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A Numerical Approach to Terrain Analysis for Off-Road Trafficability

A data bank of parameters derived from such sources as digital Landsat data, aerial photography, topographic maps, laboratory results, and ground survey reports was used.

KEY WORDS: **Digital techniques; Factor analysis; Geologic basins; Numerical analysis; Remote sensing; Terrain; Terrain models; Trafficability**

ABSTRACT: A numerical classification scheme is described in which terrain is quantified in multiparameter terms using such varied data sources as remote sensing, photogrammetry, and ground survey information. The method is based on the use of a comprehensive quantitative data bank in which surficial geological units are described by a number of chosen properties. The importance of individual properties used in the classification is examined via factor analysis, and the degree of similarity between units is determined by a hierarchical, average distance, clustering procedure. Digital terrain models and different sets of parameters can be emphasized according to need. An assessment of dynamic seasonal conditions is therefore possible, thus improving accuracy and ease of quantifying terrain conditions, which is of particular importance in trafficability studies.

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Purpose and Scope

Given the current advances in automatic photogrammetry and remote sensing and the trend for national surveys to store survey results in data banks, it is important and efficient to develop a quantitative terrain classification scheme which makes use of data from all available sources. In this study, terrain conditions for off-road trafficability assessments were examined; a subject which is particularly suited to an integrated approach because trafficability is affected by a large number of factors.

Terrain trafficability may be defined as the suitability of terrain to allow off-road vehicle movement and is dependent on terrain conditions, vehicle configuration, vehicle performance, mission to be performed, and operational requirements. Because the subject is dynamic and complex, it would seem necessary to make a separate assessment for each vehicle in order to arrive at a reliable prediction. For purely practical reasons this would be an enormous task and was rejected in the present study in favor of an analysis of general terrain conditions pertinent to mobility.

Trafficability assessments are required for military and exploration activities in undeveloped areas such as in the Canadian North, where ground information is scarce. Consequently, a system was developed which fully utilizes information from geologic, hydrologic, and pedologic surveys, aerial interpretation, remote sensing, and photogrammetric techniques. The objective of this paper is to outline a procedure which is not only useful for trafficability studies but also which can readily be applied to other types of multiparameter terrain assessments.

Background

The technique of preparing desert terrain

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analogs described by van Lopik and Kolb (1959) may be considered as one of the early attempts to quantify terrain for off-road trafficability assessments. A number of terrain factors were used to quantify different areas in the world and the degree of similarity between areas was then measured with a system of map overlays and numeric ratings. Using categoric data, composite terrain analog classes ranging from high to low were determined with this semi-quantitative approach.

Numerous attempts have since been made to improve the ease, precision, and speed of the method (e.g., Garrett and Shamburger, 1967; Shamburger and Grabau, 1968; Wright and Burns, 1968, etc.), but comprehensive numerical methods have been slow in developing. Recent technological breakthroughs in computer storage, data handling, photogrammetry, and remote sensing have been significant, thus improving the potential of developing a completely quantitative and numerical solution to terrain analogs.

SPATIAL UNITS

A basic distinction has to be made between a totally parametric approach and a genetic approach. The former emphasizes property variability and the identification of spatial units is accomplished in a second step by extrapolation or superimposition. In contrast, genetic classifications emphasize the identification of units, and essential properties are then measured to verify these units. There are numerous advantages and disadvantages to both approaches (Mabbutt, 1968; Mitchell, 1974) but there is no one system which is clearly superior. The choice is dependent on the aim, ultimate use, scale, time, cost, and precision of the analysis. For general use, a hybrid system, in which some of the advantages of both the parametric and genetic methods are combined, shows greater promise. This direction was pursued in the present study.

Surficial geological units selected on the basis of genetic inference are advantageous in quantifying terrain efficiently in a regional context. First, such units are composed of materials having the same genetic history and therefore, at least on theoretical grounds, they exhibit less internal variability while maximizing the between unit difference. In addition, such units are natural and can readily and efficiently be identified from aerial photos and limited ground analysis on the basis of both form and surface material.

TERRAIN PROPERTIES

In mobility studies it is necessary to assess the relative importance of each terrain property and then to select only those which have a direct and critical effect on off-road mobility. Unfortunately, this is a difficult task because property mobility relationships are complex and often subject to interactions. In some instances, such as with microrelief, an adequate quantitative measure has yet to be developed.

The use of many properties, some of which are only partially relevant to mobility, is also dangerous because redundant information will ultimately bias the classification. The final choice remains a subjective matter, but a number of statistical procedures such as principle component and factor analysis have the capacity of determining the overall importance of the chosen properties. These techniques can be used as an aid to screen out redundant information and have been used in the present study.

Properties are usually measured in terms of indices such as mean, maximum, minimum, or critcal values. Unfortunately, only a few critical terrain values have been established for off-road mobility and mean values are usually emphasized. This is often inadequate, and it is suggested that a measure of variability be included in the terrain analysis scheme so as to partially account for spatial variations.

DATA BANKS

In the past, data for integrated terrain classification were derived from topographic maps, aerial photographs, and ground surveys. The first source provides morphological data but is very tedious and time consuming. The second source mostly provides descriptive information on morphology, hydrology, vegetation, and land use, and is dependent on the ability and experience of the interpreter to quantify interpreted information. Field surveys provide basic information on surface material and composition but are costly and time-consuming.

The general trend in gathering terrain data is towards setting up comprehensive data banks in which compatible information from different surveys and sources are stored permanently so as to be readily accessible for integrated use.

Morphology from digital photogrammetry. Recent advances in automatic digital photogrammetry make it possible to generate morphological data from digital terrain models using orthophotos or automatic analytical stereo plotters (Collins, 1973; Junkins and Jancaitis, 1974; Collins *et al.*, 1977). In this way a data bank for surface configurations is developed, thus eliminating tedious map analysis.

Surface conditions from remote sensing. To generate quantitative information from aerial photos is still a problem but some progress has been made by density slicing measurements. The direct use of multispectral digital data has proven to be more useful (U.S. Army Topographic Laboratories, 1975) and Laser profilometry promises further improvement in quantitative data generation.

Ground survey data. Routine geological, pedological, and land-use surveys have produced extensive data on terrain conditions. Efforts are being made to set up comprehensive survey data banks to improve access and data handling, and to develop a compatible system in which general survey information can be supplemented with data gathered by remote sensing techniques (Anderson, 1977).

Given these developments, numerical methods must be developed which will take full advantage of the established data base. This will reduce duplication and re-examination of already surveyed areas and will improve access and speed of analysis.

NUMERICAL METHODS

A large number of numerical procedures exist by which terrain can be analyzed. Mobility studies require the use of comprehensive data from many different sources. The method of analysis has to be flexible and rapid so as to readily account for changing conditions resulting from climatic variations. Basic clustering procedures which measure parameter similarity in Euclidian space have advantages provided they are preceded by a parameter screening procedure such as factor analysis. They are especially useful since parameter choice and emphasis have to be altered according to circumstances and aims. In addition, a great deal of information can be considered comprehensively and simultaneously and, because a numerical expression is required, precision and objectivity of the analysis are improved.

Description of Method

TEST AREA

The Fort Liard area, in the Southwestern part of the Northwest Territories (southwest corner of topographic sheet #958, scale 1:250,000, 163° W, 60° 15′ N), was chosen for this study. The test area is dominated by steeply sloping foothills in the western part and a poorly drained glacial plain in the east. The foothills have eastward dipping beds of sandstones, shales, and conglomerates, while the glacial plain is characterized by a great variety of surficial deposits predominantly of glacial, lacustrine, and organic origin.

The only baseline information is provided by a 1972 Canadian Geological Survey Report (Rutter *et al.*, 1972) in which the basic surficial deposits, soils, and vegetation communities are described. The dominant soils are organics, gleysols, regosols, and brunisols, and the common vegetation cover consists of spruce, birch, tamarack, willow, alder, and poplar trees. Semi-alpine conditions occur in the mountains where the surface is covered by ericaceous plants and lichen.

DISTRIBUTION OF SPATIAL UNITS

A hybrid system was used in which surficial geological units were chosen as basic spatial units. These units were identified on aerial photographs on the basis of their morphological expression and the material make-up was verified in the field.

PARAMETERS USED

Literature recommendations by Sham-

Table 1. Types of Genetic Units in the Test Area

Genetic Categories	No. of Units in Test Area	Approximate Area
1 Organic terrain	2	1.5 %
2 Alluvial floodplain	4	12.0 %
3 Glacio-fluvial plain (channeled)	1	0.5 %
4 Glacio-lacustrine plain (channeled & plain)	5	7.0 %
5 Morainal plain (flat, rolling & veneer)	22	72.0 %
6 Colluvium (complex)	5	3.0 %
7 Bedrock (sandstone & shale)	4	7.0 %

burger and Grabau (1968), Wright and Burns (1968), Najaraj (1969), and Wong *et al.* (1975) were used as guides in parameter selection. In addition, ease of parameter identification, efficiently in quantification, and availability of data influence the choice. A list of the parameters used in the classification together with the data source are provided in Table 2.

In the absence of a good digital terrain model for the test area, it was necessary to resort to the topographic map to quantify the morphological features. The use of orthophoto-based digital terrain models or data from automatic analytical stereoplotters is recommended, however, so as to improve efficiency and accuracy (Collins, 1977).

Most of the parametric data were extracted by random stratified sampling (Holmes, 1967), and only soil texture and drainage rates could be converted directly from the geological report. The multispectral data were derived from an August 1975 Landsat tape. Bands 4 and 7 were chosen for the present study because of their capacity to contrast water and vegetation conditions, both of which influence trafficability in the test area. The data extraction was performed with the GE Image-100 system at the Canada Centre for Remote Sensing in Ottawa. To simplify the data handling it was necessary to reduce the intensity values for each pixel by density slicing. Band 4 was reduced from the possible 64 steps to five intensity categories, whereas band 7 was reduced to seven categories. For each band the most common intensity category was selected as the indicator parameter. They included:

MSS band 4, intensity category
(71.5% of test area)

MSS band 7, intensity category 11-13
(33.3% of test area)

MSS band 7, intensity category 13-15
(30.0% of test area)

For each terrain unit the percent cover was determined from the Image-100 theme map and, because no single category was dominant in band 7, the two most common were used separately. For all parameters used in the data bank the mean per unit value and coefficient of variation were measured so as to give the numerical approach a greater degree of reliability.

The parameters chosen for the present example were thought to be important to trafficability during wet summer conditions, and for this reason the August Landsat data were used. The other dominant climatic condition in the test area is winter frozen ground which lasts for approximately six months. A different set of parameters, which includes winter Landsat reflection values, was selected in order to quantify winter trafficability conditions. This new set of data was analyzed separately, thus providing a more reliable assessment of terrain under dynamic climatic conditions. For simplicity, only the results for wet summer conditions are presented in this paper.

TABLE 2. LIST OF PARAMETERS USED TO QUANTIFY TERRAIN

Parameters	Units	Data Source
1 Mean slope angle	(°)	topographic map
2 Maximum local relief	(m)	topographic map
3 Mean elevation	(m)	topographic map
4 Drainage density	(length/km²)	topographic map & aerial photos
5 Slope reversals	(no./km²)	topographic map
6 Bifurcation angle	(°)	topographic map & aerial photos
7 Bifurcation number	(no./km²)	topographic map & aerial photos
8 Area permanently waterlogged	(%)	aerial photos
9 Rate of drainage factor	(1-10 = poor to well)	geologic survey report
10 Soil texture	(% > 0.08 mm fraction)	geologic survey report
11 Forest cover	(%)	aerial photos
12 Spectral reflectance Landsat MSS band 4	(% intensity 6)	Landsat digital tape
13 Spectral reflectance Landsat MSS Band 7	(% intensity 11-13)	Landsat digital tape
14 Spectral reflectance Landsat MSS Band 7	(% intensity 13-15)	Landsat digital tape

RESULTS OF NUMERICAL PROCEDURE

A correlation analysis of all parameters in the data bank was made to determine parameter relationships. A factor analysis was then performed in which the data were screened in order to emphasize those parameters which contribute most to the total variance.

Factor analysis is a method of describing complex interrelationships between multiple variables in terms of the smallest number of factors. The scheme is based on the concept that correlated variables are not completely independent and contain redundant information. If variables are sufficiently intercorrelated they can be represented as clusters of vectors and their projection lengths, known as loadings, can be used as weights to combine the original variables into fewer factors. A detailed discussion of factor analysis is provided by Cattel (1965). In conjunction with the factor analysis, an average distance grouping procedure (Ward, 1963), which measures similarity of units in terms of the multidimensional factor scores, was used in the present study. The hierarchical clustering technique is best explained by the examples in Table 3 and Figures 1 and 2.

A 43 × 14 matrix formed the basis of the data bank. All 43 terrain units were listed separately, identified with a numeric indicator and followed by the numeric values for all 14 parameters.

Values for slope and percent sand were plotted in two-dimensional space and the distance between the position of these three units was measured using the Pythagorean theorem. It is obvious that units 1 and 2 are closer to each other than unit 3. They form the initial cluster and the distance between them can be considered as a degree of similarity. The closer the units are to one another, the more similar their properties. Once the initial cluster is formed, the mean value of the two units becomes the central point and the distance to the next nearest site is computed at a lower order of similarity so as to minimize the within-cluster variance of the new group. In this way a hierarchy can be built up.

In the examples given, two dimensions, slope and percent sand, were considered. However, this scheme can easily be extended to n-dimensions by using matrix algebra. The UBC—C-group program (Patterson and Whitaker, 1973), which is based on the average grouping technique described by Ward (1963), proved useful for this project. All units were grouped together according to their similarity with respect to all measured parameters. At least on theoretical grounds, such an approach should provide a comprehensive classification because all parameters are considered simultaneously and of equal weight. With these two techniques—factor analysis and hierarchical clustering—it was possible to screen the parameters initially, reducing their numbers, and then to classify the units using only those parameters which contribute most to the total variance.

Applying these techniques to the Fort Liard test area, the 14 initial parameters were reduced to five factors which accounted for 78 percent of the total variance. The remaining factors contributed less than 6 per cent each to the total variance and were therefore excluded from the numerical analysis. The importance of the individual parameters on the factors is shown in Table 4 where the factor loadings are listed.

The factor loadings were multiplied by the original data values in order to determine the factor score for each unit and parameter, and the hierarchical grouping procedure was then used to classify the test area numerically. The results of this numerical procedure are provided in Figures 3, 4, and 5 which show the spatial distribution of units, their degree of similarity, the mean per group values, and the mean group variability.

The groups of units derived in this way are representative of the type of terrain present in the test area during wet summer

TABLE 3. EXAMPLES USED TO DEMONSTRATE CLUSTERING PROCEDURE

	Slope (°)	% Sand	% Forest Cover
Unit 1	1.0	8	10
Unit 2	1.5	15	5
Unit 3	3.0	2	30

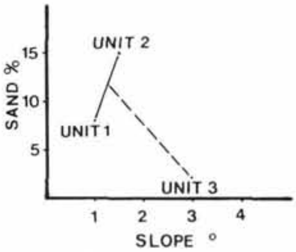

FIG. 1. Average distance clustering in two dimensions.

FIG. 2. The construction of a hierarchy.

conditions and can be used directly for trafficability assessments, especially once the choice of vehicle and type of movement have been decided.

CONCLUSIONS

Given the current developments in computer data storage and numerical data generation from remote sensing and automatic photogrammetry, it is essential that suitable numerical methods be developed which fully utilize all availabe data sources. The method described in this study is an example of such an approach and exhibits a number of advantages.

THE USE OF A COMPREHENSIVE QUANTITATIVE DATA BANK

A wide variety of parameters influence trafficability conditions and for this reason it is essential that a comprehensive data bank be used. In the present case 14 parameters derived from such a wide variety of sources as digital Landsat data, aerial photography, topographic maps, laboratory results, and ground survey reports were used. Once the quantitative data are set up in a data bank a speedy analysis is possible in which different parameters can be added and emphasized.

COMPATIBILITY OF NUMERICAL SCHEME

This method can readily utilize a great variety of data and measuring units. Topographic and morphological terrain data derived from digital terrain models (orthophoto based or from automatic analytical stereoplotters) and environmental conditions derived from digital multispectral means can easily be processed in conjunction with ground survey data, thus improving efficiency of analysis.

FLEXIBILITY AND SPEED OF ANALYSIS FOR DYNAMIC ASSESSMENTS

The system is open-ended and readily permits the addition of new data and allows the emphasis of individual parameters according to need. Once the data are set up in a computer data file, they can be processed quickly and at very low cost. This allows a quantification of dynamic conditions because summer and winter periods can be analyzed separately giving emphasis to those parameters relevant to each climatic condition.

THE USE OF MANY PARAMETERS TO QUANTIFY COMPLEX CONDITIONS

There is no restriction on the number of parameters to be used, but the use of many accessory or redundant parameters will bias the ultimate classification. This problem is solved by factor analysis by which the parameter importance is measured in terms of percent contribution to the total variance. In this way the essential parameters can be emphasized and redundant information can be excluded from the analysis.

TABLE 4. FACTOR LOADINGS

	Factors				
Parameters	1	2	3	4	5
Maximum relief	*−0.91	−0.03	−0.04	−0.06	−0.09
Elevation	*−0.85	−0.11	0.04	0.17	−0.04
Slope Angle	*−0.73	−0.37	0.30	0.08	−0.09
Drainage Factor	*−0.65	−0.49	−0.27	0.11	−0.13
Slope Reversal	*−0.50	−0.21	0.31	−0.44	−0.41
MSS-4 (6)	0.10	* 0.74	−0.20	0.03	0.06
MSS-7 (11-13)	0.35	0.48	0.29	0.40	0.22
Texture	−0.29	* 0.84	0.11	−0.04	0.12
Drainage Density	0.02	−0.50	* 0.68	−0.24	−0.02
Area Waterlogged	0.57	0.26	* 0.66	−0.24	0.16
Forest Cover	0.18	0.17	*−0.88	0.07	−0.12
Bifurcation Angle	0.25	−0.27	−0.01	*−0.77	0.24
Bifurcation Number	0.05	0.14	0.29	*−0.78	0.02
MSS-7 (13-15)	0.01	0.01	−0.15	0.15	*−0.93

* Indicates those parameters which show the most significant contribution to each factor.

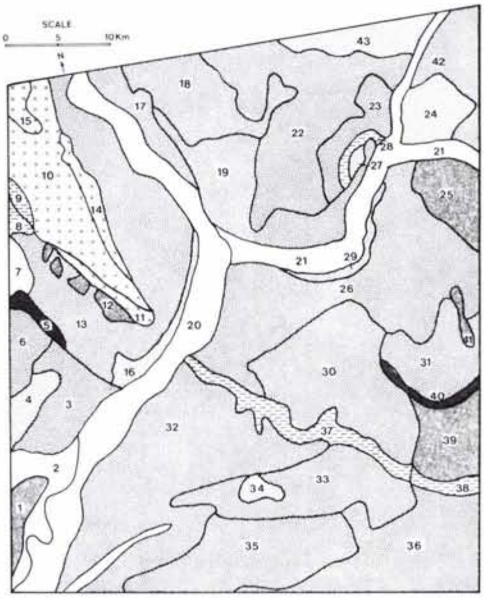

FIG. 3. Spatial distribution of units in the Fort Liard area after numerical grouping.

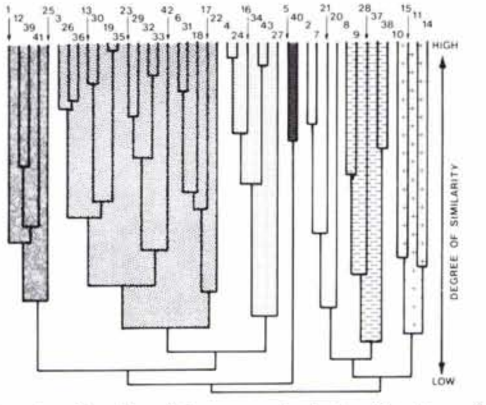

FIG. 4. Results of the numerical classification of units.

QUANTIFICATION OF SPATIAL UNITS

Spatial units cannot readily be quantified by single values since terrain conditions vary greatly over space. In order to partially solve this problem, two solutions were pursued: (i) genetic geomorphological units were chosen as basic spatial individuals because they form an important underlying framework for the terrain and the within-unit variability is minimized, at least on theoretical grounds; (ii) each unit was quantified by average parameter values but at the same time the degree of variability in each unit was measured in terms of the coefficient of variation (% CV). This provides the advantage that the degree of reliability for each mean unit value can be examined in the final classification.

DEGREE OF SIMILARITY IN A HIERARCHICAL FRAMEWORK

Few things in nature are identical, especially when viewed in multi-parameter terms. It is for this reason that a degree

PARAMETERS → / TERRAIN TYPE ↓	SLOPE ANGLE (°)	MAXIMUM RELIEF (m)	ELEVATION (m)	SLOPE (♦/Km) REVERSALS	DRAINAGE DENSITY (♦)	BIFURCATION ANGLE (°)	BIFURCATION NUMBER	AREA WATER LOGGED (%)	DRAINAGE RATE (f)	SOIL TEXTURE (%)	FOREST COVER (%)	LANDSAT MSS-7 (%)	LANDSAT MSS-4 (%)
Mean Group Values													
▨ Morainal Plain	4.3	180	441	.3	.9	32	.1	6	6	41	67	21	68
▦ Morainal and Glacio – Lacustrine Plain	1.6	140	363	.2	1.1	74	.1	20	5	41	75	27	71
░ Morainal and Glacio – Lacustrine Plain	2.5	99	385	.1	.2	0	0	12	5	42	75	28	74
■ Organic (Fen and Bog)	3.0	30	366	.1	2.4	75	0	75	2	11	27	50	72
□ Alluvial Plain with some Lacustrine Deposits	7.0	76	286	.2	1.8	78	.5	40	4	64	55	19	62
▤ Colluvial and Alluvial Deposits	6.5	113	393	.2	3.2	56	.1	27	6	80	57	18	53
⊠ Bedrock (Sandstone Shale and Colluvium)	12.6	403	673	.3	2.1	48	.1	1	7	85	45	20	57
Mean Group Variability	←					% CV							→
▨ Morainal Plain	53	–	10	74	47	13	60	56	24	6	17	16	8
▦ Morainal and Glacio – Lacustrine Plain	57	–	12	98	78	25	80	38	29	13	11	14	7
░ Morainal and Glacio – Lacustrine Plain	50	–	8	100	55	0	0	36	30	18	14	10	5
■ Organic (Fen and Bog)	29	–	4	75	26	0	50	10	72	23	30	14	13
□ Alluvial Plain with some Lacustrine Deposits	69	–	9	71	47	22	102	35	33	16	11	13	7
▤ Colluvial and Alluvial Deposits	43	–	11	113	41	24	70	65	8	17	15	19	14
⊠ Bedrock (Sandstone Shale and Colluvium)	33	–	15	63	47	13	50	23	23	35	22	18	10

FIG. 5. Mean values of terrain unit groups for wet summer conditions.

of similarity measure is more appropriate than a rigid categoric classification. The task of selecting the level at which individual groups are separated is somewhat subjective but it gives the investigator the added flexibility to determine the approximate number of groups and degree of generalization desired for his specific work.

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