TASC

© **Tyres / Tracks And**
Soil Conservation *

Soil Compaction, Soil Shearing and Fuel Consumption: A Practical Tool for Desision-Making in Farming and Forestry

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Programming
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* former TASC designation *Tyres/Track And Soil Compaction*

Outline

Part 1 - Soil compaction

- Introduction – Problem
- Valuation principle
- Topsoil hardness
- Contact pressure and contact surface
- Stress propagation
- Indicative values
- Stress limits
- Solutions

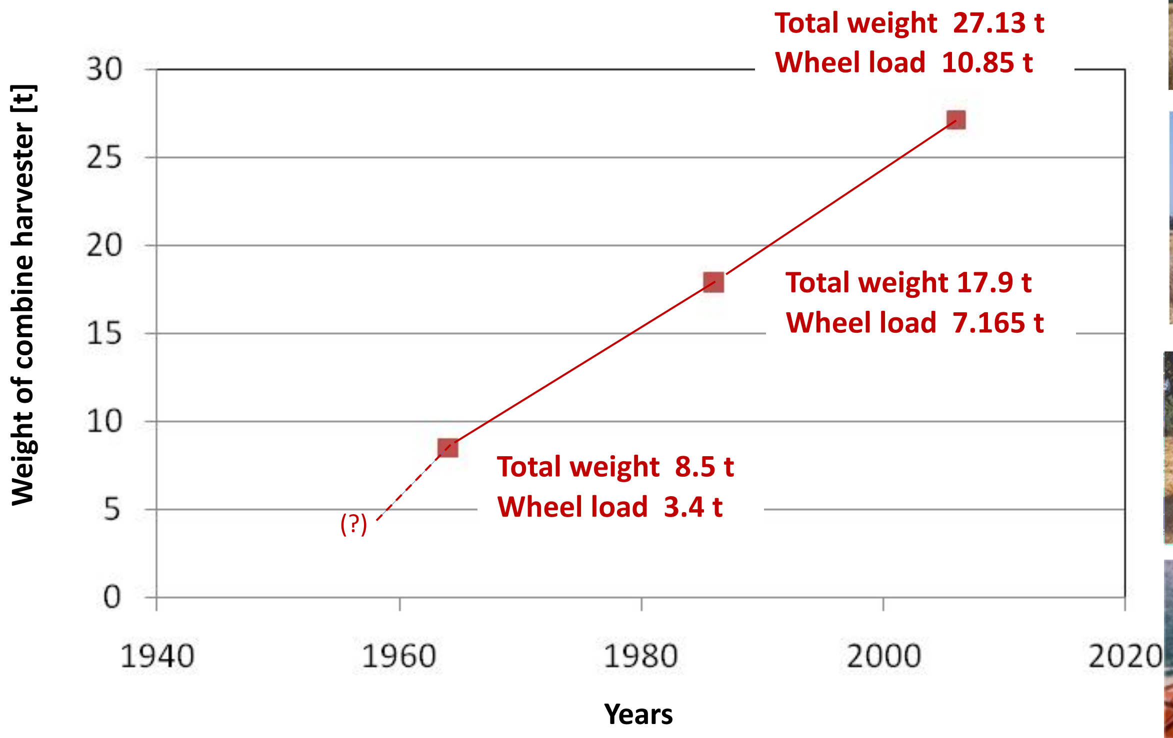
Part 2 - Slip, traction force, soil failure and fuel consumption

- Introduction – Problem
- Valuation principle
- Soil-tyres interaction model
- Soil shearing
- Traction-slip curve
- Traction force
- Fuel consumption
- Solutions

TASC – flow chart

Part 1 - Soil compaction

Size and power evolution of combine harvester



2006 – Claas Lexion 770
800/65R32 / 600/65R28
11.97 m (vario) / 261 kW

1986 – New Holland TX 34
30.5L32 / 16.70-20
5.18 m / 151 kW

1964 – Claas Matador Gigant
15-30AS
2.5 m / 88 kW

1960 –

Topsoil…

Source: L. Volk FH Soest

Ruts

Subsoil damages

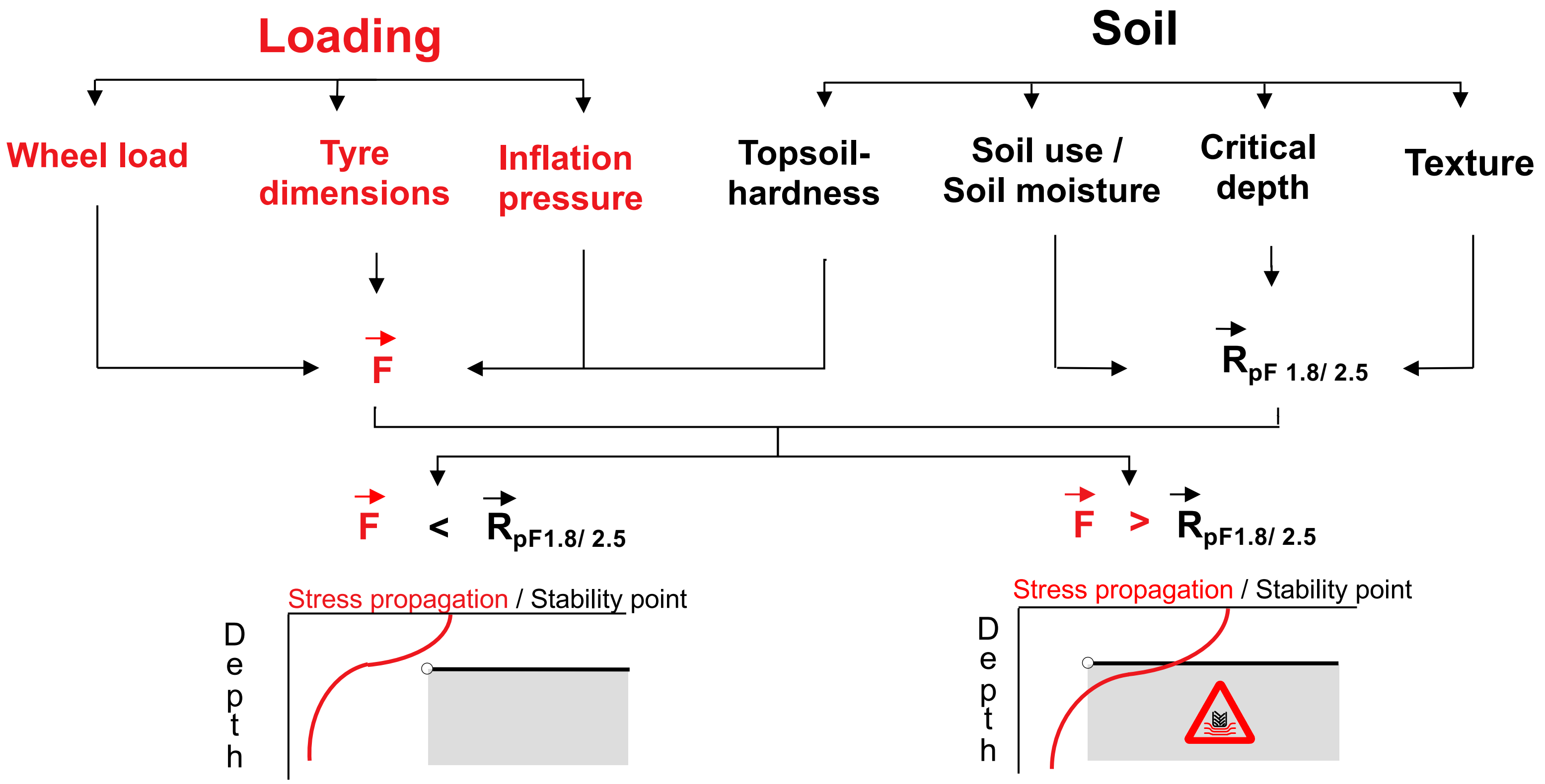
Forestry

Source: WSL

Agriculture

Soil deformation in the depth
Asphyxiation

TASC - Basic principle - Compaction damage at the subsoil (below the critical depth)



$\vec{F}$ = Loading

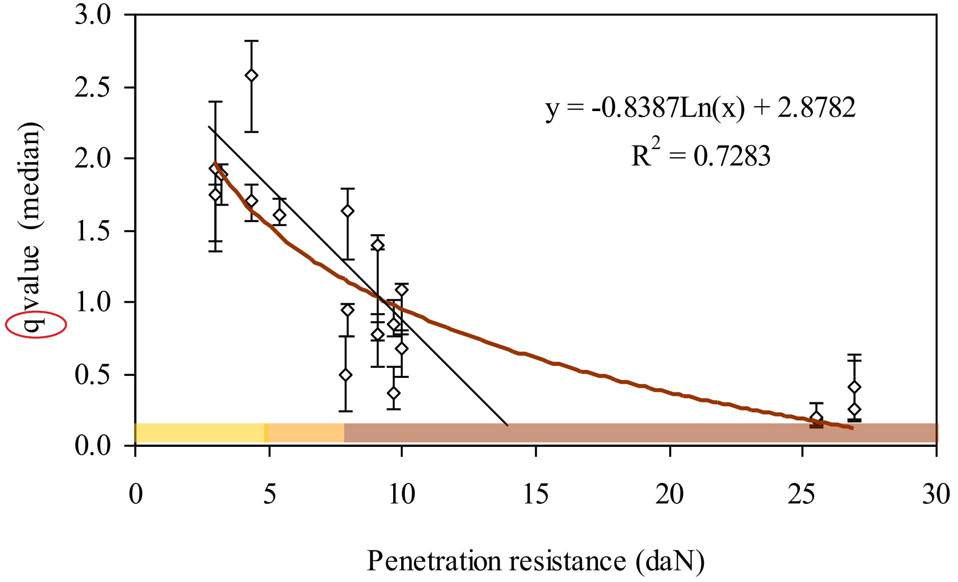
$\vec{R}_{pF1.8/\ 2.5}$ = max. permissible soil stability pF1.8/ 2.5

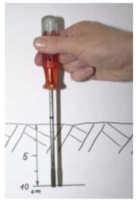
Topsoil hardness and vertical stress propagation σ_Z

$$\sigma_z = \frac{2q\sigma_m}{\pi}\left[\arctan\frac{ab}{Rz} + \frac{abz}{R}\left(\frac{1}{a^2+z^2} + \frac{1}{b^2+z^2}\right)\right] \quad \text{with} \quad R^2 = a^2 + b^2 + z^2$$

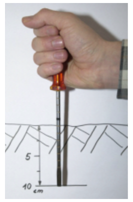
according to Boussinesq (basic algorithm)

TASC V4.0.xls q: Factor for the topsoil hardness

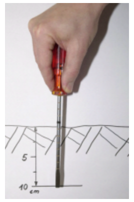




1.73 = soft
39 N



1.26 = semi-firm
69 N



0.81 = firm
118 N

Screwdrivertest

(Soil&Tillage 102 (2009) 138-143)

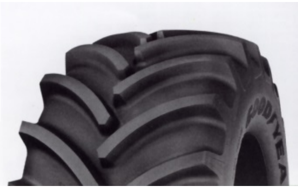
Contact pressure σ_m and contact surface A

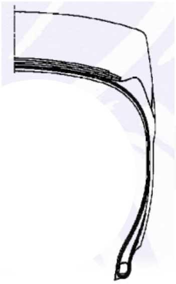
$$\sigma_z = \frac{2q\sigma_m}{\pi}\left[\arctan\frac{ab}{Rz} + \frac{abz}{R}\left(\frac{1}{a^2+z^2} + \frac{1}{b^2+z^2}\right)\right]$$

with $R^2 = a^2 + b^2 + z^2$

according to Boussinesq (basic algorithm)

Traction tyres





$A\,[m^2] = f\,(b\,[m],\, d\,[m],\, F\,[kN],\, P_i\,[kPa])$

Firm soil

b/d < 0.6 $A = 0.191\ bd + 0.460 \cdot 10^{-3}\ F - 14.8 \cdot 10^{-5}\ Pi$ $n = 22;\ R^2 = 0.973;\ p_{BD}=0.000;\ p_F = 0.004;\ p_{Pi} = 0.031$

b/d ≥ 0.6 $A = 0.187\ bd + 0.382 \cdot 10^{-3}\ F - 28.4 \cdot 10^{-5}\ Pi$ $n = 42;\ R^2 = 0.950;\ p_{BD}=0.000;\ p_F = 0.004;\ p_{Pi} = 0.069$

Biosystems Engineering 110 (2011) 73-82

Soft soil

b/d < 0.6 $A = 0.247\ BD + 0.582 \cdot 10^{-3}\ F - 19.3 \cdot 10^{-5}\ Pi$ $n = 7;\ R^2 = 0.949;\ p_{BD}=0.109;\ p_F = 0.134;\ p_{Pi} = 0.536$

b/d ≥ 0.6 $A = 0.127\ BD + 0.498 \cdot 10^{-3}\ F - 89.0 \cdot 10^{-5}\ Pi + 0.172$ $n = 29;\ R^2 = 0.917;\ p_{BD}=0.000;\ p_F = 0.000;\ p_{Pi} = 0.000$

Encyclopedia of agrophysics, Springer, 2011

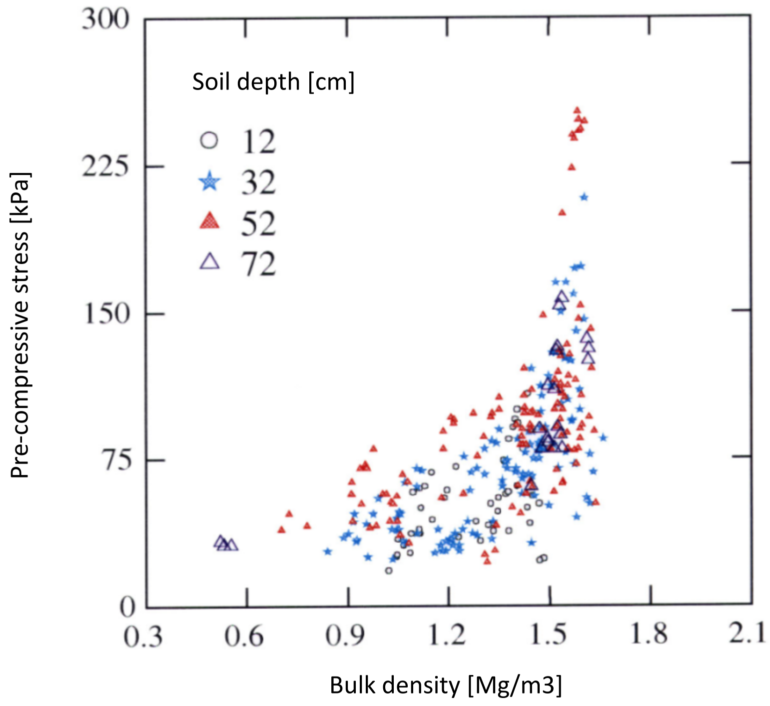
A: contact area; b: tyre width; d: tyre diameter; F: wheel weight; Pi: inflation pressure

Indicative values

Effective bulk density δ_{eff} **$\delta_{eff} = \delta_s + 0.009 \cdot C$** where: δ_s = bulk density [g/cm³] C = Clay content [%]

Indicative values δ_{eff} **for arable soil : 1.7 g/cm³**
for forest soil : 1.5 g/cm³

Relationship pre-compressive stress versus bulk density δ_s



Source: Quasem et al. 2000

Stress limits and texture under wet and dry soil conditions

Classes of texture	Soil stability limit [kPa] Forest soil pF 1.8	Soil stability limit [kPa] Forest soil pF 2.5	Soil stability limit [kPa] Agricultural soil pF 1.8	Soil stability limit [kPa] Agricultural soil pF 2.5
Clay soil 45 % C	55	70	80	95
Sily soil 15 % C, 80 % U	60	85	105	130
Clay loam, loam 21 % C	50	70	85	110
Sandy loam, loamy sand 11 % C	65	90	110	145
Sand 5 % C	75	110	130	170

Stress propagation and soil hardness - a clay and sand soil, semi-firm and firm

1964 – Claas Matador Gigant

1986 – New Holland TX 34

2006 – Claas Lexion 770

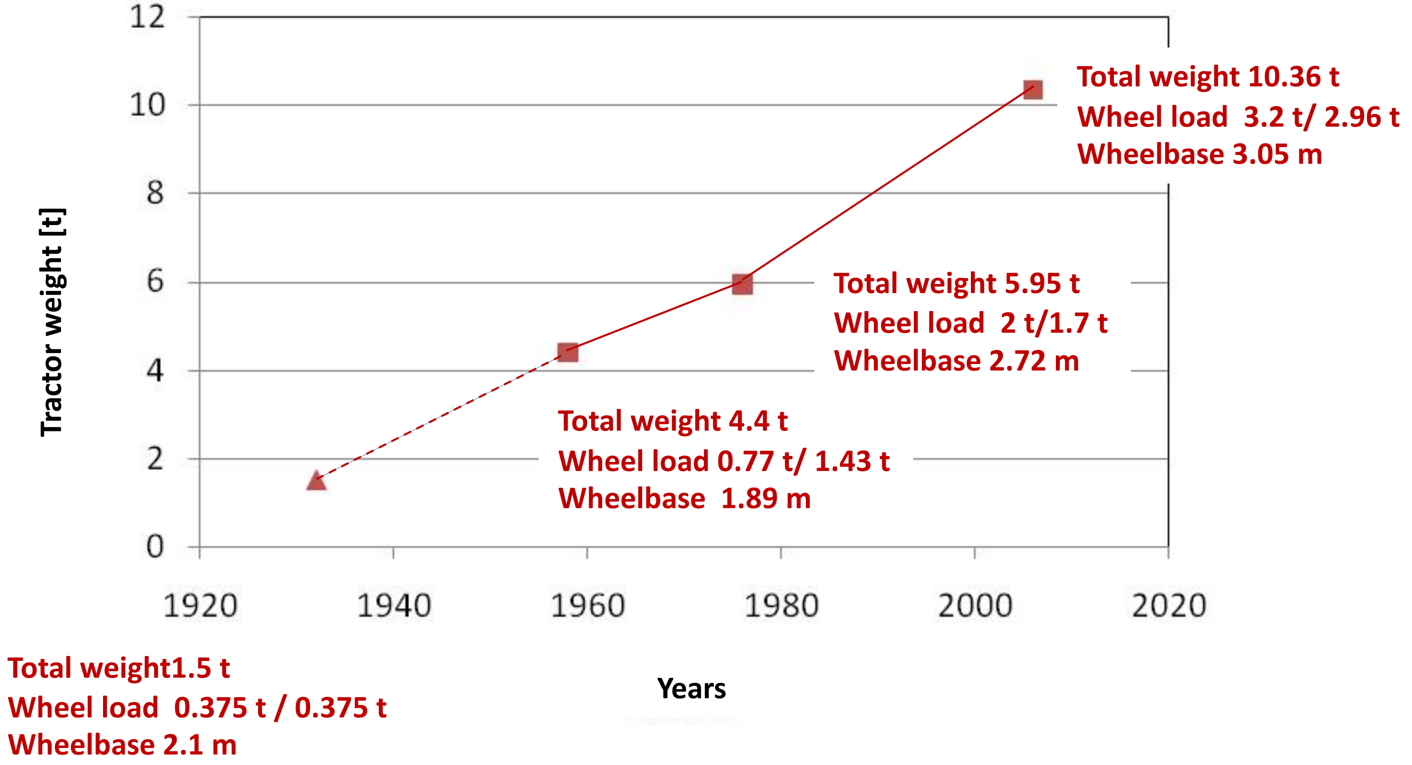
Max. tilling depth : 25 cm

soil hardness	semi firm 69 N				semi firm 69 N				semi firm 69 N			
soil moisture	dry pF 2.5		wet pF 1.8		dry pF 2.5		wet pF 1.8		dry pF 2.5		wet pF 1.8	
soill texture	clay	sand	clay	sand	clay	sand	clay	sand	clay	sand	clay	sand
soil pressure [kPa]	115				130				160			
critical depth [cm]	19	0	24	8	33	0	40	18	46	18	53	32

soil hardness					**firm 118 N**		**firm 137 N**		**firm 147 N**		**firm 167 N**	
soil moisture					dry pF 2.5		wet pF 1.8		dry pF 2.5		wet pF 1.8	
soil texture					clay	sand	clay	sand	clay	sand	clay	sand
soil pressure [kPa]					144				178			
critical depth [cm]					21	0	23	0	22	0	22	0

Part 2 - Slip, traction force, soil failure and fuel consumption

Size and power evolution of the tractors



2006 - Fendt vario 936
600/65R34 / 710/70R42
100/80 kPa
261 kW

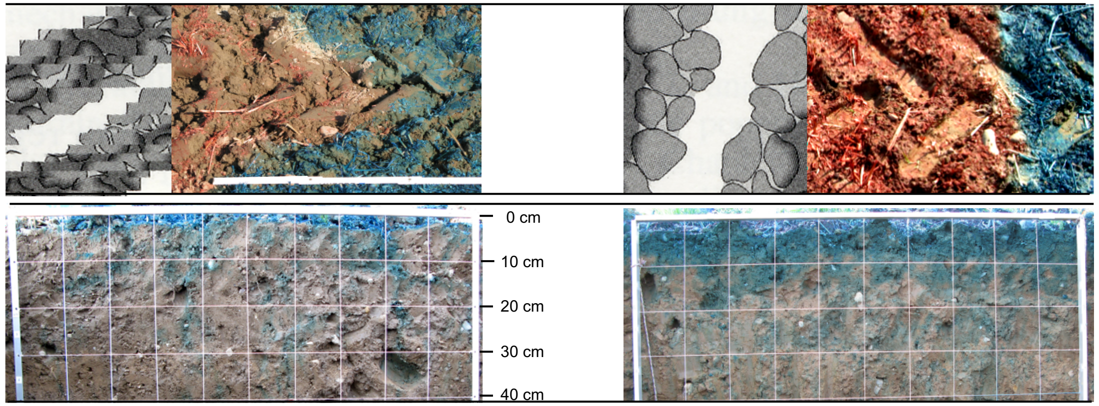
1976 - Fendt 614 SL
16.9R26 / 20.8R38
130/100 kPa
100 kW

1958 - John Deere 830
7.5-18 / 18.4-34
250/80 kPa
56 kW

1936 - Massey-Harris 101S
5.5-16 / 11.2-24
100/100 kPa
23 kW

Impact on the topsoil

Impact on the subsoil



Blue dye ** [Area distribution %]		
Depth	25 % slip	0 % slip
0.0 - 0.1 m	21,84	81,00
0.1 - 0.2 m	15,10	49,02
0.2 – 0.3 m	8,56	40,08
0.3 – 0.4 m	4,74	22,48

Water infiltration ksat [10^{-2} m/day]		
Depth	25 % slip	0 % slip
0.0 - 0.1 m	0.50	18.12
0.1 - 0.2 m	0.74	5.39
0.2 – 0.3 m	-	-
0.3 – 0.4 m	3.58	8.13

* Tractor H488 65 kW - 25 % slip

** stubble, loam soil

TASC - Basic principle - Shearing damage at the topsoil

Loading

- **Wheel load**
- **Tyre properties**
- **Tractor configuration**

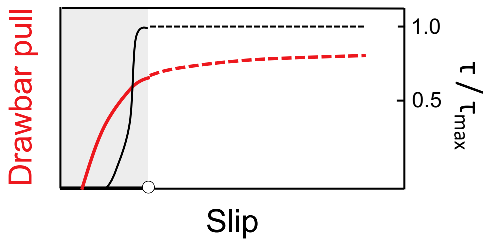
Soil

- **Lug depth**
- **Hardness**
- **Cohesion**
- **Texture**

↓

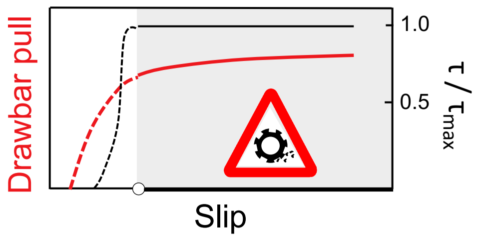
τ Shear strenght

$\tau / \tau_{max} < 1$



elasto-plastic zone
not irreversibly sheared soil

$\tau / \tau_{max} = 1$

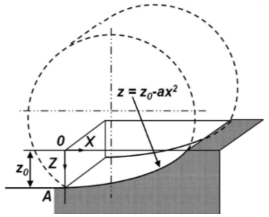


plastic zone
Irreversibly sheared soil

Failure condition : $\tau = \tau_{max}$, f (cohesion and texture)

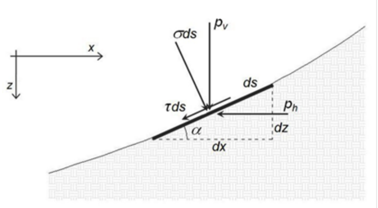
Soil-tyres interaction model

I – Soil-tyre contact surface z_0, a

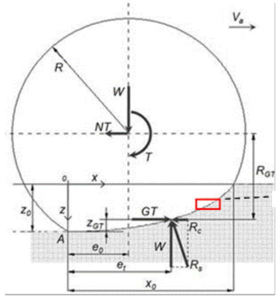


(Osetinsky & Shmulevich; 2004)

II – Stress distribution σ, τ along the contact surface



III – Gross traction *GT*, net traction *NT*, soil compaction resistance R_c, driving torque *T* and Power *P*



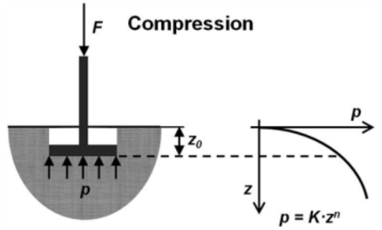
(Osetinsky A., Shmulevich I., 2004)

Soil-tyres interaction model

I – Soil-tyre contact surface z_0, a

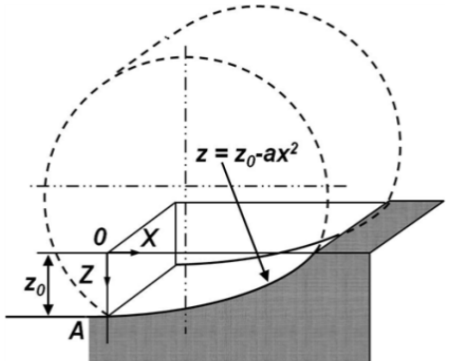
Friction modulus of deformation - K_φ and cohesive modulus of deformation K_c of the soil

$$p_s = \left(\frac{K_c}{b} + K_\varphi\right) z^n$$



Wheel load or total soil reaction

$$W = \frac{K_c + bK_\varphi}{3} z_0^n \sqrt{\frac{z_0}{a}} (3-n)$$



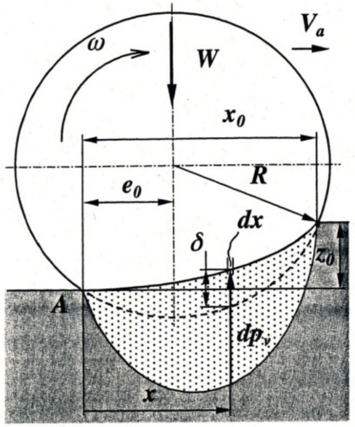
Wheel load from tyre parameters

$$W = \int_0^{x_0} K_v \delta dx$$

$$K_v = \frac{W}{R^2 \arcsin\left(\frac{x_0}{2R}\right) - \frac{x_0}{2}\left(R - \frac{W}{K_{carc} + \Delta K_P P_i}\right)}$$

Implicite solution for z_0 and a

$$W = K_v \left\{ \frac{a x_0^3}{3} - \sqrt{R^2 - e_0^2}\left(x_0 - \frac{e_0}{2}\right) + \frac{x_0 - e_0}{2}\sqrt{R^2 - (x_0 - e_0)^2} + \frac{R^2}{2}\left[\arcsin\left(\frac{x_0 - e_0}{R}\right) + \arcsin\left(\frac{e_0}{R}\right)\right] \right\}$$



(Osetinsky A., Shmulevich I., 2004)

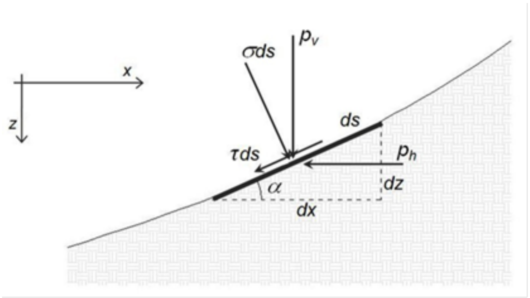
Soil-tyres interaction model

II – Stress distribution along the contact surface, σ, τ and slip i, i_f, i_r

Vertical and horizontal components of the elementary force p_v and p_h

$p_h = (\sigma ds)\sin\alpha - (\tau ds)\cos\alpha$ with $ds \sin\alpha = b dz$

$p_v = (\sigma ds)\cos\alpha + (\tau ds)\sin\alpha$ with $ds \cos\alpha = b dx$



Shear stress τ , normal stress σ and soil displacement *j*

$\tau = (c + \sigma tan\varphi)(1 - e^{-j/k})$ $\quad \sigma = \frac{\sigma_v - c(1 - e^{-j/k})2ax}{1 + tg\varphi(1 - e^{-j/k})2ax}$ with $\sigma_v = \frac{dp_v}{bdx} = \frac{K_v \delta}{b}$

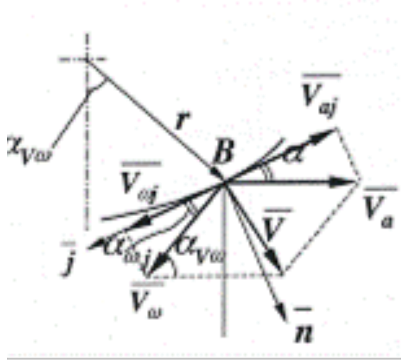
with $j = \int_0^t V_j dt$ with $V_j = V_{\omega j} - V_{aj}$

Slip *i*

$i = \frac{\omega R_r - V_a}{\omega R_r}$ with R_r as rolling radius

Slip of the front wheel- i_f slip of the rear wheel i_r

$i_f = i_r$



(Osetinsky A., Shmulevich I., 2004)

Soil-tyres interaction model

III – Gross traction *GT*, net traction *NT*, soil compaction resistance R_c, driving torque *T* and Power *P*

Gross traction *GT*

$$GT = \int_0^{x_0} p_h = \int_x^{x_0} \frac{\sigma_v\left[2ax - \tan\varphi\left(1-e^{-j/k}\right)\right] - c\left(1-e^{-j/k}\right)\left[(2ax)^2+1\right]}{1+2ax\left(1-e^{-j/k}\right)\tan\varphi} b\,dx$$

Soil compaction resistance R_c

$$R_c = \int_0^{z_0} p_z b\,dz = \left(K_c + bK_\varphi\right)\frac{z_0^{n+1}}{n+1}$$

Net traction *NT*

$NT = GT - R_c$

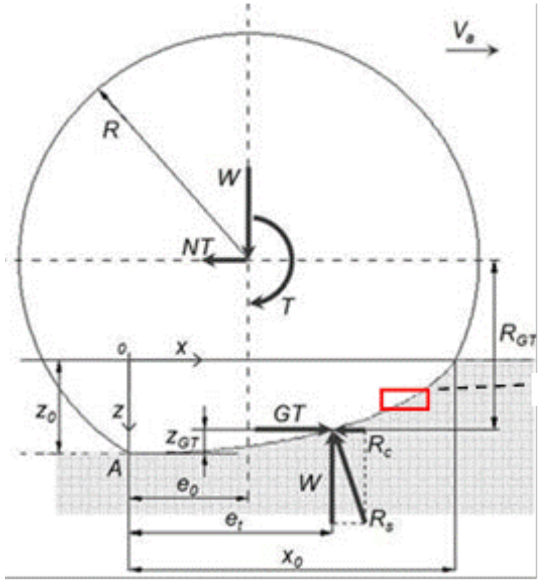
Driving torque *T*

$$M_r = W(e_t - e_0) \quad \text{with} \quad We_t = \int_0^{x_0} K_v \delta x\,dx$$

$$M_{GT} = GT \cdot R_{GT} \quad \text{with} \quad R_{GT} = \sqrt{R^2 - e_0^2} - z_{GT} \qquad T = M_{GT} + M_r$$

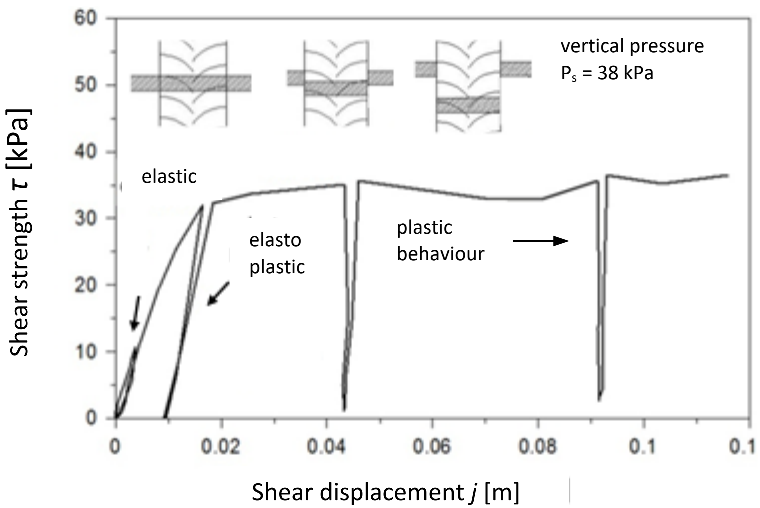
Net power P_{NT}, power on wheels P_{GT}

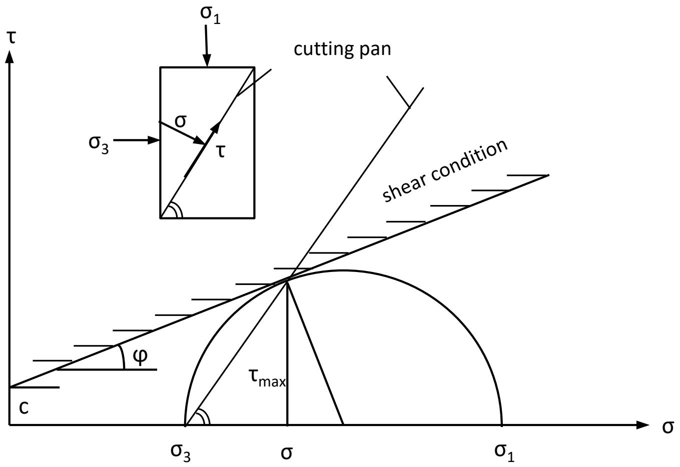
$$P_{NT} = NT \cdot V_a \qquad P_{GT} = T \cdot \omega$$



(Osetinsky A., Shmulevich I., 2004)

Soil shearing - conditions





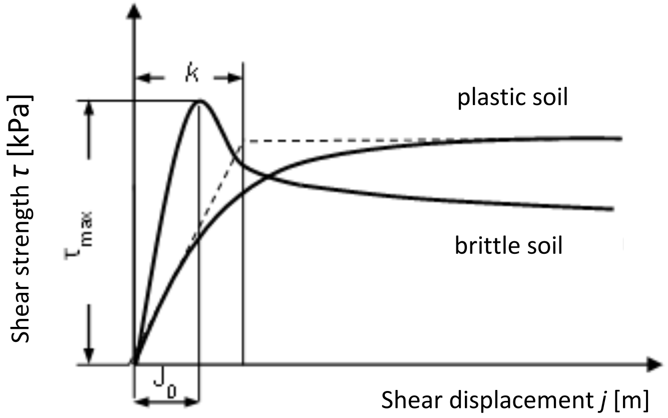
$$\tau_{max} = (c + \sigma \tan\varphi)$$

$$\tau = (c + \sigma \tan\varphi)\left(1 - e^{-j/k}\right)$$

an approximation with:

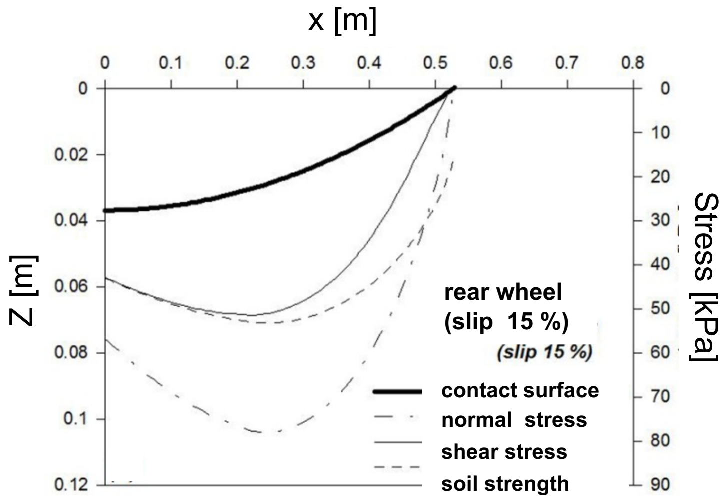
$$\frac{\tau}{\tau_{max}} = \left(1 - e^{-\frac{j}{k}}\right) = 0.99$$

$$\frac{j}{k} = 4.6$$

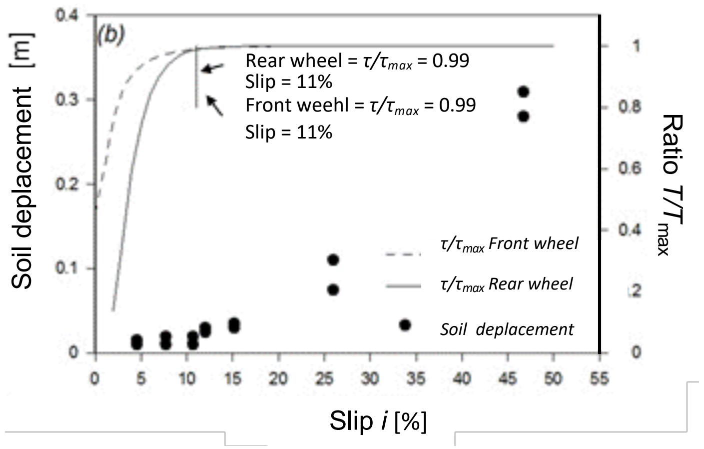


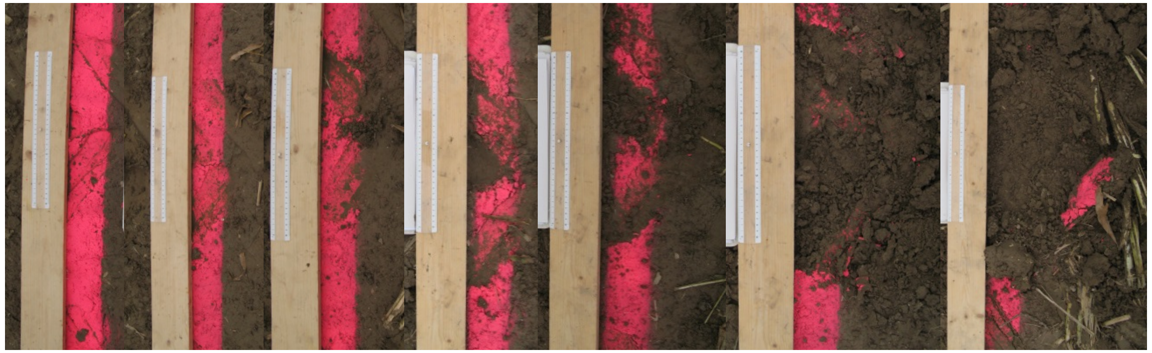
Soil shearing – measurements and simulation

Tractor: 65 kW
Total weight 4 t.
Inflation pressure : 0.6 bar
Soil: 27 % C; 53 % U; 20 % S



Soil shearing – measurements and simulation

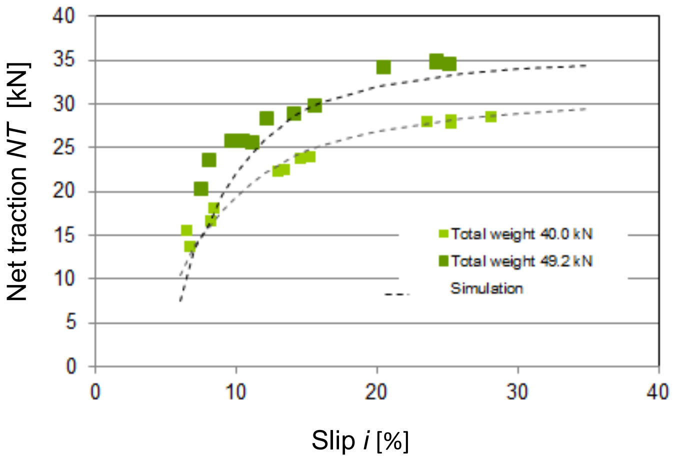




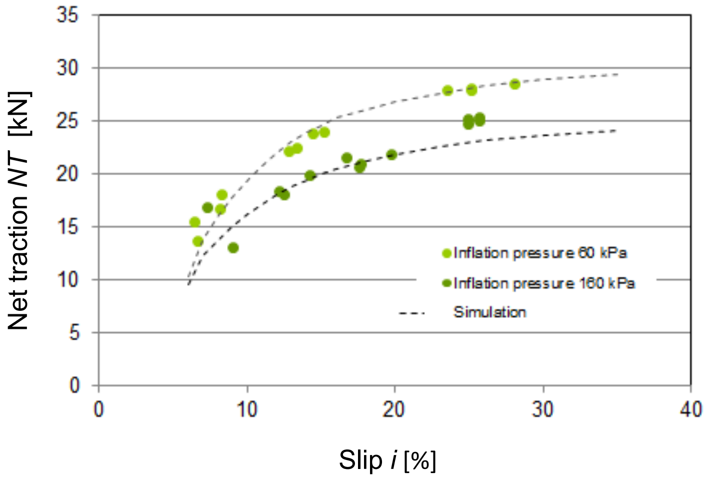
Slip [%]	0	8	11	15	20	25	30
Soil displacement [cm]	0	1	2	3	4	11	28

Traction slip curves

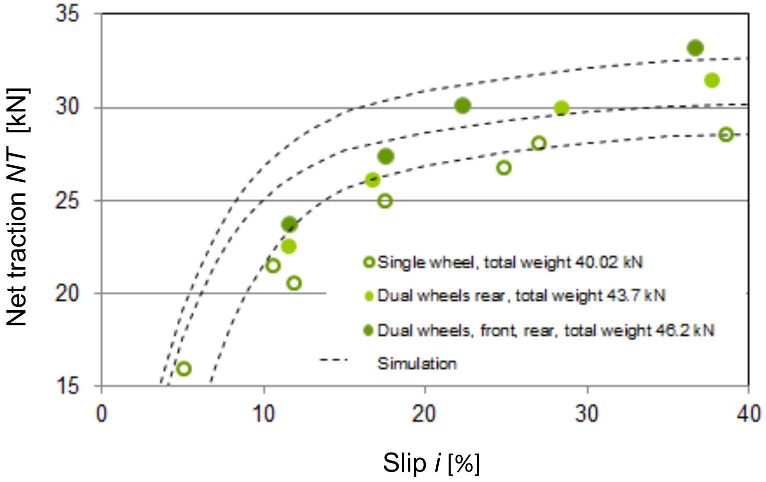
Influence of the total weight…



Influence of the inflation pressure…

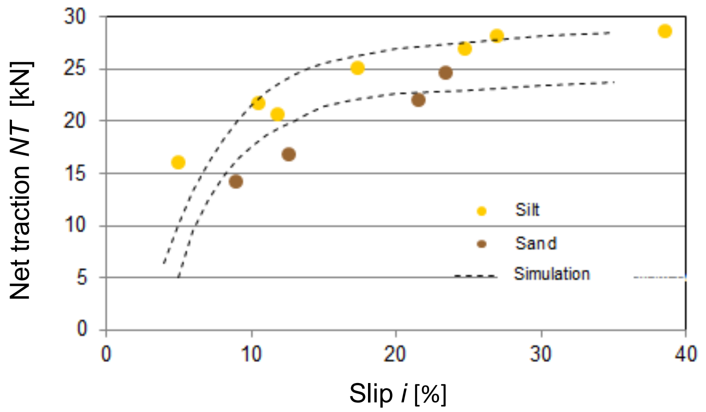


Influence of the dual wheels…

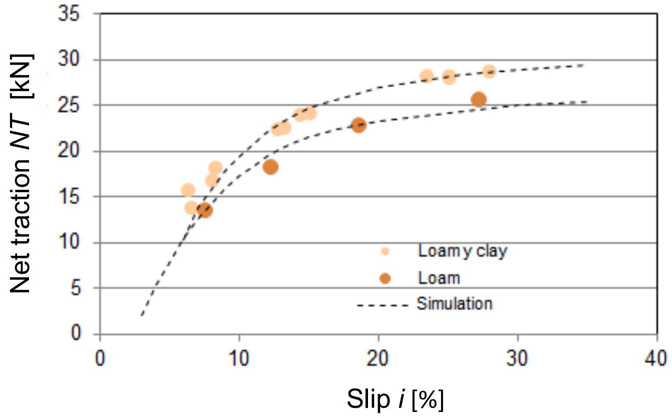


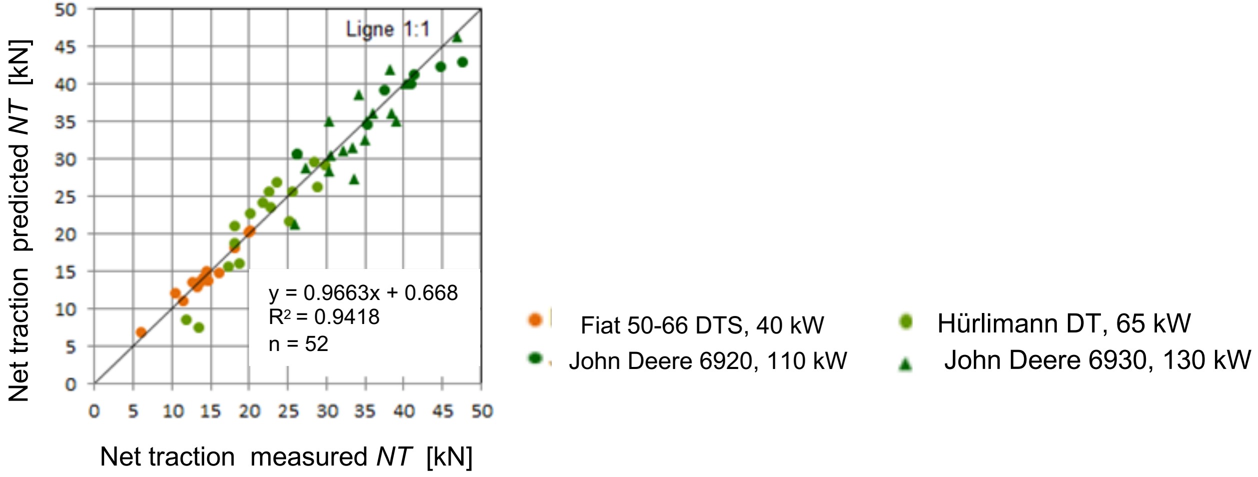
Traction slip curves

Influence of the soil texture silt - sand



loamy clay – loam





Draft requirement

$$NT = F_i A = [A + Bv + Cv^2] \cdot WT$$

ASABE
American Society of Agricultural and Biological Engineers

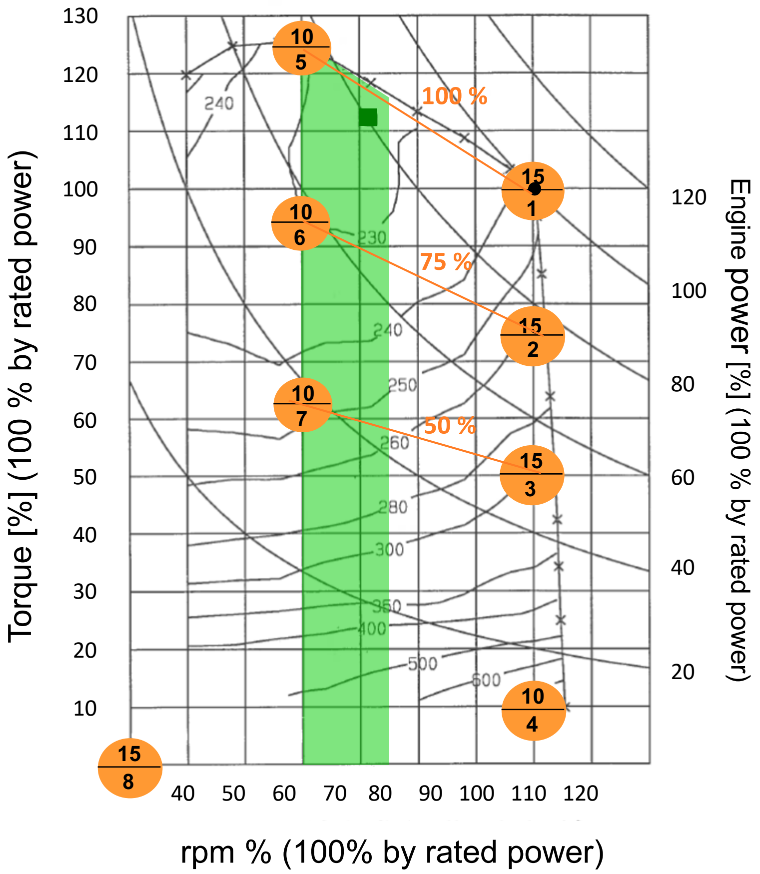
with:

D = Draft requirement [N]
F = Soil parameters, depending on texture
i = 1 for clay, 2 for loam and 3 for sand
A, B and C = machine-specific parameters
v = field speed [km/h]
W = machine width [m] / number of tools [n_t] / number of rows [n_r]
T = tillage depth [cm]

Implements for soil tillage and seedi	Machine specific parameter						Soil specific parameter		
	Width	unit	Units	A	B	C	F_1 Fine soil	F_2 Medium soil	F_3 Coarse soil
SUBSOIL TILLAGE									
Subsoiler / Manure injector -- narrow point [t]			tools	226	0	1.8	1	0.70	0.45
Subsoiler / Manure injector - 0.3 m winged point [t]			tools	294	0	2.4	1	0.70	0.45
Moidboard Plow [m]	m			652	0	5.1	1	0.70	0.45

➡ until 41 tools for subsoil tillage, topsoil tillage, seedlings and cultivation

Specific fuel consumption (engine)



- ● 100 % rated power
- ■ lowest specific fuel consumption
- 15/8: weighting % / measuring point

ISO 8178 C1

Tractors power classes	b_{eM} [g/kWh]
< = 75 kW	248
>75 kW	223

Schäffeler U., Keller M., 2008

Calculation of the specific fuel consumption

Engine power P_M [kW]

$$P_M = \frac{P_{GT}}{\eta_G}$$

P_{GT}: tractive power on the driving wheels [kW]

η_G: efficiency faktror for the transmission **0.85**

Hourly fuel consumption B_e [l/h]

$$B_e = P_M \cdot \frac{b_{eM}}{1000} \cdot \frac{1}{\delta_D}$$

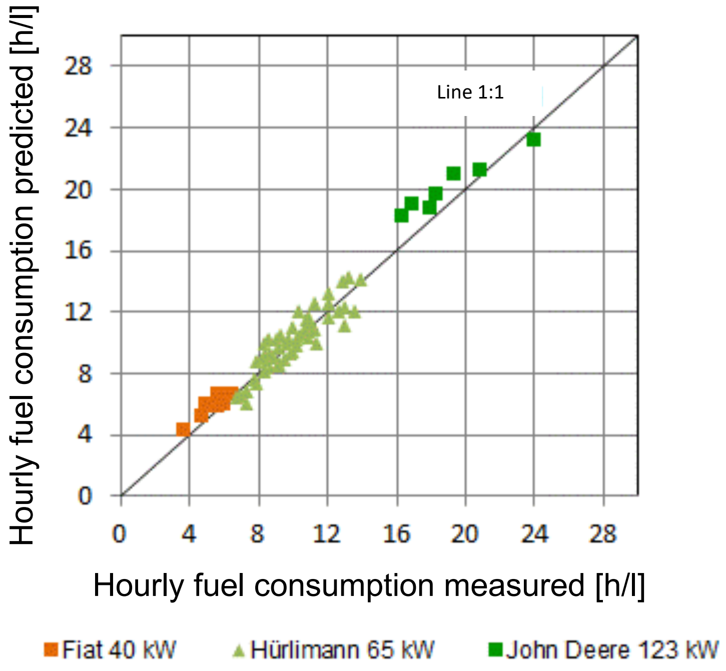
b_{eM}: specific fuel consumption of the engine [g/kWh]

δ_D: specific weight of the diesel [Mg/m^3]

Net specific fuel consumption B_{eZ} [g/kWh]

$$b_{eZ} = \frac{P_M \cdot b_{eM}}{P_{NT}}$$

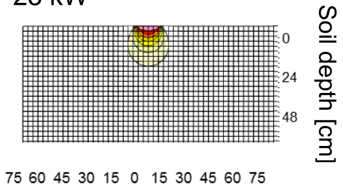
P_{NT}: tractive power [kW]



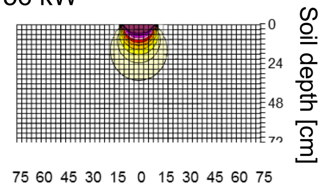
Evaluation of topsoil damages with TASC

Load transfer, compressive stress at the plouging pan and pass distribution - silty soil, semi-firm - ploughing

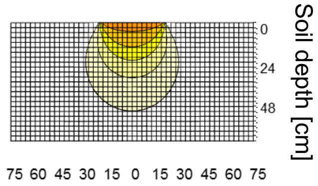
23 kW



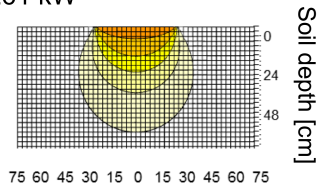
56 kW



100 kW



261 kW

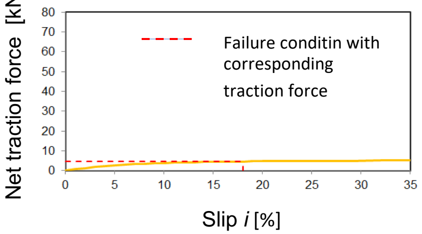


	23 kW	56 kW	100 kW	261 kW
Load transfer :	0.608 kN	1.609 kN	1.942 kN	4.513 kN
Vertical stress in the furrow :	**120 kPa**	**196 kN**	83 kPa	84 kPa
Working width:	0.35 m	1.05 m	1.75 m	4.2 m
No pass :	22.9 %	56.2 %	70.3 %	82.4 %
Multipass total :	77.1 %	43.8 %	29.7 %	17.6 %
1x	31.4 %	24.8 %	4.6 %	3.8 %
2x	47.5 %	19.0 %	25.1 %	13.8 %

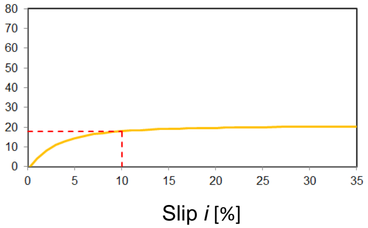
Soil failure risks and fuel consumption with TASC

silty soil, semi-firm – plough/ disk harrow – 4 km/h

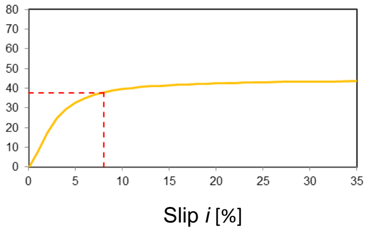
23 kW



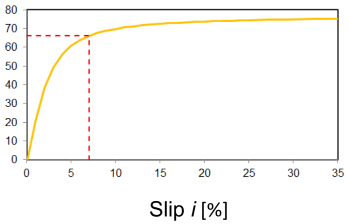
56 kW



100 kW



261 kW



	23 kW	56 kW	100 kW	261 kW
Failure condition :	18 % slip	10 % slip	8 % slip	7 % slip
Net traction:	4.6 kN	18.0 kN	37.8 kN	66.0 kN
Draft requirement:	4.5 kN	13.5 kN	22.5 kN	53.9 kN
Corresponding slip:	16 %	4 %	3 %	4 %
Plowshare 25 cm	1	3	5	12
Hourly consumption:	2.2 l/h	5.4 l/h	9.4 l/h	21.0 l/h
Consumption per hectare:	15.7 l/ha	12.9 l/ha	13.4 l/ha	12.5 l/ha
Disk harrow offset 15 cm	0.7 m	3.0 m	6.0 m	10 m
Hourly consumption:	1.9 l/h	7.4 l/h	13.6 l/h	21.0 l/h
Consumption per hectare:	6.8 l/ha	6.2 l/ha	5.7 l/ha	5.3 l/ha

TASC - flow chart