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Original Article

Development of an Automatic Device for Maintaining Normal Air Pressure in Pneumatic Tires

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Abstract *- The purpose of the article is to solve the problem of increasing the life of pneumatic tires, reducing fuel consumption and improving road safety. It is known that most pneumatic tires fail prematurely due to the fact that the pressure in the tires is violated; at the same time, overheating, swelling of cracks, etc., occur. Often, wheeled vehicles operate with a deviation from the recommended standards. During the hot season, when high-speed vehicles move on a hard rough road, the tire pressure rises due to heated air. There is an increase in the specific pressure at the point of contact between the tire and the road, which leads to a deterioration in braking dynamics. Depending on the low or high air pressure in pneumatic tires, the dynamic and economic qualities of cars are reduced. This leads to an increase in the cost of transportation and the likelihood of traffic accidents. As a solution to this problem, the authors proposed an automatic device for maintaining normal air pressure in the tires using compressed nitrogen. The proposed device includes a high-pressure cylinder, filling valve, high-pressure reducer and locking device. High-pressure cylinders can be mass-produced by manufacturers for various vehicles. They can be structurally made in the cavity of the wheel disk. Refilling of these cylinders can be carried out at special gas stations, tire shops or service centers.*

Keywords *- Compressed nitrogen, Fuel consumption, High pressure reducer, Pneumatic tires, Tire pressure.*

1. Introduction

The movement of wheeled vehicles is carried out due to the interaction of the pneumatic wheel mover and the supporting surface. This interaction causes significant energy losses that characterize the vehicle’s dynamics and efficiency.

It should be noted that pneumatic tires and wheels represent the vehicle's very responsible and expensive part. It has been established that up to 25% of pneumatic tires fail prematurely (of which 90% fail due to violations of tire pressure standards). In this case, overheating, delamination of cord fabrics, local inflations, cracks, etc., occur. About 95 ... 98% of all wheeled vehicles operate with a deviation from recommended tire pressure standards (the deviation ranges from 15 to 60% of the norm) [1,2].

Manufacturers allow deviation of tire pressure:

- for cars – no more than 0.01 MPa;
- for trucks and tractors – no more than 0.02 MPa.

Decrease in tire pressure by 0.05 MPa increases fuel consumption by 4.5% and up to 0.1 MPa – by 10...12% (on the hard ground) [3-5]. In the hot season, when high-speed vehicles move on a hard rough road, the tire pressure rises due to heated air, and its excess can reach 0.10 ... 0.12 MPa. It leads to a deterioration of the braking dynamics due to an increase in the specific pressure at the point of tire-road contact, increased local wear of the tire tread during intensive acceleration and braking, strong springs deflection and their breakage, etc. [6].

The area of the tire-road contact decreases, which leads to a decrease in the vehicle's cross-country ability on poor road surfaces and increases their tendency to skid on slippery roads (Figure 1) [7-9].

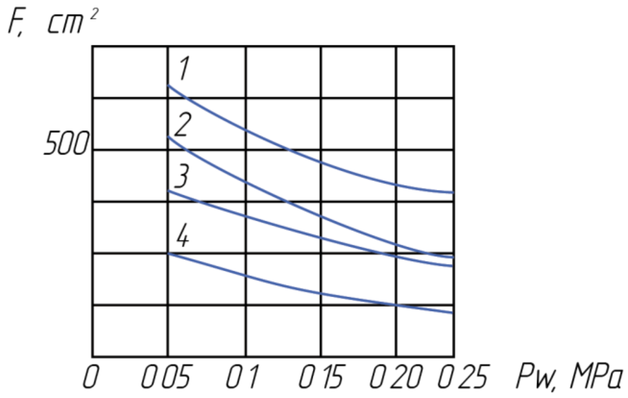

Fig. 1 Changing the contact area (F) depending on tire pressure (P_w) for different loads on the tire (G_T): 1 – G_T = 3000 kg; 2 – G_T = 2000 kg; 3 – G_T = 1500 kg; 4 – G_T = 1000 kg

The above-mentioned makes it possible to conclude that with low or high air pressure in pneumatic tires, the vehicles dynamic and economic qualities are significantly reduced, which leads to an increase in the cost of transportation and the likelihood of road traffic accidents [10-12].

Checking the air pressure in the tire should be carried out: for cars – every 3...5 days; for trucks – once every 8...10 days [13]. However, statistics show that testing by known devices for all types of vehicles is carried out no more than once every 20...30 days. Otherwise, it is carried out visually by crumpling the tire or by pressing the "tire iron on the tire sidewall". However, these methods are highly inaccurate.

Often, driving with reduced tire pressure occurs for quite a long time; the average mileage can reach 2000 kilometers. Reduced pressure in one of the driving wheels leads to a change in the average wheel radius and to the constant operation of the differential, which leads to premature wear of its parts [14].

In addition, a change in the wheel radius reduces the braking performance, which causes drifts, rollovers, and changes in the trajectory of rectilinear movement when cornering [15]. At the same time, most of the currently developed tire inflation devices installed on cars are not automatic. They require manual activation, complicating drivers' activities [16, 17].

Existing research on the creation of automatic systems for maintaining normal tire pressure is aimed at developing complex electronic components. Most researchers suggest installing compressors in their devices [18-21].

Specified circumstances significantly complicate the developed devices design and increase their cost, which limits the possibility of their practical use.

Considering all of the above, the purpose of this research was to create an automatic device for maintaining normal air pressure in the tires using compressed nitrogen, which differs in its simplicity of design.

The following research objectives were defined.

1. Develop a schematic diagram of an automatic device.
2. Obtain dependencies to determine its main design parameters.
3. Make an experimental device and test its workability and efficiency in real conditions.

2. Proposed Methodology

In order to prevent premature tire wear, reduce fuel consumption and improve vehicles directional stability, the authors of this paper carried out theoretical studies, developed an automatic device for maintaining normal air pressure, conducted a series of experiments and processed experimental data (Table 1).

Table 1. Research algorithm

No.	Name of the research phase
1	Theoretical research
2	Development of an automatic device for inflating pneumatic tires with nitrogen
3	Experimental studies
3.1	Determination of the device's workability and efficiency
3.2	Determination of the degree of tire pressure reduction without inflating for a period of 30 days
3.3	Determination of the influence of the developed device on fuel consumption
3.4	Determination of the value of the effort on the steering wheel at various vehicle speeds depending on the tire pressure
3.5	Experimental data processing

After theoretical research, the automatic device for maintaining normal air pressure in the tires using compressed nitrogen was developed.

The first stage of experimental research was to test the proposed device's workability. For this purpose, the UAZ-2206 vehicle with a 4x4 wheel arrangement was used. The car passed tests with mileage of 2000 km in the warm season and in winter conditions.

The degree of tire pressure reduction without inflating was evaluated in the second stage. Tests were carried out for 30 days in a parking lot and while driving

During the third stage, the influence of the developed device on fuel consumption was determined. The test car (UAZ-2206) was moving at the speed of 60...70 km/h along a given route, the length of which was 100 km.

The fourth stage was to determine the value of the effort on the steering wheel at various vehicle speeds depending on the tire pressure.

3. Result Analysis

3.1. Theoretical Research

The theoretical substantiation of an automatic device for maintaining normal tire pressure consists in substantiating the parameters and modes of operation of its most important systems and mechanisms. Let's consider some of them (tire pressure, the ratio of the volume of nitrogen compressed in the device's cylinder to the volume occupied by it in the tire).

Depending on the design features, a range of geometrically similar tires is used to determine the normal tire pressure.

The normal tire pressure can be determined by the following formula:

$$P = k \cdot \frac{\frac{B}{D} \cdot \frac{f}{B}}{\pi \cdot \sqrt{2\chi}\left[\left(\frac{f}{B}\right)^2 - k \cdot a\right]}, \tag{1}$$

where f – tire deflection, mm; B – width of the tire profile, mm; D – tire outer diameter; a – coefficient that has a constant value for a certain type of tire; k proportionality factor ($\boldsymbol{k = \frac{G_T}{B^2}}$, where – G_T load on the tire); χ – the ratio of the tire tread curvature radius Rc to the tire outer diameter D (for trucks, χ = 0.18…0.23 is accepted) [22,23].

This pressure is the sum of the pressures of the injected air P_i in the tire and the nitrogen supplied by the reducer (according to Dalton's law):

$$P = P_i + P_N. \tag{2}$$

The pressure of gaseous nitrogen PN can be determined by the Mendeleev-Clapeyron equation:

$$P_N = \frac{m \cdot R \cdot T}{\mu \cdot V}, \tag{3}$$

where V – tire volume, m^3; m – mass of nitrogen, kg; R – universal gas constant; μ –molar mass of nitrogen; T – temperature, K.

The mass of gaseous nitrogen can be calculated using the equation $\boldsymbol{m = \rho_0 \cdot V_0}$, where ρ0 is the density of nitrogen, kg/cm^3, and V0 is the volume occupied by nitrogen, m^3.

Then, the nitrogen pressure will be:

$$P_N = \frac{\rho_0 \cdot V_0 \cdot R \cdot T}{\mu \cdot V}. \tag{4}$$

For an approximate estimate of the tire volume, the torus volume formula can be used (Figure 2): $\boldsymbol{V = \pi^2 \cdot D \cdot d^2/4}$.

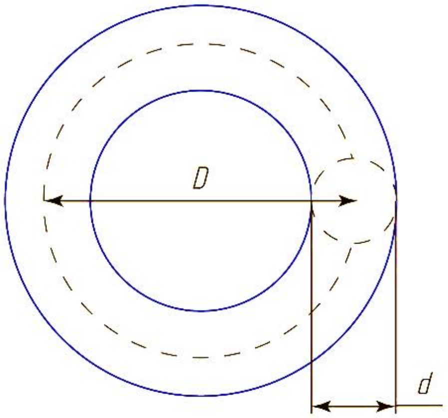

Fig. 2 Scheme for determining the torus volume

Combining equations (1), (2) and (4), we obtain:

$$P_b + \frac{\rho_0 \cdot V_0 \cdot R \cdot T}{\mu \cdot V} = k \cdot \frac{\frac{B}{D} \cdot \frac{f}{B}}{\pi \sqrt{2\chi \cdot \left[\left(\frac{f}{B}\right)^2 - k \cdot a\right]}}. \tag{5}$$

Then, the ratio of the volume of nitrogen compressed in the device's cylinder to the volume occupied by it in the tire will be defined as follows:

$$\frac{V_0}{V} = \frac{\mu}{\rho_0 \cdot R \cdot T} \cdot \left\{ k \cdot \frac{\frac{B}{D} \cdot \frac{f}{B}}{\pi \sqrt{2\chi \cdot \left[\left(\frac{f}{B}\right)^2 - k \cdot a\right]}} - P_b \right\} \tag{6}$$

Equation (6) allows us to estimate the ratio approximately $\boldsymbol{\frac{V_0}{V}}$. It is possible to improve the accuracy of its estimating if we take into account changes in the tire volume during its deformation.

3.2. Structure and Operation of the Device

The proposed device includes (Figure 3): high pressure cylinder 1, filling valve 2, high pressure reducer 3, and locking device 4.

The high pressure cylinder serves as a container for high pressure gas, which enters the pneumatic tire when the air pressure decreases. It can have a different design and configuration (capsule, torus, etc.) and be attached to the wheel disk in various ways.

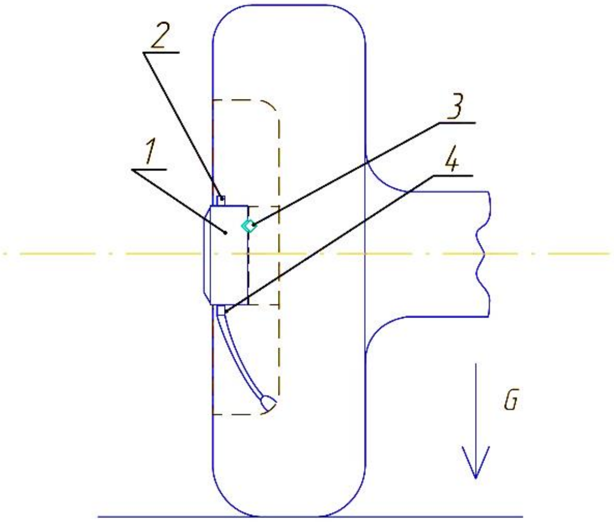

Fig. 3 General view of the automatic device for maintaining normal air pressure in pneumatic tires: 1 – high pressure cylinder; 2 – filling valve; 3 – locking device; 4 – high pressure reducer

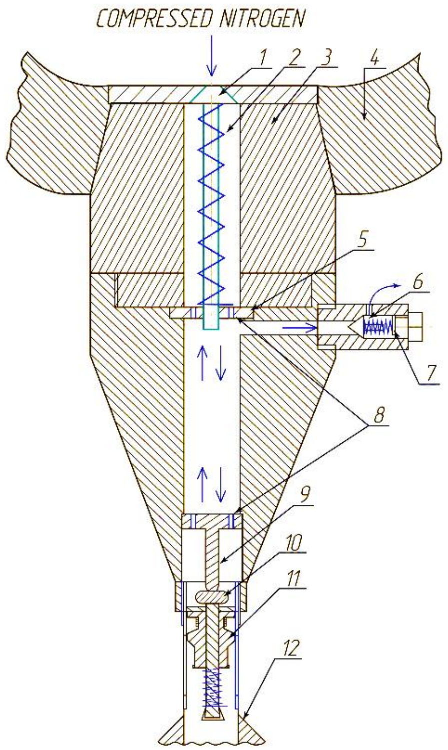

Fig. 4 High-pressure reducer: 1 - cone valve; 2 - cone valve spring; 3 - upper part of the high-pressure reducer; 4 - the wall of the high-pressure cylinder body; 5 - spring stop with holes for gas; 6 – release valve; 7 - spring of the release valve; 8 - holes for air; 9 - tappet; 10 – slide-valve head; 11 - slide-valve; 12 – valve

The filling valve is used to fill the high-pressure cylinder with nitrogen. The high pressure reducer (Figure 4) is a mechanism for bypassing gas from a high pressure cylinder through a gas pipeline (air duct) into a pneumatic tire when the air pressure is reduced. The release valve with a spring reduces the tire pressure when exceeded.

When the tire pressure is reduced, cone valve 1, overcoming the resistance of spring 2, goes down. At the same time, it opens the opening of the main air duct. High-pressure gas, entering the main air duct, passes through the slide-valve 11 and, expanding, fills the volume of the pneumatic tire. After the air pressure in the pneumatic tire returns to normal, the cone valve closes.

When the tire pressure is exceeded, release valve 6 opens, playing off the excess air to normal pressure; in case of dynamic tire impacts, or when the center of gravity shifts on slopes or corners, when braking, an instantaneous increase in tire pressure can occur.

3.3. Experimental Studies

To test the proposed automatic device for inflating pneumatic tires, the UAZ-2206 vehicle with a 4x4 wheel arrangement was used. The car, before the tests, passed maintenance No. 2. Tire mileage was about 7000 km. Type of tire – universal.

Cylinders with compressed nitrogen were installed using locking devices on all wheel hubs. Previously, each tire had a different pressure. The left front – 0.22 MPa; the right front – 0.18 MPa; the left rear – 0.15 MPa; the right rear – 0.25 MPa. 5-10 minutes after installation of the developed automatic device, the pressure in each tire was measured again with a pressure gauge. It was found that the operation of the device ensured that the tire pressure was brought into line with the manufacturer's standards.

The car passed tests with a mileage of 2000 km. Every 100 km, the tire pressure was checked. It was also checked in the warm season after running 50 km at a relatively high speed on a dirt or rocky road, when the tire temperature was significantly higher than in normal conditions and ranged from 70 to 80 °C.

The workability of the proposed automatic device was also tested in winter conditions. These tests were carried out to determine the possibility of freezing of the air entering (exiting) through the device’s valves during parking and while driving.

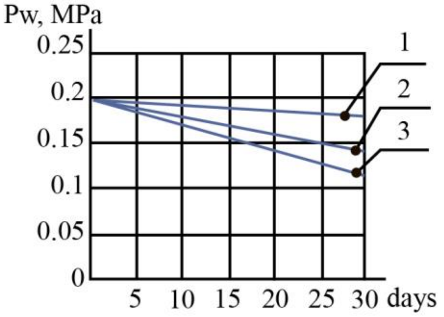

Fig. 5 Reduction of the pressure P_W in the pneumatic tires of the UAZ-2206 car front wheels for a period of 30 days (without inflating): 1 - tire pressure reduction in the parking lot; 2 - pressure reduction in the tires of unladen UAZ-2206 car (average daily mileage 80 km); 3 - pressure reduction in the tires of laden UAZ-2206 car (average daily mileage 80 km)

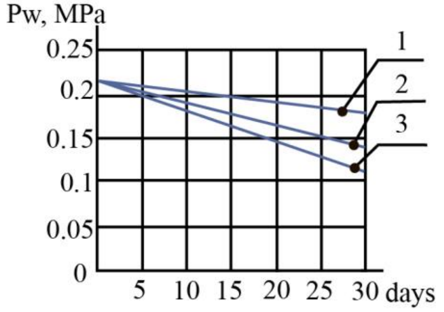

Fig. 6 Reduction of the pressure P_W in the pneumatic tires of the UAZ-2206 car rear wheels for a period of 30 days (without inflating): 1 - tire pressure reduction in the parking lot; 2 - pressure reduction in the tires of unladen UAZ-2206 car (average daily mileage 80 km); 3 - pressure reduction in the tires of laden UAZ-2206 car (average daily mileage 80 km)

Tests also took place directly in the parking lot. The averaged results of 20 UAZ-2206 vehicle tests are shown in Figure 5 and Figure 6. From the graphs, it can be seen that the pressure in the pneumatic tires without inflating them for 30 days decreases on average by 0.05 ... 0.07 MPa.

Also, according to the Research Institute of Tire Industry, a decrease in tire pressure by 0.05 MPa leads to an increase in fuel consumption by 4.5%, and a decrease in pressure to 0.1 MPa increases fuel consumption by 10 ... 12% (on hard roads).

In order to refine these data, experimental studies were carried out to determine fuel consumption.

Experimental studies were carried out in 3 stages. In the first stage, the air pressure in all tires of the UAZ-2206 vehicle was measured. The measurement showed that the air pressure in the rear axle wheels corresponded to the norm and amounted to 0.21 MPa. In the front axle wheels, the deviation from the norm was revealed and amounted to 0.17 MPa and 0.19 MPa in the left and right wheels, respectively, which is 19.04% and 9.52% below the norm.

The test car was moving at the speed of 60...70 km/h along a given route, the length of which was 100 km. As a result of the tests, it was found that the fuel consumption per 100 km of run was about 19 liters.

In the second stage of experimental studies, the pressure in all tires of the same UAZ-2206 vehicle was measured again, and in those tires, the air pressure did not meet factory standards; it was brought to the normal value.

The test vehicle was sent along the same route. As a result, it was found that the fuel consumption of the UAZ-2206 car with tire pressure brought to normal was 17 ... 18 liters per 100 km of run, which is 5 ... 11% lower on average than in the previous test.

Experimental studies have confirmed the Research Institute of Tire Industry data on the effect of tire pressure on vehicle fuel consumption.

The third stage of experimental research was carried out on the UAZ-2206 vehicle equipped with a developed device (Figure 7). Before testing, the air pressure in the tires was also measured. The measured pressure was normal in all tires.

The car was tested on the same route. As a result of experimental studies, it was found that fuel consumption per 100 km of run was 17 ... 17.5 liters.

The obtained data were processed, and a graph of fuel consumption against the tire pressure was plotted (Figure 8).

Fig. 7 Automatic device for maintaining normal tire pressure installed on the UAZ-2206 car

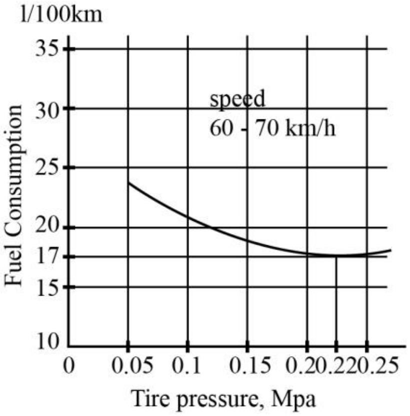

Fig. 8 Changing the fuel consumption depending on the tire pressure of the UAZ-2206 car

The graph shows that a decrease in air pressure in pneumatic tires leads to an increase in fuel consumption.

We also conducted research to determine the value of the effort on the steering wheel at various vehicle speeds.

The obtained results (Figure 9) showed that a decrease in tire pressure of one of the steerable wheels by 0.1 MPa leads to an increase in the effort on the steering wheel by more than 15% on average. This, in turn, increases the degree of operator fatigue, negatively affects the vehicle's directional stability and causes it to skid when cornering [24-26].

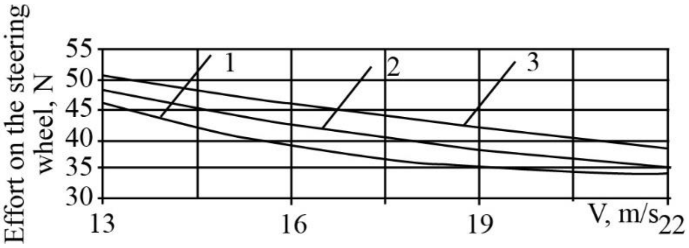

Fig. 9 Changing the effort on the steering wheel depending on the vehicle speed: 1 - normal pressure in all tires; 2 – tire pressure in one of the steerable wheels, reduced by 0.05 MPa; 3 – tire pressure in one of the steerable wheels reduced by 0.1 MPa

4. Conclusion

It is concluded that the system can operate in automatic mode sequentially. After venting through the release valve, the cone valve opens, equalizing the pressures in the pneumatic tire and the high pressure cylinder.

The developed automatic device makes it possible to maintain a normal level of tire pressure and, thereby, prevents premature tire wear, improves the safety of drivers and passengers, as well as improves the vehicle's grip and braking performance and reduces fuel consumption.

Inflating tires with compressed nitrogen also has a number of additional benefits. Oxygen passes through the tire walls 30-40% faster than nitrogen, and leakage continues until the partial pressure in the tire equalizes. If the oxygen content in the tire does not exceed 5 ... 6% for cars and 2 ... 3% for trucks, then the ratio of gas pressure inside and outside the tire will be balanced, and there will be no leakage. In addition, filling (pumping) tires with nitrogen make it possible to reduce tire heating at high speeds, the likelihood of a tire "explosion", and improve its cushioning properties and grip. At the same time, the fact that the nitrogen content in the atmospheric air is at least 78% and there is no point in additionally pumping another 12% is not a pure disadvantage of the considered method.

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