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RUT DEPTH MODEL FOR TIMBER TRANSPORT ON MORAINE SOILS

Martti Saarilahti [1] and Tero Anttila [2]

[1] Bulevardi 15 B 22, FIN-00120 Helsinki Tel/Fax +358 9 69 33 102

[2] University of Helsinki

SUMMARY:

The increased awareness of environmental issues has created a need for evaluating the usefulness of mobility models for Nordic forestry conditions. A frame of reference based on the WES-method was used for developing empirical rut depth models for moraine forest sites. It was found that the penetration resistance in critical layers alone was an adequate soil input variable, even if the studied soils had very large variations in stoniness. When comparing the results with earlier models developed for organic soils, it was found that the same models apply for both types of soils. The method and models seem reliable enough for avoiding operations on too risky soils.

Keywords: environment, forestry, mobility, penetrometer, rut, soil compaction, WES-method

Symbols:

δ	deflection, m
μ_R	rolling resistance coefficient
a	empirical constant
b	empirical constant
d	tyre diameter, m
h	section height, m
l	wheelbase, m
r	wheel radius, m
r	correlation coefficient
z	wheel sinkage, m
z_{RUT}	rut depth, m
z_{MAX}	maximum penetration depth obtained, m
x	empirical scale factor
x	independent variable
y	dependent variable
A	tyre or track contact area, m^2
C	penetration resistance, kPa
CI	penetration resistance of the critical layer (= 0.12...0.18 m in this study), kPa
C_N	wheel numeric
N_{CI}	wheel numeric

N_B wheel numeric
W wheel load, kN
W_R rated wheel load, kN

INTRODUCTION

Mobility is not an acute problem in today's logging in Finland, but the environmental impacts are of great interest. An earlier study showed, that the principles of the widely used WES-method are useful in predicting rut formation on peatlands (Saarilahti et al 1997). Most Finnish forest soils are, however, of different types of moraine, and the stoniness is one peculiarity. Most of the mobility studies carried out elsewhere concern homogeneous deep soils, such as on worked agricultural soils or typical friction or cohesive soils, resembling a perfect elastic or plastic body.

There are several Nordic studies on rut formation (Scholander 1973, Hallonborg 1983, Sondell 1986, Ericsson et al 1987, Sirén et al 1987, Karsson & Myhrman 1990a, 1990b, Myhrman 1990, Wästerlund 1990a, 1990b, 1992, Löfgren 1991, Keränen 1993, Högnäs 1997), which show, that the rut depth depends on soil properties, mass of the tractor or wheel load, slip, characteristics of wheels, chains and tracks, but none of them uses the WES-method as the frame of reference.

The aim of the study is to verify the usefulness of the WES-method for predicting rut formation on the Nordic moraine forest floor, where the nonhomogeneity is remarkable, and several soil horizons can be found (Westman 1990).

MATERIALS AND METHODS

Basic assumptions

It is assumed that rut depth is equal to or correlated with wheel sinkage. Based on the rigid wheel theory, the rolling resistance coefficient (μ_R) depends on the wheel sinkage (z) and diameter (d) (Kaje 1968, Gee-Clough 1979, Saarilahti 1991):

$$\mu_R = \sqrt{\frac{z}{d}} \qquad (1)$$

If, as assumed, the rut depth is equal to or (linearly) correlated with sinkage we can write the following model for rut depth (z_{RUT}), Eq(2), where **x** is an empirical scale factor.

$$z_{RUT} = d \cdot \mu_R{}^2 \cdot x \qquad (2)$$

There is a large number of mobility studies based on the WES-method (Saarilahti 1997a). In the simplest model the rolling resistance coefficient can be estimated based on wheel numeric (C_N or N_{CI}) and empirical constants **a** and **b** Eq(3), (Wismer & Luth 1973, Maclaurin 1990). Constant **a** represents the component of the rolling resistance due to tyre deformation, and factor $\frac{b}{N_{CI}}$ depends on the resistance due to soil deformation.

$$\mu_R = a + \frac{b}{[C_N;N_{CI}]} \qquad (3).$$

By combining equations (2) and (3), the following rut depth model (Eq,(4)) can be developed. This means that rut depth can be predicted using the WES-principle.

$$z_{RUT} = d \cdot \left(a + \frac{b}{[C_N;N_{CI}]} \right)^2 \qquad (4)$$

Data collection

The field tests were carried out in connection with normal forest operations in West-Central and Southern Finland. Eleven logging sites (A-K) were picked to represent different soil conditions. Sites A-F were studied in May, soon after the thaw period, and they represent poorer spring conditions. Sites G-J were operated on in August, after an exceptionally long dry season, and they represent good summer conditions. Logging on site K took place in October, after autumn rains.

Because the study was done to investigate the usefulness of the WES-method, test sites were selected so that the variations in wheel slip or changes in dynamic wheel load were minimised. The lanes were straight and smooth on flat horizontal terrain (± 2% slope) where the tractors were able to keep a constant velocity.

For each site, a short trail was marked for the study. Vegetation and the loose humus layer was removed from 10 patches over which the tractor wheels were to go. After the passing of the empty tractor, the rut depth and width were measured using a special gauge. In this study the rut depth of the central point only is used as rut depth variable (Z_{RUT}). When the tractor returned loaded the rut depth was measured anew, and the load volume recorded. Later the load weight was calculated using suitable volume-weight tables. The rut depth of a site is the average rut depth of the ten patches. As the tractor was observed empty and loaded there are two rut depth observations for each site.

The soil properties of one site were measured from 2 to 4 plots (A1,A2...K1,K2,K3) close to the rut depth measuring patches. The total number of sample plots is 32. For each plot, 5 to 10 soil penetration resistance recordings were made using a self recording penetrometer, driven by an electric drill. The force transducer was placed between the cone and the shaft, so that the penetrating resistance does not include the skin friction of the shaft. The idea was to investigate the occurrence of stones and roots and the properties of the soil between them. Later the average penetration resistance was calculated for each 25 mm layer, and the layer averages are used as input variables in the study. The maximum penetration force the drill was able to generate was equal to 2800 kPa of penetration resistance. This means that the full penetrometer depth was not always reached. When calculating the average of a site, an arbitrary value of 3000 kPa was used for deeper layers. Also the maximum penetration depth (Z_{MAX}) was recorded as an input variable.

Site properties

The sites were subjectively classified into 5 different classes after the soil type, stoniness and trafficability estimate. The description of the site properties (Type in Table 1) are the following:

1 Peaty soils, shallow depressions with peat deposit on mineral soil
2 Typical cohesion soils, fertile Myrtillus-Oxalis sites
3 Typical friction soils, poorer sandy sites, Vaccinium site
4 Silty moraines with few stones, poor bearing capacity
5 Stony moraine, good bearing capacity

The stoniness index was calculated using the Viro method (Viro 1952). In the original Viro method, the penetration depth is measured using a metal rod. In this paper the cone penetration depth is used. Sirviö (1994) found, that the rod and cone penetrometer depths are about the same. The stoniness index is calculated using the model, Eq(5)

$$\text{STONINESS INDEX} = 83 - 2.75 \cdot \text{PENETRATION DEPTH}\,(\text{cm}) \qquad (5)$$

Soil physical properties, the share of fine grained components, dry density and water content were determined using the standards of the Finnish Forest Research Institute (Heiskanen & Tamminen 1992). The average site properties are given in Table 1.

Table 1. Average soil properties

Site	Type	Soil	Fine particles, %	Dry density, kg/m³	Moisture Content, %	Stoni-ness Index	CI, kPa
A	3	Fine sand	5	983	17	1	814
B	3	Fine sand	6	979	15	13	929
C	1	Fine sand, peat	6	1079	30	1	269
D	4	Fine sand moraine	21	390	57	30	865
E	5	Coarse sand moraine	10	1143	16	37	1427
F	5	Gravel moraine	NA[1)]	NA	NA	57	1848
G	2	Fine silt	79	887	21	40	1140
H	2	Fine silt	76	903	22	40	951
I	3	Fine silt moraine	9	1081	17	41	1248
J	3	fine silt moraine	12	1113	13	42	1222
K	2	Fine silt	69	963	32	14	739

[1)]Too stony for soil sampler

Forwarders

Five different forwarders were studied, Table 2. For the empty tractor, the wheel load on the front and rear wheel was calculated based on normal load distribution between axles. The load was charged totally to the rear axle. When travelling empty, the wheel load on the front axle is higher, and therefore the front wheel data was used for calculating wheel numeric (C_N and N_{CI}) for the empty tractor. For the loaded tractor, the rear wheel characteristics were used. Wheel numerics were calculated using Eq(5) and Eq(6) based on tyre diameter (d) and width (b), wheel load (W), deflection (δ) and section height (h). Different penetration resistance values (CI) were tested when developing empirical rut depth models.

Table 2. Characteristics of the forwarders.

Forwarder	Sites	Tractor mass, kg	Tyres	Wheel equipment	Wheel load, kN	Wheel load, rear, kN
Valmet 872	A, B, C	11 700				
Front			23,1- 26	Chain	30,8	(A) 31,4
Rear			17,5/25	track	10,3	(B) 25,6
						(C) 26,0
Timberjack 810B	D, E	11 000				
Front			700/45 - 22,5	1/4 Chain	16,2	(D) 25,6
Rear			700/45 - 22,5	2/4 Chain	10,8	(E) 25,6
Timberjack 1110	F, G, H	15 500				
Front			700/50 - 26,5	-	22,1	(F) 37,7
Rear			700/50 - 26,5	-	14,7	(G) 37,8
						(H) 37,8
Valmet 832	I, J	10 200				
Front			700/55 - 34	Chain	26,5	(I) 28,0
Rear			600/55 - 26,5	track	8,8	(J) 28,0
Timberjack 1210B	K	17 700				
Front			700/50 - 26,5	1/4 Chain	24,3	(K) 45,6
Rear			700/50 - 26,5	track	16,2	

1/4 Chain means that one wheel of the four is equipped with a chain

$$C_n = \frac{CI \cdot b \cdot d}{W} \qquad (6)$$

$$N_{Ci} = \frac{CI \cdot b \cdot d}{W} \cdot \sqrt{\frac{\delta}{h}} \cdot \frac{1}{1 + \frac{b}{2 \cdot d}} \qquad (7)$$

Only one tractor was working with bare tyres. Three tractors were equipped with chains at least on one front wheel. Three tractors were fitted with tracks over rear tandem axle wheels, and one had chains on the rear wheels. The influence of the chains was neglected in calculations. The deflection (δ) was calculated using tyre manufacturers' data.

The data were analysed both by sites (N=22) and by plots (N=64). The results refer to plotwise analysis. Linear regression analysis technique was used for developing models. For dependent variables, rut depth (z_{RUT}) and relative rut depth, ($\frac{z_{RUT}}{d}$) were compared. Two different Mobility Numbers, C_N and N_{CI}, were compared as independent variables in one entry models. For two entry models, maximum penetration depth (Z_{MAX}) was also used. Due to nonlinearity between dependent and independent variables, different transformations were tested ($y'=\ln(y)$, $x'=\ln(x)$, $x'=x^{-1}$) for developing models.

RESULTS

Modelling of the tracks

Three of the five forwarders were fitted with flexible tracks on the rear bogie. Therefore, in the first phase the possible influence of tracks was analysed.

The commonly used equation for calculating the track contact area (A) is based on the track width (b), wheel base (l) and wheel diameter (r), Eq(8): (Terrängmaskinen 1981).

$$A = b \cdot (1.25 \cdot r + l) \tag{8}$$

In soil settlement theory, model (8) assumes a rigid plate with an evenly distributed load (Helenelund 1974), which is not the case with a flexible track with road wheels. Hence, model (8) is based on an incorrect theoretical approach. Different studies of the soil pressure under a flexible track show that the true contact pressure can be estimated based on one track element under the road wheel (Young et al 1984, Littleton & Hetherington 1987, Larminie 1992). The suitability of model (8) was tested using the data by replacing the contact area factors b·(d), used in WES-models by the factor b·(1.25·r+l). The prediction power of the rut depth model with wheel parameters (WES-model) was much higher (r^2=0.911) than with track parameters (r^2=0.549), see Figure 1. Further analyses confirmed that the influence of tracks can be neglected.

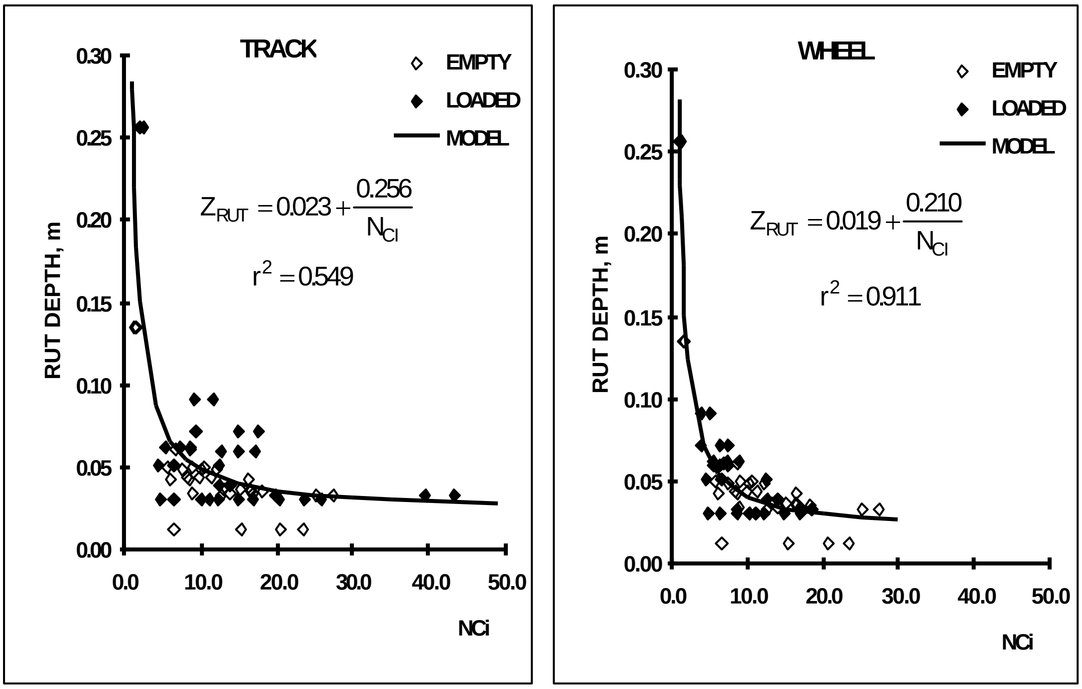

Figure 1. The rut depth (Z_{RUT}) model developed using the rigid plate contact area model (**TRACK**) and pneumatic wheel model (**WHEEL**).

Critical layer

Due to stones or shallow A and B horizons, maximal penetration depth was often less than 0.15 m, and the variation between profiles was evidently greater than in agricultural soils or in soil bin tests. Therefore, the suitability of one typical penetration resistance value, the “critical layer value”, was tested by using each 25 mm layer as an input variable in the rut depth model, model (9).

$$z_{RUT} = d \cdot \left(a + \frac{b}{N_{CI}} \right) \qquad (9)$$

where ***a*** and ***b*** are empirical constants. The results of regression analysis are presented in Figure 1. It can be seen, that the highest correlation coefficient squared (r^2=0.863) was obtained using the CI of layer 7 (z = 0.163 m). Shallower than 100 mm layers gave very low correlation coefficients. Layers between 0.10 and 0.25 m gave rather similar results. The critical layer matches well with the average depth of B-horizon (after Westman 1990), as seen from Figure 2. The average penetration resistance of the 0.138 to 0.188 m layer is the most reliable input variable, (r^2=0.878). All the later analyses are based on the average penetration resistance of the 0.1375 to 0.1875 m layer.

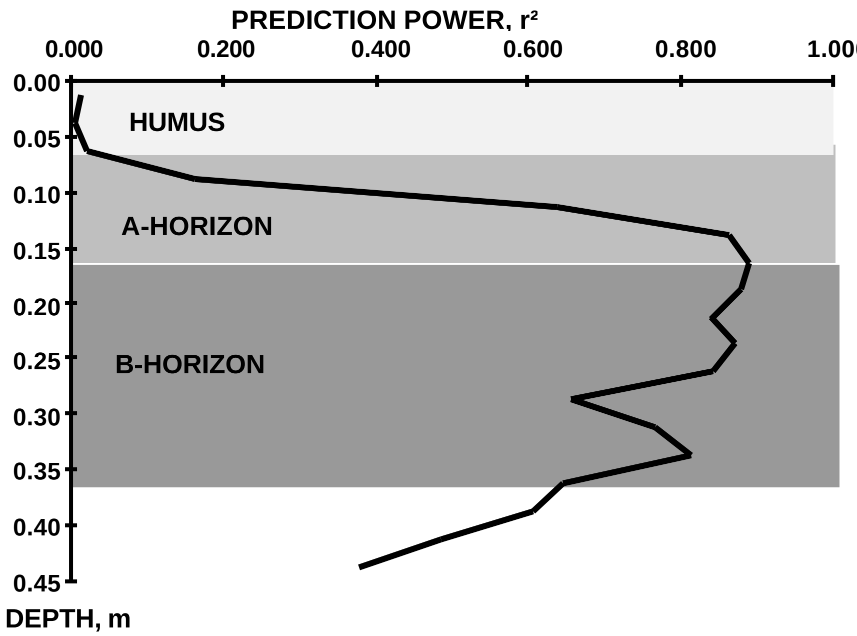

Figure 2. Correlation coefficient squared (=prediction power) as a function of sample depth. Different average soil horizons after Westman (1990).

Testing of WES-models

Eight different rolling resistance models and one sinkage model were tested, see Table 3. The rut depth estimate was calculated using model (4). Linear regression was used to analyse the fit between estimated and observed rut depth. The results are given in Table 3. As a rule, rather a good fit can be found. In most cases the correlation coefficient is highly significant, and constant **a** is small and constant **b** is close to 1, between 0.66 and 1.36. It can be seen that the models developed for older military vehicles for determining go/no-go conditions (Turnage 1972a,b) are not quite appropriate for current machinery. In most cases, constant **a** is 20 to 30 mm, which can be interpreted to represent the rut depth due to lugs, chains or tracks. Figure 3 is used to visualise the results, but a constant of 20 mm is added to different models.

Table 3. Correlation between observed and estimated rut depth using different WES models.

Source	Model	**a**	**b**	r^2
Turnage (1972a)	$\mu_R = 0.04 + \frac{0.20}{N_{CI} - 2.50}$	0.030	1.69	0.115
Turnage (1972b)	$\mu_R = 0.04 + \frac{0.20}{N_{CI} - 150}$	0.040	0.02	0.066
Wismer&Luth (1973)	$\mu_R = 0.04 + \frac{120}{C_N}$	0.025	1.23	0.848
Gee-Clough (1980)	$\mu_R = 0.049 + \frac{0.287}{N_{CI}}$	0.023	1.36	0.873
Dwyer (1984, 1987)	$\mu_R = 0.05 + \frac{0.29}{N_{CI}}$	0.023	1.33	0.873
Ashmore et al. (1987)	$\mu_R = -0{,}1 \cdot \left(\frac{W}{W_R}\right) + \frac{0.22}{C_N} + 0{,}20$	-0.107	5.32	0.573
Brixius (1987)	$\mu_R = \frac{19}{N_B} + 0.04 + \frac{0.5 \cdot S}{\sqrt{N_B}}$	0.024	0.78	0.854
Maclaurin, rr (1990)	$\mu_R = 0.017 + \frac{0.435}{N_{CI}}$	0.029	0.66	0.864
Maclaurin, z (1990)	$\frac{z}{d} = \frac{0.224}{N_{CI}^{125}}$	0.022	0.68	0.878

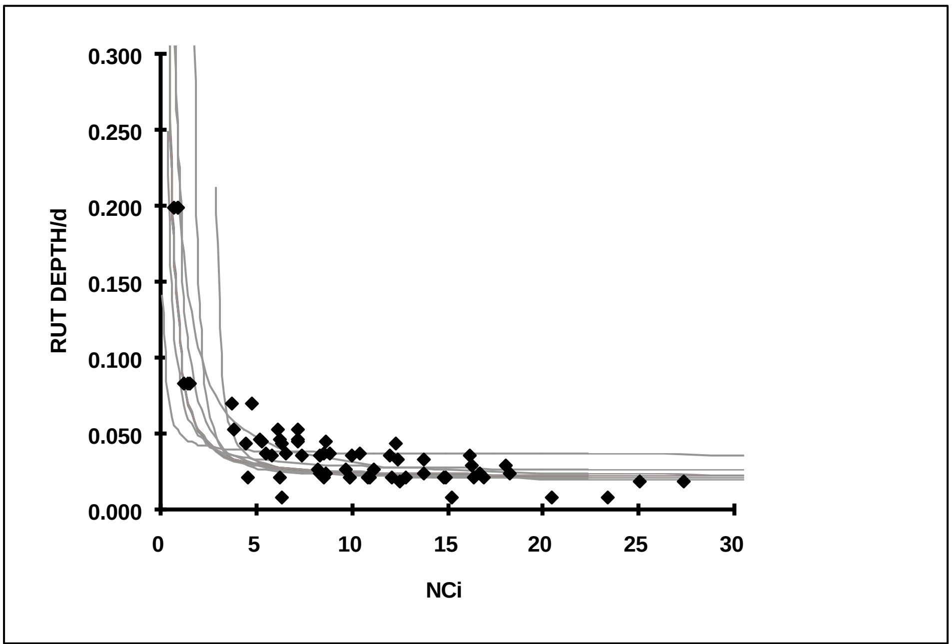

Figure 3. Estimate for relative rut depth +0.02 m using different models (grey lines) compared with observed relative rut depth (black points).

Because none of the tested models gave accurate enough estimates, new empirical rut depth models had to be developed.

Empirical rut depth models

The comparison of the different one entry models is given in Table 4. The best model consists of rut depth as dependent variable and N_{CI} as independent variable. As a rule, rut depth was a somewhat better dependent variable than relative rut depth, because the r^2 was higher (r^2=0.90-0.91 for Z_{RUT}) (r^2=0.84-0.87 for $\frac{Z_{RUT}}{d}$). The differences between models have no practical meaning, however.

Table 4. Comparison of linear one entry rut depth models, $y=\mathbf{a}+\frac{b}{x}$

Dependent variable	Independent variable	**a**	**b**	r^2	Model
Z_{RUT}	N_{CI}	0.019	0.210	0.911	(10)
Z_{RUT}	C_N	0.022	0.793	0.900	(11)
Z_{RUT} /d	N_{CI}	0.014	0.157	0.878	(12)
Z_{RUT} /d	C_N	0.016	0.587	0.844	(13)

Different models using different combinations of wheel numeric and maximum penetration depth were tested. The only significant improvement into the best one entry model was adding the maximum penetration depth (Z_{MAX}). The model becomes:

$$Z_{RUT} = 0.005 + 0.086 \cdot Z_{MAX} + \frac{0.185}{N_{CI}} \qquad r^2=0.926 \qquad (14)$$

In Figure 4 model (14) is tested against the observations.

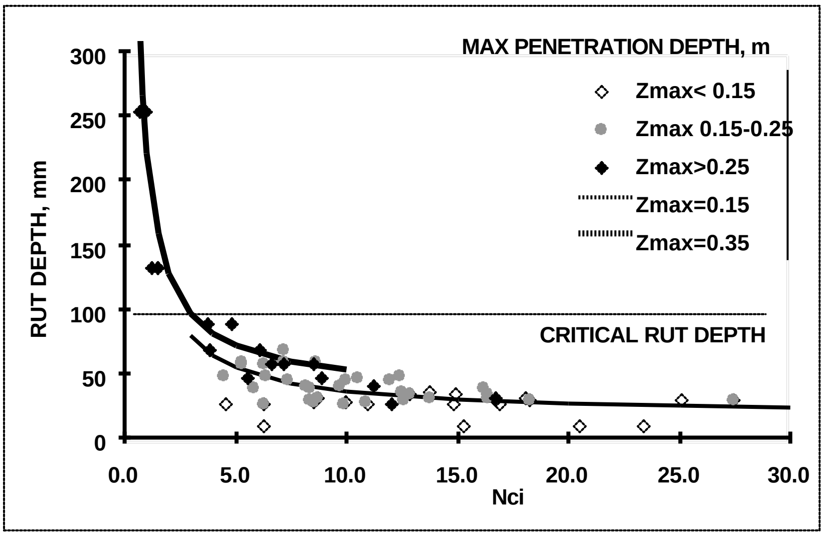

Figure 4. Model (14) compared with observations at two different maximum penetration conditions. Critical rut depth is used to assess work quality, see Chapter Discussion.

DISCUSSION

In previous papers, rut depth models on deep peatlands were developed separately for a wheel and tracked bogie (Saarilahti 1997) and for both together (Saarilahti et al. 1997). The models are compared with the model (10) in Figure 5. The following conclusions can be drawn:

- models developed for peatland apply fairly well for moraine soils and vice versa
- the lug+chain effect becomes more pronounced on harder surface

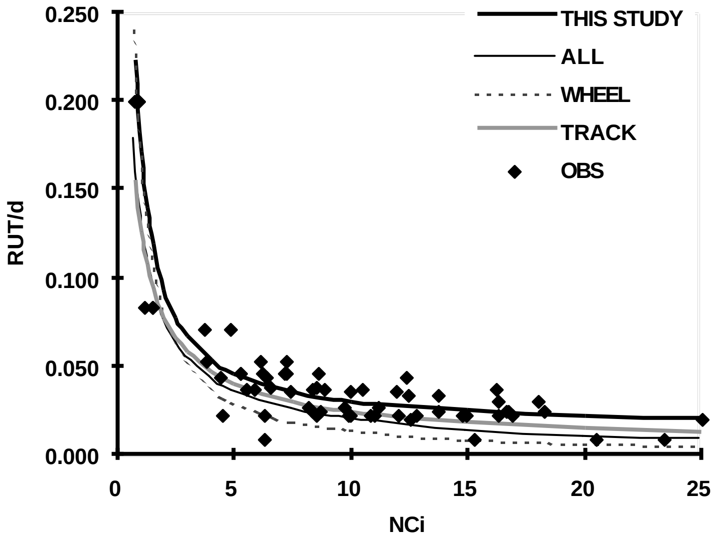

Figure 5. Models developed separately for a wheel (WHEEL) and tracked bogie (TRACK) (Saarilahti 1997) and for both together (ALL) (Saarilahti et al. 1997) compared with model (10) (THIS STUDY).

The data also match other studies with a certain margin, as seen in Figure 3 and Table 3.

In Finland, the quality of timber terrain transport is classified as "acceptable" if the share of tracks deeper than 0.1 m is less than 10% of the total track length. The quality of logging is "excellent", if the share of overdeep ruts is less than 5% of the total track length (Harvennushakkuiden... 1990). Figure 4 shows, that the critical depth (0.1 m) is closely connected with a certain culmination point of the rut depth model. If the N_{CI} value is less than 4, the risk of deep ruts (on deeper soils) increases drastically. For harder and shallow soils, the risk for deeper ruts is minimal.

CONCLUSIONS

Simple rut depth models based on the WES-principles, the use of soil penetration resistance and wheel numeric, seem to be reliable enough to avoid too risky operations on Finnish forest sites. The same models seem to apply both for mineral and organic soils.

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