Combined braking system for hybrid vehicle

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Abstract. The paper presents an analysis of surface vehicle’s existing braking systems. The technical solution and brake-system design were developed for use of regenerative braking energy. A technical parameters comparison of energy storage devices of various types was made. Based on the comparative analysis, it was decided to use supercapacitor because of its applicability for an electric drive intermittent operation. The calculation methods of retarder key components were proposed. Therefrom, it was made a conclusion that rebuild gasoline-electric vehicles are more efficient than gasoline ones.

1. Introduction
Nowadays, the most prevalent vehicle's drive is a system with internal combustion engine (ICE). However, a demand for electromobiles increases, that is shown in Figure 1, and it will increase along with the development of road electric transport infrastructure. According to the International Energy Agency (IEA) in 2015, an electric car quantity has amounted to 1.26 million units in the world [1], but gasoline-fuelled and diesel-engined cars – over one milliard units.

![Figure 1. The electromobile manufacture statistics according to IEA estimates](Image)

The electric motor drive is the most advanced and cost-beneficial solution in the context of its use in the transport infrastructure. Nevertheless, it is impossible to change an ICE actuator to an electric motor drive simultaneously for economic and engineering purposes. Statistically [2], ICE vehicles’ average lifespan is 12 years and 320000 operational kilometers. Consequently, in spite of the electric drive development, the manufacturing and maintenance of the vehicle with ICE will be continued.
As a result, it is necessary to change the driver of vehicles with ICE to either hybrid or electric motor. It allows one to extend not only lifespan of the already-existing vehicle, but also to develop transport infrastructure.

The fuel and maintenance costs are the most important factors for commercial transportation. Under highly competitive conditions, it is rational to use additional equipment, which reduces transportation expenses. One of these is a retarder. It is equipment, which is needed for significant safety improvement, reliability growth and efficiency upgrading of the brake system in the long-sustained load. Generally, it is used in case of heavy-duty trucks or buses driving along the mountain road. Also the retarder can be applied for urban buses, which work in the cycle mode with excessive fuel consumption.

There are some retarder advantages:

- fine dust emissions reduction, absence of oil or another liquids;
- lifespan extantion along with the reduction of the maintenance costs;
- braking system does not run hot in case of extended braking;
- there is a possibility of recuperation energy use.

Thus, the main objective of this research is to simulate the energy recuperation process of the brake system for the vehicle with internal combustion engine. In this regard, the tasks are following:

- to carry out an analysis of the existing retarders;
- to compare characteristics and possibility of using retarder systems for the recuperation;
- to develop the calculation methodology for retarder’s major elements for various vehicle types.

2. The main part

2.1. Figures in parts

For vehicle braking, the following systems are used:

- service brake, which is a device for arresting or preventing the motion of a vehicle usually by means of friction;
- motor braking, which is carried out by fuel delivery decrease and cessation by downshifting a gear;
- exhaust retarder (different devices for vehicle braking onto the long slope);
- retarder brake (retarder) – equipment for vehicle’s speed reduction without the service brake use.

There are electrodynamic retarders (eddy-currents or with permanent magnets) and hydrodynamic (intarders), which use for operation either automatic transmission oil or ICE coolant.

2.2. The analysis of the retarders’ existing designs

Currently there are four installation methods of retarders to the vehicle. Some big gearbox manufacturing companies install intarders just after the gearbox because of retarder brake’s local integration possibility. The necessity of transmission mount strengthening is a disadvantage of this design, because the overall equipment weight increases [4].

The most commonly used retarder’s installation place is a construction unit between cardan shafts, where mount adjusting with the gearbox or drive axle is not necessary. However, it is important to make the cardan axle a little bit shorter that is presented in Figure 2 [5].
One of the important conditions of the system installation is its cost-benefit in comparison with electromobiles. Such design is classified as the mild hybrid car [6], where the low-powered electric motor operates at a low speed range, and the energy storage device provides a short driving distance. In table 1 an example of the control algorithm realization is given.

Table 1. An example of the presupposed control algorithm realization

| Condition                                      | Standstill                        | Low speed (less than 10 kilometers per hour) | Braking                      | Full power condition (the required power is greater than the engine can produce) | Average and low power | Both engines are switched off | Only electromotor (EM) operating | Regenerative braking | Both engine operates | ICE operates |
|------------------------------------------------|-----------------------------------|---------------------------------------------|------------------------------|---------------------------------------------------------------------------------|-----------------------|-----------------------------|---------------------------------|----------------------|---------------------|--------------|

Retarder’s operating peculiarities is visualized in figure 3, where the segment 1-2 is a battery charge during regenerative braking, segment 3-4 is vehicle acceleration by means of the electric traction, and segment 4-5 – vehicle acceleration and movement with the help of ICE [7].

Figure 2. Retarder’s installation method

It is offered to make vehicle engineering changes for realization of a regenerative braking process:
— to use a drive motor, which can be a generator;
— to install a traction drive’s control system;
— to adjust a control system for the control logic of traction and braking modes;
— to place an energy storage device on-board.

Based on the previously discussed operating modes of the traction drive [8], recommendations for calculating the main elements of the drive are given.

2.3. The braking system calculation methodology
To select a suitable traction motor, it is necessary to perform a series of calculations that determine its technical features [9].

The moving force during starting duty is equal to:

\[ F_s = \left\{ a \cdot (1 + \gamma) + \omega_0 \right\} \cdot G_s \cdot Z^{-1} \cdot N \]  

where \( G_s \) - gross weight; \( Z \) - number of the vehicle engine; \( (1 + \gamma) \) - inertia constant, \( \omega_0 \) - basic motion resistance under current.

The braking force peak value by the adhesion conditions is:

\[ B_{max} = \psi \cdot G - W, \text{kN} \]  

The necessary implementation of the engine power is:

\[ P = B \cdot V \cdot 3.6^{-1}, \text{kW} \]  

The rim moment depends on the gear box ratio \( \mu \), vehicle’s wheel diameter \( D_w \) and gear drive efficiency \( \eta_{gd} \):

\[ M = B_{max} \cdot D_w \cdot (2 \cdot \mu \cdot \eta_{gd}), \text{N} \cdot \text{m} \]  

2.4. The energy storage device selection and calculation
Quantity of energy, produced by the engine during the braking mode, is defined in accordance with equation [10]:

\[ A_{rec} = A_{kin} = (1 + \gamma) \cdot m \cdot \left( V_{mb}^2 - V_{eb}^2 \right) \cdot 0.5, \text{kJ} \]  

The power of the energy storage device is:

\[ t_b = \left( V_{mb} - V_{eb} \right) \cdot (a \cdot 3.6)^{-1}, \text{sec} \]  

\[ P_{rec} = A_{rec} \cdot \tau^{-1}, \text{W} \]

For efficient recuperation it is necessary to choose a suitable energy store device. Table 2 gives comparative analysis of the energy storage different types [11].

| Energy storage types | Cycle efficiency, % | Specific energy density, Wh/kg | Specific power density, W/kg | Lifespan, years |
|---------------------|---------------------|--------------------------------|-----------------------------|----------------|
| NiCd                | 85                  | 45-80                          | -                           | ~15            |
| NiMn                | 80                  | 60-120                         | -                           | ~15            |
| Lead Acid           | 85                  | 30-50                          | 10-50                       | -              |
| Li-ion              | 70-80               | 110-160                        | 100-400                     | 5-15           |
| Li-ion Polymer      | 81-83               | 100-130                        | -                           | 5-20           |
| Supercapacitor      | 90-95               | 2-10                           | Over 15                     | 15             |

The use of supercapacitors is the most relevant solution because of engine intermittent operation, for which the implementation of high power in a short time is required [7].
When determining the capacity of the energy storage, it is advisable to use $A_w$ [12] that the segment 1-2 of Fig. 3 shows. The mechanical energy accumulated by the rolling stock at the breaking start moment is equal to:

$$E_{kin} = \left\{ G \cdot (1 + \gamma) + \left( G_g - G \right) \right\} \cdot 0.5 \cdot V_{at}^2, kJ$$

(8)

From the equation of the uniformly retarded motion, one can determine the braking length $l_b$.

$$l_b = V_{at} \cdot t - \frac{1}{2} \cdot a_{at} \cdot t^2 \cdot 0.5, m$$

(9)

The energy consumed by friction is:

$$E_f = \omega_{at} \cdot n \cdot l_b, kJ$$

(10)

![Figure 4. Energy datum of batteries and supercapacitors](image)

Regenerative power, where $\eta_c$ – efficiency of converters, $\eta_{es}$ – energy storage efficiency, is:

$$E_{rec} = \left( E_{kin} - E_f \right) \cdot \eta_c \cdot \eta_{es} \cdot \eta_{at}, kJ$$

(11)

The energy stored in the selected supercapacitor is calculated by the following formula, where $k$ – coefficient of energy storage discharge [13]:

$$E_{st} = C \cdot \left( U_{max}^2 - U_{min}^2 \right) \cdot 0.5 \cdot k, kJ$$

(12)

To evaluate the unit operation in the traction mode, one can determine the vehicle speed after the discharge of the energy storage, taking into account the movement resistance losses:

$$V_b = \left( \frac{E_{st} \cdot \eta_c \cdot \eta_{es} \cdot \eta_{at}}{G \cdot (1 + \gamma) + \left( G_g - G \right)} \right)^{1/2}, km/h$$

(13)

The acceleration path of the vehicle is:

$$l_a = \left( \frac{E_{st} \cdot \eta_c \cdot \eta_{es} \cdot \eta_{at}}{G \cdot (1 + \gamma) + \left( G_g - G \right)} \right)^{1/2} \cdot t^{-1}, km$$

(14)

The energy expended on the resistance to movement during acceleration is:

$$E_a = \omega_{at} \cdot l_a \cdot G \cdot 9.81, kJ$$

(15)

The definition of the acceleration rate value in the function of the resistance to movement is:

$$V_a = \left( \frac{(E_{st} - E_a) \cdot \eta_c \cdot \eta_{es} \cdot \eta_{at}}{G \cdot (1 + \gamma) + \left( G_g - G \right)} \right)^{1/2}, km/h$$

(16)
For example, Table 3 shows the estimated data, obtained from equations (1) - (16), for a two-axle passenger bus "MAN Lion’s Star" with a gross weight of 18 tons.

| $B_s$, kgf | $B_{max}$, kgf | $P$, kW | $P'$, kW | $M$, $N \cdot m$ | $A_{rec}$, kJ | $V_s$, km/h | $P_{rec}$, kW |
|------------|----------------|---------|-----------|-----------------|--------------|-------------|--------------|
| 2985       | 4900           | 326     | 108       | 212.6           | 1962         | 55 ÷ 5     | 317.6        |

Due to analysis results, it is possible to select the main elements for physical model of the retarder and to determine the vehicle’s energy datum experimentally.

3. Conclusion
The paper introduces retarders for vehicle's braking energy use, which consist of a drive motor, an energy storage device and a control system. The elements calculation algorithm was developed, and retarder calculation for the typical rolling stock was made. Further research will be focused on the development of the retarder control system and the creation of a simulation model in the MatLAB Simulink to assess its impact on the vehicle's energy performance.

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