Decreasing Emissions of PM by Vehicles through Brake Energy Recovery

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Abstract. A significant contribution to the formation of PM 10 and PM 2.5 in the atmosphere of large cities is made by frequent braking by friction brake mechanisms. The author considers electrodynamic regenerative braking as one of the advantages of hybrid and electric vehicles, which can significantly reduce the formation of PM during braking. Using experimental studies, the author estimates the wear of the brake pads of the same vehicle during regenerative and mechanical braking. During the experiment, a series of acceleration and braking cycles was performed from a given speed to a complete stop, after which the friction brake pads were dismantled and their weight was measured. Then, during the calculation and comparison, the PM emission reduction is determined in a test with braking energy recovery.

1. Introduction
Features of the operation of vehicles in urban conditions are: low average speeds caused by traffic jams; frequent acceleration and braking; long stops with the engine running. Under such conditions, pollutant emissions are much higher than normalized ones. At the same time, traffic density at key intersections of the road network during peak hours is significantly increased, and a large number of people are forced to be in the local zone of increased concentration of toxic and polluting substances. In such conditions, the negative impact of the environment on people is extremely high. According to the WHO, people living near highways or spending a lot of time in motor vehicles have a 15% higher risk of cancer and illness than the average level [1]. These circumstances are the cause of numerous studies evaluating the environmental impact of vehicles on humans.

2. Relevance, scientific significance of the issue with a brief review of the literature
According to Russian and foreign studies, emissions of solid fine particles are one of the main causes of oncology of the human respiratory system and improper lung development in children [1-4]. It is believed that the main source of pollution is particulate soot in the exhaust gases of diesel engines. The environmental standard of the 5th and 6th generation actually 10 times reduces the maximum emissions of these particles [1]. However, at the same time, solid dispersed particles are formed when the road surface deteriorates 60–90%, tires 9–36% and braking mechanisms 1–4% [5]. According to the research of Azarov V.K. these emissions are much higher in volume than those from exhaust gases, however, at present they are not given due attention [6, 7].
Improving the traction and speed qualities of cars in recent years inevitably leads to an increase in emissions of particulate matter from tire wear, road surface and brake mechanisms. Moreover, passenger cars account for more than 90% of all emissions [5].

The solution to the problem of reducing emissions of fine particles from tire wear and paving is currently seen in limiting the use of cars in cities in favor of rail or bicycle transport [5], limiting the use of studded tires. But such decisions will inevitably lead to an increase in social risks, which also needs to be taken into account. A radical solution to this problem is still missing.

In the brake mechanisms of automobiles, the wear elements are brake discs, drums and friction linings of brake pads. The products of their wear are fine particulate dust particles, which according to research [2] contain approximately 28% iron, 12% organic carbon, 5.6% barium, 5.3% silicon, approximately 4% magnesium, 3.4% copper. In different types of friction materials, aluminum, calcium, cadmium, manganese, and zinc can also be found [8, 9]. Asbestos content in many countries in friction materials is severely limited. However, the presence of magnesium, silicon and silicon oxides in the wear products indicates the presence of asbestos in the wear products in an amount of about 5-10%.

Estimates of the effect of recovery on PM emissions reduction are still subjective, in this regard, the author in this paper sets the goal of determining the effect of regenerative braking on particulate emissions from brake wear.

3. Statement of the problem
The main objective of the work is also to offer methodological approaches to achieve the goal.

This work is carried out in conjunction with other studies and is part of a larger study by the author: "Evaluation of the performance properties of hybrid cars" [10, 11].

Regenerative inhibition, unlike mechanical inhibition, implies the accumulation of braking energy and its reuse [12-14]. In passenger rail transport, as well as trolley buses, recovery is sometimes used by returning the generated electricity back to the contact network. In the subway, due to the fact that the stations are built on hills, recovery is very well carried out passively in the train’s own potential energy.

In hybrid and electric cars, recovery is implemented by an active process of electrodynamic braking by a traction electric motor operating in generator mode. The electric energy generated in this case, minus some losses, is accumulated in the high-voltage battery and then consumed repeatedly [15, 16].

4. Theoretical part
In any automobile, regenerative braking in a certain amount can be realized by changing the load on the electrical generator of the on-board network and air conditioning during acceleration and braking. It can also be carried out during movement on ups and downs, accumulating in the potential energy of the car, which was discussed in detail earlier [17].

Regenerative braking helps to reduce the load on the working brake system, which reduces the wear of the brake mechanisms, and hence the PM emissions into the atmosphere. According to available research results, up to 50% of brake wear products are fine particles [18-23].

To evaluate the effect of recovery on PM emissions from brake wear, a full-scale experiment was conducted in which cars with hybrid engines were involved. The production car Toyota Prius ZVW30 and an experimental running layout with hybrid engine Lada 1118.
In both vehicles, regenerative braking can be completely disabled by software. Thus, it becomes possible to conduct tests with mechanical or electrodynamic braking on the same vehicle. The main evaluation parameter is the brake lining wear rate, which indirectly characterizes PM emissions.

As a measure of deterioration, the mass of brake pads and the thickness of the brake drums before and after the test were used.

Before the test, all the brake pads, brake discs were replaced, the brake fluid was completely replaced and pumped, the caliper guide elements were lubricated, and the electronic braking system was checked and programmed.

Toyota Prius ZVW30 has a nickel metal hydride energy storage with an available energy reserve range of about 1.8 MJ (residual capacity of the high-voltage battery is 3.8 Ah).

Before installing new brake pads and discs, their initial mass and geometric dimensions are measured and recorded in the test report.

During testing, the car was repeatedly accelerated to a predetermined speed of 40 km/h, then regular braking was performed by the working brake system.

The results of superimposing a series of cycles are presented in Fig. 1. Based on the averaged values, graphs of changes in the velocity V (t) and acceleration a (t) are plotted. At an initial braking speed of 40 km/h, the time to a complete stop was on average 7.8 seconds.

![Figure 1. Braking graph with an approximating curve.](image)

Upon reaching 50 cycles, tests were completed and wear measurements were carried out. After which the test continued again. The following tests were carried out already with the electrodynamic brake system forcibly disconnected.

The measurement processing results are presented in the table 1.

| Type of braking     | Number of cycles | Front axle (g) | Rear axle (g) | Total (g) |
|--------------------|------------------|----------------|--------------|----------|
| Mechanical         | 50               | 1.2            | 0.9          | 2.1      |
| Electrodynamic     | 50               | 0.6            | 0.2          | 0.8      |
After 50 braking cycles with recovery from a speed of 40 km/h to a complete stop, the total wear of the brake pads was 0.8 g, which is 0.016 g per braking.

After 50 braking cycles without recuperation from a speed of 44 km/h to a complete stop, the total wear of the brake pads was 2.1 g, which corresponds to 0.042 g per braking (Table 2), which, when switching to the standard NEDC or WLTC driving cycle, corresponds to 0.126 g/km.

Reducing wear on brake pads when applying electrodynamic braking will be:

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\Delta W = \left( \frac{W_{MB} - W_{RB}}{W_{MB}} \right) \times 100 = \left( \frac{0.042 - 0.016}{0.042} \right) \times 100 = 61.9\%
\]

\( W_{MB} \) – wear during testing with mechanical braking; \( W_{RB} \) – wear during testing with electrodynamic braking.

5. Results

Tests on a traveling prototype with a hybrid engine with a capacitor energy storage based on the LADA 1118 car showed even lower wear rate of brake linings in the recovery mode. Condenser types of drives are able to receive much larger charge currents, which favorably affects the absorption of braking energy. But, at the same time, the amount of stored energy in a capacitor storage is much lower than in Ni-MH, Li-Ion electrochemical storage devices.

The wear of the friction linings when using a mechanical brake system was 0.042 g per braking, which, when converted to the standard NEDC or WLTC driving cycle (low speed section), corresponds to 0.126 g/km.

6. Discussion

It is worth noting that the wear rate of brake linings depends on operating conditions and braking intensity, however, the test conditions in the experiments were identical, which excludes the influence of external conditions. Energy recovery in the urban driving mode allowed to absorb a significant part of the braking energy and reduce particulate emissions from wear of friction brake mechanisms by 62%.

The possibilities of regenerative braking also depend on the characteristics of the elements of the traction drive, the capacity of the high-voltage drive, and its temperature. Indirectly, we can conclude that with a maximum deceleration of \( 2 \text{ m/s}^2 \) from an initial speed of 40 km/h, braking is provided for the most part due to recovery.

7. Conclusions

The tests performed showed the possibility of a significant reduction in particulate emissions from the wear of brake mechanisms by motor vehicles in urban conditions due to regenerative braking. Although this will not affect the total amount of particulate emissions from vehicles, in local zones of intersection of high-density vehicles with high intensity and traffic density, where hundreds of vehicles per hour are forced to slow down, brake dust emissions will be significantly lower.

Further research by the author will be aimed at establishing the effect of recovery on emissions of pollutants in the exhaust gas and the economic characteristics of vehicles.

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