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Analysis of Regenerative Braking Strategies

Abstract: *Theoretical issues related to the use of regenerative braking systems in two-axle vehicles have been presented. In the introduction, the trends observed in the development of vehicles with electric and hybrid drive systems have been described. In the subsequent part of this article, the impact of regenerative braking on driving safety has been analysed, with taking into account the steerability and directional stability of the vehicle. The braking ratio (distribution of braking effort between the front and rear wheels) has been calculated for specific data of a prototype vehicle. Various regenerative braking strategy systems (RBS) divisions as proposed in a number of publications have been presented. For the purposes of this study, simulation tests were carried out according to the NEDC (New European Driving Cycle) test procedure for two regenerative braking strategies, referred to as serial and parallel ones. The presentation of simulation test results has been preceded by a description of the method of implementing the aforementioned strategies in an electric vehicle.*

Streszczenie: *W pracy przedstawiono teoretyczne zagadnienia związane z zastosowaniem systemów hamowania odzyskowego w pojazdach dwuosiowych. We wstępie opisane zostały tendencje w rozwoju pojazdów z napędem elektrycznym i hybrydowym. W dalszej części pracy rozważono wpływ hamowania odzyskowego na bezpieczeństwo jazdy, uwzględniając kierowalność i stateczność. Przeprowadzono obliczenia rozkładu sił hamowania dla konkretnych danych pojazdu prototypowego. Przedstawione zostały podziały strategii hamowania odzyskowego proponowane w różnych publikacjach. Na potrzeby niniejszej pracy przeprowadzano badania symulacyjne w cyklu jezdnym NEDC (New European Driving Cycle) dla dwóch strategii hamowania odzyskowego – szeregowej i równoległej. Prezentacja wyników symulacji została poprzedzona opisem sposobu realizacji wymienionych strategii w samochodzie elektrycznym. (**Analiza strategii hamowania odzyskowego**)*

Keywords: regenerative braking, electric vehicles, hybrid vehicles, energy recuperation
Słowa kluczowe: hamowanie odzyskowe, pojazdy elektryczne, pojazdy hybrydowe, rekuperacja

Introduction

One of the advantages of the use of electric drive systems for the propulsion of motor vehicles is the possibility of accumulation of electrical energy. The beneficial effects of such a solution stem from the possibility of recuperating a part of the kinetic energy of the vehicle when the vehicle is braked. First, this makes it possible to reduce the energy consumption, which corresponds to the fuel consumption of internal combustion (IC) engines [1]. The reduction of the energy consumption, resulting from the use of electric vehicles for the transportation of passengers and goods, is an advantage from the economy and ecology point of view. The energy recuperation makes it possible to extend the distance that can be travelled by a vehicle with using the energy stored in a traction battery or to reduce the energy capacity of the energy storage system without reducing the vehicle range [1] [2] [3].

Good cooperation between the friction brakes and the propulsion system of a vehicle may have a significant impact on the efficiency of energy recuperation [4] [5], while this is often treated as an issue of secondary importance in the present-day designs of electric drive systems. The efficiency of energy recuperation may have a considerable influence on the range of an electric vehicle, especially in such a vehicle-driving test cycle that is abundant in accelerating and braking (as it is e.g. in the urban driving cycle). At present, two types of the regenerative braking are chiefly in use. The first and simplest one is a system that makes it possible to use energy recuperation during vehicle coast-down. Another and frequently used option is braking with simultaneously using the friction brakes and the electric machine. Literature studies, simulation tests, and authors' experience show that the introduction of algorithms where the power of braking a vehicle by means of its electric machine is raised to reduce the power of frictional braking results in a considerable growth in the efficiency of the regenerative braking and, in consequence, in an increase in the range of the electric vehicle. In the subsequent sections of this article, a theoretical energy analysis has been presented, where the braking with limiting the torque applied by friction brakes is compared with the braking without a limitation of this kind. Moreover, the said cooperation between the brakes and the propulsion system of a vehicle does not require, in most vehicle designs, the use of any additional actuators and sensors because the existing components of the braking and drive systems, including some components of the integrated safety systems such as ABS, ASR, and ESP, may be made use of.

Braking forces

The electrodynamic braking of an electric vehicle powered by electrochemical batteries (battery electric vehicle – BEV) may be analysed from various points of view. The first approach is the energy analysis, focused on the energy flows between individual powertrain components, i.e. wheels, transmission, electric machine, electronic power converter, and energy storage battery [6] (Fig. 1).

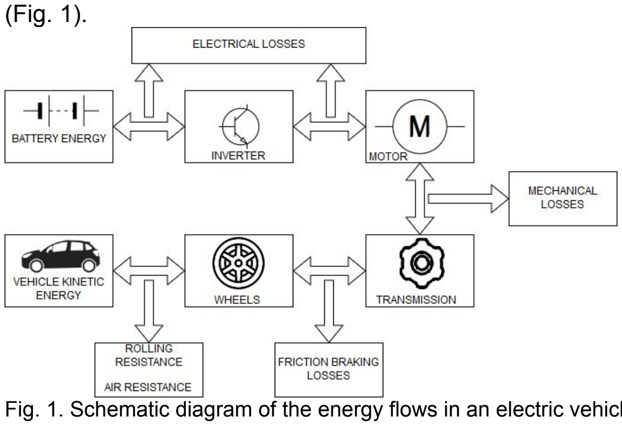

Fig. 1. Schematic diagram of the energy flows in an electric vehicle

Another issue worth analysing is the impact of regenerative braking on the dynamics and directional stability of a vehicle. The way how friction brakes cooperate with the electric propulsion system of a vehicle is a matter of significant importance for both of these problems. The scientists and engineers involved should optimize this cooperation to recuperate as much energy as possible without deterioration in the safety of the vehicle driving [7].

The requirements that have to be met by the vehicle braking system to ensure maximum safety during braking have been comprehensively presented in many monographs dealing with vehicle braking [8] [9] [10]. For the directional stability of a vehicle to be maintained and, simultaneously, for the maximum braking efficiency to be achieved, the braking force should be so distributed that it is proportional to the temporary loads on individual axle wheels. In practice, various devices limiting the rear wheels braking force are used to utilize the tyre-road adhesion to the maximum possible extent.

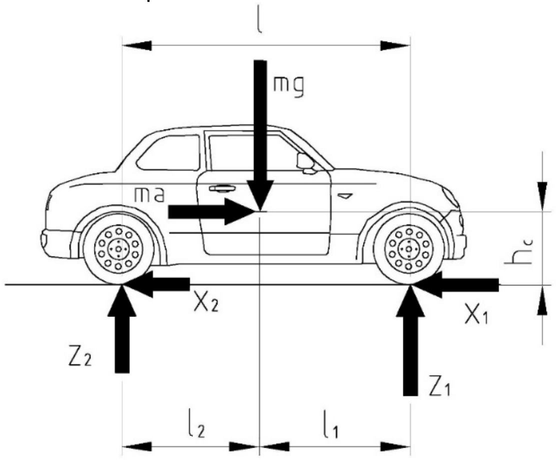

Fig. 2. Schematic presentation of the forces that act on a vehicle during the braking process. Z_1, Z_2 – vertical reaction forces; X_1, X_2 – horizontal forces; l_1 and l_2 – distances between the vehicle axles and the horizontal position of the centre of vehicle mass

Fir. 2 shows the system of forces that act on a vehicle during the braking process. In result of the braking, an inertial force proportional to the vehicle deceleration (i.e. negative acceleration) acts on the vehicle. The vehicle weight is balanced by the sum of vertical reaction forces Z_1 and Z_2. The values of these forces change depending on the vehicle deceleration, as the load of the front axle increases with the deceleration and the load of the rear axle drops accordingly (the Z_1 value rises, Z_2 value decreases). The vertical reaction forces may be calculated from the following equations:

(1) $$Z_1 = m\left(g\frac{l_2}{l} + a\frac{h_c}{l}\right)$$

(2) $$Z_2 = m\left(g\frac{l_1}{l} - a\frac{h_c}{l}\right)$$

where: m – vehicle mass; a – vehicle deceleration; g – acceleration of gravity; l – vehicle wheelbase; h_c – height of the centre of vehicle mass above the road surface.

The horizontal force of the tyre-road contact point is equal to the product of the vertical reaction (Z) and the tyre-road adhesion coefficient (μ):

(3) $$X = Z\mu$$

The adhesion coefficient is limited by various conditions, among others contact between the tyre and the road, including the type and condition of vehicle tyres and the road surface on which the vehicle is moving [11]. For an equation to be formulated that would determine the braking force ensuring the optimum utilization of the tyre-road adhesion, an assumption can be made that the factor of proportionality between the resultant longitudinal force and the sum of normal forces at the tyres-road contact points is the braking rate [9]:

(4) $$\mu = \gamma = \frac{a}{g}$$

Based on the above, the following equations describing the optimum distribution of braking forces may be derived:

(5) $$X_1 = m\left(\frac{al_2}{l} + \frac{a^2 h_c}{gl}\right)$$

(6) $$X_2 = m\left(\frac{al_1}{l} - \frac{a^2 h_c}{gl}\right)$$

A conclusion may be drawn from the equations as above that the curves representing the desirable braking forces as functions of deceleration are parabolic-shaped. When points are plotted for acceleration values varying from zero to a maximum limited by the tyre-road adhesion (i.e $\mu \approx 1$ [11]), an ideal braking force distribution curve (often referred to as “I-curve”) will be obtained. Such a curve plotted for a vehicle taken here as an example has been shown in Fig. 3. The data for plotting this graph have been given in Table 1.

Table 1. Technical data of the example car

	Symbol	Value
Wheelbase [m]	l	2.49
Vehicle mass [kg]	m	1 247
Height of the centre of vehicle mass above the road surface [m]	h_c	0.4
Dynamic radius of vehicle tyres [m]	r	0.29
Overall gear ratio of the power transmission system [–]	i	4.84
Overall efficiency ratio of the power transmission system [%]	η	95

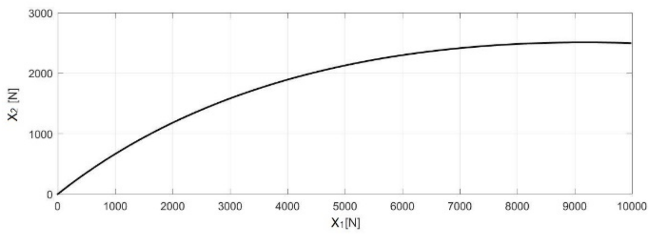

Fig. 3. Ideal braking force distribution curve (“I-curve”) plotted for the data specified in Table 1.

The curve has been plotted for braking deceleration values varying from 0 m/s^2 to 10 m/s^2. Based on such a curve, the maximum possible efficiency of the regenerative braking may be determined, depending on which of the vehicle axles is the driving one. Averaged simulation test results obtained from various deceleration values have been given in article [12]. For the front-wheel drive systems, 40 % of energy was recuperated in a single test cycle, as against 28 % for the rear-wheel drive systems and 68 % for the four-wheel-drive systems [12]. Of course, the results depend to a significant extent on the geometric and mass characteristics of the vehicle. In reality, the vehicle braking is never in conformity with the ideal curve. Depending on the vehicle’s braking system, the curve characterizing the distribution of braking forces may be a polyline (when a braking force regulator is used) [9] or a straight line intersecting the ideal curve at a specific point predefined by a system designer. In modern braking systems, the braking forces developing on individual wheels may be regulated by means of the actuators used in the ABS, ASR, or ESP systems [4], [13], [14]. The percentage of the energy recuperated depends on the algorithm used to implement the cooperation of the friction brakes with the electric drive system and on the specifications of the energy storage system. In vehicles with electric or hybrid drive systems, the frictional braking force may be decreased in order to raise the energy recuperation level.

Review of the strategies of regenerative braking

In the English-language literature, the ways of cooperation of friction brakes with the vehicle propulsion system are referred to as regenerative braking strategies

(RBS) [4], [6]. Various RBS classification systems (i.e. systems of the braking torque being split into regenerative braking and frictional braking) are proposed. As an example, the author of the study [2] proposes the following three strategies of regenerative braking.

1. The electric machine alone is used for the vehicle braking until the electrically generated braking torque becomes insufficient for braking the vehicle with a required deceleration; then, the friction brakes are additionally applied [4].

This strategy is advantageous in energy recuperation terms, as the driven axle wheels are usually braked. Of course, this strategy is inacceptable from the safety point of view, because the vehicle is retarded by the wheels of only one axle, i.e. the whole braking force in the tyre-road contact area is transmitted by the tyres of only one vehicle axle. This phenomena results in a higher degree of utilization of the tyre-road adhesion, it may cause tyre slip and a loss of the side force transmission capability of a tyre and, in consequence, a loss of the directional stability of vehicle motion.

2. The vehicle is braked in accordance with the ideal braking force distribution curve, which is implemented by combining the braking forces generated by both the electric machine and the friction brakes so that the tyre-road adhesion is utilized in the best possible way [4].

This strategy ensures the best driving safety. On the other hand, the amount of the energy recuperated is smaller than it is in the case of the first method. Therefore, the author of study [4] has proposed the third strategy.

3. When the vehicle is driven straightforward or along a road bend with a large radius (when the steering wheel angle is insignificant), strategy 1 is used. When the road bends becomes too sharp (its radius becomes smaller than a predefined limit), the regenerative braking is turned off.

Such a combination of the strategies can only be implemented in vehicles with a braking system where the braking forces can be regulated. According to another RBS classification system, proposed in publications [15] [6] and often mentioned in the literature, parallel and serial strategies of regenerative braking are discerned. In the parallel strategy, the vehicle is simultaneously braked by its electric machine and friction brakes. The functioning of the serial system is different, i.e. the braking force generated by the friction brakes is reduced and superseded by the braking effect caused by the electric machine of the vehicle. The division of braking forces in the parallel and serial strategies has been presented in Fig. 4.

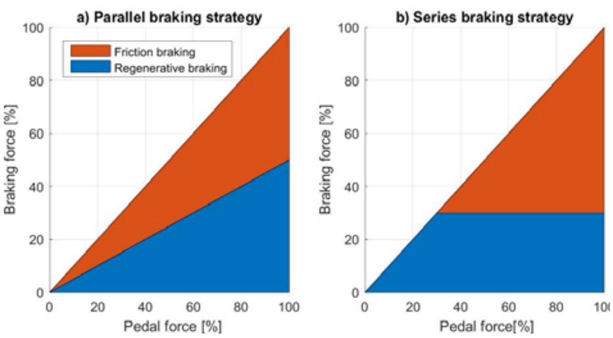

Fig. 4. Division of braking forces into frictional braking and regenerative braking: a) Parallel strategy; b) Serial strategy

Serial braking

In the first method used in vehicles with electric and hybrid drive systems to substitute the frictional braking with the electric braking, a free pedal displacement is added to the pedal travel. In such a system, a brake pedal position sensor must be used and a part of the pedal movement is made without operating the brake master cylinder. Thus, regenerative braking may be forced at small pedal displacements. At bigger pedal displacements, the driver begins to operate the brake master cylinder and the parallel braking of the vehicle is started.

The most promising and technologically advanced method of implementing the serial braking strategy consists in reducing the frictional braking force by means of automatized braking system control. The service brake may be operated hydraulically, pneumatically, or electro-mechanically. As one of the electro-mechanical methods, the "brake-by-wire" system may be mentioned, where the pneumatic, hydraulic, and electrical sources of the braking force are controlled by an additional electrical signal coming from e.g. the brake pedal. In the case of hydraulic braking systems, the braking force may be limited by means of the final control elements of the ABS/ESP systems required for some vehicle categories, thanks to which the costs of implementation of advanced braking strategies are reduced (as no extra systems that would otherwise be necessary have to be provided).

As an example, the serial braking was analysed for the vehicle data specified in Table 1. The braking torque on the front axle wheels is:

$$T_1(a) = X_1(a)r \tag{7}$$

When substituting equation (5), which represents the horizontal force acting at the tyre-road contact point, we obtain:

$$T_1(a) = mr\left(\frac{al_2}{l} + \frac{a^2h_c}{gl}\right) \tag{8}$$

For the torque on the driving (front) axle wheels to be made comparable with the torque generated by the electric machine during the solely electrodynamic braking, the torque as above should be multiplied by the efficiency ratio and divided by the gear ratio of the power transmission system, which produces:

$$T_e(a) = \frac{mr\eta}{i}\left(\frac{al_2}{l} + \frac{a^2h_c}{gl}\right) \tag{9}$$

Based on equation (9), a curve has been plotted that represents the maximum electric machine braking torque as a function of braking deceleration:

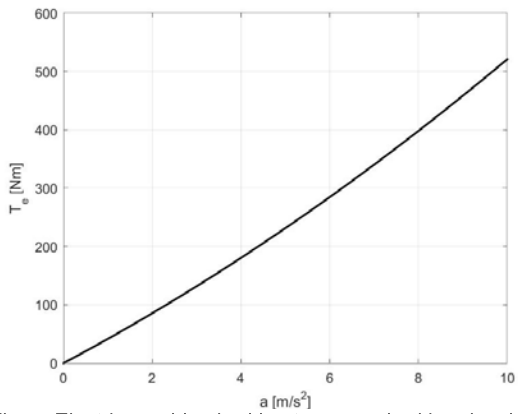

Fig. 5. Electric machine braking torque vs braking deceleration

A curve as presented above cannot be obtained from the electric machine in the whole range. Therefore, for the problem of serial braking to be comprehensively analysed, another condition determined by the performance curve of the electric machine was considered. Namely, the torque was limited depending on the electric machine shaft speed with using the performance curve of the EMRAX synchronous machine (Fig. 6).

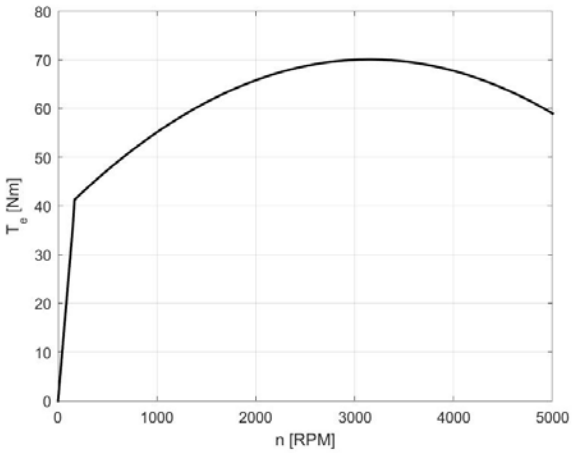

Fig. 6. Performance curve of the electric machine for the continuous generator operation mode: T_e – maximum braking torque of the machine; n – machine shaft speed

The curve as shown is identical in a part with the performance curve of this machine for the continuous motor operation mode. A representation of the torque drop for the lowest shaft speeds was added. Drive systems with electric machines cannot effectively function as brakes at low shaft speeds [16]. This is because their electromotive force at low speeds is insufficient to generate a braking torque. The other part of the performance curve, applicable to the generator operation mode, was assumed as a mirrored curve for the motor operation mode, because the analysis was carried out with an assumption made that the vehicle would move at one constant transmission gear ratio. The electric machine torque curve was converted to the torque on the driving axle wheels of the vehicle according to the equation below:

(10) $$T_1(V) = \frac{T_e i}{\eta}$$

The relation between the linear speed of vehicle wheels and the rotational speed of the motor shaft is expressed by equation (11).

(11) $$V = \frac{\pi n r}{30 i}$$

Thus, a curve may be obtained that characterizes the electric machine braking torque reduced to vehicle wheels and the shape of this curve is identical to that of the curve shown in Fig. 6. Based on equations (9) and (10) and on the graph presented in Fig. 6, which define the relations between the wheel braking torque and the vehicle deceleration and speed, the braking torque may be determined as a function of these two limitations:

(12) $$T_1(a,V) = \begin{cases} T_1(a) & if \ \ T_1(a) < T_1(V) \\ T_1(V) & if \ \ T_1(V) < T_1(a) \end{cases}$$

When the lower of the two torque values is assigned to every point on the (a, V) plane, a surface is obtained that shows the limitation of the regenerative braking torque on the vehicle speed and braking deceleration (Fig. 7).

Based on the three-dimensional characteristic relationship presented in Fig. 7, the share of the regenerative braking torque in the total braking torque may be determined for a specific vehicle-driving test cycle. For the purposes of the analysis of regenerative braking, let the vehicle's resistance to motion be ignored[1]. Then, the braking force will be described by the equation:

(13) $$X = ma$$

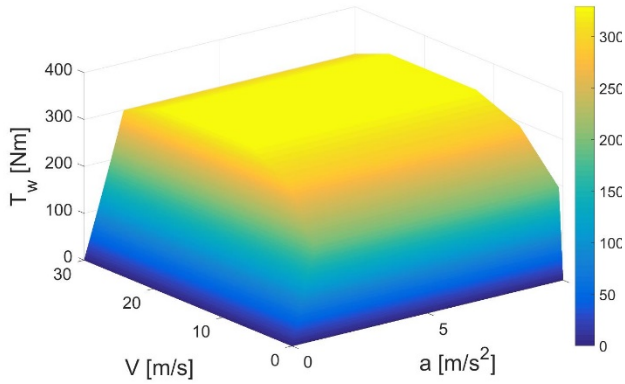

Fig. 7. Limitation of electrical braking torque on vehicle speed and braking deceleration:T_w – regenerative braking torque reduced to vehicle wheels

The total braking force X consists of the braking forces on the front and rear axle wheels. The distribution of forces between the vehicle axles was assumed as consistent with the ideal distribution of braking forces. Moreover, the braking force on the driving (front) axle is a sum of the forces generated by the friction brakes (frictional braking forces) and the forces generated by the vehicle propulsion system (regenerative braking force):

(14) $$X = X_1 + X_2 = X_{1f} + X_e + X_2$$

where: X_1 – front axle braking force; X_2 – rear axle braking force; X_{1f} – frictional braking force on the front axle wheels; X_e – braking force generated by the electric machine.
Since not only the entire rear axle braking force but also a part of the front axle braking force is generated by friction brakes, the total frictional braking force was denoted by X_f, where:

(15) $$X_f = X_{1f} + X_2$$

Force X_e is directly proportional to the maximum braking torque generated by the electric machine and the value of this torque may be obtained from the graph shown in Fig. 7. The value of the regenerative braking force is limited by on both the vehicle speed and braking deceleration.
In general, the braking power is defined as follows:

(16) $$P_b = XV$$

Consistently, the regenerative braking power may be expressed by an equation:

(17) $$P_e = X_e V$$

Hence, the following equations describe the braking work (W_b) and the regenerative braking work (W_e):

(18) $$W_b = \int_0^t P_b \, dt = \int_0^t XV \, dt$$

(19) $$W_e = \int_0^t P_e \, dt = \int_0^t X_e V \, dt$$

For the purposes of this analysis, a dimensionless energy recuperation factor (also referred to as "energy accumulation efficiency" [17]) has been introduced here,

[1] If the analysis were carried out with taking into account the resistance to motion, then this resistance should also be taken into account in determining the distribution of braking forces, for the analysis to be coherent.

which is defined as the ratio of the regenerative braking work to the total braking work:

$$\chi = \frac{W_e}{W_b} = \frac{\int_0^t X_e V dt}{\int_0^t X V dt} \qquad (20)$$

The value of this factor at serial braking was determined by using the NEDC (New European Driving Cycle) test procedure and it was found to be $\chi = 0.55$. The time histories of the total and regenerative braking power in the NEDC test have been presented in Fig. 8.

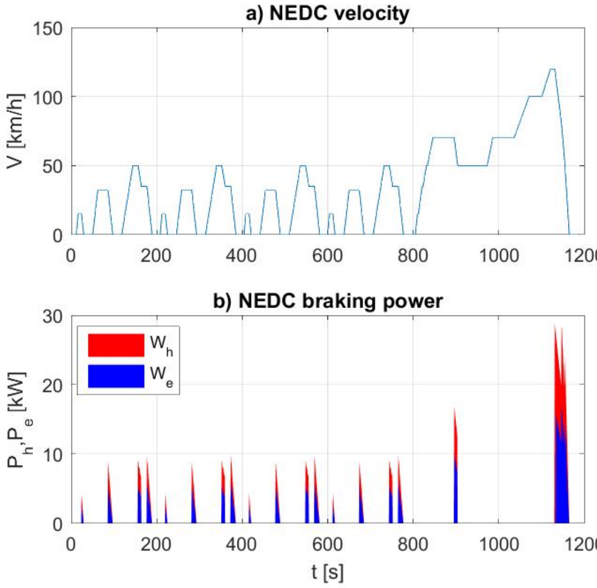

Fig. 8. a) Time history of vehicle speed in the NEDC test; b) Braking power division between frictional braking and regenerative braking (series braking)

In Fig. 8, the areas coloured in blue represent the braking work done by the electric machine and the red areas represent the energy dissipated in the friction brakes. Of course, the analysis of the entire drive system should be carried out with taking into account the performance of not only the electric machine but also the power converter and the electrochemical energy storage system. Moreover, when the vehicle speed exceeds about 60 km/h, the impact of resistance to motion becomes significant; at a speed of 120 km/h, the power of the resistance to motion will reach about 1/6 of the total braking power.

Parallel braking

The parallel braking is the simplest way to put energy recuperation into practice. The strategy of this type has been in use in the vehicles with electric and hybrid drive systems where the braking force cannot be limited automatically. For the regenerative braking to be possible, the brake pedal must be provided with a position sensor. When the brake pedal is depressed by the driver, the conventional service brake system is operated and a signal is simultaneously sent from the pedal position sensor to the converter that controls the operation of the electric machine. Usually, the converters have a separate analog or digital input through which the braking torque is set. Thanks to this information, the electric machine generates a predefined braking torque. In such a system, any demand as regards distribution of the braking forces is not taken into account. The braking force generated by the electric machine is added to the frictional braking force. In this strategy, the possibilities offered by the tyre-road adhesion cannot be fully utilized. In the case of a rear-wheel drive vehicle, another bad point is the possibility of the rear wheels being blocked before the front ones, which may adversely affect the vehicle steerability [4], [9], [10]. Such a strategy is also disadvantageous from the energy efficiency point of view, because most of the braking energy is lost in the form of heat released in the friction brakes. On the other hand, an important good point is the lack of necessity to interfere in the braking system and simplicity of controlling the system. Therefore, the parallel braking is a good solution for the manufacturers of light motorcars (e.g. of the L7e category), where no expensive electrohydraulic systems are necessary for the regenerative braking to be implemented.

For the energy recuperation factor to be determined for the parallel braking, the braking of a vehicle where the frictional braking torque cannot be limited was analysed. In the analysis, assumptions were made that the distribution of frictional braking forces between vehicle axles is linear (Fig. 9) and the braking torque generated by the electric machine is proportional to the brake pedal position.

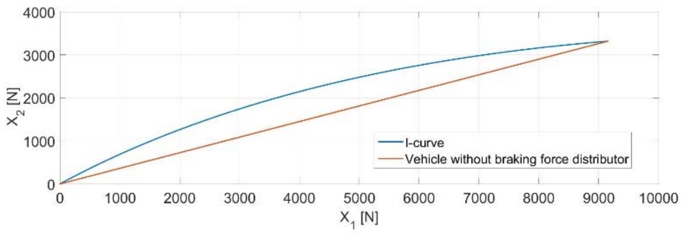

Fig. 9. Ideal braking force distribution curve (I-curve) and distribution of braking forces for a vehicle with no braking force regulator

The braking force is approximately proportional to the force exerted by the driver on the brake pedal. However, the dependence of the braking force on the pedal position is different. At an assumption made that the braking force is proportional to the fluid pressure in the hydraulic braking system, the shape of the fluid pressure vs pedal travel curve would be as shown in Fig. 10. The issues related to the dependence of braking forces on driver's actions on the brake pedal have been presented in detail in publications [8] and [18].

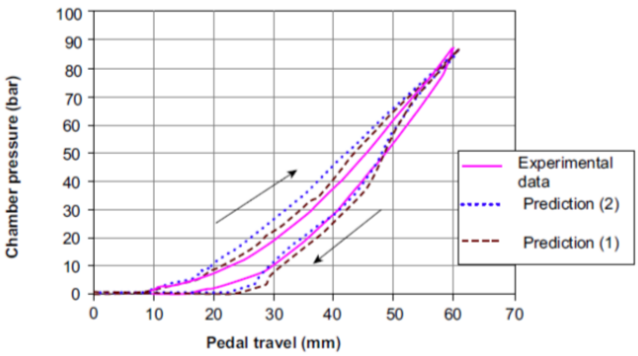

Fig. 10. Brake fluid pressure vs brake pedal travel curve [8]

The non-linearity of these curves may be explained, *inter alia*, by non-linear deformations of hydraulic system components, compressibility of brake fluid and friction. Noteworthy is the fact that the curve representing the fluid pressure has the form of a hysteresis loop. When the brake pedal is depressed, the pressure increases according to the upper part of the hysteresis loop, and when the pedal is released, the changes in the pressure are represented by the lower part of the loop. In a wider context, it is also worth noticing that in such a case, the value of the fluid pressure, and the braking force as well, depends not only on the pedal position but also on the sign of the braking jerk, which is defined as follows:

(21) $$z = \frac{da}{dt}$$

For the purposes of modelling the regenerative braking, the upper part of the hysteresis loop was used. Based on the course of this pressure vs pedal travel curve and with an assumption made that the braking force is proportional to the fluid pressure, the characteristic curve presented in Fig. 11a was plotted. The dependence of the frictional braking force on the brake pedal position was approximated by a second-degree function.

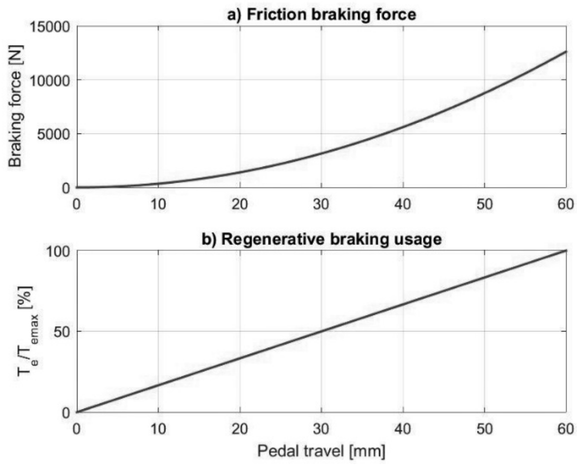

Fig. 11. a) Frictional braking force vs brake pedal position; b) Degree of utilization of the electric braking (ratio of the torque actually generated by the electric machine to the maximum braking torque obtainable from the machine at a specific operating point)

Fig. 11b shows a linear dependence of the degree of utilization of the regenerative braking torque available on the brake pedal position. Of course, this characteristic curve may be shaped as desired, e.g. to raise the energy recuperation or, in order to improve driver's feel related to the braking process. Similarly as it was in the case of serial braking analysed previously, the braking torque available will also depend on the vehicle speed (the analysis was carried out for a vehicle with a constant transmission gear ratio).

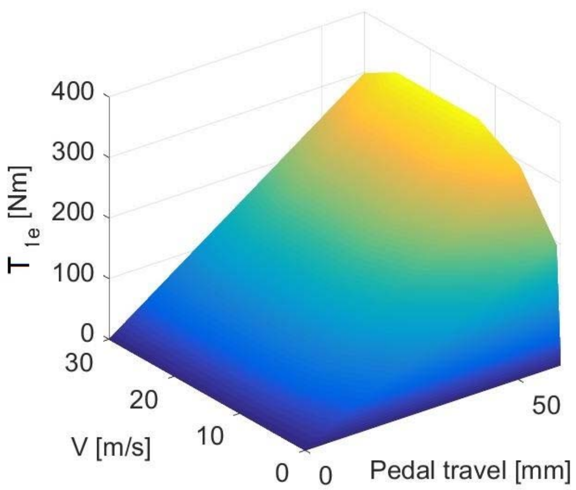

Fig. 12. Regenerative braking torque as a function of brake pedal position and vehicle speed

With an assumption of linear changes in the degree of utilization of the braking torque of the electric machine, a 3D characteristic graph was obtained that shows the available braking torque on the wheels of the axle driven (front) by the electric machine as a function of two variables, i.e. vehicle speed and brake pedal position (Fig. 12). In such a case, the braking force is described by equation (22).

(22) $$X = X_f + X_e = X_1 + X_2 + X_e$$

where: X_f – frictional braking force; X_e – regenerative braking force.

The X_1 and X_2 values are defined by the distribution of the frictional braking force and the total braking force X_b is developed as a specific braking deceleration value. Similarly as it was in the previous case, the power of electrical braking and the total braking power, i.e. the power of combined electrical and frictional braking, were determined. The time histories of the total and regenerative braking power for the parallel braking in the NEDC test have been presented in Fig. 13.

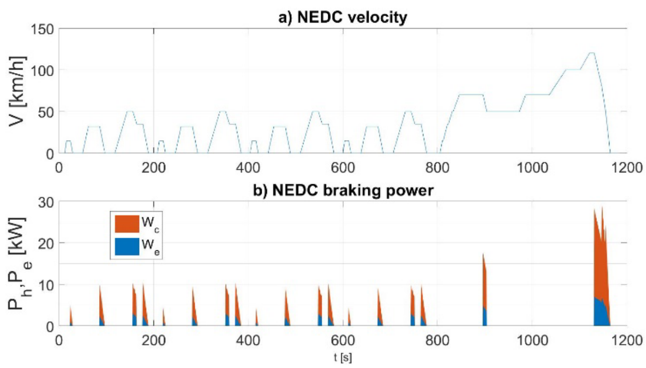

Fig. 13. a) Time history of vehicle speed in the NEDC test; b) Braking power division for the parallel braking in the NEDC test

In this case, the value of the energy recuperation factor was χ = 0.24.

Conclusion

The regenerative braking is an issue willingly raised both in scientific and research works and in marketing materials concerning vehicles with electric or hybrid drive systems. However, the question of physical implementation of regenerative braking systems is rarely discussed. In the simplest cases, the strategy of parallel splitting of braking forces is adopted. This often applies to simple single-circuit or dual-circuit braking systems with no braking force regulators. In the vehicles where such a strategy is applied, the braking energy recuperation will be much lower than it is in the case of the serial braking strategy. For the examples quoted, calculations revealed that the energy recuperation factor value determined for the serial braking strategy was about twice as high as that for the parallel braking strategy (0.55 as against mere 0.24, respectively). Of course, these values determined for another vehicle-driving test cycles will differ from the figures specified above, obtained from the simple NEDC test; however. The use of a regenerative braking system operating in accordance with the serial braking strategy instead of the parallel one enables the vehicle designers to extend the vehicle range without changing the capacity of the on-board energy storage system. The applications of energy storage systems are not limited to electric vehicles. The equations presented herein will also hold in the case of vehicles with other hybrid drives [19] (e.g. hydrostatic drives combined with IC engines), with inertial energy storage devices (e.g. of the flywheel type) [17], or with supercapacitors . In the case of hydraulic and inertial accumulators, however, their applicability is limited by insufficient energy density. On the other hand, the high power density, often unavailable from electrochemical storage batteries, is an advantage of such devices. It is this feature of electrochemical energy storage systems that may cause the implementation of the serial braking strategy to be uneconomic in terms of energy management. This may be explained by the fact that the safe transmission of high regenerative braking powers (higher in the serial braking system) to the storage cells may be impossible and, therefore, they will have to be dissipated with using a converter e.g. on braking resistors. The controlling of a drive system operating in accordance with the serial braking strategy is a complex issue. The braking system must be provided with a possibility of automatic reduction of the friction braking force, similar to the reduction that takes place during the operation of such safety systems as ABS and ESP. While the said systems only operate in emergency situations, the system of limiting the frictional braking force in this case must be designed for continuous operation. A problem that remains to be solved is the necessity to optimize the braking system so that the maximum safety is maintained as regards both the braking efficiency (as short a braking distance as possible) and directional stability (optimum braking ratio, i.e. optimum distribution of braking effort between the front and rear wheels, in current road conditions). It seems that the controlling of brakes as described above will be easier in the case of pneumatic braking systems (provided with a compressed gas storage tank, such as those used e.g. in buses) compared with conventional hydraulic brakes. In such systems, the braking force may be made independent on the brake pedal[2]. In an electric vehicle, the target solution should be the “brake-by-wire” system, where electromechanical, electromagnetic, or electrohydraulic final control elements would be used.

Although the parallel braking strategy is less efficient in energy management terms, it should also be pointed out that it has some advantages. Its most important good point is the fact that the braking system is less complicated and that no interference in the hydraulic braking system is necessary. In the examples quoted, a linear relation between the degree of utilization of the regenerative braking torque and the brake pedal position has been presented. However, this relation may be modified so that the energy recuperation is raised to bring the efficiency of parallel braking closer to that of serial braking.

Noteworthy is the fact that due to a high degree of complication of the serial braking strategies, they are still applied rather to prototype vehicles; in the mass-produced solutions, chiefly the parallel strategy is implemented.

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