UDC 629.01 DOI: 10.30977/AT.2019-8342.2022.50.0.01

Indirect assessment of the rolling resistance of a car tire in the starting mode of motion

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Abstract. Problem. *On the condition of the tires and their correct choice depending on the weather conditions, first of all, the indicators of many operational properties of the car depend. The internal pressure and temperature of the tire increases during driving, as a result, there is a significant effect on the rolling resistance of the tire. At high values of the rolling resistance coefficient, first of all, fuel consumption increases, tire wear increases, etc. It is important to know how the rolling resistance coefficient changes during the starting period of motion.* ***Goal.*** *The purpose of this work is to determine the starting mode of motion time for specific vehicles. Based on the obtained dependences of the internal pressure and temperature of the tire on time, it is necessary to evaluate how the rolling resistance coefficient changes.* ***Methodology.*** *As a result of experimental studies, on vehicles equipped with tires of various sizes and seasonality, the dependences of the pressure and temperature of the tire material at three points (tread zone, shoulder part and sidewall) were obtained. Using the results of the experiment, as well as based on the dependencies presented in scientific papers devoted to the study of the performance characteristics of car tires, an indirect assessment of the rolling resistance coefficient when driving in the starting mode is made.* ***Results.*** *The value of the increase in the internal pressure of the gas filler in the tire has been established and the driving time for the studied vehicles in the starting mode has been determined. The most intense temperature rise is observed in the shoulder area of the tires. The temperature of the surface layer of winter tires increases less than summer tires, and, accordingly, driving on winter tires is safer at temperatures close to 0°C and below.* ***Originality.*** *A technique for indirectly assessing the rolling resistance of a car tire when driving in the starting mode (on "cold" tires) is presented, that is, knowing how the internal air pressure and tire temperature change, it is possible to predict a change in the rolling resistance coefficient.* ***Practical value.*** *Using the dependences obtained as a result of an indirect assessment of the rolling resistance of car tires, one can judge the value of the rolling resistance coefficient without resorting to experiments. The well-known assertion that it is necessary to timely replace summer tires with winter ones (when the ambient temperature can reach +5 ° C and lower) is confirmed, thereby significantly improving road safety.*

Key words: *car tire, starting mode, rolling resistance, internal pressure, tire temperature, stabilization, safety, pressure monitoring.*

Introduction

Rolling resistance, along with such important tire performance characteristics as road grip, internal gas filler pressure, temperature, resource, hydroplaning resistance ability, load capacity, plays a key role in road safety [1,2]. Unfortunately, thousands of traffic accidents occur on the roads every year. For example, in the period from 01/01/2021 to 09/30/2021, according to official data, 154,480 accidents occurred, which is 13.9% more than in the same period of 2020. Of these, 24905 were injured and 2592 were dead [3]. Naturally, the causes of such a number of accidents are many different factors. First of all, it all depends on the skills and abilities of the driver. Also now there is an active fight against violations of traffic rules, in particular with violations of the speed limit, which can partially improve the situation. But do not forget about maintaining the good technical condition of vehicles and road surfaces. From the condition of the tires and their correct choice depending on the weather conditions, first of all, the indicators of many operational properties of the car depend. An important role is played by the internal pressure in the tire, which must be maintained within the limits recommended by the manufacturers. In some works devoted to the study of the performance characteristics of car tires, as a result of experiments, it was found that when driving at speeds up to 50 km/h, the rolling resistance coefficient changes slightly [4]. But after all, when operating cars in the urban cycle, the speed of movement, in general, does not exceed 60 km / h. During the starting movement of the car, the filler pressure and tire temperature change [5]. If pressure and temperature change, then the coefficient of rolling resistance changes accordingly.

It is especially important to monitor the pressure during the period when the average daily temperature can fluctuate between -5 and +5°C. At this time, the tire pressure may deviate from the standard values by about 20% [5]. Regulatory pressure means exactly the pressure that the manufacturer recommends, of course it depends on many different parameters and, above all, on the load on the car. It is quite clear that, in addition to filler pressure, rolling resistance depends on many other factors, such as wheel speed, weather conditions (ambient temperature and humidity), road surface conditions, etc. The right combination of these parameters helps to increase the efficiency of vehicle operation and, first of all, road safety. In this work, attention is focused primarily on the effect of gas filler pressure and tire temperature on rolling resistance. Knowing, for a particular case of car operation, the range of changes in the tire rolling resistance coefficient in the starting period, one can also judge the performance properties of the car.

Analysis of publications

The issue of studying the rolling resistance of a car tire does not lose its relevance. At the moment, many scientific papers devoted to the study of this issue have been published. The authors often focus on the influence of the most important characteristics for each specific case (depending on the type of vehicle and its operating conditions).

For example, in [6], the methodology and results of experimental studies are given to determine the rolling resistance force of transport and technological machines in road conditions, where the main goal is to reduce the level of impact of running systems on the soil.

In [7], the time dependences of the temperature and internal air pressure in an oversized tire are studied. Tires of this type operate under conditions of high loads, incommensurable compared with the tires of passenger cars that we are considering. Nevertheless, the results obtained in [7] show that the rate of temperature rise is much higher than the rate of pressure rise. Further, it will be possible to compare these conclusions with the results obtained in our work for passenger car tires.

The authors of [8] estimate the coefficient of wheel rolling resistance according to the diagram of the specific load in the zone of contact with the road. Thus, a new method for estimating the rolling resistance coefficient is presented and theoretical studies of its compatibility with the previously known method developed by the authors are carried out.

The work [9] is aimed at studying the factors affecting the change in gas pressure in tires and predicting it during the operation of the Gazelle car. To predict the pressure (p) in a rolling tire, this paper uses the approximate formula of V.I. Soroko-Novitsky (1):

$$p = \frac{p_0}{T_0}\left(\frac{G_k \cdot f \cdot V}{12900 \cdot k \cdot D_c \cdot B} + 273\right), \qquad (1)$$

where p_0 – pressure in the tire, which is stationary, before the start of movement, MPa; T_0 – temperature in the tire, which is stationary, before the start of movement, К; G_k – tire load, Н; V – tire rolling velocity, m/s; D_c – middle tire diameter, m; B – tire profile width, m; k – heat transfer coefficient from the tire surface; W/(m²·К); f – rolling resistance coefficient.

All components of this empirical dependence are quite obvious, difficulties can arise only with the heat transfer coefficient from the tire surface, in fact, this value characterizes how the heat flux density changes with a temperature difference of 1 K. In reality, it is not always constant and may even depend on the temperature difference. If we consider the heat flux as a vector, then it is directed perpendicular to the area of the surface through which it flows [10]. Approximate values of this coefficient in the case of interaction of the tire with the road surface – 110 W/(m²·К) [11].

In this expression, the pressure is directly proportional to the coefficient of rolling resistance. It can be said that if the car is driving on a road with a “large” rolling resistance coefficient, for example, on a dirt road, then the tire pressure will be greater than if the car is driving on an asphalt-concrete road, where the rolling resistance is lower. That is, in this formula, to predict tire pressure, the drag coefficient takes into account the condition of the road surface on which the car will move. It is also worth noting that this dependence is not a function of time. That is, using this formula, it is possible to determine only a certain amount of pressure that will be achieved in a tire with a diameter *D*, profile width *B*, tire load G_k, after a certain period of driving at a constant velocity *V*, on a road with a rolling resistance coefficient *f*.

In [12], for an approximate determination of the rolling resistance coefficient *f* in cars, depending on the velocity of their motion, the following empirical formulas (2), (3) are recommended:

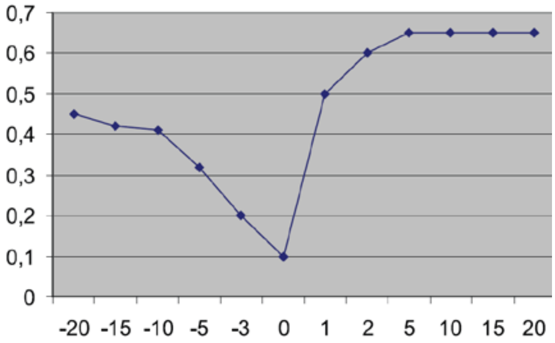
$$f = 0,001\left[5,1 + \left(\frac{5,5 + 18G_k}{p} + \right.\right.$$
$$\left.\left. + \left(\frac{8,5 + 6G_k}{p}\right)\frac{V^2}{10000}\right)\right]; \qquad (2)$$

$$f = \frac{0,019}{\sqrt[3]{p^2}} + \frac{2,45 \cdot 10^{-3}}{\sqrt{p}}\left(\frac{V}{100}\right)^2 +$$
$$+ \frac{0,0042}{\sqrt[3]{p^4}}\left(\frac{V}{100}\right)^3, \qquad (3)$$

where *p* – tire pressure, kg/cm²; G_k – wheel force on the road, t; *V* – tire rolling velocity, km/h.

Dependence (2) is called the Claue and Cloy formula, and (3) the Michelin formula. In these formulas, tire pressure and rolling resistance are inversely related. This phenomenon is quite obvious, because at lower values of internal pressure, tire deformations increase, and as a result, the rolling resistance of the tire increases. It is also worth paying attention to the fact that in dependence (2) the rolling resistance coefficient is a function of three variables - G_k, *V* and *p*. In expression (3), the drag coefficient depends only on the speed and internal pressure of the filler in the tire (load is not taken into account).

The performance of car tires is highly dependent on weather conditions. In [13], a study was made of the influence of the coefficient of adhesion of bus tires with a road surface on the value of the total braking distance under various weather conditions. The paper presents the results of experimental studies on measuring the stopping distance at different ambient temperatures. The following results were obtained: at an ambient air temperature of - 27°C, the full braking distance was 28 m, at a temperature of -21°C, 18 m, and at a temperature of +2°C, 32 m [13]. In the work under consideration, the dependence of the tire adhesion coefficient on the road surface temperature was also obtained (Fig. 1), which in turn directly depends on environmental conditions (air temperature and humidity).



Road temperature, °C

Fig. 1. Effect of road temperature on grip coefficient [12]

It can be seen from the figure that the coefficient of grip of tires with the road has the lowest performance at temperatures close to 0°C. In Ukraine, according to [14], temperatures ranging from -5 to 5°C are observed from October to April. We can say that about 180 days a year the average daily temperature fluctuates in the range of temperatures that have the most unfavorable conditions, i.e. grip properties of tires have the worst performance.

Purpose and Tasks

The purpose of this work is to determine the range in which the values of the internal pressure and temperature of the tire can change during operation, in particular, in the starting movement mode. Based on the obtained values of internal pressure and temperature, using the dependencies given in other scientific papers, it is possible to make an indirect assessment of the rolling resistance of a car tire. It is also necessary to compare the results obtained during the experiments with the results obtained in the works that are considered in the analysis of the literature. Based on the analysis carried out, it is necessary to obtain recommendations, following which it is possible to ensure traffic safety under various operating conditions.

To achieve this goal, it is necessary to conduct experimental studies under weather conditions that are most conducive to changing the air pressure and tire temperature (the period of the year when the ambient air temperature ranges from -5°C to +5°C). It is also of interest to conduct research using vehicles equipped with tires of various sizes, as well as seasonality (winter/summer).

Experimental studies of changes in the internal pressure and temperature of the tire in the starting movement mode

The purpose of the experiments is to obtain the dependences of tire pressure and temperature on the time of movement in the starting period, using the results obtained, it is possible to evaluate how the rolling resistance of a car tire changes in the starting mode of movement.

Tire pressure and temperature changes were studied on technically sound Lexus RX 300 and Lexus RX 450h vehicles equipped with 235/60R18 and 235/55R20 summer tires, respectively. All experimental races were carried out on a general purpose track, which has two lanes in each of the directions, separated by a safety island. Thus, the tests were carried out without interfering with the movement of other vehicles, but at the same time under normal conditions and with the ability to maintain a stable speed limit within the city.

In view of the fact that the experiments should be carried out on cold tires, the pressure in the test tires was set to the standard value in the evening, at a temperature of 20°C (indoors). For the Lexus RX 300, the standard pressure corresponds to - 0.21 MPa, for the Lexus RX 450h - 0.24 MPa. The cars were then left on the street. The experiment itself was carried out in the morning, after a 10-hour parking of the vehicles under study.

At the beginning, studies were carried out with a Lexus RX 300 car. The experiment was carried out at an ambient air temperature of 1°C, humidity was 81%. Before carrying out the research, the temperature and internal pressure in all tires were measured. The pressure in all tires of the car was 0.18 MPa, the tire temperature was -1°C. The negative value of the temperature can be explained by the fact that at night the air temperature in the street was in the range from -2 to 1°C.

The change in air pressure in the tire and the average temperature of the gas filler was carried out using external sensors mounted on the wheels. And also for control every 20 minutes, measurements of the internal pressure and temperature of the tires were made. The pressure was measured using an electronic pressure gauge, the temperature of all tires was measured in the tread, shoulder and side areas, points A, B, C (Fig. 2, 3).

The tire pressure was set at a value of 0.21 MPa, after about 25-30 minutes. Tire temperatures are shown in table 1.

The experiment on a Lexus RX 300 car was also carried out under other environmental conditions: the temperature was 5°C, humidity 75%. It is also important to note that the initial temperature and tire pressure were different from the first experiment. The tire temperature was 5°C, the internal pressure was 0.2 MPa.

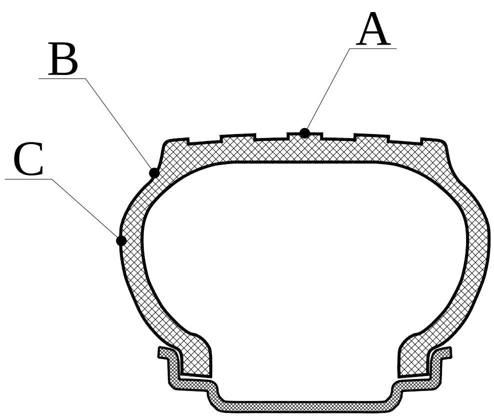


Fig. 2. Points at which the surface layer temperature was measured

Further studies were carried out on a Lexus RX 450h car equipped with summer tires - 235/55R20. During the experiment, the ambient temperature was 6°C, humidity 78%. After overnight parking, the pressure in all tires was 0.22 MPa, the temperature of the tires was 3°C. Tire pressure and temperature checks were also taken every 20 minutes. The tire pressure was set at 0.24 MPa after 25-30 minutes. The results of temperature measurement are shown in Table 1.

Fig. 3. Measurement of temperature in the tread and shoulder zone using a non-contact thermometer

In the autumn-spring period, when the ambient temperature can range from -5°C to +10°C, cars are usually equipped with different tires (summer or winter). It all depends on car owners, some change summer tires earlier, some drivers when the average daily temperature drops below 0. In order for the results obtained in this paper to be useful both for drivers whose cars are equipped with winter tires, and for those who uses summer tires, the experiment was once again carried out on a Lexus RX300 equipped with winter tires. The ambient temperature during the experiment was 0°C, humidity - 79%. The temperature measurement results are shown in Table 1.

Table 1. Tire temperature measurement results (°C)

Time, min	Lexus RX300									Lexus RX 450h		
	235/60R18 (summer tires) at a temperature 1°C			235/60R18 (summer tires) at a temperature 7°C			235/55R18 (winter tires)			235/55R20 (summer tires)		
	A	B	C	A	B	C	A	B	C	A	B	C
start	-1	-1	-1	7	8	9	0	-1	-1	3	3	3
20	16	22	14	21	22	19	9	15	10	20	21	15
40	17	20	16	22	23	20	13	14	13	21	23	17
60	17	20	17	21	23	18	12	13	11	22	23	28

The highest temperature is observed in the shoulder area of the tire, which is confirmed in [2, 11].

Below is a graph of temperature changes in the shoulder area for all experimental studies (Fig. 4).

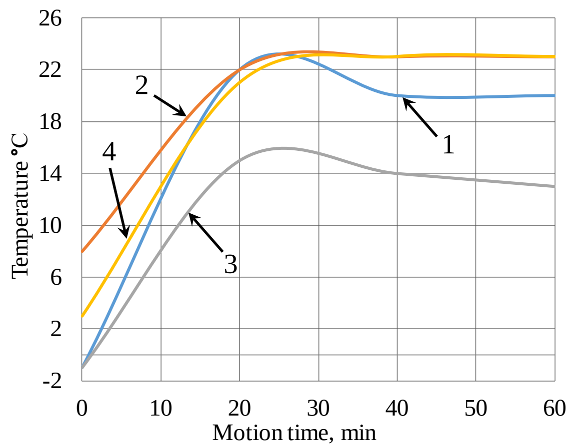


Fig. 4. Graph of the change in the temperature of the surface layers in the shoulder area of the tire during the starting mode motion: 1 – 235/60R18 (summer tires) 1°C; 2 – 235/60R18 (summer tires) 6°C; 3 – 235/55R18 (winter tires) 1°C; 4 – 235/55R20 (summer tires) 1°C

From the analysis of this figure, we can conclude that the least intense temperature increase is observed precisely in the winter tire 235/55R18. That is, the well-known statement is confirmed that a winter tire is more resistant to operation at low ambient temperatures, since the temperature of its surface layer reaches the operating temperature faster, and accordingly, all performance properties that directly depend on temperature indicators reach their standard values faster.

Based on the results obtained, it can be argued that it is necessary to timely replace summer tires with winter ones. Since driving on winter tires during the period when the ambient temperature can reach values from + 5°C to -5°C and lower is safer. Moreover, in some countries there are paragraphs of traffic rules that indicate if the average daily ambient temperature drops below a certain value, then it is necessary to replace summer tires with winter ones.

Also in fig. 4 shows that over time the temperature of the surface layers of the tire stabilizes, which coincides with the conclusions made in [5].

As a result of experimental studies, it was found that the temperature of the surface layer of summer tires during operation in the autumn-spring period stabilizes after about 30-40 minutes of motion.

Evaluation of the rolling resistance of a car tire by changing the internal pressure and temperature of the tire during the starting mode motion

Using formula (2) given in the literature review, one can obtain a graph of the dependence of the rolling resistance coefficient on the internal pressure in the tire (Fig. 5). Let us represent expression (2) given in [12] in the following form:

Next, we obtain the dependence of the rolling resistance coefficient of the vehicle under study on the change in the internal pressure of the gas filler in the tire. When plotting the graph, the wheel pressure force on the road is assumed to be constant - 5000 H, velocity - 16.67 m/s (60 km/h).

$$f = 0{,}001\left[5{,}1 + \left(\frac{5{,}5 + 18\cdot\dfrac{G_k}{10^4}}{\dfrac{100}{g}\cdot p} + \left(\frac{8{,}5 + 6\dfrac{G_k}{10^4}}{\dfrac{100}{g}\cdot p}\right)\frac{(3{,}6\cdot V)^2}{10000}\right)\right], \qquad (4)$$

where p – tire pressure, MPa; G_k – wheel force on the road, H; V – tire rolling velocity, m/s; g – acceleration of gravity, m/s^2.

From fig. 5 shows that with increasing pressure, the coefficient of rolling resistance decreases. This is explained by the fact that with a reduced internal pressure in the tire, the area of the contact patch with the supporting surface increases, as a result of which more energy is spent to overcome rolling friction.

During the experimental studies described earlier, it was found that the pressure in the summer tires of the Lexus RX 300 increased from 0.18 MPa to 0.21 MPa. On fig. 5, a pressure of 0.18 MPa corresponds to a rolling resistance coefficient of 0.0153, and a pressure of 0.21 MPa corresponds to 0.0138.

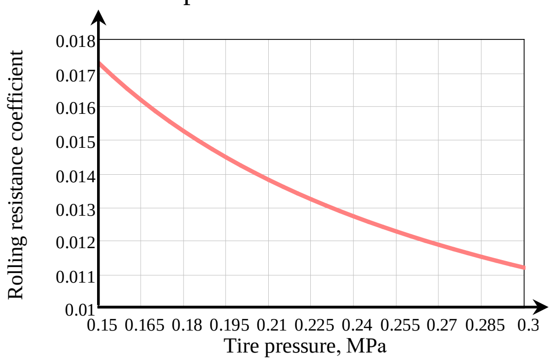


Fig. 5. The dependence of the coefficient of rolling resistance on the internal pressure of the gas filler in the tire

The paper [12] also shows the dependence of the rolling resistance coefficient on the internal pressure in the tire (3). Below are the dependences of the rolling resistance coefficient on internal pressure (Fig. 6).

Expression (3) does not take into account the load on the wheel. Accordingly, the formula is not valid for all cars, but only for vehicles of certain weight categories. From Fig. 6, we can conclude that expression (3) is valid only for small cars, the weight of which is approximately 1 - 1.2 tons.

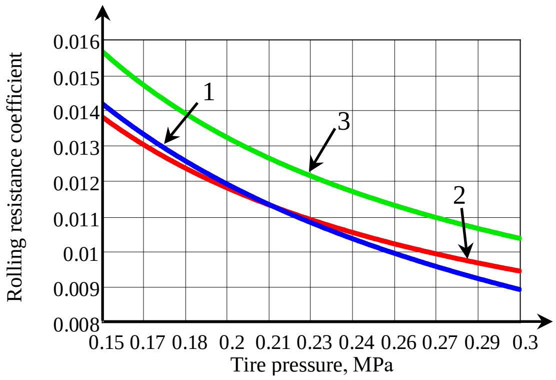


Fig. 6. The dependence of the rolling resistance coefficient on the internal pressure of the gas filler in the tire: 1 – without taking into account the load on the wheel; 2 – wheel load 2500 H; 3 – wheel load 4000 H

The paper [15] presents the dependence of the rolling resistance coefficient on the temperature in the shoulder area (Fig. 7).

From the analysis of Fig. 7, we can conclude that with an increase in temperature, the coefficient of rolling resistance decreases. As you know, a hot tire has high performance indicators, so driving on a hot tire is safer [5]. Using the graph (Fig. 7), one can also indirectly judge the rolling resistance of a tire.

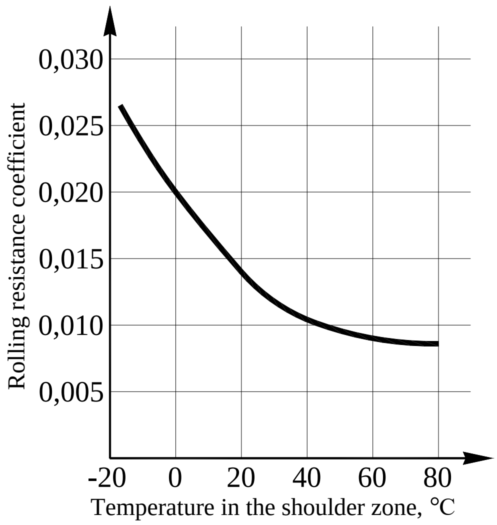


Fig. 7. The dependence of the coefficient of rolling resistance on the temperature in the shoulder zone [13]

A temperature of 0°C corresponds to a rolling resistance coefficient of approximately 0.016. As a result of the experiments, it was found that the temperature in the shoulder area of the tires increases to about 20°C, this temperature value on the graph corresponds to a coefficient of 0.014. The difference between the rolling resistance coefficient readings is approximately 15%. The results of an indirect assessment using a change in temperature in the shoulder zone practically coincide with the results of an assessment through a change in the internal pressure of the gas filler.

Conclusion

The paper provides a review of the literature devoted to the study of the relationship between the performance characteristics of a car tire. Descriptions of experimental studies are given, during which the dependences of the internal pressure and temperature of the tire on the time of movement in the starting movement mode are established. The experiments were carried out on vehicles equipped with tires of different sizes and seasonality. It is found that the internal pressure and temperature of the tire is increased by about 15%. On the basis of the dependences given in the literature, a graph of the change in the rolling resistance coefficient from the internal pressure in the tire was constructed. An indirect assessment of the rolling resistance of a car tire during the starting period of movement was made, as a result of which the following conclusions can be drawn:

— the internal pressure and temperature of the surface layers of the tire, in the starting movement mode, stabilizes after about 20-30 minutes of uniform movement, respectively, during this time it reaches the most optimal values and the rolling resistance coefficient;

— the rolling resistance coefficient during the starting movement changes by about 15%;

— winter tires, at an ambient temperature of +5 ° C and below, adapt to operation faster than summer tires. This is supported by studies where the surface temperatures and inflation pressures of winter tires stabilize over a shorter period. But it should be noted that this applies only to the starting period of the car's movement. Therefore, it is important to timely replace summer tires with winter ones, which entails an increase in all performance characteristics, and most importantly, road safety.

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Непряма оцінка опору коченню автомобільної шини в режимі стартового руху

Анотація. Проблема. *Від стану шин та правильного їх вибору залежно від погодних умов, насамперед, залежать показники багатьох експлуатаційних властивостей автомобіля. Внутрішній тиск і температура шини збільшуються в процесі руху, внаслідок чого здійснюється значний вплив на опір коченню шини. При високих значеннях коефіцієнта опору коченню насамперед збільшується витрата палива, підвищується знос шини і т.д. Важливо знати, як змінюється коефіцієнт опору коченню в стартовий період руху.* ***Мета.*** *Метою даної роботи є визначення часу стартового руху для конкретних автомобілів. За допомогою отриманих залежностей внутрішнього тиску і температури шини від часу необхідно оцінити, як змінюється коефіцієнт опору коченню.* ***Методологія****. В результаті проведення експериментальних досліджень, на автомобілях, оснащених шинами різних типорозмірів та сезонності, отримані залежності тиску та температури матеріалу шини у трьох точках (протекторна зона, плечова частина та боковина). Використовуючи результати експерименту,* *а також ґрунтуючись на залежностях, представлених у наукових працях, присвячених вивченню експлуатаційних характеристик автомобільних шин, проводиться непряма оцінка коефіцієнта опору коченню під час руху у стартовому режимі.* ***Результати.*** *Встановлено величину приросту внутрішнього тиску газового наповнювача у шині та визначено час стартового руху для досліджуваних автомобілів. Найбільш інтенсивне зростання температури спостерігається в плечовій зоні шин. Температура поверхневого шару зимових шин збільшується менше ніж літніх, відповідно рух на зимових шинах є більш безпечним при температурах близьких до 0ºC і нижче.* ***Оригінальність.*** *Представлено методику непрямої оцінки опору коченню автомобільної шини під час руху у стартовому режимі (на «холодних» шинах), тобто, знаючи, як змінюється, внутрішній тиск повітря і температура шини, можна прогнозувати зміну коефіцієнта опору коченню.* ***Практичне значення.*** *Використовуючи залежності, отримані в результаті непрямої оцінки опору коченню автомобільних шин, можна судити про величину коефіцієнта опору коченню, не вдаючись до експериментів. Підтверджується загальновідоме твердження, що необхідно проводити своєчасну заміну літніх шин на зимові (коли температура довкілля може досягати +5ºC і нижче), цим можна значно підвищити безпеку дорожнього руху.*

Ключові слова: *автомобільна шина, стартовий режим, опір коченню, внутрішній тиск, температура шини, стабілізація, безпека, моніторинг тиску.*

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