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ON THE LEGAL, SAFETY AND CONTROL ASPECTS OF REGENERATIVE BRAKING IN HYBRID/ELECTRIC VEHICLES

O ASPEKTACH PRAWNYCH, BEZPIECZEŃSTWA ORAZ STEROWANIA HAMOWANIEM REKUPERACYJNYM W POJAZDACH HYBRYDOWYCH/ELEKTRYCZNYCH

Abstract

This paper highlights some of the legal and safety requirements, which concern the development, control system design and optimisation of regenerative braking modalities in H/EVs. Moreover, some early stage investigation within regenerative braking strategies especially during an active driving safety systems event will be introduced. The paper also includes simulation results, as well as road tests results for H/EV, which are highlighted with a view to the desirable characteristics for regenerative braking technology.

Keywords: hybrid/electric vehicles, regenerative braking, regenerative braking control

Streszczenie

W artykule przedstawiono wybrane aspekty dotyczące przepisów homologacyjnych oraz bezpieczeństwa, które wpływają na kierunek rozwoju oraz sterowania hamowania regeneracyjnego w pojazdach o napędzie hybrydowym i elektrycznym. Omówiono wstępne badania dotyczące strategii hamowania regeneracyjnego, szczególnie podczas działania aktywnych układów bezpieczeństwa ruchu. Zaprezentowano również wyniki symulacji oraz badań drogowych hamowania regeneracyjnego pojazdu o napędzie hybrydowym.

Słowa kluczowe: pojazdy hybrydowe, elektryczne, hamowanie rekuperacyjne, sterowanie hamowaniem rekuperacyjnym

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1. Introduction

The introduction of hybrid/electric (H/E) propulsion systems has been prompted primarily by two factors. The first is connected with diminishing fossil fuel supplies. The use of H/E plug-in vehicles make it possible to reduce the use of fossil fuels by utilizing electricity, which can be produced with a use of renewable sources. This idea reveals, however, some major issues connected with energy availability, charging infrastructure, and power grid capability (e.g. power grid balance). The second issue concerns the international legislative force to bring down CO_2 emission, hence fuel consumption [1]. In a view of H/E vehicles (H/EVs) both presented factors can be fulfilled by incorporation of a regenerative braking mode. In this mode, part of the vehicle kinetic energy can be recaptured via regenerative action during a braking manoeuvre and fed back to energy storage devices installed on-board. An increase in the regenerative braking recaptured energy ratio (specified as the restored energy to the sum of the energy restored and energy dissipated in the friction brakes) is of key importance in terms of total vehicle efficiency improvement. Currently available vehicles on the market (equipped with a regenerative braking mode) have the ability to regenerate some part of the vehicle kinetic energy. The limitation in the recaptured energy ratio is caused by the relatively low level of electric motor (E-Motor) torque and storage devices charging ratio. For current vehicles equipped with regenerative braking technology, the maximum vehicle deceleration generated only by an E-Motor can reach up to 0.1g. Higher levels of regenerative braking ratio are currently not available; however, even a small ratio (vehicle deceleration) is of great importance from the reduction of fuel consumption point of view. In recent years, much research effort has been made in order to improve this situation; however, the regenerative braking ratio remains on the same low level. The main problem that concerns the regenerative braking mode, as well as the electro-mechanical limitations, is the control issue, which in the case of deceleration greater than 0.1g, requires the interaction of regenerative braking control with vehicle active driving safety systems (ADSS) [2, 3].

2. EU regenerative braking legislation

The development of vehicle brake systems is driven by two factors. The first concerns its main purpose – safe vehicle speed reduction (to a halt) or vehicle hold if already halted. The second is connected with legal regulations, which concern the braking system. The European Union regulations regarding the braking systems in passenger vehicles are described by two documents:

1) European Directive 71/320/EEC [4],
2) ECE Regulation 13H and 13.11 [5].

These regulations are largely similar in terms of vehicles with conventional propulsion systems (non H/EVs). The only difference concerns the requirements for H/EVs, which are given in the ECE Regulation 13H and 13.11. The Regulations 13H and 13.11 divide the braking systems equipped with a regenerative braking mode into two categories; A and B, where the category B is split further into two systems; non-phased and phased.

Category A – describes the braking systems in which the regenerative braking system is not a part of the main braking system. Such systems use the regenerative braking only for throttle-off braking.

Category B, non-phased – includes the braking systems in which the regenerative braking exists as a part of the main braking system. The regenerative braking torque can be delivered together with the friction braking torque or slightly after an activation threshold – parallel braking strategy.

Category B, phased – the regenerative braking is a part of the main braking system. However, in this category the regenerative braking torque can be deployed before the braking torque generated by the friction brakes. Such a system allows the maximum amount of energy to be recovered.

In addition to the above systems interactions, some additional requirements, which concern the regenerative braking control, are described in Regulations 13H and 13.11.

For all systems with regenerative braking capability, the anti-locking braking system (ABS) must have control over regenerative braking torque.

For the systems described in Category B the braking input from other sources of braking (e.g. E-Motor) may be suitably phased in order to allow the regenerative braking only application with the two conditions being fulfilled. The first concerns the inertial variations of the regenerative braking torque, which should be automatically compensated with the use of foundation brakes (in this study the term foundation brakes has the same meaning as friction brakes). This also includes the compensation of system nonlinearity, e.g. caused by battery state of charge (SoC). The second refers to the braking rates, which should remain related to the driver's braking request with reference to the available tyre/road friction coefficient. Moreover, the braking system should automatically act on all wheels. In a practical sense, the system should possess the ability to automatically apply the braking torque on the non-regenerative braking axle in the case when the regenerative braking axle encounters a low friction coefficient surface (e.g. ice) in order to maintain the driver's expected deceleration until the low friction coefficient surface reaches both axles. Such restriction does not exist for non-H/EVs.

The above regulations influence the foundation brakes and regenerative braking technology considerably, especially the regenerative braking control strategy in terms of regenerative braking control and their interactions with the ADSS. This is currently of great interest and is being investigated by research groups around the world.

3. Regenerative braking strategies

3.1. Preliminary regenerative braking and friction brakes blending

Regenerative braking strategies are usually focused on a few aspects that are important from safety, economic and ride comfort points of view. The most fundamental assumption concerns the vehicle safe operation. However, economical aspects are of great importance not only for car manufacturers but also for customers. This requirement can be fulfilled by an increase of the regenerative braking ratio whilst maintaining the vehicle steer-ability and stability for all encountered road conditions (e.g. low mu surface) and manoeuvres (e.g. emergency braking). This requires an interaction of the regenerative braking control with the vehicle ADSS for maximum energy recovery.

The first regenerative braking strategy considered is dependent upon the way the regenerative braking and friction brake operation is combined. The regenerative braking can be considered as [6].

- Parallel braking strategy, where the regenerative brake starts to operate together with the friction brake, see Fig. 1, left.

The first strategy (parallel braking) is already used in H/EVs. A variation of such a system was used in the Porsche Cayenne Hybrid (all wheel drive vehicle). This strategy ensures the regeneration some of the vehicle kinetic energy during the braking activity, also during an ADSS operation. This relatively simple braking strategy presents, however, the lowest energy recuperation ratio. Unquestionably, this strategy eliminates the requirement for use of an additional system for 'pedal feel' simulation.

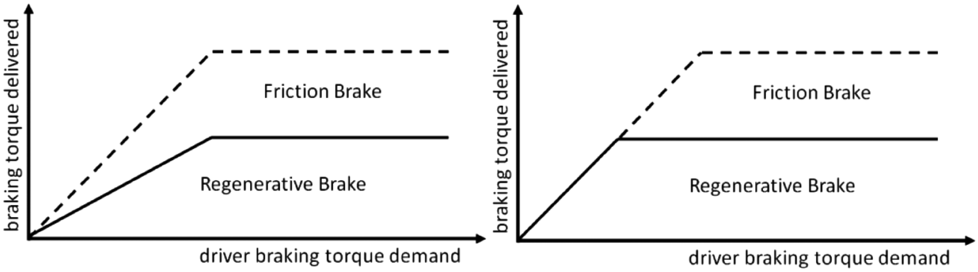

Fig. 1. Parallel (left) and serial (right) regenerative braking actuation strategy

Rys. 1. Strategia równoległa (lewa) oraz szeregowa (prawa) aktywacji hamowania rekuperacyjnego

- Serial braking strategy, where the regenerative brake starts to operate ahead of the friction brake, see Figure 1, right. In this strategy, the regenerative braking ratio can be increased in comparison to the parallel braking strategy. The friction brake starts to operate only in the case, when the regenerative brake reaches its maximum, which is lower than that requested by the driver.

The serial regenerative braking strategy is also used in H/EVs, however, the regenerative braking share in the total braking activity is relatively small. This ratio is apparently reduced in order to prevent the interaction of the regenerative braking with the ADSS. In the literature for serial regenerative braking strategies, the deceleration generated by a regenerative braking (E-Motor) does not exceed 0.1 g. The regenerative brake operates in the early move of the brake pedal, and then the regenerative braking torque stays at the assumed maximal level (this level can be variable according to the E-Motor torque characteristic). The difference between driver braking torque request and the regenerative braking maximum torque is compensated with the use of friction brakes. This strategy, however, creates a need for use of a 'pedal feel' simulator.

- Regenerative braking system as a main braking system (Fig. 2). This system requires fulfilling more conditions in comparison to systems presented above. The first concerns the need for individual wheel torque control. In this case, the use of one E-Motor fitted with an axial differential cannot be successful because of the potential lack of availability of separate wheel torque control.

In addition, use of the electronic differential (E-Diff) does not solve this issue as the E-Diff operates too slowly for implementation of the ADSS functions. Another very important point is that the continuous regenerative braking torque delivery must be independent e.g. on battery SoC or battery temperature.

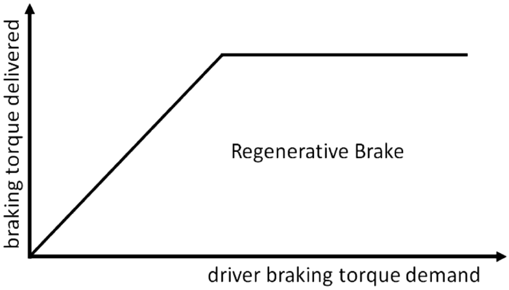

Fig. 2. Regenerative brake as the main braking system

Rys. 2. Hamowanie rekuperacyjne jako główny system hamulcowy

3.2. Regenerative braking strategies during an ADSS event

For maximum energy recovery, the interaction between the regenerative braking control and the ADSS has been assumed. The origin of this assumption is connected with expected interaction of the mentioned control systems in the case of braking situations, which greatly exceeds the deceleration level of 0.1 g. The level of 0.1 g denotes the situation when even for a low mu surface the vehicle is still free of the ADSS intervention. In this research, the following strategies have been taken into account:

- regenerative braking cut off during ADSS event (without blending phase);
- torque ramp down to a variable level (only friction torque modulation for ADSS purposes);
- regenerative braking torque modulation for ADSS purposes.

3.2.1. Regenerative braking cut off during an ADSS event

The first strategy for regenerative braking control during the ADSS event does not assume any blending phase between the regenerative braking and friction braking (Fig. 3).

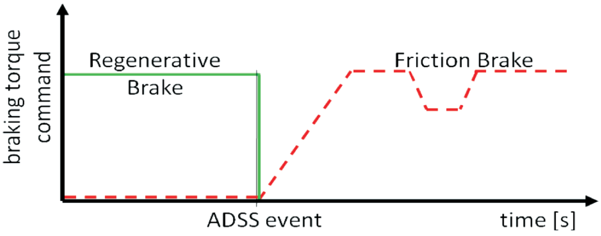

Fig. 3. Regenerative and friction brake torque trace for 1st strategy after an ADSS event occurs

Rys. 3. Przebieg momentu hamującego generowanego przez silnik elektryczny oraz hamulce cierne, w trakcie aktywności systemów ADSS, dla pierwszej strategii sterowania

The regenerative braking torque is immediately reduced to zero without a blending phase. Such a control strategy generates a temporary braking torque deficit. This, however, helps to regain the wheel grip but adversely affects the braking distance. In this strategy, the ADSS functions (e.g. ABS torque modulation) can be introduced only with the use of foundation brakes.

3.2.2. Ramp down regenerative braking to a variable level

In this second strategy the regenerative braking torque, during the ADSS events, is reduced gradually to the variable level (Fig. 4). The level of regenerative braking torque ensures obtaining a greater recapture energy ratio. For special circumstances (e.g. low mu surface and high deceleration request), the regenerative braking may be reduced to zero.

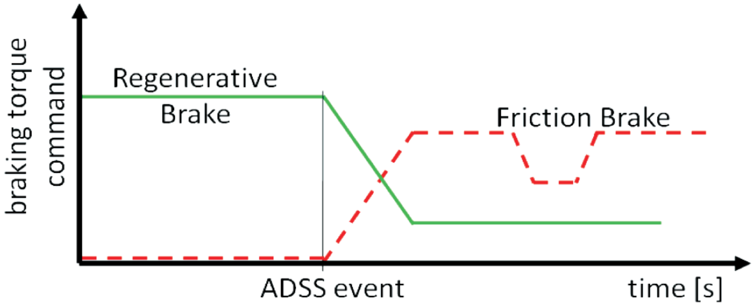

Fig. 4. Regenerative and friction brake torque trace for 2nd strategy after an ADSS event occurs

Rys. 4. Przebieg momentu hamującego generowanego przez silnik elektryczny oraz hamulce cierne, w trakcie aktywności systemów ADSS, dla drugiej strategii sterowania

In this regenerative braking strategy, the ADSS braking torque modulation is executed via foundation brakes. Theoretically, the vehicle that uses this strategy will be prone to frequent use of ADSS, as part of the braking torque (delivered by regenerative braking source) is out of the ADSS control.

3.2.3. Regenerative braking torque modulation for ADSS purposes

The third strategy ensures the ‘best’ energy recapture ratio in comparison to the first two regenerative braking strategies. The main advantage of this strategy is that the regenerative braking torque is not reduced during an ADSS event. Moreover, the braking torque modulations are preformed with use of regenerative braking source (or sources), Fig. 5. This is, however, highly dependent the E-Motor parameter and its characteristic. In addition to this, the driveline configuration is of key importance for considering the use of this strategy.

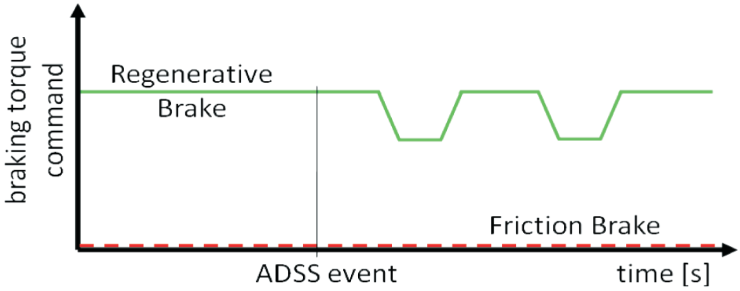

Fig. 5. Regenerative and friction brake torque trace for 3rd strategy after an ADSS event occurs

Rys. 5. Przebieg momentu hamującego generowanego przez silnik elektryczny oraz hamulce cierne, w trakcie aktywności systemów ADSS, dla trzeciej strategii sterowania

4. Regenerative braking additional functionalities

4.1. Low velocity regenerative braking switch off threshold

Use of the E-Motors instead of (or together with) foundation brakes generate some additional safety problems, e.g. the generation of negative torque. This is especially dangerous for low velocity brake applications such as up/down hill braking situations. For this consideration, the regenerative braking switch off threshold should be set up. The level of the threshold is a trade-off between the recaptured energy via regenerative braking and the safety considerations, which is determined by the control system and the E-Motor properties. It may also be dependent upon the E-Motor and wheels connection, e.g. the fixed driveline ratio will required higher regenerative braking switch off velocity level in comparison to the driveline equipped with a multi-speed or Continuously Variable Transmission (CVT) gearbox.

4.2. Throttle-off replication

The vehicle model used in this study has the possibility to replicate the throttle-off functionality. For the assumed vehicle driveline architecture the throttle-off braking torque has been simulated via activation of the E-Motor with the use of a vehicle supervisory controller (VSC). The braking torque trace as a function of vehicle velocity is presented in Fig. 6. The maximal value of throttle-off torque has been established at the level of 400 Nm.

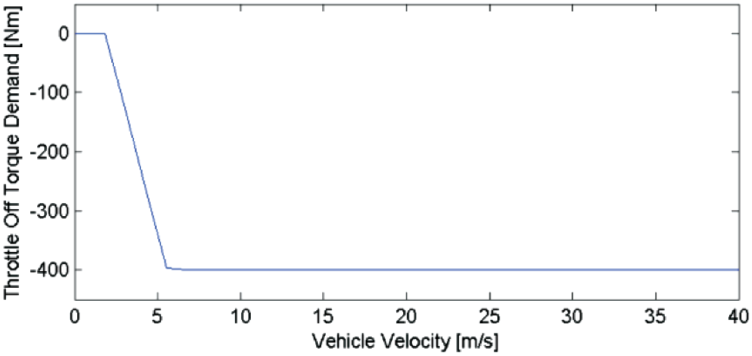

Fig. 6. Throttle-off torque characteristic, as a function of vehicle velocity, replicated by an E-Motor

Rys. 6. Przebieg momentu hamującego, dla funkcji hamowania silnikiem, generowanego przez silnik elektryczny

5. Description of the simulation platform

With the purpose of building a comprehensive vehicle representation model the simulation platform used in this research was developed with the use of three software products that are appropriate for different system simulation domains [7].

5.1. Model integration

All created models have been integrated using the MATLAB/Simulink software. Moreover, in Simulink the brake torque apportionment controller (BTAC), electronic brake force distribution model (EBD) and VSC have been designed. Drive line, E-Motor, hydraulic brake circuit and friction brakes, as well as their interactions have been modelled with a use of Dymola. In IPG CarMaker the road features and environment, vehicle dynamics, suspension model, driver model and tyre were modelled. Figure 7 presents the model physical connections assumed for an E-Motor fitted with a rear axle differential.

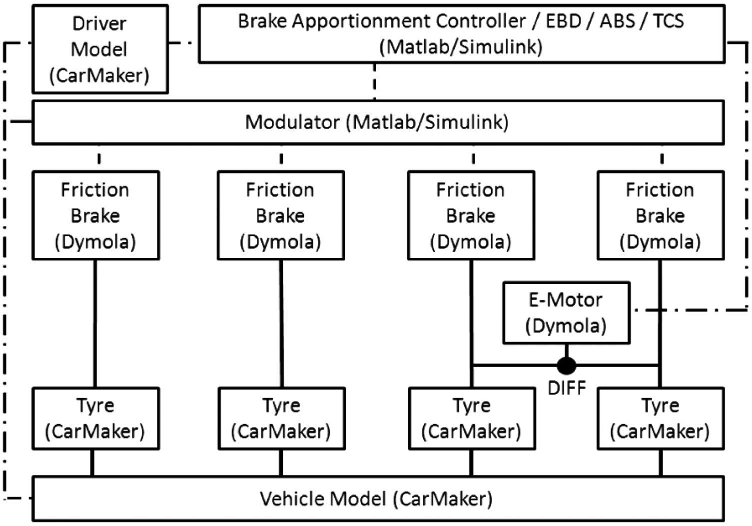

Fig. 7. Model integration diagram for rear wheel drive vehicle with one E-Motor connected to Rear Differential (continuous line – mechanical connection, dashed line – hydraulic connection, dashed dot line – electrical connection)

Rys. 7. Blokowy schemat układu napędowego z napędzaną tylną osią za pomocą silnika elektrycznego połączonego z mechanizmem różnicowym (linia ciągła – połączenie mechaniczne, linia przerywana – połączenie hydrauliczne, linia przerywana punktowa – połączenie elektryczne)

5.2. Driveline architecture and model parameters

In this research, the serial hybrid vehicle with rear axle regenerative braking facility has been investigated. The vehicle model has been modelled with use of the IPG CarMaker software (Fig. 8). The vehicle chassis model was created assuming a rigid body and with use of parameters presented in Table 1. The created vehicle model has been validated with use of road tests results for a braking system operation and systems characteristics, which are presented in [7, 8].

The tyre model has been created using the Magic Formula MF-Tyre 5.2 [9] with an additional term, which simulates the relaxation behaviour of the tyre. The simulation platform has the possibility of replicating vehicle handling situations with the use of the IPG Driver (lateral vehicle dynamics).

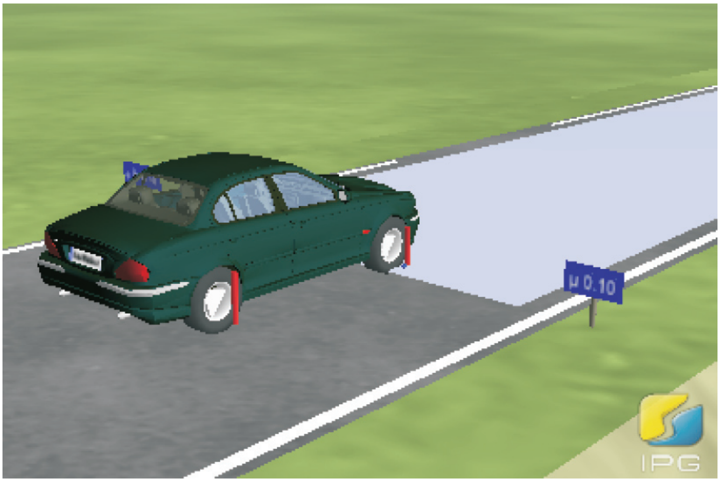

Fig. 8. Basic vehicle representation for low mu surface braking manoeuvre

Rys. 8. Widok modelu samochodu podczas symulacji hamowania na powierzchni o niskiej przyczepności

Table 1

Vehicle parameters

Parameter	Unit	Value
Unloaded Weight	[kg]	1796
Wheelbase	[mm]	3032
Turning Circle	[m]	12.3
Max Steering Angle	[deg]	500
Drag Coefficient	–	0.29
Wheel Size Front	–	19/45/245
Wheel Size Rear	–	19/40/275
Main Body	–	rigid body

The regenerative braking torque source (E-Motor modelled using Dymola software) has a nonlinear torque characteristic represented by a 1st order dynamical relationship and has been fitted with a rear differential through a three speed gearbox.

The BTAC has been designed for regenerative braking and friction brakes control. The more detailed operation of this controller will be described in a further publication. The main functions of the BTAC are focused on determination of the driver braking torque demand from brake pedal position and blending the regenerative braking torque with the foundation brakes.

The friction brakes model has been realised using the Dymola software with an assumed friction coefficient nonlinearity as a function of the brake lining temperature.

The driveline model has also been modelled using Dymola software. A rear axle electrically driven driveline architecture has been used.

6. Simulation results

The vehicle model described above has been simulated against a single, straight line braking manoeuvre on the high mu road surface. In this paper, some of the key results are shown and analyzed. The simulations have been carried out for the parameters presented in Table 2.

Table 2

Simulation manoeuvres parameters

Test specification	Parameter	Initial velocity	Mu coefficient	Normalized brake pedal position/vehicle deceleration	
[–]	unit	[km/h]	[–]	[–]/[m/s^2]	
Braking Torque Blending	value	100.0	1.0	0.10	0.25
Regenerative Braking Power and Energy Potential	value	50.0/70.0/90.0		2.0–3.0	

The proposed braking manoeuvre has been simulated against two different regenerative braking switch off thresholds 3.0 and 12.0 km/h (Fig. 9). The velocity thresholds chosen have been proposed following the idea of maximum recaptured braking energy (3.0 km/h). This, however, requires advanced control strategies and a high performance electro-mechanical system (e.g. controller, inverter, E-Motor). The second threshold (12.0 km/h) enables a reduction of the control algorithm complexity especially for low velocity coasting. In order to present the throttle-off characteristic in the simulation the normalized brake pedal positions corresponding to the levels of 0.10 and 0.25 have been chosen. The normalized brake pedal position is calculated by dividing actual brake pedal position and the maximal available brake pedal position. Normalized brake pedal position of 1.0 means a fully pressed brake pedal.

6.1. Braking torque blending

The chosen manoeuvre (single, straight line braking) also enables the assessment of the regenerative braking and foundation brakes blending strategy. Fig. 9 presents single braking results for the 0.25 normalized brake pedal position. The left part of the Fig. 9 shows results for braking with the regenerative braking switch off threshold on the 3.0 km/h level. The right part of Fig. 9 presents the results for braking with the same threshold on the level of 12.0 km/h.

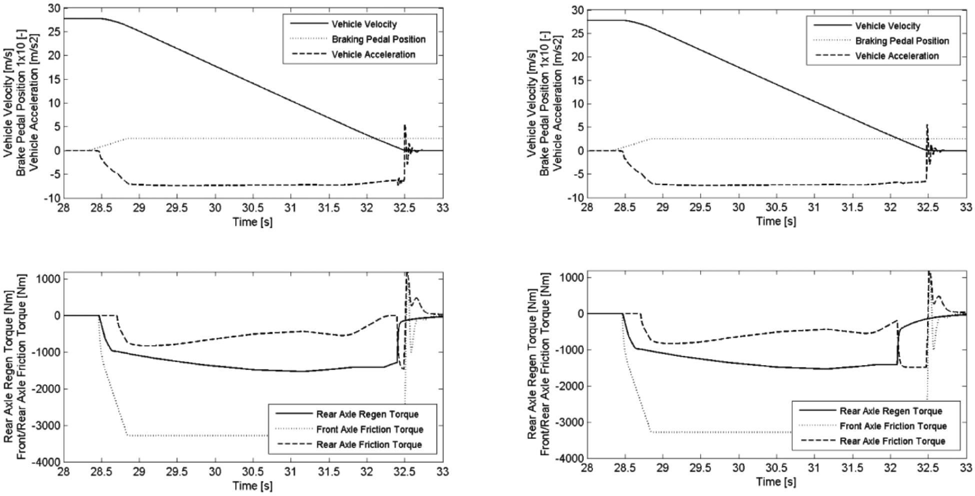

Fig. 9. Comparison of simulation results for 0.25 normalized brake pedal position initial velocity v = 100 km/h, and road surface coefficient *mu* = 1.0. Left for 3.0 km/h regenerative braking switch off threshold, right – 12.0 km/h regenerative braking switch off threshold

Rys. 9. Porównanie wyników symulacji dla 0,25 znormalizowanej pozycji pedału hamulca, prędkości początkowej v = 100 km/h, na drodze o wysokim (1,0) współczynniku tarcia. Wyniki dla deaktywacji hamowania rekuperacyjnego na poziomie 3,0 km/h – kolumna lewa, dezaktywacji hamowania rekuperacyjnego na poziomie 12,0 km/h – kolumna prawa

6.2. Regenerative braking power and energy potential

The main purpose of this simulation is to examine the restored/dissipated energy during the braking manoeuvre. Moreover, the investigation of power potential during the braking manoeuvre is possible, which is of importance from a hardware evaluation point of view. Fig. 10 presents the simulation results for a single brake application for the parameters presented in Tab. 2. All tests have been carried out on the fine mu road surface (*mu* = 1.0).

The numerical results corresponding to the simulations conducted are presented in Tab. 3. For all tests, the maximum regenerative braking power was limited to 78 kW (the E-Motor power limit). Further analysis shows that the amount of restored energy for the 0.10 brake pedal position is greater than that restored for the 0.25 brake pedal position. This observation is connected with the E-Motor power limit and vehicle load transfer, which for rear axle regenerative braking vehicle limits the possible braking force in the case of a braking manoeuvre with a high level of deceleration.

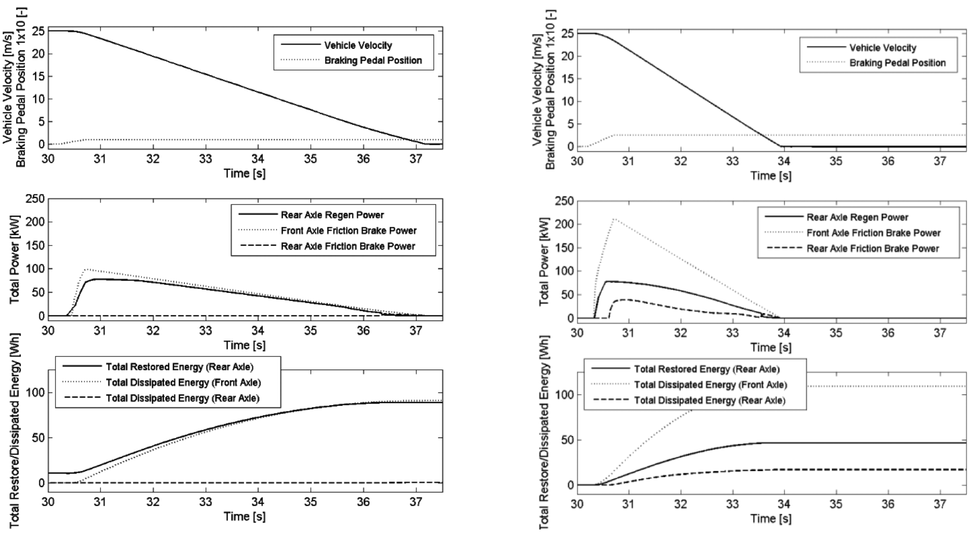

Fig. 10. Comparison of simulation results for 0.10 (left) and 0.25 (right) normalized brake pedal position, initial velocity *v* = 90 km/h, and road surface coefficient *mu* = 1.0

Rys. 10. Porównanie wyników symulacji dla 0,1 (kolumna lewa) oraz 0,25 (kolumna prawa) znormalizowanej pozycji pedału hamulca, prędkość początkowa *v* = 90 km/h na drodze o wysokim (1,0) współczynniku tarcia

Table 3

Manoeuvre energy and power potential

Initial vehicle velocity *v* [km/h]	Normalized brake pedal position [–]	Front axle friction brake maximum power [kW]	Rear axle friction brake maximum power [kW]	Re-gen maximum power [kW]	Front axle dissipated energy [Wh]	Rear axle dissipated energy [Wh]	Rear axle restored energy [Wh]
50.0	0.10	53.8	4.2	41.7	28.8	0.5	23.6
	0.25	110.2	9.1	52.9	34.6	3.1	15.7
70.0	0.10	76.4	4.2	60.6	55.5	0.5	47.2
	0.25	160.5	18.0	70.7	66.9	7.5	30.1
90.0	0.10	98.9	4.2	77.8	90.8	0.5	78.2
	0.25	210.8	39.2	78.0	109.1	16.8	46.4

An analysis of the simulation results obtained shows that in the case of a high deceleration braking manoeuvre (0.25 normalized brake pedal position) the recaptured energy ratio is of a greater value for the lower initial vehicle velocity (50 km/h – 29.4%, 70 km/h – 28.8% and 90 km/h – 26.9%). This is directly connected with the E-Motor power limit and can be observed in an increase of the dissipated energy via rear axle friction brakes. This phenomenon, however, has been not observed for low deceleration levels (0.1 normalized brake pedal position) as the E-Motor power limit (78.0 kW) exceeds the value of power (77.8 kW) used in this simulation.

7. Road tests

In order to present the recaptured energy ratio for road tests, the passenger hybrid vehicle with serial-parallel propulsion system (Fig. 11) has been considered.

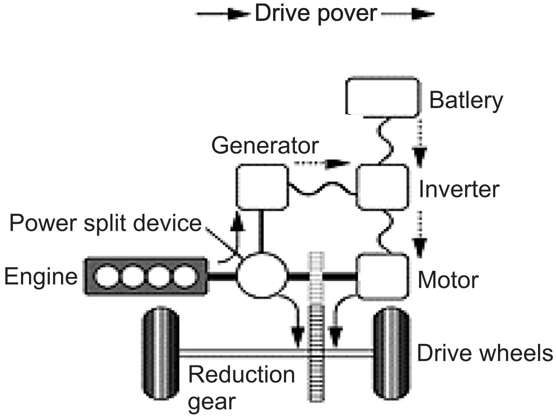

Fig. 11. The model of tested propulsion system hybrid vehicle

Fig. 11. Blokowy schemat układu napędowego badanego pojazdu hybrydowego

The driveline set-up presented enables the front axle regenerative braking by the operation of the E-Motor in a generator mode. The foundation brake system, which brakes all wheels, is handled by the electro-hydraulically activated brake system (EHB) with a brake pedal position sensor, brake pedal feel simulator, high pressure pump and a high pressure hydraulic accumulator.

During the braking activity, the control system uses the brake pedal position signal from the sensor. This signal is converted into the driver requested deceleration level. On this basis, the control system calculates the braking forces and executes the regenerative braking on the front axle. If the maximal regenerative braking deceleration is lower than the driver's deceleration request the EHB system is activated. The braking process is also supported by the internal combustion engine (ICE), however the throttle-off braking is reduced by the change in the timing angles, which reduces the compression pressure in the combustion chamber (use of the Atkinson cycle).

The road tests have been performed for the straight road single braking manoeuvre on a high mu surface (dry asphalt). The tests have been performed for three different initial vehicle velocities; 50, 70, and 90 km/h. The brake pedal position was established at a certain level that guarantees the vehicle deceleration in the range between 2.0 m/s^2 and 3.0 m/s^2. For all vehicle velocities, the number ‘n’ of repetitions have been performed with a continuously logged sum of the restored energy, given as:

$$E = \sum_{i=1}^{n} \int_{t_1}^{t_2} U(t) I(t) dt$$

where:

U – charging voltage,
I – charging current,
$t_2 - t_1$ – charging/braking time.

Recaptured energy readings were obtained with use of the on-board vehicle computer for which the measurement error is in a range between –25.0 Wh and 0 Wh. The recorded results have been normalized with the vehicle kinetic energy at the beginning of the braking test. The sum of the energies for ‘n’ tests is given by:

$$E_{\mathrm{kin}} = \sum_{i=1}^{n} \left(\frac{m v_0^2}{2} + \frac{I_w \omega_0^2}{2} \right)$$

where:

m – vehicle mass,
I_w – second moment of inertia for rotating elements (e.g. wheels),
v_0, ω_0 – initial vehicle velocity, initial angular velocity of the wheels.

The recaptured energy ratio was calculated as follows:

$$k_{\mathrm{reg}} = \frac{E}{E_{\mathrm{kin}}} 100\%$$

The road tests results are presented in Fig. 12. The calculation error of the recaptured energy ratio (k_{reg}) is caused by the error of the initial vehicle velocity measurements and the accuracy of the readings corresponding to the recaptured energy (in the range of –2% to 5%).

For the low deceleration braking with an average braking deceleration in the range between 2.0 m/s^2 and 3.0 m/s^2 it was possible to regenerate between 21% and 46% of the initial vehicle kinetic energy. The greater percentile recovery of the energy has been recorded for the lower initial vehicle velocity. This phenomenon is connected with the limited charging current of the battery and the E-Motor power limit (P_{gen}) in comparison to the continuous braking power described as:

$$P_{b,\max} = m g_b v$$

where:

m – vehicle mass,
g_b – braking deceleration,
v – vehicle velocity during braking.

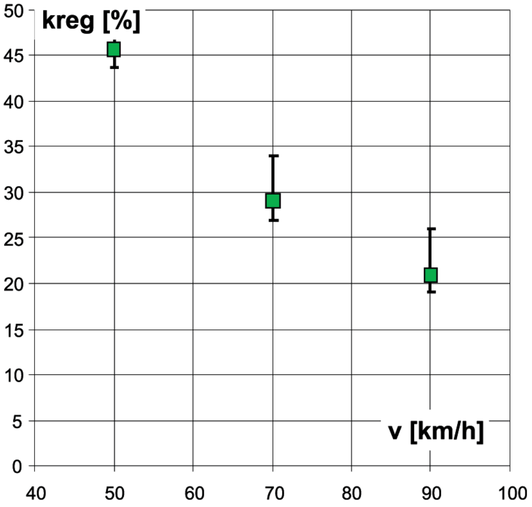

Fig. 12. The recaptured energy ratio as a function of the initial vehicle velocity

Rys. 12. Wartości współczynnika odzysku energii hamowania

For the initial vehicle velocity 70 km/h and the braking deceleration in a range between 2.0 m/s^2 and 3.0 m/s^2 the initial braking power for the tested vehicle reached the range between 60.5 kW and 90.5 kW, whereas the maximal E-Motor power limit is 50 kW. For the initial velocity 50 km/h and deceleration, the initial braking power is between 43.0 kW and 65.0 kW. For this velocity, the percentile energy recovery level can be considerably higher in comparison to that received for 70 km/h and 90 km/h initial velocities. The level of recaptured energy also depends on the battery state of charge (SoC) before the braking manoeuvre.

The road tests of the hybrid vehicle in the city traffic environment show that the regenerative braking activity covers almost 23% of the driving time. However, the amount of recovered energy is highly driver ride technique dependent.

8. Conclusions

The paper presents some of the key regenerative braking mode considerations, which are of importance for the development of operation-ready applications. Part of the requirements is already determined by EU Regulations, which have been briefly presented in this paper. Other important requirements are determined by the driver and passengers accepted vehicle behaviour, e.g. ride comfort, brake pedal feel. Moreover, the presented material explicitly shows that there still exist a number of challenges, which are connected with the interaction of the regenerative braking controller and the safety systems already installed on a vehicle. In this case, the regenerative braking strategy determines the regenerative braking ratio. In addition, the complexity of the system is highly dependent on the regenerative braking strategy.

The simulations of the various road tests indicate the following observations:

1. The use of regenerative braking switch off threshold is required for vehicle safe operation.
2. In the case of high regenerative braking deceleration (greater than 0.1 g) the interaction of regenerative braking control with the ADSS needs to be acknowledged and controlled.
3. The high regenerative braking deceleration (greater than 0.1 g) can be difficult to achieve by the electro-mechanical system limitations (e.g. power limit, charging capacity limit), as well as the vehicle safe operation in terms of vehicle dynamics.

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