Minimization of resource costs, improving the environmental and operational safety of urban road transport using braking energy recovery systems

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Abstract. The article assesses the cost minimization, as well as the environmental and operational safety of urban road transport in the Russian Federation. It is clear that the most reliable and promising systems for the recovery of car braking energy are systems equipped with a pneumo-hydraulic accumulator. Pneumo-hydraulic braking energy recovery systems can reduce fuel costs and the emission of harmful substances more than 2 times.

1. Introduction

Braking energy recovery systems (BER) are developed and applied in order to minimize the cost of resources, mainly for fuel, as well as to improve the environmental and operational safety of urban motor vehicles. It is more expedient and advantageous to use BER systems for buses, minibuses and cars-taxis, since they are operated in the city and they often perform regular accelerations and braking at intersections, crossings and stopping points (Figure 1) [1-12].

Analysis of Figure 1 shows that in the overwhelming majority of cases, braking is carried out until the vehicle comes to a complete stop and begins at a speed of about 40 km/h. The average time between stops is 75 seconds. During the 12 hour shift, a city car makes at least 576 acceleration-stop cycles, and more than 200,000 cycles per year. This leads to rapid deterioration of the engine, clutch, parts of the brake and other systems, which leads to big resource costs associated with the repair and downtime of vehicles. The use of BER systems reduces the resource costs of operating the urban motor vehicle, not only by saving fuel, but also by increasing the reliability (time to failure) of the following units, components, and parts:

- engine (during acceleration it is less loaded);
- clutch (skidding is excluded when starting off);
- gearbox (reduced load during acceleration and the number of switchings);
- driveshaft (reduced load bearing during acceleration);
- brake pads and cylinders (reduced wear when braking).

The BER system partially assumes their functions and relieves from wear which not only reduces...
the costs associated with the repair and replacement of units, components, and parts, but also reduces the losses associated with downtime of the vehicle under repair.

Figure 1. Graph of change in vehicle speed $v$ during the time of $\tau$ movement at a distance of 12 km along the city route.

The increase in the level of reliability of the vehicle brake system also leads to an increase in their operational safety, and a reduction in fuel consumption reduces the emission of harmful substances and improves the environmental safety of the urban motor transport which makes the use of BER systems for city motor transport very relevant. No wonder that the “Forecast of the scientific and technological development of road transport systems in the Russian Federation” (approved by the Government of the Russian Federation on January 3, 2014) contains an item on the transition to vehicles with hybrid power plants in 2030.

We will assess the resource cost minimization, the environmental and operational safety of urban motor transport in the Russian Federation provided by the BER system based on data from the Avtostat agency which contain the following information. In the Russian Federation, motor transport accounts for more than 60% of all trips made by public transport, with the number of trips increasing by 20 million annually. As of January 1, 2017, there are about 395,400 buses registered in our country. Most of the bus equipment is in Moscow (19.1 thousand units), the second line is occupied by Krasnodar Region (15.8 thousand units), and the top three belong to Moscow region (14.5 thousand units). At least 10 thousand buses are also registered in Tatarstan, St. Petersburg, Rostov and Irkutsk regions, Krasnoyarsk, Novosibirsk and Sverdlovsk regions. The leader among the brands is PAZ (168.1 thousand units, diesel fuel consumption – 23.9 l/100 km, gasoline consumption – 36.0 l/100 km), followed by KAVZ (55.8 thousand units) and LiAZ (34 thousands of pieces, fuel consumption for different models – 22-67 l/100 km). According to experts, these three brands account for 65% of the total bus fleet in Russia. Hyundai is leading among foreign brands (16.2 thousand units). The average age of the Russian bus fleet is 15.9 years, with 45% of cars over 15 years old. The percentage of foreign cars is 27%. During the shift, the total mileage is about 250 km. At the beginning of 2018, 466,683 permits were valid for work in a taxi. Average fuel consumption was about 10 l/100 km. The total annual bus mileage was about 70 thousand km, and taxi cars – from 50 thousand km. Only 14% of cars complied with Eco-standard "Euro-4".

Taking into account the above statistics, as well as the fact that the price of fuel is now around 40 rubles per liter, the costs of resources for fuel for vehicles operated in the cities of our country are:

- for the bus fleet – 7,465,488,000 rubles;
- for the taxi fleet – 186,673,200 rubles;
- total for the entire park – 7,652,161,200 rubles.

For today, according to the authors of the article, the most promising systems for motor vehicles are
BER systems which convert the kinetic energy of a car during braking to compressed gas energy in a pneumatic-hydraulic accumulator (Figure 2). A pneumatic-hydraulic accumulator (PHA) allows charging it fully for less than 10 seconds, which is unattainable for an electrical accumulator. The scheme of the vehicle chassis with the parallel pneumatic-hydraulic system of BER is shown in Figure 2. Its main components are: high pressure accumulator, low pressure accumulator, pump-motor, hydraulic fluid conditioning system, and controller.

**Figure 2.** Chassis scheme of a car with a parallel pneumatic-hydraulic BER system: 1 – high pressure accumulator or oil tank; 2 – pump-motor; 3 – low pressure accumulator; 4 – energy flows.

As a rule, a hydraulic pump-motor (HPM) of a gear or axial-piston type with a constant or adjustable displacement is used for energy conversion. In the pumping mode, it converts the kinetic energy of the vehicle into the potential energy of the gas pressure (inert gas nitrogen is used – N₂) accumulated in the PHA. In the motor mode, the HPM transforms the potential energy of the compressed gas accumulated in the battery into the kinetic energy of the car during its acceleration. Modern HPMs operate at high pressure of the working fluid (up to 30-35 MPa), they have an efficiency comparable to that of electric motor-generators (0.95), and almost ten times higher specific power – 4.0 against 0.5 kW/kg, i.e. less mass. A low pressure accumulator (up to 1.2-1.4 MPa) is often used instead of a tank to prevent cavitation in the HPM. Modern PHAs develop specific power up to 15 kW/kg. The cleaning system provides oil cleaning from wear products, and the controller monitors the driver’s actions, accelerates and brakes of the vehicle, and controls the operation of the BER system.

To save fuel and improve environmental safety, it is advisable to turn off the engine at vehicle stops eliminating its work at idle. Let's estimate how much this will reduce the cost of fuel and increase the environmental safety of a bus. We will use the distribution of the time during the work in the city for various modes obtained as a result of monitoring the work of buses (Figure 3).

**Figure 3.** The distribution of the bus time in the city by different modes: 1 – movement; 2 – braking; 3 – overclocking; 4 – idling.

From the distribution it follows that if you turn off the engine at the time of the start of braking and...
start it only after the bus is accelerated by the BER system, you can reduce the engine running time by 57%, which will reduce the cost of fuel and the emission of harmful substances more than 2 times.

To reduce the mass and cost of BER system, it is important to make a rational choice of PHA capacity which can be done using energy balance. The energy balance of the car during braking was considered by Academician E.A. Chudakov, Professor N.A. Bukharin [2, 3] and other researchers. The energy balance of the braking process of a bus to a full stop during normal braking with constant deceleration and rolling of all the braked wheels on a flat horizontal surface without BER system can be represented as follows:

\[ W_b = \frac{\delta \cdot m_b \cdot \delta^2}{2} = \Sigma A_j \]  \hspace{1cm} (1)

where \( W_b \) is the total kinetic energy of the bus, Nm; \( \delta \) is the coefficient taking into account the influence of the rotating mass of the transmission and the wheels of the bus (with the engine off \( \delta = 0.09 \)); \( m_b \) is the mass of the bus, kg; \( \delta_k \) is the speed of the bus at the start of braking, m/s; \( \Sigma A_j \) is the resulting work of various resistance forces when braking the bus.

\[ \Sigma A_j = A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7, \]  \hspace{1cm} (2)

where \( A_1 \) is the work of the resulting friction force in the brake mechanisms of the bus between the pads and discs or drums:

\[ A_1 = F_{\text{avr}} \cdot \alpha \cdot (1 - \sigma) \cdot s_b \]  \hspace{1cm} (3)

where \( F_{\text{avr}} \) is the average value of the resulting friction force between the pads and discs or drums; \( \alpha \) is the coefficient equal to the ratio of the average radius of the friction force to the radius of the wheel; \( \sigma \) is the slip coefficient of the braked wheel relative to the road surface.

\( A_2 \) is the work of the air resistance force:

\[ A_2 = P_{\text{avr}} \cdot s_b \]  \hspace{1cm} (4)

where \( P_{\text{avr}} \) is the average value of the air resistance force on the braking path of the bus; \( s_b \) is the brake-path length.

\( A_3 \) is the work of the friction forces during sliding of the braked wheels is relative to the road:

\[ A_3 = m_b \cdot g \cdot f_{\text{slip}} \cdot \sigma \cdot s_b \]  \hspace{1cm} (5)

where \( g \) is the acceleration of gravity; \( f_{\text{slip}} \) – coefficient of adhesion of the tire tread to the road; \( \sigma \) is the slip coefficient of the braked wheel relative to the road surface.

\( A_4 \) is the work of friction forces in the transmission:

\[ A_4 = P_{\text{fr}} \cdot (1 - \sigma) \cdot s_b \]  \hspace{1cm} (6)

where \( P_{\text{fr}} \) – the average friction force of the transmission reduced to the radius of the wheel.

\( A_5 \) is the work of friction forces between the wheels and the road:

\[ A_5 = m_b \cdot g \cdot f_{\text{visc}} \cdot s_b \]  \hspace{1cm} (7)

It is necessary to take into account the energy accumulated in the PHA, the loss in the hydraulic machine, and the friction loss of the PHA floating piston seals for the energy balance of the braking process of a bus equipped with BER system to a full stop during normal braking. Then, the full kinetic energy of the bus:

\[ W_b = W_u + A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7. \]  \hspace{1cm} (8)

Here \( W_u \) is the energy accumulated in PHA; \( A_6 \) is the work associated with the loss of energy in the hydraulic pump; \( A_7 \) is the work associated with the loss of the seals of PHA floating piston:

\[ A_6 = \sum \eta \cdot (1 - \eta), \]  \hspace{1cm} (9)

where \( \eta \) is the power efficiency in the hydraulic pump (for gear pump \( \eta = 0.7 \), for axial pump \( \eta = 0.9 \)).
where $\eta$ – the power efficiency of PHA piston ($\eta = 0.95$).

From the formula (8) we obtain the following equation for the energy accumulated in the PHA of the bus:

$$W_a = W_b - A_1 - A_2 - A_3 - A_4 - A_5 - A_6 - A_7.$$  \hspace{1cm} (11)

If the braking is carried out only by BER system and the brake mechanisms are not used, then the work of the last $A_1 = 0$.

The share of kinetic energy of the bus accumulated in the battery of the recovery system during braking:

$$D = \frac{W_a}{W_b}. $$  \hspace{1cm} (12)

Calculations made for the GAZel minibus showed that when using the cheapest gear HPM, the share of energy that can accumulate in a piston pneumo-hydraulic accumulator is 60% of the kinetic energy of the bus at the start of braking, and when using an axial pump having a higher power efficiency, it is up to 80%.

An experimental verification of the pneumo-hydraulic system of BER was carried out in our country and abroad. Experimental tests with buses LAZ-695 and LAZ-4202 carried out by scientists of Kursk Polytechnic Institute showed that the pneumo-hydraulic system of BER with the use of idling at stops gives fuel savings of up to 30% and reduces the exhaust gases toxicity almost 3 times. Similar research results were obtained in Germany with buses having the BER pneumo-hydraulic system at Berlin’s city routes. Fuel economy was 20-25%, acceleration intensity was increased by 60% and noise during acceleration was reduced. However, experimental samples did not go into a series, since these BER systems have weaknesses that impede implementation.

First, it is a large mass and high price, especially when using imported components and parts. For example, the main and most expensive unit of the BER system is an Italian-made PHA for the Gazel minibus which weighs 100 kg and costs about 120,000.00 rubles. The same PHA of domestic production costs about 30,000.00 rubles. However, there is a possibility of reducing the mass and price of BER system. For example, a pneumatic cylinder of the required volume used in gas-balloon equipment (from which PHA can be made) is 3 times cheaper – 10,000.00 rubles weighing 30 kg. Foreign hydraulic machines are much more expensive than domestic ones. Domestic gear motors of the company “Stroymashservice” (Table 1) have the lowest mass and price. As you see from Table 1 (considering both in mass and in price), it is more profitable to use two hydraulic motors with a working volume of 50 cm$^3$/rev than one with a working volume of 100 cm$^3$/rev.

The problem of creating highly reliable pneumo-hydraulic systems of BER is also in the special conditions of operation of the HPM which has to transmit a large torque at low speed. This is unacceptable because it leads to intensive wear of parts of the cumulated pressure sensor, especially when braking, when the rotor speed of the hydraulic machine drops to zero with a continuously increasing effective torque. For most hydraulic machines, the minimum speed is 50 rpm. The problem is aggravated by the fact that in the existing pneumo-hydraulic systems of BER, the rotor of the hydraulic machine rotates and pumps oil even with an equal movement of the vehicle, since it is associated with the transmission. This leads to oil heating, reduction of HPM life and the deterioration of the fuel economy of the vehicle.
Table 1. The price of gear motors of the company “Stroymashservice”.

| Index    | Mass, kg | Price, rubles |
|----------|----------|---------------|
| GMSh-50U3 | 5.70     | 1265          |
| GMSh-50A3 | 7.00     | 2652          |
| GMSh-100A3 | 17.0    | 4998          |

In order to increase the reliability of the BER system in the braking mode, it is necessary to include in the structure of the BER system additional devices that open the power flow in the BER drive when the HPM rotor reaches the minimum allowable rotational speed during braking. This device can be a clutch which can also provide an acceptable mode of operation of HPM when starting the vehicle off. However, the introduction of a clutch increases the cost of the BER system, while the BER system cannot stop the vehicle until its full stop. To solve these problems, the authors of the article develop a new system of BER where the function of HPM is performed by a ball screw drive, which allows reducing the rotational speed to zero and having a high power efficiency [7].

2. Conclusions

- It is proved that today the most promising systems for motor vehicles are BER systems which convert the kinetic energy of a car during braking to compressed gas energy in a pneumatic-hydraulic accumulator. It improves the operational safety of the urban motor transport vehicles by increasing the level of reliability of the braking system.
- It is defined that if you turn off the engine at the time of the start of braking and start it only after the bus is accelerated by the BER system, you can reduce the engine running time by 57%, which will reduce the cost of fuel and the emission of harmful substances more than 2 times.

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