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

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SOIL INTERACTION MODEL

APPENDIX REPORT No 11

SIMPLE FORWARDER MODEL
FOR ESTIMATING THE ECOEFFICIENCY OF TIMBER TRANSPORT

M. Saarilahti 1)

1)University of Helsinki, Department of Forest Resource Management

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SIMPLE FORWARDER MODEL
FOR ESTIMATING THE ECOEFFICIENCY OF TIMBER TRANSPORT

1. GENERAL FEATURES OF THE MODEL

1. TRACTOR MODEL
   1.1 NET POWER ON DRIVE WHEELS
   1.2 WHEEL AND SOIL CONTACT MODEL
   1.3 DRIVER MODEL

2. SOIL AND TERRAIN MODEL
   2.1 TERRAIN MODEL

3. TRAFFICABILITY OF THE SOIL
   3.1 RESISTING FORCE MODEL
      3.1.1 Rolling resistance
      3.1.2 Slope resistance
      3.1.3 Obstacle resistance
      3.1.4 Winding resistance, steering resistance
   3.2 THRUST

4. MOBILITY
   4.1 NET THRUST
   4.2 TRACTIVE FORCE
   4.3 TORQUE
   4.4 ROLLING RESISTANCE

5. ENVIRONMENTAL MOBILITY

6. DRIVING SPEED
   6.1 ENGINE POWER
   6.2 VIBRATIONS
   6.3 STEERABILITY
   6.4 Literature
   6.5 Appendix 1. Admissible acceleration limits
   6.6 Appendix 2. NSR Terrain classes

EXECUTIVE SUMMARY

A simple EXCEL-programmed forwarder model to estimate the technical and ecological mobility of a forwarder on slopes.

Keywords: Forwarder, modelling, mobility
1. GENERAL FEATURES OF THE MODEL

The model consists of different submodels containing different input variables influencing the productivity.

INPUTS
- tractor model
  - net power on drive wheels
  - wheel and soil contact model
  - driver model
- soil and terrain model
  - terrain model
    - macrorelief, slope
    - microlrelief, obstacle, surface roughness
    - winding of the forwarding paths
  - soil model
  - wheel/soil interaction models, Wheel Numerics

OUTPUTS
- mobility: net thrust, tractive force
- rut depth
- tractor speed

1. TRACTOR MODEL

The simple tractor model contains three submodels
- net power model
- wheel and soil interaction model
- driver model

1.1 NET POWER ON DRIVE WHEELS

Input variable: ENGINE POWER from Manufacturer’s specification

For a tractor model we need to know the net power at the drive line. Three factors influences on this
- energy losses due to hydraulic pumps, alternator, cooling etc, (net engine power model)
- drive line losses, depending on number of gearboxes or efficiency of converters etc (drive line model)
- energy losses due to engine wear and inadequate maintenance (true engine gross power model)
All those factors we can model by a simple assumption, that about 50% of the maximum engine power is at the use for the wheels. If needed different empirical coefficient between 40...60% can be used.

\[ P_e = 0.5 \cdot P \]  (2.1)

where
- \( P \) is engine power, kW
- \( P_e \) is power on driveline, kW

### 1.2 WHEEL AND SOIL CONTACT MODEL

Tractor input variables:

- TYRE DIAMETER, m
- TYRE WIDTH, m
- WHEEL LOAD, m
- ASPECT RATIO OR TYRE SECTION HEIGHT
- TYRE DEFORMATION
- TYRE INFLATION PRESSURE

As the tyre deflection is seldom known, the deflection model, Eq(2.2) is used.

\[ \delta = \left( 0.365 + \frac{170}{P_i} \right) \cdot \frac{W}{1000} \]  (2.2)

where
- \( \delta \) is tyre deflection, m
- \( P_i \) is tyre inflation pressure, kPa
- \( W \) is wheel load, kN

As the semiempirical WES-method (Turnage 1965) has been selected as the frame of reference for the study the wheel/soil interaction model is based on WHEEL NUMERIC. During the years several Wheel Numerics have been selected (Saarilahti 2000) of which 3 are presented here.

Wismer & Luth (1972)

\[ C_N = \frac{C \cdot b \cdot d}{W} \]  (2.3)

Freitag (1965)

\[ N_{CI} = \frac{C \cdot b \cdot d}{W} \cdot \frac{\sqrt{\delta}}{h} \cdot \frac{1}{1 + \frac{b}{2 \cdot d}} \]  (2.4)
Maclaurin (1997)

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

(2.5)

### 1.3 DRIVER MODEL

The driver commands the engine, and very seldom he uses the maximal power. One part of that is already included into net power model. The influence of drivers can easily be added into model using coefficient 0.8 for slow and 1.2 for fast driver type.

\[ P_e = k_{\text{DRIVER}} \cdot 0.5 \cdot P \]  

(2.6)

where the coefficient \( k_{\text{DRIVER}} \) gets a relative value 0.7 to 1.2. Normal driver \( k_{\text{DRIVER}} = 1 \) is used in the model.

### 2. SOIL AND TERRAIN MODEL

Terrain or soil are not modelled, but their properties are given directly by different input variables.

#### 2.1 TERRAIN MODEL

Terrain model contains the following micro- and macrotopography variables:

Input variables

- SLOPE PERCENT, + ADVERSE, - FAVOURABLE TO DRIVING LOADED DIRECTION
- TERRAIN CLASS, A ROUGH CLASSIFICATION OF SURFACE ROUGHNESS
- WINDING, A ROUGH CLASSIFICATION TO DESCRIBE THE WINDING OF FORWARDING PATHS

The sole soil parameter is penetration resistance measured using a standard penetrometer.

CI, AVERAGE CONE PENETRATION RESISTANCE VALUE AT 0.15 m LAYER

If the penetrometer value is not known, some soil models can be used or a "standard value" for an average conditions, Table 3.1.

Table 3.1. Approximate CI-values for different conditions

<table>
<thead>
<tr>
<th>MC, %</th>
<th>Description</th>
<th>CI, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50</td>
<td>Wet depressions, poor bearing capacity</td>
<td>400</td>
</tr>
<tr>
<td>35</td>
<td>Moist conditions, some kind of limit for forwarder</td>
<td>500</td>
</tr>
<tr>
<td>25</td>
<td>Well bearing forest soil</td>
<td>750</td>
</tr>
</tbody>
</table>
3. TRAFFICABILITY OF THE SOIL

3.1 RESISTING FORCE MODEL

Simply we can write the following resisting force model

\[ F = F_R + F_S + F_O + F_W + F_A + m \cdot a \]  \hspace{1cm} (4.1)

where

- \( F \) is the total resisting force, kN
- \( F_R \) is the rolling resistance, kN
- \( F_S \) is the slope resistance, kN
- \( F_O \) is the obstacle resistance, kN
- \( F_W \) is the winding resistance
- \( F_A \) is the air resistance, kN (negligible for forwarder terrain velocities)
- \( m \) is the tractor mass, kg
- \( a \) is the acceleration, m/s²

3.1.1 Rolling resistance

Different WES-submodels for calculating rolling resistance can be used. If the penetration resistance of the soil is not known, the following empirical rolling resistance coefficients, Table 4.1, can be used.

Table 4.1. Empirical rolling resistance coefficients for different conditions

<table>
<thead>
<tr>
<th>Soil and surface conditions</th>
<th>Apparent wheel sinkage, mm</th>
<th>Rolling resistance coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard surface, smooth bearing soil</td>
<td>10-15</td>
<td>0.05</td>
</tr>
<tr>
<td>Well bearing dry forest floor, thin humus layer</td>
<td>35-45</td>
<td>0.10</td>
</tr>
<tr>
<td>Normal forest floor, thick humus and root layer</td>
<td>65-85</td>
<td>0.15</td>
</tr>
<tr>
<td>Moist fine grained soil, some rutting</td>
<td>95-120</td>
<td>0.20</td>
</tr>
<tr>
<td>Wet fine grained soils, remarkable rutting</td>
<td>130-200</td>
<td>0.25</td>
</tr>
<tr>
<td>Wet peat and fine grained soils</td>
<td>185-300</td>
<td>0.33</td>
</tr>
</tbody>
</table>
If the Cone Index is known, the following WES-models are used:

Wismer&Luth (1973), Eq(4.2).

\[ F_R = W \cdot \left( 0.04 + \frac{1.2}{C_N} \right) \]  

(4.2)

where

- \( F_R \) is rolling resistance force, kN
- \( W \) wheel load, kN
- \( C_N \) Wheel Numeric

Maclaurin’s (1990), Eq(4.3) gives somewhat higher rolling resistance coefficient.

\[ F_R = W \cdot \left( 0.017 + \frac{0.453}{N_{Ci}} \right) \]  

(4.3)

3.1.2 Slope resistance

Slope resistance force is directly derived from the inclined plane geometry

\[ F_S = W \cdot \tan \alpha \]  

(4.4.a)

\[ F_S = W \cdot \frac{S\%}{100} \]  

(4.4b)

where

- \( F_S \) is slope resistance, kN
- \( W \) wheel load, kN
- \( \alpha \) slope, rad
- \( S\% \) slope percent

3.1.3 Obstacle resistance

Obstacle resistance is due to the fact, that a certain amount of work has to be done to overcome stones and other unevenness. This variable describes the influence of microtopography in the terrain/vehicle system. A theoretical model can be derived (Saarilahti 1979a)

\[ R_O = k \cdot \frac{\sum_{i=1}^{i} h_i}{d} \cdot W \]  

(4.5)

where

- \( R_O \) is obstacle resistance, kN
- \( k \) vehicle dependent constant
There is no data available for modelling of the constant $k$. Therefore some tentative obstacle resistance coefficients can be used, if needed, Table 4.2.

Table 4.2. Obstacle resistance coefficient

<table>
<thead>
<tr>
<th>Terrain class</th>
<th>Description</th>
<th>Obstacle resistance coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Even, a few stones &lt; 0.1 m</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>Rather even, stones &lt; 0.2 m</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>Uneven, stones 0.2…0.4 m</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>Rough, stones 0.4 - 0.5 m</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>Very rough, stones &gt;0.5</td>
<td>0.20</td>
</tr>
</tbody>
</table>

3.1.4 Winding resistance, steering resistance

There are no studies on winding (steering) resistance because the trajectories in agriculture and military applications are generally rather straight compared to dwindling forwarding trails in forestry. An arbitrary winding resistance ($\mu_W$) coefficient 0.05 to 0.1 can be used, if the trail is very winding. In thinnings the driving velocity is lower due to narrow trails, and it can be simulated somewhat by adding winding resistance to the model. Also more realistic constraint models for curve velocities can be constructed based on steering geometry, but they are not discussed in this context.

3.2 THRUST

Thrust, traction, can be used as a variable describing the trafficability of the soil. There are several frames of references to determine the thrust, or traction, which develops into the wheel/soil interface. In WES-method Cone Index (CI) is used as a sole soil parameter. There are many different empirical models developed for predicting the thrust, for the model a simple Wismer & Luth (1972) model has been chosen

$$T = 0.75 \cdot (1 - \exp^{-0.3C_N S}) \cdot W \quad (4.6)$$

where

- $T$ is thrust, kN
- $CN$ wheel numeric
Maclaurin’s (1990) model is as follows, Eq(4.7)

\[ T = W \left( 0.8 - \frac{3.2}{N_{\text{CI}} + 1.91} \right) + F_R \]  

(4.7)

4. MOBILITY

4.1 NET THRUST

Net thrust, net traction, drawbar pull can be used as a mobility variable. It is simply

\[ T_{\text{NET}} = T - F \]  

(3.1)

Net thrust must be positive (<0), negative value indicates no-go situation, where the tractor cannot operate. Low net thrust value indicates poor mobility, and net thrust coefficient should be over 0.1 for economically and environmentally acceptable operations. The following mobility classes can be used, Table 3.2.

Table 4.1. 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>

4.2 TRACTIVE FORCE

Maximum tractive force is a machine parameter, which indicates the maximum force the transmission is designed to support. It should appear on the Manufacturer’s technical data specifications.

If the total resistance forces (T) exceeds the tractive force (TF), then one technical mobility limit is being passed, and the suitability of the machine for the condition is “no”.

An easy variable for machine comparison is relative traction force. If the value passes 1 then the technical mobility limit has been passed.
\[ T_{REL} = \frac{T}{TF} \]  

(3.2)

where

- \( T_{REL} \) is relative tractive force
- \( T \) total resisting force, kN
- \( TF \) maximum tractive force

### 4.3 TORQUE

Maximum torque is left out from this simple model.

### 4.4 ROLLING RESISTANCE

High rolling resistance indicates poor mobility, and the following Table 5.1. can be used as one classification variable for mobility.

**Table 4.1.** 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>

### 5. ENVIRONMENTAL MOBILITY

Deep rut depth and severe soil compaction are evident soil damages due to excess wheel loads. Soil compaction modelling is more complicated, and therefore some simple rut depth models has been selected

Anttila’s (1997) rut models for a cycle pass, Eq(4.1) and (4.2)

\[ z = d \cdot \left( 0.003 + \frac{0.910}{C_N} \right) \]  

(4.1.)

\[ z = d \cdot \left( \frac{0.248}{N_CI} \right) \]  

(4.2)

Maclaurin (1990) sinkage model for a wheel pass
\[
z = d \cdot \left( \frac{0.224}{N C_l^{1.25}} \right)
\]  

(4.3)

6. DRIVING SPEED

Driving speed is influenced by
- Engine power and resisting forces
- Vibrations, rocking and swaying
- Steerability
- Driver’s ability and motivation, see Driver model, Chapter 1.3

6.1 ENGINE POWER

Driving speed depends on the ENGINE POWER and the resisting forces following the general Physics laws

\[
P = F \cdot v \quad \text{v} = \frac{P}{F}
\]

(5.1)

where

\begin{align*}
  P & \text{ is power, kW} \\
  F & \text{ force, kN} \\
  v & \text{ speed, m/s}
\end{align*}

Letting net power on drive wheels and total resisting forces into the Eq(5.1) we get the following driving speed model, Eq(5.2)

\[
v = \frac{P_e}{F}
\]

(5.2)

6.2 VIBRATIONS

A simple wheel/obstacle model (Saarilahti 1997b) is used for calculating the obtainable ground speed as a function of obstacle height for a tandem axle wheel.

\[
v_{\text{MAX}} = \frac{\sqrt{a_{\text{ZMAX}} (h + r_2 - h)}}{r_1 + r_2} \cdot \sqrt{2}
\]

(5.3)

where

\begin{align*}
  v_{\text{MAX}} & \text{ is maximum speed on uneven ground, m/s} \\
  a_{\text{ZMAX}} & \text{ maximum admissible vertical acceleration, m/s}^2 \\
  r_1 & \text{ tyre radius, m}
\end{align*}
\[ r_2 \quad \text{obstacle (stone) radius, m} \]
\[ h \quad \text{obstacle height, m} \]

Different maximal admissible vertical accelerations are (ISO 1978):
- Efficiency limit, for continuous working 1 m/s²
- Tolerance limit, occasional small terrain units, 2 m/s²
- Technical limit, maximum attainable safe speed, 10 m/s²

For practical applications \( a_{Z\text{MAX}} \) 6.7 m/s² is used.

### 6.3 STEERABILITY

Only one factor on steerability is taken into consideration in this respect. When driving along favourable slope the gravity does not limit the driving speed, and therefore the engine power velocity model gives values far beyond of the reality. Because the braking and manoeuvring on steep favourable slopes become one of the determining factors, replacing slope by effective slope gives more realistic velocity values.

\[ S_{\text{eff}} = \text{ABS}(S + 10) - 10 \quad (5.4) \]

Often it is more rational, however, to set some empirical maximum velocities for different conditions.

\[ v = \frac{P_E}{(W + L) \left( \mu_R + \mu_O + \mu_w + \frac{S_{\text{eff}}}{100} \right)} \quad (5.5) \]

### 6.4 Literature:


Turnage, G. 1972b. Using dimensionless prediction terms to describe off-road wheel vehicle performance. ASAE Paper No. 72-634.

### Appendix 1. Admissible acceleration limits

ISO NORMS 1978

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Z-direction</th>
<th>X- and Y-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 min</td>
<td>4 h</td>
</tr>
<tr>
<td>Hz</td>
<td>Acceleration, m/s²</td>
<td></td>
</tr>
<tr>
<td>Tolerance limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11.20</td>
<td>2.12</td>
</tr>
<tr>
<td>4</td>
<td>5.60</td>
<td>1.06</td>
</tr>
<tr>
<td>63</td>
<td>44.80</td>
<td>8.50</td>
</tr>
<tr>
<td>Efficiency limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.60</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>2.80</td>
<td>0.53</td>
</tr>
<tr>
<td>63</td>
<td>22.40</td>
<td>4.25</td>
</tr>
<tr>
<td>Comfort limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.78</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>0.89</td>
<td>0.17</td>
</tr>
<tr>
<td>63</td>
<td>7.11</td>
<td>1.35</td>
</tr>
</tbody>
</table>
### 6.6 Appendix 2. NSR Terrain classes

NSR- Terrain classes

- 20 cm classes (20, 40, 60, 80 cm obstacle height)
- Obstacle density (average obstacle distance, m)
  - 1.6 m = 3900 Nb/ha (0.39 Nb/m²)
  - 5.0 m = 400 Nb/ha (0.04 Nb/m²)
  - 16.0 m = 39 Nb/ha (0.004 Nb/m²)

<table>
<thead>
<tr>
<th>Surface class</th>
<th>Obstacle height, cm</th>
<th>Admissible</th>
<th>Obstacle height, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average distance, m</td>
<td></td>
</tr>
<tr>
<td>1 H(20)</td>
<td>a) 1.6-5.0</td>
<td>b) 5.0-16.0</td>
<td>&gt;16.0</td>
</tr>
<tr>
<td>2 H(20-40)</td>
<td>a) &lt;1.6</td>
<td>b) 1.6-5.0</td>
<td>&gt;16.0</td>
</tr>
<tr>
<td>3 H(40-60)</td>
<td>a) &lt;1.6</td>
<td>b) 1.6-5.0</td>
<td>5.0-16.0</td>
</tr>
<tr>
<td>4 H(40-80)</td>
<td>a) &lt;1.6</td>
<td>b) 1.6-5.0</td>
<td>1.6-5.0</td>
</tr>
<tr>
<td>5 H(40-80)</td>
<td>a) &lt;1.6</td>
<td>i) &lt;1.6</td>
<td>1.6-5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>j) &lt;1.6</td>
<td>1.6-5.0</td>
</tr>
</tbody>
</table>

0 No stones  
1 Even surface  
2 Intermediate class  
3 Rather rough surface  
4 Intermediate class  
5 Very rough surface

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1 Eriksson et al. (1978) p. 51