Reduction of the carbon footprint of cargo vehicles with pneumatic recovery of braking energy

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Abstract. Reducing carbon dioxide emissions by passenger vehicles allows you to achieve the use of electric power plants and hybrid power plants made on the basis of thermal internal combustion engines and electric machines. However, the application of the above-mentioned approach for trucks is associated with significant difficulties due to the low specific capacity of the chemical current sources currently used. The recovery of braking energy of cargo vehicles in the pneumatic form is constrained by the need to achieve a high speed of switching on the pneumatic recuperator. In order to minimize the energy losses of the pneumatic recuperator during acceleration and steady-state. Without changing the design and reducing the reliability of the internal combustion engine, it is possible to supply air to its inlet at pressures not exceeding 350 kPa. When air is supplied to the internal combustion engine inlet at pressures of 200 and 300 kPa, it is possible to reduce specific carbon dioxide emissions by 16 and 37 % per unit of generated mechanical energy, respectively, compared to air supply under normal atmospheric conditions.

1. Introduction
Reducing carbon dioxide emissions by passenger vehicles allows you to achieve the use of electric power plants and hybrid power plants made on the basis of thermal internal combustion engines and electric machines. However, the application of the above-mentioned approach for trucks is associated with significant difficulties due to the low specific capacity of currently used chemical current sources (batteries), which is indirectly confirmed by the work carried out in this direction in the world [1-8].

Thus, to date, a contradiction has formed: it is necessary to reduce the carbon footprint of trucks, and the physical capabilities of electric batteries do not allow this to be done.

One of the possible solutions to this contradiction is the use of braking energy recovery systems for trucks based on a high-speed braking energy recovery system in pneumatic form and the subsequent use of compressed air for high boost of the internal combustion engine with a significant depletion of the mixture.
2. Materials and equipment
To date, a significant number of studies have been carried out on the use of pneumatic engines in motor vehicles, but mainly in the form of separate sources of mechanical power [9-10].
Scientific research in the field of recovery of braking energy of vehicles and its subsequent use in the form of supercharging of internal combustion engines is practically not conducted.
Perhaps this is due to the difficulty of ensuring the minimum turn-on time of the pneumatic recuperator when braking a vehicle, less than 1 s.
Figure 1 shows a circuit of a recuperative power plant of a motor vehicle with a minimum turn-on time of a pneumatic recuperator due to its constant kinematic connection through a differential mechanism with the driving wheels.

![Figure 1. Recuperative power plant of a motor vehicle. 1 - internal combustion engine; 2 - transmission; 3 - torque transmission shaft; 4, 17 - non-lockable differentials; 5, 16 - drive wheel axles; 6 - drive wheels; 7 - hydraulic brake mechanisms; 8 - hydraulic line; 9, 13 - controlled hydraulic safety valves; 10, 12, 14 - hydraulic lines; 11 - brake hydraulic cylinder; 15 - hydraulic brake mechanism; 18 - compressor shaft; 19 - compressor; 20 - compressor suction line; 21, 31 - air filters; 22 - compressor discharge line; 23 - pneumatic accumulator; 24, 26, 27, 28, 30 - pneumatic lines; 25 - controllable valve; 29 - check valve; 32 - mechanical transmission; 33 - output shaft of mechanical transmission.](image_url)

The operation of the power plant is described in the application for the invention [11]. The power plant allows you to implement the driving mode in atmospheric air, to carry out high-speed recovery of braking energy in a pneumatic form and to implement the driving mode on the air recovered in the braking mode.
A distinctive feature of the power plant is the constant kinematic contact between the driving wheels and the compressor shaft, which remains stationary in the accelerated or steady motion mode and rotates in the braking mode.
3. Results
To simulate the operating modes of the developed recuperating power plant, the following parameters were used:

- Chevrolet NIVA car with the following parameters: Curb weight - 1350 kg; Trunk volume - 320 liters; Engine capacity - 1689 cm³; Engine speed at maximum power - 5200 rpm; Maximum power - 80 hp; Engine stroke – 4.
- REMEZA SB4-F110-14 compressor: Pressure - 14 atm.; Length/width/height on the frame-1100/620/820; Capacity - 22 hp at maximum speed.
- Pneumatic accumulator with parameters: Volume - 110 liters.; Pressure - 16 atm.; Length/width/height - 670/820/560; Weight - 60 kg.

Air flow through the engine (table 1):

\[ Q = \frac{n}{260} \cdot V \cdot 10^{-3} \]

Table 1. Air flow through the engine.

| Rotation speed, n, rpm | 1000 | 2000 | 3000 | 4000 | 5000 | 5200 |
|------------------------|------|------|------|------|------|------|
| Consumption, Q, l/s    | 14   | 28   | 42   | 56   | 70   | 73   |

Braking energy available for recovery from different speeds up to 0 km/h (table 2):

Table 2. Braking energy available for recovery from different speeds.

| Speed, V, km/h | 90   | 80   | 70   | 60   | 50   | 40   | 30   | 20   | 10   |
|----------------|------|------|------|------|------|------|------|------|------|
| Energy, E, kJ  | 422  | 333  | 255  | 188  | 130  | 83   | 47   | 21   | 5    |

The number of liters of air at a pressure of 14 atm, which can be recovered when braking at the appropriate speed (the gear ratio between the drive wheels and the compressor shaft is 1; the compressor efficiency is 0.85; the power transmission efficiency is 0.8 and the average compressor capacity is 11 l/s) is shown in table 3.

Table 3. The number of liters of air that can be recovered when braking from an appropriate speed.

| Speed, V, km/h | 90   | 80   | 70   | 60   | 50   | 40   | 30   | 20   | 10   |
|----------------|------|------|------|------|------|------|------|------|------|
| Minimum recovery time by the compressor REMEZA SB4-F110-14, s | 20   | 16   | 12   | 9    | 6    | 4    | 2    | 1    | 0    |

The operating time of the engine (at a shaft rotation speed of 5200 rpm) when using recuperated air (at a speed of 90 km/h), depending on the amount of excess pressure at the engine inlet (the polytrope of expansion of the air in the tank 1.2) is shown in table 4.

Table 4. Engine operation time depending on the value of excess pressure at the engine inlet.

| Air pressure at the engine inlet, kPa | 200 | 300 | 400 | 500 | 600 |
|--------------------------------------|-----|-----|-----|-----|-----|
| The operating time of the internal combustion engine at resp. inlet pressure, s | 31  | 19  | 14  | 10  | 8   |

The data in table 4 allow us to speak about the satisfactory operating time of the internal combustion engine of the power plant on the air recovered during braking, even at the maximum power mode.

Using the mathematical model of the internal combustion engine thermal calculation [12], with an error of up to 1 %, we calculate the actual maximum pressure of the pz cycle and the hourly fuel
consumption (gasoline) Internal combustion engine \( G_m \) at a rotation speed of \( n = 5200 \) rpm, an excess air coefficient equal to \( \alpha = 1 \) and normal atmospheric conditions:

\[
p_z = 7.4 \text{ MPa}, \ G_m = 20.9 \text{ kg/hour}.
\]

Achieving the same actual maximum combustion pressure \( p_z \) = 7.4 MPa in the case of air supply to the engine inlet with pressures of 200, 300 kPa is possible with a reduction in hourly fuel consumption to the values of \( G_{m200} = 17.6 \text{ kg/hour} \); \( G_{t300} = 13.2 \text{ kg/hour} \).

When air is supplied to the engine inlet at a pressure of more than 350 kPa, the pressure at the end of the compression process will be greater than the pressure at the end of the combustion process in an internal combustion engine operating under normal atmospheric conditions.

According to [13], burning 1 kg of gasoline leads to emissions of approximately 3.05 kg of CO\(_2\). The amount of carbon dioxide emissions during the operation of an internal combustion engine on alcohols is shown in [14-15].

At a flow rate of \( G_t = 20.9 \text{ kg/hour} \), carbon dioxide emissions will amount to \( G_{CO2} = 63.7 \text{ kg/hour} \).

When air is supplied to the engine inlet at a pressure of 200 and 300 kPa, CO\(_2\) emissions will amount to \( G_{200CO2} = 53.7 \text{ kg/hour} \), \( G_{300CO2} = 40.3 \text{ kg/hour} \) and decrease, respectively, by 16% and 37%.

With a high degree of probability, we can say that a commensurate reduction in CO\(_2\) emissions will occur in the entire available range of engine crankshaft speeds.

4. Conclusions

The development of electric recovery of braking energy of cargo vehicles is limited by the achieved small values of the specific energy intensity of battery accumulator.

The recovery of braking energy of cargo vehicles in the pneumatic form is constrained by the need to achieve a high speed of switching on the pneumatic recuperator.

The rapid activation of the pneumatic recuperator of the braking energy of the vehicle is possible with constant kinematic contact of the driving wheels and the compressor shaft.

In order to minimize the energy losses of the pneumatic recuperator during acceleration and steady-state movement of the vehicle, it is advisable to connect it to the driving wheels through a differential mechanism.

Without changing the design and reducing the reliability of the internal combustion engine, it is possible to supply air to its inlet at pressures not exceeding 350 kPa.

When air is supplied to the internal combustion engine inlet at pressures of 200 and 300 kPa, it is possible to reduce specific carbon dioxide emissions by 16 and 37% per unit of generated mechanical energy, respectively, compared to air supply under normal atmospheric conditions.

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