

Analytical assessment of the efficiency of the energy recovery process in decelerating motion of the vehicle with electric or hybrid drive in variable conditions

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Abstract. The paper presents the problem of mechanical energy recovery during the decelerating motion of a vehicle and its conversion into electric energy stored in vehicle batteries. It is known that each energy conversion is accompanied by some losses that cause a reduction in the efficiency of the transformation. The aim of the study is the analytical determination of efficiency occurring in the energy conversion system. The methodology developed by the authors will allow for an analytical estimation of the energy amount that will be accumulated in the battery of an electric or hybrid vehicle as a result of recovering part of the braking energy. Simulation tests were conducted under the assumption of specific, different traffic conditions.

1. Introduction

Current emission standards oblige vehicle manufacturers to introduce far-reaching changes in the use of environmentally friendly drive systems. In recent years, these changes have been noticeable in the form of numerous vehicle models with hybrid drive and slightly less numerous models with electric drive. And it is the electric vehicles that are characterized by zero emissions. This is important in urban agglomerations where the concentration of toxic components of exhaust gases often exceeds the applicable standards. It would seem, therefore, that electric vehicles will become an effective antidote to air pollution. In reality, however, the situation is different because electric energy must be produced, and in many countries (including Poland) the main fuel in the energy sector is coal. In this case, the only thing that is changed is the place of pollutants emission. It should be mentioned that in the production of electricity in coal power plants, the primary combustion product is carbon dioxide CO₂ and water vapour, the remaining components are emitted in small amounts and are captured by filters. CO₂ emission, although the gas itself is not toxic, causes the greenhouse effect so it should be limited. By the way, the question arises whether, indeed, in Polish conditions electric vehicles emit less CO₂ than vehicles powered by petroleum fuels. The answer to this question will be obtained by comparing the amounts of CO₂ emitted during the production of one megawatt-hour of electricity in a coal power plant and work equal to one megawatt-hour obtained from the combustion of gasoline. These values are the following: coal power plant while producing one megawatt-hour of electric power emits about 890 kg CO₂ while obtaining 1 kWh of energy from burning petrol will result in 246.8 kg CO₂ emission. Even taking into account the efficiency of converting the chemical energy of fuel into mechanical energy, the internal combustion engine is more preferably (apart from

the other exhaust components of course)[1,2,3,4]. The presented comparison, of course, is not aimed at discrediting electric vehicle, but as long as electricity is generated exclusively from coal, it is important to remember about the results of the comparison. Electric motors have a very important advantage, they are reversible machines, so they can work as a motor and generate mechanical energy from electricity and as a generator that converts mechanical energy into electricity. Unfortunately, an internal combustion engine does not possess such a feature. Therefore it is essential, according to the authors, to estimate what amount of energy can be recovered during the decelerating motion of the vehicle.

2. Purpose and methodology of simulation

The purpose of the simulation tests was to determine the amount of energy released during the decelerating motion of a vehicle and the possibility of its storage in the accumulator battery.

The main element of the adopted methodology of simulation tests was developing a mathematical model describing sources and receivers of energy generated in a decelerating motion. The purpose and methodology adopted in this way assumed the use of technical and operational parameters of the test object and the selected environmental parameters.

2.1. Research object

As the object of simulation tests, the Nissan Leaf electric vehicle was adopted, the technical data of which is presented in Table 1. The operational characteristics of the electric motor of the test object are shown in Fig.1.

Table 1. Technical parameters of the Nissan leaf vehicle [5,6,7]		
Vehicle data	Value/Description	Unit
Max motor power	109/ 80	[HP/kW]
Rotational speed of max power	3000-10000	[rpm]
Max motor torque	254	[Nm]
Rotational speed of max torque	0-3000	[rpm]
Usable electric capacity of batteries E_e	21.3	[kWh]
Type and transmission of the drive	Locked front-wheel, no clutch, cylindrical gear fixed position, 7.9377:1	-
Vehicle weight m	1550	[kg]
Height H	1.549	[m]
Breadth B	1.770	[m]
Aerodynamic resistance coefficient c_d	0.28	-
Wheel size	205/55R16	

3. Mathematical model of energy consumption

The authors of the publication used a mathematical model on the basis of publications [10,11]. After identifying the data and defining the limits, the purpose function was presented, based on which the analysis of the Nissan Leaf energy consumption for selected driving cycles was carried out.

3.1. Data identification

The technical parameters of the vehicle (in accordance with Table 1) were used for simulation tests and the following traffic conditions were adopted:

- rolling resistance coefficient of tyres = 0.012 – F class of tyres,
- mass of passengers and cargo – 100 kg,
- air density = 1.177 kg/m³,
- external pressure = 100 kPa,
- external temperature= 23⁰C (296 K),

3.2. Definition of limitations

For the adopted mathematical model of energy consumption the limitations were used [24,25]:

- a) the power of the electric motor - $0 < P^d \leq 80$ [kW],
- b) efficiency of the electric motor - $0.85 \leq \eta_{SE} \leq 0.95$
- c) efficiency of the main gear - $0.85 \leq \eta_{PG} \leq 0.95$
- d) coefficient of rotating masses– 1.04,
- e) efficiency of the energy recovery system– 0.6,
- f) vehicle speed: $0 \leq v \leq 130$ km/h
- g) acceleration of the vehicle: $0 \leq a \leq 1.6$ m/s²
- h) the car moves on a flat surface.

Finally, the constant value of the main gear $\eta_{PG} = 0.9$ was adopted for the calculations and a constant value of the electric motor efficiency $\eta_{SE} = 0.9$. It was assumed that the efficiency of the electric machine is the same for motor and generator work.

In addition, the efficiency of the charging system $\eta_{UL} = 0.75$ must still be taken into account. The overall efficiency of energy recovery is calculated from:

$$\eta_{OE} = \eta_{PG} \cdot \eta_{SE} \cdot \eta_{UL} \quad (1)$$

As a result, the overall efficiency of converting mechanical energy into electricity is $\eta_{ON} = 0.6$ [8,9].

3.3. Purpose function

The purpose of the analyzes is to determine what amount of energy will be delivered to the traction batteries of the car as a result of braking energy recovery.

Kinetic energy of the translational and rotational motion of a moving vehicle can be expressed by dependence [10]:

$$E_k = \frac{m \cdot v^2}{2} + \frac{I_k}{2} \omega^2 \quad (2)$$

where: E_k – kinetic energy, m – total vehicle weight, v - linear velocity of the vehicle, I_k – moment of inertia of elements in rotational motion (road wheels), ω - angular velocity of the wheels. After transformation, it is finally obtained:

$$E_k = \frac{\delta \cdot m \cdot v^2}{2} \quad (3)$$

where: δ - coefficient of rotating masses (the analysis assumed that $\delta = 1,04$)

During the decelerating motion, the kinetic energy is transformed into a different kind of energy. Typically, the decelerating motion is realized in the vehicle's braking system in which the kinetic energy is converted into thermal energy. The electric drive makes it possible to use the braking energy to generate electric energy and to collect it, for example in a battery.

Of course, it is impossible to use 100% kinetic energy of braking. Energy conversion results in losses (1), and in addition the vehicle is slowed by resistance to motion. In this case the rolling resistance and air forces act on the vehicle. The forces of motion resistance are relatively small and are often overlooked when considering classical braking with the use of a braking system [10]. However, in the analyzed case they constitute an additional force slowing down the car. The next decelerating force is the force coming from the braking moment of the generator producing electric energy. Taking the above into account the braking energy of the vehicle can be expressed by the dependence [10,11]:

$$E_h = \frac{\delta \cdot m \cdot v^2}{2} - \left(\frac{m \cdot g \cdot f_t (v_k^2 - v_p^2)}{2 \cdot a_h} + \frac{\rho_p \cdot c_x \cdot A (v_k^4 - v_p^4)}{4 \cdot a_h} \right) \quad (4)$$

The energy expressed in this way applies to uniformly retarded motion. Taking into account the efficiency of energy conversion (1), the following energy will be delivered to the battery:

$$E_{reg} = E_h \cdot \eta_{OE} \quad (5)$$

Similarly, the braking power P_h can be determined [10,11]:

$$P_h = \frac{dE_k}{dt} = \frac{\delta \cdot m \cdot a_h \cdot v}{2} \quad (6)$$

Power lost to overcome the resistance motion:

$$P_{t+p} = \int_{v_1}^{v_2} \left(m \cdot g \cdot f_t + \frac{\rho_p \cdot c_x \cdot A \cdot v^2}{2} \right) dv \quad (7)$$

The difference in P_h and P_{t+p} is the power that will be supplied to the generator with regard to efficiency.

$$P_{reg} = 0,6(P_h - P_{t+p}) = 0,6 \int_{v_1}^{v_2} \left[\frac{\delta \cdot m \cdot a_h}{2} - \left(m \cdot g \cdot f_t + \frac{\rho_p \cdot c_x \cdot A \cdot v^2}{2} \right) \right] dv \quad (8)$$

Multiplying the obtained power by the duration of braking will result in the energy that the battery will be charged.

4. Analysis results

Using the numerical data describing the vehicle and the environment, taking into account the assumptions and limitations contained in point 3 and applying the relation (4), the dependence of the braking energy E_h as a function of the vehicle's linear velocity for different decelerating values is obtained (Fig.1). The initial speed for each decelerating value was the maximum speed of the vehicle, while the final speed was the speed equal to zero. Therefore, it was possible to consider the total energy that is released on the vehicle's brakes until it stops. Braking energy can also be considered for different initial and final values.

Fig. 1 shows that the highest braking energy was obtained for the highest decelerating value, while the lowest braking energy was obtained for the lowest braking deceleration value. It is also seen that the higher the decelerating value, the differences in the braking energy obtained are lower. Differences in energy obtained for different braking deceleration also increase as the speed increases. The differences are minimal for low speeds. This is due to the increasing impact of vehicle motion resistance as the speed increases.

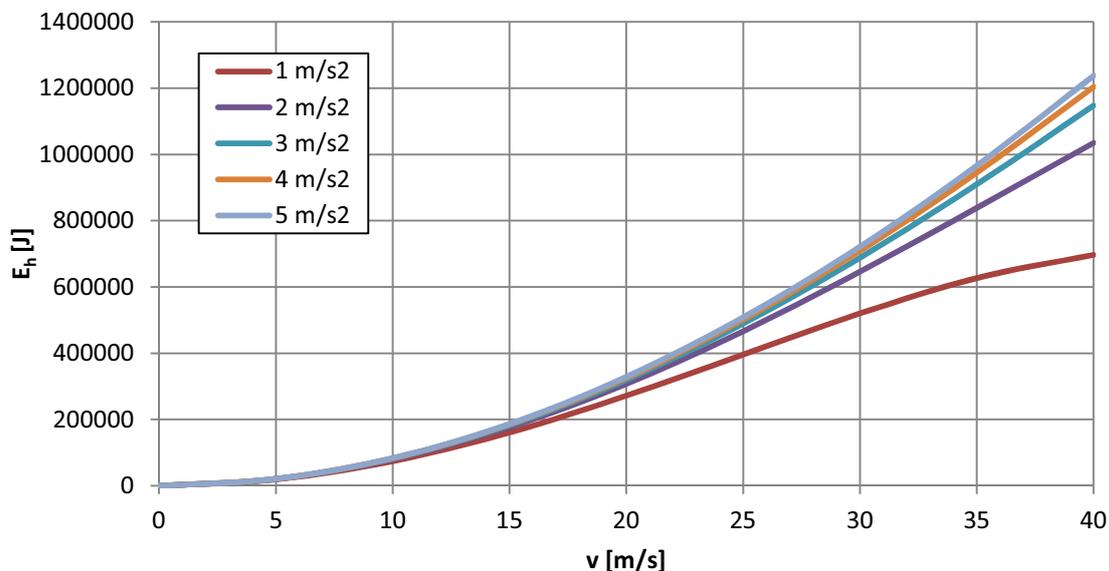


Figure 1. Dependence of braking energy on linear velocity for different deceleration values

The power delivered to the battery, taking into account the losses expressed in individual efficiencies, was calculated using the relation (8) and presented in Fig. 2. as the dependence of the braking power, minus the P_{reg} losses as a function of the vehicle's linear velocity.

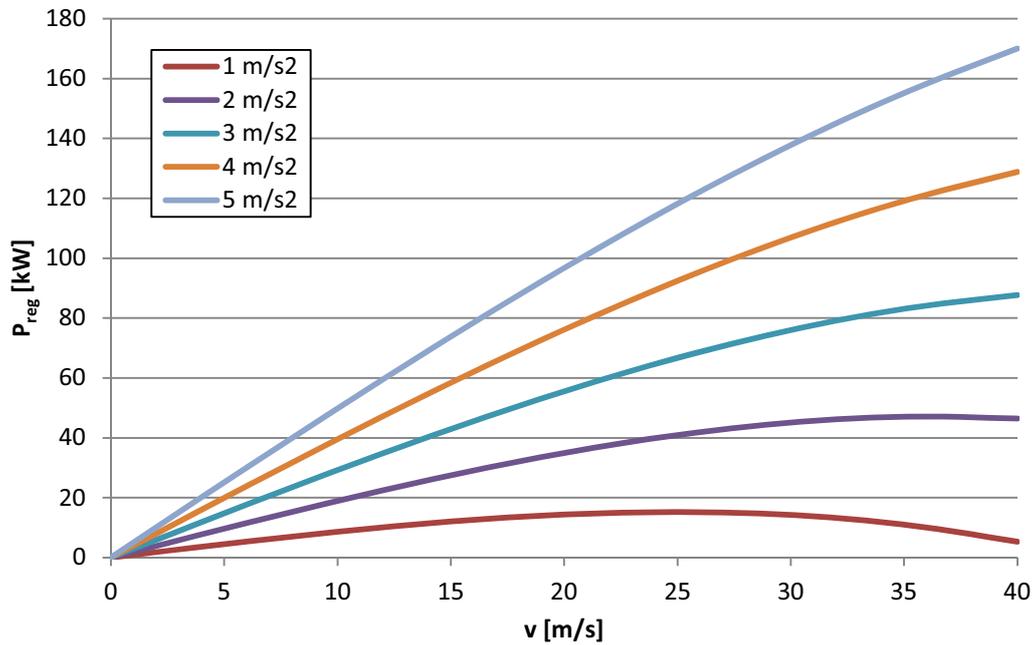


Figure 2. Dependence of power supplied to the battery on the linear velocity for various deceleration values

As in the case of energy, the highest braking power will be obtained at a higher braking deceleration. However, it should be noted that braking with a higher deceleration will result in a shorter braking time which can result in less energy transferred to the battery.

Thus, it seems reasonable to present the power P_{reg} delivered to the battery as a function of the duration of braking (Figure 3).

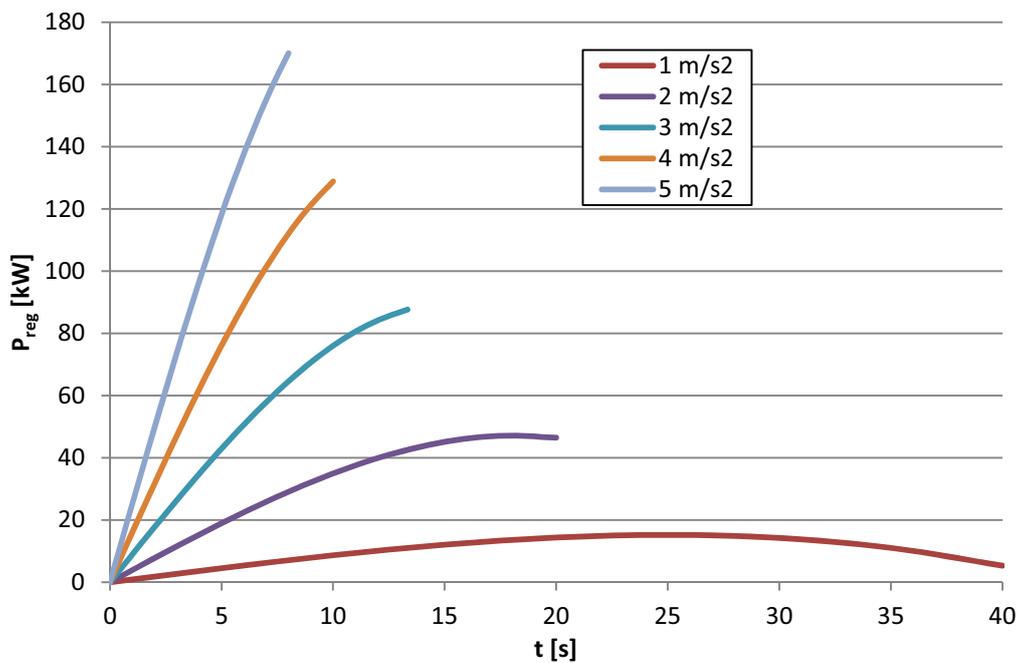


Figure 3. Dependence of power supplied to the battery on the duration of braking for different deceleration values

It should be noted that the area below the power line considered for a given deceleration represents the energy transferred to the battery. The highest energy value was obtained for the largest considered braking deceleration. By changing the integration limit, energy in any speed range can be determined. It should be noted that to some extent the power lines are close to the straight line, which makes it possible to calculate the energy from the triangle field without making a big mistake.

5. Conclusions

The theoretical analysis of the braking energy that can be supplied to the battery showed that the highest energy will be received by the battery with a high braking deceleration. The value of braking energy with a deceleration of 5 m/s^2 was about 0.19 kWh, for the deceleration of 4 m/s^2 it was about 0.18 kWh, while for the deceleration of 1 m/s^2 it was only about 0.02 kWh.

The above analysis was carried out for decelerating motion caused only by the resistance of motion and the resistance moment of the generator, without the use of a braking system. If the braking system is used, the energy transferred to the battery will be reduced accordingly.

According to the authors, in electric vehicles there is the possibility of replacing, to a certain extent, the classic brakes with the system that recognizes the pressure of the driver's leg on the brake pedal and the appropriate regulation of the battery charging current affecting the power value, and what is related to this, the value of the anti-torque produced by the generator. Similar operating systems are used in the so-called brakes of mountain trucks and buses powered by internal combustion engines. In this case, the anti-torque is changed by changing the average pressure in the engine cylinders.

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