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The influence of inflation pressure and ambient temperature on the value of the truck tires rolling resistance

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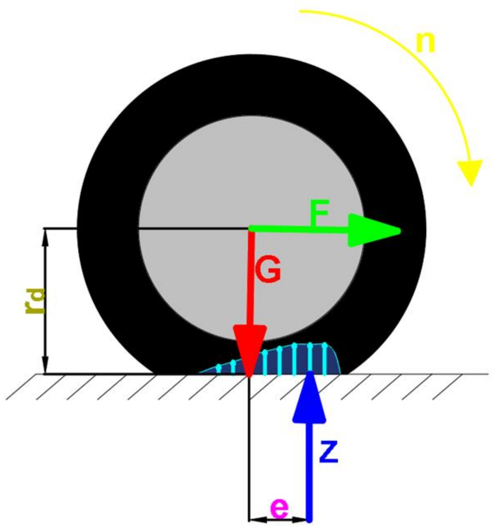
The article discusses the effect of inflation pressure and the ambient temperature on the value of the rolling resistance of truck tires which directly translates into fuel consumption. For this purpose, a series of measurements was made at two ambient temperatures (at 25°C and -15°C), using different pumping pressures.

Słowa kluczowe: truck tires, rolling resistance, fuel consumption.

Wstęp

Rolling resistance of car tires is one of the most important parameters describing the cooperation of a tire with a road surface. It has a direct impact on the energy consumption of a moving vehicle, the emission of toxic compounds into the atmosphere (such as NH_3, CO_2 or NO_2), and its performance, such as maximum speed, acceleration or maximum range. The high value of rolling resistance also increases the tire temperature, which accelerates the aging process and reduces mechanical strength. Rolling resistance is one of the basic motion resistance (along with air resistance, elevation and inertia). Depending on traffic conditions, a 10% reduction in rolling resistance results in a 2-4% reduction in fuel consumption. [1,2,3].



$$f_t = \frac{e}{r_d}$$

Fig. 1. Diagram of the forces acting on the rolling car wheel (own material)

Rolling resistance is the force that resists the movement of a body rolling on a horizontal surface. While ISO 28580: 2018 defines rolling resistance as energy loss (or energy consumption) per unit of distance traveled [4]. However, the rolling resistance coefficient is more commonly used, which is the ratio of the vertical displacement value of the ground reaction e to the dynamic radius of a rolling wheel (Figure 1). Rolling resistance of car tires results directly from energy losses arising during the cyclical deformation of the tire structure during pressures occurring on the track of contact with the surface. Sagging the tire requires some work that must be delivered to the system from the vehicle side. The materials used to manufacture tires are characterized by a significant hysteresis, which means that the amount of energy used to deform the tire is greater than the amount of energy returned when the tire returns to its original shape. The vast majority of energy lost by the vehicle as a result of rolling resistance is converted into heat. The remaining, much smaller part of energy is converted into acoustic energy as well as permanent deformation of the surface and abrasion of the tire. Resistance is generated by deflections of the tire support structure (tread belt, sidewalls) and by deformations of the tread elements [3]. Part of rolling resistance also results from surface deformations.

Rolling resistance of car tires is conditioned by factors such as [2]:

– Tire structure (width, height, rim diameter, pattern and depth of the tread pattern, number of cord layers and material it is made of, banding material, type of rubber compound). For example wide base truck tires exhibit significantly lower rolling resistance thant conventional ones [13].
– Movement conditions, (wheel loads, tire pressure, tire temperature, rolling direction, rolling speed).
– Road surface, (type, texture, stiffness and technical conditio).

1.Rolling resistance measurement methods

1.1.Road methods

Road and laboratory methods are used to measure rolling resistance. In road conditions, two measurement methods are used: trailer and coast down. The first methods is based on the use of a special test trailer towed by a car. There are only a few research trailers in the world that perform measurements in road conditions. Examples are two trailers built and used for research at the Technical University of Gdansk (eg. R2Mk.2 trailer, Fig.2). They use a measuring system based on a vertical swing arm that aims to compensate for the horizontal component of the vertical force loading the measuring wheel. Moreover there is used a mechanical system which eliminates the influence of the road inclination and the acceleration [5]. The swingarm measurement system and the system determining the position of the trailer relative to the surface are based on high-quality lasers.

The second of road methods, coast down method, consists in accelerating the test vehicle to a specific speed, and then disconnecting the drive. During coast down, parameters such as speed and distance are recorded as a function of time until the vehicle comes to a stop. The data obtained in this way are used in calculations involving the solution of vehicle motion equations, which results in rolling resistance. This method is quite troublesome to use due to the need to know parameters such as the aerodynamic factor of the vehicle, frontal section, vehicle mass, moments of inertia of rotating elements connected to the wheels and energy losses in the drive components coupled to the wheels of the vehicle. In addition, the wind speed and direction should also be recorded during the measurement (at the place where the vehicle is currently located). In order to eliminate the influence of the slopes of the tested section, the measurement should be made in both directions (which is not always possible) [3].

Fig. 2. R2 Mk.2 trailer for measuring the rolling resistance coefficient of tires and pavement [11]

1.2. Laboratory methods

For laboratory methods, due to ISO standard recommendations (ISO 18164: 2005 Passenger car, truck, bus and motorcycle tires - Methods of measuring rolling resistance), roadwheel facilities with an external steel surface are most often used to measure rolling resistance (or Safety Walk surface, i.e. a tape containing mineral particles attached with a polymer to a plastic film) [3,4]. Sometimes replicas of real road surfaces made of reinforced laminates or other materials with the original surface texture are also used. This method is characterized by high measurement accuracy, repeatability of results and control of measurement conditions The disadvantages include the time-consuming procedure of making replicas of the surface, the time of the measurement itself, the cost of building the measuring station and its operation. Furthermore used replicas are made of a different material than the original surfaces (the use of the original surface because of their large weight would cause their separation by centrifugal force), which results in different rigidity than the original. The treadmill of the machine also enforces the shape of replicas with a large curvature, which is why it is necessary to convert the obtained result to a flat surface.

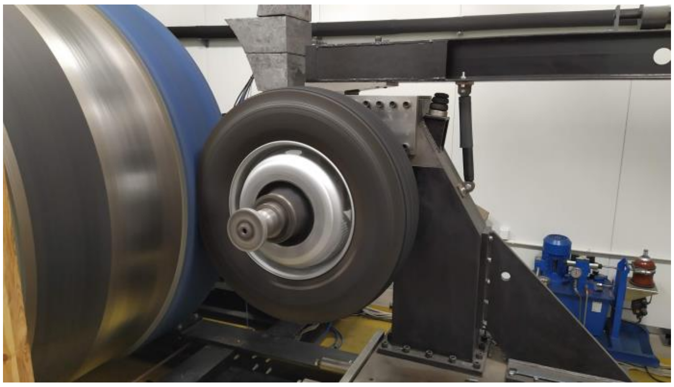


Fig. 3. Roadwheel facilitie for testing rolling resistance which is part of the Equipment Complex of the Gdańsk University of Technology (own material)

2.The influence of inflation pressure and temperature at the rolling resistance

2.1. Influence of inflation pressure

Variables such as inflation pressure, load, speed, ambient temperaturę affect the change in rolling resistance. There is general agreement that the rolling resistance of car tires decreases with increased inflation pressure [12]. The tread belt becomes stiffer and therefore deforms less. Changes in rolling resistance coefficient in relations to pressure depend on its overall value for a given tire. Those that have relatively high rolling resistance coefficient values are more sensitive to pressure changes (even above 3.5% when the pressure changes by 10 kPa) than models with a low value. The applied pressure must fulfill a compromise in order to ensure on the one hand relatively low rolling resistance and, on the other hand, even wear across the width of the tire, the sufficient stiffness and maneuverability. The graph below illustrates the dependence of the rolling resistance coefficient on the pressure (Figure 4) [10].

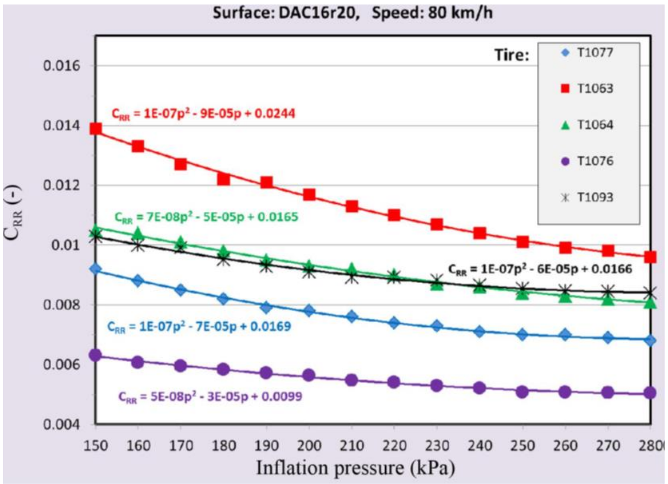


Fig.4. Relationship between rolling resistance coefficient and pressure for various tires [10]

2.2.Influence of ambient temperature

It is impossible to describe the tire temperature with one value because each component heats up to a different degree. In order to simplify the description, the average values of temperatures are determined in different zones of the tire: tread belt, shoulder, sidewall or bead (Figure 5). The tire temperature depends on many factors, which include energy loss inside the tire, cooling effect of the air stream around it, solar radiation, influence of road surface temperature and cooling under the influence of snow and rain (Figure 12) [6]. An increase in temperature causes a decrease in internal damping in the tire, which leads to a reduction in hysteresis loss, and thus a reduction in the tire rolling resistance [2,7,8].

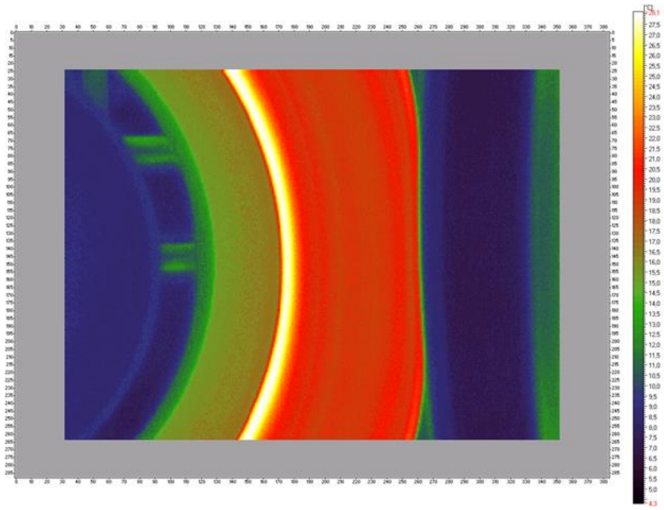


Fig.5. Thermogram showing temperature differences in different areas of the tire (own material)

3. Measuring methodology

The torque method is based on the use of roadwheel facility, where rolling resistance is measured by measuring the moment of force on the drum drive shaft. In determining the rolling resistance are considered the running resistance of their own equipment, which is determined by measuring the torque of the driving drum on which the wheel rolls pressed against a force of only 100 N (rolling resistance during that examines the-present is minimal and is less than 0.5 N) [9]. The advantage of this method is accuracy and low sensitivity to deviations or shifts of the radial force line loading the wheel from a normal line to the drum surface and passing through the center of the wheel being tested. The drum stand used during the tests is shown in Figure 6. It consists of a steel drum (1), covered with a replica of the surface (2), a support (3), an arm (4), a load (5) and a tested wheel (6). The whole is closed in a thermostatic chamber, enabling to obtain an ambient temperature from -15°C to 25°C (Figure 7). Rolling resistance was measured on a replica of the SMA8 surface made of epoxy resin, fiberglass and gelcoat (Figure 8). The original surface is an asphalt mix with a high grit content, containing a mastic stabilizer.

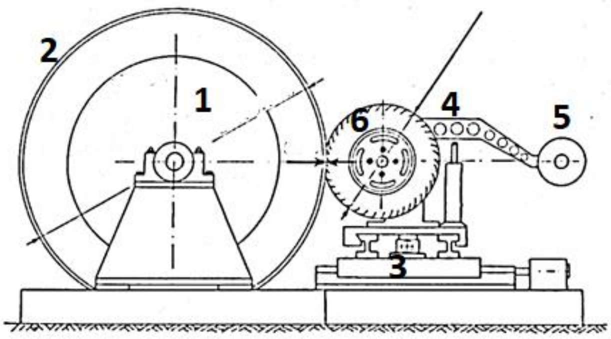


Fig.6. Diagram of the roadwheel facility [2]

Fig.7. Thermostatic chamber used in the tire testing laboratory of the Gdańsk University of Technology (own material)

Fig.8. SMA8 surface replica (own material)

4. Analysis of the results

Two truck tires were tested, tire A (275/80R22.5) and tire B (315/ 70R22.5). The measurements were made at two ambient temperatures: 25°C to simulate summer conditions and -15°C to simulate winter conditions. The applied load was 2760 kg. For tire A it was 85% of the maximum load (in accordance with the requirements of the ISO standard), while for tire B it was 69% of the maximum load (conditions corresponding to the underloaded vehicle). Table 1 shows the combinations of pressures, loads and temperatures used.

Tab. 1. Measuring conditions for individual measuring points

Tire A 275/80R22.5				Tire B 315/70R22.5			
measurement number	ambient temperature [°C]	pressure [bar]	Load [kg]	measurement number	ambient temperature [°C]	pressure [bar]	Load
1	25	9,3	2760	1	25	10	2760
2	25	8,3	2760	2	25	9	2760
3	25	6,3	2760	3	25	7	2760
4	-15	8,3	2760	4	-15	9	2760
5	-15	6,85	2760	5	-15	7,25	2760

The first part of the measurements (at 25°C) was intended to show differences in the obtained rolling resistance coefficient depending on the inflation pressure used. It was observed for both tires that as the pressure inside the tire decreases, we observe an increase in the rolling resistance coefficient (Fig.9, Fig.10). This increase is more pronounced for tire A (this could have been influenced by a higher percentage of wheel load, which caused greater heating of tire components, and thus increased pressure).

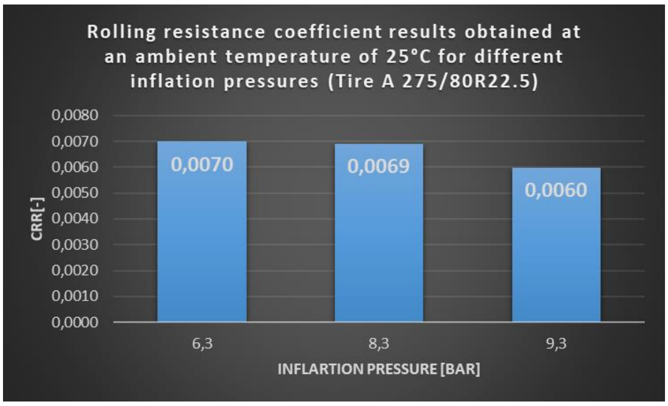


Fig.9. Rolling resistance coefficient results obtained at an ambient temperature of 25°C for different inflation pressures (Tire A 275/80R22.5)

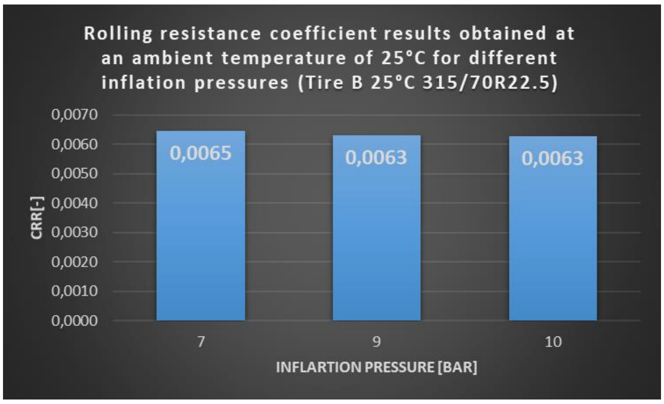


Fig.10. Rolling resistance coefficient results obtained at an ambient temperature of 25°C for different inflation pressures (Tire B 25°C 315/70R22.5)

For further analysis, the differences in fuel consumption were calculated (Tab.2). For this purpose, the following assumptions were used (example for Tire A measurement 1):

Example of calculation for Tire A measurement 1

Input data for calculations

$A = 5m^2$ frontal surface of the vehicle

$\rho = 1{,}226\,\frac{kg}{m^3}$ air density

$C_x = 1$ coefficient of aerodynamic resistance

$V = 22{,}22\,\frac{m}{s}$ vehicle speed

$f_t = 0{,}0070$ rolling resistance coefficient

$\eta = 30\%$ engine and drive system efficiency

$W_u = 43\,\frac{MJ}{kg}$ calorific value of fuel

$d_{pal} = 0{,}82\,\frac{kg}{dm^3}$ fuel density

$m_p = 33120\ \mathrm{kg}$ vehicle mass

Air resistance force:

$$F_p = \frac{1}{2}\rho A C_x V^2$$

$$F_p = 1513{,}58\ N$$

Rolling resistance force:

$$F_t = f_t m_p g$$

$$F_t = 2270{,}47\ N$$

The power needed to overcome resistance to motion:

$$N_{op} = \left(F_p + F_t\right)V = 84090{,}03N$$

The power needed to overcome resistance to motion, taking into account the efficiency of the engine and drive system:

$$P_p = W_u \cdot G$$

Where:

$$G - mass\ flow\ rate\ [\frac{kg}{s}]$$

$$G = \frac{P_p}{W_u} = 0{,}0065\ [\frac{kg}{s}]$$

Fuel mass used to travel 100 km (at a speed of 80 km/h):

$$m_{pal} = G \cdot t = 29{,}33\ kg$$

The volume of fuel consumed for running over 100km (at a speed of 80km / h):

$$V = \frac{m_{pal}}{d_{pal}} = 35{,}77\ dm^3$$

Tab.2. Calculated fuel consumption depending on the rolling resistance coefficient (25°C)

Tire A 275/80R22.5				Tire B 315/70R22.5			
Measurement	Pressure [bar]	Rolling resistance coefficient [-]	fuel consump. [dm3]	Measurement	Pres sure [bar]	Rolling resistance coefficient [-]	fuel consump. [dm3]
1	6,3	0,0070	35,8	1	7	0,0065	34,2
2	8,3	0,0069	35,5	2	9	0,0063	33,7
3	9,3	0,0060	32,7	3	10	0,0063	33,6

The largest differences in fuel consumption were obtained for tire A. Between the measurements obtained at 9 bar and 6.3 bar the difference was 3.1 liters per 100km. In the case of tire B, the differences were smaller and amounted to 0.6 liters. This was probably due to a lower tire load (69% of maximum load).

In the second part of the measurements, the results of rolling resistance coefficients obtained in the following measuring conditions were compared. The measurements were intended to show differences for two hypothetical situations:

1. The driver pumps the tires to the set pressure in the summer season, then does not regulate it in the winter season (the pressure decreases). The tire has been inflated to a set pressure at 25°C (value according to ISO standard; Table 1, measurement number 2). Then the tire was transferred to a thermostatic

chamber, where the ambient temperature was -15°C. The measurement of the rolling resistance coefficient was made after the tire had cooled to ambient temperature.
2. The driver pumps the tires to the set pressure in the summer season and adjusts them to the same value in the winter season. The tire was inflated to a set pressure at -15°C (value in accordance with ISO standard; Table 1 measurement number 4), after which the rolling resistance coefficient was measured.

In first scenario for tire A, the pressure at 25°C was 8.3 bar, while at -15°C it dropped to 6.85 bar (at this pressure a measurement was made). In the second scenario, the measurement was made at -15°C with a pumping pressure of 8.3 bar (the same as for 25°C). The obtained differences in rolling resistance coefficient values are practically imperceptible. In first scenario (unregulated pressure), the rolling resistance coefficient is 0.3% higher than in the second scenario where the pressure was regulated (Fig. 11).

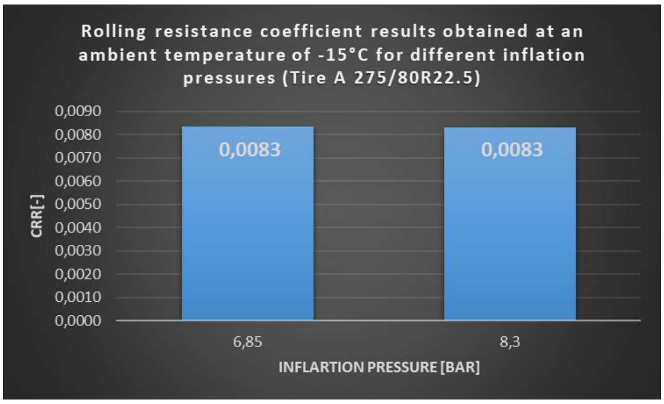


Fig.11. Rolling resistance coefficient results obtained at an ambient temperature of -15°C for different inflation pressures (Tire A 275/80R22.5)

In first scenario for tire B, the pressure at 25°C was 9 bar, while at -15°C it dropped to 7.25 bar. In the second scenario, the measurement was made at -15°C with a pumping pressure of 9 bar (the same as for 25°C).The differences in rolling resistance coefficient values in this case are larger. Rolling resistance coefficient for lower pressure is higher by 2.7% (first scenario)(Fig. 12).

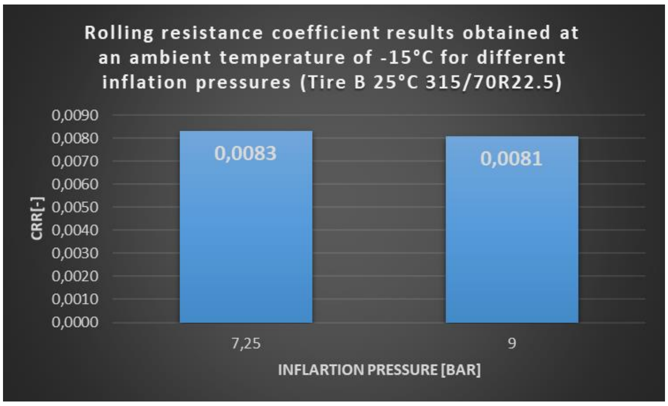


Fig.12. Rolling resistance coefficient results obtained at an ambient temperature of -15°C for different inflation pressures (Tire B 25°C 315/70R22.5)

For further analysis, the differences in fuel consumption were calculated.

Tab.3. Calculated fuel consumption depending on the rolling resistance coefficient (-15°C)

Tire A 275/80R22.5			Tire B 315/70R22.5		
Measurement	Rolling resistance coefficient [-]	fuel consumption [dm3]	Measurement	Rolling resistance coefficient [-]	fuel consumption [dm3]
First scenario: Inflation pressure regulated in -15°C	0,0083	39,85	First scenario: Inflation pressure regulated in -15°C	0,0081	39,15
Second scenario: Inflation pressure not regulated in -15°C	0,0083	39,92	Second scenario: Inflation pressure not regulated in -15°C	0,0083	39,83

Summary

The measurements showed that the rolling resistance value increases as the pumping pressure and ambient temperature increase. For an ambient temperature of 25°C, the largest differences in the rolling resistance coefficient were observed for tire A for which 85% of the maximum load was applied. This difference was 14.3% between the lowest and the highest pumping pressure (the difference in the calculated fuel consumption was 8.7%). In the case of tire B, the differences were smaller, which was probably due to a lower load (69% of maximum load). The rolling resistance coefficient for the lowest pressure was higher than that obtained for the highest pressure by 3.1% (the difference in the calculated fuel consumption was 1.8%). In the case of measurements made at -15°C, two scenarios were compared. The first in which the pumping pressure was regulated only in the summer season (in the winter season, as a result of lowering the temperature, the pressure decreased). The second scenario in which the driver regulates the pumping pressure to the same value in both summer and winter seasons. The differences in the obtained rolling resistance values were small, for both tires. The largest differences in the values of the rolling resistance coefficient were 2.7%, and in terms of fuel consumption 1.7% (in favor of the second scenario). The measurements described in this article were made on a rigid surface SMA8. It is planned to continue the tests carried out under the same conditions, but on a poroelastic surface. A greater impact of ambient temperature on the rolling resistance coefficient is expected.

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Wpływ ciśnienia pompowania i temperatury otoczenia na wartość oporu toczenia opon ciężarowych

W artykule omówiono wpływ ciśnienia pompowania oraz temperatury otoczenia na wartość oporu toczenia opon ciężarowych, który bezpośrednio przekłada się na zużycie paliwa. W tym celu wykonano serię pomiarów w dwóch temperaturach otoczenia (25°C i -15°C), stosując różne ciśnienia pompowania.

Keywords: opony do samochodów ciężarowych, opór toczenia, zużycie paliwa.

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