Examination of Rolling Losses on Loamy Sand

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Abstract

The power loss of an off-road vehicle consists of the gear loss, the slip loss and the rolling loss. Off-road operations are important in many fields. Vehicle performance is affected by the tire-terrain interaction. In this study determination of coefficients of rolling resistances and rolling losses are discussed.

To implement the research objectives pulling tests were carried out on arable land. The main aim of the field measurements was to determine the rolling resistance factor and rolling losses on soils of various load-bearing capacities. The tests were carried out on the same field on soil in three different conditions: stubble, harrow-tilled stubble and subsequent tilling by cultivator. Measurements were also made on concrete.

The coefficients of rolling resistance in each measurement area were determined at various tire pressures. The coefficient of rolling resistance was between 0.010 and 0.021 on concrete, 0.066 and 0.078 on stubble, 0.026 and 0.086 on disc-tilled soil, and 0.140 and 0.153 on cultivator-tilled soil, depending on the tire pressure.

The measurement results demonstrate that rolling resistances and rolling losses varied exponentially with cone index. On loose soils, coefficients of rolling resistance and the rolling losses are higher than on a hard surface.

Key words: power loss, rolling loss

1. Introduction

Off-road operations are critical in many fields and the complexity of the tire-terrain interaction affects the vehicle performance (Kiss, 2003). The locomotion performance of a terrain vehicle depends on the load capacity (as known as CI-cone index) of the terrain and on the mobility of the vehicle.

In this paper determination of rolling resistance coefficients and rolling losses of an off-road vehicle is discussed.

Scientific investigations into wheel rolling resistances, power losses, and vehicle tractive performances have been taken up by many workers (Lyasko, 2010; Rebati & Loghavi, 2006; Kiss & Laib, 1999), and this subject continues to be of interest today.

2. Material and method

Pulling tests were made on an arable land to implement the research objectives by the Department of Automotive Technology of Szent István University. The main purpose of the field measurements was to determine the coefficients of rolling resistance and the rolling losses on soils of various load-bearing capacities (cone index).

The measurements were made on the same arable land in three different conditions: stubble, disc-tilled, and cultivated field. Comparative measurements were also made on concrete. The area of the test field was 30000 m^2. The measurements were carried out on a 10 m measurement section and 25 m approach and deceleration sections (Fig. 1). Four different tire pressures were set at each soil condition, so that there were four measurement sections on each area. During the measurements a John Deere 6600 tractor was the pulling vehicle, and a GAZ-69 was the pulled one.

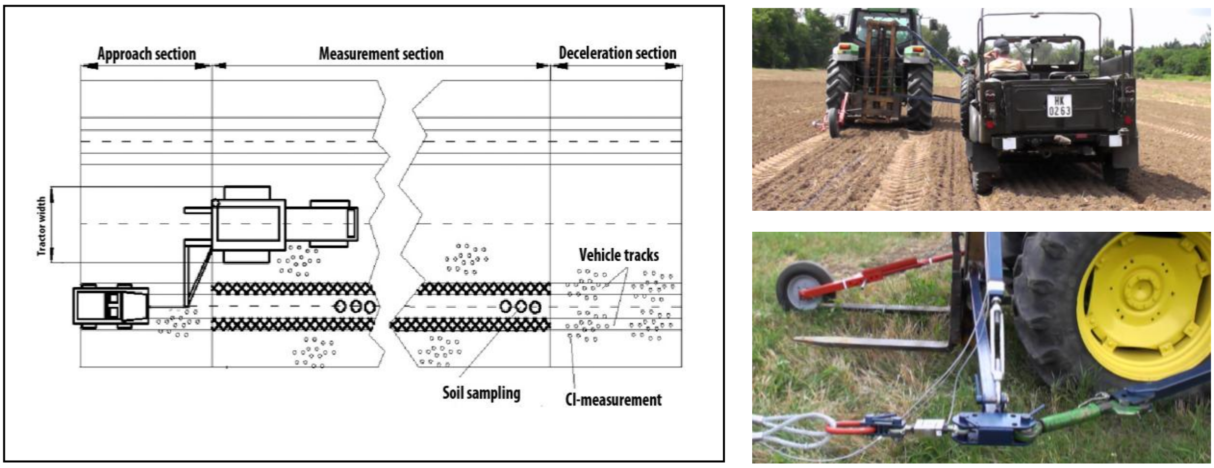

FIGURE 1: Measurement set-up and pulling test

2.1. Measurement on rigid surface

Comparative measurements were made on rigid, concrete surface as well. Comparing these with the measurements on agricultural land the losses of tire deformation can be determined. The pulled jeep was connected behind the tractor, and the pulling force and accelerations were measured.

2.2. Measurement on arable land

The special pulling device enabled the test jeep to roll over a virgin surface (Fig. 1). The main measurements were of rolling and gradient resistances, pulling forces, slip, and power losses. (Table 4-5).

To define the tractive power and the losses of the test vehicle, the first equation was used which describes that the tractive power is equal to the total of power losses (Kiss & Laib, 1999).

$$P_t = P_{rr} + P_{air} + P_g + P_i + P_{slip} \quad [kW] \tag{1}$$

where:

- $P_t = F_t \cdot v$ tractive power
- $P_{rr} = m \cdot g \cdot f_{rr} \cdot v \cdot \cos\alpha$ rolling loss
- $P_{air} = 0.5 \cdot A \cdot \rho_{air} \cdot c_w \cdot v^3$ air loss
- $P_g = \pm m \cdot g \cdot v \cdot \sin\alpha$ gradient loss
- $P_i = \pm \delta \cdot m \cdot v \cdot dv/dt$ inertia loss
- $P_{slip} = F_t \cdot slip \cdot v$ slip loss

Substituting into relation (1):

$$P_t = m \cdot g \cdot f_{rr} \cdot v \cdot \cos\alpha + 0.5 \cdot A \cdot \rho_{air} \cdot c_w \cdot v^3 \pm m \cdot g \cdot v \cdot \sin\alpha \pm \delta \cdot m \cdot v \cdot \frac{dv}{dt} + F_t \cdot slip \cdot v \tag{2}$$

Rearranging for rolling loss (P_{rr}):

$$P_{rr} = F_t \cdot v - 0.5 \cdot A \cdot \rho_{air} \cdot c_w \cdot v^3 \mp m \cdot g \cdot v \cdot \sin\alpha \mp \delta \cdot m \cdot v \cdot \frac{dv}{dt} - F_t \cdot slip \cdot v \tag{3}$$

where m is the vehicle mass, g is the acceleration of gravity and f_{rr} is the rolling resistance coefficient, dv/dt is the deceleration or acceleration, δ is the reduction constant of rotating masses, A is the cross-sectional area of the vehicle, c_w is the vehicle's drag coefficient, v is the vehicle's velocity, α is the slope angle, and ρ_{air} is the air density.

Table 1 gives the parameters of the pulled vehicle, and Fig. 2 depicts the used jeep.

TABLE 1: Vehicle parameters

Vehicle Type	GAZ-69 (69A)		
Own Weight	m_o	1520	kg
Mass on the front axle	m_f	810	kg
Mass on the rear axle	m_r	710	kg
Length	L_l	3850	mm
Width	W	1750	mm
Height	H	2030	mm
Wheelbase	L_w	2300	mm
Track	L_t	1440	mm
Tire Type	Taurus 6.50-16"		(coll)
Wheel Diameter	D	710	mm
Wheel Breadth	B	165	mm
Section Height	h	152	mm
Tire Deformation	δ	~35	mm

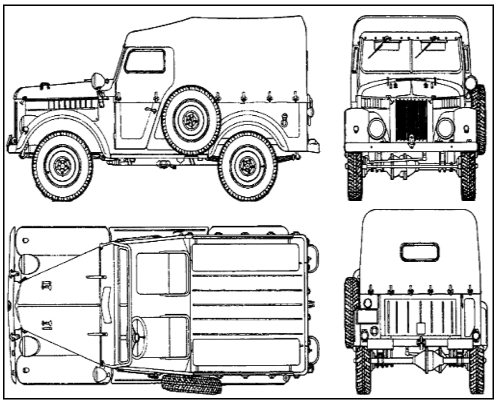

FIGURE 2: Pulled vehicle (GAZ 69)

2.3. Measurement procedure

The measurement section was surveyed and marked out with posts and ropes. The route of the towed vehicle and the profile base point were marked out. The soil profile was recorded on the designated track at 10 cm intervals, with 101 measurements on each wheel track path before and after towing. Soil samples were taken from the soil surface using three sampling cylinders. The cone index values were measured on the vehicle tracks before and after the test. The moisture content was measured by in-situ device beside every soil sampling point. The tractor and jeep were set up on the marked-out section. The vehicle was towed at 10 km/h. The soil mechanics measurements were repeated after the vehicles had traversed the test section. The measurement data were stored and assessed.

2.4. Used devices

The following devices were used during the measurements: drawbar mechanism for pulling, 5-tonne load cell for tractive force measurement, 3-axis acceleration sensors, Spider-8 data logger and measurement computer, revolution counter, Eijkelkamp-type penetrologger for measuring the load-bearing capacity of the soil (described by the cone index, CI), SMM1-type field soil moisture meter, terrain profile meter, soil sampling cylinders for laboratory measurements, wheel load weighers to measure vehicle weight.

3. Results

Table 2 gives the physical properties of the soil of test field. These results were evaluated in the laboratory of soil sciences. Table 3 shows the constants that were used for the calculations. Table 4 describes the travel resistances on each soil conditions that were evaluated. This table also gives the measured parameters, like tractive force, slope angle, slip, coefficient of rolling resistances, cone index, and tire inflation pressure. The travel resistances are the rolling resistance, slip resistance and gradient resistance. The air resistance was constant and there wasn't accelerating during the measurements.

TABLE 2: Physical properties of the test field

Field condition:		Stubble-filed	Disc-tilled	Cultivated
Soil type:		Loamy sand		
Moisture content (mass %)	**[%]**	15.8	11.5	10.8
Pore volume	**[%]**	36.0	38.0	42.0
Bulk density	**[g/cm^3]**	1.61	1.65	1.52
Vegetation:	**-**	Stubble+weeds	A few weeds	No plants

TABLE 3: Constant values

m_v = 1600 kg	Weight of vehicle (with driver)
A = 2.923 m^2	Front surface of vehicle
c_w = 0.43	Vehicle's shape factor
ρ_{air} = 1.29 kg/m^3	Air density
v = 10 km/h = 2.78 m/s	Traction velocity
g = 9.81 m/s^2	Gravitational acceleration
F_{air}= 6.266 N	Air resistance (at constant speed)
F_i=0	(During the measurement there wasn't accelerating)

TABLE 4: Evaluation of the travel resistances

	TIP [bar]	**F_t [N]**	**α [°]**	**slip [%]**	**f_{rr} [-]**	**CI [N/mm^2]**	**F_g [N]**	**F_{slip} [N]**	**F_{rr} [N]**
Concrete	1.5	336.1	0	0.6	0.021	80	0	2.0	327.8
	1.8	258.1	0	1.1	0.016	80	0	2.8	248.9
	2.1	211.2	0	1.9	0.013	80	0	4.1	200.9
	2.4	167.7	0	2.9	0.010	80	0	4.8	156.5
Stubble field	1.5	1326.8	0.92	2.8	0.066	1.078	252.0	37.1	1031.3
	1.8	1583.5	1.10	2.8	0.078	0.880	301.3	44.3	1231.5
	2.1	1527.3	1.17	2.8	0.074	0.618	320.4	42.7	1157.7
	2.4	1463.4	0.90	3.0	0.074	1.163	246.5	43.9	1166.6
Disc-tilled field	1.5	749.2	1.13	2.8	0.026	1.772	309.5	20.9	412.4
	1.8	1438.7	0.91	2.8	0.073	1.466	249.2	40.2	1142.8
	2.1	1378.6	1.22	2.8	0.064	1.795	334.1	38.6	999.5
	2.4	1693.2	1.07	2.8	0.086	1.469	293.1	47.4	1346.4
Cultivated field	1.5	2817.4	1.21	4.8	0.149	0.699	331.4	135.2	2344.4
	1.8	2876.6	1.29	4.8	0.152	0.722	353.3	138.0	2378.8
	2.1	2667.4	1.22	4.8	0.140	1.025	334.1	128.0	2198.9
	2.4	2841.7	1.11	4.8	0.153	0.882	304.0	136.4	2394.9

Table 5 summarizes the power losses that were evaluated from the travel resistances on each soil condition and on concrete as well. The effective power losses are the gradient loss, slip loss and rolling loss. The air loss was constant and very small (P_{air} = 0.017 kW).Table 5 shows the relation between the cone index and the power losses. The looser structure the soil has the higher cone index value appears. As the cone index increased the power losses increased as well. The most significant loss is the rolling loss as it can be seen in Table 5.

TABLE 5: Evaluation of the power losses

	TIP [bar]	CI [N/mm^2]	P_t [kW]	P_g [kW]	P_{slip} [kW]	P_{rr} [kW]
Concrete	1.5	80	0.934	0	0.006	**0.911**
	1.8	80	0.718	0	0.008	**0.692**
	2.1	80	0.587	0	0.011	**0.559**
	2.4	80	0.466	0	0.013	**0.435**
Stubble field	1.5	1.078	3.689	0.701	0.103	**2.867**
	1.8	0.880	4.402	0.838	0.123	**3.424**
	2.1	0.618	4.246	0.891	0.119	**3.218**
	2.4	1.163	4.068	0.685	0.122	**3.243**
Disc-tilled field	1.5	1.772	2.083	0.860	0.058	**1.146**
	1.8	1.466	4.000	0.693	0.112	**3.177**
	2.1	1.795	3.833	0.929	0.107	**2.779**
	2.4	1.469	4.707	0.815	0.132	**3.743**
Cultivated field	1.5	0.699	7.832	0.921	0.376	**6.517**
	1.8	0.722	7.997	0.982	0.384	**6.613**
	2.1	1.025	7.415	0.929	0.356	**6.113**
	2.4	0.882	7.900	0.845	0.379	**6.658**

5. Conclusions

At different tire pressures the coefficient of rolling resistances, the slip values and the slope angles were determined on each measurement area. Cone index values were also determined at the same time. The tractive forces were measured by a force meter and a data logger at each field condition at varying tire pressures. The travel resistances (rolling resistance, slip resistance, air resistance and gradient resistance) were evaluated from the measured data. The power losses (rolling loss, slip loss, gradient loss and air loss) were calculated from the travel resistances and the measured vehicle speed.

In Table 4 it can be seen that the coefficient of rolling resistances increased when the cone index values increased as well. Depending on the tire pressure the coefficient of rolling resistance changed between 0.010 and 0.021 on concrete, 0.066 and 0.078 on stubble, 0.026 and 0.086 on disc-tilled field, and 0.140 and 0.153 on cultivated field. Moving on a soft soil the rolling resistance, as travel resistance is higher than on hard surface. To reduce the travel resistances power is needed, it means that the vehicle looses power from its tractive performance.

Cone index values were highest on disc-tilled land, followed by stubble and cultivated area. The high result after harrowing was because the tractor compacted the ground then broke it up only in 10-15 cm depth. The stubble hadn’t been touched since the previous harvesting, so the soil had looser structure than on the harrowed area. The cultivated field had also been passed over by an agricultural machine. The depth of the tillage was 15-20 cm which means that the soil was broken up to a greater spread.

Table 5 gives the values of power losses at each measurement area at different tire pressures. The significant loss is the rolling loss, the others are not relevant beside these. The table shows that the higher the cone index values the higher the rolling losses.

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