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ASSESSMENT OF HYBRID VEHICLE BRAKING TECHNOLOGIES

OCENA TECHNOLOGII HAMOWANIA W POJAZDACH HYBRYDOWYCH

Abstract

More than ever before the current automotive market offers a variety of vehicles. This diversity is concerned with not only different vehicle body or traction parameters but also the variety of propulsion systems. In particular the conventional systems (equipped with internal combustion engine only), hybrid electric, as well as fully electric drivelines are now becoming available. The fully electric vehicles require significant development, as the current technology (e.g. in area of storage devices) needs to be markedly improved. The interim solution will be the hybrid electric vehicles, which appear to be technically mature and affordable for typical vehicle users. However, hybrid electric vehicles can be even more technically advanced than the fully electric vehicles due to need to switch (blend) between the propulsion modalities. This paper presents selected road test results for two commercially available hybrid electric vehicles equipped with front and all wheel drive systems. The results are considered to be important from a regenerative braking technology point of view, combining their control strategies and interactions with vehicle safety systems such as the anti-locking braking system (ABS) taken in to account. The examined vehicles operation represents a step in the development of regenerative braking control algorithms not only for hybrid vehicles but also for fully electric vehicles.

Keywords: hybrid vehicles, regenerative braking, braking strategies

Streszczenie

Rynek samochodowy bardziej niż kiedykolwiek obfituje w różne typy pojazdów. Zróżnicowanie to dotyczy nie tylko typu nadwozia czy parametrów trakcyjnych, ale również różnych systemów napędowych, takich jak konwencjonalne systemy wyposażone w silnik spalinowy, pojazdy hybrydowe oraz pojazdy z napędem elektrycznym. Pojazdy o napędzie elektrycznym wymagają istotnego wkładu w ich rozwój ze względu na obecny, niezadowalający stan technologii (np. w zakresie urządzeń gromadzących energię). Pośrednim rozwiązaniem mogą być pojazdy o napędzie hybrydowym, które wydają się technicznie dopracowane oraz finansowo dostępne dla użytkowników. Jakkolwiek pojazdy hybrydowe może cechować znacznie wyższy poziom zaawansowania technicznego w porównaniu z pojazdami elektrycznymi, ze względu na zastosowanie systemu przełączania pomiędzy systemami napędowymi. W artykule zaprezentowano wyniki wybranych testów drogowych komercyjnie dostępnych pojazdów hybrydowych, wyposażonych w napęd przednich oraz wszystkich kół. Otrzymane rezultaty dotyczące technologii hamowania rekuperacyjnego są istotne w aspekcie strategii sterowania oraz współdziałania z systemami bezpieczeństwa, np. anti-locking braking system (ABS). Zaobserwowane strategie pracy prezentują postęp w rozwoju algorytmów sterowania hamowaniem rekuperacyjnym, nie tylko w aspekcie pojazdów hybrydowych, lecz również pojazdów elektrycznych.

Słowa kluczowe: pojazdy hybrydowe, hamowanie rekuperacyjne, strategie hamowania

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1. Introduction

Developments in the automotive sector have been focused on many different factors, e.g. vehicle top velocity, power, comfort, and others. Nowadays, the vehicle safety, operational cost, etc. are still of great importance, however the current development in the automotive sector is mainly focused on increased vehicle efficiency and reduction of vehicle CO_2 emission. The hybrid electric vehicles and fully electric vehicles are of great interest due to the possibility to reduce the CO_2 emission not only by the higher efficiency of current vehicle technology but also by the possibility of using the electricity generated by the use of renewable sources. The capacity for CO_2 reduction and overall vehicle efficiency increase are directly connected with the regenerative braking mode [1]. Regenerative braking technology helps to restore the vehicle kinetic energy, normally dissipated in the friction brakes during velocity reduction (braking process).

Hybrid electric vehicles already exist on the automotive market. Their marketing success is connected with eco-friendly systems, which help to increase vehicle efficiency and reduce CO_2 emission. Nowadays, a great majority of car manufacturers offer vehicles with hybrid electric propulsion systems. The unquestionable popularity is connected with the reasonably low price of the initial vehicle cost in comparison to fully electric vehicles, which are considerably more expensive, mainly due to the cost of the battery pack. In addition, the limited range of fully electric vehicles can be an issue for some users, particularly in rural areas.

Regenerative braking technology can be described as being under development as the systems currently available on the market present some functionalities, which are not always desired by the driver [2]. However, appropriate understanding of the limitations, which are present in hybrid electric vehicles, will help in the further development of such vehicles, as well as in the development of fully electric vehicles, and their control strategies. The limitations and conditions, which should be fulfilled in hybrid electric vehicles, are connected with the following requirements: legal, safety, and user perspective (e.g. pedal feel characteristic).

In order to examine the current development level of regenerative braking technology that exists in hybrid electric vehicles two vehicles have been selected and tested under typical road conditions.

2. Specification of tested vehicles

The road tests have been performed for two hybrid electric vehicles, together with their conventional equivalents. In this paper only the general description of the vehicles without their brand names will be given. The description of the tested vehicles is presented in table 1, and includes; front wheel drive (FWD) non-hybrid, FWD hybrid, all wheel drive (AWD) non-hybrid and AWD hybrid, numbers 1, 2, 3, and 4, respectively.

For the FWD hybrid vehicle, there exist two coastdown mode characteristics that can be selected by the transmission lever. In addition to the standard a ‘D’ mode (for drive) a ‘B’ mode (for brake) is available. In the ‘B’ mode, regenerative braking is activated for the acceleration pedal throttle-off position. Moreover, in the case of approaching a 100% state of charge (SoC) the internal combustion engine (ICE) starts the throttle-off procedure, which enables the speeding up the ICE by the motor-generator Number 1 (MG1), see Fig. 1, which receives earlier regenerated (in a regenerative braking process) energy by the motor-generator number 2 (MG2). Fig. 1 also shows the axial differential (Diff), and power split device. A similar FWD hybrid driveline, as tested in this study, has been described in [3] and [4].

Table 1

The data for tested vehicles

No		Kerb vehicle mass	Traction E-Motor peak power	ICE + E-Motor (peak power)	Battery capacity	CO_2 rating	Vmax
	Units	[kg]	[kW]	[kW]	[kWh]	[g/km]	[km/h]
1	1.6L Petrol Manual, FWD	1315	–	97	–	146	195
2	1.8L Petrol (Atkinson) CVT, FWD Power Split Full Hybrid	1420	60 (Permanent Magnet)	101	1.3 (Ni Metal Hydride)	89	180
3	3.0L V6 Diesel autom. transm., AWD	2100	–	176	–	195	218
4	3.0L V6 Supercharged Petrol autom. transm., AWD Parallel Full Hybrid	2240	34 (3 Phase Sync)	279	1.7 (Ni Metal Hydride)	193	242

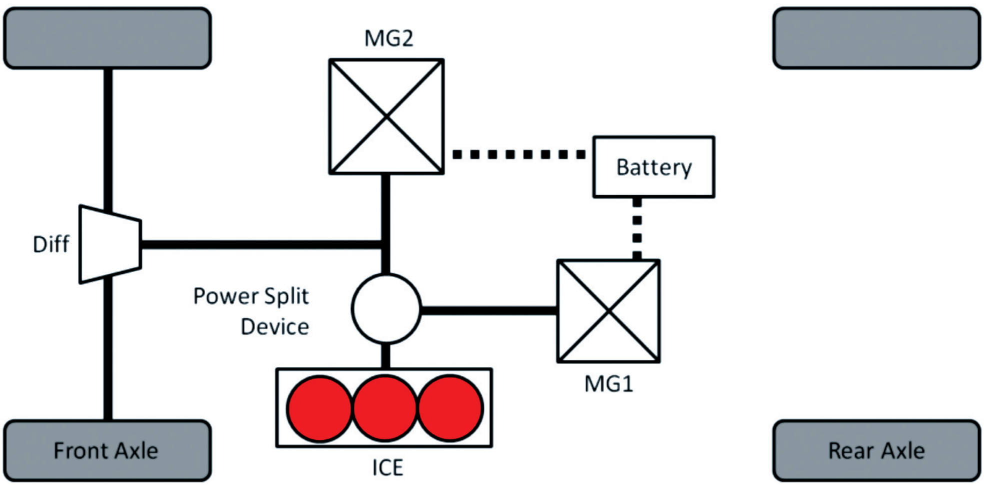

Fig. 1. FWD hybrid power split drivetrain

Rys. 1. Równoległo-szeregowy układ napędowy pojazdu hybrydowego typu FWD

The driveline architecture of an AWD hybrid vehicle is presented in Fig. 2. This powertrain has been equipped with the ICE, only one motor/generator (MG), and a clutch in-between. The correct torque direction for the AWD system has been achieved by making use of three differentials; two axial and one inter-axial. A vehicle, which uses a similar configuration of powertrain, has been described in [5].

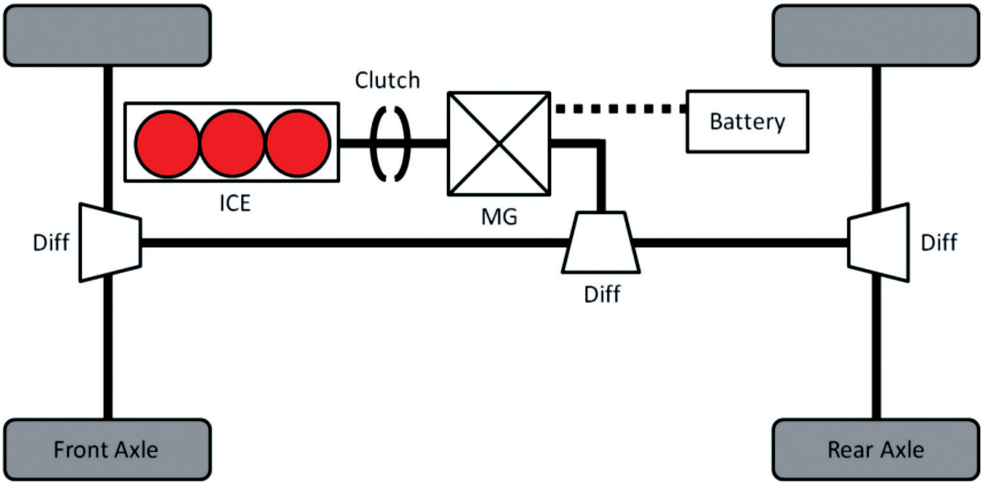

Fig. 2. AWD hybrid power split drivetrain

Rys. 2. Układ napędowy pojazdu hybrydowego typu AWD

3. Road tests

In order to investigate the behaviour of the chosen hybrid vehicles, as well as non-hybrid equivalents, a number of specific road tests have been performed.

3.1. Test descriptions

For this study, only a straight-line braking manoeuvre has been investigated. However, a range of conditions and settings have been tested:
- Low (0.3) and high (0.9) mu surface, also mu transition (from high to low mu).
- Low and high SoC.
- Low and high vehicle deceleration.
- For FWD hybrid vehicle two different lever positions; ‘D’, and ‘B’.
- For AWD hybrid vehicle two ICE operation modes; on and off.

The high mu surface was simulated by dry asphalt with road mu coefficient of approximately 0.9. Use of wet basalt tiles, with an approximate mu coefficient of 0.3, simulates the low mu surface.

3.2. Measurement descriptions

For all tests, the parameters presented in Table 2 were logged. Some of the parameters have been accessed via a controller area network bus (CAN Bus), such as vehicle velocity and electric motor (E-Motor) torque, the others were measured with a use of additional, external measuring equipment.

It should be noted that for the FWD hybrid vehicle it was possible to log the E-Motor torque via a CAN Bus, whereas for the AWD hybrid vehicle only the battery current data (without current direction sensing) was accessible.

Table 2

Parameters measured during tests

Measurement description	Unit	Origin	Vehicle
Vehicle velocity	[m/s]	CAN Bus	FWD/AWD
Front left wheel velocity	[m/s]	wheel speed encoder	FWD/AWD
Front right wheel velocity	[m/s]	wheel speed encoder	FWD/AWD
Rear left wheel velocity	[m/s]	wheel speed encoder	FWD/AWD
Rear right wheel velocity	[m/s]	wheel speed encoder	FWD/AWD
Vehicle deceleration	[m/s^2]	decelerometer	FWD/AWD
Buttery current (without current direction sensing)	[A]	current sensor	AWD
Brake pedal effort	[N]	load cell	FWD/AWD
Brake pedal travel	[mm]	travel transducer	FWD/AWD
Front left calliper pressure	[bar]	pressure transducer	FWD/AWD
Front right calliper pressure	[bar]	pressure transducer	FWD/AWD
Rear left calliper pressure	[bar]	pressure transducer	FWD/AWD
Rear right calliper pressure	[bar]	pressure transducer	FWD/AWD
E-Motor (MG2) torque	[Nm]	CAN Bus	FWD

3.3. Road tests results

Selected results from the vehicle benchmarking are presented here. Attention has been focused on the regenerative braking characteristic and the associated vehicle operation.

3.3.1. Low velocity regenerative braking switch off

The regenerative braking system uses an E-Motor in generator mode as a braking device. The main difference between the E-Motor and friction brakes (apart from working principles) is that the E-Motor produces negative torque, which can have an adverse influence on the vehicle safe operation. The case of near standstill vehicle velocities is of special interest according to this phenomenon. In order to examine the hydraulic brakes operation for low velocity (end stop blending) a low deceleration (0.1 g) braking manoeuvre with a medium initial velocity (70 km/h) on a high mu surface has been performed, see Fig. 3.

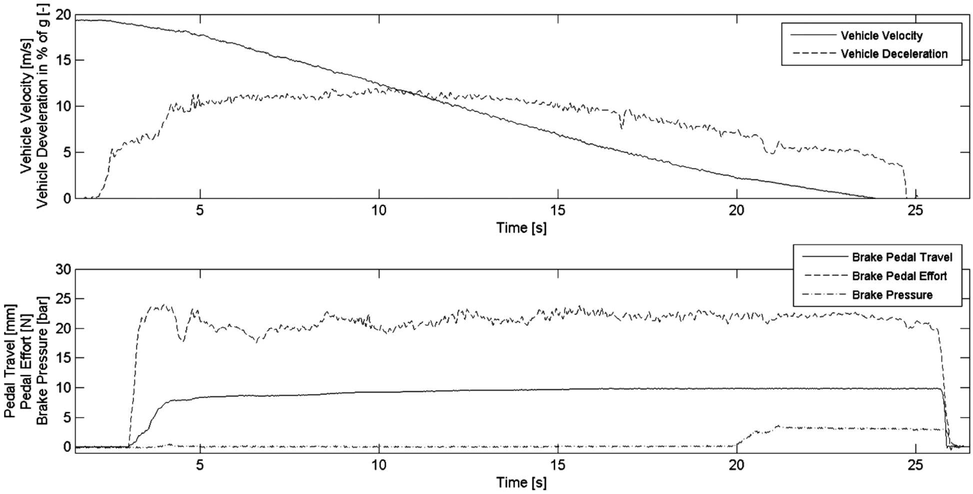

Fig. 3. Road test results for FWD hybrid vehicle. High mu surface, 0.1 g deceleration with transmission lever on 'D' position

Rys. 3. Wyniki testu drogowego dla hybrydowego pojazdu z napędem FWD. Opóźnienie 0.1 g, lewarek skrzyni biegów w pozycji 'D'

In this test the brake pedal effort and pedal position are maintained at the steady level regardless of changes in the vehicle deceleration. For t = 20.0 s (8 km/h) the regenerative braking is terminated and the hydraulic pressure starts to rise in order to activate the friction brakes that can safely reduce the vehicle speed to zero.

3.3.2. E-Motor assistance in grip recovery for high wheel slip

For a transition from high to low mu surface test with high initial vehicle velocity, the E-Motor assistance in grip recovery has been recorded. Fig. 4 presents a braking manoeuvre, where for t = 2.60 s the road condition has changed from high mu (0.9) to low mu surface (0.3). In this case the front left wheel achieved high slip together with the front right (slightly lower slip level). Attention should be focused on the substantial increase of MG current, which suggests the E-Motor assistance in elimination of the wheel slip. The E-Motor current is reduced, when the front axle wheels velocities match the rear axle wheels velocities.

A similar situation is presented in Fig. 5, which shows the road test results for FWD hybrid vehicle during low-level braking on the low mu surface. Approximately, from t = 5.20 s the front wheels start to slide reaching a considerable high slip level for t = 6.20 s, when the front brakes pressure is reduced. Prior to this (t = 6.10 s) the E-Motor (MG2) torque has been increased from a negative level to zero for t = 6.20 s and further increased supplying a positive torque, which helps to recover from a high value of slip.

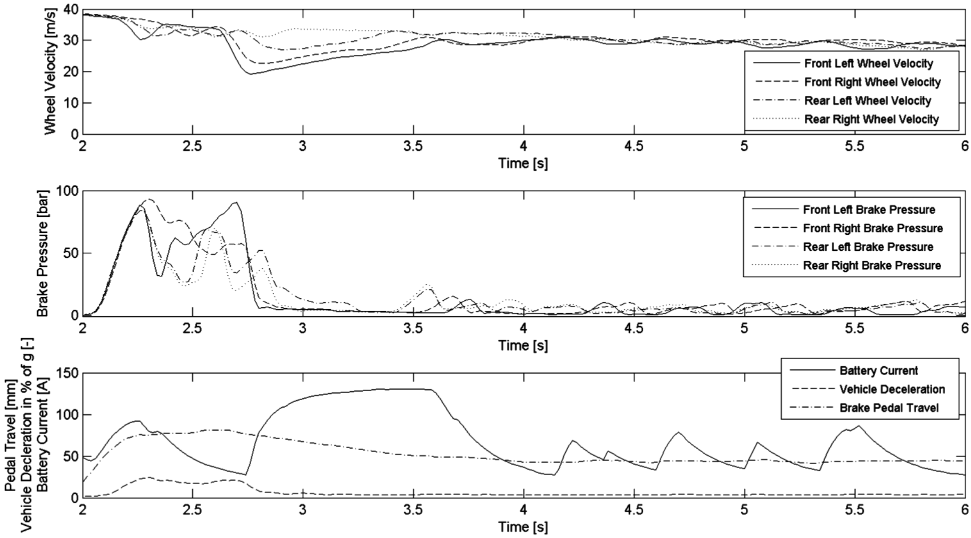

Fig. 4. Transition high to low mu surface test for AWD hybrid vehicle, low-level brake application

Rys. 4. Wyniki testu drogowego dla hybrydowego pojazdu z napędem AWD – przejście pomiędzy wysokim a niskim współczynnikiem przyczepności, niskie opóźnienie

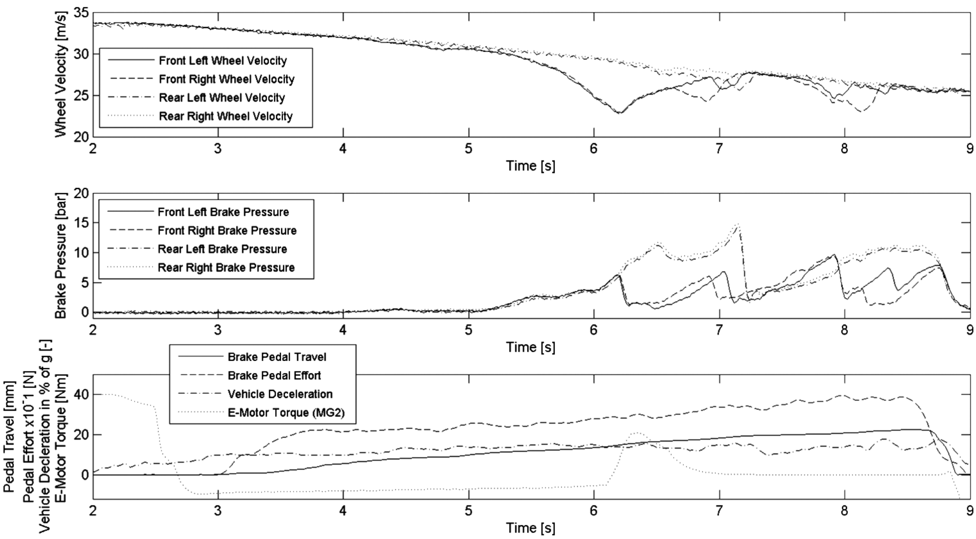

Fig. 5. Road test results for FWD hybrid vehicle, low mu surface, low-level brake application

Rys. 5. Wyniki testu drogowego dla hybrydowego pojazdu z napędem FWD. Niski współczynnik przyczepności, niskie opóźnienie

3.3.3. Deceleration responsibility

For a braking manoeuvre on a low mu surface (0.3) for both tested hybrid vehicles (FWD and AWD) the individual wheel braking pressure control has been recorded. The braking strategy allows the system of fulfil the Regulation 13 [6], stated as follows:
„5.2.7.2 Wherever necessary, to ensure that braking rate remains related to the driver's braking demand, having regard to the available tyre/road adhesion, braking shall automatically be caused to act on all wheels of the vehicle".

In other words, the paragraph 5.2.7.2 of the Regulation 13 states that in the case of one axle (wheel) being if a higher slip the other axle (wheel) should take over the responsibility for generation of the driver requested deceleration.

Figure 5 illustrates the functionality described by the paragraph 5.2.7.2 in Regulation 13, which presents results for low level braking on the low mu surface for FWD hybrid vehicle. From $t = 6.20$ s the front axle brakes pressure decreases in order to reduce front wheels slip. At the same time, the rear axle brake pressure is increased in order to maintain the requested driver vehicle deceleration.

Figure 6 presents the situation, where the front right wheel has the lowest slip starting from $t = 3.40$ s. For $t = 3.65$ s the front left wheel pressure has been considerably reduced with a simultaneous increase of the front right wheel pressure, as this wheel presents the lowest slip among all the wheels.

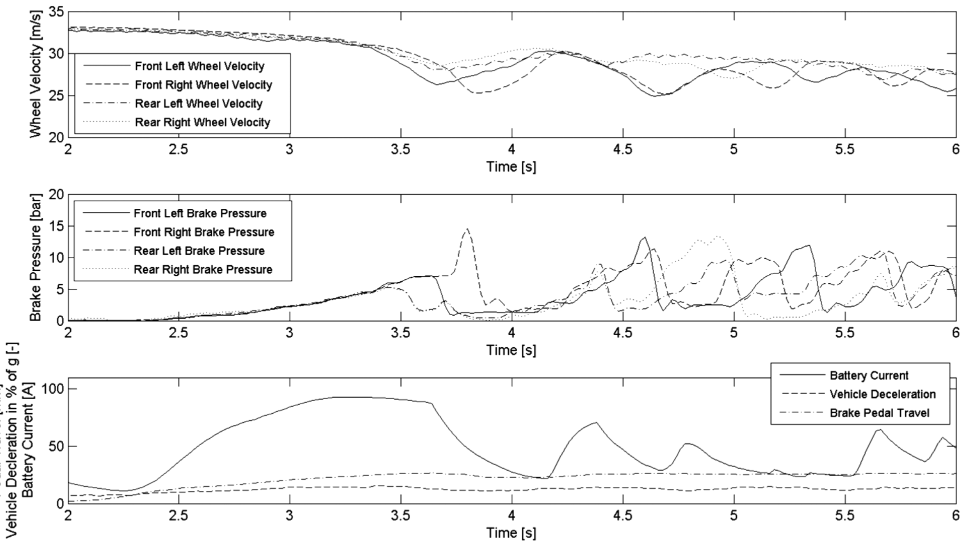

Fig. 6. Road test results for AWD hybrid vehicle. Low mu surface, low level of brake application

Rys. 6. Wyniki testu drogowego dla hybrydowego pojazdu z napędem AWD. Niski współczynnik przyczepności, niskie opóźnienie

In addition to this the battery current should also be examined. The battery current, which in this case also represents the regenerative braking torque in a qualitative way, was maintained at the high level up to t = 3.65 s, when it was reduced along with front left brake pressure. A similar operation was repeated for t = 4.60 s.

3.3.4. Modified electronic brake-force distribution

During tests, a modification to the standard electronic brake-force distribution (EBD) operation has been noted. In conventional – non-hybrid vehicles, the EBD, system, when required reduces the rear axle braking pressure in order to prevent the possibility of wheel lock-up. However, the rear axle brake pressure is always calculated as a percentile of the front axle brake pressure, which implies that the only possibility of receiving zero a level rear axle brake pressure is when the front axle brake pressure is also zero [7]. Fig. 7 shows road test results for a FWD hybrid vehicle carried out for a low mu surface braking manoeuvre where the modified EBD system operation (modified in comparison to the well known EBD system operation presented in [7]).

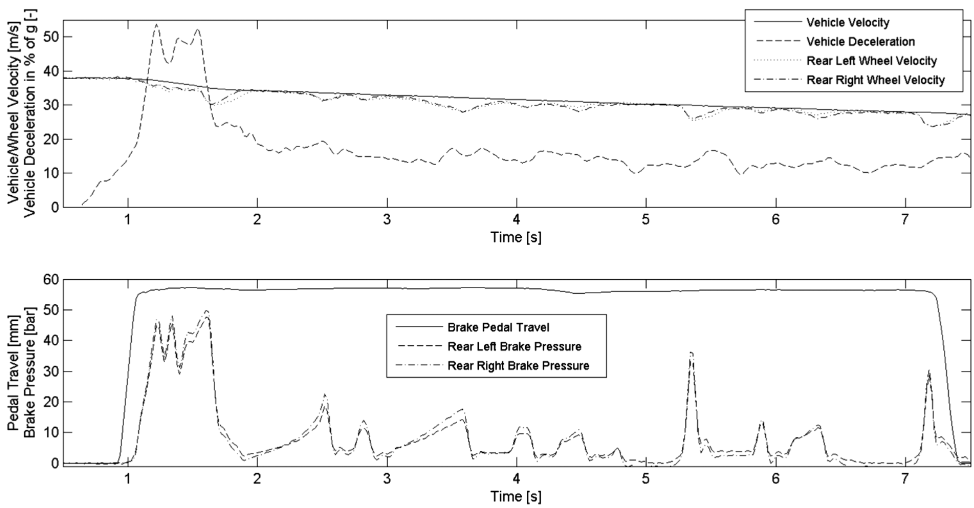

Fig. 7. Road test results for FWD hybrid vehicle. Low mu surface, low-level brake application with lever on 'D' position

Rys. 7. Wyniki testu drogowego dla hybrydowego pojazdu z napędem FWD. Niski współczynnik przyczepności, niskie opóźnienie, lewarek skrzyni biegów w pozycji 'D'

Figure 7 presents the periods when the rear axle brake pressure is maintained at the zero level; from t = 4.80 s to t = 5.15 s and t = 6.50 s to t = 7.0 s, even though there is no wheel slip. The modified EBD system enables maximum energy recovery, as the regenerative braking axle (front axle in this example) is fully responsible for vehicle braking. The short brake pressure spikes, which follow these periods, should be noted.

3.3.5. ICE on/off state

Both investigated hybrid vehicles (FWD and AWD) behaved comparably to their non-hybrid equivalent vehicles. However, for the AWD hybrid vehicle (parallel full hybrid), the ICE tends to be deactivated after approximately 5.0 seconds of throttle-off mode application. This action affects the vehicle operation when the sudden application of the acceleration pedal is performed. It is observed that for this action approximately 1.0 second elapses between the total back-off of the braking action and application of positive torque for the requested acceleration. This is referred to as a torque time lag.

3.3.6. Coastdown characteristic according to shift lever position

The FWD hybrid system is equipped with the two driving positions ‘D’ and ‘B’. For the ‘B’ lever position the regenerative braking is deployed in the case of an acceleration pedal throttle-off application, producing approximately 0.05 g vehicle deceleration, whereas for tests with the ‘D’ lever position the throttle-off braking does not take place. The ‘D’ lever position results in a so-called vehicle ‘sailing’ coastdown.

3.3.7. Deceleration versus pedal position and ICE operation

It has been noted that for high and low mu road surfaces for the hybrid systems the vehicle deceleration is not consistent when the pedal position is at a steady value, whereas this is not observed for non-hybrid vehicles. For the AWD hybrid vehicle, the following observations have been made:

– The vehicle deceleration tends to decay for a constant brake pedal position for deactivated ICE, see Fig. 9. This does not occur for an active ICE, see Fig. 8.
– Also for deactivated ICE the brake pedal displacement tends to be shorter, see Fig. 9.

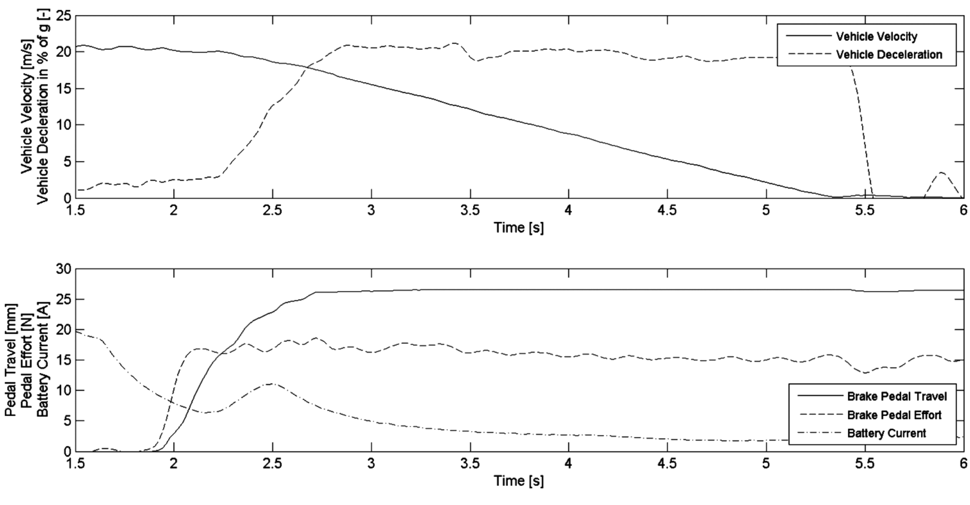

Fig. 8. Road test results for AWD hybrid vehicle. High mu surface, ICE on, 0.2 g deceleration

Rys. 8. Wyniki testu drogowego dla hybrydowego pojazdu z napędem AWD. Wysoki współczynnik przyczepności, włączony silnik spalinowy, opóźnienie 0,2 g

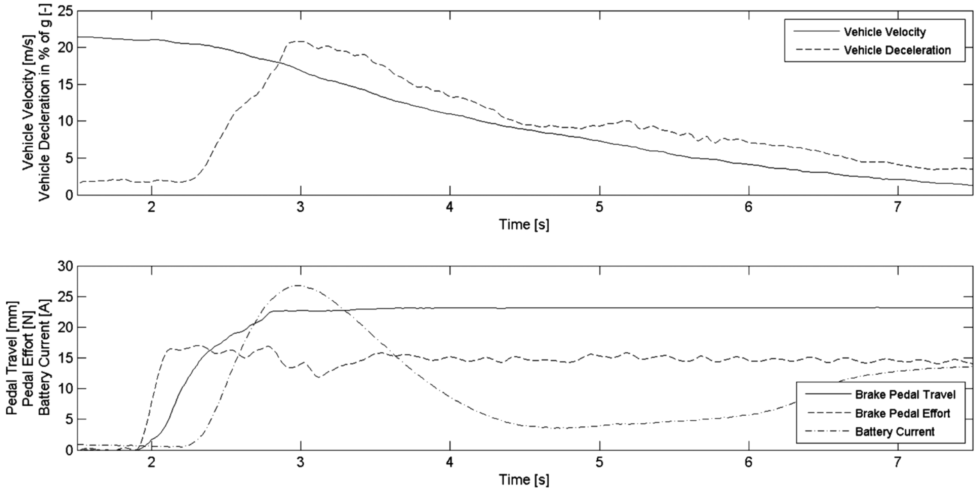

Fig. 9. Road test results for AWD hybrid vehicle. High mu surface, ICE off, 0.2 g deceleration

Rys. 9. Wyniki testu drogowego dla hybrydowego pojazdu z napędem AWD. Wysoki współczynnik przyczepności, wyłączony silnik spalinowy, opóźnienie 0,2 g

3.3.8. Friction brakes downsizing and SoC limit

For the tested FWD hybrid vehicle the front axle (regenerative braking axle) friction brakes have been downsized. The friction brakes on the front axle are similar to the brakes used in a non-hybrid vehicle, which is more than 100 kg lighter. This is possible only in the case of permanent regenerative braking energy absorption/dissipation capability (e.g. with the use of a rheostat element). The independency of the regenerative braking activity has been achieved by making a use of a strategy, which is deployed all powertrain elements (ICE, MG1, MG2). In the case of the 100% SoC the regenerative braking is still active but instead of transferring the recovered electrical energy to the battery it is sent to the MG1, coupled with the ICE. The ICE changes the operation to throttle-off mode, for which the possibility of dissipation of the recovered energy delivered to the crankshaft exists.

4. Summary

Results for simulated road tests of the hybrid electric vehicles and their equivalent non-hybrid counterparts have been reported. The vehicles under consideration are commercially available passenger cars with hybrid propulsion systems:

– Power split full hybrid with front wheel drive system.
– Parallel full hybrid with all wheel drive system.

The road tests results have been analysed in view of regenerative braking control and their implications in comparison to the equivalent conventional vehicles (with internal combustion engine). The following observations have been made:

– Deceleration of hybrid electric vehicles are inconsistent in comparison to conventional vehicles for steady brake pedal demands.
– Front wheel drive power split full hybrid requires less brake pedal force in comparison to conventional vehicle to achieve the same vehicle deceleration. Such dependency is not observed for the all wheel drive parallel full hybrid vehicle.
– All wheel drive parallel full hybrid vehicle has an internal combustion engine deactivate possibility.
– All wheel drive parallel full hybrid vehicle indicates long lag time for sudden change in deceleration (from deceleration to acceleration request).
– All hybrid vehicles have a low speed regenerative braking switch off trigger.

The simulation tests results indicate that there is much scope for improvement in regenerative braking strategies for hybrid electric, as well as fully electric vehicles.

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