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A Limited NRMM Validation Study for ISTVS

by Newell R. Murphy, Jr., Donald D. Randolph

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and U.S. Army Cold Regions Research and Engineering Laboratory

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Final report

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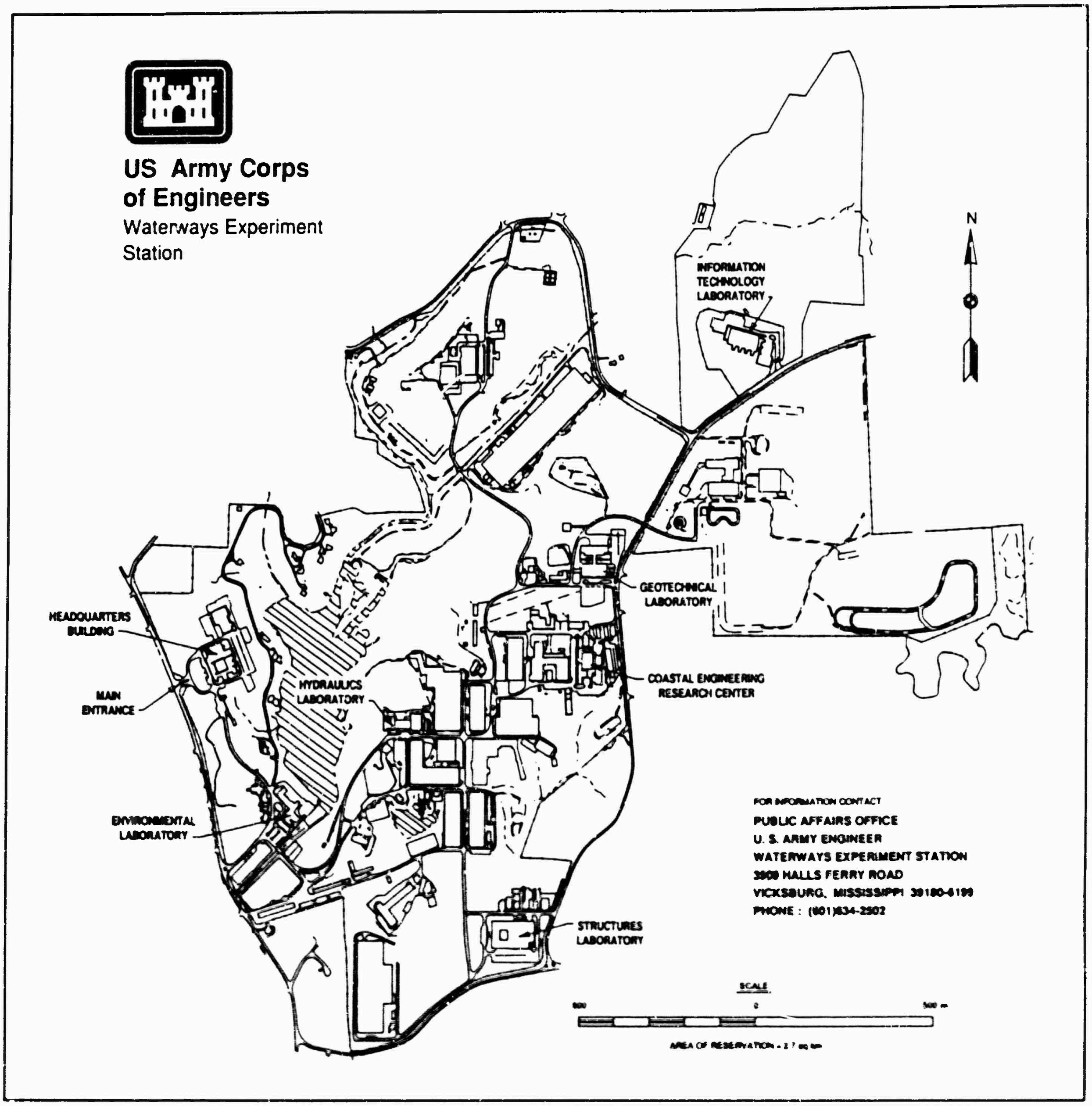

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Contents

Preface

Personnel of the U.S. Army Engineer Waterways Experiment Station (WES) and the Nevada Automotive Test Center (NATC) conducted this study during the period September 1993 through December 1993 in support of a mobility demonstration for the International Society of Terrain-Vehicle Systems' 11th International Conference. In addition to support of the ISTVS demonstration, the study also provided a partial validation of the latest version of the NATO Reference Mobility Model (NRMMII). The validation effort was funded jointly by the U.S. Army Tank-Automotive Command and the U.S. Army Cold Regions Research Engineering Laboratory.

The study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, Geotechnical Laboratory and under direct supervision of Mr. N.R. Murphy, Jr., Chief of the Mobility Systems Division, WES, and Mr. H.C. Hodges, Jr., Vice-President, NATC. Messrs. D.D. Randolph and R. H. Johnson, WES, and S.C. Ashmore, NATC, were responsible for selecting and characterizing the test courses, and developing the demonstration program. Mr. R.B. Ahlvin, WES, conducted the mobility simulations using the NATO Reference Mobility Model (version 2) with the able assistance of Mr. T.D. Hutto and Ms. F.B. Ponder, WES, who prepared the NRMM input data files. Mr. Ashmore and NATC personnel conducted the demonstration. Messrs. Murphy and Randolph conducted the analysis of the demonstration and simulation results and prepared this report. Appendix C was written by Mr. Ahlvin. The report was typed by Ms. K. Friar and Ms. J. Calhoun..

Special acknowledgment is made to the NATC personnel and especially to Mr. H.C. Hodges, Jr., and Mr. S.C. Ashmore for their support and invaluable contributions during this study.

Any future inquiries pertaining to information in this report should be directed to either Messrs. Murphy or Randolph, WES . They can be reached by telephone at (601)634-2447/2694, respectively. Specific inquiries concerning the field tests should be directed to Mr. Ashmore at (702)882-3261.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard.

Conversion Factors, Non-SI to SI Units of Measurement

Non-Si units of measurements used in this report can be converted to SI as follows:

Multiply	By	To Obtain
feet	0.3048	metres
horsepower	745.6999	watts
horsepower per ton (U.S.)	822.15986	watts per ton (metric)
horsepower (U.S.)	1.01387	horsepower (metric)
horsepower per ton (U.S.)	1.11779	horsepower (metric) per ton (metric)
inches	2.54	centimetres
miles (U.S. statute)	1.609344	kilometres
miles per hour (U.S. statute)	1.609344	kilometree per hour
pounds (weight)	0.4535024	kilograms
pounds per sq in.	6.894757	kilopascals
tons (2,000 lb) (U.S.)	907.1847	kilograms
tons (U.S.)	0.90718470	tons (metric)

1 A LIMITED NRMM VALIDATION STUDY FOR ISTVS

INTRODUCTION

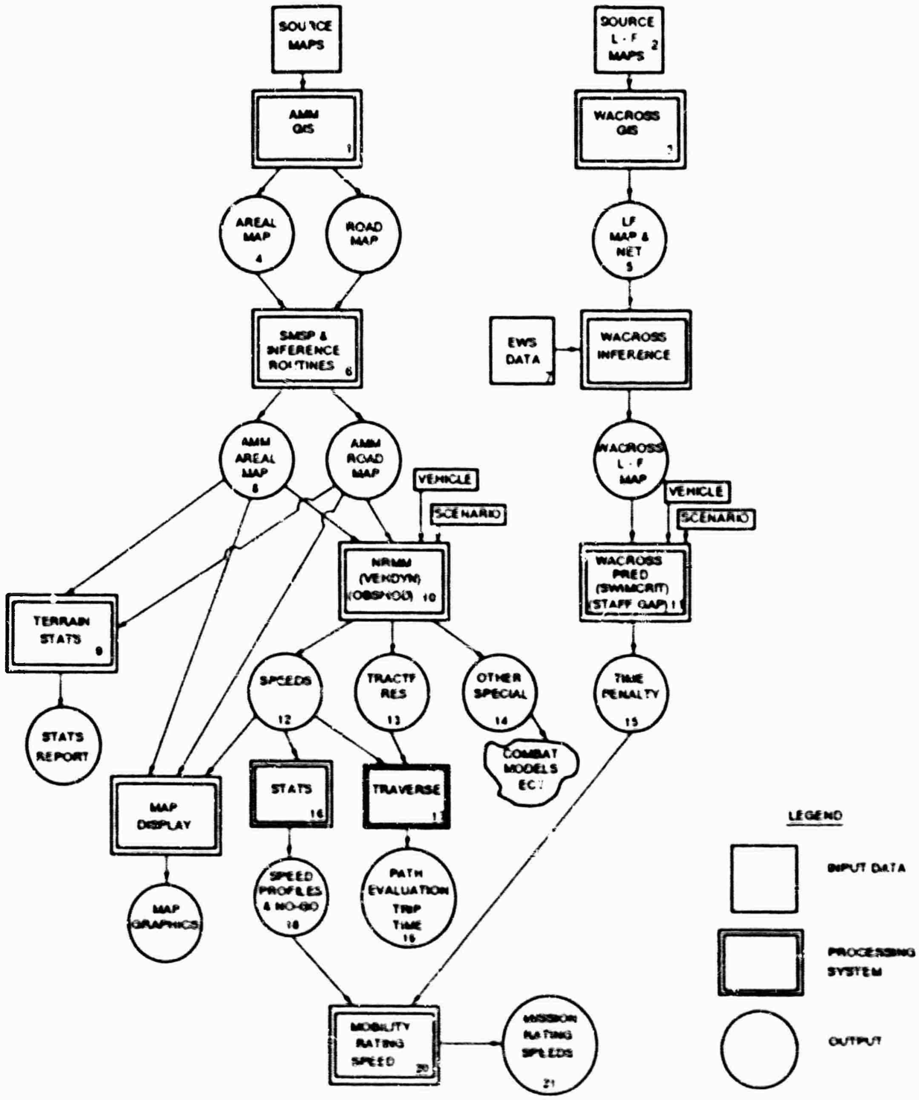
Background

The NATO Reference Mobility Model (NRMM) is a comprehensive model that simulates the mobility performance of any vehicle in homogeneous terrain or road units. The model requires as input vehicle characteristics, a detailed description of the terrain/road units, and driver characteristics data. The principal output of NRMM is the maximum speed for crossing a specific unit considered to be infinite in length. To provide a means for standard mobility performance assessments, the NATO AC/225 (Panel 2) adopted NRMM as its mobility model in 1979. The NRMM is managed by the NRMM technical management committee (NRMM TMC). As a result of continuing research developments, the NRMM TMC approved several modifications and upgrades to NRMM between 1979 and 1991. In 1992 the NRMM TMC approved the use of a second generation model labeled the NRMM2 (Ahlvin and Haley, 1992).

The NRMM was largely developed from empirical algorithms. The primary structure that was built into the model balances available and required forces to obtain a speed. This speed is then reduced or limited, if necessary, by factors which cause the driver to slow the vehicle as a result of surface roughness, visibility, maneuvering in vegetation, obstacles, and road or trail curvature. Figure 1 shows an overviw flow diagram of NRMM2.

A traverse model that considers direction of slopes, length of terrain units, influence of adjacent units, driver familiarity with the terrain, vehicle acceleration, deceleration, braking and momentum is used with the NRMM predicted speeds to predict speed along specified paths or traverses (McKinley, 1988). See Appendix A for a brief description.

OUTLINE OF PROCESSES USED BY THE
ANALYTICAL NRMM USER COMMUNITY



GLOSSARY

1 ARMY MOBILITY MODEL GEOGRAPHIC INFORMATION SYSTEM
2 LINEAR - FEATURE (TERRAIN GAPS, RIVERS, STREAMS)
3 WATER CROSSING MODEL GEOGRAPHIC INFORMATION SYSTEM
4 AREAL - TERRAIN FEATURES THAT TAKE UP AREA
5 LINEAR - FEATURE MAP AND NETWORK
6 SOIL - MOISTURE - STRENGTH PREDICTION MODEL AND INFERENCE
7 EUROPEAN WATERWAYS STUDY DATA
8 ARMY MOBILITY MODEL SYSTEM
9 TERRAIN STATISTICS
10 NATO REFERENCE MOBILITY MODEL INCLUDING VEHICLE DYNAMICS MODULE (VEHDYN) AND OBSTACLE PERFORMANCE MODEL (OBSMOD)
11 WATER CROSSING PREDICTION MODEL INCLUDING SWIMMING CRITERIA MODEL (SWIMCRIT) AND BRIDGING PART OF THE STATISTICAL TERRAIN AND FORCE FOR GAPS MODEL (STAFF GAP)
12 SPEED
13 TRACTIVE FORCE AND RESISTANCE
14 OTHER SPECIAL PURPOSE OUTPUTS
15 CROSSING TIME PENALTIES
16 PREDICTIVE STATISTICS
17 TRAVERSE PREDICTION MODEL
18 SPEED PROFILES & PERCENT NO - GO
19 ROUTE EVALUATION - TRAVEL TIME
20 MOBILITY RATING SPEED COMPUTATION
21 MISSION RATING SPEEDS

Figure 1. Flow diagram of NRMM2 processes

Purpose

The purpose of this study was to demonstrate NRMM2's mobility prediction capabilities to participants at the International Society of Terrain-Vehicle Systems' (ISTVS) 11th International Conference and to provide a partial validation demonstration of the NRMM2.

Scope

The U.S. Army Engineer Waterways Experiment Station (WES) was asked to assist the Nevada Automotive Test Center (NATC) in preparing for a field demonstration during the ISTVS 11th International Conference. Specifically, NATC and WES worked together in selecting test courses; describing these test courses in the required quantitative terms for use with the recently released version of the NATO Reference Mobility Model (NRMM2); and conducting vehicle mobility demonstrations with four vehicles over these test courses. The four vehicles were the M1025 High Mobility Multi-Purpose Vehicle (HMMWV), the M923A1 5-ton cargo truck, the Medium Tactical Vehicle Replacement (MTVR) 8-ton technology demonstrator built for the U.S. Marine Corps, and the Swedish BV206 rubber-tracked Small Unit Support Vehicle (SUSV). Figure 2 is a photograph of these vehicles. A German UNIMOG (U2150L) cargo truck, which was not originally scheduled for the demonstrations, was also run over the courses. In addition, WES was to provide vehicle performance predictions for the first four vehicles using the NRMM2. Because the UNIMOG was not originally scheduled for the demonstrations, NRMM2 predictions were not made for this vehicle. Also, there were no NRMM vehicle data readily available for the UNIMOG. NRMM2 predictions were made for the four vehicles and the results distributed to the conference participants at the NATC site <u>prior to the demonstrations</u>.

Definitions

The following are definitions of terrain and vehicle terms:

(1) **Absorbed power.** The rate at which vibrational energy is absorbed by a typical human measured in watts. A criterion of 6-watt average absorbed power has been established as the upperbound of vibration that will permit crew members to perform their tasks. Humans will accept considerably higher absorbed power levels (20 or more watts) for short period (10 to 12 min) at the risk of injury and vehicle and cargo damage. Thus, the 6-watt absorbed power level is not an absolute human tolerance limit but represents an effective performance limit.

(2) **Cone Index (CI).** An index of the shearing resistance of soil obtained with a cone penetrometer.

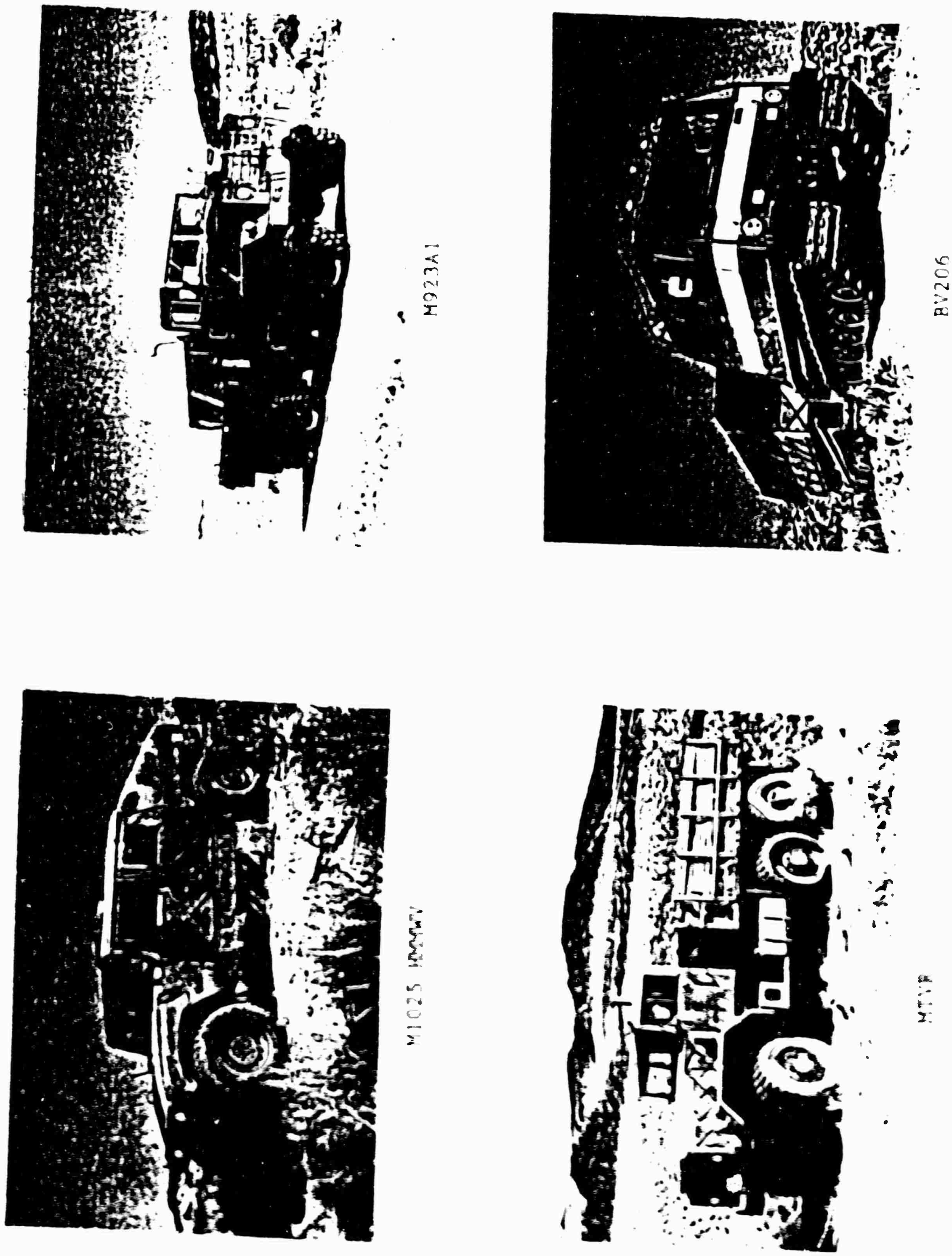


Figure 2. Photographs of demonstration vehicles

(3) **Critical Layer.** The layer of soil that is most pertinent to establishing relations between soil strength and vehicle performance. The depth of the critical layer is dependent upon vehicle weight and the characteristics of the soil's rating cone index (RCI) profile. If the critical layer and the 6-in.(15.2 cm) layer below the critical layer have the same RCI or show an increase in RCI with depth, the strength profile is considered normal. If the 6-in.(15.2 cm) layer below the critical layer has an RCI less than that of the normal critical layer the RCI is considered abnormal and the 6-in.(15.2 cm) layer below the normal critical layer is used as the critical layer.

(4) **Coarse-grained soil.** A soil of which more than 50 percent of the grains, by weight, will be retained on a No. 200 sieve (larger than 0.074 mm in diameter.

(5) **Detrend.** A process of removing unwanted trends or components (long wavelengths, slopes, etc.) from a terrain surface prior to calculating surface roughness.

(6) **Fine-grained soil.** A soil of which more than 50 percent of the grains by weight will pass a No. 200 US standard sieve (smaller than 0.074 mm in diameter.

(7) **Gross Vehicle Weight (GVW).** Weight of a vehicle fully equipped, loaded and serviced for operation including operating personnel.

(8) **Immobilization.** The inability of a self-propelled vehicle to move forward or backward.

(9) **Lean clay.** A definition used to describe a fine-grained mixture of silt and clay with a low to medium plasticity and a liquid limit less than 50. Very sensitive to slight changes in moisture.

(10) **Rating Cone Index (RCI).** The product of the remolding index (RI) and the average of the measured insitu CI for the same layer of soil.

(11) **Remolding Index (RI).** A ratio that expresses the proportion of the original strength of a soil that will be retained after traffic of a moving vehicle.

(12) **Ride.** The random, semiuniform vibrations transferred by the vehicle to the driver or other occupants as a result of traveling over an uneven surface.

(13) **Road Factor.** Any attribute of the road that can be adequately described at any point by a single measurable value; for example, curvature, surface roughness.

(14) **Road Unit.** A homogeneous segment of road described by a series of nine road factors, each of which is considered reasonably uniform throughout the segment. If any one or more of the road factors change, a new road unit is described.

(15) **Sand.** A coarse-grained soil with the greater percentage of coarse fraction (larger than 0.074 mm) passing the No. 4 sieve (4.76 mm).

(16) **Speed-made-good.** A speed obtained by dividing the straight-line distance between two widely separated points in a terrain or test situation by the total travel time between them, irrespectively of path actually taken.

(17) **Surface roughness.** A measure of the variation of the surface elevations. It is the root-mean-square value normally expressed in inches of the detrended elevations. The detrending process filters (removes) wavelengths larger than 60 ft (18.3 m) which produce little effect on vehicle ride.

(18) **Terrain Factor.** Any attribute of the terrain that can adequately be described at any point by a single measurable value; for example, slope, plant stem diameter.

(19) **Terrain Unit.** A homogenous area or patch of ground described by a series of 22 mathematically independent terrain factors, each of which is considered reasonably uniform throughout the area. If any one of the terrain factors change, a new terrain unit is described.

(20) **Ton-Mile/Hour.** A measure of the production or cargo delivery rate of a hauling vehicle. In a hauling cycle, it includes effects of speed, payload, length of haul, terrain/road conditions, and load/unload times.

(21) **Unified Soil Classification System (USCS).** A soil classification system based on identification of soils according to their textural and plastic qualities and on their grouping with respect to engineering behavior.

(22) **Vehicle Cone Index (VCI).** The minimum RCI that will permit a vehicle to complete a specified number of passes; thus VCI_{50} means the minimum RCI necessary to complete 50 passes, and VCI_1 means the minimum RCI to complete one pass.

2 Test Courses

Test Course Selection

Five test courses were selected at NATC which were all in a close proximity to the NATC Headquarters. The criteria for course selection were (a) ease of transportation of participants, (b) the vehicle mobility tests could be conducted within a reasonable time frame, (c) the tests could be readily observed by ISTVS participants and (d) to provide a reasonable range of different terrain and trail conditions. Figure 3 shows a schematic of the course layout.

Test Course Descriptions

Test course 1 was approximately 1300 ft (0.4km) in length and consisted of one 250 ft (0.08 km) selected segment to represent the terrain unit. The course consisted of a medium strength sand on a level surface that had been prepared by tilling. It was originally intended to represent a soft sand with a cone index of about 30 that would test the GO/NOGO capabilities of the vehicles and NRMM2's ability to predict GO/NOGO. However, there was a three day period between the tilling and the field demonstration. Consequently, the resulting cone index on the day of the demonstration was 80, which was considerably higher than the vehicle cone index of any of the test vehicles. Consequently, all vehicles readily negotiated this course without any immobilizations. (Experience in measuring the strength of fresh wind-blown desert sands has indicated the strength (in terms of cone index) will change from a minimum of CI=30 or 35 to a CI=80 or more in a matter of one or two days due to settlement). Because each vehicle traversed the course in different, unconstrained random slalom paths, it was not possible to make comparable speed-made-good predictions with NRMM.

Test course 2 was slightly less than two miles (3.0 km) in length. It began as a trail up a steep slope (ranging from 20 to 37%) with a rough rocky surface (about 2.7 rms), returned down the same trail, followed by a trail with gentler slopes that were relatively smooth but contained sharp curves, then over some off-road terrain containing large boulders and finally off-road

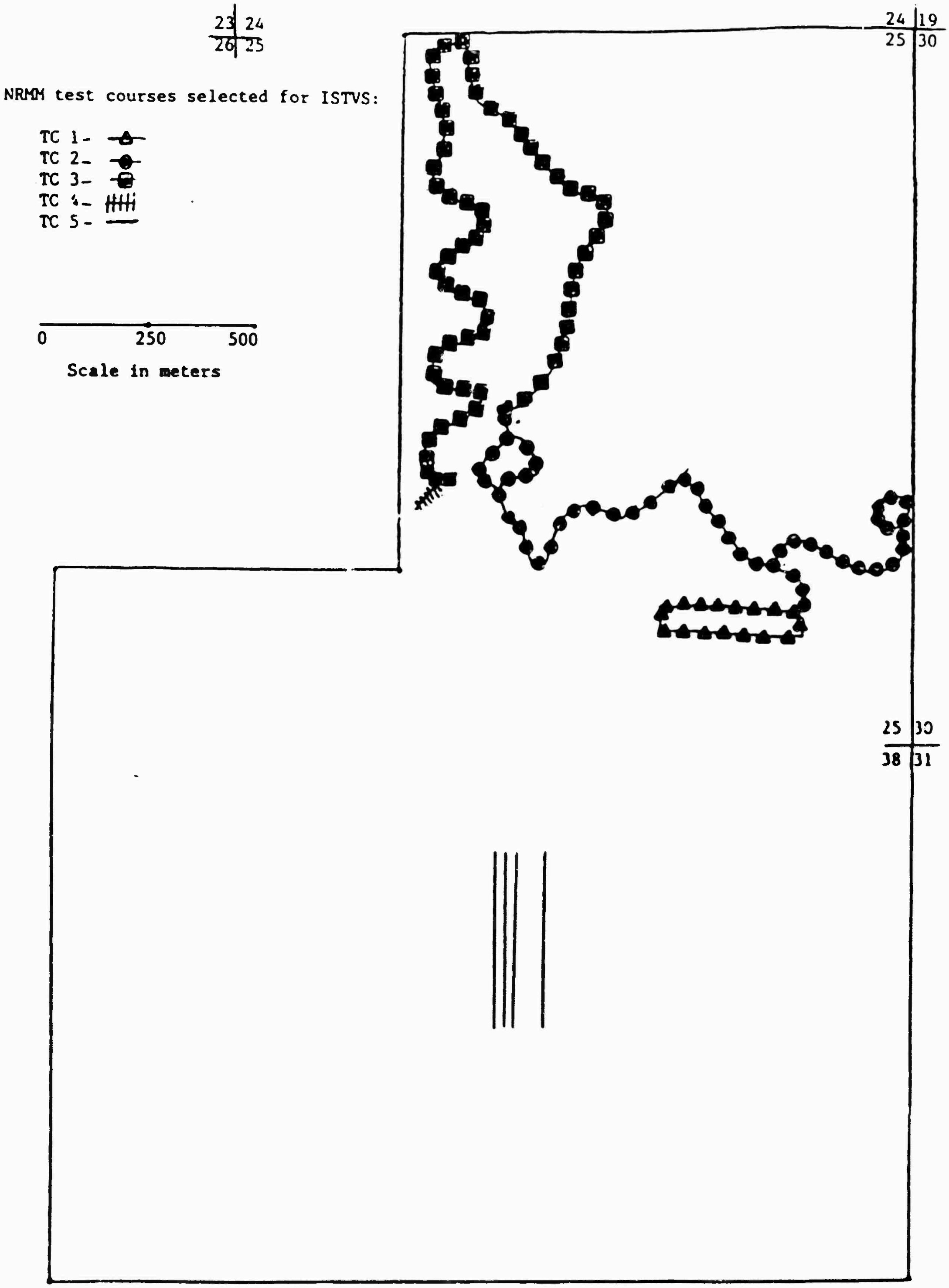


Figure 3. Locaiotn of test courses at Nevada Automotive Test Center (NATC)

over some steep sandy slopes (ranging from ± 5 to 31%) of medium soil strength. The principal mobility challenges for this course were steep slopes, surface roughness, and sharp curves. It was determined that the M1025 HMMWV could not negotiate the large boulders in a portion of this course. Consequently, the course was divided into two courses termed course 2a and course 2b. Course 2b, which was used only by the HMMWV, detoured around the boulders. Course 2a and 2b each contained 38 contiguous terrain units.

Test course 3 contained 17 contiguous terrain units and was slightly over 1.5 miles (2.5 km) in length. It followed along a sandy trail with numerous medium to sharp curves, some gentle slopes, and mostly smooth sandy surfaces. The principal mobility challenge of this course was curvature limiting speeds.

Test course 4 was selected to demonstrate a comparison of the relative slope climbing capability of the vehicles and an evaluation of NRMM2's prediction capability. The course was approximately 75 ft (23m) in length. However, there was only about 32 ft (9.8 m) in the middle that consisted of relatively constant slopes that could be used for performance evaluations. During the initial course selection prior to the survey, the test course originally was divided into three terrain units. However, the results of the survey indicated only two distinct slopes present in the area. Consequently, the course was divided into two terrain units consisting of 25% and 45% sand slopes of medium strength (0-6 in/0-15 cm, CI=73).

Test course 5 contained four prepared level test lanes (each considered a terrain unit) which consisted of (a) wet-soft sandy-clay soil with a smooth surface, (b) wet firm sandy-clay soil with a smooth surface, (c) dry firm sandy-clay soil with a smooth surface, and (d) a dry firm sandy-clay soil with a very rough surface. Each test lane was approximately 800 ft (245 m) in length.

Each test course was broken into terrain units that were assumed to be reasonably homogeneous. Grades, direction of slope, soil strength, curvature, obstacle geometry, and recognition distance were measured for representative terrain units. Surface roughness was measured with a survey rod and level at 1-ft (0.3 m) intervals for some of the terrain units that were considered representative of the surface roughness ranges of the test courses. Not all terrain units could be surveyed because of time constraints. Surface roughness values were estimated for other units by comparing them with those for which measurements were made. NATC's Dynamic Force Measurement Vehicle (Ashmore and Hodges, 1992) was driven over the test courses and the surface roughness data processed from these measurements were made available to WES. These data, which compared favorably with the corresponding survey data, were used to help in assigning values when no rod and level data were available (See Table 1). Figure 4 contains selected photographs of the test areas.

TC1, TU1 - Loose sand

TC2, TU22 - Sandy trail with buried boulders

TC2, TU7 - Rough trail with steep grade

TC2, TU24 - Boulder area

TC3, TU4 - Sand trail with curves

TC3, TU5 - Rough trail

TC3, TU12 - Sandy trails with curves

TC4, TU1 - Sandy slopes

TC5, TU1 - Flooded test lanes

Figure 4. Selected Photographs of test areas

3 Mobility Tests

Test Drivers

Test drivers from NATC drove all the vehicles except the Swedish BV206 SUSV and the UNIMOG. The test driver for the SUSV was an employee of the Hagglund Vehicle AB, which manufactures the vehicle. The driver of the UNIMOG was a test driver from the Mercedes Proving Grounds in Germany. The NATC drivers of the HMMWV and the MTVR were very familiar with a large portion of these test courses each having driven over most of these courses many times. The driver of the M923A1 five ton during the demonstration was a new NATC employee and had not driven the test route previously. However, due to tire failures both the MTVR and the M923A1 vehicles were unable to complete the demonstration and were rerun the next day. Mr. Hank Hodges, Jr, who is one of the most experienced of all the NATC drivers and thoroughly familiar with the test courses, drove both vehicles during the reruns. The drivers of the BV206 and the UNIMOG were shown the courses the morning of the demonstration. All drivers were allowed to walk the test courses the morning before the official running. This variation in driver familiarity with the test courses presented a bias that caused some problems in comparing measured and predicted speeds, which will be discussed in following paragraphs.

Test Course 1

Because of the relatively high soil strength (CI=80), all vehicles were able to negotiate this test course and to follow a random slalom maneuver pattern. Likewise, NRMM predicted a GO for all the vehicles on this test course. These predictions were contained in the handouts distributed prior to the demonstrations. (See Appendix B).

Test Courses 2 & 3

Test vehicles were driven over each of these test courses as fast as they could be safely driven. The measured performance was based solely on the total time to complete each test course, measured by observers with stop watches from a remote position on a hill overlooking all the courses. The extremely harsh surface roughness on course 2 due principally to the large boulders which ranged in height from about 4 inches (10 cm) to 24 inches (60 cm) resulted in the blowout of one tire on the MTVR and two tires on the M923A1 5-ton, which precluded completion of the test runs. Consequently, these vehicles were rerun the next day and the results submitted to the on-site WES personnel.

Test Course 4

The vehicles were driven up the sand slopes on this course to determine a GO or NOGO situation. However, as mentioned previously, the areas containing relatively constant slopes were too short (about the length of the M923A1 vehicle) and variable to conduct consistent slope climbing tests in which all the vehicles were negotiating the same slope. After passage of the first two vehicles, the general area was so distorted due to rutting that the subsequent vehicles were negotiating different slope conditions. The BV206 vehicle actually went outside of the course boundaries. Although the vehicles stopped at the base of the grade, the short slopes also allowed too much influence due to vehicle momentum. This course was selected primarily to demonstrate differences in slope performance of the test vehicles. However, for the reasons stated above, these slopes are not adequate to fully evaluate NRMM capability to predict slope climbing performance. A more consistent group of slopes with a range of slope values is needed to properly evaluate NRMM slope climbing prediction capability. NRMM2 predictions were made prior to the demonstration; however, due to these constraints, the validity of these predictions is highly suspect.

Test Course 5

Mobility tests, were conducted in the four different terrain units that composed test course 5. Test vehicles accelerated from a standing start down terrain unit 1 to its end, turned, and then accelerated back down terrain unit 2 to its end, turned, and drove at a constant speed of about 5 mph (8 km/hr) down terrain unit 3 to its end, turned, and drove back down terrain unit 4 as fast as safely possible. The demonstrations conducted at test course 5 were considered to be inadequate for comparisons of measured vehicle performance with NRMM2 predicted vehicle performance for the following reasons:

(1) Lack of test control on terrain units 1 and 2 (variable turning times outside the test lanes were included in the total acceleration times within the test lanes).

(2) Although all vehicles were GO as predicted by NRMM2, the non-uniform soil strengths on terrain unit 3 were considered unacceptable for NRMM validation.

(3) The surface roughness on terrain unit 4 consisted of a semi-uniform predominant frequency which biased the vehicle's absorbed power-rms (surface roughness) response.

4 NRMM MOBILITY PREDICTIONS AND ANALYSIS

Initial NRMM Performance Predictions

After deciding upon a scheme for conducting the mobility demonstrations, the NRMM2 was used to make predictions prior to the field demonstrations. The results of these predictions along with photographs of various sections of the test courses were distributed in booklets to ISTVS members at the field site just prior to the demonstrations. The results of these initial predictions are listed in Appendix B. During the demonstrations, discrepancies were noted (some of which have been previously mentioned) that influenced meaningful comparisons between measured and predicted results. These discrepancies required further investigation. ISTVS members were informed that there were problems which required a more detailed analysis to identify the cause of these discrepancies and that two of the vehicles would have to be rerun due to flat tires preventing their course completion. They were told that each would receive a report containing the results of the new analysis.

New NRMM Performance Predictions and Analysis

Only the results obtained on courses 2 and 3 were considered for further analysis. The results from the other test courses lacked either satisfactory control during the time measurements (course 5) or the courses (courses 1 and 4) did not fully meet all the conditions required for validating NRMM2 as previously explained. Courses 2 and 3 were the only courses containing contiguous terrain units that required use of the traverse model to predict overall speeds over each course. WES reviewed the initial NRMM2 input data and predictions and found several errors in the basic input data. Input data which have been corrected are as follows:

(1) SUSV vehicle weight was found to be in error. It was changed from a curb weight of 9540 lb (4322 kg) that was used in the initial NRMM2 predictions to the correct curb weight of 10580 lb (4794 kg) for the demonstration vehicle.

(2) SUSV vehicle data for the initial predictions reflected a five cylinder engine used in older models; it was modified to reflect the six cylinder engine in the demonstration vehicle with engine data obtained from Hagglunds.

(3) The initial motion resistance coefficient for the SUSV, which was based upon that for a single unit steel tracked vehicle, was too low by nearly a factor of two. This coefficient was modified based on results from recent SUSV motion resistance tests at WES.

(4) The power train data for the M923A1 was modified based upon data recently obtained from Aberdeen Proving Grounds. The modification, however, resulted in only minor performance changes.

(5) Reexamination of the terrain input after analyzing the results of the initial simulations revealed some faulty estimates in surface roughness for some of the terrain units. Additionally, further review revealed two errors in slope direction, and an error in one of the obstacle descriptions. These corrections were made. Table 2 contains the new terrain descriptions.

Table 3 contains the results of the new NRMM2 performance predictions after the corrections to the input data. Predictions were made to reflect speeds based upon ride limits of both 6 watts absorbed power (normally associated with continuous operations of more than 60 minutes) and 12 watts absorbed power (normally associated with continuous operations of less than 30 minutes) (Murphy, 1986). The graph in Figure 5 shows the current relationship between allowable levels of absorbed power versus exposure time that was derived from the exposure time-vehicle vibration relationships of the International Organization for Standardization (ISO 2361, 1978). This relation was developed by matching comparable levels of absorbed power and the ISO root-mean-square accelerations. This relation has not yet been satisfactorily validated with controlled field tests. Since the times of operation on test courses 2 and 3 were less than 30 minutes, the NRMM2 performance speeds for 12 watts absorbed power levels should be used for comparison with the measured speeds.

Both test courses 2 and 3 contained many sharp to moderate curves. Since the drivers for the HMMWV, the M923A1, and the MTVR were NATC drivers who were very familiar with a large portion of test course 2 and all of test course 3, predicted speeds by the traverse model (which reflects skilled drivers thoroughly familiar with the test courses) for these vehicles should generally be close to the measured speeds. However, the differences were often rather substantial. NRMM2 predicted speeds in terrain units influenced by road or trail curvature are consistently lower than measured

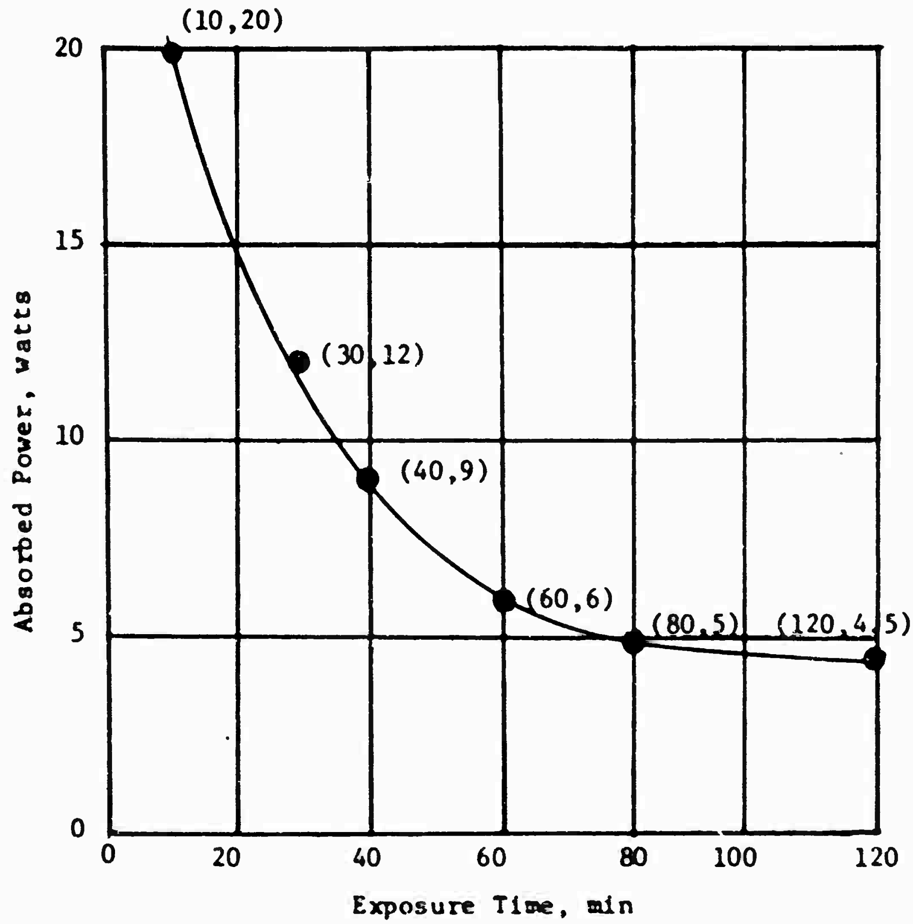


Figure 5. Upper-bound relationship between absorbed power and exposure time
(NOTE: This relation is based on test data but has not been validated)

speeds because they are based on conservative road curvature algorithms established by the American Association of State Highway Officials (AASHO) which include a large factor of safety (AASHO, 1965). Experience based on results of numerous traverse tests has shown that drivers will negotiate curves at much faster speeds than the AASHO recommendations. In fact, well trained test drivers, especially if familiar with the route, will negotiate curves at speeds very close to the tipping or sliding limits. However, it is believed performance close to the tipping/sliding limits is dangerous and not desirable and some margin of safety should be invoked. This shortcoming was discussed at a meeting at the end of the ISTVS conference and it was agreed then that WES would look at modifications that would provide more realistic predictions of curvature speeds.

Modified Curvature Performance Predictions and Analysis

The official version of NRMM can only be changed by approval of the NRMM TMC. However, for this study the NRMM2 curvature algorithms were modified to reflect two performance limits. The model containing these modifications is referred to as NRMM++ to distinguish it from the official NRMM2. One limit represented a modified AASHO relation that includes increased side friction factors based upon relations by Meyer and later extended by Moyer and Berry (AASHO, 1965) that provides slightly higher curvature speeds than the standard AASHO relation currently in NRMM2 (AASHO, 1965). The other performance limit represented the tipping/sliding limit, which provides considerably higher performance based upon the coefficient of sliding friction. It is believed that most trained drivers perform somewhere in between these two limits. Appendix C contains more detail on the curvature modifications. The performance at these respective limits can be observed in Table 3 at both the 6- and 12-watt absorbed power ride levels. Except for the BV206 SUSV, the NRMM++ predicted results and the measured results are now more in agreement, especially when comparing performance at the 12-watt absorbed power level.

Other Factors Affecting NRMM2 Initial Predictions

The M1025, M923A1, and MTVR predicted speeds at the sliding/tipping limit compare favorably (generally within 10%) with the measured speeds for these vehicles, especially if compared at the 12 watt absorbed power ride level. The lower measured values for the SUSV are attributed to the excessive steering and rough ride involved in negotiating the steep, rough slopes and curves. Steering response of the three wheeled vehicles during maneuver and negotiating curves is generally far better than that of the SUSV.

It is obvious that more attention needs to be given to modeling the mobility of the SUSV or other similar articulated vehicles.

A point of interest worth noting is that in the initial NRMM 2 predictions there was concern over the low performance predictions for the M923A1 vehicle on Course 2 (See Appendix B). During the reexamination, it was learned that a 1 ft (0.3 m) deep by 3 ft (0.9 m) wide ditch was erroneously input at the base of the steep slope which caused a NOGO for this vehicle. This NOGO slowed the vehicle movement to 0.1 mph (0.16 km/hr) during the time required to negotiate the ditch. The time required to negotiate the ditch resulted in a much lower overall speed in that section of the course. Once the ditch was removed and the other corrections included, the M923A1 predictions were more in line with the actual performance.

Additionally, NRMM slope predictions appear to be conservative and often tended to underpredict slope performance, especially on short slopes where vehicle momentum may influence the results. This underprediction has been noted by others (Garland, Watson and Irwin, 1993; TES Limited, 1991). However, the algorithms describing vehicle slope performance were derived by translating the results from drawbar-pull tests on level surfaces to performance on slopes. This is accomplished by incorporating the physics describing the relationships among force, normal load and coefficient of friction and the effects of slope resistance. A review of this theory is presented in Appendix D. The test procedures for the slope climbing tests, upon which the NRMM2 have been validated, consist of the vehicle negotiating the slope at a steady state speed to a point at which the vehicle is stopped on the slope. After stopping completely, the vehicle then resumes negotiating the slope. This conservative technique was developed to eliminate the influence of momentum and assure a consistent method of evaluating vehicle performance on long continuous slopes. Results measured from these type tests have generally agreed reasonably well with NRMM predictions. The principal source for disagreement are believed to be that surface conditions on slopes are not the same as the surface conditions on adjacent level areas (Schreiner and Willoughby, 1976).

Tables 4, 5, 6 and Appendix A are provided for convenience. Tables 4 and 5 list some of the more important vehicle characteristics. Table 6 contains a compilation of the measured performances of the five vehicles on each of the test courses. Appendix A contains a brief description of the method employed by the traverse model in predicting speeds in contiguous terrain/road units.

SUMMARY

NATC and WES personnel worked together under severe time, location and personnel restraints to provide this demonstration for the ISTVS 11th

International Conference. Because of these restraints, the demonstration was necessarily a judicious compromise between completion of all the demonstration runs for the observers and adequate quality control over the tests for validation of NRMM2 predictions. Comparison of the measured and predicted results from this demonstration clearly revealed the sensitivity of the input terrain and vehicle data on the predicted performance levels and the need to improve NRMM2's curvature algorithms. WES has shown that this improvement can be effectively accomplished by appropriately reducing the conservative safety factor built into the AASHO relations. WES will recommend to the NRMM TMC a modified curvature algorithm based upon a limit equal to approximately one half the difference between the present AASHO relationship and the tipping/sliding limits to better define an experienced military driver for consideration in future versions of NRMM Additionally, the results revealed shortcomings in NRMM2 in properly modeling the attributes of the BV206 SUSV for acceptable mobility simulations. These shortcomings need to be addressed to assure NRMM2 can properly simulate mobility performance of similar articulated vehicles.

Through the use of journal articles and ISTVS regional and international conferences, and cooperation throughout the ISTVS community, the results of validation tests such as the ones conducted during this demonstration at NATC will identify other shortfalls and show where other improvements in NRMM are needed. The NRMM TMC will use this information to continue to improve and extend the NRMM.

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Table 1. Comparison of Surface Roughness (NATC DFMV vs WES Survey)			
Test Course	Terrain Unit	Surface Roughness, rms, in. DFMV*	WES Survey**
2	2-4	2.1	2.5
2	5-10	2.6	2.8
2	11	1.4	1.6
2	20-22	1.4	1.6
2	25-27	0.6	0.6
2	30B-32	1.1	1.4
3	1-14	0.6	0.6

* NOTE: Represents a terrain profile of the entire terrain unit.

** NOTE: Represents weighted average over respective terrain units.

Table 2. Terrain Descriptions

8 7 Cources 1,4 & 5 NATC for ISTVS 27 Sep 1993

NTU	ID	IR	IS	DPT	USCS	RC1	RC2	DBR	GRD	RMS	RDA	DIST	NRT OAA	IMT OBH	ELV OBW	CURV OBL	OBS	OST	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
1	'1-1'	0	1	0	SP	25	80	15	1	0.2	150	0.0758	180	0	0	1	999	1	300	300	300	300	300	300	300	300
59	'4-1'	4	1	4	SP	73	211	15	45	0.5	150	0.0095	0	1	0	5000										
60	'4-2'	4	1	4	SP	73	211	15	25	0.5	150	0.0095	0	1	0	5000										
61	'4-3'	4	1	4	SP	73	211	15	25	0.5	150	0.0095	0	1	0	5000										
62	'5-1'	4	1	4	CL	300	300	15	0	0.5	250	0.2273	0	1	0	5000										
63	'5-2'	4	2	4	CL	250	300	15	0	0.5	250	0.2273	0	1	0	5000										
64	'5-3'	4	1	4	CL	80	160	15	0	0.5	100	0.2273	0	1	0	5000										
65	'5-4'	4	1	4	CL	300	300	15	0	4.4	150	0.2273	0	1	0	5000										

Reading across the table the following terms are defined:

NTU = Study terrain unit number
ID = Test course terrain unit identification
IR = TRADOC road type
IS = Surface condition
DPT = Surface cover depth, in., IS = 3, 4
USCS = Soil type using the Unified Soil Classification System
RC1 = Average soil strength for 0-6 in. layer, RCI
RC2 = Average soil strength for 6-12 in. layer, RCI
DBR = Depth to bed rock, in.
GRD = Grade or slope, percent
RMS = Surface roughness, rms, elevation, in.
RDA = Visibility, ft
DIST = Terrain unit segment, miles
NRT, OAA = Road type (trail unit), obstacle approach angle (road unit)
IMT, OBH = Surface material type (trail unit), obstacle height (off-road unit)
ELV, OBW = Super elevation (trail unit), obstacle width in ft (off-road unit)
CURV, OBL = Curvature, ft, obstacle length in ft (off-road unit)
OBS = Obstacle spacing in ft
OST = Obstacle spacing type
S-1 - S-8 = Tree stem spacing, in.

(Continued)

Table 2. (Continued)

36 7 Course 2-a (except 2-33a & 2-33b) (m923 only) NATC ISTVS 20 Sep 1993

NTU	ID	I R	I S	DPT	USCS	RC1	RC2	DBR	GRD	RMS	RDA	DIST	NRT OAA	IMT OBH	ELV OBW	CURV OBL	OBS	OST	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
2	'2-1'	4	1	0	SM	300	300	15	5	0.5	150	0.1536	0	1	0	273										
3	'2-2'	4	1	0	SM	240	300	15	12	0.5	150	0.0157	0	1	0	59										
4	'2-3'	4	1	0	SM	300	300	15	20	2.7	150	0.0324	0	1	0	5000										
5	'2-4'	4	1	0	SM	300	300	15	22	3.4	150	0.0275	0	1	0	177										
6	'2-5'	4	1	0	SM	300	300	15	23	2.7	150	0.0477	0	1	0	307										
7	'2-6'	4	1	0	SM	300	300	15	30	2.7	150	0.0928	0	1	0	5000										
8	'2-7'	4	1	0	SM	300	300	15	37	2.7	150	0.0483	0	1	0	149										
9	'2-8'	4	1	0	SM	300	300	15	31	2.7	150	0.0511	0	1	0	108										
10	'2-9'	4	1	0	SM	300	300	15	33	3.1	150	0.0297	0	1	0	155										
11	'2-10'	4	1	0	SM	300	300	15	17	3.1	150	0.0460	0	1	0	190										
12	'2-11A'	4	1	0	SM	300	300	15	5	1.6	150	0.0536	0	1	0	66										
13	'2-11B'	4	1	0	SM	300	300	15	0	1.6	150	0.0536	0	1	0	66										
14	'2-11C'	4	1	0	SM	300	300	15	-5	1.6	150	0.0536	0	1	0	66										
15	'2-12'	4	1	0	SM	300	300	15	-17	3.1	150	0.0460	0	1	0	190										
16	'2-13'	4	1	0	SM	300	300	15	-33	3.1	150	0.0297	0	1	0	155										
17	'2-14'	4	1	0	SM	300	300	15	-31	2.7	150	0.0511	0	1	0	108										
18	'2-15'	4	1	0	SM	300	300	15	-37	2.7	150	0.0483	0	1	0	149										
19	'2-16'	4	1	0	SM	300	300	15	-30	2.7	150	0.0928	0	1	0	5000										
20	'2-17'	4	1	0	SM	300	300	15	-23	2.7	150	0.0477	0	1	0	307										
21	'2-18'	4	1	0	SM	300	300	15	-22	2.7	150	0.0275	0	1	0	177										
22	'2-19'	4	1	0	SM	300	300	15	-20	2.7	150	0.0324	0	1	0	500										
23	'2-20'	4	1	0	SM	300	300	15	8	1.4	150	0.0805	0	1	0	98										
24	'2-21'	4	1	0	SM	300	300	15	8	1.8	150	0.0273	0	1	0	79										
25	'2-22'	4	1	0	SM	300	300	15	-13	1.8	150	0.0307	0	1	0	82										
26	'2-23A'	4	1	0	SM	300	300	15	14	1.8	150	0.0176	0	1	0	121										
27	'2-23B'	4	1	0	SM	300	300	15	-14	1.8	150	0.0176	0	1	0	121										
28	'2-24'	0	1	0	SM	201	300	15	5	1.8	30	0.0616	90	12	2	2	50	1	300	300	300	300	300	300	300	300
29	'2-25A'	4	1	0	SM	300	300	15	6	0.6	150	0.0454	0	1	0	141										
30	'2-25B'	4	1	0	SM	300	300	15	-6	0.6	150	0.0454	0	1	0	141										
31	'2-26'	4	1	0	SM	300	300	15	10	0.6	150	0.0328	0	1	0	136										
32	'2-27'	4	1	0	SM	200	300	15	-7	0.6	150	0.1027	0	1	0	5000										
33	'2-28'	4	1	0	SM	300	300	15	-11	0.6	150	0.0833	0	1	0	5000										
34	'2-29A'	4	1	0	SM	300	300	15	5	2.7	150	0.0725	0	1	0	73										
36	'2-30A'	0	1	0	SM	90	300	15	-7	4.5	50	0.1053	90	24	2	2	50	1	300	300	300	300	300	300	300	300
38	'2-31'	0	1	0	SM	82	300	15	-2	0.9	100	0.0269	135	4	0.4	2	200	1	300	300	300	300	300	300	300	300
39	'2-32'	0	1	0	SM	96	300	15	21	0.4	30	0.0180	135	4	0.4	2	200	1	300	300	300	300	300	300	300	300

(Continued)

Table 2. (Continued).

38 7 Course 2-a (all except HMMWV) WATC ISTVS 20 Sep 1993

		I	I										NRT	INT	ELV	CURV										
NTU	ID	R	S	OPT	USCS	RC1	RC2	DBR	GRD	RMS	RDA	DIST	OAA	OBH	OBW	OBL	OBS	OST	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
2	'2-1'	4	1	0	SM	300	300	15	5	0.5	150	0.1536	0	1	0	273										
3	'2-2'	4	1	0	SM	240	300	15	12	0.5	150	0.0157	0	1	0	59										
4	'2-3'	4	1	0	SM	300	300	15	20	2.7	150	0.0324	0	1	0	5000										
5	'2-4'	4	1	0	SM	300	300	15	22	3.4	150	0.0275	0	1	0	177										
6	'2-5'	4	1	0	SM	300	300	15	23	2.7	150	0.0477	0	1	0	307										
7	'2-6'	4	1	0	SM	300	300	15	30	2.7	150	0.0928	0	1	0	5000										
8	'2-7'	4	1	0	SM	300	300	15	37	2.7	150	0.0483	0	1	0	149										
9	'2-8'	4	1	0	SM	300	300	15	31	2.7	150	0.0511	0	1	0	108										
10	'2-9'	4	1	0	SM	300	300	15	33	3.1	150	0.0297	0	1	0	155										
11	'2-10'	4	1	0	SM	300	300	15	17	3.1	150	0.0460	0	1	0	190										
12	'2-11A'	4	1	0	SM	300	300	15	5	1.6	150	0.0536	0	1	0	66										
13	'2-11B'	4	1	0	SM	300	300	15	0	1.6	150	0.0536	0	1	0	66										
14	'2-11C'	4	1	0	SM	300	300	15	-5	1.6	150	0.0536	0	1	0	66										
15	'2-12'	4	1	0	SM	300	300	15	-17	3.1	150	0.0460	0	1	0	190										
16	'2-13'	4	1	0	SM	300	300	15	-33	3.1	150	0.0297	0	1	0	155										
17	'2-14'	4	1	0	SM	300	300	15	-31	2.7	150	0.0511	0	1	0	108										
18	'2-15'	4	1	0	SM	300	300	15	-37	2.7	150	0.0483	0	1	0	149										
19	'2-16'	4	1	0	SM	300	300	15	-30	2.7	150	0.0928	0	1	0	5000										
20	'2-17'	4	1	0	SM	300	300	15	-23	2.7	150	0.0477	0	1	0	307										
21	'2-18'	4	1	0	SM	300	300	15	-22	2.7	150	0.0275	0	1	0	177										
22	'2-19'	4	1	0	SM	300	300	15	-20	2.7	150	0.0324	0	1	0	500										
23	'2-20'	4	1	0	SM	300	300	15	8	1.4	150	0.0805	0	1	0	98										
24	'2-21'	4	1	0	SM	300	300	15	8	1.8	150	0.0273	0	1	0	79										
25	'2-22'	4	1	0	SM	300	300	15	-13	1.8	150	0.0307	0	1	0	82										
26	'2-23A'	4	1	0	SM	300	300	15	14	1.8	150	0.0176	0	1	0	121										
27	'2-23B'	4	1	0	SM	300	300	15	-14	1.3	150	0.0176	0	1	0	121										
28	'2-24'	0	1	0	SM	201	300	15	5	1.8	30	0.0616	90	12	2	2	50	1	300	300	300	300	300	300	300	300
29	'2-25A'	4	1	0	SM	300	300	15	6	0.6	150	0.0454	0	1	0	141										
30	'2-25B'	4	1	0	SM	300	300	15	-6	0.6	150	0.0454	0	1	0	141										
31	'2-26'	4	1	0	SM	300	300	15	10	0.6	150	0.0328	0	1	0	136										
32	'2-27'	4	1	0	SM	200	300	15	-7	0.6	150	0.1027	0	1	0	5000										
33	'2-28'	4	1	0	SM	300	300	15	-11	0.6	150	0.0833	0	1	0	5000										
34	'2-29A'	4	1	0	SM	300	300	15	5	2.7	150	0.0725	0	1	0	73										
36	'2-30A'	0	1	0	SM	90	300	15	-7	4.5	50	0.1053	90	24	2	2	50	1	300	300	300	300	300	300	300	300
38	'2-31'	0	1	0	SM	82	300	15	-2	0.9	100	0.0269	135	4	0.4	2	200	1	300	300	300	300	300	300	300	300
39	'2-32'	0	1	0	SM	96	300	15	21	0.4	30	0.0180	135	4	0.4	2	200	1	300	300	300	300	300	300	300	300
40	'2-33A'	0	1	0	SM	58	300	15	-31	0.4	30	0.0085	240	12	3.6	150	50	2	300	300	300	300	300	300	300	300
41	'2-33B'	0	1	0	SM	58	300	15	31	0.4	30	0.0085	240	12	3.6	150	50	2	300	300	300	300	300	300	300	300

(Continued)

Table 2. (Continued)

38 7 HMMWV Course 2-8 NATC ISTVS 20 Sep 1993

NTU	ID	I R	I S	DPT	USCS	RC1	RC2	DBR	GRD	RMS	RDA	DIST	NRT OAA	INT OBH	ELV OBW	CURV OBL	OBS	OST	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
2	'2-1'	4	1	0	SM	300	300	15	5	0.5	150	0.1536	0	1	0	273										
3	'2-2'	4	1	0	SM	240	300	15	12	0.5	150	0.0157	0	1	0	59										
4	'2-3'	4	1	0	SM	300	300	15	20	2.7	150	0.0324	0	1	0	5000										
5	'2-4'	4	1	0	SM	300	300	15	22	3.4	150	0.0275	0	1	0	177										
6	'2-5'	4	1	0	SM	300	300	15	23	2.7	150	0.0477	0	1	0	307										
7	'2-6'	4	1	0	SM	300	300	15	30	2.7	150	0.0928	0	1	0	5000										
8	'2-7'	4	1	0	SM	300	300	15	37	2.7	150	0.0483	0	1	0	149										
9	'2-8'	4	1	0	SM	300	300	15	31	2.7	150	0.0511	0	1	0	108										
10	'2-9'	4	1	0	SM	300	300	15	33	3.1	150	0.0297	0	1	0	155										
11	'2-10'	4	1	0	SM	300	300	15	17	3.1	150	0.0460	0	1	0	190										
12	'2-11A'	4	1	0	SM	300	300	15	5	1.6	150	0.0536	0	1	0	66										
13	'2-11B'	4	1	0	SM	300	300	15	0	1.6	150	0.0536	0	1	0	66										
14	'2-11C'	4	1	0	SM	300	300	15	-5	1.6	150	0.0536	0	1	0	66										
15	'2-12'	4	1	0	SM	300	300	15	-17	3.1	150	0.0460	0	1	0	190										
16	'2-13'	4	1	0	SM	300	300	15	-33	3.1	150	0.0297	0	1	0	155										
17	'2-14'	4	1	0	SM	300	300	15	-31	2.7	150	0.0511	0	1	0	108										
18	'2-15'	4	1	0	SM	300	300	15	-37	2.7	150	0.0483	0	1	0	149										
19	'2-16'	4	1	0	SM	300	300	15	-30	2.7	150	0.0928	0	1	0	5000										
20	'2-17'	4	1	0	SM	300	300	15	-23	2.7	150	0.0477	0	1	0	307										
21	'2-18'	4	1	0	SM	300	300	15	-22	2.7	150	0.0275	0	1	0	177										
22	'2-19'	4	1	0	SM	300	300	15	-20	2.7	150	0.0324	0	1	0	500										
23	'2-20'	4	1	0	SM	300	300	15	8	1.4	150	0.0805	0	1	0	98										
24	'2-21'	4	1	0	SM	300	300	15	8	1.8	150	0.0273	0	1	0	79										
25	'2-22'	4	1	0	SM	300	300	15	-13	1.8	150	0.0307	0	1	0	82										
26	'2-23A'	4	1	0	SM	300	300	15	14	1.8	150	0.0176	0	1	0	121										
27	'2-23B'	4	1	0	SM	300	300	15	-14	1.8	150	0.0176	0	1	0	121										
28	'2-24'	0	1	0	SM	201	300	15	5	1.8	30	0.0616	90	12	2	2	50	1	300	300	300	300	300	300	300	300
29	'2-25A'	4	1	0	SM	300	300	15	6	0.6	150	0.0454	0	1	0	141										
30	'2-25B'	4	1	0	SM	300	300	15	-6	0.6	150	0.0454	0	1	0	141										
31	'2-26'	4	1	0	SM	300	300	15	10	0.6	150	0.0328	0	1	0	136										
32	'2-27'	4	1	0	SM	200	300	15	-7	0.6	150	0.1027	0	1	0	5000										
33	'2-28'	4	1	0	SM	300	300	15	-11	0.6	150	0.0833	0	1	0	5000										
35	'2-29B'	0	1	0	SM	100	200	15	2	0.6	150	0.0972	90	4	1	1	200	1	300	300	300	300	300	300	300	300
37	'2-30B'	4	1	0	SM	300	300	15	5	0.6	150	0.1642	0	1	0	118										
38	'2-31'	0	1	0	SM	82	300	15	-2	0.9	100	0.0269	135	4	0.4	2	200	1	300	300	300	300	300	300	300	300
39	'2-32'	0	1	0	SM	95	300	15	21	0.4	30	0.0180	135	4	0.4	2	200	1	300	300	300	300	300	300	300	300
40	'2-33A'	0	1	0	SM	58	300	15	-31	0.4	30	0.0085	240	12	3.6	150	50	2	300	300	300	300	300	300	300	300
41	'2-33B'	0	1	0	SM	58	300	15	31	0.4	30	0.0085	240	12	3.6	150	50	2	300	300	300	300	300	300	300	300

(Continued)

Table 2. (Concluded)

17 7 Course 3 NATC for ISTVS 10 Dec 1993

NTU	ID	I R	I S	DPT	USCS	RC1	RC2	DBR	GRD	RMS	RDA	DIST	NRT OAA	INT OBH	ELV OBW	CURV OBL	OBS	OST	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
42	'3-1'	4	1	4	SM	300	300	15	9	0.4	150	0.1231	0	1	0	259										
43	'3-2'	4	1	4	SM	300	300	15	7	0.4	150	0.1455	0	1	0	202										
44	'3-3'	4	1	4	SM	300	300	5	11	0.5	150	0.0754	0	1	0	221										
45	'3-4'	4	1	4	SM	300	300	5	10	0.6	150	0.1057	0	1	0	191										
46	'3-5'	4	1	4	SM	300	300	1	16	1.4	150	0.0496	0	1	0	5000										
47	'3-6'	4	1	4	SM	300	300	1	-16	1.3	150	0.0318	0	1	0	231										
48	'3-7'	4	1	4	SM	300	300	15	-13	0.4	150	0.0739	0	1	0	307										
49	'3-8'	4	1	4	SM	300	300	15	-9	0.4	150	0.1222	0	1	0	231										
50	'3-9'	4	1	4	SM	300	300	15	-8	0.4	150	0.0676	0	1	0	5000										
51	'3-10'	4	1	4	SM	300	300	15	-9	0.4	150	0.0369	0	1	0	75										
52	'3-11'	4	1	4	SM	300	300	15	-9	0.4	150	0.0725	0	1	0	218										
53	'3-12'	4	1	4	SM	164	300	15	5	0.4	150	0.1449	0	1	0	95										
54	'3-13A'	4	1	4	SM	300	300	15	5	0.6	150	0.1508	0	1	0	124										
55	'3-13B'	4	1	4	SM	300	300	15	0	0.6	150	0.1508	0	1	0	124										
56	'3-13C'	4	1	4	SM	300	300	15	-5	0.6	150	0.1508	0	1	0	124										
57	'3-14A'	4	1	4	SM	300	300	15	12	0.4	150	0.0396	0	1	0	76										
58	'3-14B'	4	1	4	SM	300	300	15	-12	0.4	150	0.0396	0	1	0	76										

Table 3
Comparison of Revised NRMM Predictions and Measured Results

	6-Watts			12-Watts				
Vehicle	NRMM II	AASHO (Mod)*	Slip/Slide Limits*	NRMM II	AASHO (Mod)*	Slip/Slide Limits*	Measured	Percent Error**
Average Speed in Kilometers per hour, Course 2A								
M923A1	11.0	11.4	11.4	12.5	13.3	13.3	16.1	-17
MTVR	15.4	17.3	18.1	15.8	17.9	19.0	19.4	- 2
SUSV	15.0	15.2	15.4	16.5	16.3	17.2	10.5	64
Average Speed in Kilometers per hour, Course 2B								
M1025	20.1	23.1	24.9	22.1	26.2	29.5	30.2	- 2
Average Speed in Kilometers per hour, Course 3								
M1025	25.2	32.0	47.0	25.4	32.3	47.9	46.1	4
M923A1	21.5	25.2	27.2	21.6	25.4	29.0	31.6	- 9
MTVR	21.5	25.3	29.0	21.5	25.3	29.0	32.0	- 8
SUSV	24.4	27.4	31.5	24.5	27.5	31.8	23.7	34

* NOTE: Determined using NRMM II with modified curvature algorithms.
** NOTE: Based upon comparison using 12-watt, slip/slide limits.

Table 4
Some Important Vehicle Characteristics Input Data for NRMM II

Vehicle	Total Test Weight, kg	Test Payload, kg	Tire Size	Tire Deflection, Percent	HP/Ton U.S	HP/Ton Metric	Vehicle Length, m	Vehicle Width, m	VCI,	Ground Contact Pressure, KPa
M1025HMMWV	2,703	0	37X12.5R16.5	23	50	56	4.57	2.18	15	–
M923A1	14,603	4,535	14R20	24	14	18	7.75	2.49	25	–
BV206	4,738	0	Tracked	NA	22	24	8.89	1.85	4	9.74
MTVR	20,861	7,250	16R21	46	17	19	8.00	2.51	32	–

Vehicles	Speed at 6-Watts, KM/HR 2 rms*	Speed at 6-Watts, KM/HR 3 rms*	Speed at 12-Watts Absorbed Power, KM/hr 2 rms*	Speed at 12-Watts Absorbed Power, KM/hr 3 rms*	Speed over 30 cm obstacle, KM/hr**	Maximum Tractive Force, KG, for Selected Speeds, km/hr 0	8	16	32	48	80
M1025 HMMWV	101	39	117***	49	9	3,424	2,159	1,788	945	563	297
M923A1	29	18	37	23	7	14,265	5,701	3,134	1,470	988	597
BV206	48	21	61	22	5	5,451	3,315	1,554	881	603	603
MTVR	62	40	76	51	16	20,763	9,681	5,429	2,597	1,560	1,031

* Represents surface roughness in cm
** At 2.5 g (24.5 m/sec²) peak shock load at driver location
*** Maximum speed on hard surface tractive force speed curve (app. 73 mph)

Table 5. Additional Vehicle Information

M1025 HMMWV
Empty Configuration
37X12.5R16.5 LT Tires
Tire Pressure: Mud, Sand and Snow Pressure 10 psi front, 12 psi rear
69 KPa front, 83 KPa rear

M923A1
Loaded Configuration 5 Ton (4535 kg) payload
14R20 Tires
Tire Pressure: Mud, Sand and Snow Pressure 25 psi front and rear (per TM9-2320-272-10)
172 KPa front and rear

BV206
Empty Configuration
Tracked Vehicle with the Standard Palletized Loading System Variant

MTVR
Loaded Configuration 8 Ton (7250 kg) payload
16R21 Tires
tire Pressure: Cross Country, 25 psi front and rear
172 KPa front and rear

Unimog
Loaded Configuration 2 Ton (1995 kg) payload
13.00R20 Tires
Tire Pressure: Cross Country, 28 psi front, 24 psi rear, 14 psi mud and sand
193 KPa front, 165 KPa rear, 97 KPa mud and sand

Table 6
Measured Results for All Test Courses and All Vehicles

Vehicle	Measured Performance (GO/NOGO)
Test Course 1 (Sand Mobility Area)	
M1025 HMMWV	GO
M923A1	GO
MTVR	GO
BV206	GO
UNIMOG	GO

Vehicle	Measured Performance, mph (km/hr)	Ten-Mile Hour
Test Course 2 (Grades, Roughness and Boulder Field 3.0 km in length)		
M1025 HMMWV	18.8 (30.2)	–
MTVR	10.0 (16.1)	96
UNIMOG	11.3 (18.2)	25
M923A1	10.0 (16.1)	50
BV206	6.5 (10.5)	–

Vehicle	Measured Performance, mph (km/hr)	Ten-Mile Hour
Test Course 3 (Sand Course with Sharp Turns 2.5 km in length)		
M1025 HMMWV	28.6 (46.1)	–
UNIMOG	21.0 (33.8)	46
MTVR	19.9 (32.0)	159
M923A1	19.6 (31.6)	98
BV206	14.7 (23.7)	–

Vehicle	Measured Performance (GO/NOGO) 45 Percent Slope	Measured Performance (GO/NOGO) 25 Percent Slope
Test Course 4 (Sand Slope)		
BV206	GO*	GO
M1025 HMMWV	GO	GO
M923A1	NOGO	GO
MTVR	NOGO	GO
UNIMOG	NOGO	GO

* Climbed 53 percent slope

Vehicle	Measured Performance (sec)
Test Course 5, Terrain Unit 1 and 2 (Dry Mud Pit and 0.5-in. of Rain, 0.5 Hour Before Running Mud Pit	
M1025 HMMWV	46.9
UNIMOG	64.2
MTVR	68.0
M923A1	70.3
BV206	85.1

Vehicle	Measured Performance (GO/NOGO)
Test Course 5, Terrain Unit 3 (Flooded Mud Pit)	
M1025 HMMWV	GO
M923A1	GO
MTVR	GO
BV206	GO
UNIMOG	GO

Vehicle	Measured Performance, mph (km/hr)	Ten-Mile Hour
Test Course 5, Terrain Unit 4 (4.4-in. RMS Course)		
M1025 HMMWV	17.8 (28.6)	–
UNIMOG	12.9 (20.7)	28
MTVR	11.9 (19.2)	95
M923A1	11.7 (18.8)	59
BV206	10.4 (16.7)	–

Appendix A
Concise Description of Traverse Model

Mr. George B. McKinley at the U.S. Army Engineer Waterways Experiment Station has developed three computer models that utilize vehicle acceleration and deceleration to extend the capabilities of the NATO Reference Mobility Model. The three models are (a) the Acceleration Model, which predicts time, speed, and distance for a vehicle accelerating from a standing start on various surfaces; (b) the Traverse Model, which accounts for the acceleration and deceleration of a vehicle within terrain/road segments which comprise a traverse; and (c) the Column Movement Model, which predicts movement rates for multiple vehicles over a traverse. This appendix is concerned with only the capabilities of the Traverse Model.

The Traverse Model is an analytical model developed to describe the movement of an individual vehicle along properly quantified traverses or routes. The vehicle is first run over the digital terrain using the NATO Reference Mobility Model thus computing all the values necessary for predicting the vehicle's performance over each terrain unit.

The traverse begins with the vehicle at the start of the first terrain unit at zero velocity. When the vehicle first accelerates and upon entering any other terrain unit, the model finds the corresponding tractive force for the vehicle's current velocity. If this tractive force is found equal to the total of the resisting forces in the current terrain unit then the vehicle will not accelerate. If the vehicle is found to accelerate, then the time and distance for acceleration are calculated using the same algorithms utilized by the Acceleration Model.

Each terrain unit has two speeds associated with it. One speed is the predicted speed, which is the maximum speed which may be reached by acceleration from a lower speed in that terrain unit. The other speed is the maximum speed at which a vehicle may enter the terrain unit. This maximum entering speed is the lowest speed chosen by NRMM from the ride, visibility, and curvature limited speeds. The only sstipulation for a vehicle's entering speed is that it be less than or equal to the maximum entering speed. In the case of a soil-strength limited terrain unit, a vehicle is allowed to enter at a higher speed than that predicted for that unit, but the entering speed must still be less than or equal to the maximum entering speed as described above. In this situation, the vehicle's acceleration will be modeled by moving backwards along the tractive force versus speed curve.

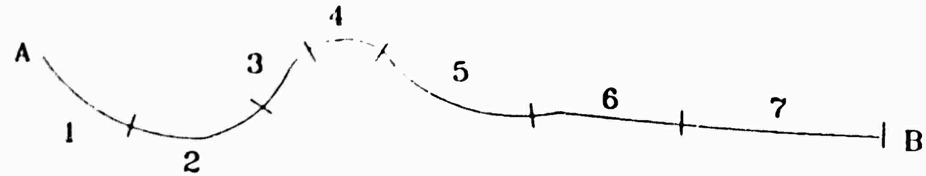
The vehicle's speed is constantly compared with the maximum entering speed of the next terrain unit that it will encounter. When the vehicle's speed becomes greater than that maximum entering speed, the distance required to brake from the current speed to that maximum entering speed is computed. This braking speed is modeled by allowing the application of the maximum braking force available for that vehicle on the current terrain. The equation F=MA is used to compute this constant deceleration. If the sum of the distance used for acceleration and that required for braking becomes greater than the length of the current terrain unit, then the intersection of the current acceleration step and the braking curve is computed to establish the limits for acceleration. From the time and distance used for both acceleration and braking, an average speed for the terrain unit can be calculated. If the vehicle reaches the predicted speed for the terrain unit, then the time and distance at that speed will also be used to calculate the average speed. If the application of brakes was ever necessary over the entire terrain unit plus portions of a previous unit, the model would revert to that previous terrain unit and take proper braking action to correct the exiting speed of that unit to allow for proper braking in the current unit.

The exiting speed of a terrain unit is used as the entering speed for the following terrain unit. The vehicle's time in each terrain unit and the length of the unit are used to compute an average speed for that unit along with an average speed for the distance up to and including that unit.

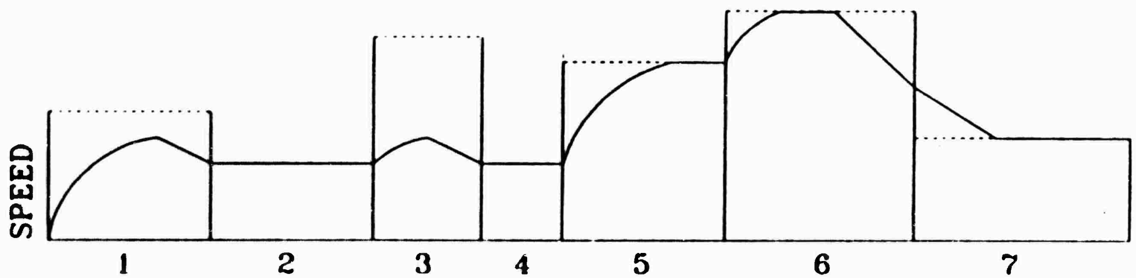
Figure A1 shows the way in which the speed of a single vehicle might vary along a route. As noted, the vehicle begins terrain unit No. 1 at zero velocity. The vehicle attempts to accelerate to the NRMM predicted speed. However, before the speed is achieved the vehicle must brake to reduce speed to the NRMM predicted speed of terrain unit No. 2. The vehicle maintains the NRMM predicted speed throughout the entire length of terrain unit No. 2. Upon entering terrain unit No. 3, the vehicle begins to accelerate toward the NRMM predicted speed. Before attaining the NRMM predicted speed, the vehicle must begin braking to reduce speed for entry into terrain unit No. 4. Terrain unit No. 5 is sufficiently long to permit the vehicle to accelerate from the exit speed in terrain unit No. 4 up to the NRMM predicted speed of terrain unit No. 5. Since the NRMM predicted speed in terrain unit No. 6 is higher than that of the previous segment, the vehicle begins to accelerate upon entry and finally attains the NRMM predicted speed. Near the end of the terrain unit the vehicle must begin reducing speed to enter the next unit. Because of a weak soil or a steep slope in terrain unit No. 7, the vehicle can enter the terrain unit at a higher speed than the NRMM predicted speed, but the entering speed must be less than or equal to the maximum entering speed. The soil/slope resistance causes the vehicle to eventually decelerate to the NRMM predicted speed.

The Traverse Model produces one record of output for each terrain unit along the route. This record consists of the sequential number of the terrain unit, the terrain unit's length, the time spent in that unit, the vehicle's average speed in the unit, the total route distance up to and including that unit, the total time, and the average speed for the traverse.

Based upon the previous discussion, it is readily apparent that the Traverse Model simulates a highly skilled driver that knows exactly what is coming up in the next terrain unit and takes the appropriate acton. The model's algorithms assume perfect interactions among the driver, vehicle and the terrain. Comparisons of measured and predicted results from previous traverse tests indicate that generally the model does reasonably well when evaluating the performance over the entire traverse. However, comparisons do not fare as well for individual terrain units as would be expected from the basic assumptions in the algorithms. This discrepancy is the result of compensating high and low predictions. If the terrain units are of sufficient length to allow attainment of steady state speeds and thus minimizing the vehicle-driver interactions, the comparisons between measured and predicted results are considerably better. One consistent shortcoming noted in the comparisons is that predictions in curves are almost always lower than the measured values.



Traverse Speed = f(Soil, Slope, Curves, Roughness, Visibility, Distance) ,



Ve > Vv

Generally : Vp > Vv

MAXIMUM ENTERING SPEED, Ve

...... PREDICTED SPEED, Vp

—— VEHICLE SPEED, Vv

Figure A1. Illustration of speed variation along a travers

APPENDIX B
INITIAL NRMM PREDICTIONS FOR DEMONSTRATION VEHICLES AT ISTVS 11TH INTERNATIONAL CONFERENCE

This appendix contains the results of the initial NRMM 2 predictions that were accomplished prior to the field demonstrations. There were errors in both the vehicle and terrain data files that required the simulations be repeated.

Vehicle	Vehicle Cone Index (VCI)	Soil Type	Remolding Cone Index (RCI)	NRMM2 GO/NOGO
Test Course 1				
M1025	18	SP	80	GO
M923A1	34	SP	80	GO
MTVR	13	SP	80	GO
BV206	4	SP	80	GO

Vehicle	Test Course	Distance, km	Time, min	NRMM2 Speed, km/hr
Test Course 2A and 2B				
M1025	2B	3	7.92	23.8
M923A1	2A	3	16.80	10.8
MTVR	2A	3	8.18	22.0
BV206	2A	3	10.78	16.7

Vehicle	Distance, km	Time, min	NRMM2 Speed, km/hr
Test Course 3			
M1025	2.5	4.42	34.5
M923A1	2.5	10.83	14.1
MTVR	2.5	5.08	30.0
BV 206	2.5	5.24	29.1

Vehicle	Terrain Unit	Soil Type	Soil Strength, RCI	Slope, Percent	NRMM2 GO/NOGO
Test Course 4					
M1025	1	SP	73	45	NOGO
	2	SP	73	25	NOGO
	3	SP	73	25	NOGO
M9 13A1	1	SP	73	45	NOGO
	2	SP	73	25	NOGO
	3	SP	73	25	NOGO
MTVR	1	SP	73	45	NOGO
	2	sp	73	25	GO
	3	SP	73	25	GO
BV206	1	SP	73	45	NOGO
	2	SP	73	25	GO
	3	SP	73	25	GO

Vehicle	Terrain Unit	Soil Type	Soil Strength, RCI	Surface Condition	NRMM2 Time to Travel 0.3657 km., sec.
Test Course 5, Terrain Units 1 and 2					
M1025	1	CL	300	DRY	23.6
	2	CL	300	WET-SLIPPERY	24.2
M923A1	1	CL	300	DRY	40.4
	2	CL	300	WET-SLIPPERY	40.5
MTVR	1	CL	300	DRY	28.8
	2	CL	300	WET-SLIPPERY	29.6
BV206	1	CL	300	DRY	29.6
	2	CL	300	WET	29.7

Vehicle	Vehicle Cone Index (VCI)	Terrain Unit	Soil Type	Soil Strength, RCI	NRMM2 GO/NOGO
Test Course 5, Terrain Unit 3					
M1025	15	3	CL	80	GO
M923A1	25	3	CL	80	GO
MTVR	25	3	CL	80	GO
BV206	4	3	CL	80	GO

Vehicle	Terrain Unit	Soil Strength, RCI	Surface Roughness, rms elevation, in.	NRMM2 Speed, kph
Test Course 5, Terrain Unit 4				
M1025	4	300	4.4	10.5
M923A1	4	300	4.4	5.7
MTVR	4	300	4.4	12.2
BV206	4	300	4.4	8.0

APPENDIX C: MODIFIED CURVATURE ALGORITHMS FOR NRMM

This appendix describes a modified scheme to predict curvature speed that was used in this study. Most of the information was obtained from the publication: A Policy on Geometric Design of Rural Highways, 1965, American Association of State Highway Officials (AASHO), now Association of State Highway and Transportation Officials (ASHATO).

The reference describes various relations between recommended safe design side friction coefficient and speed to be used in design of highway curves. These relations are depicted graphically in the reference in Figure III-4, page 156. The Meyer (1949) curve was selected as the reference relation with a maximum side friction factor $f_s = 0.21$ (for any speed < 20 mph $f_s = 0.21$). This relation is depicted graphically in Figure C1 in the AASHO recommended limits.

The relation for minimum safe radius is solved for speed. This yields the maximum safe speed (V, mph) for a given radius (R, FT), side friction coefficient (f) and super-elevation (e, ft/ft):

$$R = \frac{V^2}{14.95(e + f)} \tag{1}$$

This equation results in a very conservative speed versus radius of curvature relation and is essentially what was in NRMM 1. Experience from various tests conducted by WES indicate that it is possible to go much faster in curves than the above criteria allows. This is not surprising as very low coefficients of side friction were used.

The scheme given here attempts to predict an appropriate side friction for a less conservative situation and apply it to the curvature/speed relation given above to predict the maximum curvature speed. A safety factor variable will be introduced to indicate the amount of conservatism to apply; a value of 0 indicates no safety factor and a value of 1 will indicate full AASHO criteria.

Since NRMM does not compute side friction the following scheme was used to estimate it from the longitudinal friction which is computed. Table III-1, page 136 and the graph, Figure III-1B, page 137 in the reference show the maximum friction coefficients for dry and wet pavements. The text on pages 153-155 discusses maximum side-friction coefficients from various sources. The following data were extrapolated from this information: 0.65 at 5 mph because it should be slightly less than the longitudinal value which is 0.67; 0.5 at 40 mph, a direct data point, 0.35 at 60 mph, assumed to be "high" speed; 0.30 at 80 mph, assumed to be "very high" speeds. After plotting the above points, the 0.35 coefficient was moved to 70 mph which yielded a smoother relation. The points (x,y) selected for use in the curve fit (x = speed in mph, y = friction coefficient) were: (5, 0.65), (40, 0.5), (70, 0.35), and (80, 0.30). (See the lateral, dry pavement, relations in Figure C1). The results of a straight line fit for AASHO side friction coefficient (f_{AS}) as a function of speed (V, mph) is:

$$f_{AS} = 0.678 - 0.00468V \tag{2}$$

A straight line fit of the friction coefficient of AASHO longitudinal friction for dry pavements, obtained from a variety of stopping tests, (f_{AL}) versus speed (V, mph) using the following coordinates: (x = speed in mph, y = longitudinal friction coefficient) (30, 0.62), (40, 0.60), (50, 0.58), (60, 0.56), (65, 0.56), (70, 0.55), (75, 0.54), (80, 0.53) from Table III-1 is:

$$f_{AL} = 0.670 - 0.00174V \tag{3}$$

The ratio of this side friction (2) to longitudinal friction (3) for a given speed is used as a factor to convert the actual NRMM predicted longitudinal coefficient to an equivalent side friction. The following equation is used to determine the side friction for curvature speed predictions (f_{PS}) as a function of speed and NRMM predicted longitudinal friction coefficient (f_{PL}).

$$f_{PS} = \frac{f_{AS}}{f_{AL}} f_{PL} \tag{4}$$

The following relation is the amount of "safety factor " to include. This should be the AASHO recommended design coefficient (f_A) for a safety factor (F) of 1.0 and the maximum side coefficient (f_{PS}) for a factor of 0.0. The following equation yields the final friction coefficient (f):

$$f = (f_A - f_{PS})F + f_{PS}$$

To facilitate obtaining the AASHO recommended side friction coefficients (F_A) in Figure C1, the following curve was obtained by fitting the data points to a hyperbola. The result of a curve fit using the points (x = speed in mph, y = AAHSO recommended maximum design friction coefficient) (20, 0.21), (25, 0.19), (30, 0.18), 35, 0.168), (40, 0.158), (45, 0.15), (50, 0.142), (60, 0.128), (70, 0.116), (80, 0.106) is:

$$\begin{aligned} f_A &= \frac{1}{3.264 + 0.07648V)}, \quad V \leq 20 \\ &= 0.21, \qquad\qquad\qquad\quad V < 20 \end{aligned}$$

For speeds <20 mph the value for 20 mph (~0.21) is used.

In the implementation, the maximum AASHO recommended coefficient of friction is not allowed to exceed the model prediction for longitudinal traction.

No information about the ratio of lateral to longitudinal friction coefficients for soft soils was available. The scheme used for hard surfaces was arbitrarily applied to the soft soils.

There was less information in the AASHO reference concerning the friction coefficients for wet pavements. The implications are that the longitudinal friction coefficients are usually much less than for dry pavements. The AASHO design criteria used is the same since it is assumed to apply to an arbitrarily poor condition. Therefore, the same friction reduction scheme used for dry pavements was assumed to apply to wet pavements. Note that for the NRMM 2 implementation the AASHO information regarding coefficients of traction (friction) on dry pavements is used only to determine the ratio of longitudinal to lateral friction; the actual longitudinal friction is obtained from other relations in the NRMM 2 model.

Figures C2-C5 depict for hard surface and three soil strength conditions the three speed-curvature relations representing the NRMM 2 relation, the AASHO recommended (safety factor of 1) and the slip-sliding relation (safety factor of 0). Superelevation was considered to be zero.

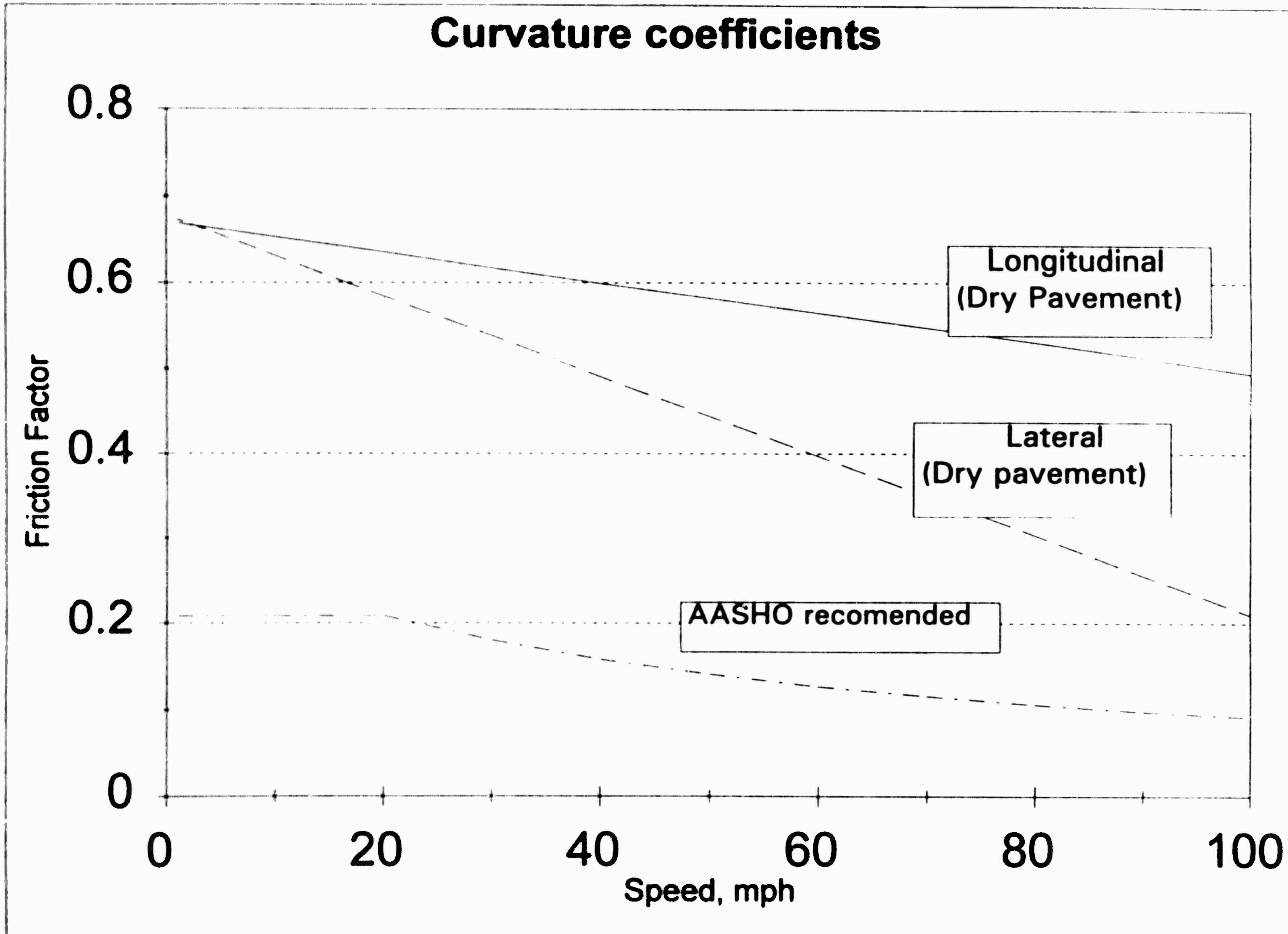

Curvature coefficients
0.8
0.6
0.4
0.2
0
Friction Factor
Longitudinal
(Dry Pavement)
Lateral
(Dry pavement)
AASHO recomended
0
20
40
60
80
100
Speed, mph

Figure C1.

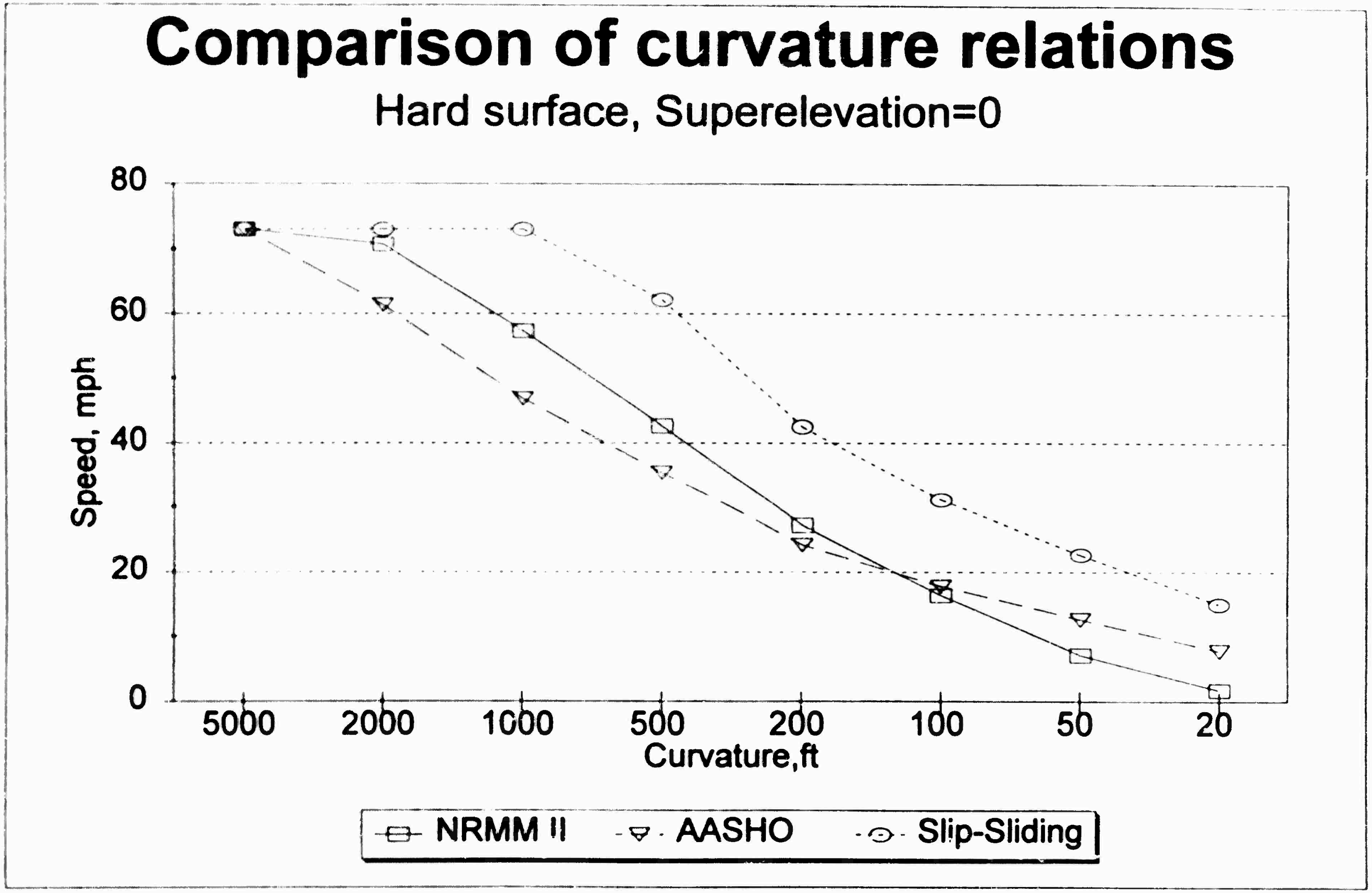
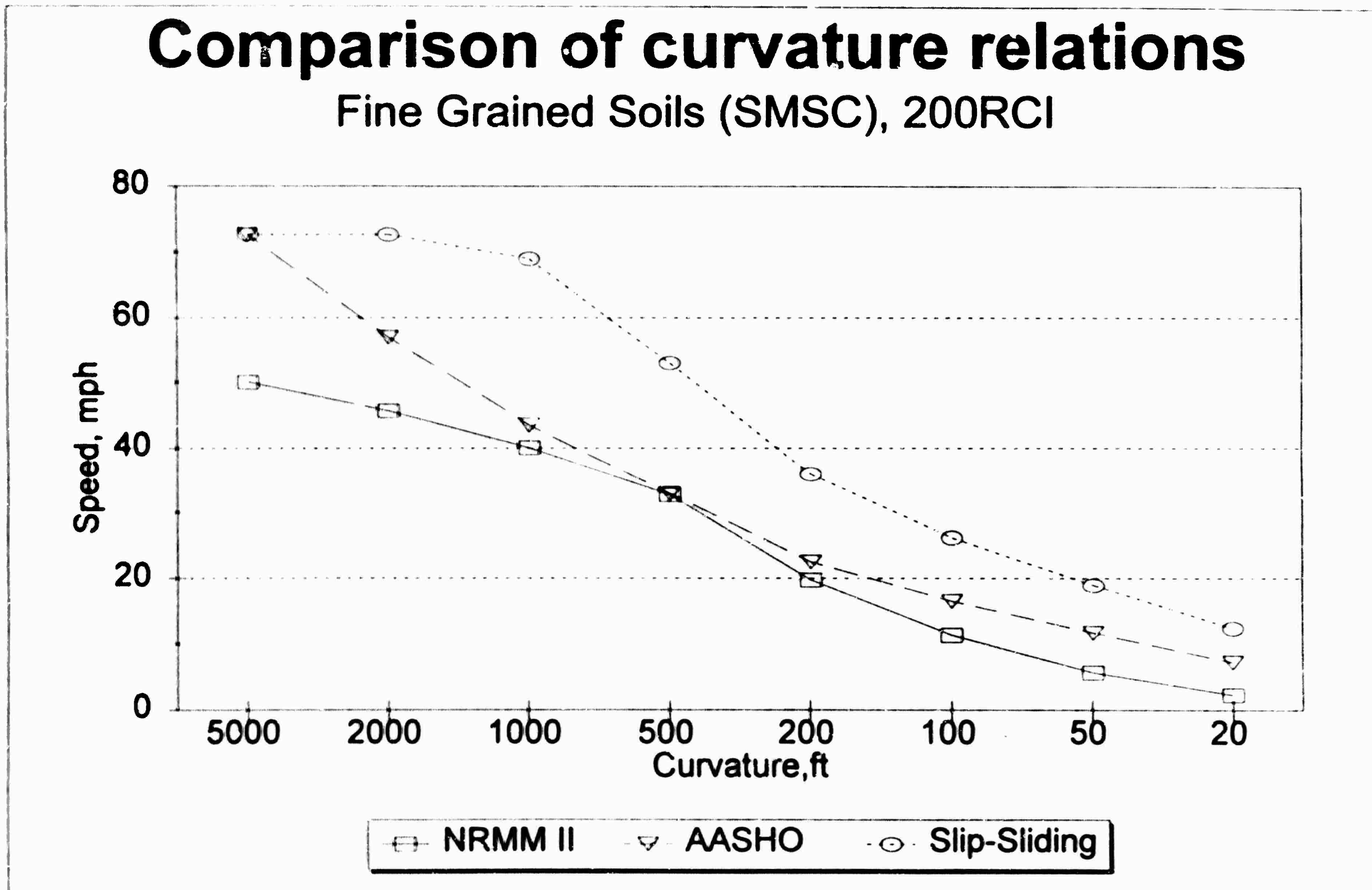

Comparison of curvature relations
Hard surface, Superelevation=0
Speed, mph
80
60
40
20
0
5000
2000
1000
500
200
100
50
20
Curvature,ft
NRMM II
AASHO
Slip-Sliding

Figure C2.



Comparison of curvature relations
Fine Grained Soils (SMSC), 200RCI
Speed, mph
80
60
40
20
0
5000
2000
1000
500
200
100
50
20
Curvature,ft
NRMM II
AASHO
Slip-Sliding

Figure C3.

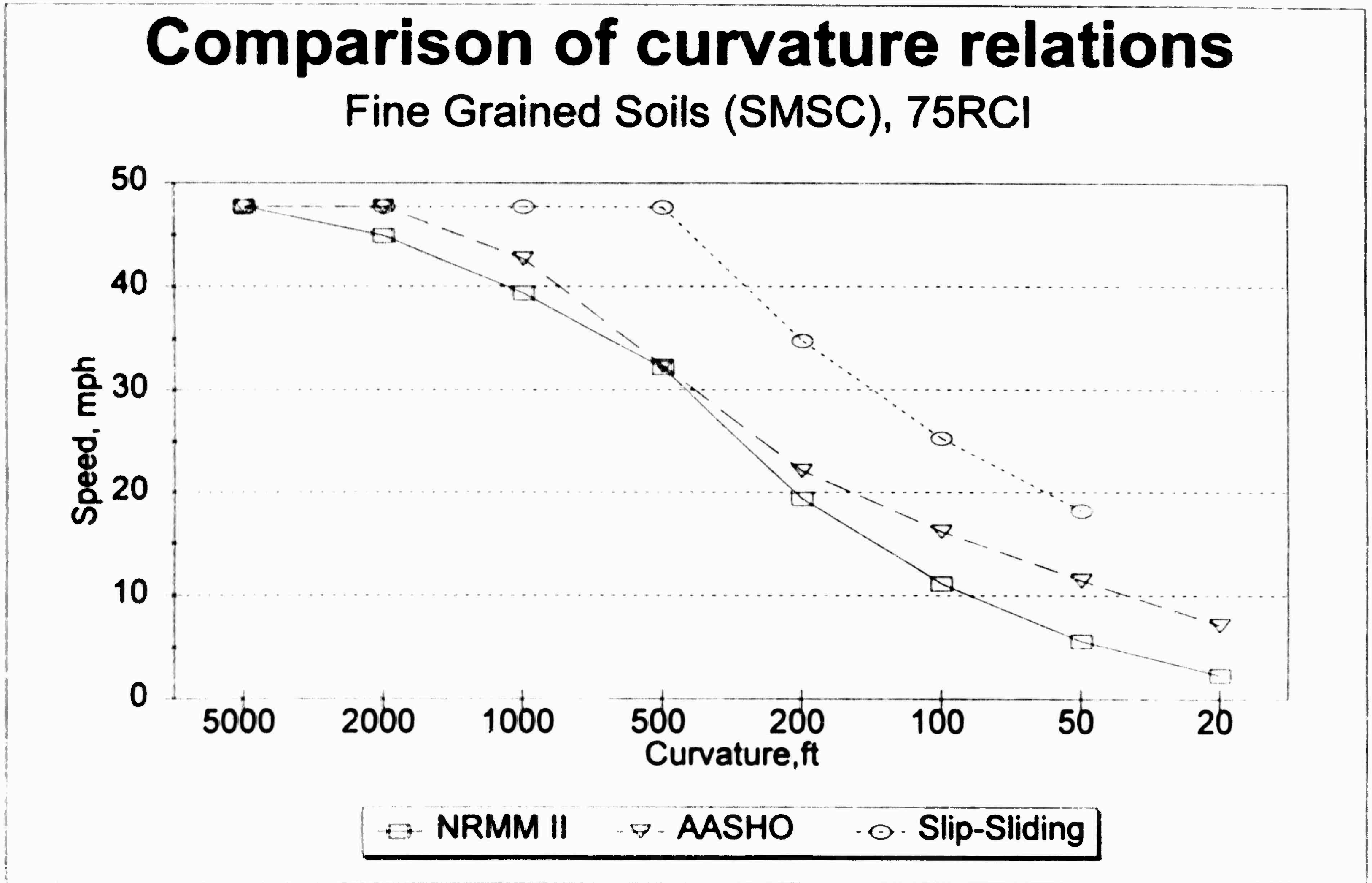

Comparison of curvature relations
Fine Grained Soils (SMSC), 75RCI
Speed, mph
0
10
20
30
40
50
5000
2000
1000
500
200
100
50
20
Curvature,ft
NRMM II
AASHO
Slip-Sliding

Figure C4.

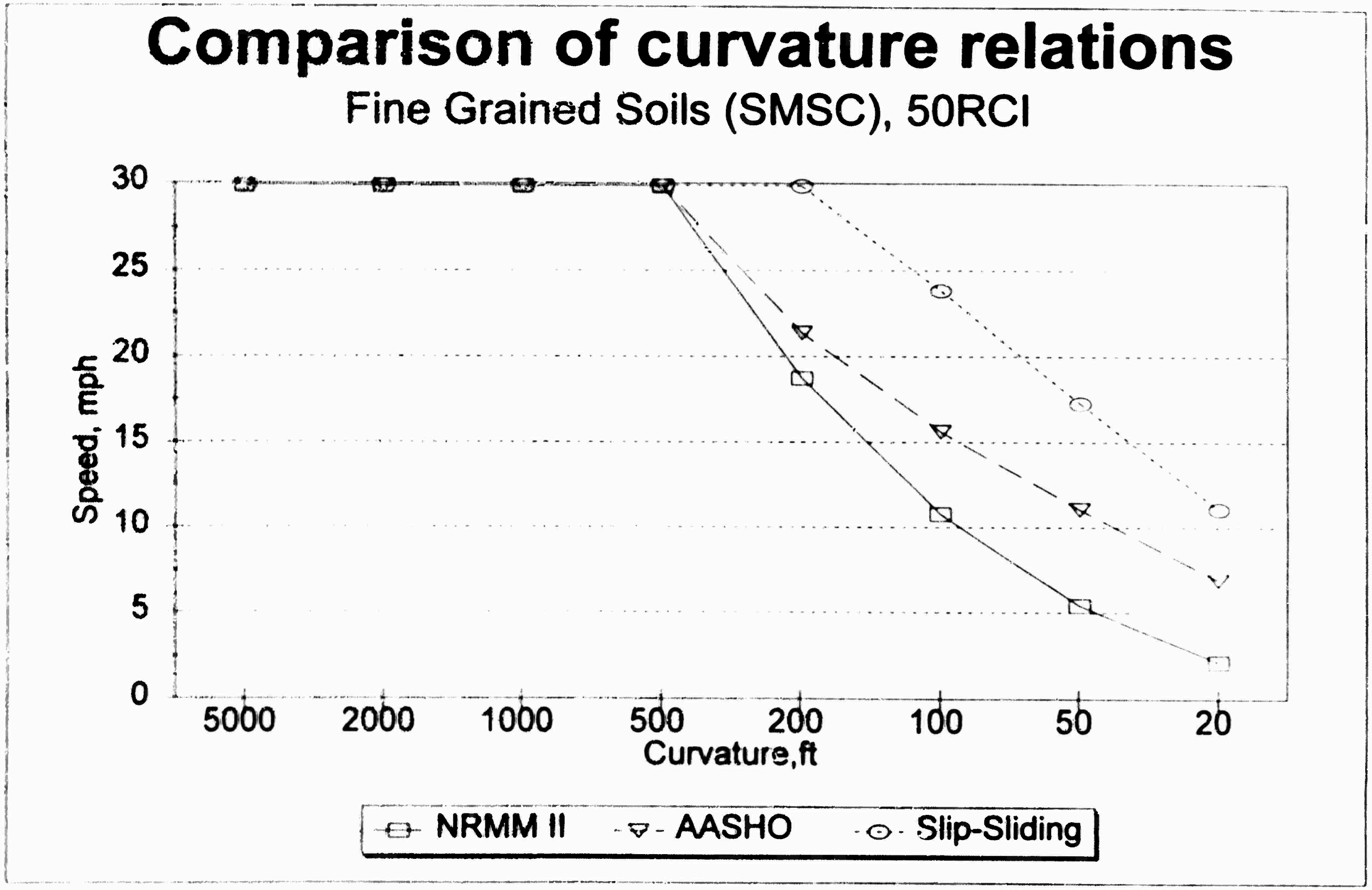

Comparison of curvature relations
Fine Grained Soils (SMSC), 50RCI
Speed, mph
30
25
20
15
10
5
0
5000
2000
1000
500
200
100
50
20
Curvature,ft
NRMM II
AASHO
Slip-Sliding

Figure C5.

APPENDIX D THEORY FOR DESCRIBING VEHICLE SLOPE PERFORMANCE

Method for Computing Maximum Tractive Force on a Slope

A vehicle can obtain a tractive force on a level surface up to some maximum, T_{max} that depends on the coefficient of traction, μ, which is a function of the normal load or in this case the vehicle weight, w

$$T_{max(level)} = \mu W \quad (1)$$

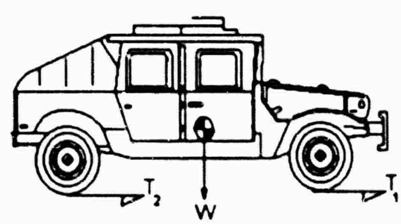


Figure D1. Vehicle developing tractive force on level surface

$$T = T_1 + T_2$$

Now the same vehicle going up a slope of angle θ with the same surface material as the level surface in Figure D1 will have a reduced coefficient of traction by virtue of the reduction in the normal load due to the slope as shown in Figure D2.

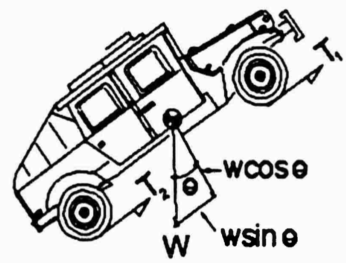


Figure D2. Vehicle developing tractive force on a slope

The coefficient of traction is based on the normal load (i.e., the component perpendicular to the slope). The maximum available tractive force on the slope is:

$$T_{max(slope)} = \mu W \cos\theta$$

But in equation (1) $\mu W = T_{max}$ on a level surface hence if the surfaces of level and slope are the same we can write the maximum tractive on a slope as

$$T_{max(slope)} = T_{max(level)} \times \cos\theta \qquad (2)$$

Therefore, having developed the maximum tractive force from tests on level surfaces, the maximum tractive force on a slope with the same material composition is given by Equation 2.

Derivation of Slope Model Used In NRMM

Given the following variables:

T	Tractive force
R	Motion resistance force
P	Drawbar-pull force
θ	Slope angle
W	Weight

N	Normal force
μ	Coefficient of friction
F	Kinetic friction force

First the assumption is made that "drawbar pull" is the total traction minus the surface and internal motion resistance:

$$P = T - R$$

From coefficient of sliding friction theory:

$$F = \mu N$$

We assume that the vehicle traction coefficient behaves as a coefficient of friction as follows:

$$T = \mu W$$

The sum of forces in the horizontal direction is:

$$F = P = T - R$$

Using the classic inclined plane model, the normal force will be reduced by the cosine of the slope angle and an additional force referred to as the slope resistance will be produced by gravity (in the direction of the plane) equal to the weight times the sine of the slope angle. Thus:

$$W\,(T/W)\cos\theta - W\,(R/W)\cos\theta - W\sin\theta = F$$

$$(T - R)\cos\theta - W\sin\theta = F$$

Substituting:

$$P = T - R$$

Then

$$P\cos\theta - W\sin\theta = F$$

The maximum slope will occur when drawbar is equal to the resistance and the external force is zero:

$$P\cos\theta - W\sin\theta = 0$$

$$P/W = \tan\theta$$

$$\theta = \tan^{-1} P/W$$

By definition, $\tan \theta$ = percent slope/100. Therefore, the maximum slope negotiable is indicated by the maximum drawbar coefficient P/W on a level surface. A rule of thumb has been formulated that slope resistance, $W\sin\theta$, amounts to about 20 lb per ton of vehicle weight for each percent of slope.

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