**ISSN**: 1231-4005
**e-ISSN:** 2354-0133
**DOI:** 10.5604/12314005.1217206

# TECHNICAL AND LEGAL DETERMINANTS OF ENERGY CONVERSION IN ELECTRIC VEHICLE EQUIPPED WITH ENERGY RECOVERY SYSTEM

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***Abstract***

*Regenerative braking in electric or hybrid driven vehicles is now commonly used feature. Development of technologies of electrical machines, secondary energy sources, power electronics and control systems allows for more efficient using of this attribute. Regenerative braking system converts the kinetic energy of moving vehicles on this form of energy that you can store in a secondary source of energy. The most common form of energy after conversion is electricity, easy to store in batteries or supercapacitors. There also are known systems with storage of mechanical energy (high-speed flywheels with composite rotors). Drive systems with optional regenerative braking should take into account a number of aspects influencing the process. It is very important to maintain the stability of the vehicle movement during braking. Another important aspect is the cooperation of regenerative braking system with conventional, mechanical brake system of the vehicle driven by a single axis. Sizing of the electrical machine (or machines) is associated with the needs of the propulsion of the vehicle, which limits the amount of absorbed energy in the initial stage of braking. Individual elements of the system energy conversion efficiency chain complexity affect the energetic results of this process. On the energy, efficiency of the process of braking energy recovery affects string conversion efficiency in the individual components of the system. Regenerative braking is the important factor, which could improve electric vehicle market chances, particularly in the city or neighbourhood personal transport. The article contains a description of the technical and legal circumstances of the process of regenerative braking and energy aspects of this process.*

***Keywords:*** *transport, regenerative braking, energy conversion*

## 1. Electric vehicle braking

### 1.1. Vehicle stability and brake force distribution

In various road conditions the distribution of braking forces between the front and rear axles must be designed to minimize braking distances while maintaining stability of the vehicle. The actual braking force generated at the contact of wheels with the ground is dependent on the traction and the load component perpendicular to the road substrate. Fig. 1 shows vehicle parameters, which are necessary for vehicle movement describing. Therefore, in order to obtain maximum braking on both axles, the relationship must be satisfied [1]:

$$\frac{F_{bf}}{F_{br}} = \frac{W_f}{W_r}, \tag{1}$$

$$\frac{F_{bf}}{F_{br}} = \frac{L_a + h_g \dfrac{j}{g}}{L_b - h_g \dfrac{j}{g}}. \tag{2}$$

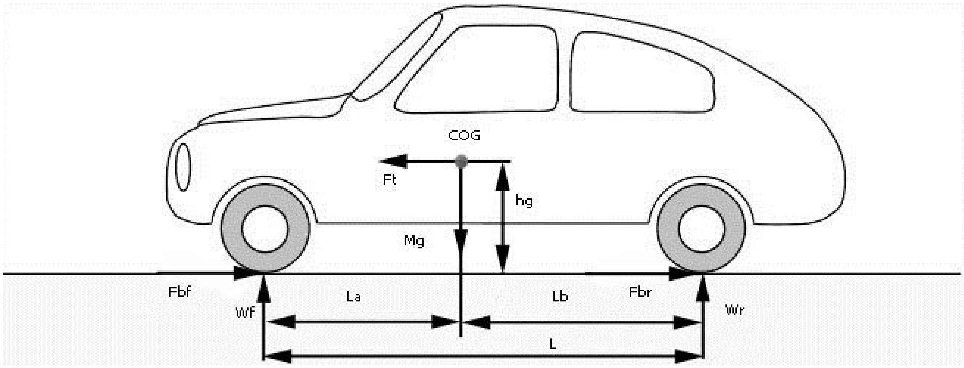

*Fig. 1. The forces acting on the vehicle during braking on a road flat*

$$F_{bf} + F_{br} = M \cdot j\,. \tag{3}$$

Above mentioned dependence can produce ideal brake force distribution curve between the front and rear axles for the vehicle with specific parameters (weight, wheelbase, the centre of mass). In Fig. 2, this curve is marked "I". In the case of brake force distribution in accordance with the course of the curve "I", all the wheels of the vehicle should stop at the same time, the braking distance should be optimal. The condition under the curve "I" is difficult to meet in all conditions, so typical of braking systems usually use a constant ratio of braking force front and rear axles, amounting for example. 0.7.

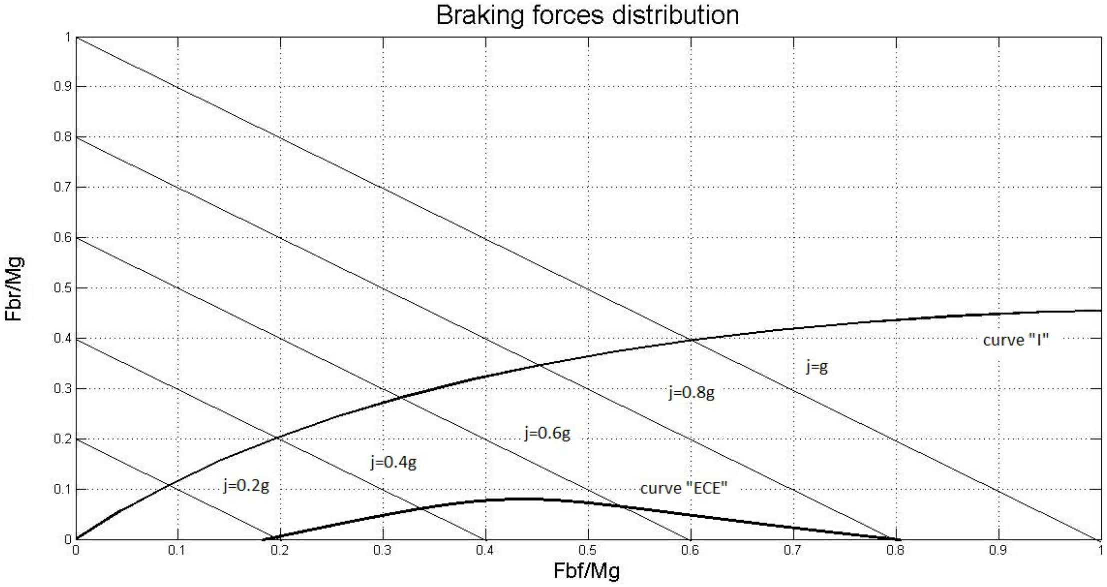

*Fig. 2. Distribution of vehicle braking forces ideal and consistent with regulation ECE*

The curve labeled "ECE" due to the ECE regulations for M1 vehicles, it means for vehicles intended for the carriage of passengers having not more than nine seats, including the driver. The curve "ECE" defines the following relationship:

$$\frac{F_{bf}}{W_f} \geq \frac{F_{br}}{W_r}\,, \tag{4}$$

$$z \geq 0.1 + 0.85(\mu - 0.2)\,, \tag{5}$$

$$z = \frac{j}{g}\,, \tag{6}$$

where:
$F_{bf}$ – the braking force front axle,
$F_{br}$ – the braking force of the wheels of the rear axle,
$W_f$ – reaction force at the point of contact front axle from the ground,
$W_r$ – reaction force at the contact point of the rear axle wheels from the ground,
$L_a$ – distance from the centre of gravity to the contact point of the front wheel axis [cm],
$L_b$ – distance from the centre of gravity to the contact point of the wheels on the rear axle [cm],
$h_g$ – the height of the centre of gravity COG [cm],
$j$ – deceleration of the vehicle [m/s$^2$],
$g$ – acceleration due to gravity [m/s$^2$],
$M$ – mass of the vehicle [kg],
$\mu$ – adhesion factor,
$z$ – the intensity of the braking.

ECE standard sets minimum conditions for brake force distribution; it means in all conditions, the actual brake force distribution must lie in the area between the curves of “I” and “ECE” [2]. Limit ECE is a non-linear, which affects the complications of create control system.

### 1.2. Braking process

The relative comfort of the driver and passengers of the vehicle during regenerative braking is available in most typical cases of braking. In case of necessity emergency braking, comfort aspect is no longer relevant. Feeling comfortable is relative and varies for different people. At the feeling of comfort, decisive impact is deceleration of the vehicle and the associated spurt, defined as the change deceleration in time; it means the third derivative of the distance on time. As can be relatively comfortable average deceleration of less than 2.0 m/s$^2$ [6]. When designing a control system of regenerative braking to be taken into account above mentioned value for the typical cases of vehicle braking. In cases of emergency braking course allowed a significant excess of these values. Brake control systems for electric vehicles allow you to control braking torque values in order to meet the requirements of the smooth and effective course of deceleration [3].

## 2. Energy conversion in drive mode and regenerative mode

Analysis of the efficiency of braking energy recovery should take into account the direction of energy flow through the entire chain of components. Output power (shaft) of the electric machine during the drive mode is smaller than the power supplied to the machine from the battery (electric machine and power electronics efficiency) [6]. The chain of energy conversion during drive mode is shown in Fig. 3.

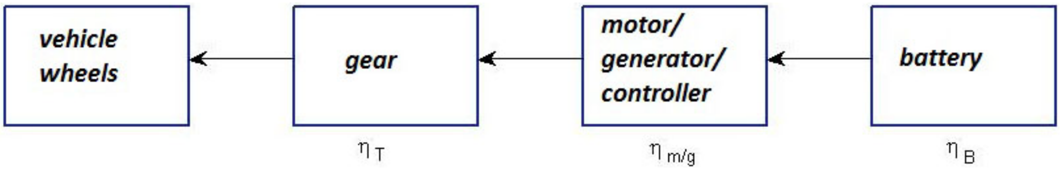

Fig. 3. The electric vehicle energy conversion chain during drive mode

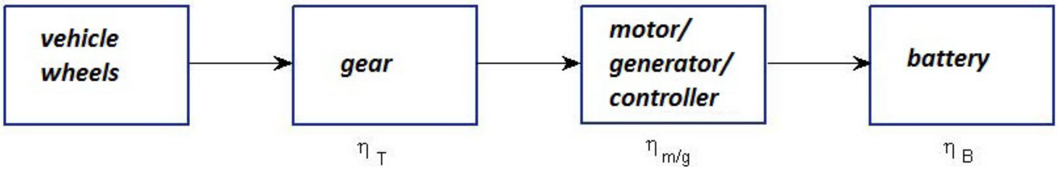

Fig. 4. The electric vehicle energy conversion chain during regenerative braking mode

Accordingly, during regenerative braking mode power on the shaft of the electric machine is greater than the power transmitted to the battery. The chain of energy conversion during regenerative mode is shown in Fig. 4.

During braking, the vehicle speed from $v_1$ to $v_2$ kinetic energy available for the recovery is:

$$E_{KT} = \frac{M(v_1^2 - v_2^2)}{2}, \tag{7}$$

where:
$E_{KT}$ – the total kinetic energy when changing the speed of the vehicle [J],
$M$ – mass of the vehicle [kg],
$v_1$, $v_2$ – initial and final vehicle speed [m/s].

Regenerative braking is usually available only for the driven axle, which significantly affects the ratio of energy recovery. Other limitations are associated with the selection of the size of the electrical machine and the permissible amount of the battery charging current. At the end of the braking process, at low speeds, the electric machine produces too little braking torque, which enforces the need for a conventional brake system. The efficiency of the electric machine controlled through modern power electronic systems and digital controllers takes into account energy losses in those parts of the system.

$$P_{GI} = \eta_T \, v(M\, a_x - F_R), \tag{8}$$

$$P_{GI} = \eta_T \,(v M\, a_x - P_R), \tag{9}$$

where:
$P_{GI}$– mechanical power available during deceleration [W],
$\eta_T$ – total efficiency of the drive unit of the vehicle [%],
$\eta_B$ – battery charging mode energy efficiency [%],
$v$ – the vehicle velocity [m/s],
$a_x$ – longitudinal acceleration of the vehicle [m/s$^2$],
$F_R$ – the sum of the forces of resistance (rolling, aerodynamic) [N].

The efficiency of the set electric machine/controller is determined with a good approximation by the relation [5]:

$$\eta_{m/g} = \frac{T\,\omega}{T\,\omega + k_c\, T^2 + k_i\, \omega + k_w\, \omega^3 + C}, \tag{10}$$

where:
$T$ – torque of machine [Nm],
$\omega$ – speed [rad/s],
$k_c$, $k_i$, $k_w$ – permanent losses in copper, iron and air resistance of the rotating armature [],
$C$ – permanent loss of power independent of the speed [W],
$\eta_{m/g}$ – efficiency of the electric machine and power electronic systems [%].

The efficiency of the electric motor is usually represented graphically in the form of a contour line graph. The power available at the terminals of the battery with regard to the efficiency of the electric machine:

$$P_{GO} = \eta_G P_{GI}, \tag{11}$$

where:
$P_{GO}$ – output power generator (with batteries) [W],
$\eta_G$ – efficiency of the electric machine (in generator mode) [%].

The power acquired by the battery is in turn:

$$P_{BI} = \eta_G \, \eta_B \, \eta_T (v M\, a_x - P_R), \tag{12}$$

where:
$P_R$ – power resulting from the forces of resistance and vehicle speed [W].

Assuming stability of voltage and limited value of the battery charging current, maximum power absorbed by the battery will be:

$$P_{BM} = U\, I_M\,, \tag{13}$$

where:
$P_{BM}$ – maximum power absorbed by the battery [W],
$U$ – voltage battery charging [V],
$I_M$ – the maximum charging current [A].

In any case, when the mechanical power available is greater than the maximum power divided by the chain of energy conversion efficiency ($\eta_G\ \eta_B\ \eta_T$), the power absorbed by the battery is $P_{BM}$, and the total system efficiency of energy recovery braking is determined the relationship:

$$\eta_R = \frac{E_B}{E_{GI}} = \eta_G\, \eta_B\, \eta_T\,. \tag{14}$$

## 3. Energy conversion in the driving cycle

Taking into account all the circumstances arising from the above mentioned according to the calculations of utility for the vehicle electrical parameters as shown in Fig. 2. In order to ensure reproducibility of the conditions of calculation the cycle based on the standard cycle ECE15, limited to the speed achievable by the test vehicle, was adopted. Cycle with a duration of 120 s is shown in Fig. 5.

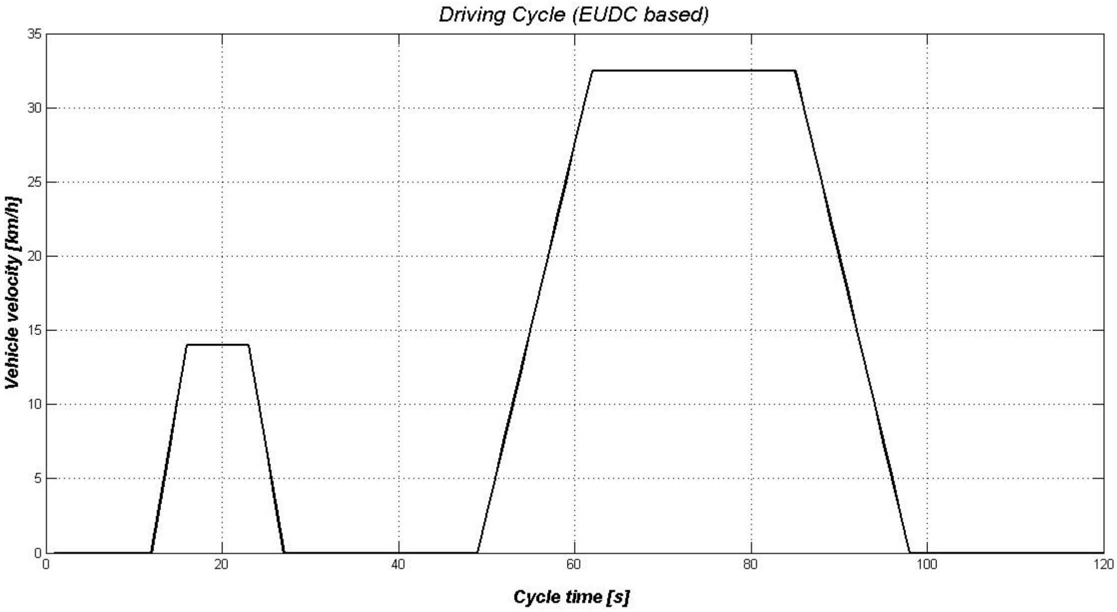

*Fig. 5. Based on ECE 15 low speed driving cycle*

Fig. 6 shows the dependence of power to the wheels of the vehicle as a function of cycle time. This is the power drawn from the battery in drive mode or fed back to the battery mode regenerative braking. Reduced power consumption and a negative power values refer to those parts of the cycle, within which a regenerative braking of the vehicle and the energy increases the electrochemical battery charge.

Validation traction tests of the vehicle were conducted on straight and flat stretch of road with a flat, paved surface. Journeys to the registration of the results is carried out only in one direction,

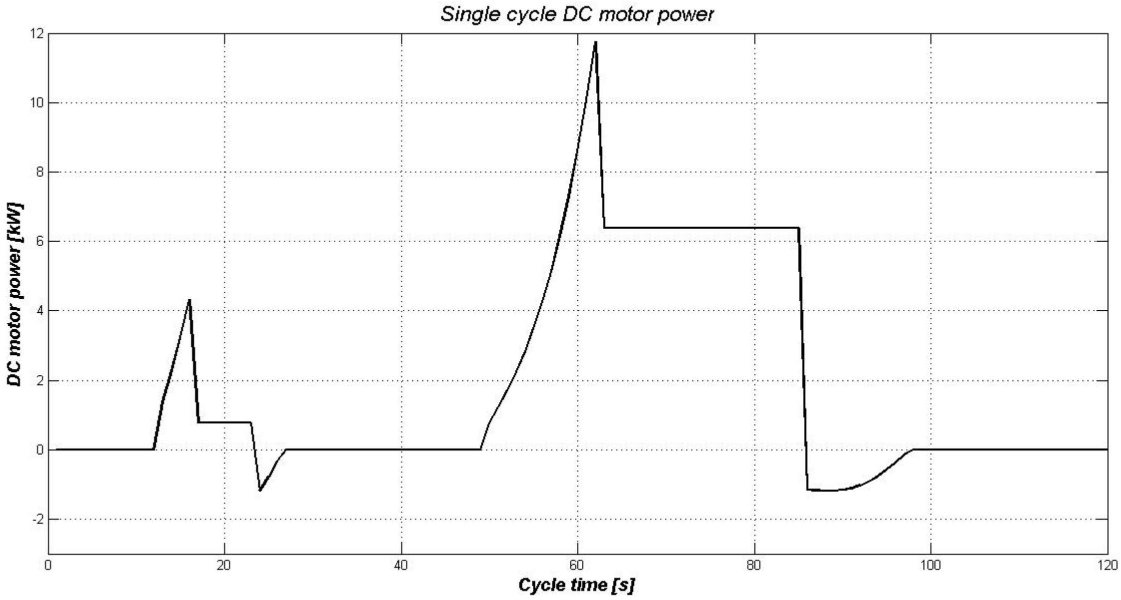

*Fig. 6. The course of power at the terminals of the electric machine*

so as to avoid the influence of the inclination of the road on the obtained results. For analogous reasons, the research, the vehicle ran one driver. Before testing, the batteries were fully charged. Vehicle load was about 165 kg (driver, passenger handling system for data acquisition and recording device signals). The study took place in calm and dry weather, at an ambient temperature of 10°C. The test involves a single vehicle acceleration in conditions WOT (maximum acceleration pedal position) and regenerative braking to stop the vehicle

Figure 7 shows the course of the armature current, engine power and vehicle speed during the real road test. Negative values of the armature current and power during braking (16 to 22 second of test) signs to the generator mode and the recovery of braking energy. The maximum amount of recovered energy is limited by the allowable current battery charging and maximum parameters of the machine in the field of the armature and excitation currents.

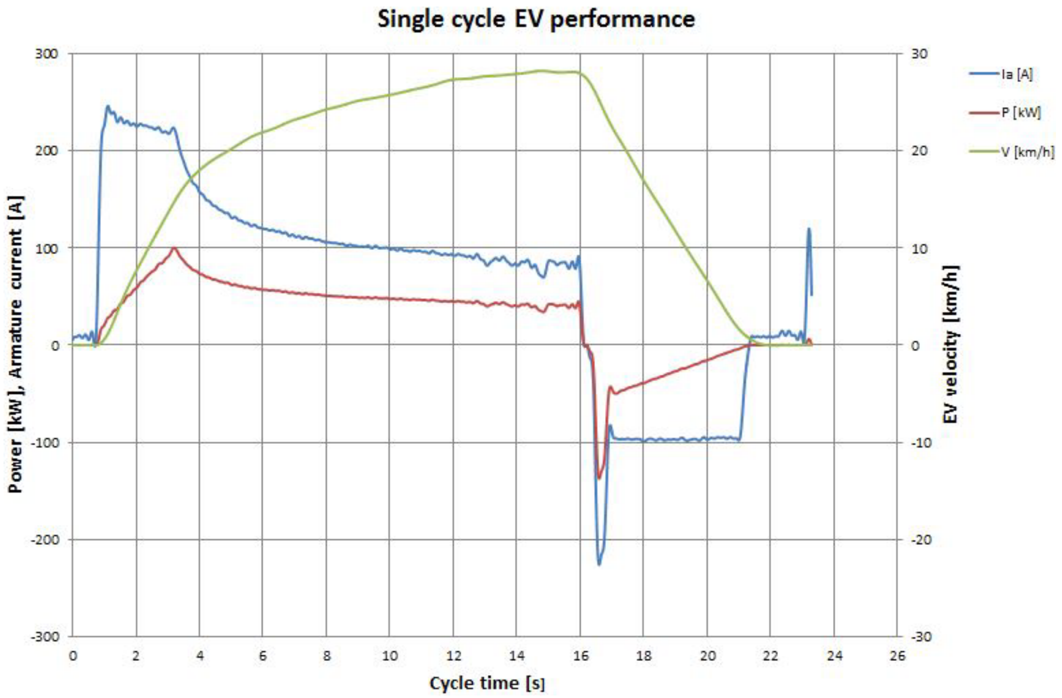

*Fig. 7. Armature current, DC motor power and vehicle velocity*

## 4. Conclusions

The process braking utility electric vehicles makes it possible to maximize the use of regenerative braking mode via the driven axle. Due to the low vehicle, speed to maintain a stable movement of the vehicle is possible even when braking the wheels only driven axle. On the other hand, from the standpoint of comfort, this type of vehicle braking distance is short enough at low values of the delay and spurt. Fig. 2 shows that, in accordance with the requirements of Regulation ECE (Directive 2001/116 / EC), the inclusion of a conventional braking system should take place after reaching the deceleration of the vehicle exceeding almost 1.85 m/s$^2$. Processed by regenerative braking portion of energy supplements the battery charge, thereby extending the driving range between charges the battery. By appropriate control of driving the electrical machine can be in electric vehicles achieve energy savings while maintaining the required braking performance and feel the comfort of users.

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