Terrain Characterization for Trafficability

Sally A. Shoop

June 1993
Abstract
Terrain material characterization is needed to predict off-road vehicle performance, trafficability, and deformation (compaction and rutting) resulting from vehicle passage. This type of information is used by agricultural engineers, foresters, military engineers, the auto and tire industry, and anyone else concerned with off-road, unpaved, or winter mobility. This report appraises the state-of-the-art of terrain (or substrate) characterization techniques for vehicle traction studies. It concentrates on field measurement of strength-related properties for soil, snow, muskeg, and vegetation, but also discusses how these compare with laboratory measurements and the importance of other terrain features (slopes, drainage, and obstacles).
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PREFACE

This report was prepared by Sally A. Shoop, Research Civil Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The project was funded by DA Project 4A762784AT42, Design, Construction, and Operations Technology for Cold Regions - Task CS, Work Unit 007, Off-Road Mobility in Thawing Soils.

The report was originally written to be included in an American Society of Agricultural Engineers monograph on traction mechanics, Advances in Soil Dynamics, edited by Sverker Persson.

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CONTENTS

Preface ............................................................................................................................... ii
Introduction ....................................................................................................................... 1
Soil ................................................................................................................................. 1
  Penetration resistance ................................................................................................. 1
  Plate sinkage ................................................................................................................. 3
  In situ shear tests ......................................................................................................... 4
  Devices reproducing wheel motion ............................................................................. 7
  Comparison of test methods ....................................................................................... 8
  Availability .................................................................................................................. 9
Organic terrain and vegetation ...................................................................................... 9
Snow cover .................................................................................................................... 15
  Unique aspects of snow ............................................................................................. 16
  Snow strength indices ............................................................................................... 17
Other factors affecting mobility .................................................................................... 19
Literature cited ............................................................................................................... 20
Bibliography .................................................................................................................. 22
Abstract ....................................................................................................................... 25

ILLUSTRATIONS

Figure
  1. Hand-held cone penetrometer .............................................................................. 2
  2. Components of a bevameter ................................................................................ 4
  3. Shear vane device .................................................................................................. 4
  4. Vane-cone ............................................................................................................. 5
  5. Cohron sheargraph ................................................................................................ 5
  6. Shear annulus ....................................................................................................... 6
  7. Portable shear annulus ........................................................................................ 6
  8. Grouser shear plate .............................................................................................. 7
  9. In situ direct shear apparatus ............................................................................... 7
 10. Wheel arc test rig .................................................................................................. 7
 11. Use of an instrumented wheel to measure tire/terrain interface forces and tire/terrain strength parameters ........................................... 8
 12. Yield envelopes on silty sand for different test methods .................................... 9
 13. Typical organic terrain profile ............................................................................ 10
 14. Vehicle performance on seven common muskeg terrains ................................ 11
 15. Relative effectiveness of vehicle design parameters on different muskeg terrains ................................................................. 12
 16. The muskeg fluke ................................................................................................ 12
 17. Instruments used to measure shear resistance and tensile strength of the vegetation mat .......................................................... 13
TABLES

Table
1. Comparison of cohesion and friction angle measurements .......... 9
2. Structural classification of vegetal cover of muskeg ................. 10
3. Characteristics of seven common muskeg terrains .................. 11
4. Tearing resistance of muskeg measured with the muskeg fluke ........ 12
5. Breaking lengths and yield/rupture ratios from tearing resistance tests on forest soils ........................................................................ 13
6. Muskeg topographic classifications ........................................ 14
7. Bearing strength of frozen peat .............................................. 15
8. CTI snow compaction gauge values ........................................ 17
Terrain Characterization for Trafficability

SALLY A. SHOOP

INTRODUCTION

This report appraises the state-of-the-art for characterizing terrain material (or substrate) for off-road vehicle traction or trafficability studies. It was originally written for inclusion in Traction Mechanics (Persson, in preparation), a monograph in the Advances in Soil Dynamics series of the American Society of Agricultural Engineers. Therefore, although I concentrate on soil strength characterization, which is of primary importance to agricultural engineers, I also include the unique aspects of other surfaces such as snow and organic terrain, of particular interest to military and forest engineers and others dealing with operation of off-road vehicles. The emphasis is on field measurements, with brief mention of their comparison to laboratory techniques.

Terrain includes the material that comprises the terrain (soil, snow, vegetation) as well as the geometry of the terrain surface (topography). The ability of the terrain to support and provide traction for vehicle operation is called trafficability. In trafficability studies, the emphasis is on the interaction between the vehicle and the surface material, whereas mobility considers the entire effects of the terrain, including obstacles and topography, on vehicle operation. This report focuses on the terrain material properties that influence trafficability and includes a brief discussion of other effects to be considered for off-road mobility, such as terrain features (slopes, obstacles, drainage) and climatic effects on the terrain environment (changes in moisture, freeze–thaw).

A means of characterizing the surface material is needed to predict off-road vehicle performance, trafficability, and soil deformation (compaction and rutting) that results from vehicle passage. Predictive models calculate the forces developed between the wheels or tracks and the terrain surface and generally assume the surface material is a well-behaved continuum (perhaps a bold assumption). A good review of various predictive models, along with their theoretical and experimental basis, is given in Plackett (1985). Each model may require different material properties as input, and although many different methods of material characterization exist, none is universally adequate. The same is true of the predictive models. It is of the utmost importance that the strength characterization technique satisfy the need for the information and be suitable for the terrain material in question.

SOIL

The fundamental parameters commonly used to describe soil for engineering or agricultural purposes are soil type, structure, grain size distribution, Atterberg limits, moisture content, and density. These and other physical properties of soils, as well as how they influence soil strength, are fully described in Chancellor (1993). The strength of soil depends on these basic physical properties. Measuring soil strength in the field rather than the laboratory has the advantage of testing the soil in its natural state. It is also generally less expensive and less time-consuming. Although carefully controlled laboratory tests may be more exact theoretically, they are impractical for a quick assessment of field terrain strength.

Penetration resistance

The field of traction mechanics has a keen interest in developing an easy and accurate field tool for terrain characterization for vehicle traction studies. One of the most popular tools, which the U.S. Army uses extensively, is the hand-held cone penetrometer (Fig. 1) described in ASAE standard S313.2 (ASAE 1985), SAE Standard J939 (SAE 1967), and U.S. Army Tech-
The hand-held cone penetrometer is a simple instrument designed to give a quick and easily obtained index of soil strength. The standard WES (Waterways Experiment Station) cone penetrometer consists of a proving ring, or some other force recording device, and a choice of two sizes of 30° cones. The large cone has a 323-mm\(^2\) (0.5-in.\(^2\)) base area (15.9-mm-diameter shaft) and is used with soft soils and sands. For harder soils and soils with fines, a smaller cone, 130-mm\(^2\) (0.2-in.\(^2\)) base area with a narrow shaft, is used.

The force required to press the cone through the soil layers is called the cone index (CI). Five to seven penetrations should be performed to get a good statistical average and an estimate of the variability of the terrain both laterally and with depth. The cone is pressed into the soil at a uniform rate of approximately 30 mm/s (72 in./min), although this rate may not be achievable in harder soils. The first reading is taken when the base of the cone is flush with the soil surface and then every 25 or 50 mm (1 or 2 in.) thereafter, depending on the application. The index is reported with depth, as an average over a range of depths or as a gradient.

For fine-grained soils, a remolding test may also be performed. The remolded sample is obtained by subjecting a 50.8-mm (2-in.) radius by 152.4-mm (6-in.) height soil sample contained in a tube to 100 blows (for fine-grained soils, or 25 blows for sands with fines) with a 1.14-kg (2.5-lb) remolding cylinder dropped from a height of 0.3 m (12 in.). The cone penetrometer is then used to measure the cone index of the remolded soil. The ratio of the remolded CI to the original CI is called a remolding index (RI). The product of the CI and the RI is called the rating cone index (RCI) and is a measure of the soil response to repetitive loads, such as multiple vehicle passes.

A vehicle cone index (VCI) is obtained using vehicle weight, dimensions, engine, and transmission factors in a series of equations and graphs detailed in U.S. Army TM 5-330 (U.S. Army 1968). The VCI is representative of the minimum RCI required for 50 passes of the vehicle. A comparison of the VCI and the soil RCI will result in a prediction of whether the vehicle is mobile or not in a particular soil.

Several adaptations have been made to the basic hand-held cone penetrometer, primarily in the form of continuous readouts, electronic data acquisition, and hydraulic rather than manual applied pressure (Olsen 1987; Rawitz and Margolin 1991). In these advances, the proving ring is replaced with a load cell, and the depth of penetration is measured with a proximity sensor. The output of the device is then automatically recorded on a data storage module or data logger. These developments allow full characterization of an inhomogeneous material in an efficient manner and at a low cost.

A similar device is the drop cone (Godwin et al. 1991), in which a 2-kg, 30° cone is dropped from a height of 1 m. This has the advantage of imparting a large force on the soil without the need to transport large weights or hydraulic equipment to the field (as would be needed to impart large forces with the standard "static" cone penetration). Tests at several field sites indicate linear rela-
tionships between the drop cone penetration and soil moisture, vane shear strength indices, and mean wheel rut depth, enabling prediction of soil and crop damage from driving machinery in the field (Godwin et al. 1991). Another impact device, the Clegg Impact Soil Tester, is used to assess the condition of low-volume unsurfaced roads (Mathur and Coghlan 1987) and has also been effective at monitoring soil strength recovery after spring thaw for assessing trafficability (Alkire and Winters 1986). The variation of impact measurements within a site is less than for other hand-held tools because of the larger soil volume incorporated in the test. For this same reason, some researchers have found that the drop cone is not sensitive enough and prefer the static penetrometer.

The penetration resistance measured by cone penetrometers is determined by a combination of soil strength properties: shear, compression, tension, and soil/metal friction. To use mobility prediction techniques that rely on the more fundamental soil properties, Rohani and Baladi (1981) developed relationships between the cone index and the shear strength and stiffness of the soil. Unfortunately, these relationships work only for homogeneous, frictional soils. Using the theory they developed, a cone index can be calculated knowing the cohesion, friction angle, and stiffness of the soil, however, the inverse procedure is more difficult because of the number of unknowns. A solution to this inverse problem was proposed by Hettiaratchi and Liang (1987) for a drop indenter (cone) test. By carefully choosing the geometry of the indenter and the type of tests performed, solutions to a mathematical model of the soil indenter can be achieved based on cavity expansion theory. The solutions are presented in the form of nomograms relating indentation to soil strength.

A series of controlled experiments to determine the relationship between penetration and soil strength was performed by Mulqueen et al. (1977). Their conclusions are that the relative proportions of the different strengths (shear, compression, and tension) reflected in the cone readings vary with moisture content and the cone becomes insensitive to shear strength as the moisture content increases. In addition, while performing the experiments they noted that soil compacted ahead of the cone effectively changed the shape of the cone and that the cone shaft sometimes interfered with the readings.

Similarly, several researchers have studied the effects of soil physical properties on cone resistance (Collins 1971, Voorhees and Walker 1977, Wells and Treswuan 1977, Ayers and Perumpral 1982, etc.). A good review of the factors affecting the penetration resistance—water content, bulk density, root density, soil structure, penetration rate, and soil type—is given in Perumpral (1987).

The cone penetrometer is very useful for determining go/no-go scenarios based on a large database of known vehicles. Problems may be encountered, however, in extrapolating results to predict performance of new or different vehicles. One of the best applications of the cone, because of its sensitivity, is for spatial characterization of the terrain. For example, Hadas and Shmulewich (1990) use a spectral analysis of cone data to determine the spatial arrangement of soil clods. Ohmiya and Masui (1988) have taken this type of analysis one step further, using three-dimensional graphical representation of the cone data to aid in visualization of the spatial variation of soil strength. The penetrometer has also been very successful in agricultural studies as an indicator of plant growth or root penetration (Taylor et al. 1966, Bowen 1976).

Although the value of the cone penetrometer depends on the type of study, it is no doubt the most universally used and widely accepted index of soil strength for vehicle mobility studies.

Plate sinkage

The plate sinkage test is used to determine the pressure-sinkage relationship (or flotation characteristics) of the soil. The plate sinkage test performed for mobility studies differs from that commonly used in civil engineering for determining bearing capacity. For mobility studies, the area of the plate should be large enough to simulate the contact patch of the tire. (The same plate is also used to predict mobility of tracks, it is not the total area of a track but rather simulates the contact area of the track pads supporting the peak load.) Sometimes a range of plate shapes and sizes are used. The plate penetration equipment can be mounted either on a portable test rig or on an off-road vehicle where it is possible to generate large normal loads. Repetitive loading is used to provide information on terrain response to multiple passes.

The plate sinkage test, along with a shear annulus measurement, is used in a well known terrain characterization apparatus called a bevameter (for Bekker value meter), shown in Figure 2. With a bevameter, plate penetration is used to measure bearing capacity, and the shear annulus (discussed later) is used to determine the shearing characteristics of the soil. Hence, both the normal and shear loading of a vehicle are simulated. These strength parameters (c, φ, and K representing shearing behavior and n, k_c, and k_v representing sinkage) are then used in Bekker's analytical model for predicting vehicle performance (Bekker 1969). Karafiath and Nowatzki (1978), however, argue that the fundamental assumptions behind the test method and analysis are not entirely consistent with the tractive behavior of a wheel or track. Wong (1989) gives bevameter results on a range
of terrains including different mineral soils, organic terrain (muskeg), and snow. Two vehicle-mounted bevameters are described in Wong (1989) and Alger (1988).

**In situ shear tests**

While the penetration techniques mentioned above relate to vehicle sinkage and motion resistance, measurements of the shear strength of soil give information more indicative of tractive performance. Several field methods for assessing the shear strength of soil are summarized briefly below.

**Shear vane**

The shear vane device is a simple tool designed to measure the shear strength of clays (Fig. 3). The vanes are typically about 70 mm in diameter and 100 mm in height but may vary in size depending on the purpose of the instrument. The instrument is pressed into the soil and then rotated, and the shear strength of the soil is reflected in the torque needed to rotate the device as the soil fails in shear in a cylindrical shape around the vane circumference. Since there is no way to change the load normal to the shear plane, the shear vane is not suitable for frictional soils, but it is handy in silts and clays. Although there is an ASTM standard for laboratory
tests using a miniature shear vane (ASTM Standard D 4648-87), no standard exists for the field technique.

**Vane-cone**

Combining the penetration resistance measurement of the cone penetrometer with the shear strength of the shear vane, a vane-cone penetrometer (Fig. 4) was proposed by Yong et al. (1975). The idea is that the compression and flotation behavior as well as soil shear resistance can be evaluated with one simple and easy-to-use device. The vane-cone is pressed into the soil and then, at a specified depth, is rotated while the depth is held constant. Vehicle mobility prediction equations based on the parameters given by the results of vane-cone measurements are presented by Yong and Youssef (1978). In a soil test bin study on a soft clay, they found that predictions based on the vane-cone were favorable, but additional studies and acceptance of this combination device are yet to come.

**Cohron sheargraph**

Other types of shear devices apply a shearing force along the surface of the soil. Of this category of instruments, the Cohron sheargraph is the most compact and easy to use. It is hand operated by placing the shear head on the soil using the desired normal load and then applying a shearing force by rotating the device. Both the normal and shear forces are recorded on the drum graph attached to the instrument (Fig. 5). Although the
Annular shear tests were proposed by Bekker (1969) and are a part of the bevameter technique of assessing soil strength for mobility prediction (Fig. 2). To assess shear strength, an annular plate is placed on the soil with an applied normal load and rotated at a constant rate. The annular plates can have either a metal or rubber surface as well as grousers (Fig. 6). The test is performed at a range of normal loads to determine the Coulomb shear strength parameters corresponding to the soil/metal or soil/rubber shear. Stafford and Tanner (1982) suggest that more than six different normal loads be used during the field procedure to obtain significant results.

The shear annulus is commonly mounted on an off-road vehicle as part of a bevameter, as described in Wong (1989) and Alger (1988). However, a smaller and simpler set-up, which can be operated by one person (Fig. 7), is described by Stafford and Tanner (1982).

A drawback to the technique is that the failure of the soil beneath the shear ring can occur on a plane oblique to the plane of the annulus ring, so the true normal and shear stress values along the failure plane are unknown (Liston 1973). The development of the oblique failure planes, however, can be avoided by placing a surcharge on the soil around and inside the annular ring (Karafiath and Nowatzki 1978).

**Grouser shear plate**

A similar concept is the shear plate where a plate or grouser is placed on the soil surface with a range of normal loads and the plate is then sheared across the soil.
ditions (moisture, density, and texture) remain closer to
the actual field conditions, as compared with gathering
and removing a sample to be tested in the laboratory.
Sample preparation consists of carefully cutting an
"undisturbed" sample or excavating the soil so that the
shear box can be placed around the soil in situ (Fig. 9).
As in the laboratory, the soil is sheared at several applied
normal loads. Because of the time-consuming nature of
sample preparation, however, usually too few samples
are tested so a good sampling of the material is generally
not obtained.

Devices reproducing wheel motion

Wheel-shaped devices

To characterize the tractive capacity of the soil
accurately, the test device should more closely simulate
the motion of a wheel (or track). Thus, a new kind of test
device, where the device acting against the terrain is shaped
like a segment of a wheel and acts like a wheel slipping
over the soil surface, was proposed by Wasterlund
(1990). The simulated wheel is made of a rubber surface
over rigid steel and moves in an arc across the soil, as
shown in Figure 10. This apparatus has been used to
Figure 11. Use of an instrumented wheel to measure (top) tire/terrain interface forces and (bottom) tire/terrain strength parameters (after Shoop 1989, 1992).

characterize the strength of the forest floor to avoid terrain damage from forestry operations.

Instrumented vehicle wheels

A vehicle with instrumented wheels can also be used to assess the strength of the tire-soil system (Shoop 1989, 1992). Triaxial load cells mounted on the wheel axles measure the forces at the tire/soil interface as recorded through the response of the axle (Fig. 11 [top]). During a traction test, the measured longitudinal force is equivalent to the net traction at the wheel. Gross traction \( T_g \) applied to the soil surface is then estimated by subtracting the motion resistance, and the applied traction (longitudinal) and vertical forces are converted to stresses by dividing by the tire contact area. Traction tests are performed at a range of applied normal stresses by changing the tire contact area using different inflation pressures. The terrain–tire shear parameters are calculated using a Mohr-Coulomb approach (Figure 11 [bottom]); these mobility terrain parameters are used to characterize the soil for mobility purposes and to predict the mobility of other vehicles on the same soil conditions.

Komandi (1990) also calculated soil parameters from vehicle slip-pull curves obtained in the field. He concludes that the Mohr-Coulomb theory is a valid description of the mechanics of the tire/soil interface but for firm soils the internal angle of friction is also dependent on slip velocity.

Comparison of test methods

Several studies have been conducted comparing the results of various strength measurement techniques (Patin 1972, Johnson et al. 1987, Kogure et al. 1988, Shoop 1989). Okello (1991) strongly recommends the use of in situ techniques over laboratory techniques but emphasizes that the size of the device (referring to plate sinkage) should be comparable to the size of the lug or track elements. As expected, there is disagreement between the shear strength values obtained from the different test instruments, primarily because of the magnitude and direction of the applied stress and the rate of deformation.

One of the most comprehensive studies of shear test techniques was published by Stafford and Tanner (1982). They compared six shearing techniques on six different soils, with the results summarized in Table 1. Although results vary with soil type, the vane shear consistently yields the highest values of cohesion, except when used on remolded soils. Similarly, when comparing vane shear, direct shear, and triaxial tests, Kogure et al. (1988) report the vane shear to yield the highest values.
Table 1. Comparison of cohesion and friction angle measurements (after Stafford and Tanner 1982).

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Torsional shear (Direct)</th>
<th>Direct shear (Triaxial)</th>
<th>Shear vane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Box</td>
<td>Annulus</td>
<td>Box</td>
</tr>
<tr>
<td>a. Cohesion (kPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>28.5</td>
<td>39.3</td>
<td>14.8</td>
</tr>
<tr>
<td>2</td>
<td>36.3</td>
<td>41.9</td>
<td>54.3</td>
</tr>
<tr>
<td>3</td>
<td>81.9</td>
<td>88.6</td>
<td>50.1</td>
</tr>
<tr>
<td>4</td>
<td>33.0</td>
<td>36.1</td>
<td>19.9</td>
</tr>
<tr>
<td>5</td>
<td>40.4</td>
<td>62.3</td>
<td>28.2</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>4.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

b. Friction angle (deg.)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Torsional shear (Direct)</th>
<th>Direct shear (Triaxial)</th>
<th>Shear vane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Box</td>
<td>Annulus</td>
<td>Box</td>
</tr>
<tr>
<td>1</td>
<td>28.5</td>
<td>33.2</td>
<td>33.2</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
<td>13.1</td>
<td>-21-4</td>
</tr>
<tr>
<td>3</td>
<td>38.1</td>
<td>22.9</td>
<td>24.0</td>
</tr>
<tr>
<td>4</td>
<td>29.0</td>
<td>30.8</td>
<td>34.4</td>
</tr>
<tr>
<td>5</td>
<td>20.5</td>
<td>21.3</td>
<td>8.3</td>
</tr>
<tr>
<td>6</td>
<td>14.8</td>
<td>8.8</td>
<td>31.6</td>
</tr>
</tbody>
</table>

Soils: 1 = sandy clay loam, 2 = clay, 3 = clay with stone, 4 = peat, 5 = remolded clay, 6 = remolded sand.

of shear strength and the direct shear the lowest. Kogure also studied the effects of sample orientation for each of the tests and found the results from the vane shear to be independent of orientation. In studies that have included the (Cohron) shearograph, summarized in Johnson et al. (1987), the shearograph was found to yield the highest values of cohesion but not necessarily the highest friction angle. Shoop (1989) compared shear annulus, direct shear, and triaxial tests with terrain strength values calculated from traction tests (on silty sand) and found that the undrained triaxial tests most closely compared with the failure envelope calculated from the forces at the vehicle tire/soil interface (Fig. 12).

**Availability**

Of the techniques discussed, the sheargraph, shear vane, and cone penetrometer are commercially available through Soiltest, Inc., of Evanston, Ill., or Eijkelkamp, Agrisearch Equipment in The Netherlands (through Sauze Technical Products Corp. of Plattsburgh, N.Y.). The cone penetrometer is also available through the U.S. Army supply system. The Clegg Impact Hammer is available from Lafayette Instrument Company. The in situ direct shear is usually a modification of laboratory direct shear instruments, and the shear plate, shear annulus, and plate sinkage equipment are generally made to specifications. The wheel simulation test rig was custom-built at the Swedish University of Agricultural Sciences in Garpenberg, Sweden. Instrumented wheels and vehicles are custom built by Hodges Transportation of Carson City, Nev.; Testing Services and Instrumentation of Westfield Center, Ohio; Datamotive, Inc., of Reno, Nev.; and the Cold Regions Research and Engineering Laboratory of Hanover, N.H.

**ORGANIC TERRAIN AND VEGETATION**

Organic terrain, also called muskeg, is a term used to describe terrain comprising a surface layer of vegetation with a subsurface layer of peat or fossilized plant debris. It includes terrains such as peat bogs, swamps, tundra, and forest floor. The surface of this terrain is composed of a living organic mat of mosses, sedges, and/or grasses, either with or without tree and shrub growth. Underneath this vegetative mat is a mixture of partially decomposed and disintegrated organic material called peat or muck. To be classified as muskeg, the peat must be over 450 mm thick when undrained or 300 mm when drained and have an ash content less than 80% (Radforth and Brawner 1977). The typical stratigraphy of organic terrain is sketched in Figure 13.

As a rule, peat or muck is highly compressible...
Surface Vegetation
Mat of Live Roots
Peat Moss

Figure 13. Typical organic terrain (muskeg) profile (after Yong 1985).

Inorganic Soil (silty - sand - clay)

compared with most mineral soils; it is characterized by its very high water content and its extremely low bearing capacity (MacFarlane 1958). To a great extent, the trafficability of muskeg depends on the strength of the vegetative mat overlying the soft peat or muck below, and vehicle mobility depends on the success of the vehicle to utilize the strength of the mat effectively without tearing or breakage.

A classification system for muskeg was proposed by Radforth (1952) and compiled into a field guide by MacFarlane (1958). The classification scheme is based on the vegetation, the contained peat/muck, the underlying mineral soil, and the topography. This was integrated with the system of the British Mires Research Group yielding the nine pure vegetative coverage classes given in Table 2. No species identification is necessary; only the qualities of the vegetation are needed, making this classification system suitable for use by engineers or scientists unskilled in plant identification. Since the classes usually occur in combinations, the terrain is designated by combinations of two or three of these class letter designations, starting with the most prominent class. Seven common muskeg classifications are described by Radforth and Evel (1959) in Table 3.

The descriptions and classification of the various types of muskeg offer qualitative indications of the engineering properties of the terrain, particularly with respect to vehicle mobility. For the muskeg classifica-

Table 2. Structural classification of vegetal cover of muskeg (peatland) (integration of British and Canadian systems, from MacFarlane 1958, 1969).

<table>
<thead>
<tr>
<th>British Mires Research Group*</th>
<th>Class symbol</th>
<th>Texture</th>
<th>Stature</th>
<th>Radforth System</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees &gt; 5 m</td>
<td>A</td>
<td>Woody</td>
<td>4.5 m (15 ft) or over</td>
<td>Tree form</td>
<td>Spruce, larch</td>
</tr>
<tr>
<td>Trees &lt; 5 m</td>
<td>B</td>
<td>Woody</td>
<td>1.5-4.5 m (5-15 ft) or over</td>
<td>Young or dwarfed tree or bush</td>
<td>Spruce, larch, willow, birch</td>
</tr>
<tr>
<td>Shrub habit, 500 mm to 2 m</td>
<td>D</td>
<td>Woody</td>
<td>0.6-1.5 m (2-5 ft)</td>
<td>Tall shrub or very dwarfed shrub</td>
<td>Willow, birch, Labrador tea</td>
</tr>
<tr>
<td>Shrub habit &lt; 500 mm, creep</td>
<td>E</td>
<td>Woody</td>
<td>Low shrub</td>
<td>Blueberry, laurel</td>
<td></td>
</tr>
<tr>
<td>Broad-leaved herbs</td>
<td>G</td>
<td>Nonwoody</td>
<td>Up to 0.6 m (2 ft)</td>
<td>Singly or loose association</td>
<td>Orchid, pitcher plant</td>
</tr>
<tr>
<td>Sedge-graminoid habit, 1-3 m</td>
<td>C</td>
<td>Nonwoody</td>
<td>0.6-1.5 m (2-5 ft)</td>
<td>Tall, grasslike</td>
<td>Grasses</td>
</tr>
<tr>
<td>a) mats, b) hummocks</td>
<td>F</td>
<td>Nonwoody</td>
<td>Up to 0.6 m (2 ft)</td>
<td>Mats, clumps, or patches sometimes touching</td>
<td>Sedges, grasses</td>
</tr>
<tr>
<td>Sedge-graminoid habit, &lt; 1 m</td>
<td>I</td>
<td>Nonwoody (soft or velvety)</td>
<td>Up to 100 mm (4 in.)</td>
<td>Often continuous mats, sometimes in hummocks</td>
<td>Mosses</td>
</tr>
<tr>
<td>a) mats, b) hummocks</td>
<td>H</td>
<td>Nonwoody (feathery to crisp)</td>
<td>Up to 100 mm (4 in.)</td>
<td>Mostly continuous mats</td>
<td>Lichens</td>
</tr>
</tbody>
</table>

*Adapted by Radforth.
NOTE: Following classification, observer states percentage of cover class within 20%.
Table 3. Characteristics of seven common muskeg terrains (after Radforth and Evel 1959).

<table>
<thead>
<tr>
<th>Common formulae</th>
<th>Associated topographic features</th>
<th>Subsurface peat structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE</td>
<td>Irregular peat, plateaus</td>
<td>Coarse-fibrous, woody</td>
</tr>
<tr>
<td>AEH</td>
<td>Irregular peat, plateaus, rock enclosures</td>
<td>Woody coarse-fibrous with scattered wood erratics</td>
</tr>
<tr>
<td>DFI</td>
<td>Stream banks</td>
<td>Woody particles in nonwoody fine-fibrous</td>
</tr>
<tr>
<td>DEI</td>
<td>Ridges, stream banks</td>
<td>Woody particles in nonwoody fine-fibrous</td>
</tr>
<tr>
<td>EH</td>
<td>Even peat plateaus, polygons</td>
<td>Woody particles in nonwoody fine-fibrous</td>
</tr>
<tr>
<td>EI</td>
<td>Ridges, mounds</td>
<td>Woody particles in nonwoody fine-fibrous</td>
</tr>
<tr>
<td>FI</td>
<td>Hummocks, closed and open ponds, polygons, flats</td>
<td>Amorphous granular, nonwoody fine-fibrous</td>
</tr>
</tbody>
</table>

The Swedish Army has also been very successful using plants as indicators to predict trafficability of muskeg. Fridstrand and Persson (1990) analyzed data obtained using cone penetrometer, vane shear, bevame-
ter, and plant identification along with trafficability measurements at two bogs in Sweden, and they found that vegetation was the major factor influencing traffi-
cability.

Many of the techniques used to assess trafficability of soils have also been used on muskeg with varying de-

Figure 14. Vehicle performance on seven common muskeg ter-
rains (after Radforth and Evel 1959).
mat. In addition, repeated loading of the mat by multiple passes may pump fine-grained muck up onto the mat surface, reducing the traction through slipperiness. The mat’s ability to support vehicles is provided by the overall tensile strength of the vegetation and the interlocking stems and roots. Many of the traditional soil strength measurements fail to obtain an adequate measure of the tensile properties of the mat and therefore inadequately characterize the terrain for trafficability. Even so, some success has been reported with the cone penetrometer (U.S. Army 1959), shear vane (Thomson 1960, Irwin and Yong 1980), and bevameter (Wong 1989).

Several instruments have been designed specifically to measure the tensile or tear strength of muskeg and vegetation mats. MacFarlane (1969) describes a muskeg “fluke” consisting of several spikes (Fig. 16) inserted into the vegetation and attached to a cable to which a load is applied. Measurements of the mat tearing strength using the fluke are reported in Table 4. Scholander (1973) measured the tearing strength of several forest

**Table 4. Tearing resistance of muskeg measured with the muskeg fluke (after MacFarlane 1969).**

<table>
<thead>
<tr>
<th>Cover formula</th>
<th>Avg shearing force (lb)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fl. wet between El mounds</td>
<td>2,100</td>
<td>9,341</td>
</tr>
<tr>
<td>El mounds, E = 1</td>
<td>1,650</td>
<td>7,339</td>
</tr>
<tr>
<td>FIE</td>
<td>2,430</td>
<td>10,898</td>
</tr>
<tr>
<td>El mounds E = 1</td>
<td>1,467</td>
<td>6,525</td>
</tr>
<tr>
<td>Fl [(low, wet area)]</td>
<td>2,667</td>
<td>11,863</td>
</tr>
<tr>
<td>Fl (very wet), dense E</td>
<td>2,483</td>
<td>11,044</td>
</tr>
<tr>
<td>El mounds, dense E</td>
<td>2,788</td>
<td>12,401</td>
</tr>
<tr>
<td>IF, I very dense</td>
<td>1,700</td>
<td>7,562</td>
</tr>
<tr>
<td>El mounds, E = 1</td>
<td>1,933</td>
<td>8,598</td>
</tr>
<tr>
<td>DF1 (very wet)</td>
<td>1,950</td>
<td>8,674</td>
</tr>
<tr>
<td>Fl (very wet)</td>
<td>1,650</td>
<td>7,339</td>
</tr>
<tr>
<td>El mounds, E = 1</td>
<td>2,050</td>
<td>9,118</td>
</tr>
<tr>
<td>Fl, F = 1</td>
<td>2,417</td>
<td>10,751</td>
</tr>
<tr>
<td>IF hummocks</td>
<td>1,717</td>
<td>7,637</td>
</tr>
<tr>
<td>PIE, F &lt; 1</td>
<td>2,367</td>
<td>10,528</td>
</tr>
<tr>
<td>El hummocks</td>
<td>2,600</td>
<td>11,565</td>
</tr>
</tbody>
</table>

---

Figure 15. Relative effectiveness of vehicle design parameters on different muskeg terrains (after Radforth and Evel 1959).

Figure 16. The muskeg fluke (from MacFarlane 1969).
Table 5. Breaking lengths and yield/rupture ratios from tearing resistance tests on forest soils (from Scholander 1974).

a. Survey of mean values of $S_{\text{breaking}}$ (stretch distance) of different types of vegetation and soils.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Soil texture</th>
<th>$S_{\text{breaking}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None present</td>
<td>Sand</td>
<td>50-100</td>
</tr>
<tr>
<td>Grass</td>
<td>Fine sand, silt</td>
<td>140-220</td>
</tr>
<tr>
<td>Dwarf-shrub</td>
<td>Sand</td>
<td>280-330</td>
</tr>
</tbody>
</table>

b. Ratio between yield and rupture limit of some uniform vegetation types.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Soil texture</th>
<th>No. of observations</th>
<th>$F_{\text{yield}}/F_{\text{rupture}}$ Mean value</th>
<th>Std. error</th>
<th>$S_{\text{yield}}/S_{\text{rupture}}$ Mean value</th>
<th>Std. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>Silt</td>
<td>32</td>
<td>0.78</td>
<td>0.02</td>
<td>0.58</td>
<td>0.03</td>
</tr>
<tr>
<td>Dwarf-shrub</td>
<td>Sand</td>
<td>22</td>
<td>0.70</td>
<td>0.03</td>
<td>0.53</td>
<td>0.04</td>
</tr>
<tr>
<td>Grass</td>
<td>Well molded peat</td>
<td>35</td>
<td>0.76</td>
<td>0.03</td>
<td>0.51</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Soils (vegetation-covered mineral soils) by inserting a vertical plate into the vegetation mat and applying a load by pulling the plate with a vehicle-mounted winch. The results show that the vegetation cover provides three to five times greater tearing resistance than bare soil (sand), and that the tearing resistance varies only moderately throughout the year. Tearing resistance varies with soil conditions, but within the same conditions the rupture force is a constant function of the breaking length. This breaking length can be compared with the wheel slip as a percentage of the contact length to determine if the vehicle will tear the mat. Some of the measured breaking lengths and yield/rupture ratios are given in Table 5. Scholander (1973) also observes that the vegetation fails first on the surface, in the pulling direction, with the final rupture occurring as a tensile failure of the root mat at the sides and bottom. This is the same failure progression observed by Niemi and Bayer (1970) from tear resistance tests on muskeg using the instruments shown in Figure 17. Bjorkhem et al. (1975) used plate sinkage tests to evaluate the effects of roots on compressive strength (or bearing), finding that even though the modulus values are nearly the same, the ultimate strength of the root-soil system was 70% greater than for soils without roots.

In a summary report describing several years of research for forest operations on peat lands in Finland, Rummukainen (1984), Saarilahti (1982), and Saarilahti

![Weights For Adjusting Normal Load](image)

**Figure 17.** Instruments used by Niemi and Bayer (1970) to measure (a) shear resistance and (b) tensile strength of the vegetation mat.
and Tiuri (1981) suggest that the traditional strength measurements are singular values, while continuous information is more appropriate for estimating vehicle mobility. They warn that indicator plants may not be reliable as they are adaptable to variations in growing conditions and competition from other plants. Based on evaluations of peat lands for trafficability using penetrometers, vane shears, and bevameters, as well as radar techniques to assess peat depth and water content, they note that the strength of peat is directly related to the moisture content and depth. A trafficability index based on vane shear strength and surface wetness class was developed and related to radiometer brightness levels, as shown in Figure 18. Thus, radio wave techniques are proposed as an alternative to the more limited point-wise measurements (cone, vane, and bevameter) for evaluating peat lands for vehicle operations.

Other factors commonly influencing mobility on muskeg terrain are associated topographic features, seasonal ice forms, and ice thickness. Small-scale terrain roughness features, such as hummocks, polygons, ridges, ponds, and bars, are included in the topographic classifications of muskeg shown in Table 6 (MacFarlane 1958), and seasonal ice forms are characterized based on their effect on mobility, as shown in Figure 19 (Radforth and Evel 1959). Some of these are not large enough or of an areal extent to stop a vehicle, but they may slow vehicle progress considerably and cause wear and tear to vehicle components. Although ice forms may impede vehicle travel, frozen peat lands are substantially stronger than when unfrozen. The compressive strength of frozen peat can be 350 to 400% higher than unfrozen peat depending on the water and vegetation content (Rummukainen 1984). Generally, 0.2 to 0.3 m of frost on wet peat lands will bear most heavy equipment (MacFarlane 1969), and less frost will bear weight

<table>
<thead>
<tr>
<th>Contour type</th>
<th>Feature Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Hummock, includes “tussock,” has tufted top, usually vertical sides, occurring in patches, several to numerous</td>
</tr>
<tr>
<td>b</td>
<td>Mound, rounded top, often elliptic or crescent-shaped in plane view</td>
</tr>
<tr>
<td>c</td>
<td>Ridge, similar to mound but extended, often irregular and numerous, vegetation often coarser on one side</td>
</tr>
<tr>
<td>d</td>
<td>Rock gravel plain, extensive exposed areas</td>
</tr>
<tr>
<td>e</td>
<td>Gravel bar, eskers and old beaches (elevated)</td>
</tr>
<tr>
<td>f</td>
<td>Rock enclosure, grouped boulders overgrown with organic deposit</td>
</tr>
<tr>
<td>g</td>
<td>Exposed boulder, visible boulder interrupting organic deposit</td>
</tr>
<tr>
<td>h</td>
<td>Hidden boulder, single boulder overgrown with organic deposit</td>
</tr>
<tr>
<td>i</td>
<td>Peat plateau (even), usually extensive and involving sudden elevation</td>
</tr>
<tr>
<td>j</td>
<td>Peat plateau (irregular), often wooded, localized and much contorted</td>
</tr>
<tr>
<td>k</td>
<td>Closed pond, filled with organic debris, often with living coverage</td>
</tr>
<tr>
<td>l</td>
<td>Open pond, water rises above organic debris</td>
</tr>
<tr>
<td>m</td>
<td>Pond or lake margin (abrupt), forming a rimmed depression</td>
</tr>
<tr>
<td>n</td>
<td>Pond or lake margin (sloped)</td>
</tr>
<tr>
<td>o</td>
<td>Free polygon, formed by a system of banked clefs in the organic deposit</td>
</tr>
<tr>
<td>p</td>
<td>Joined polygon</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness (m) of frozen peat layer</th>
<th>Bearing capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>Will bear a horse</td>
</tr>
<tr>
<td>0.15-0.20</td>
<td>Will bear 6-t horse sled traffic</td>
</tr>
<tr>
<td>0.20-0.35</td>
<td>Will bear empty 4-t truck</td>
</tr>
<tr>
<td>0.35-0.50</td>
<td>Will bear 10-t truck traffic</td>
</tr>
</tbody>
</table>

according to the guidelines (Table 7) provided by Hakkarainen (1949).

Vehicle traffic can also adversely affect the vegetation and the sensitive environment typical of organic terrains. Plant damage causes losses in forestry operations, significant changes in drainage patterns, and associated erosion. In permafrost areas, changes in the vegetation cover alter its thermal characteristics, resulting in thermokarst and changes in permafrost occurrence. These and other environmental aspects are more thoroughly presented in Radforth and Brawner (1977).

**SNOW COVER**

There are a variety of techniques for characterizing snow for vehicle mobility or tire traction testing. Snow surfaces that are used for testing are either natural or groomed and vary widely in strength and texture. In some ways, the methodology of characterizing snow is similar to that for soil. Grain size, structure, metamorphic state, temperature, density, free water content, hardness, and strength are measured or described at each significant layer within the snow pack. Since some of the techniques used are also used on soil, the following is a summary of the techniques or aspects unique to snow. A more extensive summary of snow characterization techniques for mobility and snow pavements is presented in Shoop and Alger (1991) and Abele (1990) and classification of seasonal snow cover in Colbeck et al. (1990).
Unique aspects of snow

The size and shape of the ice grains that make up a snowpack have a marked influence on the mechanical behavior of the snowpack as a whole. Large rounded crystals tend to roll past each other, while small angular crystals tend to pack tightly together when loaded. Crystal size and shape are generally documented using a magnifying glass or hand lens and a measurement grid. A comprehensive guide for classification of snow crystals is given in Colbeck (1986) and Colbeck et al. (1990).

Because snow exists close to its melting point, the temperature of the snow environment is extremely important. Temperature can be measured by use of a simple thermometer or with arrays of thermocouples or thermistors. The temperatures are normally measured in a profile through the thickness of the snow pack. Temperature can be used to estimate the probable “wetness” of the snow and, when coupled with a density measurement, can also give a very crude estimate of strength. When working with snow, the air temperature and snow temperature should always be measured. If the snow is deep or if temperature gradients exist within the snow (i.e. the air or ground temperature is significantly different from the snow temperature), a profile of snow temperature measurements is required. For shallow (uniform) snow, a temperature measurement at 25 mm and at the snow/ground interface is sufficient.

The texture and structure of a snow cover are continually changing. Because a fallen snowflake is in a physically unstable form on the ground, it changes its shape with time and is strongly influenced by temperature gradients. Typical stages of snow metamorphism are shown in Figure 20 (Colbeck 1987). Metamorphism affects the shape, size, and bonding of the crystals and therefore the strength characteristics of the snow cover and how it will react when trafficked. Freeze-thaw cycling, for instance, can cause ice lenses to form, markedly increasing the strength of the snowpack in a very short period of time.

Even when temperatures are below freezing, the snow mass may contain some free or liquid water and, because of the melting of the snow grains when heated, the free water content measurement is much different from the standard soil water content measurement. An estimate of whether water is present can be made using visual observations such as squeezing and forming the snow or by chemical indicators that change color when in contact with liquid water. The quantitative measure of liquid water content was historically determined using either freezing or melting calorimetry, which require a good deal of time and careful effort and are

Figure 20. Metamorphosis of snow crystals with temperature and time (after Colbeck 1987).
therefore not desirable for field use. A more recent advancement in liquid water measurement is a capacitance meter that is accurate and easily operated. This gauge consists of a plate that is placed on or in the snow and a small meter that is used to read out the capacitance. By taking a reading in the air and one on the snow surface, the free water content can be determined. This method is becoming increasingly more popular since it does not require any special fluids or bulky equipment and the gauge can easily be carried in a back pack. Boyne and Fisk (1990) compare these three methods of moisture measurement in snow (alcohol calorimetry, freezing calorimetry, and capacitance).

Snow density is measured in much the same way as soil density, by collecting a sample of a known volume and weighing it.

Snow strength indices

The methods presented below are a summary of field methods used for quickly assessing the strength of a snow cover. More sophisticated snow strength and index property measurements are given in a review of snow mechanics by Shapiro et al. (1993).

Bevameter and drop cone

All of the strength measurement techniques used in soils have been tried on snow with varying degrees of success. The most common of the soil strength characterization techniques that are also applied to snow are the bevameter and the drop cone. The bevameter was adequately covered above and its use on snow is discussed in more detail by Alger (1988), Alger and Osborne (1989), and Wong (1989). The drop cone, however, is slightly different from that used on soils; it is sometimes referred to as a snow compaction gauge. The snow compaction gauge shown in Figure 21, built by Smithers Scientific Services, Inc., of Akron, Ohio, is similar to a soil drop cone except that the cone has been rounded. The 220-g (7.75-oz) cone is dropped from a height of 219 mm (8.5 in.). The penetration is a result of vertical and horizontal compaction and shear and indicates the compaction resistance of the snow cover. The penetration distance is converted to compaction numbers using the standardized scale shown in Table 8.

Rammsonde

The rammsonde is similar to the cone penetrometer except the standard ramm cone is much larger in size and is driven into the snow using a drop hammer (Fig. 22). Generally a complete ramm set-up will have two different sized hammers along with a hammer slide and

![Figure 21. Snow compaction gauge, also called a drop cone (after SAE 1985).](image1)

![Figure 22. Rammsonde penetrometer (after Abele 1990).](image2)

### Table 8. CTI snow compaction gauge values (after SAE 1985).

<table>
<thead>
<tr>
<th>Surface description</th>
<th>CTI compaction range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>100</td>
</tr>
<tr>
<td>Ice</td>
<td>93 - 98</td>
</tr>
<tr>
<td>Extra hard-pack snow</td>
<td>84 - 93</td>
</tr>
<tr>
<td>Standard medium hard-pack snow</td>
<td>70 - 84</td>
</tr>
<tr>
<td>Soft-pack or loose-pack snow</td>
<td>50 - 70</td>
</tr>
<tr>
<td>Virgin snow - No rating: Use depth and moisture content</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
</tr>
</tbody>
</table>
several rod extensions for use in deep snowpacks. To use the rammsonde, the cone is placed on the snow surface and the slide hammer is dropped from a measured height. The penetration of the cone is measured and the process is repeated until the ramm has penetrated the entire depth of the snow pack (or to whatever depth is desired). This instrument has been most successful in deep packs such as avalanche zones and in the Arctic and Antarctic to obtain hardness profiles through deep layers of snow. Correlations between the rammsonde and several other snow properties and strength measurements are presented in Abele (1990). Use of data from a rammsonde for vehicle performance prediction is described in Wong (1992).

Manual snow hardness classification

Snow hardness can also be classified manually, without the aid of gauges or instruments, as described in the Swedish Terrain Classification System for Forestry Work (Swedish Forest Operations Institute 1992) and CRREL Instructional Manual 1 (CRREL 1962). The hardness is tested and classified by the ease of pushing a fist, outstretched hand, finger, pencil, or knife into the snow. The hardness is determined along the profile of a snow cover; the overall hardness of the cover depends on the percentages of each classification present. The test technique and hardness classifications are diagrammed in Figure 23 and are roughly correlated with values from the hardness gauge, as indicated on the figure.

Canadian hardness gauge

The Canadian hardness gauge (and similarly, the CRREL hardness gauge) measures resistance to penetration with small plates designed to be carried in a pack in the field. Its major use has been in the area of avalanche prediction; it is best used in hard virgin snow. The plates are various sizes, and the size used depends on the strength of the snow cover. The plate is pushed into the snow either horizontally or vertically, depending on the purpose of the test, and the resistance to penetration registers on a gauge built into the instrument handle. Hardness is generally measured at each of the snow layers within the cover.

<table>
<thead>
<tr>
<th>Testing snow hardness</th>
<th>Hardness class</th>
<th>Corresponding hardness gauge reading (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed fist covered with glove</td>
<td>Very soft</td>
<td>0-500</td>
</tr>
<tr>
<td>Flat extended hand with glove</td>
<td>Soft</td>
<td></td>
</tr>
<tr>
<td>Extended glove-covered index finger</td>
<td>Medium hard</td>
<td>500-2500</td>
</tr>
<tr>
<td>Pencil</td>
<td>Hard</td>
<td>2500-5500</td>
</tr>
<tr>
<td>Knife</td>
<td>Very hard</td>
<td>&gt;5500</td>
</tr>
</tbody>
</table>

Figure 23. Snow hardness characterization using manual techniques and hardness gauge (after CRREL 1962, Swedish Forest Operations Institute 1992).
and on different dates throughout the winter. On a given
test date, the SRTT is tested many times throughout the
day (every third tire) to be assured that the snow is
continually meeting the standard traction criteria (Shoop
et al. 1993).

OTHER FACTORS AFFECTING MOBILITY

Aside from the strength of the substrate, other terrain
factors influencing vehicle mobility include vegetation,
obstacles, terrain profile (micro relief), water courses,
and slopes. Any of these factors may change with time
due to natural conditions such as rainfall or snowmelt or
man-made conditions such as farming or construction.

In general, the vehicle and driver respond to those
factors that absorb energy (by increasing motion resis-
tance, inducing drag, reducing traction, or activating
the vehicle suspension), thus reducing or eliminating
motion. Grabau* groups these terrain factors into three
categories based on how they affect vehicle operation:

- those dealing with surface geometry; (small- and
  large-scale surface irregularities including obsta-
  cles)
- those that produce drag on the vehicle (vegetation
  and shallow water)
- those dealing with the supporting material or sub-
  strate (discussed in detail earlier).

Surface geometry affects vehicle mobility at a range
of scales from millimeter-sized pebbles on a road to vast
changes in the slope angle and orientation of the land.
All of these scales can occur at the same location, such
as a gravel-covered, washboard road on a slope. One of
the most important considerations in assessing the ef-
facts of surface geometry is how the amplitude and fre-
quency of the surface irregularities excite the vehicle
suspension system. Small-scale surface roughness, such
as gravel on a road, may do little more than cause tire
noise, but intermediate terrain roughness of tilled farm
land or a washboard road may severely reduce the speed
and effectiveness of the vehicle operation, affecting
the driver and cargo to such an extent as to make the traverse
intolerable. Other surface irregularities (such as streams,
ditches, large boulders, mounds, and pits) create obsta-
cles to vehicle passage because of incompatibility with
the shape of the vehicle; the vehicle "hangs up" on a
steep bank or "bottoms out" on a protruding rock.*
These features can slow the motion of the vehicle, stop
progress entirely, or delay movement by the additional
time required to avoid the obstacle.

Vegetation can fall within both geometrical effects
and drag-inducing effects. Smaller vegetation causes
additional frictional resistance or drag, impeding vehi-
cle movement and in extreme cases actually stopping
vehicle motion. On the other hand, vegetation can also
provide flotation and traction, supporting vehicles in
very wet and soft ground environments not otherwise
trafficable, such as bogs or wet forest floor. In these
cases it is very important to limit the breakup of the
vegetative mat (as discussed in Organic Terrain and
Vegetation above). Larger vegetation presents obsta-
cles to vehicular movement and limits visibility. This
kind of impediment is often characterized by trunk and
stem diameter, spacing, and branching frequency. Simi-
larly, boulders can create obstacles and/or provide
reinforcement to otherwise weak terrain material (such
as wet soil).

Nearly all of these factors are subject to changes with
time: daily, seasonally, annually, or over many years.
Temporal changes occur in nearly all of the terrain-
related factors such as soil moisture and density, plant
growth, stream flow, runoff, water depth, stream cur-
rent velocity, freezing and thawing of ground surfaces
and water bodies, and accumulation of snow and ice.
For these reasons, a mobility prediction scheme must
take climatic data into account. In addition to natural
changes in terrain, human intervention in the form of
construction or agricultural practices can also change
terrain conditions (such as altering water drainage pat-
terns) very quickly.

A good overview of these types of parameters and
how they influence mobility can be found in Koeppel
and Grabau (1987). An example of how these factors are
included in terrain-based mobility prediction models is
documented in U.S. Army (1968) and Turnage and
Smith (1983). Currently, these types of terrain classifi-
cation schemes are incorporated into GIS (Geographic
Information Systems)-based mobility prediction
schemes (Edmark et al. 1990, Fridstrand and Persson
classification are used in forestry to plan forest opera-
tions and costs. Examples of forestry terrain classification
systems are presented in Swedish Forest Opera-
tions Institute (1992) and from Norway, Samset (1975).

Because of the great spatial and temporal variation in
the parameters affecting mobility, it is logical to incor-
porate a statistical representation of the variability into
any mobility prediction model. This type of probabilis-
tic approach is necessarily a current area of research in
the advancement of mobility prediction. A probabilistic
approach is needed for both the descriptive input param-
ters, such as the statistical distribution of cone penetra-
tion data (Kogure et al. 1985, Heiming 1987), as well as
the predictive end results such as vehicle speed made
good (Lessem et al. 1992). Therefore, while in essence
the mobility model may be deterministic for a specific
vehicle over a specified terrain, in reality the terrain

input is considered as an average value representing a terrain “unit” with specified variability, and thus the operational use of the model generates a range of vehicle performance that can be expected over the variable terrain.

LITERATURE CITED


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Terrain material characterization is needed to predict off-road vehicle performance, trafficability, and deformation (compaction and rutting) resulting from vehicle passage. This type of information is used by agricultural engineers, foresters, military engineers, the auto and tire industry, and anyone else concerned with off-road, unpaved, or winter mobility. This report appraises the state-of-the-art of terrain (or substrate) characterization techniques for vehicle traction studies. It concentrates on field measurement of strength-related properties for soil, snow, muskeg, and vegetation, but also discusses how these compare with laboratory measurements and the importance of other terrain features (slopes, drainage, and obstacles).