VALIDATION OF ROLING AND STEER RESISTANCE OF ARTICULATED TRACKED ROBOT

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ABSTRACT

This paper presents the results of field test and theoretical analysis driving resistance articulated 4x4 tracked robot test-bed. Tests were made on four different grounds. Designated elastomeric tracks resistance coefficients are much higher than for steel tracks. This information was important for the proper estimation of energy consumption in the process of driving.

KEYWORDS

(UGV) Unmanned Ground Vehicles, tracked robot, articulated steering, driving resistance

INTRODUCTION

Unmanned ground vehicles are gaining wider and wider range of applications. In the recent years robots intended to be used for military purposes are developed very intensively. In the initial period they were mainly designed to detect explosives and their neutralization. Nowadays the research is also being done on the platforms (structures) of other purposes. These platforms include robots directly support soldier. They must have the mobility similar to a human and let for continuous work for several hours. They serve to transport loads of different types such as food, water, radio station or other special equipment.

In The Military University of Technology the test-bed of the various type of robots have been designed (Bartnicki, 2009; Muszyński, 2011). One of them is the robot directly support soldier. Due to the long time required in the process of driving, energy consumption is very important. The article presents some results of measurements of driving and steering resistance developed for the medium tracked test-bed with articulated steering.

METHODS

Test Bed

The test-bed is equipped with a track drive system 4 x 4 and has articulated steering system (Figure 1). Its total weight is about 720 kg. Ultimately, the total weight of the vehicle is expected to be 450-500 kg, and the weight of the taken load 250-300 kg. The platform has a hydrostatic drive system with four engines (hydrostatic motors) directly driving the tracks.

There are two driving modes:

a) vehicle - the parallel combination of all four hydraulic motors driving the track (low speed and high pulling power);

b) b) Road - with a serial connection loaders hydraulic motors driving the track (high speed and low pulling power).

Energy source is the engine which drives the pump with constant flow, and the change of flow intensity is implemented by a distributor.

The turn of the front section regarding the rear section are forced by two hydraulic cylinders. Tracks are firmly connected to the frame work. Appropriate adjustment of the driving system to the base is provided by special structure of articulated joint connecting two elements of the robot.

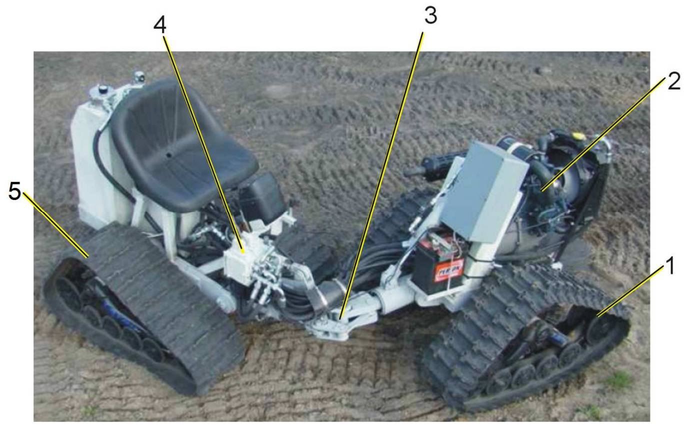

Figure 1 – Test-bed – 1 – front track, 2- engine, 3- coupler, 4 - hydraulic distributor, 5 - rear track

Basic technical parameters for the track test-bed are presented in table 1.

Table 1 - Track test-bed basic parameters

Parameter	Value
Total weight	720 kg
Width	1 m
Lenght	2,7 m
Pressure units	50 kPa
Chassis	tracks
Engine	Diesel (9,9 kW)
Driving system	hydrostatic
Steering system	articulated

The aim of this study was to determine the required real power needed to drive the robot while moving on the grounds of various load - bear capacity. Moreover, the studies were designed to allow the identification of the adhesion and rolling resistance on different surfaces.

Experimental studies of the track test-bed were carried out on the special training ground which is ordered by Military University of Technology. It is situated in the laboratory at Chair of Mechanical Engineering and it has different types of grounds and obstacles that allow to examine the mobility of the robot.

During the research pressure values on hydraulic inline and outline of driving system (study of driving force) and pressure values in hydraulic cylinders of steering system were measured.

Measuring system (Figure 2) composed of:

a) pressure sensors KOBOLD SEN-8700:
   - driving system:
     - hydraulic in - line – measure range 0-400 bar, measure class 0,5;
     - hydraulic out - line - measure range 0-400 bar, measure class 0,5;
   - steering system:
     - hydraulic in - line – measure range 0-400 bar, measure class 0,5;
     - hydraulic out - line - measure range 0-400 bar, measure class 0,5;

b) data acquisition module IO Tech Personal DAQ 3005;

c) computer recording data.

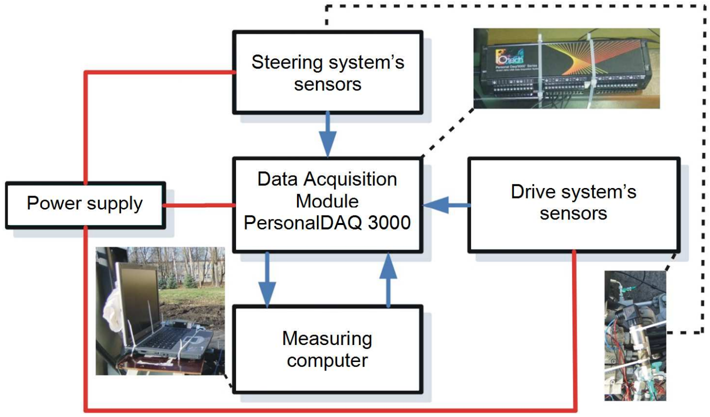

Figure 2 - A block diagram of the measuring system

RESULTS

Resistance of drive system

The resistance of the drive system of the robot have two components (Commellas, 2013). One of them is hydrostatic resistance of drive system and another one is the resistance of track rewinding. To determine the necessary strength to overcome the resistance, the vehicle was raised above the ground. Then the engine was started and the tracks were set in motion. The time course of changes in recorded resistance values are shown in figure 3.

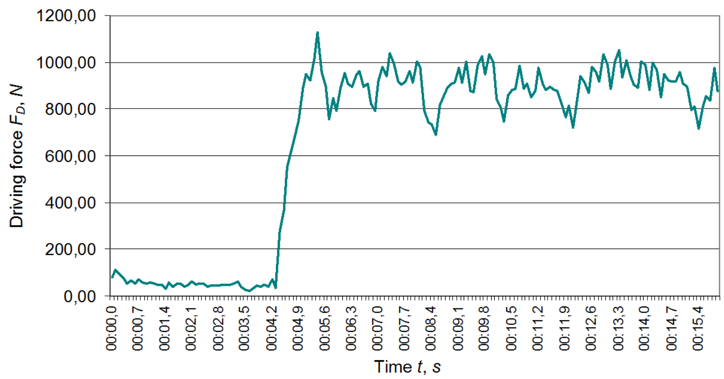

Figure 3 - The time course of the resistance of the drive system

The driving force necessary to overcome its own resistance oscillated between F_{ds} = 800 - 1000 N. This corresponds to a maximum difference of pressure recorded during the test and values up to about Δp = 1.35 MPa. It is 13.8% of the weight of the platform amounting of Q = 7200 N.

Roling resistances

The rolling resistance Ff depend on the ground that the vehicle move on and suspension system. To determine them we use relation:

$$F_f = Q \cdot f\,, \tag{1}$$

where: Q – weight of the vehicle, f – rolling resistances coefficient.

To assess the value of the f coefficient for applied elastomeric track, it was decided to conduct their own identifying research. In order to do, the measurements of the driving force FD on four types of grounds were carried out (figure 4):

a). concrete;
b). ground with a capacity of *CI*=280 kPa;
c). ground with a capacity of *CI*=290 kPa - grassy
d). ground with a capacity of *CI*=150 kPa;

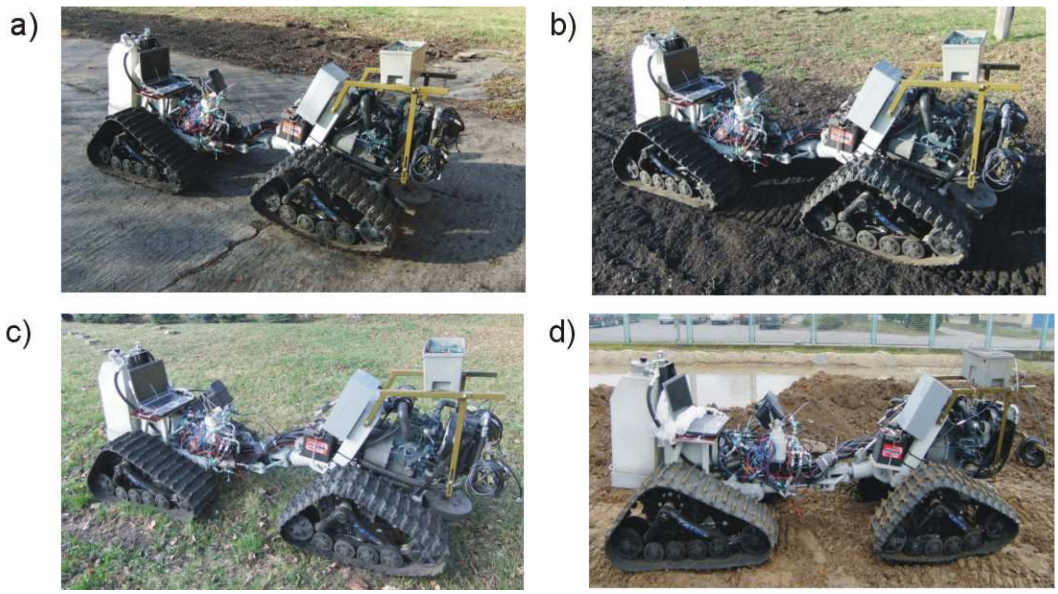

Figure 4 – Test-bed during the test: a). on concrete ground, b). ground with a capacity of *CI*=280 kPa, c). ground with a capacity of *CI*=290 kPa – grassy, d). ground with a capacity of *CI*=150 kPa

Knowing its value and the resistances in the drive system Fds the searched rolling resistance can be determined depending on:

$$F_f = F_D - F_{ds} \qquad (2).$$

And transforming equation (1) and substituting equation (2) the pattern of the rolling resistance coefficient can be obtained:

$$f = \frac{F_D - F_{ds}}{Q} \qquad (3).$$

During each test, turns were done in circles, and then the vehicle moved at the highest off-road speed**.** The time course of changes of pressure values in steering hydraulic cylinder and changes of driving force Fn value during the test carried out on the concrete ground are shown in figure 5.

The driving force when the platform moves in a set movement on the concrete ground values at the level of 2000 N. Temporary increase in strength at the beginning of the experiment results of the dynamic interaction and therefore it was omitted in further analysis.

Using equation (2) it can be found that the rolling resistance power of the platform on the concrete ground during the movement is F_f = 1000 N. In this case the resistance of their own hydraulic installation and rolling tracks are up to 50% of the total strength reached by the platform while driving on a concrete ground. According to equation (3) coefficient for resistance of rolling elastomeric tracks on the concrete ground is *f* =0,14.

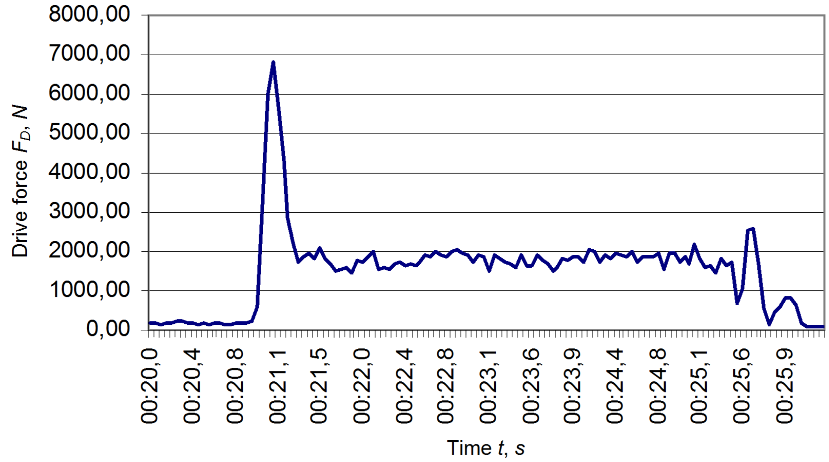

Figure 5 - The time course of changes of driving force value during the test carried out on the concrete ground

The driving force Fd during the movement (figure 6) on the ground with a capacity of *CI*=280 kPa raised in the relation to the concrete ground about 50 % and values at 3000N. rolling resistance power, in this case, values at P_f = 2000 N and the coefficient for rolling resistance valued at f =0,28. The share of own resistance of driving system representing 30 % of the value of F_D force.

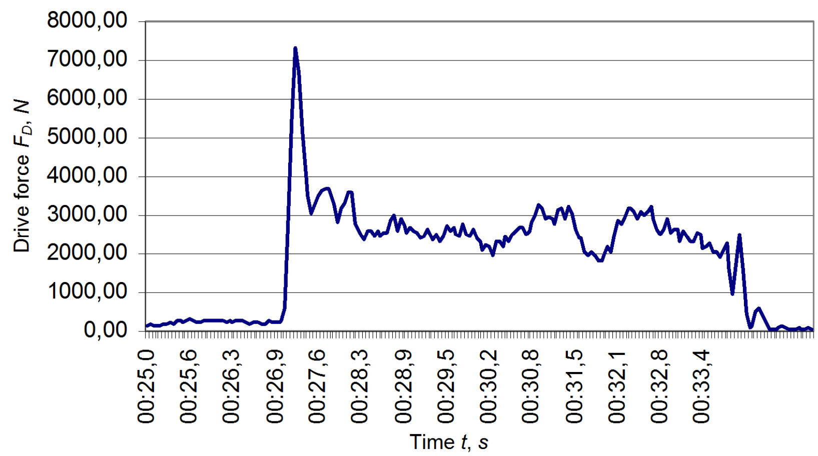

Figure 6 - The time course of changes of driving force value during the test carried out on the ground with a capacity of *CI*=280 kPa

The driving force Fd during the movement (figure 7) on the grassy ground with a capacity of *CI*=290 kPa is similar to values achieved for concrete (Figure 5). It values at the level of 2000N. Rolling resistances correspond to the same coefficient f =0,14.

The tests on the ground with the capacity of *CI*=150 kPa showed the highest values of drive force (figure 8). In contrast to the other cases it shows, however, substantial variability and it is expressed between F_d = 3000-4000N. Resistance force in this case values at the level 2000-3000N, which corresponds to the coefficient f = 0,28 – 0,42.

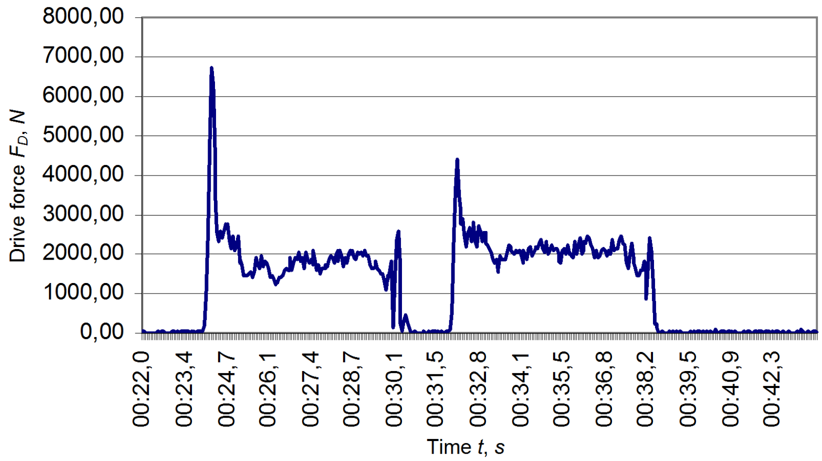

Figure 7 - The time course of changes of driving force value during the test carried out on the grassy ground with a capacity of *CI*=290 kPa

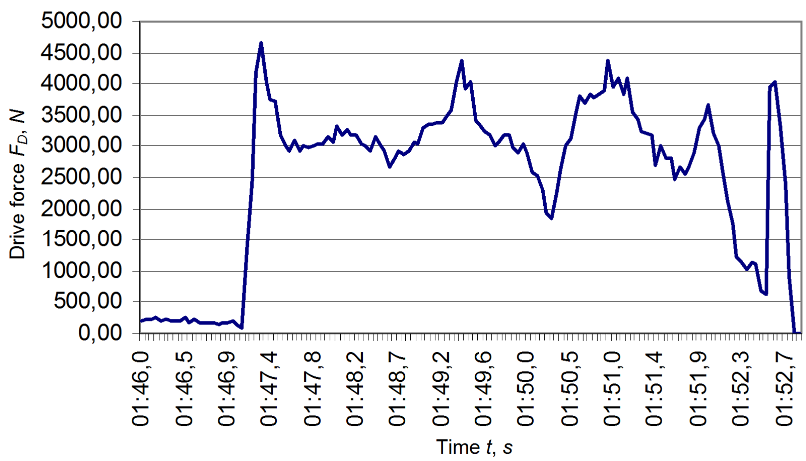

Figure 8 - The time course of changes of driving force value during the test carried out on the ground with a capacity of *CI*=150 kPa

Steering system pressure and turning resistance

Kinematics of the steering system provides the ability to rotate the front part of the platform relative to the rear part at an angle $\alpha\approx\pm70°$. The course of the theoretical value of the maximum torque generated by the hydraulic cylinders is shown in Figure 9. To do this, it is sufficient to measure the pressure in actuators during the change of the mutual angular position of the front and rear part of the vehicle.

Identification tests were performed on the same grounds as in determining rolling resistance. During the tests a full range of a turn into right and left was performed. The results are shown in figure 10.

The value of the power generated by hydraulic cylinders of steering system corresponds to the pressure Δp difference between their active and inactive part. It is indicated, as an example on figure 10a.

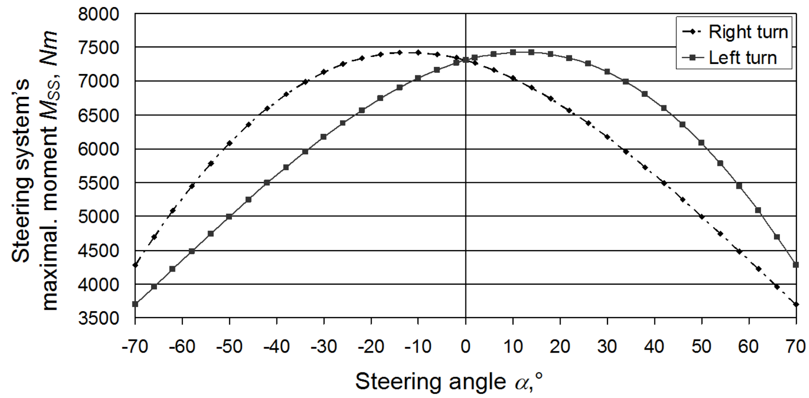

Figure 9 – The relation of torque generated by the hydraulic cylinders of steering system in steering angle

The maximum peak pressure in the steering system, recorded during tests on concrete grounds, is about 120 bar (figure 10a). It occurs in the initial phase of the turn and immediately goes down. It could be concluded that it is the result of dynamic effects connected with the starting-up process. In the further turning phase the pressure difference is between Δp=30 - 40 bar. The similar values were recorded on the ground with a capacity of *CI*=280 kPa (figure 10b). On the grassy ground the difference is a little higher and values Δp=40 - 50 bar. The highest turn resistance was on the ground with a capacity of *CI*=150 kPa. To overcome it, it was necessary to produce the difference in pressure Δp=60-70 bar. This affects steering resistance moment M_{SR_E} which is suitably 1256 Nm, 1570 Nm, 2198 Nm.

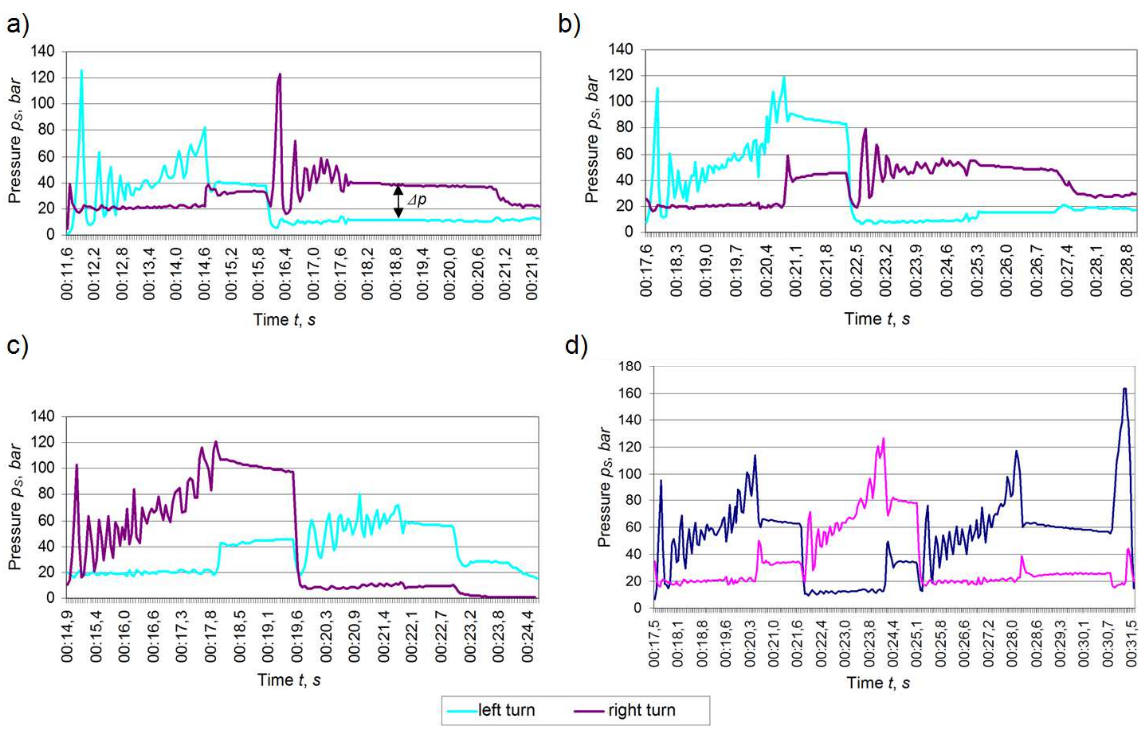

Figure 10 - The time course of value change for pressure in hydraulic cylinders of steering system during the turn on the: a). concrete ground, b). ground with a capacity of *CI*=280 kPa, c). grassy ground with a capacity of *CI*=290 kPa, d). ground with a capacity of *CI*=150 kPa

No theoretical dependence was found, in the literature, to estimate the turn resistance of articulated tracked vehicles (Cheng, 2012; Konopka, 2011). The closest relation to that issue was developed for articulated wheel loaders. And it stands as:

$$M_{SR\_T} = m_1 \cdot g \cdot f \cdot k \frac{B_1}{2} + m_2 \cdot g \cdot f \cdot k \frac{B_2}{2}, \quad (4)$$

where: m_1 = 360 kg – the weight of the front part, m_2 =360 – the weight of the rear part, f - coefficient of rolling resistance, g- gravity acceleration, k- coefficient of skidding and scraping the ground (k=1,4 - 2,5), B_1 – track of front wheels, B_2 – track of rear wheels

Substituting the vehicle data and experimentally determined values of the rolling resistance coefficient, the results were obtained, which are provided in Table 2.

Table 2 - Theoretical values of turn resistance for the test-bed

Parameter	Concrete ground		Ground with a capacity of *CI*=280 kPa		Ground with a capacity of *CI*=150 kPa	
$k_1 = k_2$	1,4	2,5	1,4	2,5	1,4	2,5
$\alpha_1 = \alpha_2$ [°]	35		35		35	
f	0,14		0,14		0,28	
M_{SR_T} [Nm]	276	492	232	414	368	656

DISCUSSION

Based on the study it can be concluded that the available data in the literature and relations would not give the correct estimation of driving and steering resistance. The discrepancies were greater than originally expected. It seems that the main reason for this is the specific characteristics of elastomeric track structure and test platform. In the further stage of the research attempts will be undertaken to detail the reasons for the observed effects.

CONCLUSIONS

The study led to the identification of values of the rolling resistance coefficients used in elastomeric track in platform. In the available literature values [3]are given mainly for the steel tracks. Comparing them to each other significant differences can be noticed(Table - 3). Measured values are several times larger than the literature gives. Probably due to the presence of additional friction resistance and deformation of elastomeric track belts on wheels.

Table 3 - Values of the rolling resistance coefficients for different grounds

	Literature value f_l	Identified value f_i	f_i / f_l
Concrete (deformable surface)	0,03 – 0,06	0,14	4,7-2,3
Ground with a capacity of *CI*=280 kPa	0,10	0,28	2,8
Ground with a capacity of *CI*=290 kPa - grassy	0,06	0,14	2,3
Ground with a capacity of *CI*=150 kPa	0,12 – 0,15	0,28 – 0,42	2,3 – 2,8

Whatever the cause may be, it can be stated that the energy consumption of the drive system equipped with elastomeric tracks is in average 3 times higher than indicated by the literature data for steel structures.

Even greater differences were found between the theoretical and experimental turn resistance. As shown in the table 4, these vary from about 3 to nearly 7 times.

Table 2 – Summary of theoretical and experimental values of turn resistance for tesbed

Parametr	Concrete ground		Ground with a capacity of CI=280 kPa		Ground with a capacity of CI=150 kPa	
M_{SR_T} *[Nm]*	276	492	232	414	368	656
M_{SR_E} *[Nm]*	1256		1570		2198	
M_{SR_E}/M_{SR_T}	4,56	2,55	6,76	3,79	5,98	3,35

Underestimation of the theoretical value may be due to the fact that the relation used in the calculation is designed for wheeled vehicles, not tracked. Analyzing its components and structural differences of driving system elements it can be concluded that it would greatly increase the value of the wheel slip and the ground scraping k coefficient. To obtain the approximate value similar to experimental value of resistance the results would be in the range of k = 6 – 9,5.

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