

Regenerative Braking Control for High Level Deceleration on Low Mu Surface

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ABSTRACT

Hybrid and electric vehicle (H/EV) technology is already well established in the automotive industry and a great majority of car manufacturers offer vehicles with alternative propulsion systems (hybrid or electric - H/E). This advancement, however, does not mean that all technical aspects of H/E propulsion systems have already been encapsulated or even fully understood. This statement is specifically valid for regenerative braking technology. In order to regenerate the maximum possible energy, which may be limited in real applications (e.g. by the charging ratio of the energy storage device(s)), the interaction of regenerative braking and the active driving safety systems (ADSSs) such as the anti-lock braking system (ABS) needs to be taken in to account. For maximum recaptured energy via electric motor (E-Motor) braking, the use of regenerative braking, which generates decelerations greater than 0.1g, should be deployed. This however, creates the possibility of ADSS intervention which limits the extensive use of regenerative braking for the full breath of the braking period.

In this paper, simulation results making use of a vehicle mathematical model are presented to highlight some important issues with regenerative braking control which are directly caused by the configuration of the driveline, namely one E-Motor fitted with an open differential. In the paper a regenerative braking controller based on slip control has been proposed to offer both a high level of restored energy and reduced braking distance, by maximizing on the traction for high deceleration braking maneuvers on a low mu surface.

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INTRODUCTION

Hybrid and electric vehicles (H/EVs) share many mechanical components with their non-H/EVs counterparts, especially when considering the powertrain components. However, although some parts of the H/E propulsion systems are bespoke for that specific design; others are taken across from non-H/EVs without or with only slight modifications (e.g. internal combustion engine, gearbox, differential). Whilst it is often the case, such methodology in unification of components can lead to integration problems since the desired system/vehicle characteristics then become difficult or even impossible to achieve.

For H/EVs it is important to regenerate as much energy as possible during a braking process (Yimin et al. 1999), i.e. by using regenerative braking within the traction limit and not causing any vehicle instability issues (Oleksowicz et al. 2013a), (Oleksowicz et al. 2013b), (Ko et al. 2014). Regenerative braking systems that have the feature of individual wheel torque control, e.g. making use of hub-electric motors (E-Motors) or a torque vectoring differential, are optimally able to utilize the traction capacity of separate wheels. Up to some extent, systems with limited slip differential can also be included in this group. In comparison, for most common drivelines, i.e. equipped with one E-Motor connected to the axle via an open differential, wheel slip based regenerative braking control should be

applied. However, an open differential may have a negative influence on the vehicle stability especially when regenerative braking and the anti-locking braking system (ABS) are applied simultaneously, as reported in (Oleksowicz et al. 2013b).

Open Differential

For better understanding of a typical open differential operation during driving situations with limited tyre-road adhesion levels (e.g. split μ surface), the following theoretical investigation has been performed. Let us define the differential efficiency η as the coefficient describing the relation between the sum of the output power P_{out} torques T_{out} and the input power P_{in} torque T_{in} (Breuer and Bill 2008):

$$\sum P_{out} = \eta P_{in} = T_{out_1} \omega_{out_1} + T_{out_2} \omega_{out_2} = \eta T_{in} \omega_{in} \quad (1)$$

The differential efficiency has been introduced in order to account for the dissipation of torque due to the friction phenomenon. In addition, the friction effect introduces torque bias along the output shafts creating the so-called locking effect. For open differentials, the locking effect usually oscillates at about 10%. This can be described by the differential slip ratio ρ that describes the locking effect between output shafts:

$$\rho = \frac{T_{out_1}}{T_{out_2}} \quad (2)$$

Where

T_{out_1} , T_{out_2} are the output torques of the shafts.

Let us define the following parameters:

I_{RG} - differential ring gear inertia,

ω_{RG} - differential ring gear angular velocity,

T_{RG} - differential ring gear torque, which can be calculated using the gear ratio r_{in_RG} :

$$r_{in_RG} = \frac{T_{RG}}{T_{in}} = \frac{\omega_{in}}{\omega_{RG}} \quad (3)$$

In order to calculate the maximal driving torque T_{in} supplied by the E-Motor as a function of the lowest wheel traction level for an open differential driveline, an exemplary representation of the rear axle regenerative braking has been taken into account, see Figure 1.

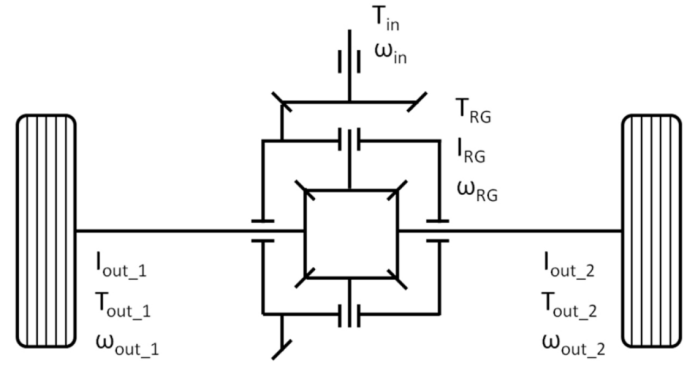


Figure 1. Schematic of an open differential driveline system with lumped axle and wheel inertia.

Using nomenclature introduced earlier, we can derive the mathematical description for an open differential:

$$r_{in_RG} T_{in} - I_{RG} \dot{\omega}_{RG} = T_{out_1} + I_{out_1} \dot{\omega}_{out_1} + T_{out_2} + I_{out_2} \dot{\omega}_{out_2} \quad (4)$$

On the basis of equations (1) and (2) we can write:

$$r_{in_RG} T_{in} - I_{RG} \dot{\omega}_{RG} = T_{out_2} \frac{1}{\eta} \rho + T_{out_2} + I_{out_1} \dot{\omega}_{out_1} + I_{out_2} \dot{\omega}_{out_2} \quad (5)$$

Further simplification results in:

$$r_{in_RG} T_{in} - I_{RG} \dot{\omega}_{RG} = T_{out_2} \left(1 + \frac{1}{\eta} \rho\right) + I_{out_1} \dot{\omega}_{out_1} + I_{out_2} \dot{\omega}_{out_2} \quad (6)$$

On the basis of the equations (3) and (5) we can calculate the shaft torques as a function of the differential input torque:

$$T_{out_2} = \frac{r_{in_RG} T_{in} - I_{RG} \dot{\omega}_{RG} - I_{out_1} \dot{\omega}_{out_1} - I_{out_2} \dot{\omega}_{out_2}}{1 + \frac{1}{\eta} \rho} \quad (7)$$

And

$$T_{out_1} = (r_{in_RG} T_{in} - I_{RG} \dot{\omega}_{RG} - I_{out_1} \dot{\omega}_{out_1} - I_{out_2} \dot{\omega}_{out_2}) \frac{\frac{1}{\eta} \rho}{1 + \frac{1}{\eta} \rho} \quad (8)$$

Considering a split μ braking situation as depicted in Figure 2, we can describe the maximum driving torque T_{in} supplied by the E-Motor as a function of the lowest wheel traction level for an open differential drive line setup:

$$\eta r_{in_RG} T_{in} - I_{RG} \dot{\omega}_{RG} = T_{ALim_1} + \frac{T_{ALim_1}}{\rho} + I_{out_1} \dot{\omega}_{out_1} + I_{out_2} \dot{\omega}_{out_2} \quad (9)$$

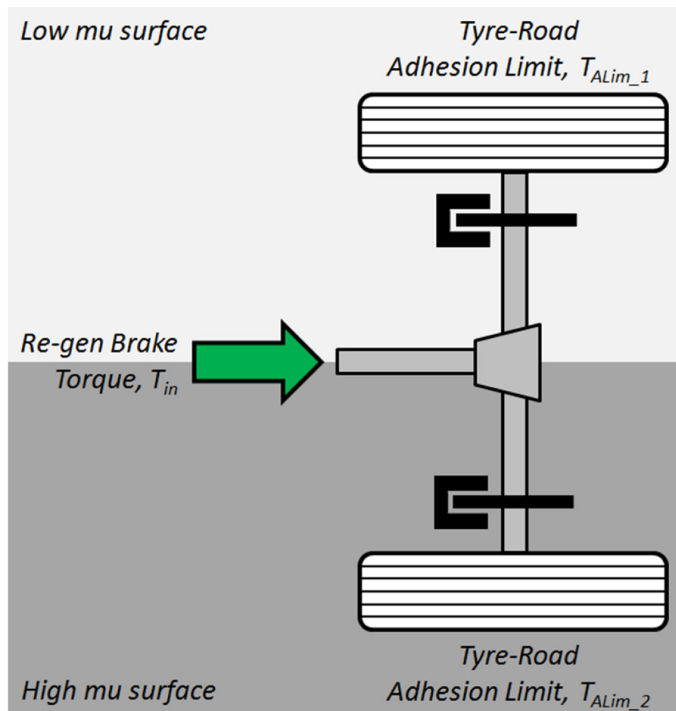


Figure 2. Rear axle regenerative braking via an open differential with separate wheels adhesion level indication for split μ braking situation.

For the sake of simplicity let us assume:

$$\eta = 1, \rho = 0.9, \text{ and } r_{in_RG} = 1 \quad (10)$$

Using equation (9) and the simplifications (10) we can write:

$$T_{in} - I_{RG} \dot{\omega}_{RG} = T_{ALim_1} + \frac{T_{ALim_1}}{0.9} + I_{out_1} \dot{\omega}_{out_1} + I_{out_2} \dot{\omega}_{out_2} \quad (11)$$

The formula for maximal torque input concerning the lowest traction along the axle can be written as follows:

$$T_{in} \approx 2.1 T_{ALim_1} + I_{RG} \dot{\omega}_{RG} + I_{out_1} \dot{\omega}_{out_1} + I_{out_2} \dot{\omega}_{out_2} \quad (12)$$

If we assume that the regenerative braking torque delivered by the E-Motor (T_{in}) exceeds the value described by equation (12), the excessive regenerative braking torque will result in backward rotation of the wheel. This situation can be also observed during an ABS event and will be investigated below (Oleksowicz et al. 2013b).

Let us imagine a braking situation on the split μ surface with a braking request that exceeds the traction level of the wheel on the higher μ surface. The three channels ABS in this case will take action with regards to the wheel with lower traction reducing the friction torque in order to regain traction. In this case when regenerative braking torque is supplied via an open differential, the open differential will transmit T_{in} as calculated according to equation (12) to the wheel with greater traction. The excessive torque will, as in the previous case, result in backward rotation of the wheel.

In order to avoid the problem mentioned above, appropriate regenerative braking control strategy should be applied for a regenerative braking system with an open differential.

Before introducing the main principles of regenerative braking control for high level deceleration on low μ surfaces, the simulation model used within this exercise is described in the following section.

SIMULATION MODEL

The simulation platform used in this exercise has been extensively described in the following papers (Oleksowicz et al. 2013a), (Oleksowicz et al. 2013b), (Cheng et al. 2010). The basic characteristics of the simulated vehicle model are (see Table 1):

- Rear wheel drive vehicle with regenerative braking capability.
- One E-Motor fitted with an open axial-differential.
- IPG CarMaker based ABS models (four channels and three channels with select-low functionality).

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]
Max Steering Angle	500 [deg]
Drag Coefficient	0.29 [-]
Vehicle Length	5122 [mm]
Vehicle Width	2110 [mm]
Vehicle Height	1448 [mm]

During simulations the following information has been assumed to be known:

- Friction adhesion level.
- Vehicle velocity.
- Wheel speed.
- Separate wheel load level.

Initial investigation of the interaction between regenerative braking and active driving safety systems (ADSS) presented in (Oleksowicz et al. 2013b) shows that the use of an E-Motor fitted with an open axial-differential may cause some vehicle stability problems during an ABS event.

Control assumptions:

- Throttle off re-gen controlled by brake torque apportionment controller (BTAC) (Oleksowicz et al. 2013b).
- Regenerative braking control strategy for restoration of maximum energy.
- ABS supervisory control has priority over regenerative braking.
- Regenerative braking is able to interact with ABS allowing the ABS to act at any time (prioritization of ABS operation) (IPG CarMaker 3.5 2011).

The tyre model has been created using the Magic Formula MF-Tyre 5.2 (Pacejka and Besselink 1997) with an additional term, which simulates the relaxation behaviour of the tyre.

The Driveline Model

The driveline model was created under the Dymola software. The model includes shaft compliance along with a typical friction model and values for bearing resistance (Oleksowicz et al. 2013a), (Oleksowicz et al. 2013b). The model characteristics and values were provided by an OEM and will be not presented due to the intellectual property and non-disclosure agreement. The driveline model includes left and right driveline shafts that are of different lengths.

Three and Four Channels ABS

In order to investigate regenerative braking operation at the adhesion limits the use of ABS is required. In this exercise two ABS algorithms have been simulated.

The first ABS algorithm operates as a three channels version with select low functionality, see Figure 3. In this strategy, the ABS control module considers the wheel that has the least amount of traction (the wheel which has a greater slip level) and takes action accordingly to neglect the wheel with higher traction. This control strategy does not utilize the available grip on the wheel with better traction. However, it is a very frequently used strategy by Original Equipment Manufacturers (OEMs) as in does not generate a yaw moment, which requires driver steering wheel counteraction.

The second ABS algorithm, based on four channels control, allows the utilization of individual wheel traction. In this algorithm each rear wheel is controlled separately. This however generates, for certain braking situations (e.g. split μ braking), a substantial amount of yaw moment, which needs to be balanced out with the use of appropriate steering action. The three channels ABS (with select low functionality) is currently widely used in passenger vehicles due to the lowest lateral influence (negligible yaw moment generation). However, it results in a longer braking distance than the four channels ABS (ABS/ASR "D" 1999), (Breuer and Bill 2008).

There are also other known ABS algorithms that use the three channels ABS control principles with an additional asymmetrical torque build up functionality in order to make use of the available traction (ABS/ASR "D" 1999), (Breuer and Bill 2008). Those systems in addition to wheel speed sensors also use a lateral/longitudinal acceleration sensor (or yaw rate sensor). Such algorithms will be not applied in this exercise as their design, tuning and verification is a vast task, appropriate for another research.

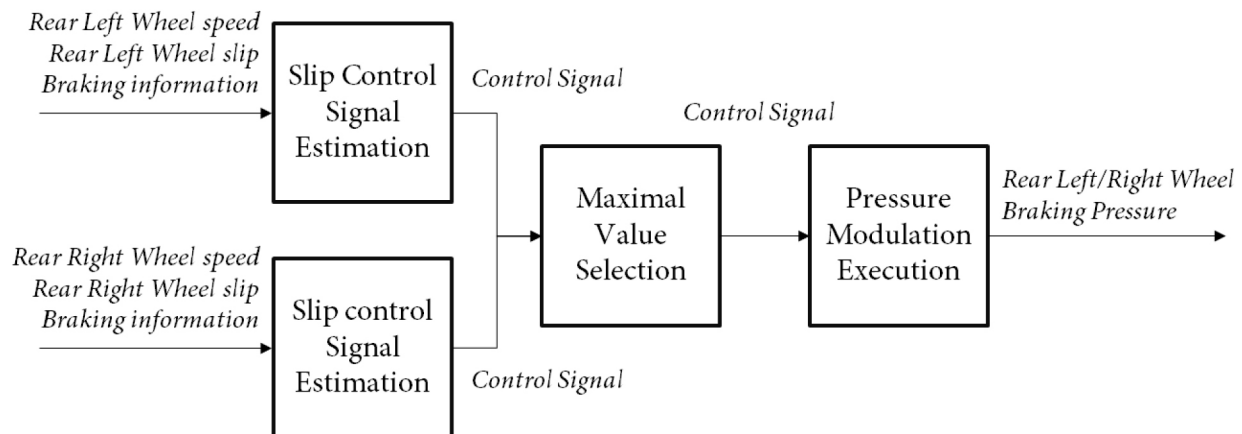


Figure 3. Simplified block diagram of Simulink model of the three channels ABS with select-low functionality.

INITIAL CONSIDERATION FOR REGENERATIVE BRAKING CONTROL

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 of a priori assumption that interaction between the two systems (i.e. ABS and regenerative braking) is technically possible. This allows regeneration of energy over the braking activity, that greatly exceeds the deceleration level of 0.1g, which corresponds to the situation when, even for low μ surfaces, the vehicle is still free of ABS intervention. In other words the regenerative braking has priority in braking activity unless ADSS kicks in.

Regenerative Braking Strategy During ABS Event

The ramp down regenerative braking torque to a variable residual level strategy has been applied for maximum recapture of energy (Oleksowicz et al. 2013b). In this strategy the regenerative braking torque is gradually reduced to a variable residual level upon an ABS event, see Figure 4. The total driver braking demand is achieved by the activation of friction brakes (blending process).

The non-zero regenerative braking torque level increases the overall restored energy level. In this strategy the ABS braking torque modulation is implemented via the friction brakes.

E-Motor Negative Torque

Regenerative braking control has been introduced on the basis of torque control (in comparison to conventional vehicle braking systems where pressure control is used). The initial analysis of the regenerative braking mode of an E-Motor shows the need for the introduction of additional control functions directly connected with torque control strategy.

In regenerative braking mode, the E-Motor will not produce negative braking torque. However, in the case of a torque controlled E-Motor, the controller can request a negative torque switching from regenerative braking mode (no additional energy supplied to E-Motor) into drive mode with negative shaft rotation request (additional energy supplied to E-Motor), see Figure 5.

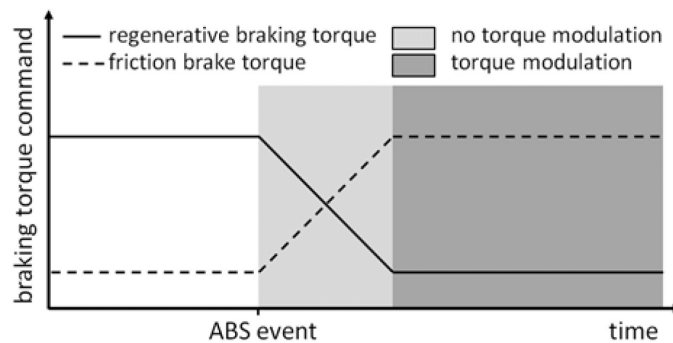


Figure 4. Regenerative and friction brake torque trace for the third strategy upon the occurrence of ABS event (Oleksowicz et al. 2013b).

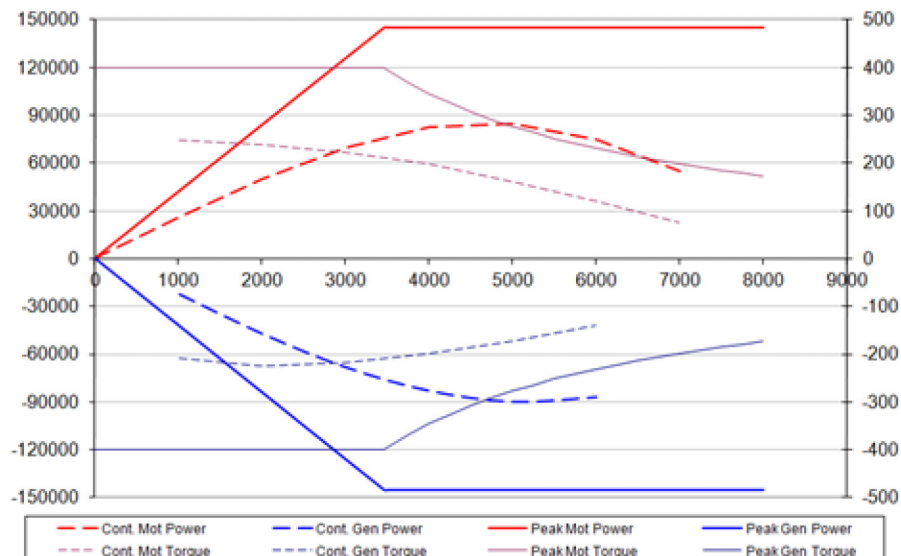


Figure 5. Typical E-Motor characteristics for drive and regenerative braking modes.