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## **THE INFLUENCE OF TIRE INFLATION PRESSURE - A COMPARISON BETWEEN SIMULATION AND EXPERIMENT**

### **1 Introduction**

Driving on soft ground is totally different from driving on prepared firm roads. One main difference is the rut which appears behind the wheel. It is caused by a plastic deformation of the soil. By the penetration of the wheel into the ground, the soil is compressed under the bottom of the wheel and is moved to the sides and to the front of the wheel, where a bow wave is built up. The plastic soil deformation produces the major part of the rolling resistance on soft ground. On rigid roads, where the rolling resistance is caused only by the energy absorption of the tyre, the rolling resistance is much lower.

Another difference on soft soil is the restriction of the circumferential force. It is well known that on a rigid road the circumferential force is limited by the friction. On soft soil the limitation is the shear strength of the soil. This leads to a much smaller circumferential force on soft soils than on rigid road.

In terrain the maximisation of traction is important not only to accelerate the vehicle but also to climb up slopes or to run over obstacles. Therefore the increase of the drawbar pull, which is the difference between circumferential force and rolling resistance, is a major aspect in the development of terrain vehicle systems. One possibility to increase the traction is the enlargement of the wheel-ground contact length. This can be realized by reduction of the tire inflation pressure. For a constant wheel load the enlarged contact area results in a reduction of

ground pressure and therefore a smaller sinkage which means a lower rolling resistance.

This paper will present the basic models of wheel-soil interaction, which are implemented in the simulation system ORIS. The configuration of a carried out field test is described. Results of simulations with varying tire inflation pressure, based on the configuration of the field test, are presented. At last the simulated data are compared with the results of the field test-drives.

## 2 Basic models of wheel-soil interaction

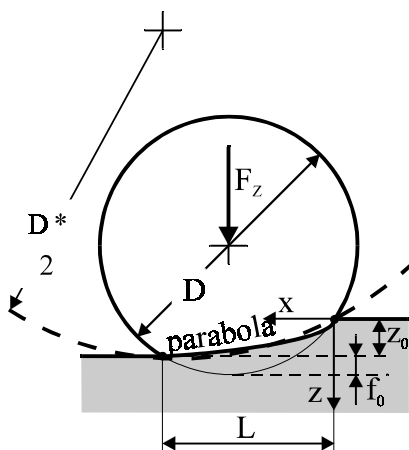
In order to prepare the wheel-soil interaction for simulation, the phenomena observed in reality have to be transferred into analytical models. At first the sinkage has to be determined.

### 2.1 Sinkage

A wheel on soft soil penetrates into the ground so deeply until the resultant ground pressure balances the wheel load  $F_z$ . Therefore the contact contour is very decisive, because the arising ground pressure  $p$  is a reaction of the vertical ground deformation  $z$  [1], [2] and can be described as

$$p = k \cdot z^n \quad (1)$$

where  $k$  means the *pressure module* and  $n$  is the *sinkage exponent*.



**Fig. 1:** Parabolic contact contour

The simulation model uses a parabolic shape [3] to approximate the contact contour of a surrogate wheel (diameter  $D^*$ ), that touches the ground tangential under the wheel. As advantage the parabolic shape leads to a proper mathematical description of pressure distribution  $p(x)$  and of sinkage  $z$ . These can be calculated by the following expressions, where  $L$  is the contact length and  $B$  is the width of the wheel.

$$z(x) = z_0 \cdot \sqrt{\frac{x}{L}} \quad \text{with } L = \sqrt{z_0 \cdot (D^* - z_0)} \quad (2)$$

$$F_Z = B \cdot \int_0^L p(x) dx \quad (3)$$

$$F_Z = B \cdot k \cdot z_0 \cdot L \cdot \frac{2}{n+2} \quad (4)$$

## 2.2 Rolling resistance

On soft soil the rolling resistance of a wheel results only to a small part from the energy absorption of the tire. Furthermore this energy loss is smaller than the energy loss with the same wheel load on a rigid road. This is, because on soft soil the vertical tire deflection  $f$  becomes smaller and the length  $L$  of the contact area becomes larger.

The major part of the rolling resistance on soft ground results from the energy absorption of the soil, which is caused by the compaction and deformation of the soil. Therefore the rolling resistance can be calculated from the plastic soil deformation under the wheel [1],[2].

$$R = B \cdot \int_0^{z_0} p(z) dz = B \cdot k \cdot \frac{z_0^{n+1}}{n+1} \quad (5)$$

## 2.3 Circumferential force

In opposite to the conditions on rigid road the circumferential force on soft soil is not limited by the friction between the wheel and the ground surface, but by the shear strength of the soil. Thereby in soft loose soil the maximum shear tension  $\tau_{\max}$  is not immediately available at the beginning of the contact area, but will be reached asymptotically with increasing shear displacement  $j$  [4].

$$\tau = \tau_{\max} \cdot \left(1 - e^{-j/K}\right) \quad (6)$$

$$\tau_{\max} = c + p \cdot \tan \varphi \quad (7)$$

The maximum circumferential force which can be transferred in the wheel-soil interaction is calculated by integration of the shear tension over the contact length.

$$U_{\max} = B \cdot \int_0^L \tau_{\max}(x) dx \quad (8)$$

$$U_{\max} = B \cdot L \cdot c + F_Z \cdot \tan \varphi \quad (9)$$

The last formula (equ. 9) points out that on soft soil the circumferential force not only depends on the wheel load  $F_Z$  but also on the size of the contact area  $A = B \cdot L$ . By reduction of the tire inflation pressure the tire deflection  $f_0$  increases in relation to the sinkage  $z_0$ . Thereby the diameter  $D^*$  of the surrogate wheel increases too. This leads to a longer contact length  $L$  (equ. 2). The proportions between tire deflection and sinkage  $f_0/z_0$  on the one hand and the two diameters  $D^*/D$  on the other hand are mutually dependent. They have to be determined iteratively [5]. Because of the enlarged contact length  $L$  the sinkage  $z_0$  decreases with constant wheel load (equ. 4) and therewith the rolling resistance is reduced (equ. 5). Furthermore the contact area becomes greater which also leads to the enlargement of the depending circumferential force (equ. 9). So it is obvious that the drawbar pull, which is the difference between circumferential force and rolling resistance, is affected favourably twice by a reduction of tire inflation pressure.

The mentioned models are implemented in the simulation system ORIS developed by IKK. They are a main part in the simulation of the wheel-soil interaction.

### **3 Preparations for simulation**

#### **3.1 Soil properties**

For the simulation of the wheel-soil interaction realistic soil properties are required. Especially to enable an expressive comparison between calculated and measured forces, these properties have to be investigated in nature on the test plant. Thereby the soil characteristics are usually divided into pressure firmness and shear firmness, and though there are two different methods of measurement.

For the inquiry of the pressure firmness, plates of different sizes were penetrated into the soil, while the pressure beneath the plate and the sinkage were measured. This provides the pressure module  $k$  and the sinkage exponent  $n$  [1], [2].

The cohesion  $c$  and the angle of internal friction  $\varphi$ , which represent the shear strength, were examined with the shear-pressure-cylinder, a surveying instrument, that has been developed by IKK [6].

The values of the soil properties often change stochastically over the test plant, so that extensive inquiries with a high number of samples have to be carried out to equalize this variations. In the present case the investigations were made for every test-drive on two or three places along the test way, so that more than twenty soil samples were taken and examined.

**Tab. 1:** Soil properties

Soil properties	loam	sand
pressure module $k$ [ $\text{N}/\text{cm}^{2+n}$ ]	9,6	8,3
sinkage exponent $n$ [-]	0,56	0,79
cohesion $c$ [ $\text{N}/\text{cm}^2$ ]	2,4	1,1
angle of internal friction $\varphi$ [ $^\circ$ ]	16,5	22

### 3.2 Test truck configuration

The test truck was a standard MAN type 451, which is usually used in the German armed forces. This truck is normally four-wheel driven, but for the test drives the drive shaft of the back axle was cut of. The differential in the front axle was locked up. Furthermore measurement equipment was built-in to measure and record the following values:

- speed
- rotational speed of front wheel
- torque in the front wheel drive shaft
- rut depth on front wheel and on back wheel

To measure the tractive force a second truck was connected with a towrope. After a short distance this truck started breaking and brought the test truck to a standstill, while the tractive force in the towrope was measured.

Modifications of the test truck as mentioned above, the changed value of mass and the displacement of the centre of gravity had been implemented in the simulation system ORIS. So in the simulation the original test truck was regarded for the driving on a ground with the

original soil properties. This ensures an expressive comparison between simulated and measured test data.

#### 4 Comparison of the test-drives

The comparison between simulated and experimental test-drives regards the circumferential force  $U$ , the rolling resistance  $R$  and the tractive force  $T$ . Thereby it has to be mentioned, that in the simulation the circumferential force and the rolling resistance are results, and the tractive force is calculated as the difference between these two forces. In contrast to this in the experimental test-drives the circumferential force and the traction were measured, and the rolling resistance was built as difference.

##### 4.1 Loam

In figure 2 the simulated and measured forces on loam are presented. The circumferential force is depicted as the total height of the bar. This bar, respectively the circumferential force, is divided into the rolling resistance (darker part at the bottom) and the traction (lighter part at the top). The forces at 2.5 bar and 1.5 bar tire inflation pressure are referred to the *normal case* with 7.5 bar inflation pressure (100%). The variations are described by percentage.

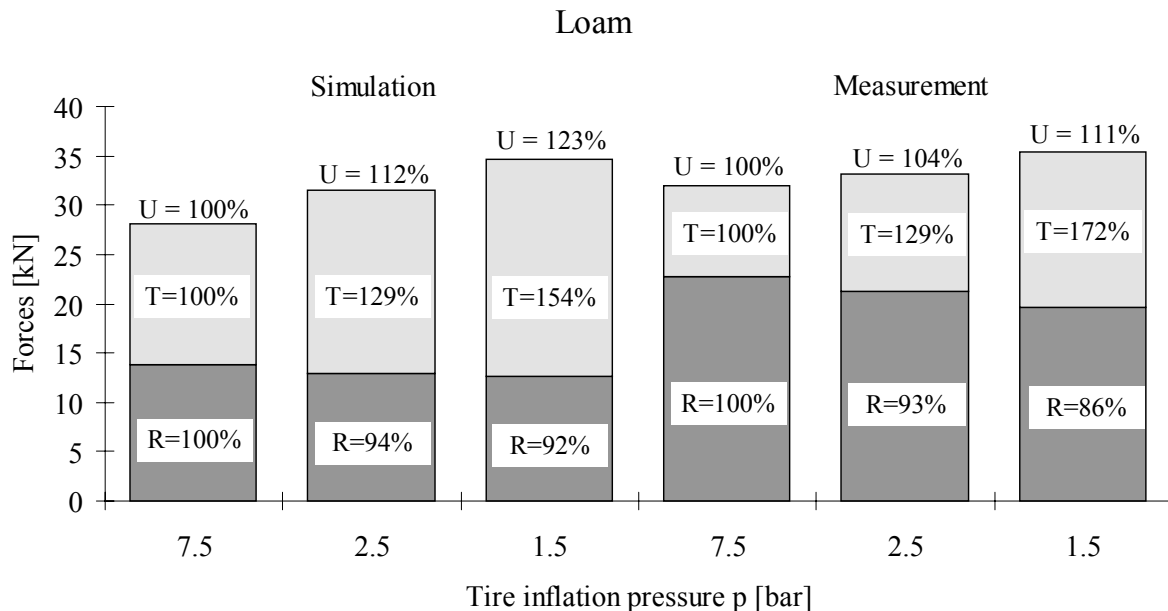


Fig. 2: Simulated and measured test-drives on loam

At first it can be seen, that the circumferential forces (height of the bars) are nearly the same in quantity at simulation and experiment.

In simulation the rolling resistance is smaller than in experiment, which can be explained by the incomplete modulation of the phenomena. In reality the rolling resistance is increased by the bow wave (bulldozing effect) in front of the wheel and the friction on the tire side walls. These two facts are not considered in the model (equ. 5) yet. But nevertheless the proportional reduction of rolling resistance is nearly the same. Thereby it has to be mentioned, that the influence of the bulldozing effect is reduced with smaller sinkage (less tire inflation pressure) and therefore the reduction of rolling resistance in experiment by 14% is higher than in simulation (- 8%).

The measured tractive forces are smaller than in simulation which depends on the increased rolling resistance in experiment. But the proportional enlargement again is very well rebuilt by the simulation.

#### 4.2 Sand

The comparison of the test-drives on sand leads to some differences.

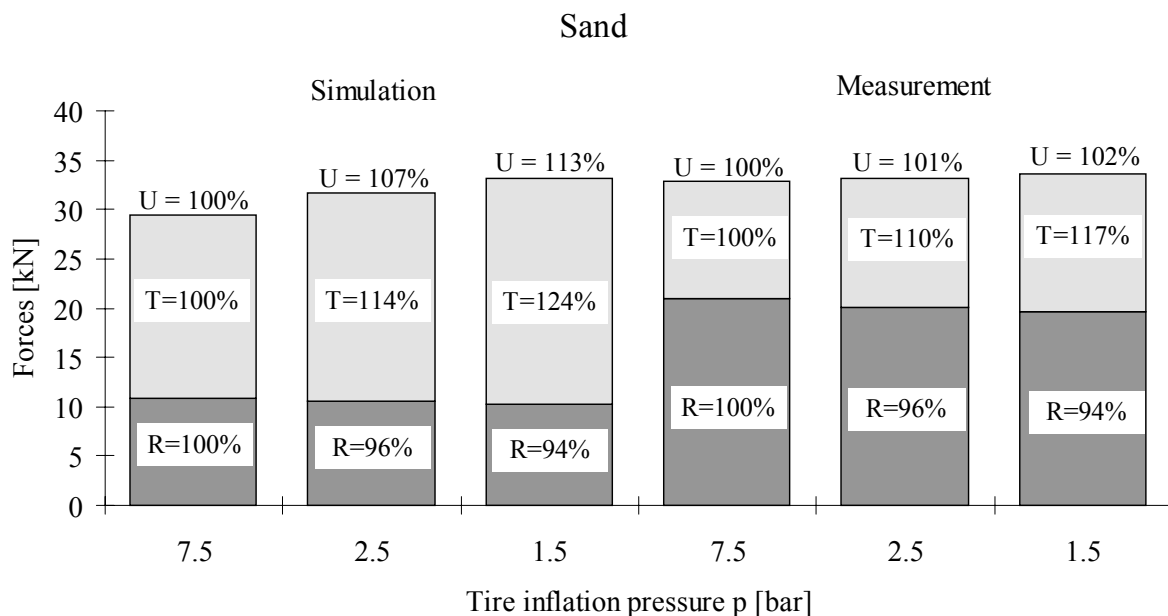


Fig. 3: Simulated and measured test-drives on sand

The increase of circumferential force with the reduction of the tire inflation pressure is

smaller than on loam. This depends on the lower cohesion in sand (equ. 9). Moreover the reduction of rolling resistance and therewith the enlargement of traction are smaller.

It is obvious that a reduction of tire inflation pressure to improve the traction is more effective on a loamy ground than on sand.

## **5 Conclusion**

The comparison between simulation and experiment shows the well known benefits of reduced tire inflation pressure, like smaller rolling resistance and higher traction. Furthermore an increase of circumferential force can be observed. The quality of these variations is very well simulated by ORIS, although the quantity of the rolling resistance is smaller in the simulation. This might be caused by the incomplete calculation models. In future, with an improvement of the calculation models the simulation will as well be able to reproduce the quantity.

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