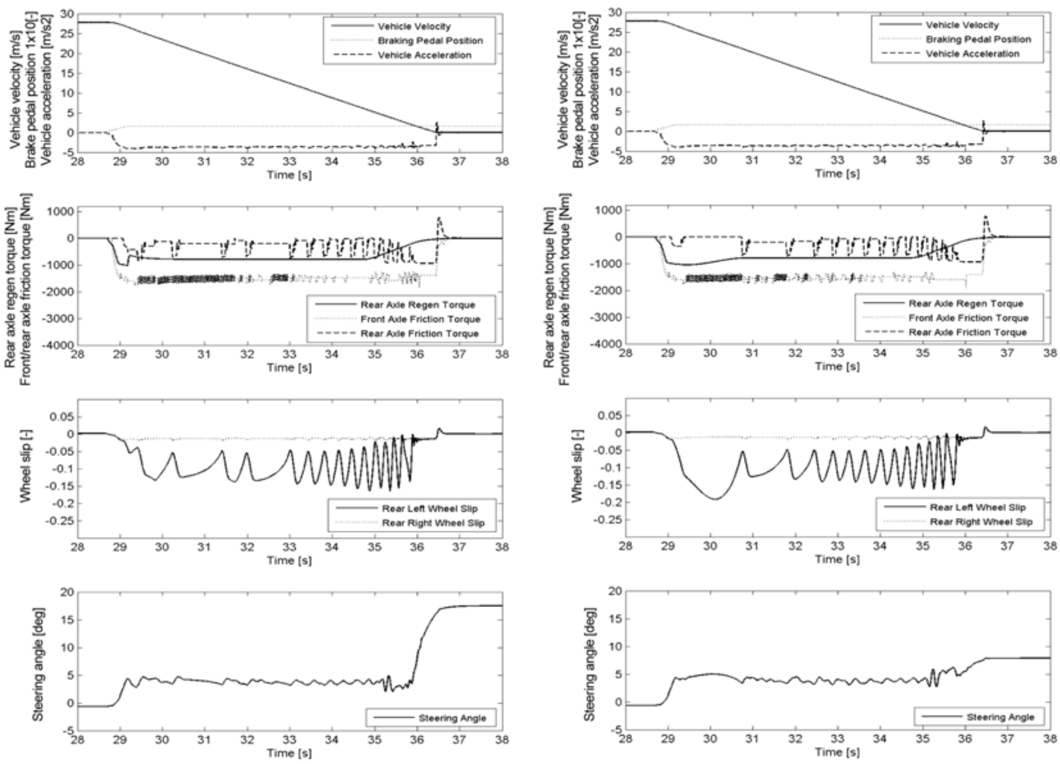

Figure 13. Simulation results for split mu braking manoeuvre. Left graphs – results for the first regenerative braking strategy, right graphs – results for the second regenerative braking strategy. Regenerative braking switch off 6.7 m/s.

This observation explicitly confirms the negative influence of the regenerative braking torque delivered via the differential.

The test shows that for the chosen drive line configuration the regenerative braking torque should be either switched off during an ABS event or an additional torque direction (electronic differential, torque vectoring system) control strategy should be applied. This conclusion is connected with the observed interaction between the regenerative braking and ABS control. The ABS action is to reduce the wheel slip level by reducing friction brakes torque (reduction of hydraulic pressure). When the regenerative braking source supplies the braking torque via an open differential, the regenerative braking torque is directed to the wheel with a lower grip. This action together with ABS friction brakes torque reduction results in the increase in the wheel slip. The slip can increase up to *100%*, and, for extreme cases, the backward wheel rotation can be observed.

4. CONCLUSION

In this paper three basic strategies for regenerative braking and friction brakes torque control during an ABS event have been proposed. The strategies are intended to increase the amount of recaptured energy whilst maintaining the vehicle stability. The regenerative braking strategies considered are generic for all possible driveline configurations. In this study, the control strategies have been simulated with use being made of rear axle regenerative braking applied to a model of a luxury car. The E-Motor torque was delivered to the wheels via a differential and a three-speed gearbox. The vehicle set-up has been arbitrarily chosen as a Low Carbon Vehicle Technology Project (LCVTP) base vehicle configuration, which was of interest to the project partners.

Various forms of the investigated regenerative braking control strategies are already present within hybrid and electric vehicles. However, their operational envelopes (level of deceleration) are currently drastically limited. In this paper, these limitations have been relaxed and the interactions of the controllers have been investigated at the extreme operating conditions. Through the range of the conducted simulations, especially in terms of road friction coefficient, some key observations are of importance for future regenerative braking technology development.

High mu surface observations;

- The use of the first regenerative braking strategy can slightly reduce the braking distance while recapturing *25%* more energy in comparison to the throttle-off only regenerative braking.
- The other investigated strategies considerably increase the energy gain up to *100%* at the expense of a longer braking distance up to *7%*.

Low and split mu surface observations;

- The use of the first and the second regenerative braking strategies can increase the energy gain up to *10%* with an increase of the braking distance up to *3%*.
- The third strategy increases the braking distance and decreases the recaptured energy level.
- For the third strategy the greater torque residual level increases a single wheel slip.
- When braking with active ABS the possibility of wheel lock-up or even backward wheel rotation has been detected.

The use of one electric motor fitted with an open differential causes uneven torque delivery and excessive slip at one wheel. The results have shown that for the strategies investigated, there is not one single regenerative braking strategy suitable for the wide range of road conditions and manoeuvres. Also some issues connected with the driveline configuration in terms of the torque delivery have been highlighted. In this case a form of torque direction monitoring system (electronic differential, torque vectoring system, or individual wheel electric motors) should be taken into account.

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