DEVELOPMENT OF A PROTOCOL FOR ECOEFFICIENT WOOD HARVESTING ON SENSITIVE SITES (ECOWOOD)

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APPENDIX REPORT No 4

EVALUATION OF THE WES-METHOD
IN ASSESSING THE TRAFFICABILITY OF TERRAIN AND THE
MOBILITY OF FOREST TRACTORS

PART 3

INTERPRETATION AND APPLICATION OF THE RESULTS

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Symbols

- $C_{I_{\text{wheel}}}$: limiting cone index for wheels
- $C_{I_{\text{track}}}$: limiting cone index for tracks
- $W_{\text{V}}$: vehicle total weight, kN
- $n$: number of axles, number of road wheels per side
- $b$: (inflated, unloaded) tyre width, track width, m
- $d$: (inflated, unloaded) tyre diameter, m
- $\delta$: tyre deflection when loaded, m
- $p$: track plate length, m
- $e$: track link area ratio

EXECUTIVE SUMMARY

Different WES mobility models and some rut depth models based on wheel numeric are presented in previous paper. In this paper the interpretation and application of the results obtained using different models are discussed.

Keywords: forestry, trafficability, terrain transport, mobility, soil damage, penetrometer, WES
1. INTERPRETATION OF THE RESULTS: CLASSIFICATION OF THE TRAFFICABILITY AND MOBILITY

The assessment of a certain site as sensitive or less sensitive should base on a comprehensive decision making. In the simplest case one variable may be sufficient, but in most cases there is not any single criterium on which the decision can be based. The decision is rather a process to compare different alternatives and find out the most appropriate machine/site matching comparison.

The results obtained by the models using different terrain, soil and machine data input can directly be used in comparison of different machines. Deeper rut depth and higher rolling resistance mean that probably this tractor is less performant than another tractor with shallower ruts and lower rolling resistance. On the others, high drawbar pull, net traction, and gross traction indicate good mobility and better performance. In some cases orderly yardsticks are needed to help the decision making. Therefore some tentative classifications for practical applications are given. There is not any standardised classification, but the class limits are set based on subjective observations and some hints found in literature (Mäkelä & Laurola 1990).

Another widely used trafficabily classification is based on the number of passes possible in some certain conditions. The technical limit go/no-go situation is 1 pass. In this case large environmental damages are to be expected, as well as high operative costs due to excessive wear of machine components and high fuel consumption. Also generally the driving velocity is low and the permitted load is minimal, hence the productivity becomes low. Also there is a high risk of total failure, with expensive rescue costs. The operational efficiency improves as a function of the number of expected passes, and thus 2 to 5-pass limit can be set as the lowest economic limit for timber transport. The conditions can be classified as good, if 25 passes are possible.

2. SOIL DAMAGE

2.1 Rut depth

For rut depth only two classes are used, acceptable/non acceptable. the limit is put to 0.1 m rut depth, which is based on the work quality assessment recommendations of Tapio, the Central Board of Forestry. For the practical evaluation the work quality is acceptable, if the average rut depth does not exceed 0.1 m for more than 10% of the total length of the skidding trails on the site. Momentarily it is therefore possible to operate on sites with deeper than 0.1 m rut depth sites, but their occurrence must be low.
Table 2.1 Rut depth classes

<table>
<thead>
<tr>
<th>Rut depth class</th>
<th>Acceptable</th>
<th>Avoidable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rut depth, m</td>
<td>&lt;=0.10 m</td>
<td>&gt;0.10 m</td>
</tr>
</tbody>
</table>

3. MOBILITY

3.1 Rolling resistance

Rolling resistance increases as an inverse function of soil bearing capacity, and high rolling resistance indicates poor terrain trafficability and tractor mobility. Limit for good and fair conditions can be put on 0.2.

Table 3.1. Mobility classes based on rolling resistance coefficient

<table>
<thead>
<tr>
<th>Mobility and trafficability class</th>
<th>Rolling resistance coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Fair</td>
<td>0.20 to 0.30</td>
</tr>
<tr>
<td>Poor</td>
<td>&gt;0.30</td>
</tr>
</tbody>
</table>

In Figure 3.1. the rolling resistance coefficient limit (0.2) is compared with assumed rut depth limit (0.1 m) using Anttila’s (1998) rut depth model and the calculated rolling resistance coefficients using different WES models and an average loaded forwarder wheel (W=35 kN, d=1.333 m, b=0.700 m, π= 400 kPa). It can be seen, that the limiting soil cone index value for rut depth limit is about 570 kPa, and for rolling resistance coefficient the limit for most of the models is 400 to 475 kPa. It is also evident, that the rolling resistance coefficient increases exponentially for weaker soil, and therefore the limit of 0.20 is rather logical. It must be beard in mind, that the obstacle resistance, winding resistance and slopes increases apparent rolling resistance, or more exactly the resistance to movement.
Figure 3.1 Rut depth limit (0.1 m (RUT)) and rolling resistance coefficient limit (0.2 (RR)) and rolling resistance limit as a function of cone index

3.2 Pull coefficient

Net pull force, drawbar pull, indicates the force the wheel or the tractor can generate over the main forces resisting to movement, consisting of rolling resistance, obstacle and steering resistance and slope resistance. In skidding is essential for dragging the logs, in forwarding is some kind of reserve, which can be used for acceleration and overcoming some minor local changes in resistance to movement, either due to lowering in bearing capacity or changes in surface profile.

For decision making some kind of recommendations can be given concerning the net pull and net pull coefficient. Too low a pull coefficient indicates, that the tyre is working close to its limits, and obviously it must increase the slip in order to generate more pull for overcoming some extra resistance. The following Table, Table xx, is presented as some kind of first attempt to use the pull coefficient as a variable for mobility and trafficability classification in order to screen out sensitive site and tractor combinations.

Table 3.2. Mobility classes based on net pull coefficient

<table>
<thead>
<tr>
<th>Mobility and trafficability class</th>
<th>Pull coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>Fair</td>
<td>0.15 to 0.25</td>
</tr>
<tr>
<td>Poor</td>
<td>&gt;0.15</td>
</tr>
</tbody>
</table>
3.3 Traction

The available traction, must exceed the total resisting force, e.g. the net traction must be positive. But the needed traction to overcome the resisting forces must also be in harmony with the
• available torque
• tyre or track characteristics

Even part of the tyre characteristics (for example deflection) are included into thrust model, it is important to compare also the needed forces (resisting forces) with the tyre characteristics, such as maximum load.

3.4 Ground pressure

As seen from Appendix Report\(^1\) there is no universally adopted method for estimating the ground pressure at the tyre/soil interface. In fact, the contact pressure at different parts of the contact area varies. For lower loads it is higher at the center than close to sides, and higher under the lugs than under the tread, but for certain conditions under high loads the peak stress may develop under the side walls. (Burt et al 1987). Some kind of average ground pressure is, however, an operational variable for assessing the machine/soil matching.

3.4.1 Nominal ground pressure

Nominal ground pressure, NGP, is widely used as a mobility variable, even it has the disadvantage of neglecting the influence of tyre deformation. It has the advantage being a simple numeric, which is easy to assess.

NOTE: The NGP formula for tracked vehicles does not apply for tandem axles fitted with flexible tracks, and therefore it is not recommended for use.

The nominal ground pressure is some kind of minimum tyre ground pressure that the tyre might develop on very soft conditions. It can be used to compare different tractors using about the same tyre configuration and inflation pressure. It leads to erroneous decisions when comparing special low pressure tyres with normal high pressure tyres. It also overestimates the positive influence of adding the tyre width. Another deficiency is, that it is independent of soil properties.

The environmental damage is related to the wheel soil interaction, and high NGP is less destructive on well bearing soils than on sensitive sites. The correct application of NGP

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\(^1\) Modelling of the wheel and soil. 1. Tyre and soil contact
presumes certain information of the soil conditions, e.g. the recommended NGP value for normal moraine soils, or for organic soils etc. Therefore the use of the ratio NGP/some soil bearing capacity variable is more rational.

Different authors have proposed the following limiting values:

Olsen & Wästerlund (1989) recommend 35 to 50 kPa NGP for the highest allowable value for (Swedish) forestry.

When taking into account the limits of using NGP, the following Table 5.4 for interpreting the NGP values can be given.

Table 3.3. Ecologically acceptable NGP values for normal forwarder tyres

<table>
<thead>
<tr>
<th>NGP limit, kPa</th>
<th>Class</th>
<th>Reference value</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Man with boots, static loading, Two feet</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Man with boots, dynamic loading, One foot</td>
<td></td>
<td>Olsen &amp; Wästerlund’s recommendation</td>
</tr>
<tr>
<td>35 to 50</td>
<td></td>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor</td>
<td></td>
</tr>
</tbody>
</table>

Wronsky & Humphreys (1994) give the following values for estimating the environmental risks

- Immobilisation at first pass occurs, when the soil strength (CI) is about 3 times the NGP
- Immobilisation at 50th pass occurs, when the soil strength (CI) is about 5 times the NGP
- Single pass causing the rut depth less than 0.15 m, CI= 4.5 times NGP
- Single pass causing the rut depth less than 0.1 m, CI= 7.2 times NGP

Assuming the wheel load of 40 kN, wheel diameter of 1.333 m and tyre width 0.700 m, corresponding to 86 kN NGP, the following indicative values can be calculated, Table 3.4. The limit for sensitive site is thus around 620 kPa penetration resistance.
Table 3.4. Minimum soil penetration resistance for forwarder transport calculated after Wronsky & Humphreys’ recommendations (1994)

<table>
<thead>
<tr>
<th>Limit</th>
<th>Ratio CI/NGP</th>
<th>Minimum penetration resistance, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical mobility</td>
<td>3</td>
<td>260</td>
</tr>
<tr>
<td>0.15 m rut depth, tolerable</td>
<td>4.5</td>
<td>400</td>
</tr>
<tr>
<td>Economic mobility</td>
<td>5</td>
<td>450</td>
</tr>
<tr>
<td>0.1 m rut depth, acceptable</td>
<td>7.2</td>
<td>620</td>
</tr>
</tbody>
</table>

Figure 3.2. CI/NGP-ratio and Wronsky & Humphreys’ (1994) limits fitted with Anttila’s (1998) data
The Wronsky & Humphreys’ limits seems applicable for fully loaded forwarders with rather high NPG-values. If tested for lower NPG values, such as partially loaded forwarders, the recommended limits seem to be some kinds of underestimates. In Figure xx different rut depth models are compared. The reference vehicle is a 10 tonne forwarder with 0 to 10 tonne loads. Tyre dimensions are b=0.700 m and d=1.330 m. The rut depth for each load is put to 0.1 m, and the corresponding CI is calculated. The calculated CI/NGP ratio is presented in Figure 3.3. It can be seen, that Maclaurin’s and Anttila’s models are load dependent, due to the inclusion of the deflection into the model. Evidently partially loaded forwarder has somewhat worse relative mobility, e.g. the low NPG does not indicate correctly the sensitiveness of the site for partially loaded tractor. It has to be kept in mind, that true tyre deflection may differ from the value, calculated based on deflection models, specially under lower loads.

### 3.4.2 Tyre ground pressure models

None of the studied tyre ground pressure models seemed perfectly suitable for assessing the goodness of tyre for sensitive sites. It is recommended, however, to adopt models, which include the tyre deflection because it leads to more environmentally acceptable selections. Because the WES-method is some kind of frame of reference for the study, the following ground pressure models may be convonble for assessing the suitability of the forwarders and processors for an ecological order

Dwyer’s (1984) “ground pressure index”

$$p = \frac{W}{b \cdot d} \cdot \sqrt{\frac{h}{\delta}} \cdot \left(1 + \frac{b}{2 \cdot d}\right)$$

(3.1)

About the same ground pressure index can be derived using Maclaurins’s formula

$$p = \frac{W}{b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}}$$

(3.2)

The ground pressure index for the average loaded forwarder tyre is 164 kPa, twice the NGP, 75 kPa. The soils having the “bearing capacity” less than 164 kPa, can thus be considered as “sensitive”. 

Figure 3.3. CI/NGP ratio using different rut depth models. Limiting rut depth is put to 0.1 m.
They represent some kind of average pressure, “G” in Figure 3.4. The Limiting Cone Index (see Chapter 3.10) is some kind of mean maximum pressure index, “CI” in Figure 3.4.

\[
p_{CI} = \frac{1.85 \cdot W}{b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}}
\]

(3.3)

Figure 3.4 Tyre contact pressure (p) and contact area (A) calculated using different models. G, ground pressure index by Dwyer, CI wheel

### 3.4.3 Mean maximum pressure, MMP

Table 3.5. MMP required for satisfactory performance (Larminie 1988)

<table>
<thead>
<tr>
<th>Condition</th>
<th>MMP levels for performance priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ideal</td>
</tr>
<tr>
<td>Temperate climate, fine-grain soils</td>
<td></td>
</tr>
<tr>
<td>Articulated steering</td>
<td>150</td>
</tr>
<tr>
<td>Skid steering</td>
<td>120</td>
</tr>
<tr>
<td>Tropical, wet soils</td>
<td></td>
</tr>
<tr>
<td>Articulated steering</td>
<td>90</td>
</tr>
<tr>
<td>Skid steering</td>
<td>72</td>
</tr>
<tr>
<td>European bogs</td>
<td>5</td>
</tr>
<tr>
<td>Muskeg</td>
<td>30</td>
</tr>
<tr>
<td>Over snow</td>
<td>10</td>
</tr>
</tbody>
</table>

As a rule the penetration resistance must be about 85% of the MMP. (q=0.827-MMP). This limit is compared with the Anttila’s (198) data in Figure x.
Figure 3.5. Larminie’s (1988) recommended CI/MMP limit compared with Anttila’s (1998) data

3.5 Soil properties

3.6 Cone index, penetration resistance

The following cone index recommendations have been given for Canadian soils, Table 3.6.

Table 3.6 Trafficability of silty soils after Murfitt et al (1975)

<table>
<thead>
<tr>
<th>Penetration resistance $^1$, kPa</th>
<th>Bearing value description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 21</td>
<td>Approximately at the liquid limit. No practical bearing value</td>
</tr>
<tr>
<td>40 to 62</td>
<td>A man has difficulty walking on the soil without sinking</td>
</tr>
<tr>
<td>103 to 165</td>
<td>A special tracked vehicle (<em>Weasel</em>) can travel about 50 passes</td>
</tr>
<tr>
<td>186 to 228</td>
<td>D4 tractor can travel for about 50 passes</td>
</tr>
<tr>
<td>276 to 352</td>
<td>D7 tractor can travel for about 50 passes</td>
</tr>
<tr>
<td>372 to 497</td>
<td>Jeep can travel about 50 passes</td>
</tr>
<tr>
<td>517 to 662</td>
<td>Track mounted heavy bulldozers</td>
</tr>
<tr>
<td>683 to 935</td>
<td>Passenger cars</td>
</tr>
<tr>
<td>1034 plus</td>
<td>No trafficability problems</td>
</tr>
</tbody>
</table>

1) Remolded soil conditions, for virgin soils about 20% higher

3.7 Limiting Cone Index

Based on the analyse of recent studies Hetherington (2001) questions the use of MMP as a simple specification of trafficability. Specially he notes, that quoting a limiting value for operations on sandy soils is not appropriate because of the fact that heavier vehicles often generate more drawbar pull on friction soils than light vehicles. Also the physical meaning of
MMP for wheel is more unclear than for tracked vehicles. It is evident, that MMP cannot be used as a norm, but still it can be used as some kind of yardstick to help the decision making for screening out sensitive sites. In stead of using directly MMP Maclaurin (1997) introduces a new concept, limiting cone index $C_{IL}$. The Limiting Cone Index is the cone index of the weakest soil, across which a vehicle can make a single pass, thus the limit of technical mobility, go/no-go situation. He gives the following models (Eq. 5.7.2.1, 5.7.2.2) for determining the limiting cone index:

\[
C_{IL\text{wheel}} = \frac{185 \cdot W_w}{2 \cdot n \cdot b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}} \tag{3.4}
\]

\[
C_{IL\text{track}} = \frac{163 \cdot W_w}{2 \cdot n \cdot b \cdot e \cdot p^{0.5} \cdot d^{0.5}} \tag{3.5}
\]

where
- $C_{IL\text{wheel}}$ limiting cone index for wheels
- $C_{IL\text{track}}$ limiting cone index for tracks
- $W_w$ vehicle total weight, kN
- $n$ number of axles, number of road wheels per side
- $b$ (inflated, unloaded) tyre width, track width, m
- $d$ (inflated, unloaded) tyre diameter, m
- $\delta$ tyre deflection when loaded, m
- $p$ track plate length, m
- $e$ track link area ratio

The $C_{IL}$-values are more suitable for cohesive soils than for friction soil, because of the different reactions of (dry) friction and (wet) cohesive soils under loading. Because sandy soils usually have better trafficability and are less problematic than cohesive soils, models can be used rather generally to screen out sensitive sites.

### 3.8 Wheel numeric

Wheel numeric is a WES-method variable calculated using a special formula, which includes tyre and soil parameters. Different authors have proposed different empirical Wheel numeric models for determining the best fitting combinations of tyre dimensions and deflection with observed tyre performance. The most common wheel numeric, $N_{CI}$, is selected as a reference. Some kind of limiting values are as given in Table 3.7.
Table 3.7. Indicative $N_{CI}$-values for estimating tractor tyre performance.

<table>
<thead>
<tr>
<th>Mobility class</th>
<th>$N_{CI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>$&gt; 3.0$</td>
</tr>
<tr>
<td>Fair</td>
<td>1.5 - 3.0</td>
</tr>
<tr>
<td>Poor</td>
<td>$&lt; 1.5$</td>
</tr>
</tbody>
</table>

Figure 3.6. Rut depth as a function of $N_{CI}$
In Figure 3.6 the rolling resistance and pull classes are depicted as a function of NCI. There seems to exist a certain acceptable compatibility between the two classifications.

Figure 3.7. Rolling resistance and pull coefficient and the corresponding mobility classes as a function of wheel numeric $N_{CI}$, calculated using NIAE and Maclaurin models.

> *Literature*


