Analysis of the usability of rolling resistance measurement methods to study the mechanisms of some wheelchairs

Ł Wargula¹, M Kukla¹, V Yurchenko², A Kukesheva³

¹ Institute of Machine Design, Faculty of Mechanical Engineering, Poznań University of Technology, pl. Marii Skłodowskiej-Curie 5, 60-965 Poznań, Poland,
² Department of Technological Equipment Mechanical Engineering and Standardization, Faculty Mechanical Engineering, Karaganda Technical University, Nursultan Nazarbayev Avenue 56, 100027 Karaganda, Kazakhstan
³ Department of transport equipment and logistic systems, Faculty Transport and Road, Karaganda Technical University, Nursultan Nazarbayev Avenue 56, 100027 Karaganda, Kazakhstan

corresponding author: lukasz.wargula@put.poznan.pl

Abstract. Reducing the driving force when propelling a wheelchair, e.g. through mechanical gears, is beneficial for people using wheelchairs. This makes it possible to overcome terrain obstacles that would be otherwise impassable with a classic drive system. However, the disadvantage of additional mechanisms supporting the propulsion of the wheelchair is usually the additional mass, ultimately increasing the rolling resistance. The article presents methods of measuring the rolling resistance – widely developed in the automotive industry – in terms of measuring the rolling resistance of wheelchairs. Innovative methods have been demonstrated to measure the rolling resistance on various surfaces and with the use of various drive mechanisms. The developed methods also enable the determination of the rolling resistance coefficient. The methods used are innovative and are subject to patent protection prepared by the authors in recent years. The results of the respondents allow to compare the measurement accuracy of the developed methods and show that the second method (being a simplification of the first method) is characterized by better accuracy.

1. Introduction

The design of machinery and vehicles in the 21st century is marked by the consideration of environmental factors [1-4]. Attention is drawn to the negative environmental impact of the materials used [5-7], the manufacturing processes [8-10] and their effects in emergency situations [11-15]. One of the trends in environmentally friendly machinery design and vehicles are designs reducing energy consumption [16-18], burning less harmful fuels [19-22] or having higher durability or service life [23-25]. Among the muscle-driven machines, designs offering a wide range of control over the variation of the driving force are being developed [26-29]. Such solutions are particularly important in machines and vehicles used by disabled and infirm people [30], as their ability to operate these devices depends on this parameter [31]. Solutions to assist or facilitate wheelchair propulsion very often include additional mechanisms [32] or other sources of propulsion, e.g. electric motors [17] (Fig. 1 a, b, f). These solutions and other wheelchair support systems, e.g. brakes preventing reverse movement...
when climbing hills [32] (Fig. 1 b, c, e). involve additional resistance to movement of these assistive technology devices.

Fig. 1. Systems supporting wheelchair propulsion and improving safety during hill climbing developed by the academic staff of the Institute of Machine Design of Poznan University of Technology where: a) hybrid manual-electric drive, b, c, e) anti-rollback safety brakes for hill climbing, d) drive wheels limiting energy losses, f) multi-speed transmission for wheelchair drive.

The availability of many design solutions contributes to the problem of selecting a specific device or evaluating the solutions developed. These designs may have different internal resistance, e.g. due to the type of transmission or bearings used. Rolling resistance measurement methods are widely developed for the testing of car tyres [33-35]. Taryma (2007) describes widely used methods for determining the rolling resistance of car tyres [36]. Among these methods, a distinction can be made between those focused on tyre testing only, e.g. laboratory methods with flat track test rig (disc, belt, or drawer) or drum test rig (external or internal). Such tests are characterized by the limitations of the surface on which the wheel can move. Another group are the road tests, which include methods designed primarily to test tyre rolling resistance, such as tests with dynamometric trailers. The second group of road tests are those using test vehicles. These methods are presented in Table 1. In their results, tests using test vehicles account for the influence of the road surface, wheels and wheel mounting mechanisms, transmission and additional equipment such as the braking system. The results may be affected by wheel toe, brake dragging moment [36], energy loss caused by wheel suspension.
Table 1. Methods for assessing the rolling resistance of objects equipped with running gear with regard to wheelchair testing

| Measurement method                  | Brief description                                                                 | Main disadvantage                                              |
|-------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Coast-down method                   | The accelerated test vehicle covers a certain distance due to inertia force after switching off the engine while losing speed gradually due to resistance to motion [36]. | Long test track                                                |
| Rolling-down method                 | A road on a hill is used for the measurements ending with a horizontal section. The test vehicle rolls down from a predetermined point on the hill and stops on the horizontal section. Used at lower measurement speeds. The rolling resistance coefficient can be determined from the equation of the potential energy of the work done on the measurement road. | Requires elevation.                                           |
| Towing method                       | A test vehicle is equipped with running gear is towed at a constant speed on a flat horizontal road. The force is measured by a dynamometer system between the vehicles. | It is difficult to maintain the constant speed of the second vehicle. |
| Method of measuring driving torque  | This method is based on measuring the driving torque transmitted to the test vehicle’s drive wheels. Based on the measured torque with a torque meter mounted on the drive shaft. | Structural interference                                       |
| Maximum speed measurement method    | It allows comparing designs indirectly by achieving maximum speed. A vehicle reaching a lower speed has a higher resistance. | Lack of ability to distinguish between aerodynamic and vehicle resistance; dangerous; difficult to implement in muscle-powered vehicles |
| Method of measuring fuel consumption| Measurement of the fuel consumed when the vehicle is running under strictly controlled road conditions. | Suitable only for vehicles with a combustion engine; depends on engine condition and replicability of driving conditions |

A specially tailored test method has been developed to address the problem of measuring the rolling resistance of muscle-powered devices. A device for the research was patented by the team Wargula, Wieczorek, Waluś, Kukla in 2020 PL235796B1 [37]. The results of tests using this method have been presented in publications on testing wheelchair rolling resistance [38]. The method measuring the rolling resistance force of objects equipped with running gear, with the possibility of determining the rolling resistance coefficient, had the following advantages:

- tests in real working conditions,
- tests maintaining actual wheel contact with the surface,
- tests on systems with running gear and either with or without self-propulsion,
- indoor testing with limited test surfaces,
- testing of external road surfaces,
- tests of systems mounted on slides,
● tests on different types of bearing surfaces,
● tests on bearing surfaces contaminated or covered by other layers created by weather conditions, e.g. snow, ice,
● tests on loose surfaces,
● tests on objects of varied construction with regard to type and shape of tyre, tyre pressure, number of wheels,
● tests with different test object driving speeds,
● testing of objects regardless of their mass,
● a wide range of test objects from railroad cars, trucks and passenger vehicles, warehouse trolleys, sliding gates to wheelchairs, etc.

In the course of the research, it has been observed that the method using the device presents difficulties in measuring surfaces with a varying rolling resistance coefficient. The paper presents pilot test results of an innovative device adapted for testing the rolling resistance of vehicles with running gear. This solution is the subject of patent application P.438203 [39] and is a development of the structures protected by patent PL235796B1 [37]. The new design is enhanced by a mechanism that limits the effect of the inertial force of the moving object resulting from the varying rolling resistance coefficient of the surface. The results of the pilot study show the influence of the measurement methodology on the nature of the recorded value of the rolling resistance force.

2. Material and method

A commercial wheelchair with pneumatic drive wheels on the rear axle and non-pneumatic, self-aligning wheels on the front axle was tested. The pressure in the wheels was 0.1 MPa, which is low for wheels of this type - therefore, they should have a relatively high rolling resistance. Such wheel pressure is common among wheelchair users who overcome terrain obstacles moving on two wheels. The weight of the wheelchair with the measuring system attached was 18.05 kg. The wheelchair was additionally loaded with a weight of 90.5 kg, which corresponds to average working conditions. The tests were conducted on a horizontal hard surface of gres tiles.

The authors have developed and applied two methods to test the rolling resistance force of objects equipped with running gear. The first method (A) is patented PL235796B1 [37] and described in detail in other publications on rolling resistance coefficient testing [34]. In the course of the research, it has been noticed that during testing on surfaces with a varying rolling resistance coefficient, slackening of the drive cable occurs, which results in a measurement error equal to the value of the inertial force. In order to eliminate this measurement error, a new measuring device was developed, subject to patent application P.438203 [39]. During testing, method B was devoid of the error caused by the slackening of the cable; hence the value tested was likewise devoid of the error due to the inertia force on surfaces with a varying rolling resistance coefficient. A view of the test stands is shown in Fig. 2 and Fig 3.
Fig. 2. Test stand for method A, where: 1 – wheelchair, 2 – force measurement sensor, 3 – data recording and activation system, 4 – drive cable, 5 – drive system.

Fig. 3. Test stand for method B, where: 1 – wheelchair, 2 – force measurement sensor, 3 – data recording and activation system, 4 – drive cable, 5 – drive system, 6 – resistance cable, 7 – system limiting cable slackening.

Conditions necessary for measurement:
- fixed attachment of the cable retraction mechanism and the system limiting cable slackening,
- the applied forces should be parallel to the symmetry axis of the force measurement sensor,
- a constant speed of the moving test object maintained by a cable retraction mechanism and a system limiting cable slackening,
- constant speed of the generated propulsion,
- measurement shall be made on a horizontal surface,
• the force measurement analysis shall be performed on a section of the results at a constant speed, ignoring the transient states, acceleration and stopping of the test object.

The results obtained from the measurements with the knowledge of the equation for total vehicle motion force are used to determine the rolling resistance coefficients, equation (1).

$$F_N = F_t + F_p + F_w + F_b + F_u,$$

where: $$F_N$$ – the driving force, $$F_t$$ – rolling resistance force, $$F_p$$ – air resistance force, $$F_w$$ – elevation resistance force, $$F_b$$ – inertia resistance force, $$F_u$$ – resistance to motion force generated by the rope slackening limiting system. Optionally, a force acting on the towbar may also be present as a result of towing trailers.

Rolling resistance and air resistance always emerge, forming the primary resistance. Elevation resistance and inertia resistance emerge periodically. Elevation resistance only emerges during acceleration. In that case, the force of inertia of the vehicle parallel to the road surface is opposite to the direction of movement. In retarded motion, this force changes its direction. The towing resistance is the sum of the resistance of the trailer or semi-trailer being towed. Regardless of the vehicle body, during tests below 15 km/h, the air resistance is so insignificant that it can be ignored in the calculations [36].

When tested under the specified measuring conditions, the force $$F_N$$ is equal to the rolling resistance force $$F_t$$ and the movement resistance force generated by the cable slackening limiting system $$F_u$$ (2).

$$F_N = F_t + F_u$$

The value of the driving force $$F_N$$ is measured and known. In addition, the value of the resistance to motion force generated by the cable slackening limiting system is known as well $$F_u$$.

The resistance force generated by the cable slackening limiting system $$F_u$$ can be determined by equation (3), accounting for the weight’s gravity $$G$$, and the internal resistance force of the mechanism of the cable slackening limiting system $$F_{ou}$$.

$$F_u = G_c + F_{ou}$$ and

$$G_c = m_c \cdot g_c$$

where: $$m_c$$ - mass of the weight, $$g_c$$ - acceleration of gravity. The internal resistance force in the mechanism of the $$F_{ou}$$ cable slackening limiting system can be determined experimentally or theoretically according to generally known machine design principles.

It follows that by measuring the driving force $$F_N$$ and knowing the resistance to motion force produced by the cable slackening limiting system $$F_u$$, the rolling resistance force can be determined by equation (5):

$$F_N - F_u = F_t$$

The rolling resistance force determined during tests of the invented device is the sum of the specific rolling resistance of all the wheels of the object, the value of which can be divided over all the wheels of the vehicle and taken as the unit rolling resistance value for the specific wheel (except for vehicles with differentiated wheel dimensions).

By limiting the effect of the toe of the system, homogenizing the type of wheels and deducting the resistance generated in the wheel bearings, it is possible to formulate the general equation for the rolling resistance force on a flat surface equation (6).

$$F_t = G_o \cdot f_t$$ and

$$G_o = m_o \cdot g_o$$

where: $$G_o$$ – force of gravity of the moving object, $$f_t$$ –rolling resistance coefficient, $$m_o$$ – mass of the weight, $$g_o$$ – acceleration of gravity.

By transforming equation (5), it is possible to formulate the equation allowing to determine the rolling resistance coefficient, knowing the value of the generated force during the test with the
force measurement sensor; the mass of the test object and the acceleration of gravity, as shown in relation (7):

\[ f_t = \frac{F_t}{m_o \cdot g_o}. \]  \hspace{1cm} (7)

The test stand makes it possible to determine the rolling resistance coefficient by measuring the force of rolling resistance under suitable measuring conditions. Additionally, the site allows for measuring the influence of changes in the construction of tested objects on this value in the following areas: type and shape of the tyre, pressure in the tyre, speed of the object in the non-corrected range (i.e. up to the speed of 15 km/h), anything above it requires taking into account the correction factor related to air resistance. The site, thanks to the developed methodology and mobile construction, allows studying the influence of the type and quality of the surface on the values of the generated rolling resistance coefficient. It is a combination of tests with features of road tests and stand tests.

3. Results
The results of force measurement tests using the described research methodology are presented in figure 4a (method A) and figure 4b (method B). The wheelchair test results are shown in Table 2.

Fig. 4. Characteristics of the resistance force values of a wheelchair (a) measurement with method A, (b) measurement with method B.
Table 2. Mean value of the resistance to motion and rolling resistance coefficient of the wheelchair measured with methods A and B; AVG – average value, SD – standard deviation

| Method A | No | Average force of resistance to motion (N) | SD | Average rolling resistance coefficient (-) |
|----------|----|-----------------------------------------|----|------------------------------------------|
| 1        |    | 24.5                                    | 5.1| 0.023                                    |
| 2        |    | 24.1                                    | 4.9| 0.023                                    |
| 3        |    | 22.6                                    | 5.5| 0.021                                    |
| 4        |    | 23.2                                    | 6.1| 0.022                                    |
| 5        |    | 25.3                                    | 5.8| 0.024                                    |
| 6        |    | 24.4                                    | 5.2| 0.023                                    |
| 7        |    | 24.7                                    | 5.3| 0.023                                    |
| 8        |    | 23.8                                    | 6.0| 0.022                                    |
| 9        |    | 22.5                                    | 5.5| 0.021                                    |
| 10       |    | 25.1                                    | 5.4| 0.024                                    |
| AVG      |    | 24.02±0.93                              |    | 0.023±0.00088                            |

| Method B | No | Average force of resistance to motion (N) | SD | Average rolling resistance coefficient (-) |
|----------|----|-----------------------------------------|----|------------------------------------------|
| 1        |    | 32.0                                    | 7.1| 0.030                                    |
| 2        |    | 34.1                                    | 8.3| 0.032                                    |
| 3        |    | 33.2                                    | 7.2| 0.031                                    |
| 4        |    | 33.8                                    | 8.5| 0.032                                    |
| 5        |    | 35.1                                    | 7.3| 0.033                                    |
| 6        |    | 32.7                                    | 6.9| 0.031                                    |
| 7        |    | 33.4                                    | 7.1| 0.031                                    |
| 8        |    | 35.3                                    | 8.5| 0.033                                    |
| 9        |    | 33.0                                    | 7.1| 0.031                                    |
| 10       |    | 33.8                                    | 8.3| 0.032                                    |
| AVG      |    | 33.64±0.97                              |    | 0.032±0.00091                            |

4. Discussion
The methodology and test stand used allowed the rolling resistance coefficients of the wheelchair to be determined, and the results compared with those provided in the literature (Figure 5). The value of the rolling resistance coefficients of a wheelchair is influenced by: the contact between the tyre and the road, including the toe-in of the system and the mounting mechanism of the wheelchair wheel to its frame. The rolling resistance coefficient of the wheelchair according to method A is 0.023, and that of method B is 0.032 – these results are consistent with those from other research [38,41,42]. The value of the rolling resistance coefficient measured with method B is on average about 39% higher, indicating that during the measurement with method A, the acting inertia force decreased the value of the rolling resistance force, reducing the resulting rolling resistance coefficient (Fig. 5)
5. Conclusion

The ageing population [43] and the associated increase in independent mobility problems for the elderly contribute to an increased demand for mobility aids. It is possible that the developed structural solutions for wheelchair equipment may reduce the driving force while increasing the resistance to motion of such vehicles. The measurement methods developed by the authors of the article make it possible to measure the resistance to motion of wheelchairs and to determine their rolling resistance coefficients. The disadvantage of Method A is the measurement error due to the inertial force caused by the wheelchair being towed over a surface with a variable rolling resistance coefficient, which emerges under actual measurement conditions for almost all the surfaces tested. Method B, on the other hand, is devoid of such measurement error, and its results differ by approximately 39%. In the future, Method B is recommended for the testing of objects equipped with running gear.

6. References

[1] Gutarevych Y, Mateichyk V, Matijošius J, Rimkus A, Gritsuk I, Syrota O, Shuba Y 2020 Improving Fuel Economy of Spark Ignition Engines Applying the Combined Method of Power Regulation Energies 13 1076. https://doi.org/10.3390/en13051076.

[2] Rymaniak Ł, Kamińska M, Szymlet N, Grzeszczyk R 2021 Analysis of Harmful Exhaust Gas Concentrations in Cloud behind a Vehicle with a Spark Ignition Engine Energies 14 1769. https://doi.org/10.3390/en14061769.

[3] Beik Y, Dziewiątkowski M, and Szpica, D 2020 Exhaust Emissions of an Engine Fuelled by Petrol and Liquefied Petroleum Gas with Control Algorithm Adjustment SAE Int. J. Engines 13(5) 739-759. https://doi.org/10.4271/03-13-05-0047.

[4] Gierz, Ł.; Przybył, K.; Koszela, K.; Markowski, P. The Effectiveness of the Application of a Chemical Agent (Dressing) to Seed Potatoes by Means of an Innovative Valve Enabling Intermittent Flow of a Liquid. Agriculture 2020, 10, 85. doi: 10.3390/agriculture10030085.

[5] Czarnecka-Komorowska D, Bryll K, Kostecka E, Tomasik M, Piesowicz E, Gawdzińska K 2021 The composting of PLA/HNT biodegradable composites as an eco-approach to the sustainability Bulletin of the Polish Academy of Sciences: Technical Sciences e136720-e136720.

[6] Lyskawinski W, Baranski M, Jedryczka C, Mikolajewicz J, Regulski R, Sedziak D, Netter K, Rybarczyk D, Czarnecka-Komorowska D, Barczewski M 2020 Tribo-Electrostatic Separation Analysis of a Beneficial Solution in the Recycling of Mixed Poly(Ethylene Terephthalate) and High-Density Polyethylene Energies 14 1755. https://doi.org/10.3390/en14061755.
Krawiec P, Różański L, Czarnecka-Komorowska D, Warguła Ł 2020 Evaluation of the Thermal Stability and Surface Characteristics of Thermoplastic Polyurethane V-Belt Materials 13 1502. https://doi.org/10.3390/ma13071502.

Wojtkowiak D and Talaśka K 2019 Determination of the effective geometrical features of the piercing punch for polymer composite belts The International Journal of Advanced Manufacturing Technology 104 1 315-332.

Krawiec P, Czarnecka-Komorowska D, Warguła Ł, Wojciechowski S 2021 Geometric Specification of Non-Circular Pulleys Made with Various Additive Manufacturing Techniques. Materials 14(7) 1682.

Wojtkowiak D, Talaśka K, Malujda I, Domek G 2018 Estimation of the perforation force for polymer composite conveyor belts taking into consideration the shape of the piercing punch The International Journal of Advanced Manufacturing Technology 98 9 2539-2561.

Krawiec P, Warguła Ł, Małozięć D, Kaczmarzyk P, Dziewierzak A, Czarnecka-Komorowska D 2020 The Toxicological Testing and Thermal Decomposition of Drive and Transport Belts Made of Thermoplastic Multilayer Polymer Materials Polymers 12 10 2232.

Przybył K, Gawalek J, Gierz Ł, Łukomski M, Boniecki P 2018 Recognition of color changes in strawberry juice powders using self-organizing feature map. Proceedings of SPIE - The International Society for Optical Engineering 10806, 1080621 DOI: 10.1117/12.2503101.

Krawiec P, Warguła Ł, Czarnecka-Komorowska D, Janik P, Dziechciarz A, Kaczmarzyk P 2021 Chemical compounds released by combustion of polymer composites flat belts. Scientific Reports 11(1) 1-10.

Gierz Ł, Przybył K, Koszela K, Duda A, Ostrowicz W 2021 The use of image analysis to detect seed contamination—a case study of triticale. Sensors, 21 (1), art. no. 151, pp. 1-14. doi: 10.3390/s21010151.

Krawiec P, Warguła Ł, Dziechciarz A, Małozięć D, Ondrušová D 2020 Ocena emisji związków chemicznych podczas rozkładu termicznego i spalania pasów klinowych (Evaluation of chemical compound emissions during thermal decomposition and combustion of V-belts) Przemysł Chemiczny 99(1) 92-98. DOI:10.15199/62.2020.1.12 (in Polish).

Wojtkowiak D, Talaśka K, Wilczyński D, Góręcki J, Wałęsa K 2021 Determining the Power Consumption of the Automatic Device for Belt Perforation Based on the Dynamic Model Energies 14(2) 317.

Wieczorek B, Warguła Ł, Rybarczyk D 2020 Impact of a hybrid assisted wheelchair propulsion system on motion kinematics during climbing up a slope Applied Sciences 10(3) 1025.

Flizikowski J, Kruszelnicka W, Macko M 2021 The Development of Efficient Contaminated Polymer Materials Shredding in Recycling Processes Polymers 13 713. https://doi.org/10.3390/polym13050713.

Kurc B, Lijewski P, Rymaniak Ł, Fuć P, Pigłowska M, Urbaniak R, Ciupek B 2020 High-Energy Solid Fuel Obtained from Carbonized Rice Starch Energies 2020 13 4096. https://doi.org/10.3390/en13164096.

Shepel O, Matijošius J, Rimkus A, Duda K, Mikulski M 2021 Research of Parameters of a Compression Ignition Engine Using Various Fuel Mixtures of Hydrotreated Vegetable Oil (HVO) and Fatty Acid Esters (FAE) Energies 14 3077. https://doi.org/10.3390/en14113077.

Rimkus A, Vipartas T, Matijošius J, Stravinskas S, Kriauciūnas D 2021 Study of Indicators of CI Engine Running on Conventional Diesel and Chicken Fat Mixtures Changing EGR. Appl. Sci. 11 1411. https://doi.org/10.3390/app11041411.

Szpica D, Kuszniar M 2021 Model Evaluation of the Influence of the Plunger Stroke on Functional Parameters of the Low-Pressure Pulse Gas Solenoid Injector Sensors 21 234. https://doi.org/10.3390/s21010234.
[23] Selech J, Ulbrich D, Romek D, Kowalczyk J, Wlodarczyk K, Nadolny K 2020 Experimental Study of Abrasive, Mechanical and Corrosion Effects in Ring-on-Ring Sliding Contact Materials 13(21) 4950.

[24] Gierz Ł, Selech J, Marcinkiewicz J, Ulbrich D, Romek D, Staszał Ż, Wojcieszak D 2018 A simulation analysis of the strength of an innovative supporting structure of a mechanical pneumatic jack. In 4th International Conference ENGINEERING MECHANICS 2018 Svrata, Czech Republic, May 14 –17, 2018, Paper#220, pp. 237–240, DOI: 10.21495/91-8-237.

[25] Gierz Ł, Przybłą K, Koszała K, Sanklo Ł, Kwicień S 2020 An Assessment of the Functional and Ecological Aspect of Novel Intermittent Stream Valves for Spraying Seed Potatoes. Agronomy 10, 541. https://doi.org/10.3390/agronomy10040541.

[26] Warguła Ł, Krawiec P, Waluś KJ, Kukla M 2020 Fuel consumption test results for a self-adaptive, maintenance-free wood chipper drive control system Applied Sciences 10(8) 2727.

[27] Wieczorek B, Kukla M 2019 Effects of the performance parameters of a wheelchair on the changes in the position of the centre of gravity of the human body in dynamic condition Plos one, 14(12) e0226013.

[28] Wieczorek B, Warguła Ł 2019 Problems of dynamometer construction for wheelchairs and simulation of push motion. In MATEC Web of Conferences (Vol. 254, p. 01006). https://doi.org/10.1051/matecconf/201925401006.

[29] Wieczorek B, Kukla M 2020 Biomechanical Relationships Between Manual Wheelchair Steering and the Position of the Human Body’s Center of Gravity Journal of biomechanical engineering 142(8).

[30] Wieczorek B, Kukla M, Warguła Ł. 2021 The symmetric nature of the position distribution of the human body center of gravity during propelling manual wheelchairs with innovative propulsion systems Symmetry 13(1) 154.

[31] Wieczorek B, Kukla M, Warguła Ł, Rybarczyk D, Giedrowicz M, Górecki J 2021. The Impact of the Human Body Position Changes During Wheelchair Propelling on Motion Resistance Force: A Preliminary Study. Journal of Biomechanical Engineering 143(8) 081008.

[32] Wieczorek B, Kukla M, Rybarczyk D, Warguła Ł. 2020 Evaluation of the Biomechanical Parameters of Human-Wheelchair Systems during Ramp Climbing with the Use of a Manual Wheelchair with Anti-Rollback Devices Applied Sciences 10(23) 8757.

[33] Pałasz B, Waluś KJ, Warguła Ł 2019 The determination of the rolling resistance coefficient of a passenger vehicle with the use of selected road tests methods. In MATEC Web of Conferences (Vol. 254, p. 04006) https://doi.org/10.1051/matecconf/201925404006.

[34] Pałasz B, Waluś KJ, Warguła Ł 2019 The determination of the rolling resistance coefficient of a passenger vehicle with the use of roller test bench method. In MATEC Web of Conferences (Vol. 254, p. 04007) https://doi.org/10.1051/matecconf/201925404007.

[35] Sawicki P, Waluś KJ, Warguła Ł 2018 The Comparative Analysis of the Rolling Resistance Coefficients Depending on the Type of Surface - Experimental Research. 22nd International Scientific Conference on Transport Means (Transport Means) Location: Trakai, LITHUANIA Date: OCT 03-05, 2018, TRANSPORT MEANS 2018, PTS I-III Book Series: Transport Means - Proceedings of the International Conference Pages: 434-441.

[36] Taryma S 2007 Opór tocenia opon samochodowych (Rolling Resistance of Car Tires). (Wydawnictwo Politechniki Gdańskiej) (in Polish).

[37] Warguła Ł, Wieczorek B, Waluś KJ, Kukla M 2020 Device for measuring of the rolling resistance force of the objects equipped with the trolley system (original title in Polish: Urządzenie do pomiaru siły oporów tocenia obiektów wyposażonych w układ jezdny) patent number PL235796B1 date of patent application (2018.02.02).

[38] Warguła Ł, Kukla M, Wieczorek B 2020 The impact of wheelchairs driving support systems on the rolling resistance coefficient. In IOP Conf. Series: Materials Science and Engineering, 24th Slovak-Polish International Scientific Conference on Machine Modelling and Simulations - MMS 2019, 3-6 September 2019, Liptovský Ján, Slovakia, Vol.776 (2020) 012076, doi:10.1088/1757-899X/776/1/012076.
[39] Warguła Ł, Kukla M, Wieczorek B 2021 A device for measuring the rolling resistance force of objects equipped with running gear (original title in Polish: Urządzenie do pomiaru siły oporów toczenia obiektów wyposażonych w układ jezdny) patent application number P.438203 date of the patent application (18.06.2021).

[40] Lanzendoerfer J. Motor vehicle research (Badania pojazdów samochodowych) Warszawa, WKŁ 1977 (original text in Polish).

[41] Sprigle S, Huang M, Misch J 2019 Measurement of rolling resistance and scrub torque of manual wheelchair drive wheels and casters Assistive Technology 1-13.

[42] Wargula Ł, Wieczorek B, Kukla M 2019 The determination of the rolling resistance coefficient of objects equipped with the wheels and suspension system–results of preliminary tests. In MATEC Web of Conferences (Vol. 254, p. 01005). https://doi.org/10.1051/matecconf/201925401005.

[43] Angel JL, Vega W, López-Ortega M 2017 Aging in Mexico: Population trends and emerging issues The Gerontologist 57(2) 153-162.