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The determination of the rolling resistance coefficient of objects equipped with the wheels and suspension system – results of preliminary tests

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Abstract. Rolling resistance coefficient is one of the basic resistance when moving objects. In case of objects not equipped with a motor-driven wheels and suspension system , such as: wheelchairs, mobile machinery chopper, shelving and warehouse trucks all resistances are overcome by the muscle strength of the operator. Research is carried out to limit this phenomenon, however, there is a lack of methods for measuring this parameter in the real operating conditions of devices with a wheels and suspension system without a drive unit. The article presents an innovative method of measuring the rolling resistance coefficient of objects equipped only with the wheels and suspension system accordant with the patent application P.424484 and the developed device for these tests in accordance with patent application P.424483. Additionally, the paper presents the results of preliminary tests on the measurement of pivoting coefficient of a transport truck loaded with a given mass.

Keywords: rolling resistance, wheelchairs, mobile machinery chopper, method of measuring the rolling resistance, non-pneumatic wheels

1 Introduction

The coefficient of rolling resistance of vehicle wheels depends, among other things, on the type of wheel and surface on which it moves. Bench tests are characterized by a limited selection of load-bearing surfaces due to the use of treadmills (disc, belt, drawer (in-laid), drum internal and external). In addition, the contact between the tested wheel and raceway does not always reflect the actual operating conditions. In addition, the rolling resistance forces are determined by various indirect methods (torque measurement, wheel force measurement, electric power measurement, distance measurement) introducing various measurement inaccuracies. Another group of research methods are road tests using test vehicles (coasting method, rolling downhill, towing, measuring the drive torque, measuring the maximum speed, measuring fuel consumption) are burdened with the lack of the

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possibility of separating components that are not the rolling resistance of the wheels. Methods of testing using devices such as dynamometric trailers require additional vehicles to perform their movement. This type of devices can carry out tests in open spaces (mainly roads). There is no possibility of measurements using this method in confined spaces (e.g. corridors in the building). The article presents a prototype of the device and a research methodology that allows measuring the rolling resistance force and determining the rolling resistance coefficient:

- under real operating conditions,
- with real contact of the wheel with the test surface,
- testing of systems with running gear, without or with self-propelling,
- research inside buildings with limited research areas,
- testing of external road surfaces,
- testing of systems mounted on guides,
- tests on various types of load-bearing surfaces,
- tests on load-bearing surfaces contaminated or covered with layers resulting from atmospheric conditions, e.g. snow, ice,
- research on loose surfaces,
- testing of objects with variable structure in the scope of: type and shape of the tire, tire pressure, number of wheels,
- tests at different speeds,
- examination of objects, regardless of their mass,
- a wide range of research facilities possibilities from railway wagons, trucks and cars, warehouse trucks, sliding gates or wheelchairs, etc.
- as the total value of the rolling resistance force for all wheels of the tested object.

Testing with a prototype test stand requires verification of test results. In order to do so, the values of rolling resistance coefficients available in the literature have been presented. The coefficient of rolling resistance for a pneumatic tire used in motor vehicles on a smooth asphalt or concrete surface is indicated in the range 0.007 to 0.02 [1-9], most often indicated around 0.012. In the case of pneumatic tires, the value of the coefficient changes while increasing the speed of the tire, resulting in a change of air pressure in the wheel, increased transmission of high torque, because then the circumferential deformation increases, the height of the tire tread increases when the load changes [3-13]. Another group of wheels are non-pneumatic wheels used in transport trucks, work machines or lunar vehicles. Such tires may have a rolling resistance coefficient of 0.005 to 0.03 [14]. Coefficient of rolling resistance for pneumatic wheels used in wheelchairs depending on the pressure in the wheels and surface M. Sydor indicates at nominal pressure on the hard surface approximately 0.01 [15].

The tests for non-pneumatic wheels and pneumatic tires are carried out mainly on surfaces commonly available in open spaces, mainly asphalt and concrete surfaces, taking into account their roughness. For pneumatic tires, results are available on surfaces such as a dirt road, muddy or sandy road, dry sand, a road from granite blocks, etc. [2-9]. Research on surfaces such as grassland or snow-covered surfaces is poorly understood [8-9], and as studies of acceleration and braking processes show [16-19], these surfaces are characterized by significantly different driving characteristics. There are no tests corresponding to the surfaces used inside the rooms whose values of the rolling resistance coefficient are significant for such vehicles as, for example, wheelchairs. The article presents an innovative methodology for testing the coefficient of rolling resistance developed on the basis of patent applications [20, 21] and the results of preliminary studies on the value of this coefficient for non-pneumatic wheels used in wheelchairs or mobile work machines. The research is part of the work carried out by the research team, whose main task is researching the biomechanics of hand-driven wheelchairs oriented at analysing the parameters of the

human-wheelchair antropotechnical system. Implementation of the task of the research team requires a series of partial tests, which include:
- design and construction of a test stand that will allow to carry out research on wheelchair movement mechanics,
- creation of the necessary procedures and methodology for experimental research of wheelchair biomechanics for driving a wheelchair, with particular emphasis on muscle activity,
- construction of mathematical models of wheelchair movement mechanics, which allow for a thorough analysis of parameters related to its propulsion,
- design and production of prototypes of innovative construction solutions for wheelchairs,
- development of issues related to ergonomics and driving comfort for wheelchair users.

This article is related to the problem of modelling wheelchair movement mechanics. It discusses issues related to determining the rolling resistance coefficient of wheelchairs as well as factors influencing the change of this parameter. The values of this coefficient were determined for exemplary wheels used on the front axle of wheelchairs on a hard surface. The results of these tests will be used in simulation models.

2 Object and research methodology

The research was carried out on a test trolley without a drive system, equipped with a wheel assembly used, for example, in transport trolleys, wheelchairs on the front axle, mobile work machines. The test trolley was equipped with four TENTE wheel units model 2470PJO125R05-28 (Fig. 1). The wheel unit includes a turntable with a double-row ball bearing that facilitates changing the direction of travel of the trolley. The hub of the non-pneumatic wheel is made of polypropylene and mounted on a steel core of the screw. The outer cladding of the wheel made of TENTEprene (thermoplastic rubber) [22], the wheel meets the standards of EN 12530 [23].

Fig. 1. A non-pneumatic wheel used, among others, in wheelchairs

The research was carried out on a prototype research stand developed on the basis of patent application P.424484 concerning the methodology for measuring the rolling resistance coefficient of objects equipped only with the chassis and using the developed device for these tests in accordance with patent application P.424483. The test method makes it possible to determine the rolling resistance coefficient by measuring the rolling force that connects the characteristics of road and bench tests. The essence of the method of determining the rolling resistance coefficient of objects equipped with the chassis is that the test object is moved at a constant speed, which allows to exclude the impact of inertial forces on the system and their influence on the rolling resistance force. Moreover, in this measuring method, the axis of the force measurement sensor must lie on a horizontal plane parallel to the supporting surface and on a plane perpendicular to the frontal plane of the tested object. Where the perpendicular plane of the tested object is tangential to its front face and is perpendicular to the supporting surface. During the test, the rolling resistance force is registered by means of a force sensor and processed in accordance with the program algorithm of the recording unit, which makes it possible to determine the value of the rolling resistance coefficient.

The adopted research methodology determines the implementation of the measurement test in uniform motion with a constant speed of movement of the test object relative to the supporting surface. In addition, the analysis of the rolling friction coefficient should be carried out without transitions, acceleration and stopping of the test object, because in these states there are additional resistance called resistance of inertia. These resistances result from the characteristics of uniformly accelerated or delayed motion. The measurement was carried out at a speed of not more than 15km/h. Because for such a range of motion speed of the tested object, the resistance of the air force is negligible, irrespectively of the front drag coefficient of the tested object [24]. Before the start of the measurement test, the mass of the tested object was tested because knowledge of the mass is necessary to determine the rolling resistance coefficient by measuring the rolling resistance force.

The determination of the rolling resistance coefficient of objects equipped with the chassis was carried out with the division into: preparatory activities, measurement tests, results processing and mass measurement of the tested object. The activities were carried out in accordance with the algorithm in Figure 2:

- preparation (A):
1. activity D1 - mass measurement of the tested object;
2. activity A1 - setting the force sensor so that its axis of force measurement lies on a horizontal plane parallel to the supporting surface;
3. activity A2 – setting the force sensor so that its axis lies on a plane perpendicular to the front plane of the tested object. The frontal plane is at the same time perpendicular to the supporting surface and tangent to the forehead of the test object;
4. activity A3 - acceleration of the test object to a given constant vector of linear velocity;
- measuring test (B):
1. activity B4 - maintaining the test object in uniform motion at constant speed relative to the supporting surface;
2. activity B5 - keeping the trajectory of movement of the tested object parallel to the axis of the force measurement sensor;
3. activity B6 - registration of the value of the force required to overcome the resistance of vehicle movement;
- processing of results (C):
1. activity C7 - checking if the movement of the subject is uniform with zero acceleration;
2. activity C8 - taking the measurement signal and sending it to the recording device;
3. activity C9 - determination of the rolling resistance force based on the measurement signal;
4. activity C10 - determining the coefficient of rolling resistance of the tested object on the basis of the rolling resistance force taking into account the mass of the tested object, measured in activity D1.

The process of implementing the method of determining the rolling resistance coefficient of objects equipped with the chassis was carried out under certain conditions:

- constant speed of the moving tested object,
- the axis of the force measuring sensor and the test object were located on a horizontal supporting surface, without elevations,
- omitting transient states, accelerating and delaying the movement of the test object.

D1 → A1 → A2 → A3 → B4 → B5 → B6 → C7 → C8 → C9 → C10

Fig. 2. Algorithm of conduct during tests

Meeting the above-mentioned conditions allows interpretation of the obtained results as a rolling resistance force as:
- the sum of the proper rolling resistance of all wheels of the tested object, the value of which can be divided into all wheels of the test object and assumed as a unit rolling resistance value for a specific wheel (except for vehicles with different wheel dimensions);
- the sum of the proper rolling resistance of all wheels of the test object and the resistance of the wheel connections with the object, most often the rolling or sliding friction in bearings of the suspension system and damping, possibly coupled drive transmission system, e.g. differential;
- the sum of the proper rolling resistance of all wheels of the tested object and the resistance of the wheel connections with the object and the resistance related to the lack of toe-out of the wheels system.

The rolling resistance processing algorithm allows to determine the value of the rolling resistance coefficient by performing an algebraic operation (1).

$$f_t = \frac{F_t}{m \cdot g} \tag{1}$$

where:
f_t – rolling resistance coefficient,
m – mass [kg],
g – acceleration of gravity [$\frac{m}{s^2}$],
F_t – rolling resistance force [N].

Obtained results from measurements when knowing the equation of total vehicle movement force are used to determine the rolling resistance coefficients, equation (2).

$$F_N = F_t + F_p + F_w + F_b \tag{2}$$

where:
F_N – driving force,
F_t – rolling resistance force,
F_p – air resistance,
F_w – slope force resistance,
F_b – inertia resistance.

Rolling resistance and air resistance always occur to create a basic resistance. The slope resistance and resistance of inertia occurs periodically. The slope resistance occurs only when driving uphill, it is parallel to the surface component of the gravity force when going downhill. The component takes the return in accordance with the direction of movement, becoming the force forcing the object to move. Inertia resistance occurs only during acceleration. Then, the inertia of the vehicle parallel to the surface is directed opposite to the direction of movement. In a delayed movement this force changes the return. Traction resistance is the sum of the resistance of a towed trailer or semi-trailer. Conducting research in the above indicated measurement conditions allows to interpret the driving force F_N as the rolling resistance force F_t, equation (3), because these conditions limit the impact of other forces.

$$F_N = F_t \tag{3}$$

Other factors affecting the obtained resistance to rolling are : the convergence of the system, and the resistance generated in wheel bearings. By reducing the influence of wheel alignment and by not taking into account the resistance generated by the bearings in the wheels, a general equation of the rolling resistance force on a flat surface can be determined, equation (4).

$$F_t = G \cdot f_t, \tag{4}$$

where:
G – gravity [N], where: $G = m \cdot g$
m – mass [kg],
g – acceleration of gravity [$\frac{m}{s^2}$],
f_t – rolling resistance coefficient.

By converting equation 4, one can determine the rolling resistance coefficient described in equation 1 when knowing the value of the rolling resistance force, the mass of the test object and the acceleration of gravity.

The test stand for measuring the rolling resistance force in accordance with the described methodology is shown in Figure 3.

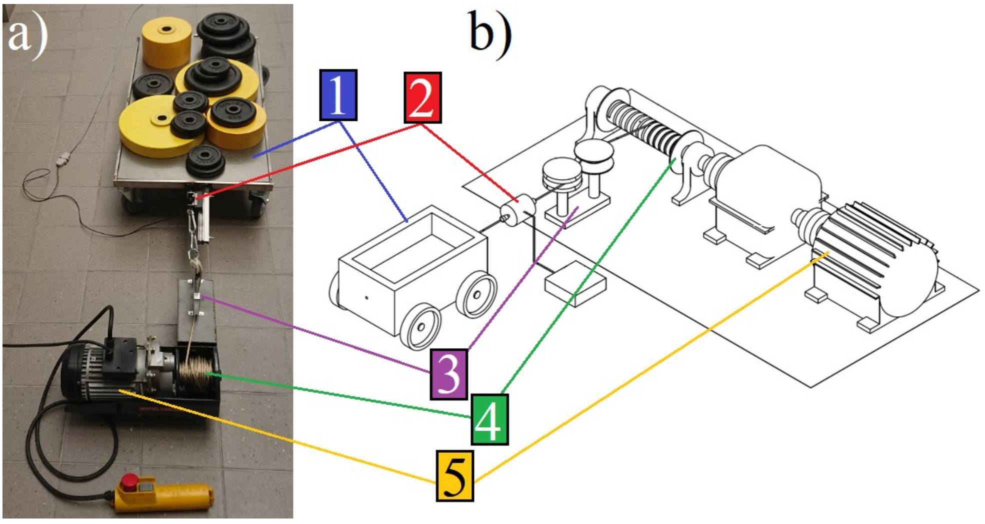

Fig. 3. Stand for determination of rolling resistance coefficients; a) prototype, b) concept drawing [21], where: 1 – tested object, 2 – force sensor, 3 – rope tension regulating system, 4 – rope winding system, 5 – drive unit

3 Research results

The results of force measurement tests using the described research methodology are shown in Figure 4, indicating the characteristics of the force measurement from the start of the movement to the stopping of the tested object. The characteristics of the force values during the constant speed movement are shown in Figure 5. The results of the tests of the average force necessary for the movement of the object at constant speed with different load are presented in Table 1.

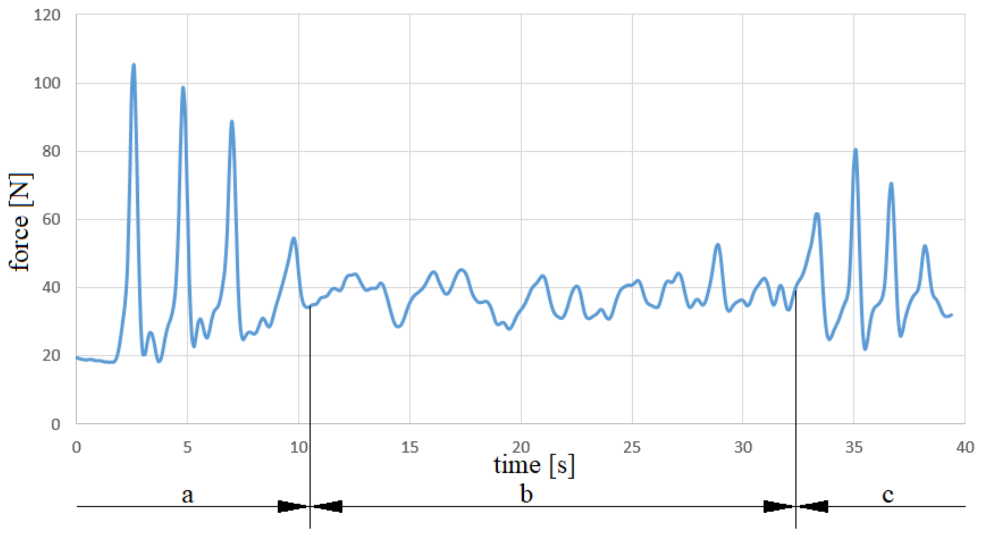

Fig. 4. Characteristic of change of force as a function of time when towing a trolley, where: a – acceleration, b – stabilization of movement, c – delay of movement

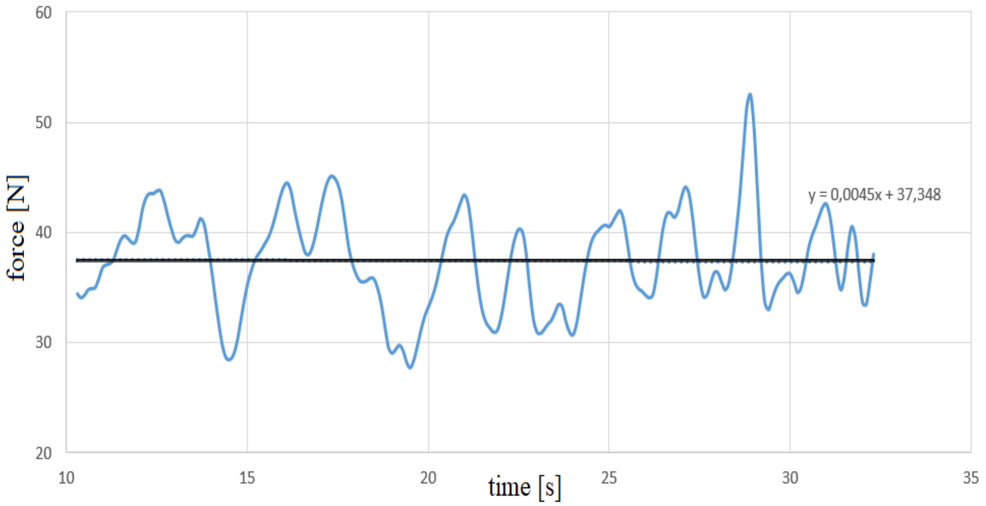

Fig. 5. The characteristics of changes in force as a function of time when towing a trolley within a range of stable movement where: blue line - force characteristic as a function of time, black line - trend line (linear)

Table 1. Average value of force when towing the trolley within the range of stable movement depending on the weight of the trolley

No	Mass							
	108 kg		123.8kg		139.8kg		192.8kg	
	F	SD*	F	SD*	F	SD*	F	SD*
1.	37.5	4.5	39.4	6.7	50.8	5.8	67	5.7
2.	36.3	5.8	41.6	7.1	47.5	6.7	65	7.8
3.	35.6	6.5	44.2	9.2	43.1	6.6	61	5.6
4.	38.4	5.6	40.1	5.9	51.3	7.8	61	6.1
5.	36.5	6.1	39.2	4.4	48.4	9.6	64	5.6
6.	38.5	5.4	42.3	8.1	49.5	5.6	65	6.3
7.	37.1	4.3	39.4	7.4	47.6	6.9	66	6.4
8.	37.3	5.4	40.5	7.9	46.9	5.5	69	6.5
9.	35.9	7.1	43.5	6.7	47.9	7.5	64	5.8
10.	36.6	4.9	41.9	7.6	48.1	5.6	63	5.9
	F	SD**	F	SD**	F	SD**	F	SD**
	36.97	0.68	40.95	1.54	48.11	1.49	64.5	0.39

F – average force [N],
SD* – standard deviation for the mean,
SD** – standard deviation for a single measurement.

4 Analysis of results

The developed method and research stand allowed to determine the rolling resistance coefficient for the tested trolley equipped with four non-pneumatic wheels on a hard surface made of ceramic tiles at the level of approximately 0.035 ± 0.00016. The set load values (from about 100 kg to 200 kg) did not affect the value of the rolling resistance coefficient. The influence of the trolley load on the value of the rolling resistance coefficient and the force necessary for moving at constant speed is shown in Figure 6.

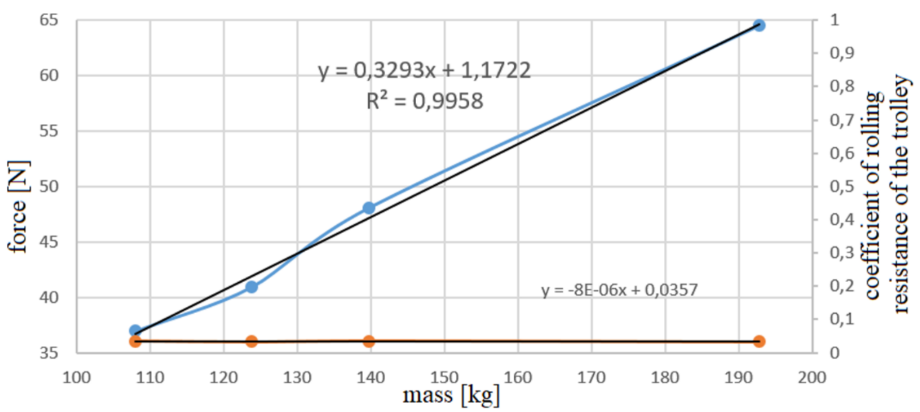

Fig. 6. Characteristics of the impact of loading the trolley with non-pneumatic wheels on the change of the rolling resistance coefficient and the force necessary for the movement at constant speed, where: blue – force, orange – coefficient of rolling resistance of the trolley

5 Conclusions

The developed method and research stand allowed to determine the coefficient of rolling resistance for the tested non-pneumatic wheels on hard surface made of ceramic tiles at the level of 0.0086-0.00016. The set values of one wheel load (from about 25 kg to 50 kg) did not affect the value of the rolling resistance coefficient. The results obtained are convergent with the data available in the literature. This indicates that the method can be used for further tests determining the value of the rolling resistance coefficient of wheeled systems. Further research will be carried out to determine the rolling resistance coefficient when moving on non-standard surfaces used in households and the impact of internal wheelchair driving mechanisms equipped with e.g. lever drive system [25, 26] or hybrid drive. Due to changes in mechanical properties due to the wear of drive mechanisms and surfaces [27, 28], research will be carried out on determining the impact of exploitation on the value of the rolling resistance coefficient.

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