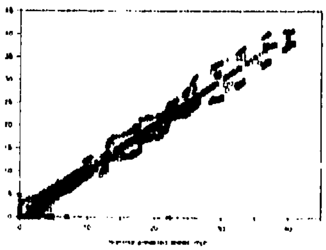
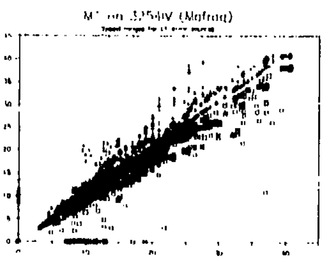
TECHNICAL REPORT GL-92-11

2

US Army Corps of Engineers





STOCHASTIC VEHICLE MOBILITY FORECASTS USING THE NATO REFERENCE MOBILITY MODEL

Report 1

BASIC CONCEPTS AND PROCEDURES

by

Allan Lessem, Richard Ahlvin, George Mason

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

and

Paul Mlakar

JAYCOR
Structures Division
1201 Cherry Street, Vicksburg, Mississippi 39180

August 1992

Report 1 of a Series

Approved For Public Release; Distribution Is Unlimited

54 pgs

GEOTECHNICAL LABORATORY

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1992

3. REPORT TYPE AND DATES COVERED
Report 1 of a series

4. TITLE AND SUBTITLE
Stochastic Vehicle Mobility Forecasts Using the NATO Reference Mobility Model; Report 1, Basic Concepts and Procedures

5. FUNDING NUMBERS
Military RDTE Task
No. AT40-AM-011

6. AUTHOR(S)
Allan Lessem, Richard Ahlvin, George Mason, Paul Mlakar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Engineer Waterways Experiment Station, Geotechnical Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199;
JAYCOR, Structures Division, 1201 Cherry Street, Vicksburg, MS 39180

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report GL-92-11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes concepts and procedures that convert the NATO Reference Mobility Model (NRMM) from a deterministic code to a stochastic one. The motivation for the conversion is the opportunity being presented by advances in computer technology that can allow NRMM to be used in the fast-paced tactical environment of a battlefield.

Appropriate components of a stochastic mobility forecast are identified as a speed map, a "fingerprint," a mission-rating speed and a range for the mission-rating speed. The speed map and the mission-rating speed are the current NRMM products; the fingerprint and range are new components that describe the performance of NRMM when its data contain errors. Quantification of error performance becomes very important to mobility planning in a tactical sett'ng.

The procedures are illustrated by means of a comprehensive and robust example involving four vehicles, four terrain maps and two scenarios. The procedures are somewhat preliminary in the sense that alternative implementations are possible. Minimization of computational bottlenecks motivates the selections; other selections may be more appropriate in the future.

14. SUBJECT TERMS
Mathematical models — Sensitivity
Mobility — Vehicles, military

15. NUMBER OF PAGES
51

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

SUMMARY

This report describes concepts and procedures that convert the NATO Reference Mobility Model (NRMM) from a deterministic code to a stochastic one. The motivation for the conversion is the opportunity being presented by advances in computer technology that can allow NRMM to be used in the fast-paced tactical environment of a battlefield.

Appropriate components of a stochastic mobility forecast are identified as a speed map, a "fingerprint", a mission-rating speed, and a range for the mission-rating speed. The speed map and the mission-rating speed are the current NRMM products; the fingerprint and range are new components that describe the performance of NRMM when its data contain errors. Quantification of error performance becomes very important to mobility planning in a tactical setting.

The procedures are illustrated by means of a comprehensive and robust example involving four vehicles, four terrain maps, and two scenarios. The procedures are somewhat preliminary in the sense that alternative implementations are possible. Minimization of computational bottlenecks motivates the selections; other selections may be more appropriate in the future.

PREFACE

Personnel of the US Army Engineer Waterways Experiment Station (WES) conducted this study during the period October 1990 through February 1992 as direct-allotted Military RDTE Task No. AT40-AM-011.

The study was conducted under the general supervision of Dr. William F. Marcuson III, Chief, Geotechnical Laboratory (GL) and Mr. Newell R. Murphy, Jr., Chief, Mobility Systems Division (MSD). Dr. Allan S. Lessem devised the stochastic methodology and guided the development of software by Mr. Richard B. Ahlvin and the construction of error descriptors for historic MSD field data by Mr. George B. Mason. Dr. Paul Mlakar contributed statistics expertise and developed the use of the mission rating speeds in a stochastic context. The report was prepared by Dr. Lessem and edited by Mrs. Joyce Walker, Information Technology Laboratory, WES.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
miles (US statute)	1.609347	kilometres
miles (US statute) per hour	1.609347	kilometres per hour
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals

STOCHASTIC VEHICLE MOBILITY FORECASTS USING THE NATO REFERENCE MOBILITY MODEL: BASIC CONCEPTS AND PROCEDURES

PART I: INTRODUCTION

Background

1. The NATO Reference Mobility Model (NRMM) is a computer code used to characterize the ability of ground vehicles to move in various operational settings. Based on many years of field and laboratory work by the USAE Waterways Experiment Station (WES), the Army Tank-Automotive Command, and containing contributions from NATO members, NRMM considers many terrain, road, and tactical gap attributes, vehicle geometries, and human factors (Haley, Jurkat, and Brady 1979). Its fundamental output is a mobility forecast based on speed predictions keyed to specific areal units of terrain and to specific lineal portions of a road network.

2. Like many other mathematical models of broad scope, NRMM requires the assembly of a comprehensive dataset. Users of NRMM understand that confidence in results is governed by data quality. Informal trials are often made to infer the effects of variation in important data elements. In addition, it is essential to remember that the algorithmic basis of NRMM is founded mainly on empirical field studies having unavoidable errors associated with experimental control and measurement.

3. In addition to its service in user communities concerned with vehicle design, war-gaming, and strategic planning, continuing developments in computer technology are creating an opportunity for NRMM to serve a tactical role on the battlefield. The battlefield setting requires high-resolution data and expedient dataset preparation. Adaptation of NRMM to this role requires that its users come to grips with the effects of errors in vehicle and terrain data and of inherent algorithm errors.

4. Years of experience with NRMM have resulted in qualitative impressions of unusual or unanticipated aspects of vehicle performance, both measured and predicted, as ranges of terrain attributes are studied. It is now desired to formally quantify the variation performance of the model. By

"variation performance" is meant the responses of NRMM when some dataset elements are represented, individually or jointly, as random variables. Random variation can arise from errors of measurement or judgment, and from intentional variation in the context of design studies. In addition, errors associated with regression-line representations of empirical data contribute to variations in NRMM outputs.

5. NRMM is an equilibrium model: supply it with all the numbers it needs to make a speed prediction and its prediction is applicable to the one terrain unit and vehicle represented by those numbers. No neighboring terrain units exert an influence; no past prediction influences the present one. Each terrain-unit/vehicle combination has a unique equilibrium speed. Considered in a map-wide context there are many such equilibria, and no characteristic prediction patterns emerge. Our approach to the determination of NRMM variation performance is, therefore, project-specific. Each time NRMM is called upon to make a speed prediction, its variation performance will be determined for that terrain unit and that vehicle. The trick is to make this determination efficiently, to state outcomes clearly, and to integrate meaningfully over the many terrain units that compose a mobility map.

Purpose

6. WES has undertaken the task of making NRMM capable of delivering stochastic mobility forecasts in which the impacts of data and algorithm uncertainties, large and small, are clearly evident in the model's predictions of vehicle speeds. The principal benefit will be the presentation in numerical terms of the quality of NRMM vehicle speed prediction products. With this information, tactical decisions which depend upon vehicle performance can be made with pertinent assessments of risks. The purposes of this report are to present the scope and avenue of approach of current work, to show initial results, and to provide guidance for the continuation of work.

An Illustration of NRMM Principles

7. The interaction of factors affecting NRMM variation performance can be glimpsed with an illustration. Consider the graph in Figure 1a. The basic ideas that form the foundation of NRMM are present in this graph.

8. Forces are plotted against speeds. The stair-step curve represents the ability of a vehicle's power train to deliver a tractive force to wheels or tracks. It is derived from actual dynamometer data or powertrain models and includes the influence of terrain-unit-specific soil strength through conversion of wheel or track speeds to vehicle speeds by means of slip. Call it the "effort" line.

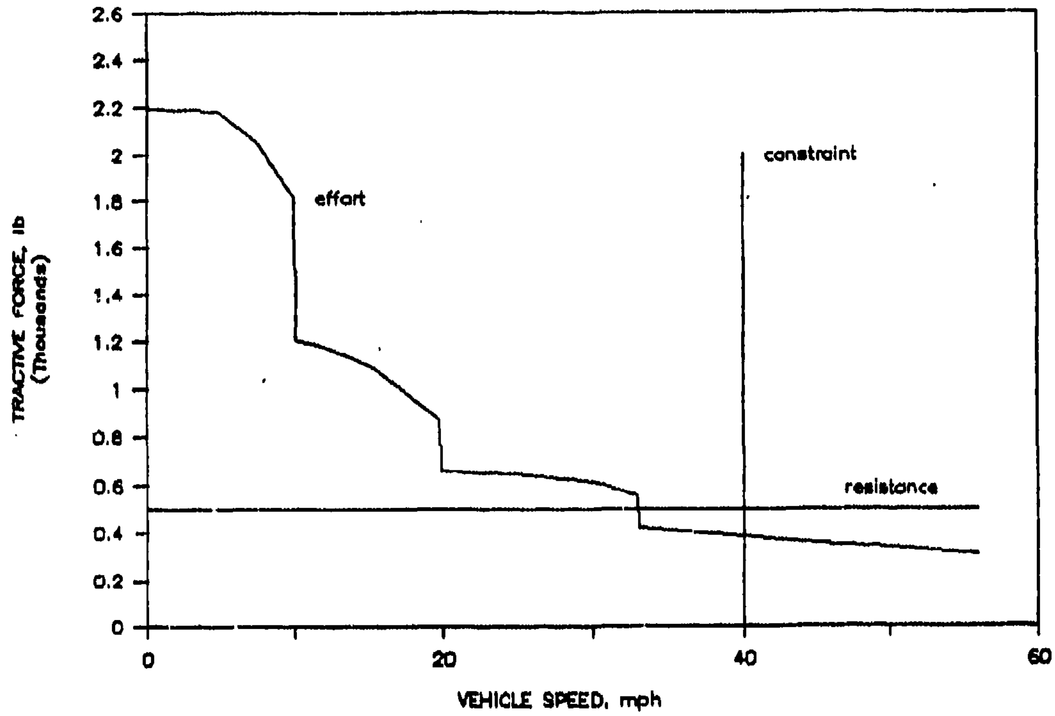
9. The horizontal line is a resistance force. It derives from several components, among them motion resistance, slope, and vegetation resistances considered by stem size classes. When the terrain-unit-specific resistance is found, it is viewed as independent of speed. Call it the "resistance" line.

10. Speed constraints are independently expressed for such human factors as intolerance to visceral resonances and to horizontal and vertical shocks. Visibility and certain tire performance limits are also considered. The smallest of these terrain-unit-specific constraining speeds is taken as the "constraint" line.

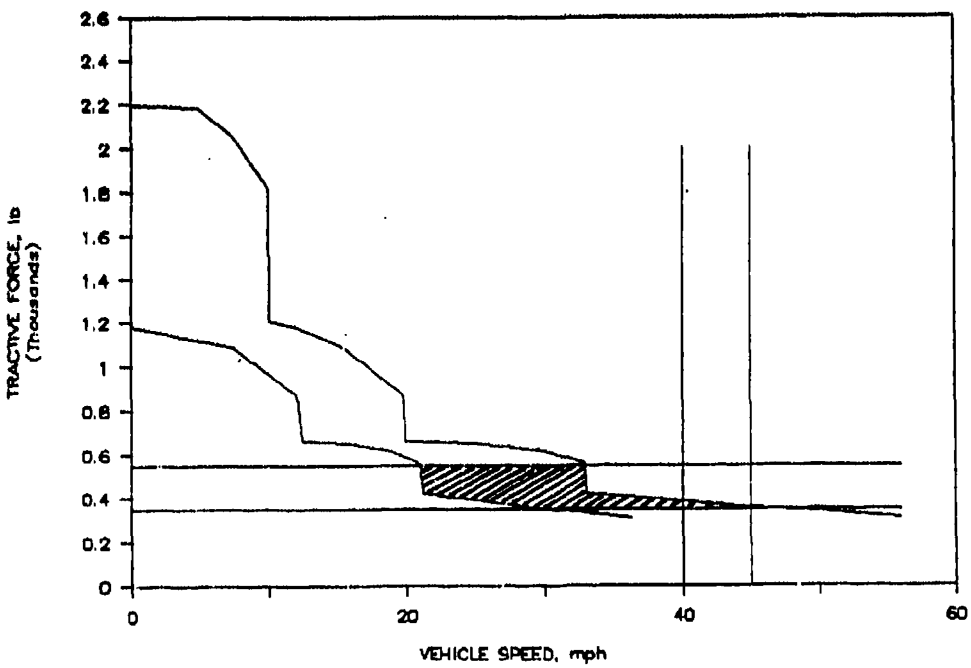
11. The intersection of the effort line and the resistance line defines the nominal NRMM speed prediction unless the constraint line lies to the left of the intersection and thereby dictates a lower speed. The vehicle can actually operate at any speed corresponding to the area beneath the effort line and above the resistance line; NRMM provides the maximum of these speeds. The figure depicts the relationships among the effort, resistance, and constraint factors as they may exist for a given vehicle in a given terrain unit. Let that same vehicle traverse many terrain units and, separately, the effort, resistance, and constraint lines will change their relative positions along the traverse. The intersection points and activation of constraints change with them.

12. In Figure 1b, the effects of data sensitivity and algorithm inaccuracy are suggested. The effort, resistance, and constraint lines spread into bands, and the intersection point spreads into a prediction zone. The lines spread because random variations in data and algorithms preclude the fixing of precise positions. Along a traverse, not only will the mean positions of the three lines change, their widths will change as well and predictions zones can vary significantly among terrain units.

13. Current use of NRMM yields forecasts of vehicle speeds in relatively small homogeneous units of terrain. Quad-sheet-size areas require acquisition of data for hundreds to thousands of terrain units. Predictions



a. Power source, resistance, and constraint



b. Effects of sensitivity and inaccuracy

Figure 1. Basic ideas of NRMM

are currently made without consideration of the quality of terrain, vehicle, and human performance data. Judgments must often be made about appropriate values. In addition, the curve-fits in the model lack the scatter bands associated with their experimental origins. As a result, mobility forecasts are incorrectly interpreted as error-free. Adaptation of NRMM to a stochastic orientation is imperative if it is to be used in the high-resolution battlefield context. It must deliver measures of quality for speed predictions that reflect the quality of data and algorithms for both per-terrain-unit and per-map forecasts.

Discussion

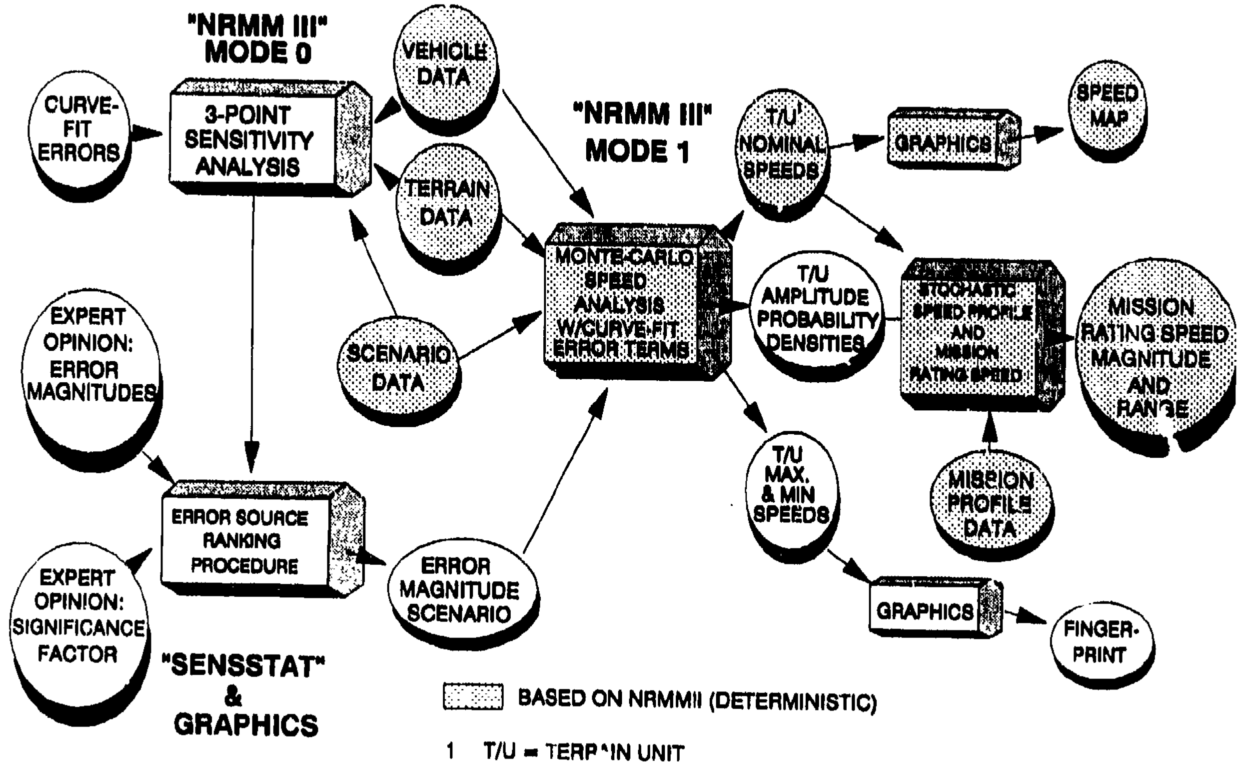
14. It is instructive to consider how NRMM could be developed into a stochastic model if infinite resources were available. The model has many parameters that must be numerically supplied by vehicle, terrain, and scenario datasets. Expert opinions can be used to assign error statistics, large and small, to these parameters. Algorithm errors can be characterized by standard errors assigned to regression lines refitted to the historic field data. With nominal datasets and error statistics specified, NRMM can be made to iterate speed predictions repeatedly while treating its data as a set of jointly varying random variables. This approach constitutes a classic brute-force Monte Carlo simulation and develops probability densities of the speeds predicted for individual vehicles on every unit of terrain.

15. Infinite resources would obviate any need to consider the number of parameters subject to variation, the number of iterations required to delineate probability densities, or the time required to perform computer simulations on extensive datasets. When resources are finite these factors assume dominating roles. For example, a representative terrain map may contain about 2,000 terrain units. When all dataset parameters are considered to be random variables, approximately 100 variates would have to be generated for each iteration of the speed prediction. A representative number of iterations suitable for defining the speed prediction probability densities would be expected to be about 1,000. Thus, about 2,000,000 speed predictions requiring 200,000,000 variate updates would be executed to generate the raw materials for a stochastic mobility forecast. Representative computation rates (within a factor of 2 and vehicle-dependent) for NRMM on a state-of-the-art

supercomputer are about 1,500 speed predictions and 7,500 variate updates per second; thus, almost 8 hr would be required for a forecast. For a conventional mainframe computer, the rates are about 100 speed predictions and 500 updates per sec with a forecast time of about 116 hr. For a fast desktop machine, which is the type actually desired for a battlefield setting, the computation rates are about 60 speed predictions and 300 updates per sec with a forecast time of about 194 hr. Such forecasting times are clearly inconsistent with the tactical performance desired of NRMM. It is quite apparent that finite resources require a somewhat more subtle approach.

16. The key to removal of computational bottlenecks is reduction of the number of random variables. Surely, the parameters of NRMM are not equally important in their corrupting effects when data errors are present. It is reasonable to expect, and engineering intuitions derived from field experience suggest, that their relative influences change from vehicle to vehicle and from terrain to terrain. If they can be screened individually by vehicle and terrain, which is to say on a project-specific basis, then the parameters whose errors influence predicted speeds the least in a given setting can be dismissed from further consideration. These remarks are tantamount to saying that an analysis of parameter sensitivity should precede the brute-force Monte Carlo simulation, which, in turn, is conducted with a reduced set of variates. For example, should the screening process reduce the number of random variables from 100 to 20 in the given setting, computation times for variate updates are proportionately reduced and the forecasting times would become roughly 2, 28, and 46 hr for the supercomputer, mainframe computer, and desktop computer, respectively. It would be important, of course, not to pay a big price for the screening process.

17. In similar fashion, refinements in procedures discovered if only by trial and error can be sought for the purpose of reducing forecasting times to the point of practicality. By studying small quantities of data at the outset, by examining the impacts of reducing the number of speed prediction iterations, and by searching for efficiencies in the coding of algorithms, incremental improvements in procedures can nibble away at forecasting times. When combined with relentless ongoing improvements in computation technology, such an approach can genuinely succeed in developing a useful adaptation of NRMM to a stochastic orientation.



STOCHASTIC MOBILITY FORECAST

Figure 2. Analysis pathways to the stochastic mobility forecast

PART II: A PROTOTYPE STOCHASTIC MOBILITY FORECASTING PROCEDURE FOR NRMM

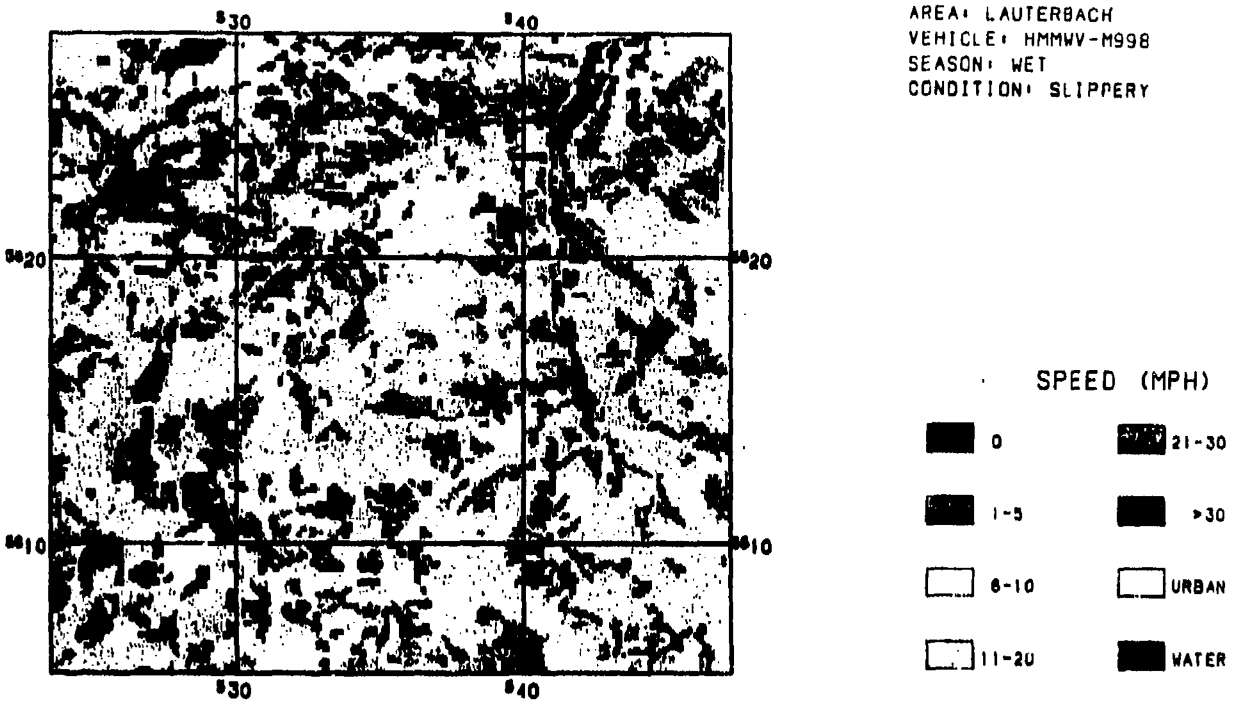
The Components of the Stochastic Forecast

18. The thoughts expressed rather generally above are made more specific in Figure 2 in which procedural pathways are spelled out. The shaded elements of Figure 2 use procedures that are similar to those in place for the non-stochastic mobility forecasts now provided by NRMM (in its most current form: NRMM II). These are appropriately modified, and other elements added, to develop the stochastic forecasts. Pathway elements will be discussed in broad terms in the following paragraphs; subsequent discussions will elucidate details through the agency of a comprehensive and robust example. It is best to begin by examining the nature of the products delivered as a stochastic mobility forecast. These consists of four items: a speed map, a "fingerprint," a "mission rating speed," and a range for the mission rating speed.

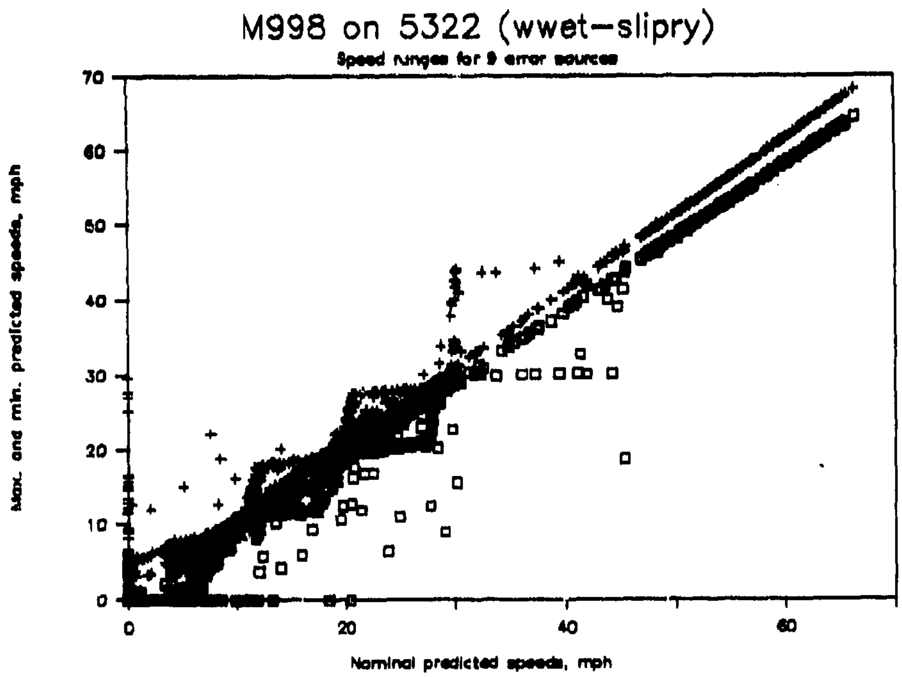
19. The speed map is a graphical presentation of nominal predicted speeds for one vehicle operating according to one scenario on one terrain map (consisting of hundreds to thousands of terrain units) made under the assumptions of error-free data and an error-free model. It is the product obtained from NRMM at the present time. See Figure 3a for a representative example. The fingerprint is a graphical presentation of the error performance of NRMM specific to the one vehicle and the one terrain map and is capable of quick visual comprehension. The greater the departure of the fingerprint from a straight line of unit slope, the greater the error associated with the speed predictions. Clustered errors are easy to spot. See Figure 3b. The mission rating speed is a concept used by NRMM analysts who postulate a mission "profile" expressing on-road and off-road percentages to arrive at a one-number measure of vehicle performance on the terrain map. This useful concept is preserved and extended by expressing its range thereby indicating in an integrated and quantitative way the quality of the entire NRMM speed map.

Sensitivity Analysis

20. The pathways to these products begin with datasets assembled for vehicle, terrain, and scenario of interest. Unlike their use with NRMM in its



a. The speed map



b. The fingerprint

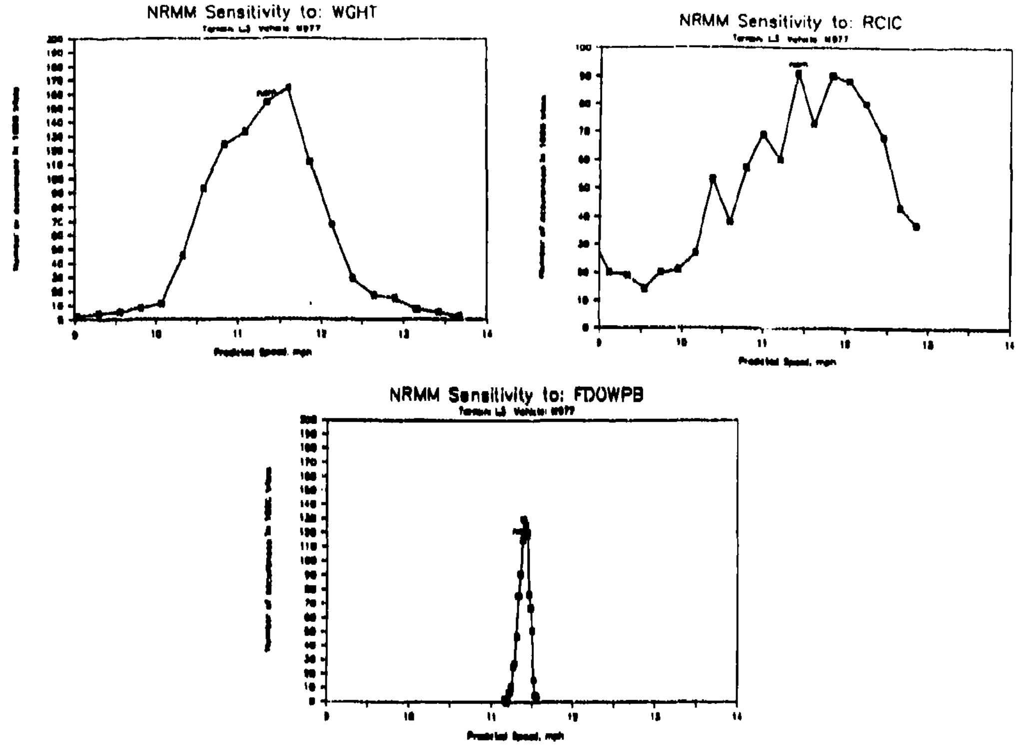
Figure 3. The speed map and the fingerprint

deterministic form, these data are first examined to evaluate the sensitivity of the speed predictions to standardized small variations in dataset elements taken one at a time. The variations are in the range of plus-and-minus 10 percent of nominal values. This approach was studied with a version of NRMM modified to repeat speed predictions with specified parameters updated in accordance with uniform probability distributions. In effect, this was a Monte Carlo procedure applied to the case of one variable only, an overkill situation. However, earlier trials aimed at isolation of parameters important for error performance considered possible joint variations and suggested that in the main it was sufficient to examine individual variation only.

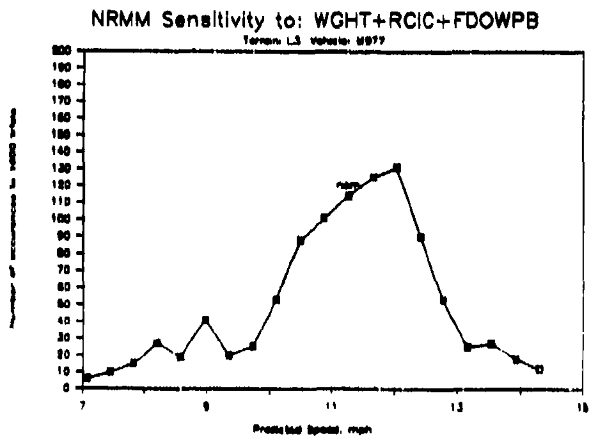
21. Some effects of individual and joint parameter variations are illustrated in Figure 4 where, for one vehicle and one terrain unit, three parameters are varied individually and then jointly. The vertical axes indicate the number of occurrences in 1,000 trials of predicted speeds in a sequence of speed subranges. From such plots are derived probability densities of the predicted speeds. The points labeled "nom" represent the speeds computed from nominal dataset values. Outcomes such as these change greatly among terrain units, vehicles, and parameters. Numerical experiments were performed to identify, if possible, a minimum number of Monte Carlo samples to sufficiently resolve the sensitivity of individual parameters. That number seems to be about 200, a significant improvement over the 1,000 thought at first to be needed.

22. Further experimentation and growing experience suggested that, in spite of NRMM's inherently nonlinear structure, it would suffice in the vast majority of cases simply to associate extreme values (maximum and minimum) of predicted speeds with extreme values of the range of variation assigned to each parameter whose sensitivity was wanted. Thus, instead of 200 variates to examine sensitivity, only 3 would be required: one for the nominal dataset value and two for the maximum and minimum limits of variation. In effect, variation is set aside in favor of 3 fixed points. This element of the procedural pathway has been named "3-point extremum analysis"; its use goes far to remove a computational bottleneck, but does so by losing the ability to see probability densities in the predicted speeds.

23. Determinations of sensitivity to vehicle, terrain, and scenario parameters are augmented by sensitivities to algorithm errors. These errors are inherent to the many regression curve-fits worked into the fabric of



a. Sensitivity to vehicle weight (WGHT), soil strength (RCIC), and drawbar pull coefficient (FDOWPB) considered separately



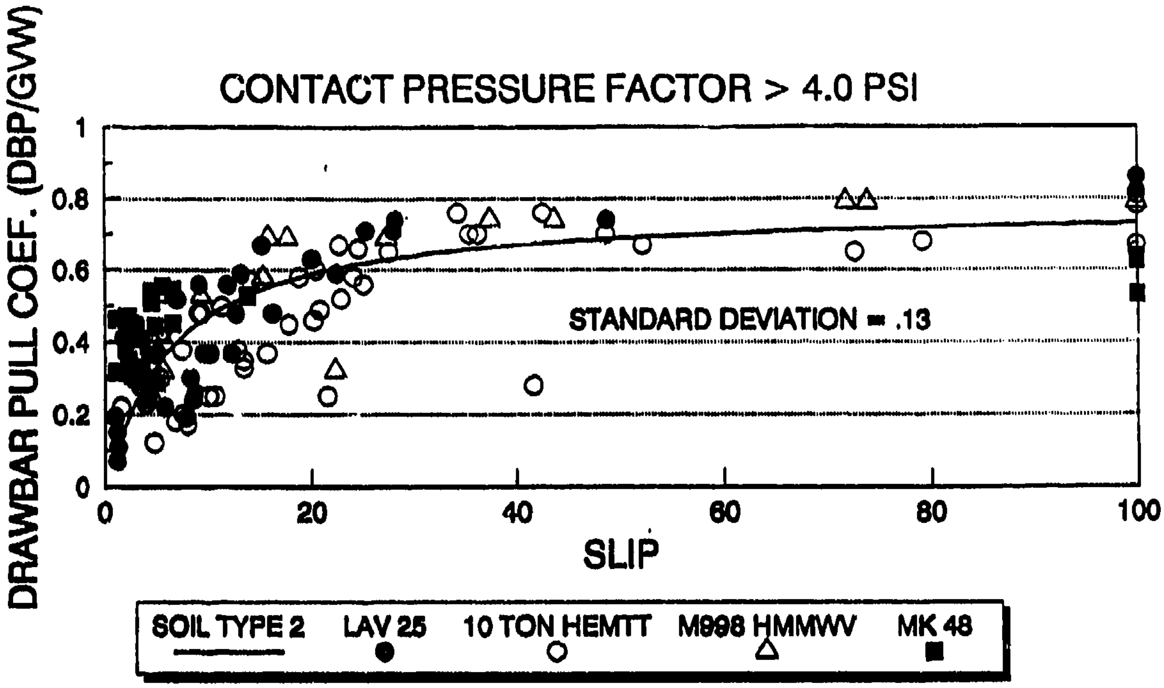
b. Sensitivity to WGHT, RCIC, and FDOWPB taken jointly

Figure 4. Some effects of parameter variations on predicted speeds

NRMM. The procedure assumes that all curve-fits have been identified and that the original field data from which they were derived have been re-examined such that standard errors of estimate can now be assigned to the curve-fits. See Figure 5 for two examples. Each standard error of estimate is viewed as the standard deviation of a zero-mean Gaussian error probability density assigned to its particular curve-fit. Every value taken from that curve-fit during the normal running of NRMM is assigned an additive error taken from its associated error probability density. For the purpose of the 3-point extremum analysis used in the screening process, the inherent variability is set aside and the 3 points applicable to each curve-fit are the nominal value, and values that are plus and minus 14 percent of the nominal. This percentage was arrived at in preliminary fashion by numerical experimentation and appears to be effective in representing effects of a standard Gaussian algorithm error. Refinement is certainly possible.

Quantification of Sensitivity

24. Quantification of sensitivity is accomplished by formulating a rank indicator specific to a given vehicle, terrain unit, and parameter. A nominal predicted speed is computed using the nominal parameter taken from the data-set. Maximum and minimum speeds are then computed corresponding to values of the parameter that are greater and lesser than the nominal by 10 percent, or, in the case of curve-fit errors, greater or lesser than the regression value by 14 percent. These percentages (but not their relative values) are completely arbitrary. In most cases, the maximum speed will correspond to the maximum value of the parameter and the minimum speed to the minimum value of the parameter. For example, larger values of speed can result from larger values of soil strength. In the remaining cases, the relationship will be reversed. For example, larger values of speed can result from smaller values of slope. In any event, extreme values of parameter and speed are assumed to correspond. In reality it is possible for NRMM to deliver maximum or minimum speeds that do not correspond to the range limits of the parameter, but such occurrences have been rare.



SOIL TYPE 2 (USCS CH)
NO CHAINS
STANDARD DEVIATION = 0.13

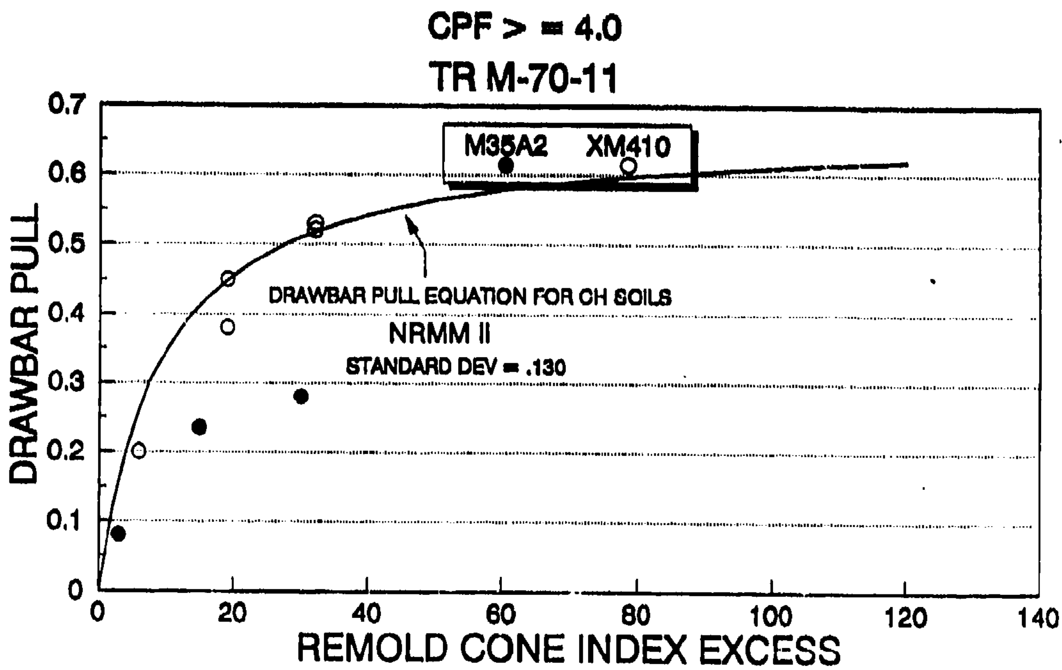


Figure 5. Examples of NRMM curve-fits

25. The rank indicator is defined as follows.

$$I_R = (V_{max} - V_{min})/V_{nom} \tag{1}$$

where I_R is the rank indicator for the specific vehicle, the specific terrain unit, and the specific parameter subject to variation; V_{max} is the maximum speed; V_{min} is the minimum speed; V_{nom} is the nominal speed; and the magnitude of I_R is constrained to the interval $0.0 < I_R < 2.0$.

26. The arithmetic average of the rank indicators over all terrain units on the map for the given vehicle is taken as the rank or sensitivity of the parameter.

27. The rank indicator is formulated to express the idea that greater speed differences between maximum and minimum constitute greater sensitivity of NRMM to the parameter of interest in the given vehicle/terrain setting. Division by the nominal speed renders the rank indicator dimensionless and also implements the engineering intuition that as nominal speeds increase greater speed differences are appropriate to the same sensitivity. For example, a speed difference of 2 mph* at a nominal speed of 10 mph and a speed difference of 12 mph at a nominal speed of 60 mph express the same sensitivity to the variation of a given parameter.

28. Experimentation with this formula involving many terrains, vehicles, and parameters revealed that most values of the rank indicator fall within the range 0 to 0.8, and that some cases occur as high as 1.8. The formula, of course, has the potential for infinite values when the nominal speed is zero and variation produces a finite speed range. This case has, by definition, been assigned the value of 2. Very rare occurrences when the rank indicator exceeds 2 with non-zero nominal speeds have also been constrained to a maximum value of 2. These occur when large speed variations are encountered with very small nominal speeds. The case of zero nominal speed and zero speed difference has been assigned the value of 0.

---

* A table of factors for converting non-SI to SI (metric) units of measurement is presented on page 4.

The Screening Process

29. Quantitative comparisons of the ranks of many parameters lead naturally to a screening process. For the given vehicle/terrain setting, variation of parameters in sequence produces a sequence of quantitative ranks; small values indicate low sensitivity and large values indicate high sensitivity. By selecting a certain threshold value, all parameters whose ranks fall below the threshold need be considered no further. Rankings change with the vehicles and terrains considered. Numerical experiments based on these ideas have used a threshold of 20 percent of the maximum rank among those for the group of parameters under consideration. In other words, for any combination of vehicle, terrain, and scenario, the quantitative ranks of the parameters studied are determined and the largest value identified. A threshold equal to 20 percent of that value is computed and no further consideration is given to those parameters whose ranks fall below the threshold. In the numerical experiments, from 32 to 84 percent of the parameters studied were eliminated from further consideration. The 20 percent threshold is by no means a privileged quantity. Further development of the prototype procedure being presented here will include consideration of expert opinions in refining this concept. Moreover, consideration of a global threshold rather than a map-specific one would be attractive.

The Error-Magnitude Scenario

30. Once parameters have been screened and the ones that will remain under consideration as part of the stochastic mobility forecast have been identified, the pathway to that forecast requires the formulation of an "error magnitude scenario." This is simply a list of those parameters (and curve-fits) and the actual nature of the variation to be assigned to each. During the screening process, each parameter was varied plus and minus 10 percent of nominal and each curve-fit was varied plus and minus 14 percent of its regression value; during the subsequent Monte Carlo simulation, the opportunity is provided to specify the actual variation type and ranges on an individual basis for the parameters and the actual standard deviations for the curve-fit errors. During numerical experiments, specifications of parameter and curve-fit error statistics were made on an *ad hoc* basis; subsequent refinements will

call once again on expert opinions that summarize years of data-acquisition experience to suggest a listing of appropriate error statistics applicable to each NRMM parameter and detailed refitting of regression curves to historic field data will define the appropriate error standard deviations to be specified for each curve-fit.

The Monte Carlo Speed Simulation

31. With the determination of an error-magnitude scenario for a given vehicle/terrain combination, the stage is set for the principal event on the pathway to the stochastic mobility forecast. This is the Monte Carlo analysis of predicted speeds wherein the screened parameters and curve-fits are varied jointly and independently and probability densities are determined for the speeds predicted for each terrain unit. The per-terrain-unit speed probability densities and data specifying the mission profile are the raw materials from which an analysis of mission rating speed and its range can be made. Other outputs from the Monte Carlo simulation are a listing of nominal speeds by terrain unit from which the speed map is obtained and maximum and minimum speeds by terrain unit from which the fingerprint is made. For conceptual simplicity and to bound NRMM error performance, initial work with the mission rating speeds was based on maximum and minimum terrain unit speeds rather than the speed probability densities.

Speed Profiles

32. The mission rating speed is approached through the "speed profile," a useful concept worked out early in the history of NRMM. A speed profile is specific to a given vehicle/terrain combination. NRMM is used to form a sequence of records each of which shows the area and the predicted nominal speed for individual terrain units. These records are sorted in descending order by speed thus identifying the terrain units in which vehicle performance is "best" and "worst." The sum of terrain unit areas from the first record (which represents "best") to the Nth record divided by the sum of all areas defines the fraction of map area represented by the first N records. When the sorted speeds are plotted against this fraction, the result is a speed profile based on terrain unit speeds. NRMM calls it a "speed-in-unit"

profile. See Figure 6a for an example. When the area-weighted averages of the first N speeds are plotted against the fraction, an "average speed profile" is produced, as in Figure 6b. Assuming that tactical usage of the vehicles will stress deployment over the "best" terrain units, the profiles allow quantification of what is meant by best. The plots of Figures 6a and 6b show that

> "as more terrain is used, or as the challenge level goes up, the more difficult the terrain becomes, and the average speed that the vehicle can attain over that terrain, and its average speed on that terrain and all better terrain, decreases. At some point, the challenge level is so high that the vehicle encounters very difficult terrain, and NOGO's occur, shown as 0.0 mph." (Unger 1988)

33. Stochastic orientation of NRMM requires the development of stochastic speed profiles based not only on the nominal predicted speeds but also on the minimum and maximum predicted speeds. The very same computational procedures are used, beginning with records that contain nominal, minimum, and maximum speeds, and result in plots like those shown in Figures 6c and d. In effect, range limits that bound NRMM error performance are placed on the traditional speed profiles.

34. The computational procedures are summarized as follows. Let f_j be the fraction of the first j *sorted* terrain unit areas a_i and N, the total number of areas on the map.

$$f_j = \frac{\sum_1^j a_i}{\sum_1^N a_i} \tag{2}$$

35. The stochastic in-unit speed profile plots the *sorted* terrain unit nominal, minimum, and maximum predicted speeds $v_{j,nom}$, $v_{j,min}$, and $v_{j,max}$ against f_j. (Remember that sorting is based on the nominal speeds). The stochastic average-speed profile plots the following quantities against f_j :

$$\overline{V}_{j,nom} = \frac{\sum_{1}^{j} a_i}{\sum_{1}^{j} \frac{a_i}{V_{i,nom}}} \quad (3)$$

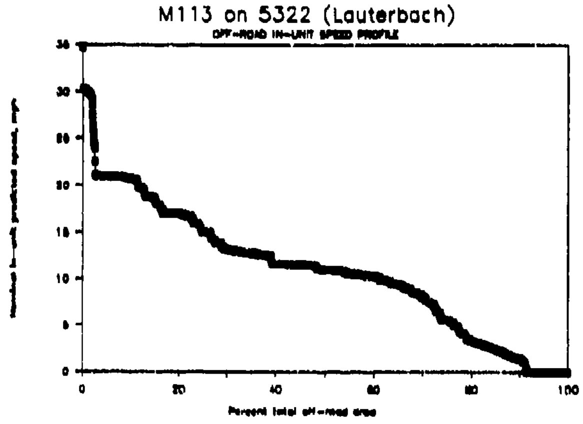
$$\overline{V}_{j,min} = \frac{\sum_{1}^{j} a_i}{\sum_{1}^{j} \frac{a_i}{V_{i,min}}} \quad (4)$$

$$\overline{V}_{j,max} = \frac{\sum_{1}^{j} a_i}{\sum_{1}^{j} \frac{a_i}{V_{i,max}}} \quad (5)$$

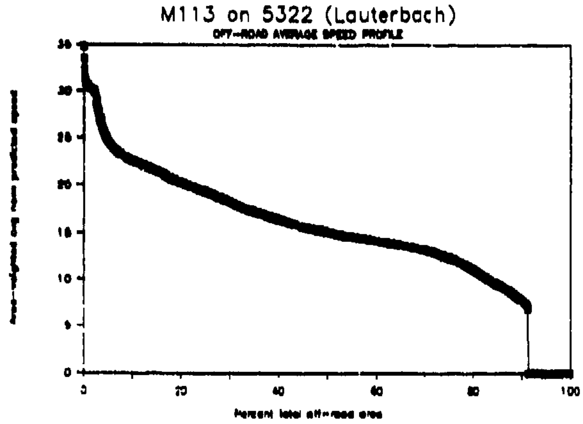
36. Similar speed profiles are defined for mobility forecasts that pertain to on-road performance rather than off-road. The computational approach is unchanged except that terrain-unit areas are replaced by road-unit lengths.

Mission-Rating Speeds

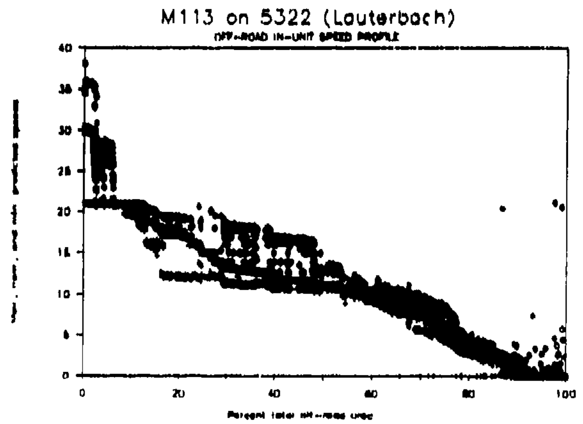
37. Speed profiles form the basis for the calculation of the mission rating speeds. A mission rating speed is, as mentioned earlier, a one-number measure of vehicle performance that factors in the parameters of a tactical mission defined on a terrain map. The parameters are (a) percentages of total operating distance spent on-road and off-road and (b) percentages of the best terrain and road units so occupied. Thus, a mission might be characterized as 80 percent on-road in the 75 percent best road units and 20 percent off-road in the best 10 percent areal units, and the mission rating speed would convey an overall speed for these percentages by entering the on-road speed profile at 75 percent and the off-road profile at 10 percent and appropriately combining the two speeds read from the profiles. There are several ways to make the combination depending on the depth of resolution desired. For example, are



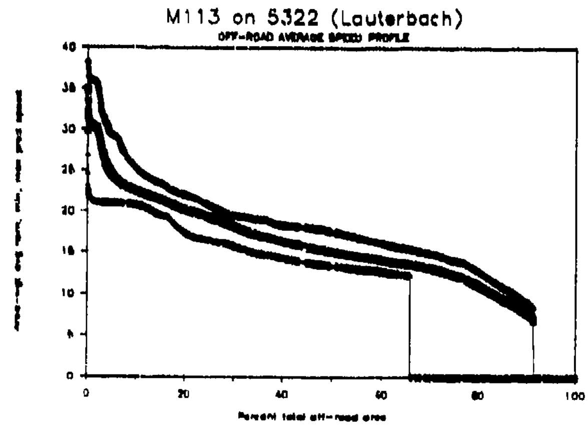
a. **Deterministic speed-in-unit**



b. **Deterministic average speed**



c. Stochastic speed-in-unit



d. Stochastic average speed

Figure 6. Speed profiles

roads to be considered separately as primary, secondary, and so forth; are predefined "tactical mobility levels" to be considered; are time penalties for crossing linear features to be considered? See Robinson, Smith, and Reaves (1987) for insights and typical applications. For the present, this combination is being made according to the following especially simple formula. If P is the off-road operations percentage, C is the percentage of terrains negotiated while operating off-road, R is the percentage of roads negotiated while operating on-road, and V_C and V_R are the corresponding speeds from the off-road and on-road profiles, then the mission rating speed V_{MR} is

$$V_{MR} = \frac{100}{\frac{P}{V_C} + \frac{100-P}{V_R}} \tag{6}$$

38. NRMM applications make use only of the average speed profiles to compute mission rating speeds and leave the in-unit profiles for other purposes. Accordingly, stochastic mission rating speeds are derived from the stochastic average speed profiles by evaluating the equation three times: first using the nominal values of V_C and V_R, and then the minimum and maximum values. These define $V_{MR,nom}$, $V_{MR,min}$, and $V_{MR,max}$. The range in the mission rating speeds so computed from minimum to maximum, together with the nominal value, constitutes a one-number descriptor of NRMM error performance for the given terrain/vehicle combination and the given mission. A smaller range suggests improved error performance.

PART III: AN ILLUSTRATION OF THE STOCHASTIC MOBILITY FORECAST

39. It will be helpful to fix these ideas by presenting a robust and comprehensive example of the prototype stochastic forecasting procedure. Because the orientation of the procedure is project-specific, several vehicles and several terrains are considered. The range of outcomes as different vehicles are studied on a common terrain and as different terrains are studied with a common vehicle will suggest how the error performance of NRMM can be very different from project to project.

Vehicles

40. Four vehicles were considered. It is quite reasonable to say that a certain vehicle represents a class of vehicles and to infer attributes of the class from those of the representative. Thus the illustration deals with a light wheeled vehicle, a heavy wheeled vehicle, a light tracked vehicle, and a heavy tracked vehicle as detailed in Table 1 and illustrated in Figure 7.

Table 1

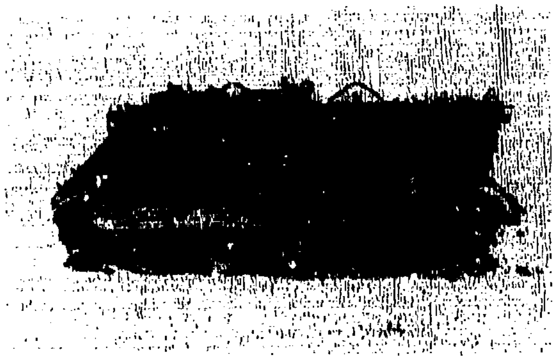
Representative Vehicles

Attributes	Vehicle
Wheeled, light	M998 (HMMWV)
Wheeled, heavy	M977 (HEMTT)
Tracked, light	M113 (APC)
Tracked, heavy	M1 (MBT)

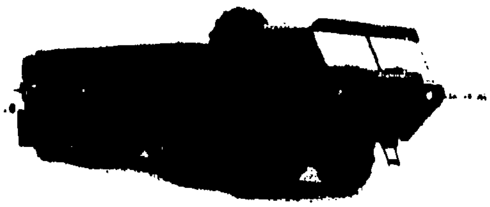
Terrains

41. With respect to terrains, however, it is not reasonable to deal with representatives and classes. There are too many exceptions. Thus it is a matter of gaining experience with terrain after terrain. From WES's extensive library of terrain datasets, four were studied to develop skills in handling larger and larger datasets. They are detailed in Table 2. The datasets represent areas of 25 to 100 sq km of terrain. Figure 8 shows the relationship of quadrangle boundaries to political borders.

a. M988 HMMWV



b. M113 APC



c. M977 HEMTT

d. M1 Main Battle Tank

Figure 7. The representative vehicles used in procedure development

Table 2

Specific Terrains

Dataset Name	No. of Units	Location	Attributes
2726.A90	866	FRG-Winsen	Off-road; plains
5520.R90	917	FRG-Schotten	On-road; highlands
3254IV.A90	1879	Jordan-Mafraq	Off-road; desert
5532.A90	2707	FRG-Lauterbach	Off-road; highlands

42. Stochastic mobility forecasts were made for all vehicles on each terrain. A common scenario was used corresponding to dry soil conditions in October. In addition, the simulations involving the Lauterbach quad were repeated with a scenario corresponding to wet, slippery conditions in June.

Parameters Varied

43. Because of the prototype nature of the forecasts, speed predictions were undertaken in modest amounts as practical details of the procedure were worked out. The stochastic form of NRMM used in the forecasts (called NRMM III) allowed access to 92 parameters for variation. Of these, 66 pertained to the attributes of the vehicle, 17 to the terrain units, and 9 to the scenario. In addition, two major algorithms based on regression equations had error terms installed. It was out of the question (at the time) to deal with variability in all of these quantities. Instead, to begin the development procedure, judgments were made to select a few parameters likely to be important in terms of error performance. Vehicle, terrain, and scenario parameters were all represented, together with regression equations, in the selection which is detailed in Table 3.

Sensitivities, Screenings, and Fingerprints for a Sub-example

44. The first step in studying NRMM error performance for a given terrain and given vehicle was to rank these parameters and screen out those whose sensitivities were relatively low. For the three off-road terrains studied,

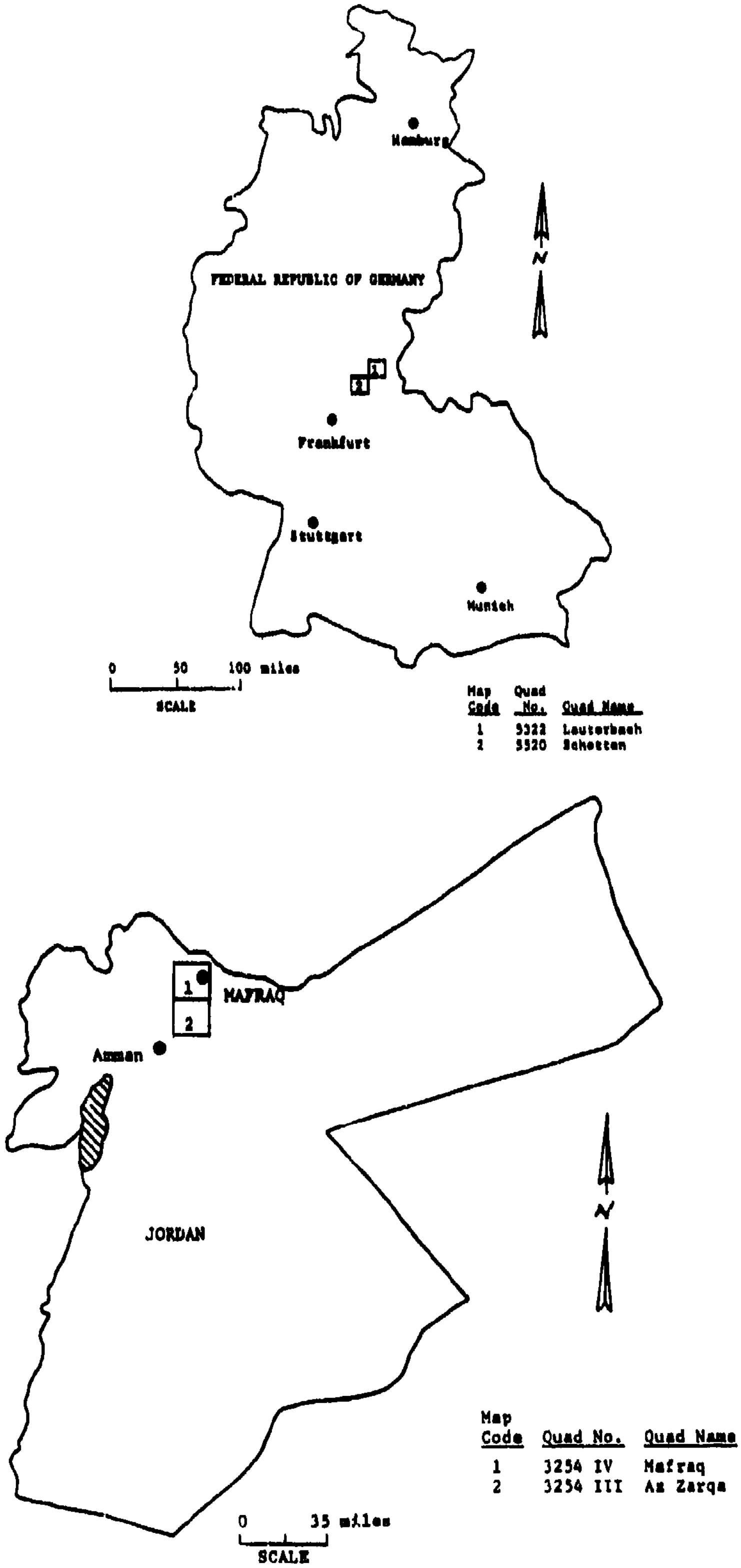


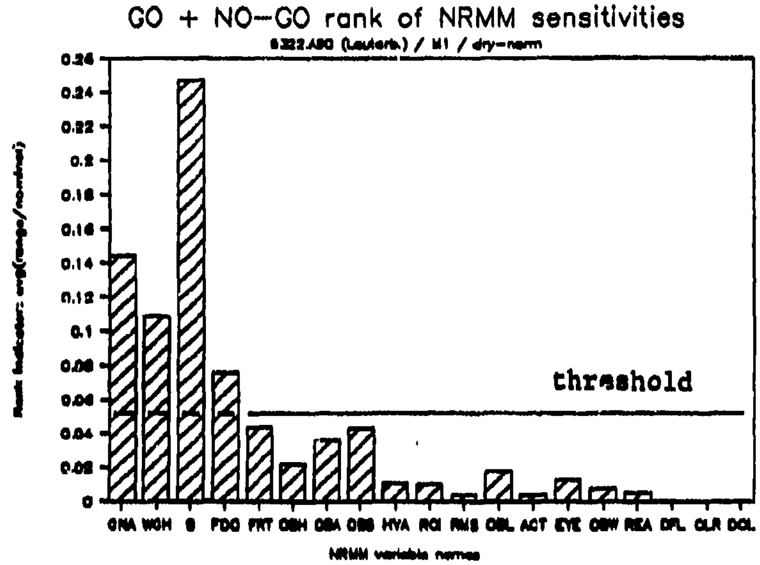
Figure 8. Locations of terrains used in procedure development

Table 3

Parameters Used in Prototype Procedure

			Acronym
Vehicle:			
	Weight on each vehicle assembly		WGH
	Minimum ground clearance for each assembly		CLR
	Tire deflection for each assembly		DFL
	Driver eye height above the ground		EYE
	RMS roughness component of ride vs speed curve		RMS
	Speed component of ride vs speed curve		HVA
Terrain:	Off-road:	On-road:	
	Soil strength	Soil strength	RCI
	Terrain slope	Terrain slope	GRA
	Obstacle approach angle		OBA
	Obstacle height		OBH
	Obstacle length		OBL
	Obstacle spacing		OBS
	Obstacle width		OBW
	Stem spacing by size class		S
	Ground roughness	Ground roughness	ACT
		Recognition distance	RDA
		Radius of curvature	RAD
		Superelevation	ELE
Scenario:			
	Driver reaction time for braking		REA
	Maximum deceleration driver will accept		DCL
Regressions:			
	Drawbar pull coefficient versus excess rating cone index		FDO
	Motion resistance coefficient versus excess rating cone index		FRT

19 parameters were considered; for the on-road terrain, 16. As presented above, the 3-point extremum analysis was used to compute numerical values for the ranks. As a sub-example, in Figure 9 are seen the ranks of the 19 variables for the M1 traversing the Lauterbach and Mafraq quads. (Note that the variable-name acronyms appear at different positions on the horizontal axes of the two plots.) The numerical values of the rank indicators represent averages over all terrain units in each quad. The relative sensitivities of the parameters were seen to be quite different between the two quads. When a sensitivity threshold was defined as 20 percent of the value of the highest



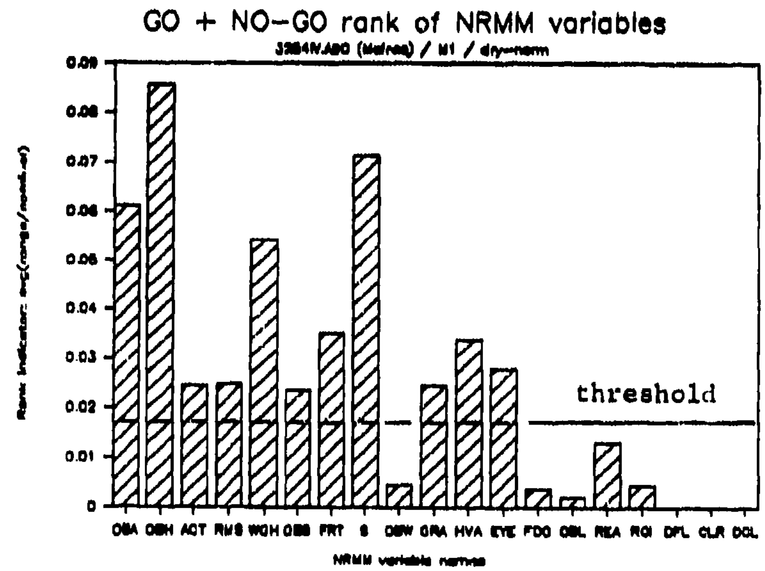


Figure 9. Ranking of parameters

rank in each quad, 4 parameters remained significant for the Lauterbach quad and 11 for Mafraq.

45. By the way, the ranking of parameters can yield some interesting insights. The rankings shown in Figure 9 are marked "GO plus NO-GO", meaning that every terrain unit was included in the ranking formula whether or not its minimum speed was zero. (Zero is clearly a NO-GO speed.) If only those terrain units are included whose minimum speeds are positive, the rankings represent GO conditions exclusively; and if minimum speeds are zero, NO-GO. Thus, selective rankings suggest the conditions under which parameters exhibit sensitivity. For example, in Figure 10 the rankings of Figure 9 are partitioned into GO and NO-GO contributions and the influence of, say, obstacle approach angle (OBA) for the M1 on Mafraq terrain (0.061) is much greater in a NO-GO context (0.052) than in a GO context (0.009). Similarly, the influence of stem spacing (S) for the M1 on Lauterbach (0.250) is almost as important in NO-GO situations (0.105) as in GO situations (0.145).

46. Continuing with the sub-example of the M1 and the Lauterbach and Mafraq quads, the Monte Carlo iterations of speed predictions were made allowing 4 and 11 parameters, respectively, to vary simultaneously and independently. These were done with 200 iterations per terrain unit. All other parameters were held constant. The statistical attributes of the random variables were drawn from Table 4 whose contents were composed for this example on a conjectural basis following extensive review of field-measurement procedures. Uniform distributions were used to suggest that errors would be found with equal likelihood anywhere within their ranges. All entries of Table 4 are subject to refinement and served only as a starting point during procedure development. Selections of attributes from Table 4 for the parameters identified as sensitive constituted the formulation of the error-magnitude scenario.

47. The Monte Carlo speed predictions resulted in 200 speeds computed for each terrain unit. These were analysed to determine their probability densities, and to determine the maximum, minimum, and nominal speeds in all terrain units. By nominal speed is meant the speed calculated when all data-set entries were taken at their nominal values and curve-fit errors were taken as zero. The maximum and minimum speeds were handed off to the procedure used to calculate speed profiles and mobility rating speeds. The maximum, minimum,

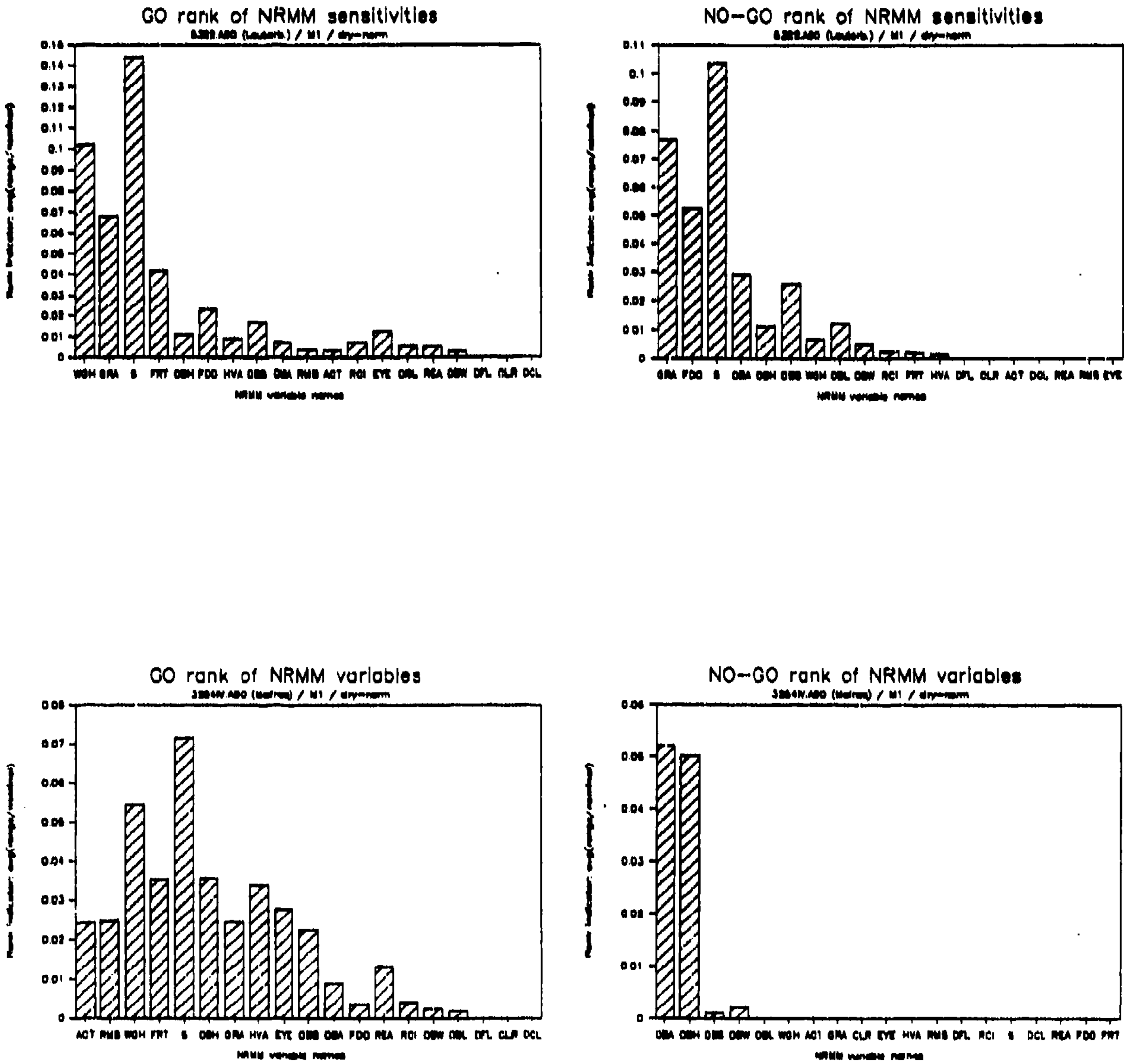


Figure 10. Elaboration of parameter ranks

Table 4

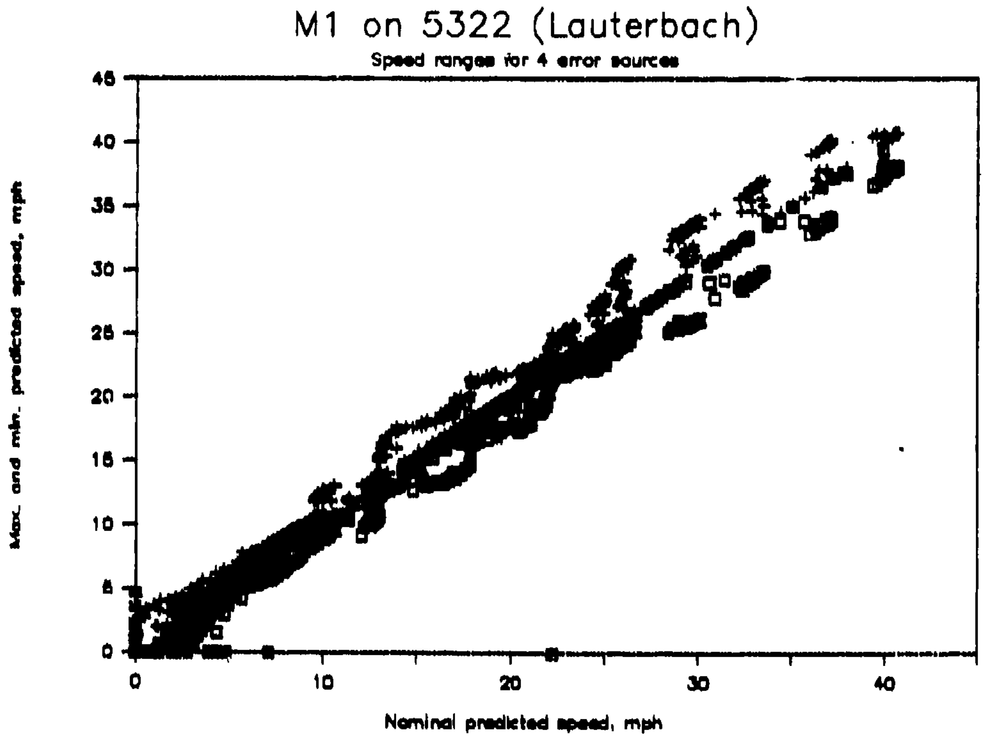
Conjectured Statistical Attributes of Parameters

Selected for the Error-Magnitude Scenario

Parameter Acronym	Distribution Type	Range
WGH	Uniform	Plus and minus 10 % of nominal
CLR	Uniform	Plus and minus 3 % of nominal
DFL	Uniform	Plus and minus 15 % of nominal
EYE	Uniform	Plus and minus 5 % of nominal
RMS	Uniform	Plus and minus 5 % of nominal
HVA	Uniform	Plus and minus 4 % of nominal
RCI	Uniform	Plus and minus 3 % of nominal
GRA	Uniform	Plus and minus 5 % of nominal
OBA	Uniform	Plus and minus 5 % of nominal
OBH	Uniform	Plus and minus 5 % of nominal
OBL	Uniform	Plus and minus 10 % of nominal
OBS	Uniform	Plus and minus 5 % of nominal
OBW	Uniform	Plus and minus 5 % of nominal
S	Uniform	Plus and minus 3 % of nominal
ACT	Uniform	Plus and minus 15 % of nominal
REA	Uniform	Plus and minus 15 % of nominal
DCL	Uniform	Plus and minus 20 % of nominal
FDO	Gaussian	Standard deviation 5 % of regression value
FRT	Gaussian	Standard deviation 5 % of regression value
RDA	Uniform	Plus and minus 5 % of nominal
RAD	Uniform	Plus and minus 5 % of nominal
ELE	Uniform	Plus and minus 5 % of nominal

and nominal speeds were used to make the "fingerprints." The probability densities were available to resolve fine details of error performance.

48. Fingerprints for the M1 on Lauterbach and Mafraq are shown in Figure 11. They are intended to convey a global view of NRMM error performance for given vehicle/terrain/scenario combinations. If there were no sources of error, maximum and minimum speeds would be identical to the nominal speeds and the plot would consist of a straight line inclined to the right at unit slope. Departures from a straight line result from the data and algorithm errors. The greater the departures, the greater the effects of the errors. The appearance of certain structural features in the fingerprints was totally unanticipated. The fingerprints show that NRMM error performance is not uniform over the range of predicted speeds but is clustered. Thus, some of the



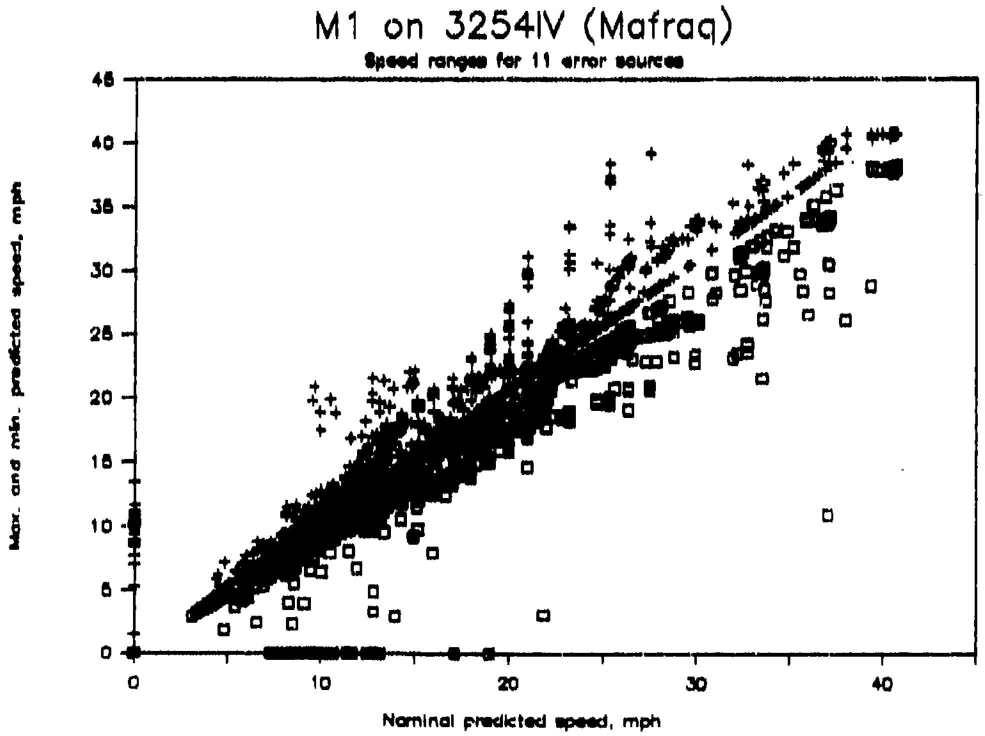


Figure 11. Example fingerprints

speed predictions in the map have little error associated with them and others have much error. The fingerprints convey this information at a glance.

Sensitivities, Screenings, and Fingerprints for the Full Example

49. Returning now to the main example, and considering the outcomes of all the vehicle/terrain combinations that were studied, Figures 12a-e show the parameter rankings and fingerprints; Table 5, the results of the parameter screenings. Computation times on a mainframe computer ranged from less than 1 hr to almost 4 hr, depending mainly on the number of terrain units and parameters. Casual review of Figures 12a-e conveys an almost bewildering impression of variety in the responses from NRMM. The parameters selected as sensitive vary markedly among vehicles and terrain maps.

Speed Profiles and Mission Rating Speeds

50. To illustrate how mission rating speeds are obtained, consider that the off-road terrain in the Lauterbach quad and the roads in the Schotten quad pertain to the same geographic area. The quads are actually adjacent and their data are quite reasonably used this way. Stochastic in-unit speed profiles for the M113 on the 2 quads are shown in Figures 13a and 13b. These turn out to be closely related to the M113 fingerprints as the same speed data are used but are combined with the terrain unit areas and road unit lengths, respectively.

51. Stochastic average speed profiles for the M113 on the two quads are shown in Figures 13c and 13d. These figures provide data for the calculation of mission rating speeds and their ranges. In Table 6 three mission profiles are hypothesized and the corresponding mission rating speed magnitudes and ranges are listed. See also Figure 14. In the third case note the intriguing possibility of optimizing a mission rating speed by selecting an appropriate combination of off- and on-road percentages. Unfortunately, there is no guarantee that a specific pathway through a quad map could be devised that would concatenate terrain and road units so that such an optimal mission rating speed could actually be achieved.

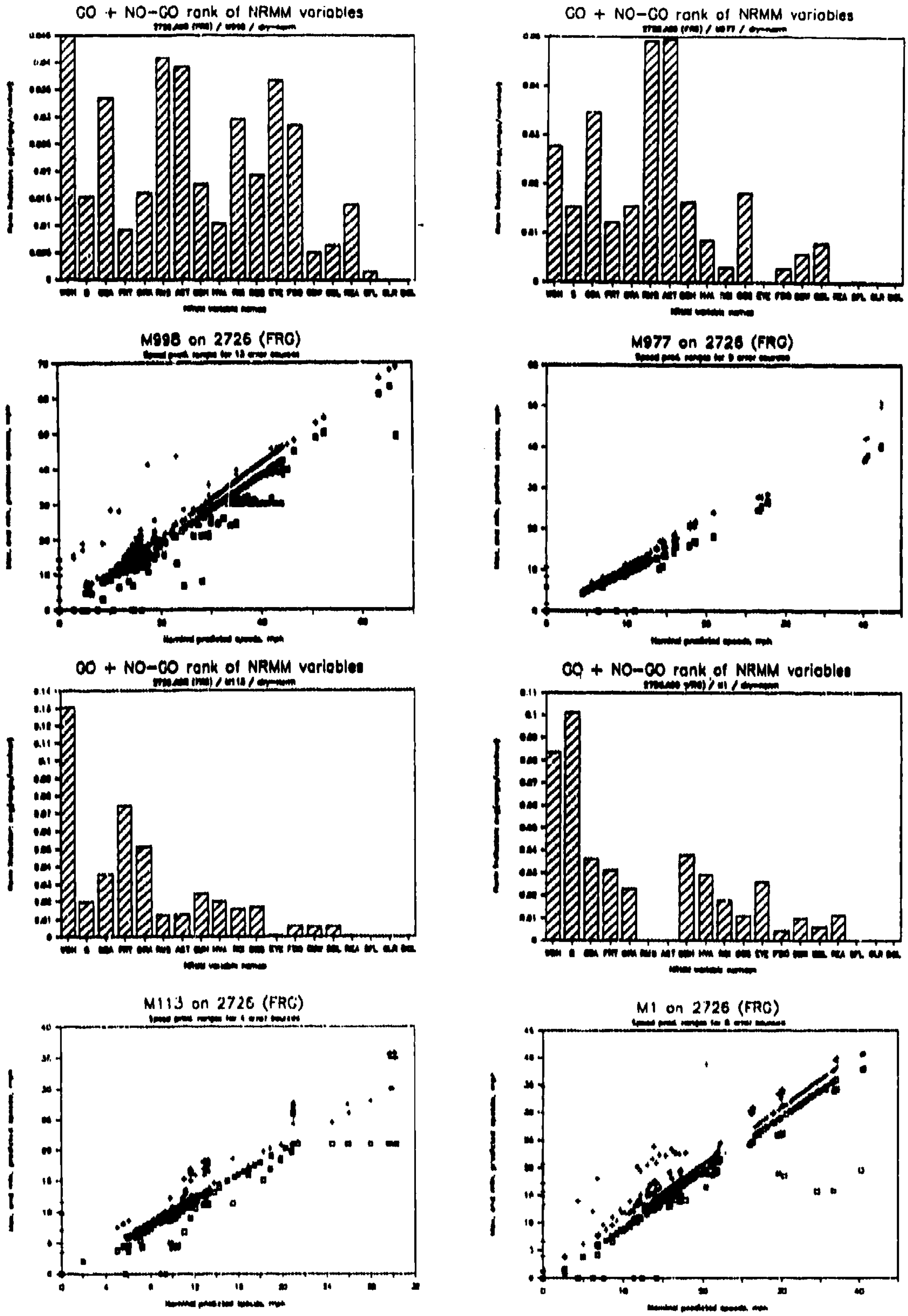


Figure 12a. Ranks and fingerprints: Winsen quad

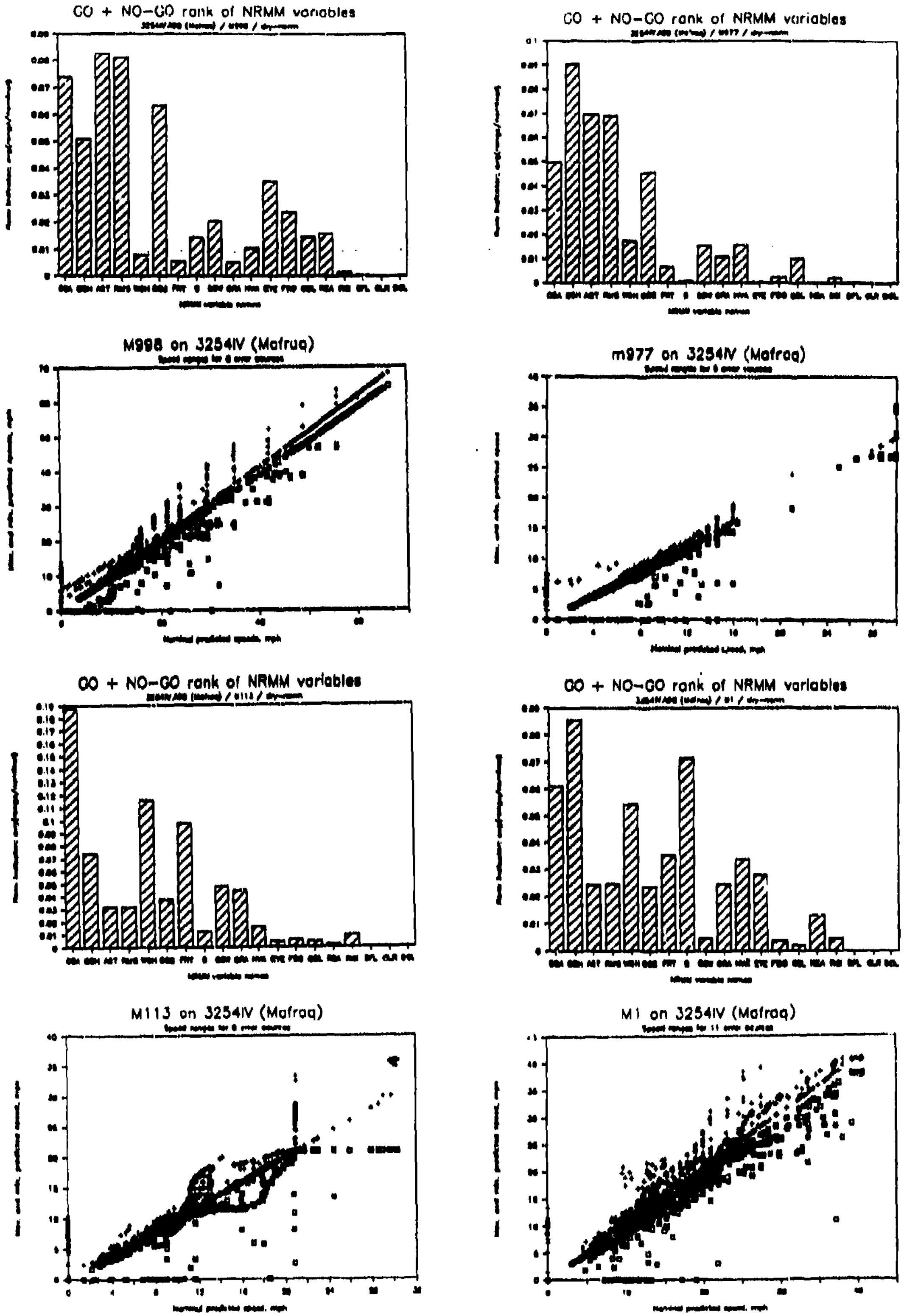


Figure 12b. Ranks and fingerprints: Mafraq quad

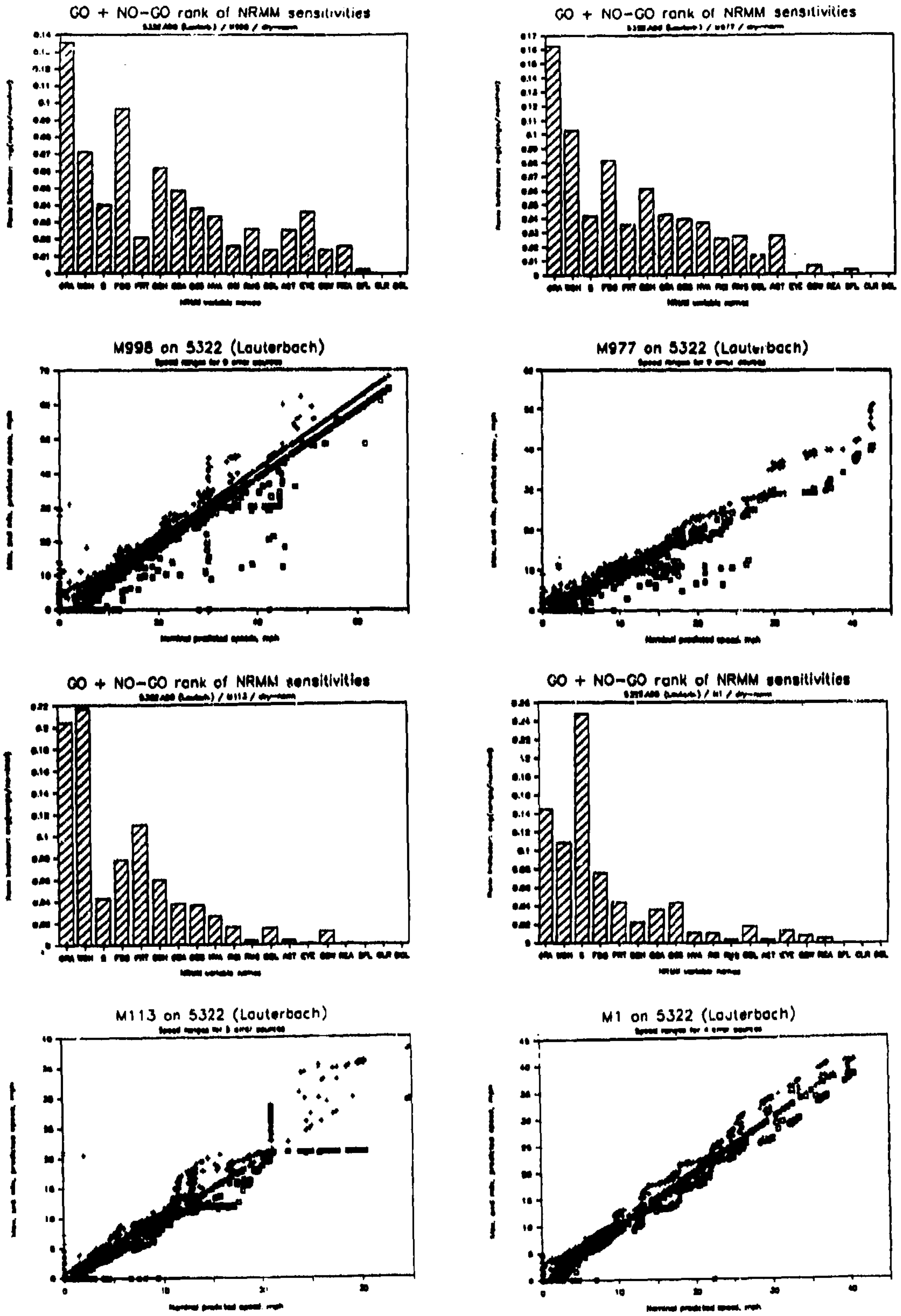


Figure 12c. Ranks and fingerprints: Lauterbach quad

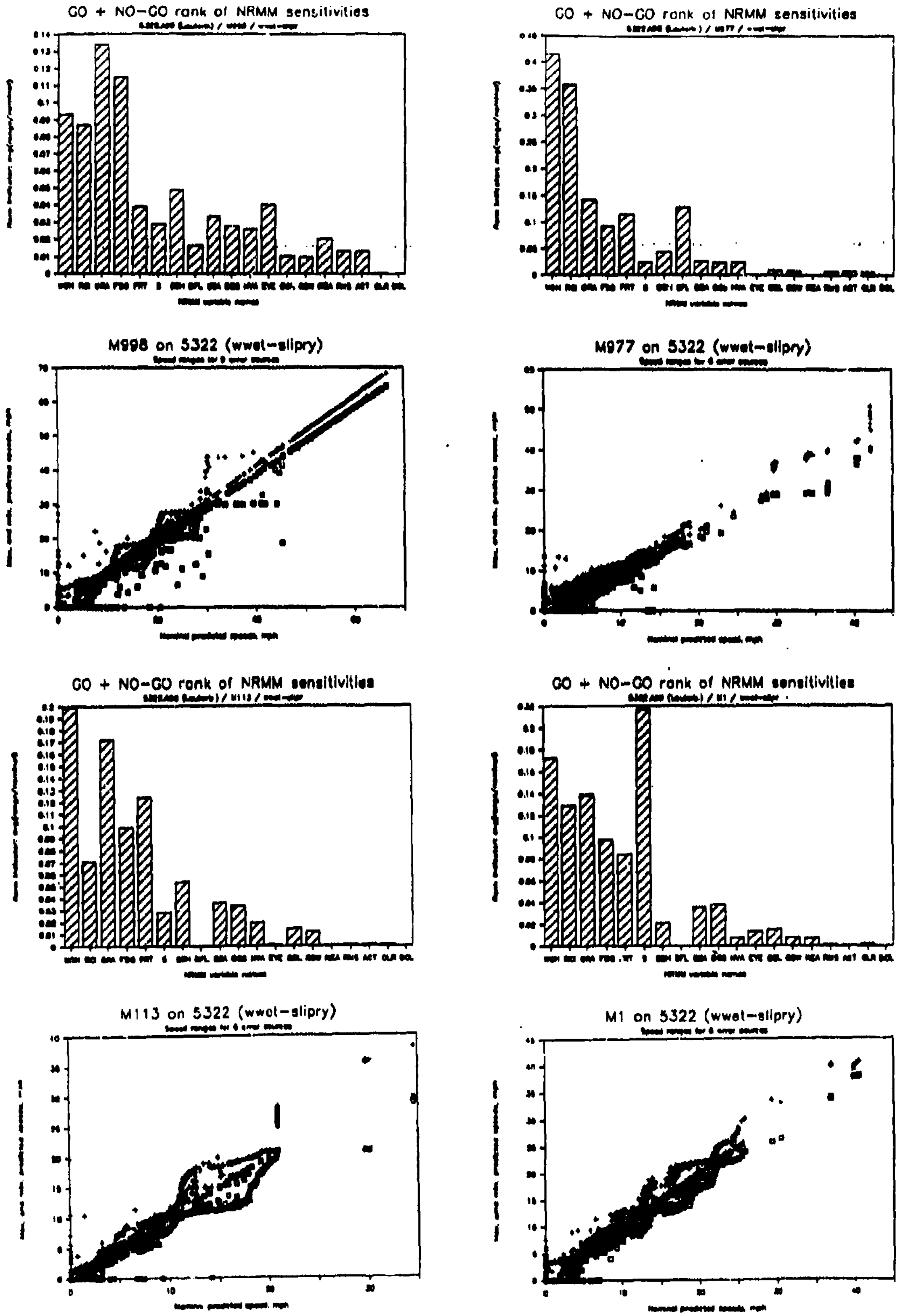


Figure 12d. Ranks and fingerprints: Lauterbach quad (wet, slippery scenario)

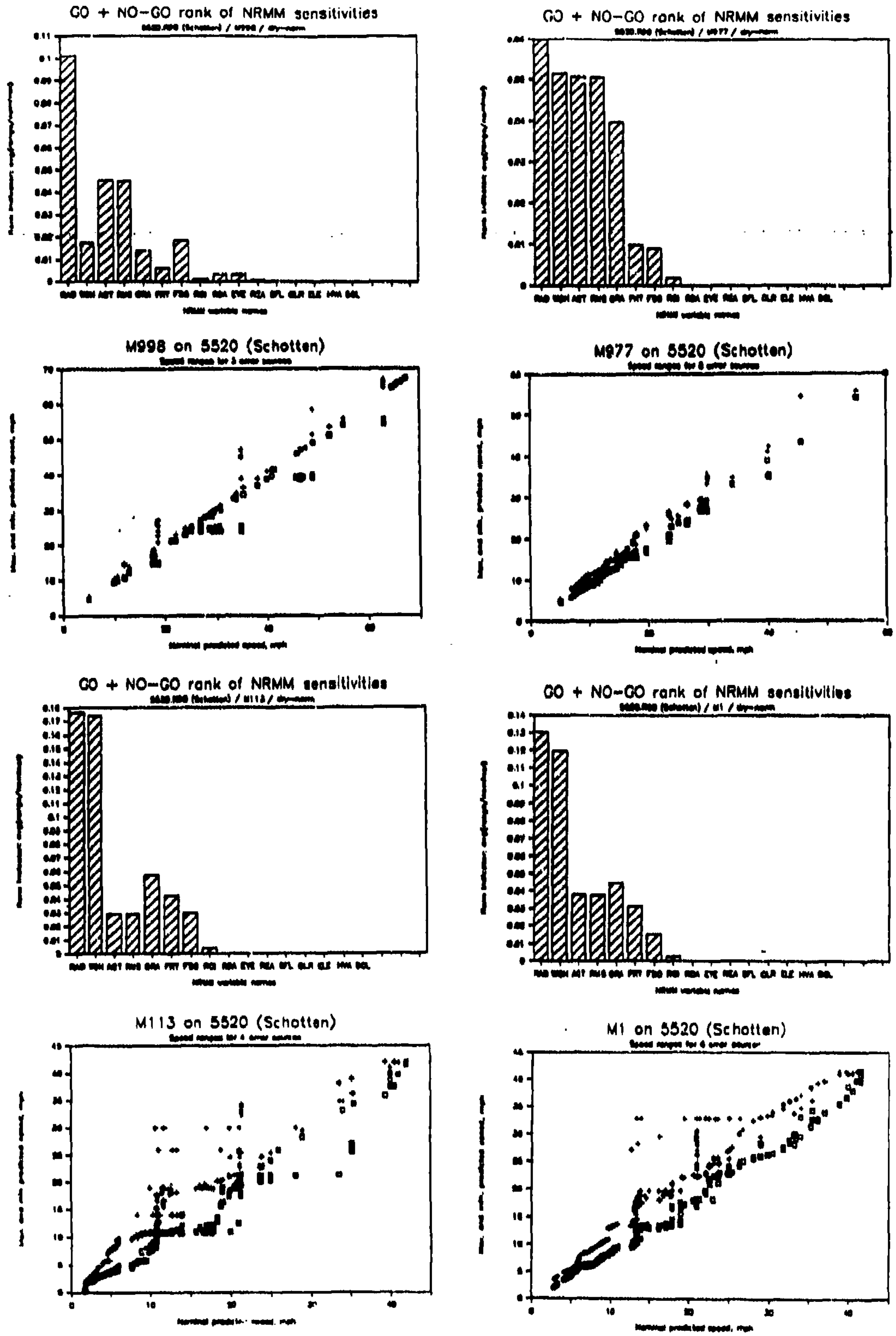


Figure 12e. Ranks and fingerprints: Schotten quad (roads)

Table 5

Identification of Sensitive Parameters

Terrains: 2726 = Winsen; 5520 = Schotten; 3254 = Mafraq; 5322 = Lauterbach

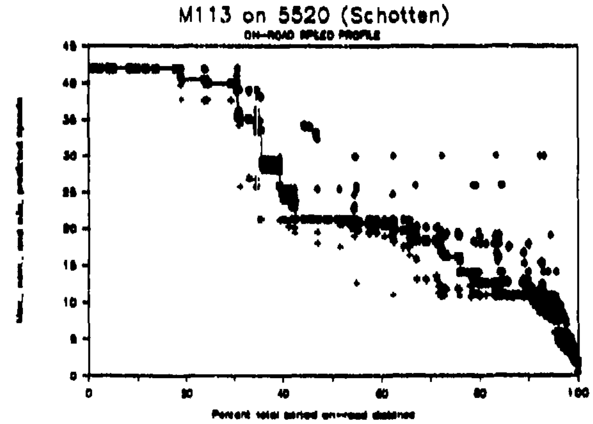
Scenarios: A = Dry, normal; B = Wet, slippery

Vehicles: M998, M977, M113, M1

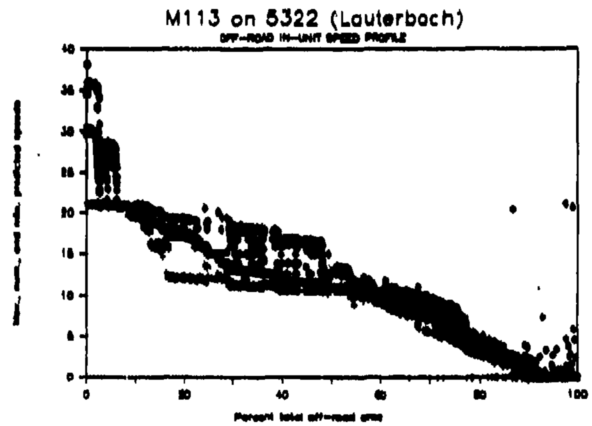
Parameter Acronyms:	Vehicle:						Terrain: Off-road									Terrain: On-road			Scenario:		Curve-fit:		
	WGH	CLR	DFL	EYE	RMS	HVA	RCI	GRA	OBA	OBH	OBL	OBS	OBW	S	ACT	RDA	RAD	ELE	RER	DCL	FDO	FRT	
Screenings:																							
2726 A M998	*			*	*	*	*	*	*	*		*		*	*				*		*		= 13
M977	*				*			*	*	*		*		*	*							*	= 9
M113	*							*	*													*	= 4
M1	*			*		*		*	*	*				*								*	= 8
3254 A M998				*	*				*	*		*	*		*							*	= 8
M977						*				*	*		*			*							= 5
M113	*							*	*	*			*									*	= 6
M1	*			*	*	*		*	*	*		*		*	*							*	= 11
5322 A M998	*			*		*		*	*	*		*		*							*		= 9
M977	*					*		*	*	*		*		*							*	*	= 9
M113	*							*		*											*	*	= 5
M1	*							*						*							*		= 4
5322 B M998	*			*			*	*	*	*				*							*	*	= 9
M977	*		*				*	*													*	*	= 6
M113	*						*	*		*											*	*	= 6
M1	*						*	*					*								*	*	= 6
5520 A M998						*										*		*					= 3
M977	*				*			*							*		*						= 5
M113	*							*									*					*	= 4
M1	*				*			*							*		*					*	= 6

Discussion of Results

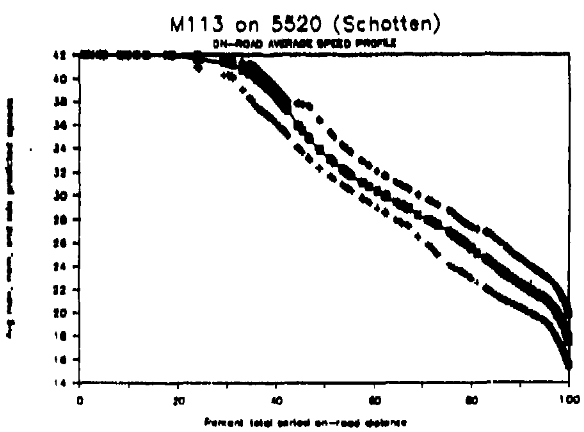
52. The tables and figures exhibited above all point to the fact that NRMM presents a variety of faces to its users. It mirrors the variety of outcomes observed in the field as significantly different vehicles encounter significantly different terrains. In this respect there is no surprise. As a spectrum of vehicles is examined against a spectrum of terrains, it is reasonable to expect that the relative importance of individual parameters will differ.



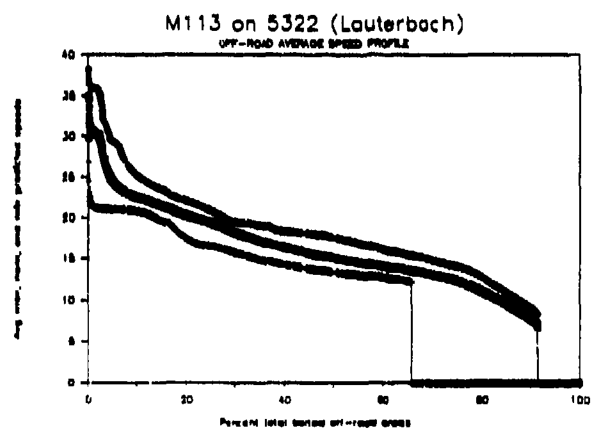
a. In-unit-speed, Schotten



b. In-unit-speed, Lauterbach



c. Average speed, Schotten



d. Average speed, Lauterbach

Figure 13. M113 stochastic speed profiles

Table 6

Mission Rating Speed Magnitudes and Ranges for the M113 on the Lauterbach and Schotten Quads Considered Together

Mission Definition				Mission Rating Speed, mph			
Percent on-road (100-P)	Percent best roads used (R)	Percent off-road (P)	Percent best terrains used (C)	Nominal	Minimum	Maximum	Range
99	10	1	80	40.8	8.1	41.8	33.7
90	10	10	80	32.8	1.0	34.3	33.3
80	10	20	80	26.9	0.5	29.0	28.5
70	10	30	80	22.8	0.3	25.2	24.9
60	10	40	80	19.7	0.3	22.2	21.9
50	10	50	80	17.4	0.2	19.9	19.7
40	10	60	80	15.6	0.2	18.0	17.8
30	10	70	80	14.1	0.1	16.4	16.3
20	10	80	80	12.9	0.1	15.1	15.0
10	10	90	80	11.9	0.1	14.0	13.9
1	10	99	80	11.1	0.1	13.1	13.0
99	50	1	50	33.1	31.5	35.4	3.9
90	50	10	50	29.8	27.9	32.4	4.5
80	50	20	50	26.9	24.8	29.6	4.8
70	50	30	50	24.5	22.2	27.3	5.1
60	50	40	50	22.4	20.2	25.2	5.0
50	50	50	50	20.7	18.5	23.5	5.0
40	50	60	50	19.3	17.0	22.0	5.0
30	50	70	50	18.0	15.8	20.7	4.9
20	50	80	50	6.9	14.8	19.5	4.7
10	50	90	50	15.9	13.8	18.4	4.6
1	50	99	50	15.1	13.1	17.6	4.5
99	99	1	1	17.6	15.7	20.1	4.4
90	90	10	10	22.7	20.5	24.7	4.2
80	80	20	20	24.3	21.3	26.0	4.7
70	70	30	30	24.0	21.8	25.7	3.9
60	60	40	40	22.5	20.4	24.4	4.0
50	50	50	50	20.7	18.5	23.5	5.0
40	40	60	60	18.7	16.9	20.9	4.0
30	30	70	70	16.3	0.1	18.7	18.6
20	20	80	80	12.9	0.1	15.1	15.0
10	10	80	90	0.1	0.1	0.1	0.0
1	1	99	99	0.1	0.1	0.1	0.0

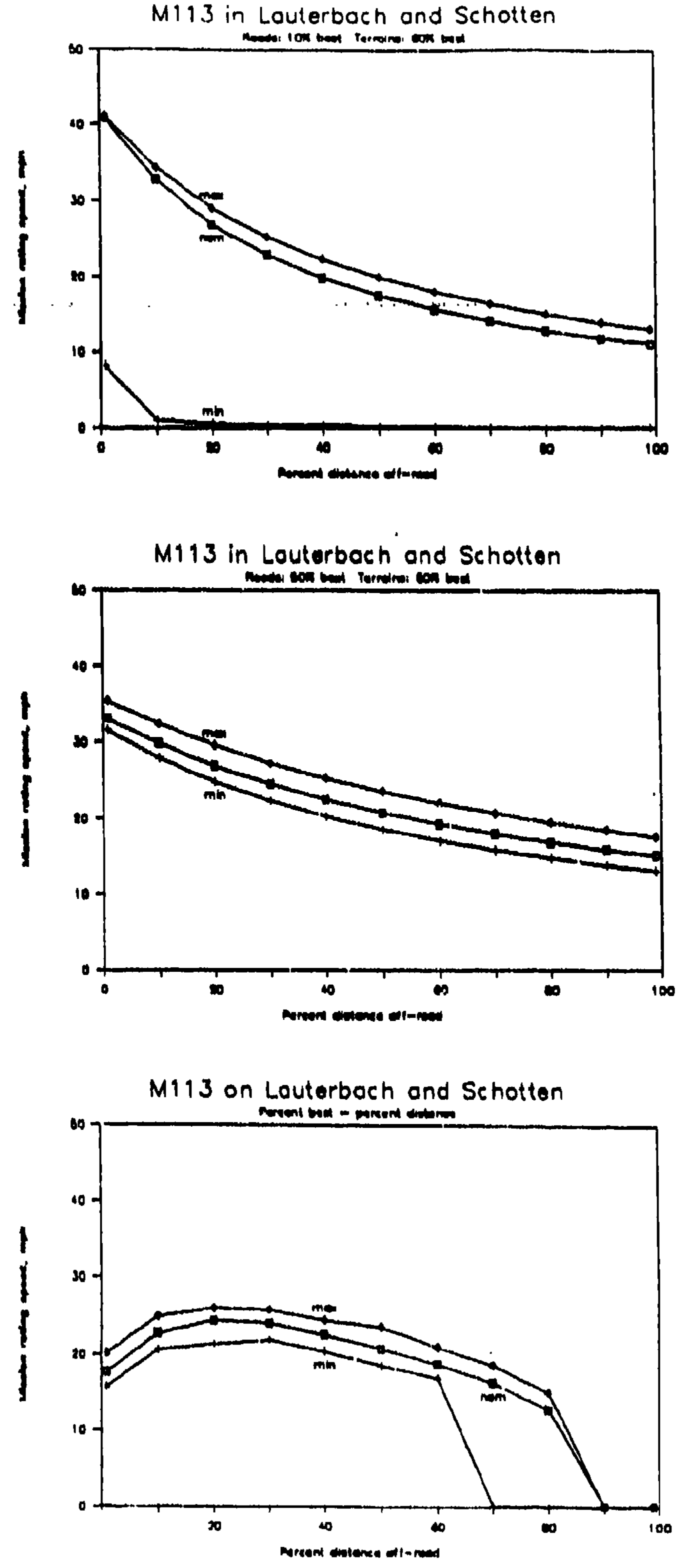


Figure 14. M113 mission rating speeds, Lauterbach/Schotten

53. But two features of these outcomes were unexpected. The first is that some parameters were never important. This does not mean that sensitivity was never seen but that the sensitivities were always small compared with those of other parameters. Vehicle minimum clearance (CLR), obstacle length (OBL), and maximum tolerable driver deceleration were never important for the vehicles and off-road terrains studied; recognition distance (RDA) and superelevation (ELE) were never important for the on-road terrain. Should these results continue to be seen as more vehicles and terrains are studied, then the need for these parameters to be included in NRMM can be questioned.

54. The second unexpected feature was the appearance of certain characteristic shapes in the fingerprints. "Bulges" and "spikes" are seen to abound. Examination of all the fingerprints for a given vehicle reveals that these shapes are characteristic of the vehicle and are seen with greater or lesser clarity from terrain to terrain. The origins of these features are unknown at present. The fingerprints are the most important component of the stochastic mobility forecasting procedure. They reveal how NRMM's error performance is distributed over the range of its predicted speeds on a project-specific basis.

55. It is also important to note that the thrust of procedures developed and illustrated above to change NRMM's orientation from deterministic to stochastic result in worst-case estimates of errors. A number of reasons contribute to this outcome. First, the main Monte Carlo speed simulations, while inherently capable of determining the probability densities of the predicted speeds in every terrain or road unit, were required to pass only the minimum and maximum speeds in each unit to the fingerprints. Thus the fingerprints mark the outermost boundaries of the errors in the speed calculations. Second, the speed profiles also use minimum and maximum speeds to define ranges of error, and these are passed to the mission rating speeds. Actual errors can be expected to fall within the limits expressed by the foregoing products. This approach to the presentation of error performance is, therefore, quite conservative and is expected to be welcomed by users of NRMM as initially preferable to an approach that cites an error statistic, such as standard deviation, that is often exceeded in individual cases.

56. It should be remarked that worst-case error estimates can be expected to exceed actual errors and that cases will arise where higher resolution is needed in the error estimates. This can be accomplished by

developing the speed profiles and mission rating speeds in a Monte Carlo context using the terrain-unit speed probability densities as input data. Speed profiles are recalculated many times using speeds taken as variates from these densities; then probability densities become associated with each areal fraction in the speed profile. Similarly, the mission rating speeds are recalculated many times to develop a probability density.

57. Some exploratory Monte Carlo simulations were conducted to pursue these ideas. A certain amount of correlation was observed among terrain-unit speeds that countered the assumption of independence. However, the resulting speed profiles and mission rating speeds were distributed within the ranges obtained from the worst-case procedures discussed above. This pathway invites further exploration.

Continuation

58. The purpose of the foregoing example has been to convey a global view of the procedures that adapt NRMM to a stochastic orientation. Many judgments and conjectures were identified. Prototypic procedural elements should now be supplanted by refinements worked out while enlarging an experience base. An extensive library of vehicle and terrain datasets is available. These datasets should be methodically analyzed in stochastic contexts. None of the procedural elements should be regarded as unexpendable or unalterable; growing experience with more vehicles and terrains could result in significant revisions.

59. The example focused on 17 parameters and 2 algorithms; there are many more. Economies of effort must be sought so that a potentially five- or six-fold increase in the numbers of parameters and algorithms will not create computational bottlenecks. One apparent tactic is to transfer computations to a supercomputing environment and to follow up the initial speed benefit with the restructuring of NRMM code to ensure optimum use of that environment.

60. Two procedural elements call for a consensus of expert opinions. These are the screening threshold that separates the relatively sensitive parameters from the insensitive ones and the table of statistical attributes needed to formulate the error-magnitude scenario for the project-specific NRMM Monte Carlo speed predictions. The development of this consensus, whether by individual interview or the convening of panels of experts, is an important

requirement. It may well be the case that a single screening threshold could be applicable for parameter reduction rather than thresholds pertinent to specific vehicle-terrain combinations. If this were true, more parameters would be eliminated from consideration because those sensitive in a local setting where numerical values of the ranking indicators were small could be insensitive in a global setting.

61. It would be of considerable interest to find the causes of the unusual features of the fingerprints. Do the bulges and spikes arise from recognized sources such as the highly nonlinear tractive-force-speed characteristics, or are they manifestations of logic flaws in NRMM?

62. The worst-case procedure developed above is computationally tractable, comprehended intuitively, and accurate in estimating the ranges associated with speed profiles and mission rating speeds. However, the estimation of the corresponding standard deviations would actually represent a more robust result because it would allow the quantification of confidence intervals. In addition, it would allow testing for the significance of differences in mobility performance among different vehicles, terrains, and scenarios using well-known and accepted statistical procedures.

Summary

63. Responding to the need to make NRMM suitable for use in a tactical setting, the procedures discussed above transform its present deterministic orientation into a stochastic one. The main problem being addressed is the inevitable error environment that will surround the collection of data for NRMM in battlefield situations. This problem is viewed as basically unsolvable; so the approach of this work is to live intelligently with the problem, to understand the effects of the errors, and to allow users of NRMM to state its error performance with clarity.

64. Many refinements to these procedures are possible and desirable. Some have been suggested above; others will become apparent as more stochastic forecasts are made. All should strive to make the error performance of NRMM readily apparent to its users.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

65. Based on this study, the following conclusions can be drawn:

a. Stochastic mobility forecasts can be obtained by supplementing current deterministic NRMM mobility forecasts with procedures involving determination of parameter sensitivity, ranking and screening of parameters, Monte Carlo speed simulations, development of fingerprints, and extension of stochastic mobility rating speeds.

b. The stochastic mobility forecasts developed by the prototype procedures studied here define worst-case error performance of NRMM.

c. The error performance of NRMM will be found to vary widely among terrains and vehicles, underlining the importance of the fingerprint as a means of visually grasping the clustering of errors.

Recommendations

66. The following recommendations are made:

a. Development of procedures should continue in order to allow their refinement and application to greater numbers of NRMM parameters and curve-fits, and to include expert opinions in the screening of parameters and defining of error-magnitude scenarios.

b. Application of the procedures should be made to several significant historical mobility forecasting studies to further nail down concepts and to provide experience in presenting stochastic forecasts to the NRMM user community.

c. As experience grows, developers should be alert to the possible need to resolve NRMM error performance more selectively by appealing to analysis of speed probability densities rather than ranges of speeds.

REFERENCES

Haley, P. W., Jurkat, M. P., and Brady, P. M. 1979 (Oct). "NATO Reference Mobility Model, Edition 1 User's Guide," Technical Report 12503, US Army Tank-Automotive Command, Warren, MI.

Robinson, J. H., Smith, R. P., and Reaves, A. M. 1987 (Nov). "Mobility Performance of Candidate Vehicles for the Fiber-Optic-Guided Missile Component of the Forward Air Defense System," Technical Report GL-87-26, USAE Waterways Experiment Station, Vicksburg, MS.

Unger, R. F. 1988 (Sep). "Mobility Analysis for the TRADOC Wheeled Versus Tracked Vehicle Study," Technical Report GL-88-18, USAE Waterways Experiment Station, Vicksburg, MS.

Waterways Experiment Station Cataloging-in-Publication Data

Stochastic vehicle mobility forecasts using the NATO Reference Mobility Model. Report 1, Basic concepts and procedures / by Allan Lessem ... [et al] ; prepared for Department of the Army, US Army Corps of Engineers.
51 p. : ill. ; 28 cm. — (Technical report ; GL-92-11)
Includes bibliographic references.
1. Vehicles, Military — Dynamics —Statistical methods. 2. Stochastic analysis. 3. Transportation, Military — Forecasting — Statistical methods. I. Lessem, Allan S. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-92-11.
TA7 W34 no.GL-92-11