Abstract: The goal of this paper was to analyze a possibility of improving a tractive performance of an off-road car with new design of special driving wheels with spikes. Design of the special driving wheels uses the spikes segments placed in tire-tread pattern similar to snow chain. An inactive position of the spike segments allows transportation of a car on roads using standard tyres. An active position is designed for operation under terrain conditions. The article presents comparison of the active special driving wheels with the standard tyres without the special driving wheels. The experiments were realised on a mowed grass field at soil moisture of 24.8%. Comparing the active special driving wheels with standard tyres without the special driving wheels, the increase in drawbar pull reached value of 39.5% at wheel slip of 10%. The results showed improvement of drawbar properties of the off-road car under real terrain conditions.

Key Words: driving wheels, slip, tyre-soil interaction, tyre-tread pattern

INTRODUCTION

A relatively large part of vehicle power is wasted at tyre-soil interface. This fact is very important in case of off-road cars and agricultural tractors operating out of roadways. Besides the parameters of tyre-tread pattern, a tyre inflation pressure, wheel load, tyre width and diameter of unloaded tyre affects the tractive performance of driving wheels due to the change of contact area between driving wheels and ground. Poor drawbar efficiency due to a wheel slip wastes an energy of a vehicle engine, increases a fuel consumption (Uhrinová et al. 2013) makes worse emissions in exhaust gases (Králik et al. 2016) and a soil compaction in case of off-road vehicles and agricultural tractors (Malý et al. 2015). Many researchers designed and tested various concepts of special driving wheels with lugs or spikes (Yang et al. 2014, Gasparetto et al. 1992). The objectives of this study were to design special driving wheels with spikes and test an off-road car tractive performance.

MATERIAL AND METHODS

Principle of special driving wheels

The aim of this article is a design and test of new special driving wheels with spikes for tyres of the off-road car. An off-road tyre has a relatively large space between the segments of a tyre-tread pattern and allows placing the spikes within them to improve the drawbar properties of the car. The principle of the special driving wheels is based on works presented by Abrahám et al. (2015), Abrahám et al. (2018), Majdan et al. (2018) and Abrahám, R. et al. (2019). The principle of the special driving wheels is shown in Figure 1. Eight spike segments (2) with three spikes are placed in riffles of the tyre-tread pattern (1). All segments can rotate to change the spike position. During the transportation on roads the spikes do not exceed the tyre-tread pattern and do not interfere the road (Figure 1b). During the worse adhesive conditions, control lever (3) turns the spike segments to the active position where the spikes exceed the tyre-tread pattern and improve drawbar properties of driving wheels. The carry wire rope (4) keep the contact between the spike segments and tyre during the driving wheels rotation and tyre deformation. The control wire rope (5) with the control levers (3) allow to control the spike position.
Test of the off-road car tractive performance

Figure 2 shows the measurement of drawbar parameters of the off-road car Daihatsu Eroza type (2) with special driving wheels (7) according to the OECD test code 2 and standard STN ISO 789-9:2002, which were adapted for the testing of this car type performed in field conditions. The standard rear driving wheels of the car was replaced by the prototypes of the special wheels. The force sensor (3) was connected between the load tractor Zetor 25 type (1) and the off-road car through a steel chain (4).


To state the drawbar parameters of the car, the drawbar pull $F_{DB}$, actual $V_a$ and theoretical velocity $V_t$ were measured and recorded. The force sensor (3) EMS 150 type (Emsyst s. r. o., Slovak Republic) with a rated capacity of 20,000 N and with an accuracy of 0.5% of full scale, was used to measure the drawbar pull. A rotation speed sensor (5) VC2 type (Maha GmbH, Germany) with a 300 to 9,999 min⁻¹ measuring range and 10 min⁻¹ resolution measured the car engine speed. A stopwatch (6) with 0.01 s resolution was used for measuring the time between the start and the end of the measurements. A Hydac model HMG 3010 (Hydac GmbH, Germany) portable 12-bit data acquisition system with accuracy of 0.1% of full scale was used, with a 100 Hz sampling frequency. The special driving wheels was equipped with the tyres Pneu Ovada Maxi Cross 195/80 R15 type (Vraník s. r. o., Czech Republic).
Table 1 Specifications of the off-road vehicle and the load tractor

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Off-road car (Daihatsu Feroza)</th>
<th>Load tractor (Zetor 25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb mass</td>
<td>1,220 kg</td>
<td>2,600 kg</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specification</td>
<td>Petrol, four-stroke</td>
<td>Diesel, four-stroke</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Displacement</td>
<td>1,590 cm³</td>
<td>2,590 cm³</td>
</tr>
<tr>
<td>Max. torque / rotation speed</td>
<td>126 N m / 3,500 rpm</td>
<td>160 N m / 2,200 rpm</td>
</tr>
</tbody>
</table>

The load tractor loaded the car during the measurement procedure using the resistance of gearbox in neutral, 1st, 2nd, 3rd and 4th reverse gears in combination with the three positions of the handbrake. The off-road car was loaded to the maximum load level until the car engine was overload and the rotation speed began to decrease. In this point, the measurements were finished. During the experiments, the off-road car was operated at maximum engine torque at 3,500 rpm in 1st gear, low range (gear ratio $u_1$ is 33.75).

Wheel slip $\delta$, an important parameter to evaluate the tractive performance of wheeled car (Majdan et al. 2016), is given by expression:

$$\delta = 1 - \frac{V_a}{V_t} = 1 - \frac{V_a}{\frac{2\pi n_r m}{u_1}}$$

(1)

Where $V_a$ – actual forward velocity of the car, m s$^{-1}$

$V_t$ – theoretical velocity of the car, m s$^{-1}$

$\omega$ – angular velocity of wheel, rad s$^{-1}$

$r$ – wheel radius, m.

Theoretical velocity $V_t$ was calculated according to measurement of engine rotation speed as follows:

$$V_t = \frac{2\pi n_r m}{u_1}$$

(2)

Where $n_r$ – the actual rotation speed of vehicle engine, rpm

$u_1$ – gear ratio.

Bashford and Kocher (1999) use the Gauss-Newton method of nonlinear regression to estimate the regression coefficients $C_1$ and $C_2$ to model relationship between net traction ratio and wheel slip. This method and statistical program (SAS EG 7.1) were used to express the functional relationship between drawbar pull and wheel slip according to Eq. (3).

$$F_{DB} = [C_1 \times \{1 - \exp \left( - C_2 \times \delta \right)\}] \times W$$

(3)

Where $C_1$, $C_2$ – regression coefficients,

$\delta$ – wheel slip,

$W$ – car weight, N.

The measurements were realised in October 2018. The off-road car with special driving wheels was tested on mowed gras field at soil moisture of 24.8% (STN ISO 11465). The soil type Cambisol (World Reference Base for Soil Resources) is typical for mountainous country (Middle Slovakia Region, Žarnovica district) where the tests were performed.

RESULTS AND DISCUSSION

Design and construction of special driving wheels

The special driving wheels (Figure 3) were designed at the Faculty of Engineering of the Slovak University of Agriculture in Nitra and mounted on the tyres body of the rear wheels.

During the transportation on roads, the vehicle uses inactive special driving wheels. The spikes do not exceed the tyre-tread pattern and do not interfere with the road. At worse adhesive conditions, all spikes segments are turned to the active position where the spikes exceed the tyre-tread pattern and improve the tractive performance of the vehicle.

The steel carry wire rope (2) connects eight spikes segments (1) and holds them in the tyre-tread pattern. The steel control wire rope (3) allows changing the active and inactive position of the spike segments (1). Spikes are made from steel bars having hexagonal cross-section. Using the pivots (4)
with threads, washers, and nuts, both wire ropes are fixed to the spike segments. All pivots (4) can turn in hoops of the spike segments. The change of the spike segments position (active or inactive) is mechanically controlled. To change the spike segments position, the safety nut (7) has to be released and next the nut (6) turned using fork wrench. It releases the fix connection of the supporting frame (8) and allows moving the control wire rope (3) and turning the spike segments (1). The shape of oscillating link (9) terminates position of the spikes in the active and the inactive position. The safety nut (7) fix the active or the inactive position. The central carrier bar (5) with the central pin is placed to the wheel rim to set a correct central position. All the parts of special driving wheels are designed and manufactured from common profiles of standard structural steel grade S355JR.

The special driving wheels were developed to fully replace the standard tyre under terrain. Yang et al. (2014) developed actively actuated lugged wheels to increase the drawbar pull of a vehicle. The actively actuated lugged wheels achieved the increase in drawbar pull but their planetary gear does not allow changing the lugged wheel to the smooth wheels in the case of transportation on a hard surface. Gasparetto et al. (1992) presented the design of steel lugged wheels for agricultural machinery on rice fields, sour and peaty soil. All the wheels mentioned above do not allow the transportation on solid surfaces. On the other hand, the design of the special driving wheels allows transportation on roads without the interactions between the spikes and ground because they do not exceed the tyre diameter in the inactive position. Abrahám et al. (2014) presented the special wheels with auto-extensible blades. These lug wheels are mounted besides the tractor driving wheels to improve the tractor drawbar properties by means of steel blades. The special driving wheels with spikes are simpler construction and do not change the tractor width in comparison with lug wheels mentioned above.

*Figure 3 Design of the special driving wheels: a) active position, b) oscillating link in inactive position, c) spike segment*

**Drawbar pull vs. slip**

The model of drawbar pull as a function of wheel slip were calculated according to Eq. (3) and compared with the experimental data in the case of the tyres without the special driving wheels and the active special driving wheels (Figure 4). Considering the measured data and using the regression analysis, the nonlinear regression coefficients of the off-road car with the tyres without the special driving wheels \((C_1 = 0.679 \text{ and } C_2 = 6.061)\) and the active \((C_1 = 0.744 \text{ and } C_2 = 8.653)\) special driving wheels were stated to model drawbar pull as a function of slip. In case of the standard tyres, the coefficient of determination \(R^2\) is 0.906, \(P\)-value is \(4.73 \times 10^{-8} < 0.05\) and \(RMSE\) is 2.47. In case of the special driving wheels the coefficient of determination \(R^2\) is 0.873, \(P\)-value is \(3.43 \times 10^{-7} < 0.05\) and \(RMSE\) is 2.69. The descriptive statistic of regression models indicates a significant regression effect so that the models well fit with the experimental data. Comparing the models of drawbar pull as function of wheel slip, the special driving wheels improved the traction properties of the off-road car, as shown in Figure 5.
Figure 4 Drawbar pull as a function of wheel slip: a) active special driving wheels, b) standard tyres without special driving wheels

Figure 5 Comparison of drawbar pull of off-road car with and without special driving wheels

Increase in drawbar pull

Considering the drawbar pull at the relevant slip, the drawbar properties of the off-road car with the active special driving wheels were compared with the tyres without the special driving wheels (Table 2). The highest drawbar pull increase of 39.5% (Table 2) occurred at the wheel slip of 10%. The higher slips due to higher load levels caused lower increase in the drawbar pulls of the car. The highest increase in the drawbar pull at low slip is caused by the better function of the steel spikes penetrating raw ground. Using a rubber track, Rasool and Raheman (2018) increased the drawbar pull of wheeled walking tractor about 93% at slip of 15%.

Table 2 Comparison of active special driving wheels and tyres without special driving wheels

<table>
<thead>
<tr>
<th>$\delta$, %</th>
<th>$F_{DB}$, N</th>
<th>Increase, %</th>
<th>$\delta$, %</th>
<th>$F_{DB}$, N</th>
<th>Increase, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Active special wheels</td>
<td>Standard tyres</td>
<td></td>
<td>Active special wheels</td>
<td>Standard tyres</td>
</tr>
<tr>
<td>10</td>
<td>6,061</td>
<td>4,344</td>
<td>39.5</td>
<td>24</td>
<td>9,155</td>
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<tr>
<td>12</td>
<td>6,761</td>
<td>4,939</td>
<td>36.9</td>
<td>26</td>
<td>9,364</td>
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<tr>
<td>14</td>
<td>7,350</td>
<td>5,467</td>
<td>34.4</td>
<td>28</td>
<td>9,539</td>
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<tr>
<td>16</td>
<td>7,846</td>
<td>5,934</td>
<td>32.2</td>
<td>30</td>
<td>9,687</td>
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<tr>
<td>18</td>
<td>8,262</td>
<td>6,347</td>
<td>30.2</td>
<td>32</td>
<td>9,811</td>
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<tr>
<td>20</td>
<td>8,613</td>
<td>6,714</td>
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<tr>
<td>22</td>
<td>8,907</td>
<td>7,039</td>
<td>26.5</td>
<td>36</td>
<td>10,003</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The drawbar properties of the off-road car with special driving wheels were evaluated and compared with standard tyres without the special driving wheels. The tractive performance of the off-road car was analysed based on experiments under real operation conditions. Experimental data was used to model the drawbar pull as a function of the wheel slip. The active special driving wheels were compared with standard tyres without the special driving wheels. The increase in drawbar pull reached highest value 39.5% at the wheel slip of 10%. The next research will be aimed at automatization of spike extension and influence of the special driving wheels on fuel consumption because the increase in drawbar pull improves this factor.

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REFERENCES