US Army Corps of Engineers
Waterways Experiment Station

Technical Report GL-93-15
July 1993

Stochastic Vehicle Mobility Forecasts Using the NATO Reference Mobility Model

Report 2
Extension of Procedures and Application to Historic Studies

by *Allan Lessem, Richard Ahlvin*
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Report 2 of a series

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Task No. AT40-AM-011

Monitored by Geotechnical Laboratory
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

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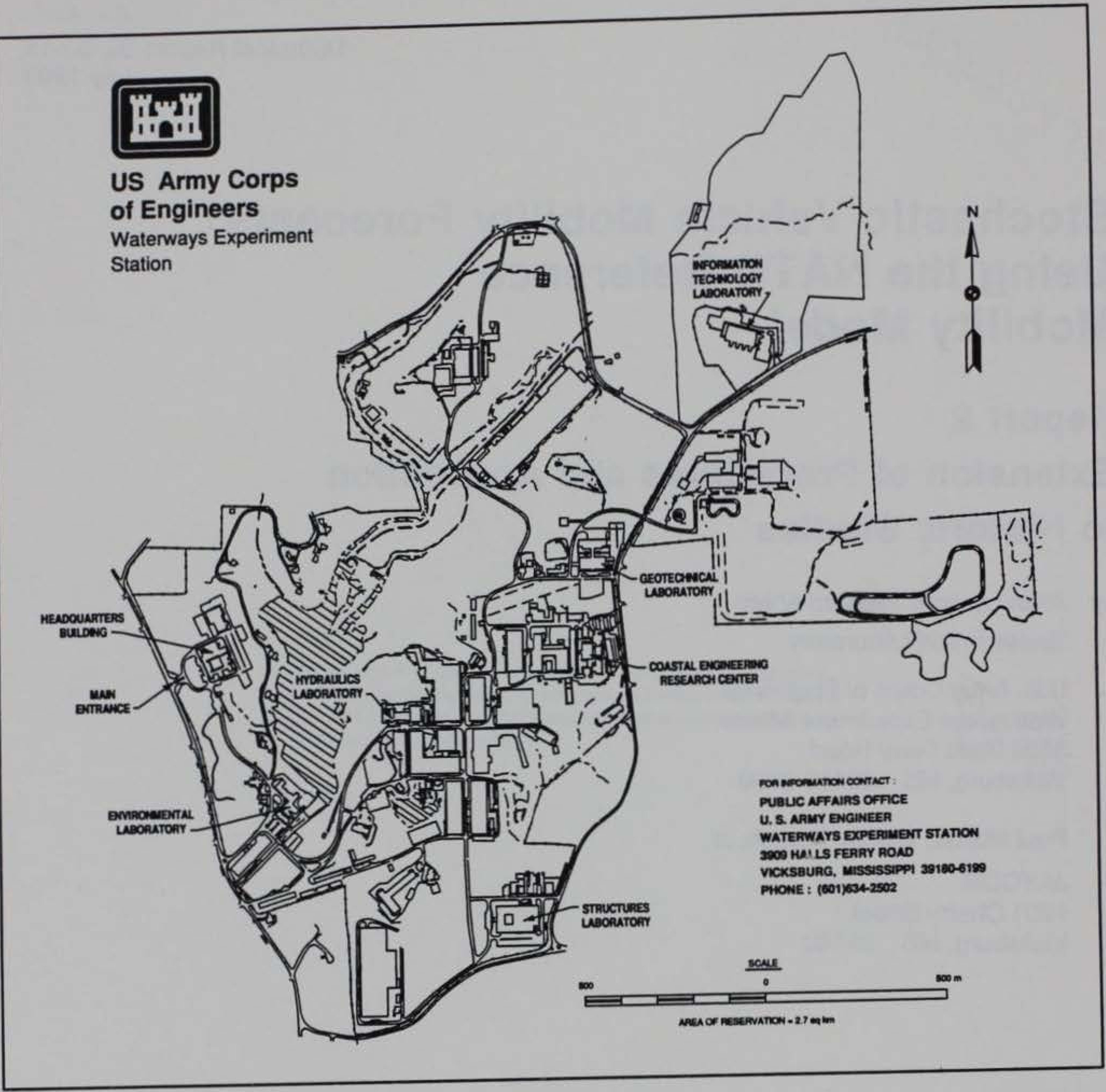


Waterways Experiment Station Cataloging-in-Publication Data

Stochastic vehicle mobility forecasts using the NATO Reference Mobility Model. Report 2, Extension of procedures and application to historic studies / by Allan Lessem ... [et al.]; prepared for U.S. Army Corps of Engineers, monitored by Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station.

170 p.: ill.; 28 cm. -- (Technical report; GL-93-15 rept. 2)

Includes bibliographical references.

1. Transportation, Military -- Forecasting -- Statistical methods. 2. Vehicles, Military -- Dynamics -- Data processing. 3. Stochastic processes. I. Lessem, Allan. 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-93-15 rept. 2.

W34 no.GL-93-15 rept.2

Contents

Preface

Personnel of the U.S. Army Engineer Waterways Experiment Station (WES) conducted this study during the period February 1992 through July 1992 under RDTE Work Unit No. AT40-AM-011 entitled "Stochastic Analysis Methodology for NRMM."

The study was conducted under the general supervision of Dr. William F. Marcuson III, Director, Geotechnical Laboratory (GL) and Mr. Newell R. Murphy, Jr., Chief, Mobility Systems Division (MSD). Dr. Allan S. Lessem devised the stochastic methodology, guided the development of software by Mr. Richard B. Ahlvin, and made one of the applications to historic studies. Dr. Paul Mlakar and Mr. William Stough, JAYCOR, contributed statistics expertise and made the other application to historic studies. The report was prepared by Dr. Lessem with the exception of Chapter 5 which was prepared by Dr. Mlakar and Mr. Stough.

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

1 Introduction

Background

This report is the second in a series intended to describe the conversion of the NATO Reference Mobility Model (NRMM) from a deterministic vehicle mobility forecasting resource to a stochastic one. The following remarks, drawn from Report 1 (Lessem, Ahlvin, Mason, and Mlakar 1992), may be helpful to the reader as an orientation.

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) and 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.

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.

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.

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.

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 is 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

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 extend the basic procedures presented in Report 1 of this series and to apply the procedures to two historic studies that influenced vehicle procurement decisions in the past. These applications are intended to attract the attention of the user community to the significance of stochastic mobility forecasts and to see whether or not the mobility assessments that influenced prior decisions would undergo substantive changes when data and model uncertainties are considered explicitly.

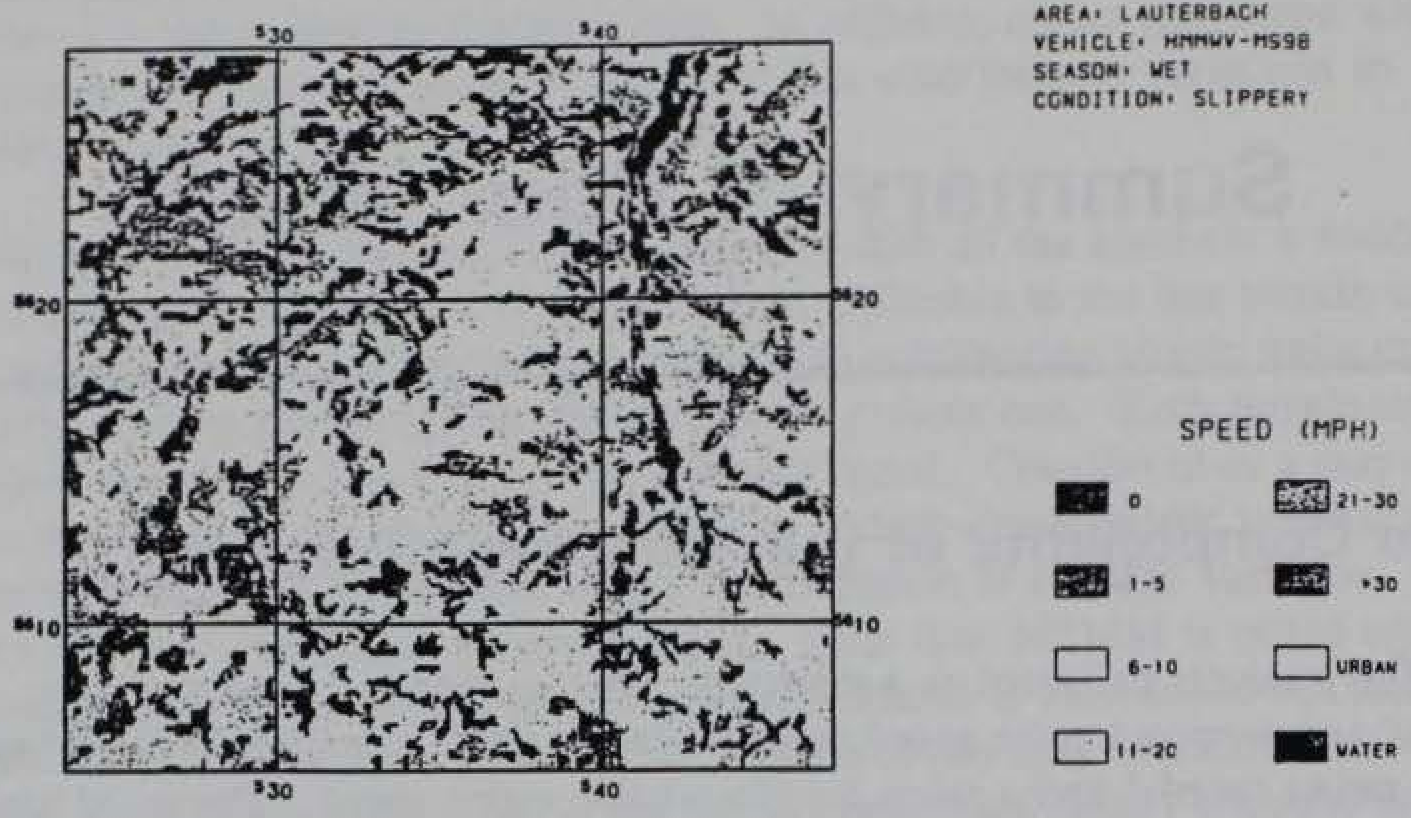
2 Summary of Prior Work

The Components of the Stochastic Forecast

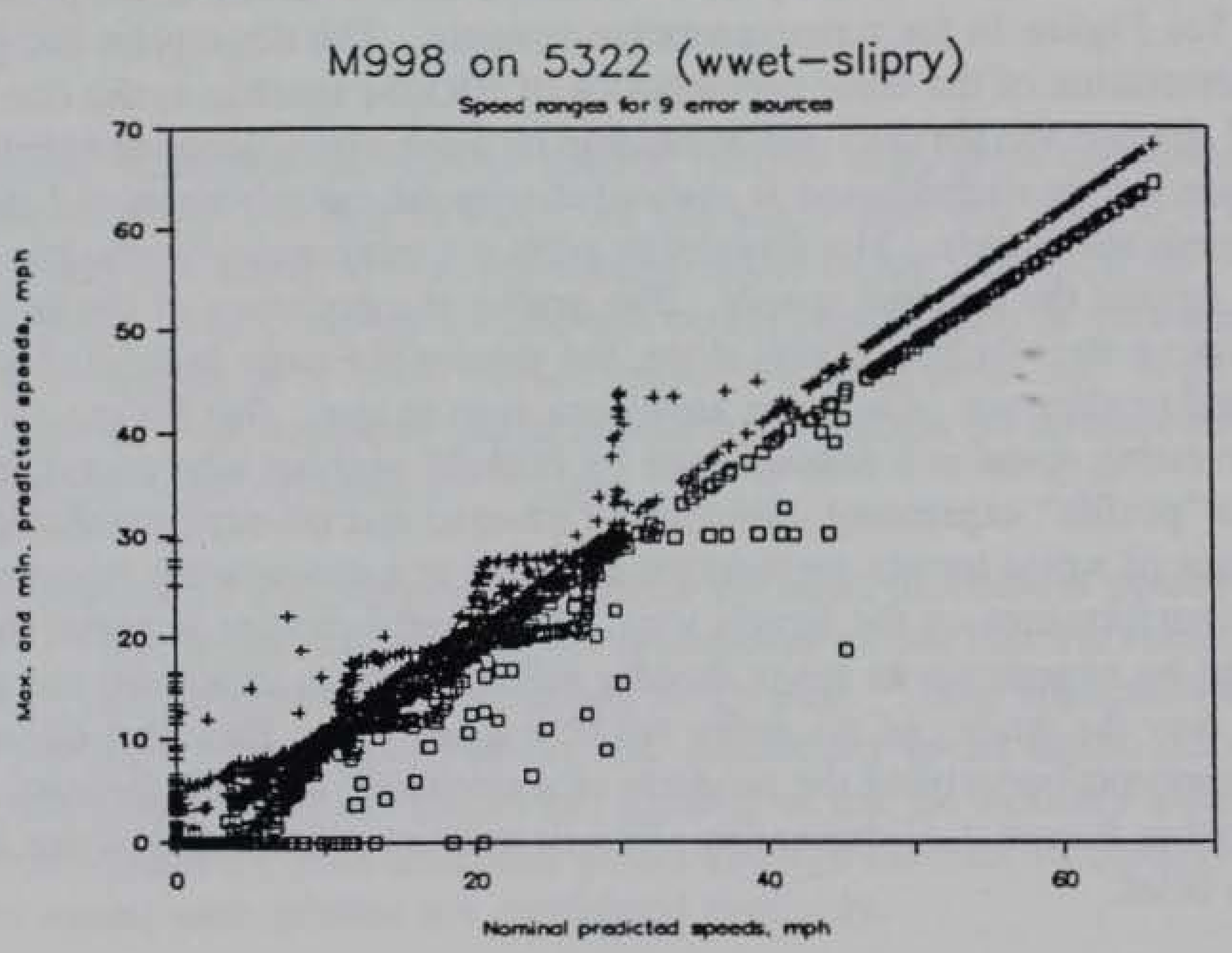
The products delivered as a stochastic mobility forecast consist of four items: an expected value speed map, a "fingerprint," an expected value "mission rating speed," and a range for the mission rating speed. The speed map is a graphical presentation of nominal predicted speeds for one vehicle operating 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 1a 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. Each nominal predicted speed is associated with related minimum and maximum predicted speeds. The fingerprint plots the minimum and maximum speeds against the nominal speeds. 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 1b. The mission rating speed is a concept used by NRMM analysts who postulate a mission "profile" expressing a mixture of on-road and off-road percentages an avoidance of worst terrain 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. Extended discussions of the concepts underlying the products of a stochastic mobility forecast are presented in Report 1 of this series. The descriptions which follow are intentionally brief.

Sensitivity Analysis

The first step in a stochastic mobility forecast is the determination of the sensitivity of NRMM to uncertainty in its numerous data elements and to variation in its experimentally derived algorithms. Sensitivity is found to vary widely among vehicles and terrains and is thus very much project-specific. In fact, it is tempting to require sensitivity to be determined on a terrain-unit-by-terrain-unit basis within a given map, but consideration of the large number of



a. The speed map



b. The fingerprint

Figure 1. The speed map and the fingerprint

units to be found in a map (1500 to 5000, typically) quickly dispels notions of such detailed resolution.

Sensitivity is determined parameter by parameter with each being treated as independent of any other. Issues of joint sensitivity were examined and found to be of secondary importance. An especially uncomplicated procedure, called "3-point extremum analysis," was devised therein to examine sensitivity based on nominal, maximum, and minimum values of each independent variable parameter. The maximum and minimum values are taken as the nominal value plus and minus 10 percent, respectively. For the experimental curve-fits extensively used in NRMM, sensitivity is expressed in terms of nominal regression values and maximum and minimum values taken as 14 percent of the nominal values, respectively.

Quantification of Sensitivity

In order to prepare the way for a screening process that discards insensitive parameters, a means for numerical specification of sensitivity was devised that is at once simple and effective. Nominal, maximum, and minimum NRMM predicted speeds corresponding, for the most part, to nominal, maximum, and minimum parameter values are combined as the ratio of maximum minus minimum speeds to the nominal. This ratio is not permitted to exceed 2. When the ratio is evaluated for a given vehicle in each terrain unit of the map and averaged over all the terrain units, it yields numerical values that vary widely among the parameters considered and discriminates quite well among sensitive and insensitive parameters. The ratio was termed a "rank indicator."

The Screening Process

Evaluation of the sensitivity of NRMM parameters in the project-specific setting of a given vehicle and a given terrain yields as many rank indicators as parameters examined. By selecting the maximum rank indicator and multiplying its value by 20 percent, a threshold value was defined below which corresponding parameters were viewed as insensitive. During all subsequent procedures in the stochastic mobility forecast, sensitive parameters are treated as random variables and insensitive parameters are treated as constants.

The Error-Magnitude Scenario

An error magnitude scenario is a list of the sensitive 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.

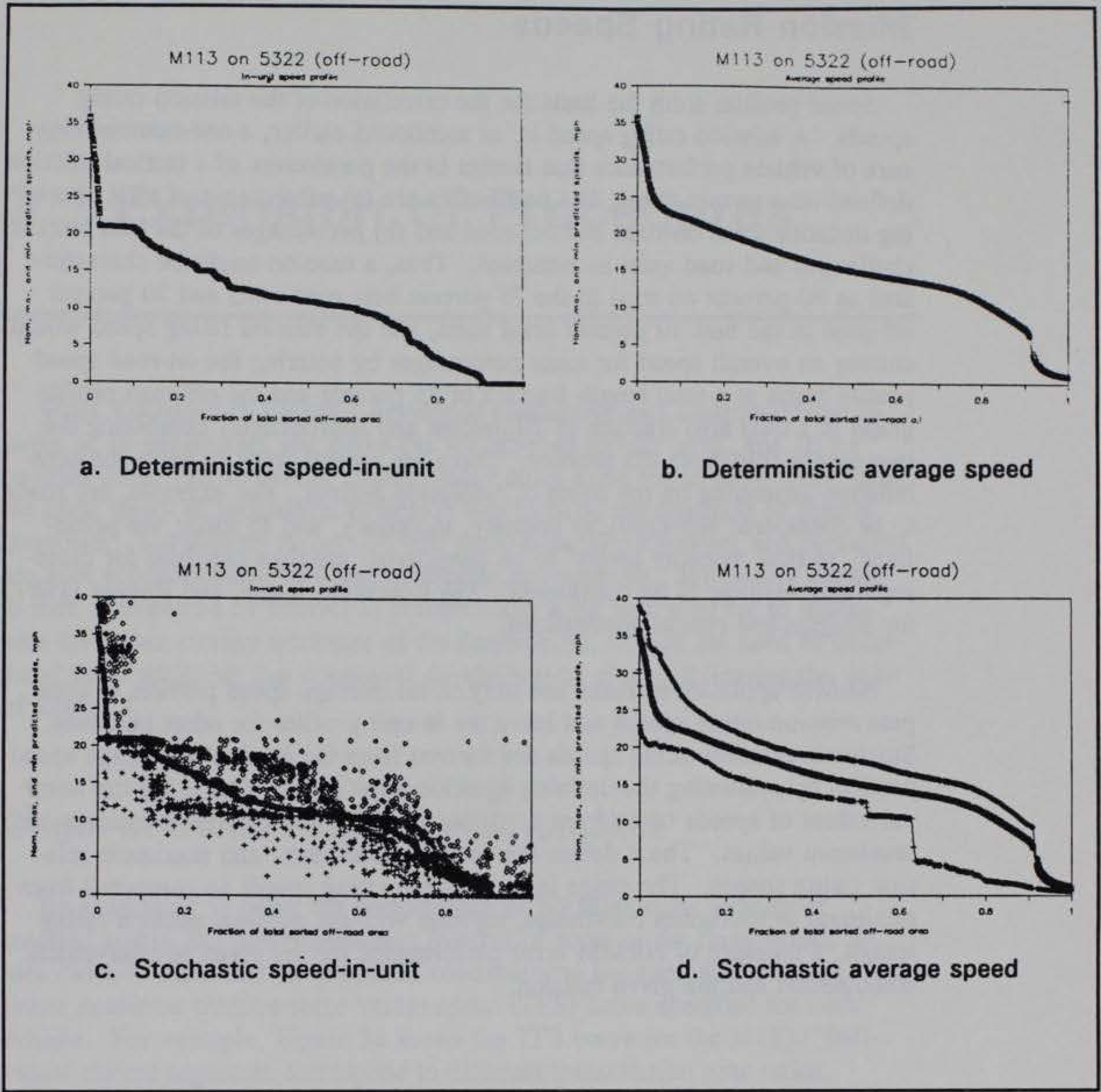
The Monte Carlo Speed Simulation

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, is the major element of analysis leading to the stochastic mobility forecast. The per-terrain-unit speed probability densities and data specifying the mission profile are the raw materials from which an analysis of mission rating speeds and their ranges 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

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/scenario 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 2a 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 2b. 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 2a and 2b 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)



a. Deterministic speed-in-unit

b. Deterministic average speed

c. Stochastic speed-in-unit

d. Stochastic average speed

Figure 2. Speed profiles

Stochastic orientation of NRMM requires the development of stochastic speed profiles based not only on the nominal predicted speeds but also on the minimum[1] and maximum[1] predicted speeds. The very same computational procedures are used and result in plots like those shown in Figures 2c and d. In effect, range limits that bound NRMM error performance are placed on the traditional speed profiles.

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[1] Anywhere these terms appear, it is possible via Monte Carlo simulation to replace them with mean ± one or two standard deviations whichever the user wishes to calculate.

Mission-Rating Speeds

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 challenged 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 graph at a total length fraction of 75 percent and the off-road profile graph at a total area fraction of 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 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.

NRMM applications make use only of the average speed profiles to compute mission rating speeds and leave the in-unit profiles for other purposes. Stochastic mission rating speeds are derived from the stochastic average speed profiles by evaluating the defining equation three times: first using the nominal values of speeds taken from the speed profiles, and then the minimum and maximum values. These define the nominal, minimum, and maximum mission rating speeds. The range in the mission rating speeds so computed from minimum to maximum constitutes, together with the nominal mission rating speeds, a measure of NRMM error performance for the given terrain/vehicle combination and the given mission.

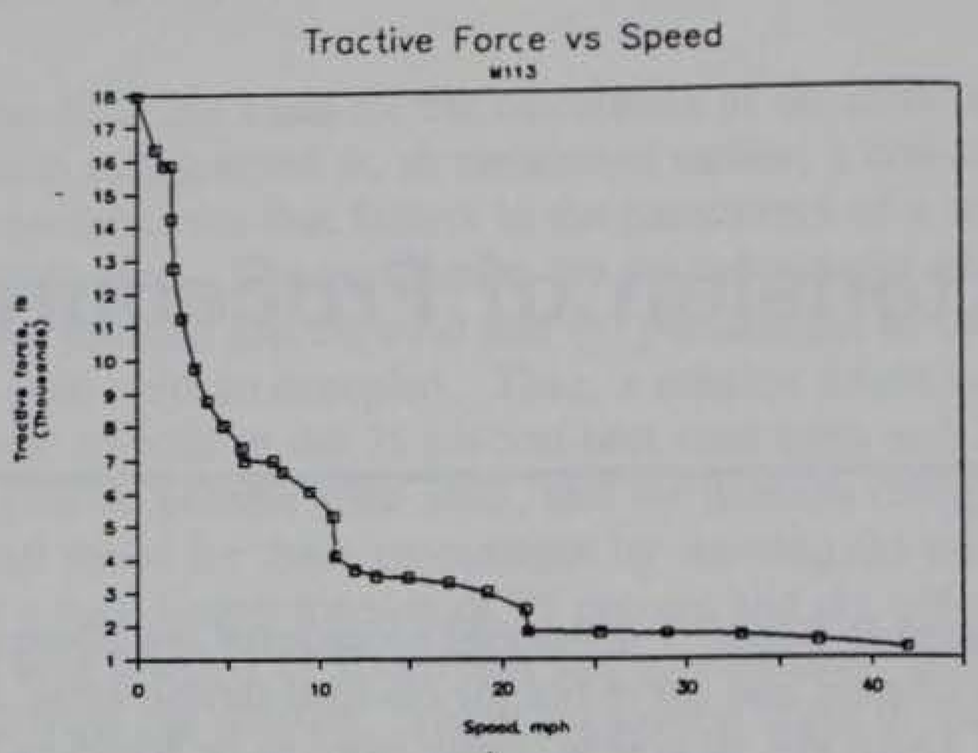
3 Extension of Procedures

Work discussed in Report 1 developed procedures and illustrated them in terms of 19 parameters and curve-fits for off-road terrain units, and 16 for on-road units. There are, of course, many more to be found in NRMM; thus, the main thrust of procedural extension was to be in the direction of greater quantities. Subsequent discussion will detail how 90 parameters and curve-fits are now accommodated in a supercomputer environment. But before getting to that, it would be of interest to present some work that went far to illuminate the rather strange attributes of the fingerprints. It was the need to understand these attributes that consumed developmental energy following the work of Report 1.

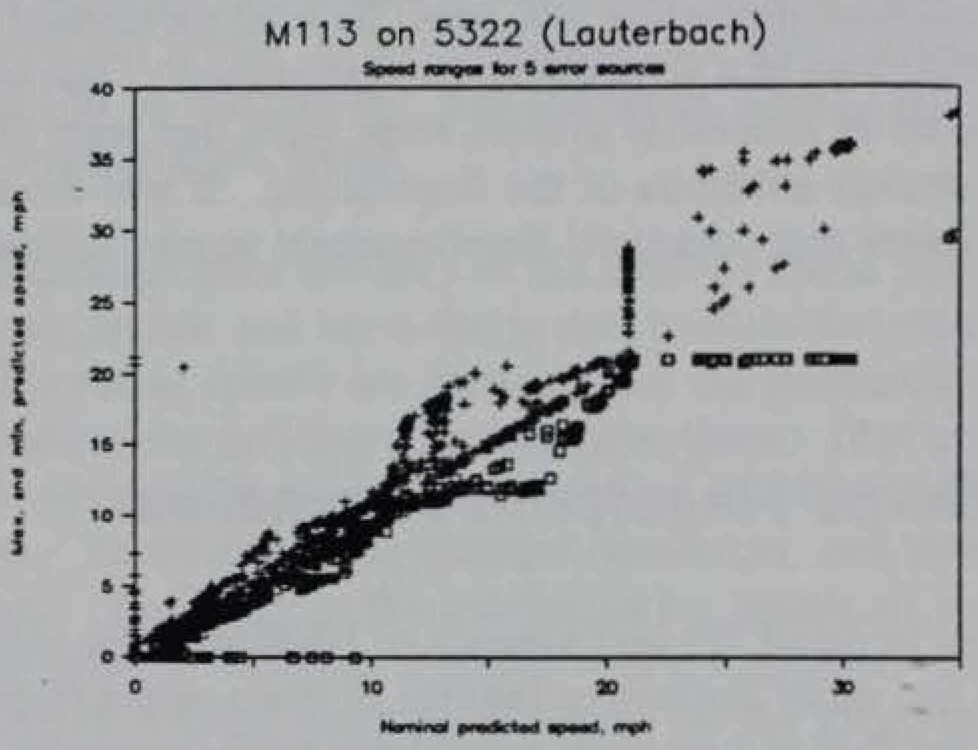
Origin of Some Fingerprint Anomalies

By examining in detail the performance of NRMM in the vicinity of assorted spikes and other distinctive features of some of the fingerprints, an idea came to mind that an important contributor to the anomalies was the rather nonlinear tractive-force versus speed (TFS) curve specified for each vehicle. For example, Figure 3a shows the TFS curve for the M113. Individual curved segments correspond to different transmission gear ratios. Figures 3b and c show the fingerprints for the M113 on the Lauterbach and Schotten quads in a highlands area in West Germany. The first is an off-road setting; the second, on-road. The clustered nature of NRMM speed predictions is quite apparent.

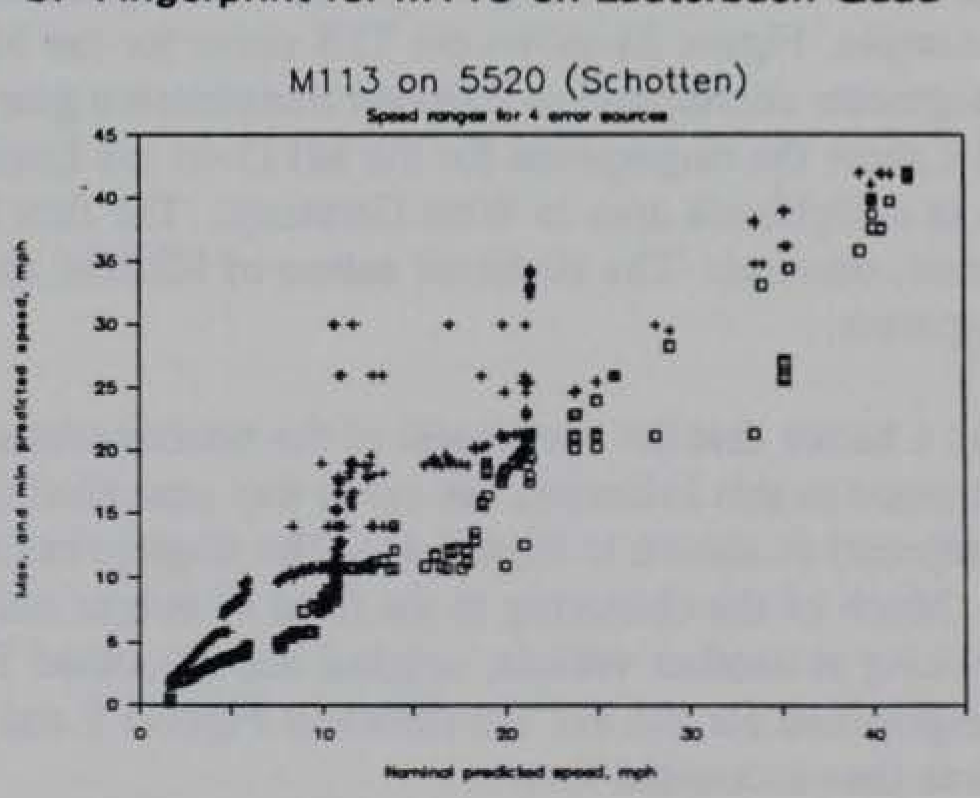
Motivated by a hunch that the abruptness of the nonlinearities in the TFS curve were important to this behavior, the curve was smoothed (it is, of course, still nonlinear) as shown in Figure 4a. The fingerprints of Figures 4b and c resulted. Much of the clustering in the form of bulges and spikes was eliminated. Looking at another vehicle, original and smoothed TFS curves and resulting fingerprints for the M1 are shown in Figures 5 and 6. Most of the clustering was thus accounted for.



a. Tractive force versus speed for M113

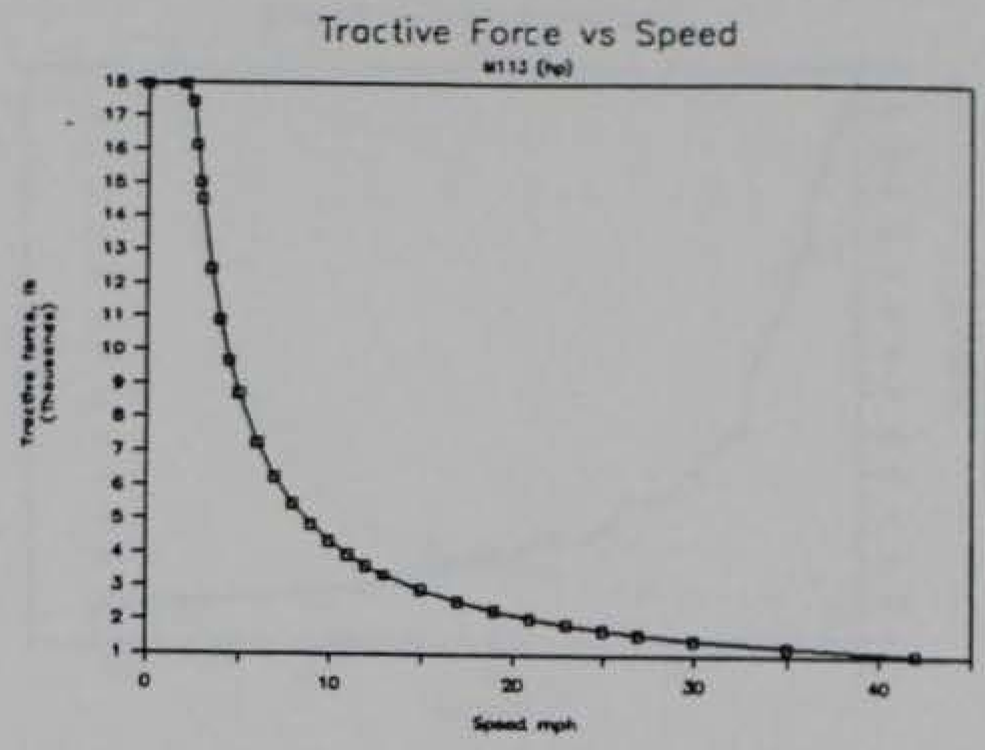


b. Fingerprint for M113 on Lauterbach Quad

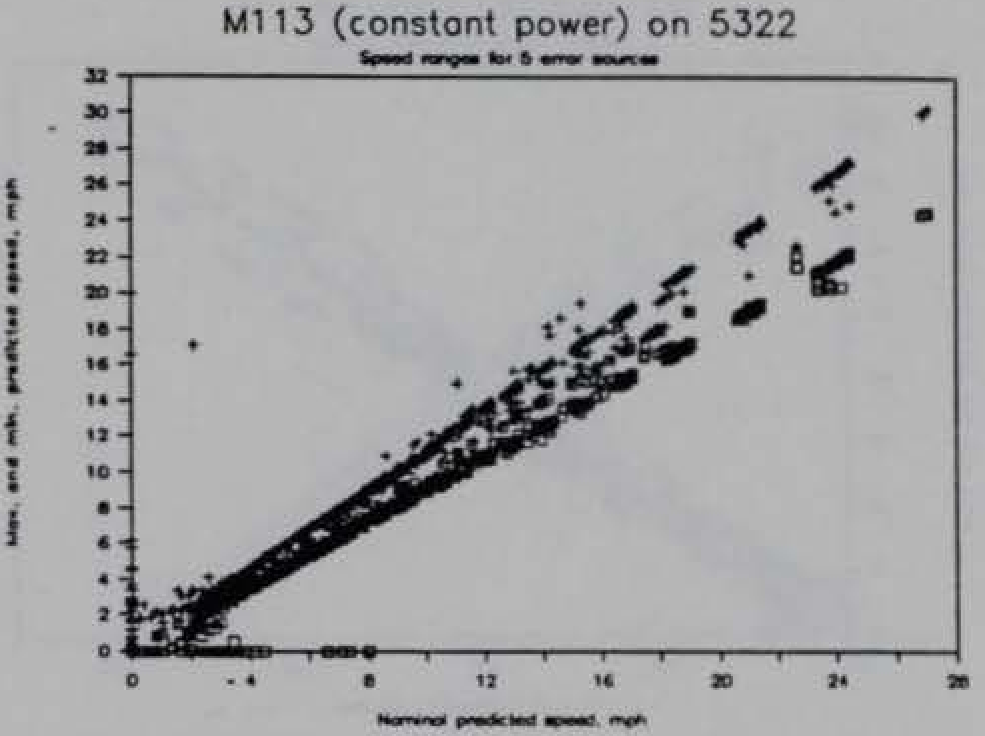


c. Fingerprint for M113 on Schotten Quad

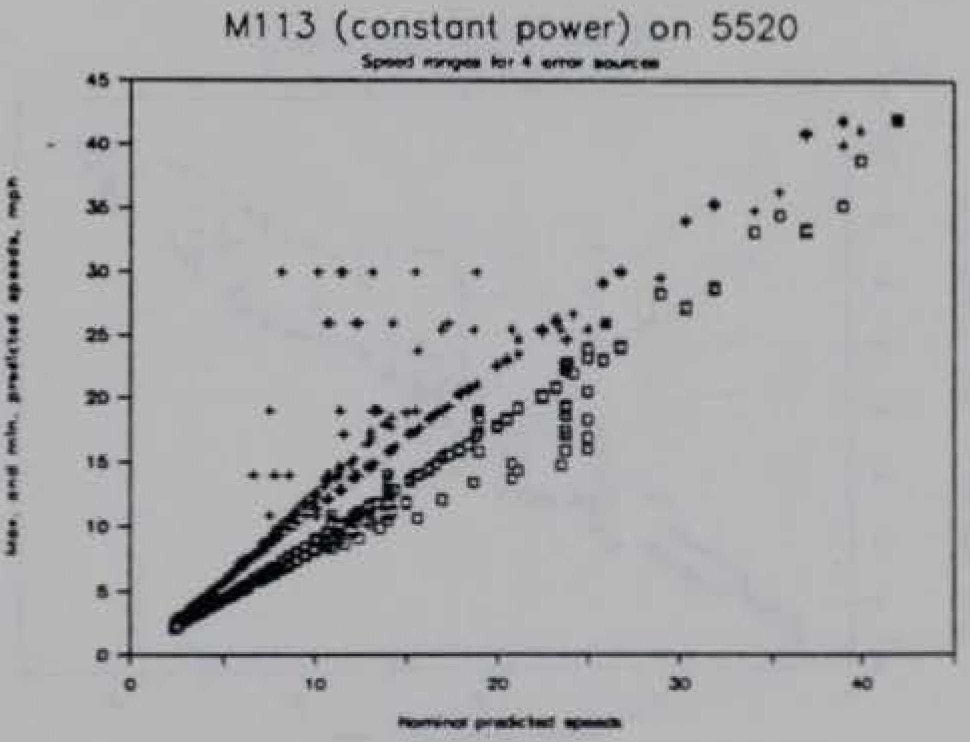
Figure 3. Clustering anomalies in M113 fingerprints



a. Smoothed tractive force versus speed for M113

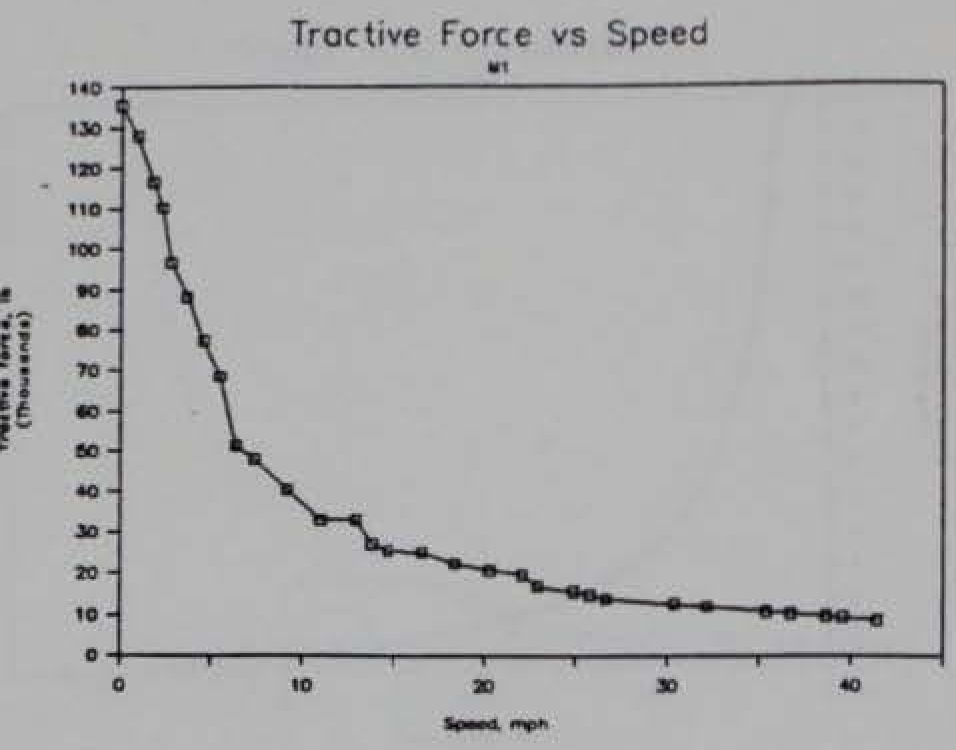


b. Fingerprint for M113 on Lauterbach Quad

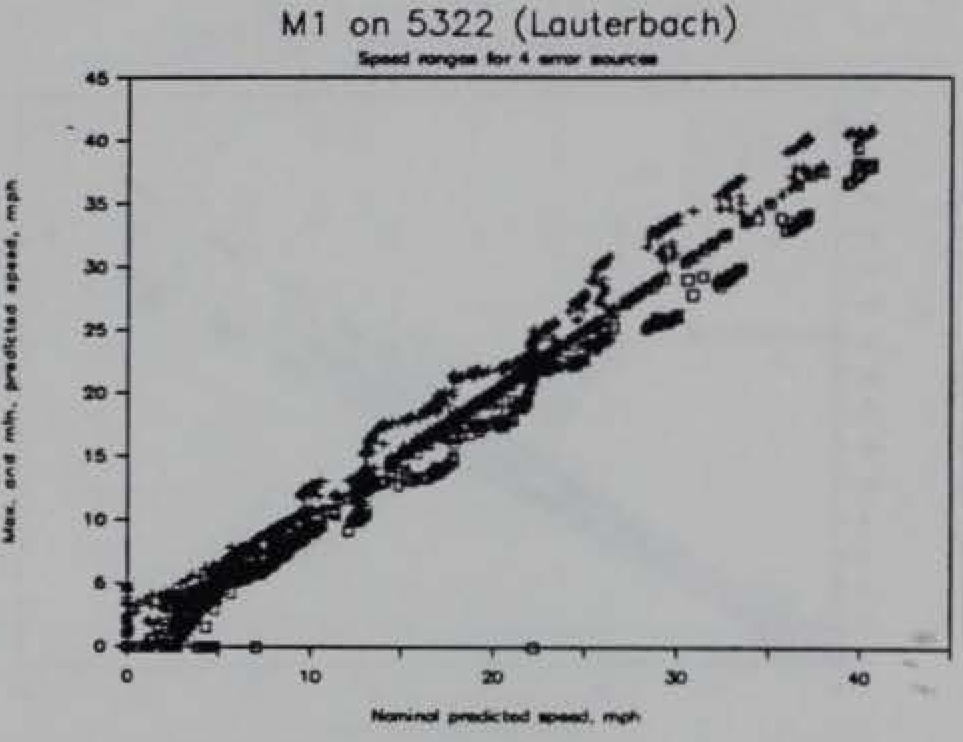


c. Fingerprint for M113 on Schotten Quad

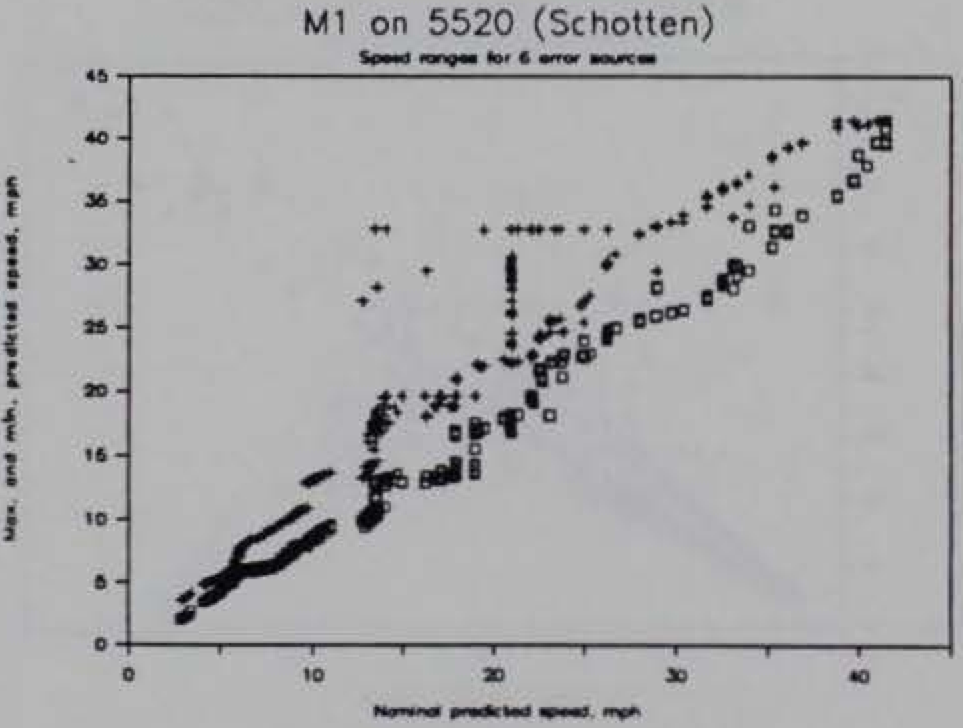
Figure 4. Elimination of most fingerprint anomalies for M113



a. Tractive force versus speed for M1

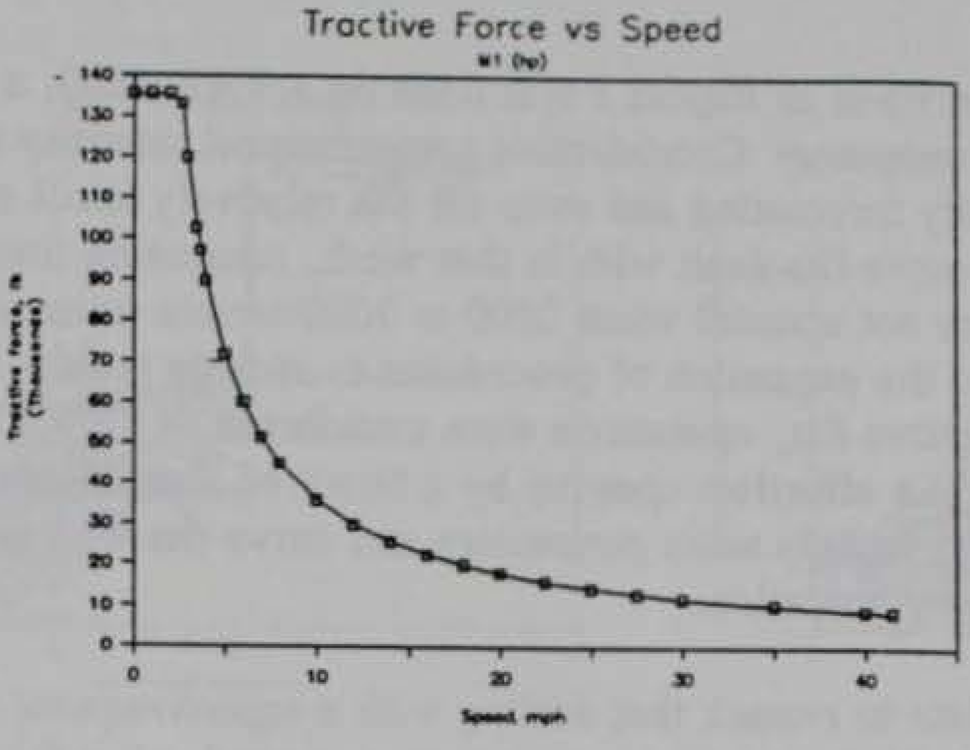


b. Fingerprint for M1 on Lauterbach Quad

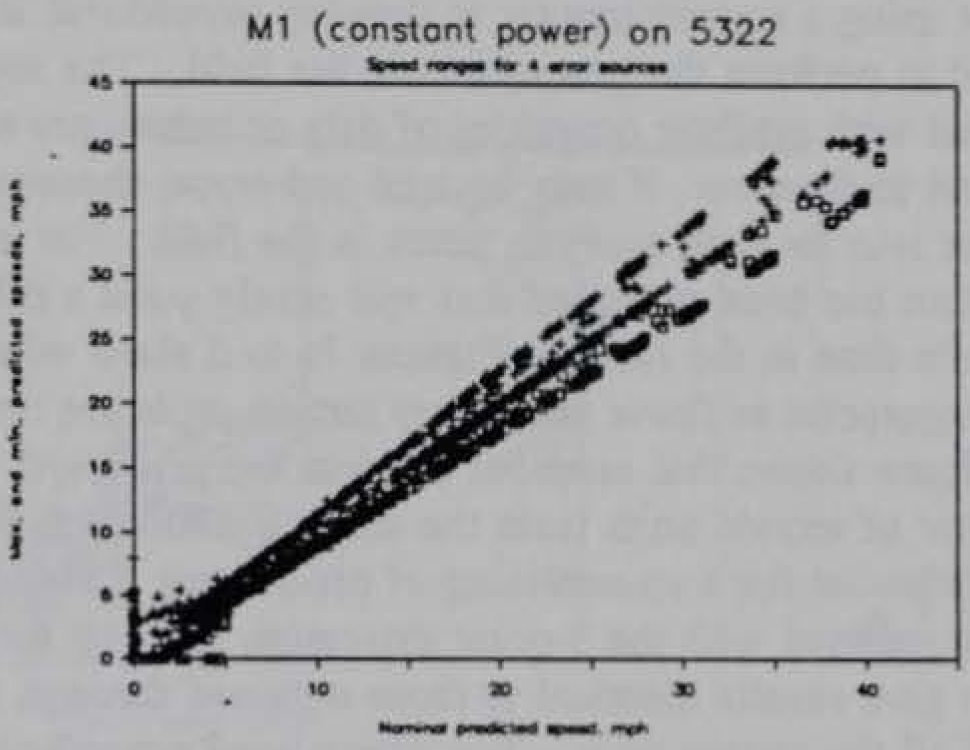


c. Fingerprint for M1 on Schotten Quad

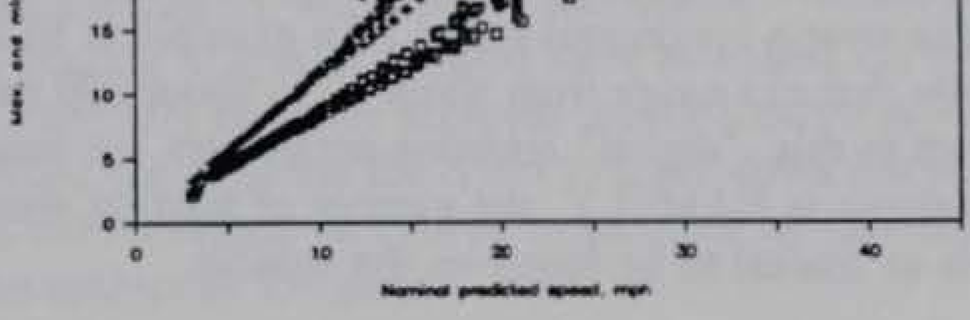
Figure 5. Clustering anomalies in M1 fingerprints



a. Smoothed tractive force versus speed for M1



b. Fingerprint for M1 on Lauterbach Quad



c. Fingerprint for M1 on Schotten Quad

Figure 6. Elimination of most fingerprint anomalies for M1

Change of Computing Environment

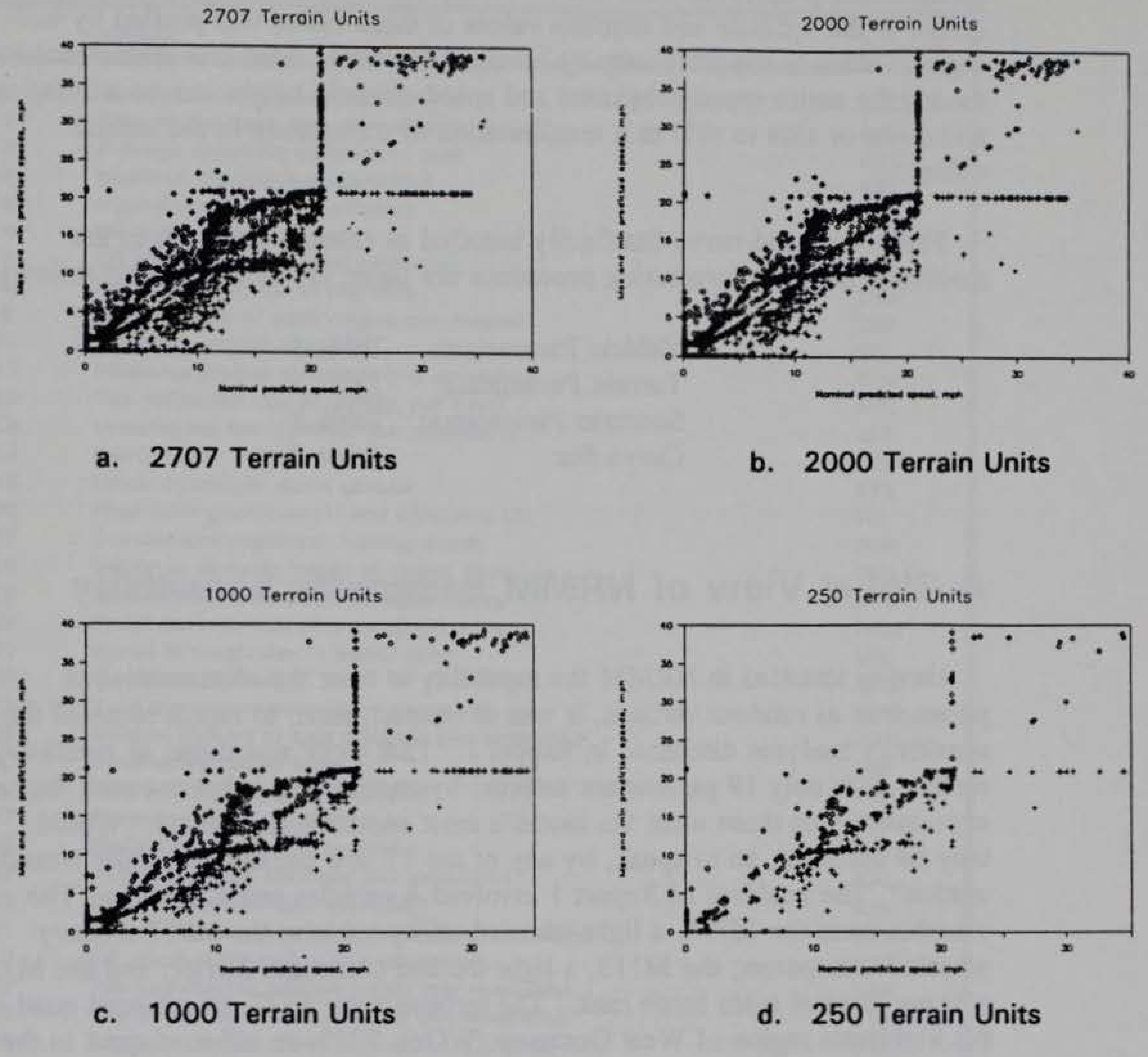
The work described in Report 1 was done on a VAX 8800, a fully competent mainframe computer. Considerable computational intensity is a part of stochastic mobility forecasting and even for the relatively small number of parameters and curve-fits dealt with in that work, computing times of 90 to 180 minutes were not unusual when 2000 to 3000 terrain units were involved. In anticipation of the expansion of procedures to include greater numbers of parameters and curve-fits, operations were transferred to a CRAY YMP supercomputer. An effortless speedup by a factor of about 5 resulted. Work then proceeded to include more parameters and curve-fits with no special attention paid to optimization.

It is appropriate to remark that dealing with a supercomputer may seem to have little to do with the tactical setting seen as a motivation for the development of these procedures. One can hardly drag a supercomputer around a battle zone. But using a supercomputer to develop procedures is not a commitment to use it to perform the procedures in the field. The supercomputer allows one to deal with <u>realistic quantities of data</u> as means are sought to optimize code and to discover, if only by trial and error, those procedural shortcuts that can lead to short analysis times in the field. For example, one procedural shortcut has been glimpsed that will surely yield a substantial savings in analysis time in the future. Figures 7a to d show what happens to a representative fingerprint as fewer and fewer terrain units are involved in the analysis. The figure shows that essential features are preserved despite reduction in the number of terrain units from the original 2707 to as few as 250. There is a real potential for a streamlining of procedures if reduced numbers of terrain units combined with the 3-point extremum analysis for sensitivity can be shown to give results identical to those obtained through Monte Carlo consideration of all the terrain units. The streamlined procedures could then be expected to perform well with fast desk-top machines in tactical settings as originally desired.

Parameters and Curve-fits Considered

The intent of this work was to make each "analog" parameter and, later, each curve-fit available for variation. An analog parameter is one that can be assigned any value over a continuous range. An example is RCIC, the soil strength parameter that can range from about 10 to about 300 rating cone index. In contrast to this, "digital" counting parameters are unsuitable for variation. An example is NAMBLY, the number of traction element assemblies (i.e. wheels or tracks) to be found on the vehicle.

Work went ahead in stages to incorporate more and more parameters into the stochastic forecasting procedures, testing along the way. In most cases, the additional parameters were easily merged into the procedures. The only significant problem arose when parameters associated with the computation of



a. 2707 Terrain Units

b. 2000 Terrain Units

c. 1000 Terrain Units

d. 250 Terrain Units

Figure 7. Reduced-dataset fingerprints

TFS curves from engine torque-speed characteristics and from torque converter speed ratio characteristics were dealt with. Fingerprints arising from variation of these parameters were clearly anomalous. However, when it was realized that no historic usages of NRMM have exercised the option to generate TFS curves internally but have accepted the TFS curve as vehicle input data, it was decided not to spend the effort to track down the problem. Instead, all TFS curves would be viewed as certified by the vehicle manufacturers and not be subject to variation.

Finally, it was realized that the tables of values contained in the vehicle data files which represent the speed constraints due to rough terrain and due to obstacle-induced acceleration are actually curve-fits in their own right. However, unlike the other curve-fits which consist of coded equations inaccessible to the user, these consist of tables of values that are very accessible. Because of their tabular form, it was decided to manage data variation in a manner fundamentally different from that of the equations. Sensitivity of NRMM to errors in the ordinate and abscissa values of these tables was studied by having all values in the table vary by identical amounts. This was tantamount to having the entire speed-roughness and speed-obstacle height curves moving up and down or side to side as a manifestation of uncertainty in the tabular values.

Parameters and curve fits finally installed as random variables in the stochastic mobility forecasting procedure are listed in tables 1 to 4 as follows:

Vehicle Parameters:	Table 1
Terrain Parameters:	Table 2
Scenario Parameters:	Table 3
Curve-fits:	Table 4

A Global View of NRMM Parameter Sensitivity

Having installed in NRMM the capability to treat the aforementioned parameters as random variates, it was of interest, then, to repeat some of the sensitivity analyses discussed in Report 1. That work was done, as mentioned earlier, with only 19 parameters selected by engineering judgment with the expectation that these were the model's most sensitive parameters. Would they be upstaged, so to speak, by any of the 71 new parameters under consideration? The analyses of Report 1 involved 4 vehicles and 4 terrains. The vehicles were the M998, a light wheeled utility vehicle; the M977 a heavy wheeled transporter; the M113, a light tracked personnel carrier; and the M1, a heavy tracked main battle tank. The terrains were 5322, an off-road quad in the highlands region of West Germany (WGe); 2726, an off-road quad in the plains region of WGe; 3254, an off-road quad in a Jordan desert region; and 5520, an on-road quad in the highlands of WGe. Figures 8 to 11 illustrate the values of the sensitivity rank indicators of 87 of the 90 parameters. (The last three, numbers 88, 89, and 90, had not been installed at the time the analysis was performed and were later found to be relatively insensitive.) It was found that, indeed, the original 19 parameters whose sensitivities were studied in Report 1 were among the most sensitive parameters but that the most sensitive ones (in at least some of the cases) had actually been overlooked. These were the parameters associated with the speed constraints due to ground roughness and obstacle traversal. Note that these parameters are NOT ALWAYS the most sensitive ones, pointing out once again the wide range of outcomes of which NRMM is capable. The study showed that it is possible to make a general statement that certain independent parameters will dominate performance predictions in all terrain unit-vehicle combinations.

Table 1
Vehicle Parameters Capable of Being Treated as Random Variables

	Vehicle	Acronym
1	Aerodynamic drag coefficient	ACD
2	Area of one track shoe (per assembly)	ASH
3	Average cornering stiffness of tires	AVC
4	Interaxle spacing (per assembly)	AXL
5	Hydrodynamic drag coefficient	CD
6	CG height above ground	CGH
7	CG lateral distance from center line	CGL
8	Horiz distance, CG to rear axle	CGR
9	Displacement of each engine (per engine)	CID
10	Minimum ground clearance	CL
11	Minimum ground clearance (per assembly)	CLR
12	Tire deflection (per assembly, per case)	DFL
13	Undeflected tire diameter (per assembly)	DIA
14	Combination vehicle draft	DRA
15	Driver eyeheight above ground	EYE
16	Final drive gear ratio (1) and efficiency (2)	FD
17	Combination maximum fording depth	FOR
18	Height in obstacle height vs speed array	FVA
19	Speed in obstacle height vs speed array	FVO
20	Roughness in roughness vs speed array	FRM
21	Speed in roughness vs speed array	VRI
22	Track grouser height	GRO
23	Total net engine power (per assembly)	HPN
24	Vertical chassis to axle distance (per assembly)	HRO
25	Maximum pushbar force	PBF
26	Height of pushbar above ground	PBH
27	Projected vehicle frontal area	PFA
28	Maximum torque (per engine)	QMA
29	Avg suspension stiffness (per assembly)	RAI
30	Tire rim diameter (per assembly)	RDI
31	Tire revolutions per unit distance (per assembly)	REV
32	Eff. track bogie radius (per assembly)	RW
33	Tire undeflected section height (per assembly)	SEH
34	Tire undeflected section width (per assembly)	SEW
35	Engine to torque conv. gear ratio (1), eff. (2)	TCA
36	First-to-last wheel center distance	TL
37	Tire ply rating (per assembly)	TPL
38	Tire pressure (per assembly, per case)	TPS
39	Length of track on ground (per assembly)	TRL
40	Track width (per assembly)	TRW
41	Transmission gear ratios and efficiencies	TRA
42	One-pass fine-grain VCI (per assembly)	VFG
43	Vehicle maximum fording speed	VFS
44	Slope sliding speed limit	VSL
45	Max. swim speed w/o aux. propulsion	VSS
46	Max. swim speed w/ aux. propulsion	VSA
47	Slope tipping speed limit	VTP
48	Tire max. speed limit	VTI
49	Vehicle length (per unit)	VUL
50	Winch capacity	WC
51	Water depth to allow aux. propulsion	WDA
52	Max. combination vehicle width	WDT
53	Vehicle weight (per assembly)	WGH
54	Ratio of ground weight to fording weight	WRF
55	Tread width (per assembly)	WT
56	Min. width betw. traction elements (per assembly)	WTE
57	Combination vehicle braking coefficient	XBR

Table 2
Terrain Parameters Capable of Being Treated as Random Variables

	Terrain	
58	Surface roughness	ACT
59	Soil depth to bedrock	DBR
60	Superelevation angle	EAN
61	Terrain elevation	ELEV
62	Terrain slope	GRA
63	Obstacle approach angle	OBA
64	Obstacle height	OBH
65	Obstacle width	OBW
66	Obstacle length	OBL
67	Obstacle spacing	OBS
68	Road radius of curvature	RAD
69	Soil strength	RCI
70	Recognition distance	RDA
71	Stem spacing (per class)	S
72	Depth of standing water	WD

Table 3
Scenario Factors Capable of Being Treated as Random Variables

	Scenario	
73	Driver safety factor, sliding & tipping	COE
74	Cohesion of snow	COH
75	Max. braking deceleration driver will accept	DCL
76	Specific gravity of snow	GAM
77	Internal friction angle of snow	PHI
78	Driver braking reaction time	REA
79	Max. recognition distance	RDF
80	Amount of available braking driver will use	SFT
81	On-road visibility-limited speed	VBR
82	Off-road visibility-limited speed	VIS
83	On-road speed limit	VLI
84	Min. vegetation override speed	VWA
85	Snow depth	ZSN

Table 4
Regressions Capable of Being Treated as Random Variables

	Regressions	
86	Drawbar pull coefficient versus excess rating cone index	FDO
87	Powered/Braked motion resistance coefficient versus excess rating cone index	FRP
88	Towed motion resistance coefficient versus excess rating cone index	FRT
89	Slip versus pull coefficient	FSL
90	Mobility index vs several vehicle parameters	FXM

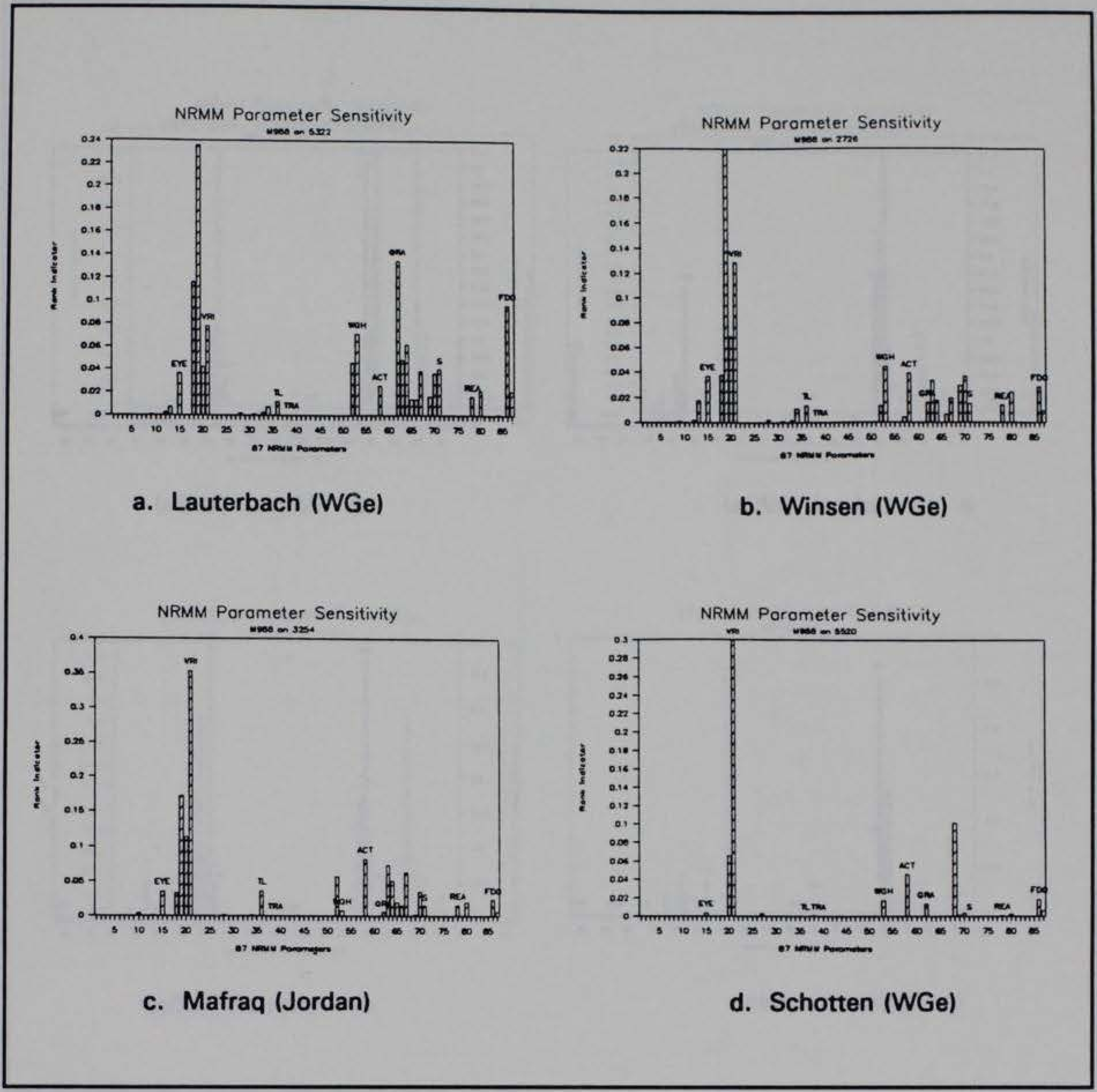


Figure 8. Global view of parameter sensitivity for M998 in four terrains

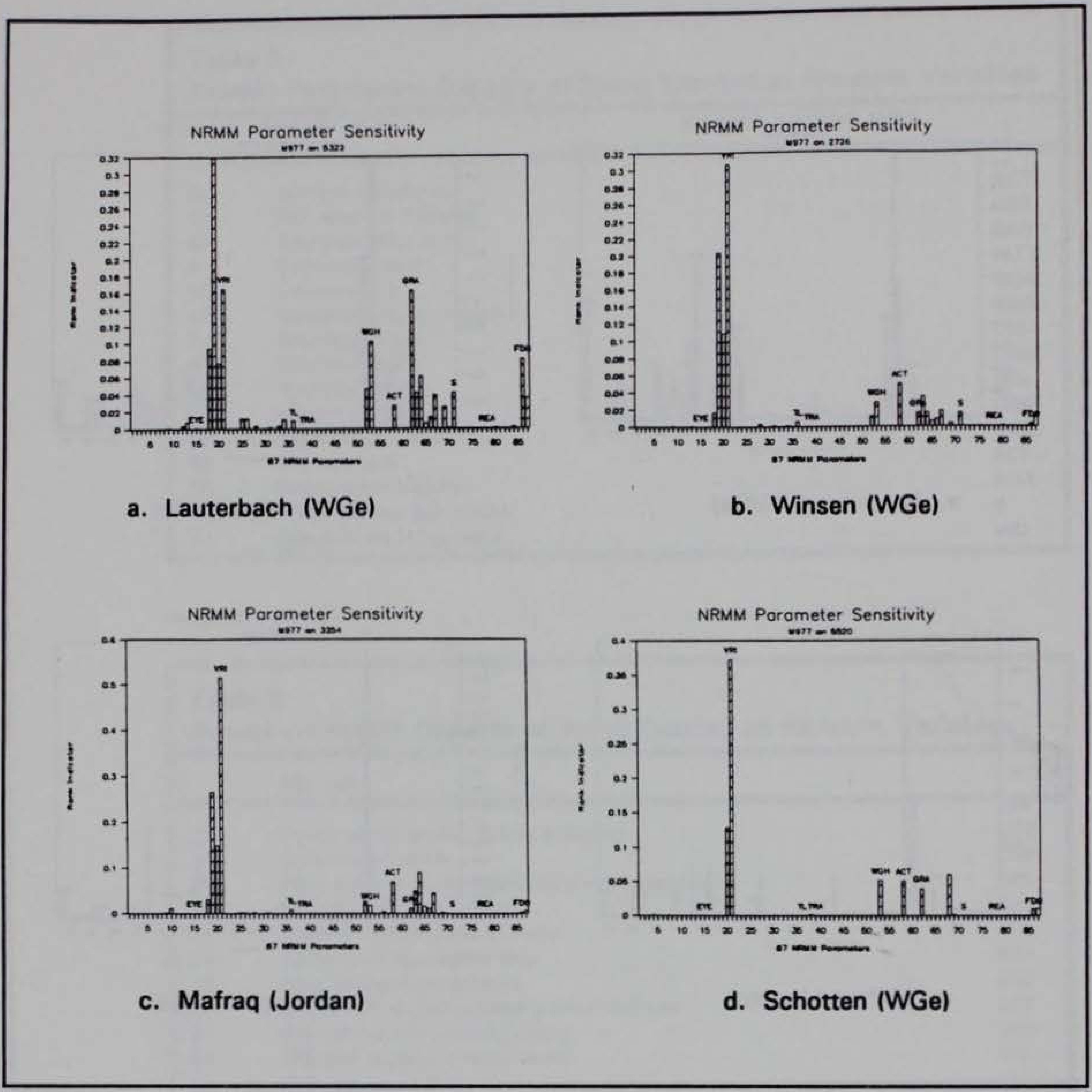


Figure 9. Global view of parameter sensitivity for M977 in four terrains

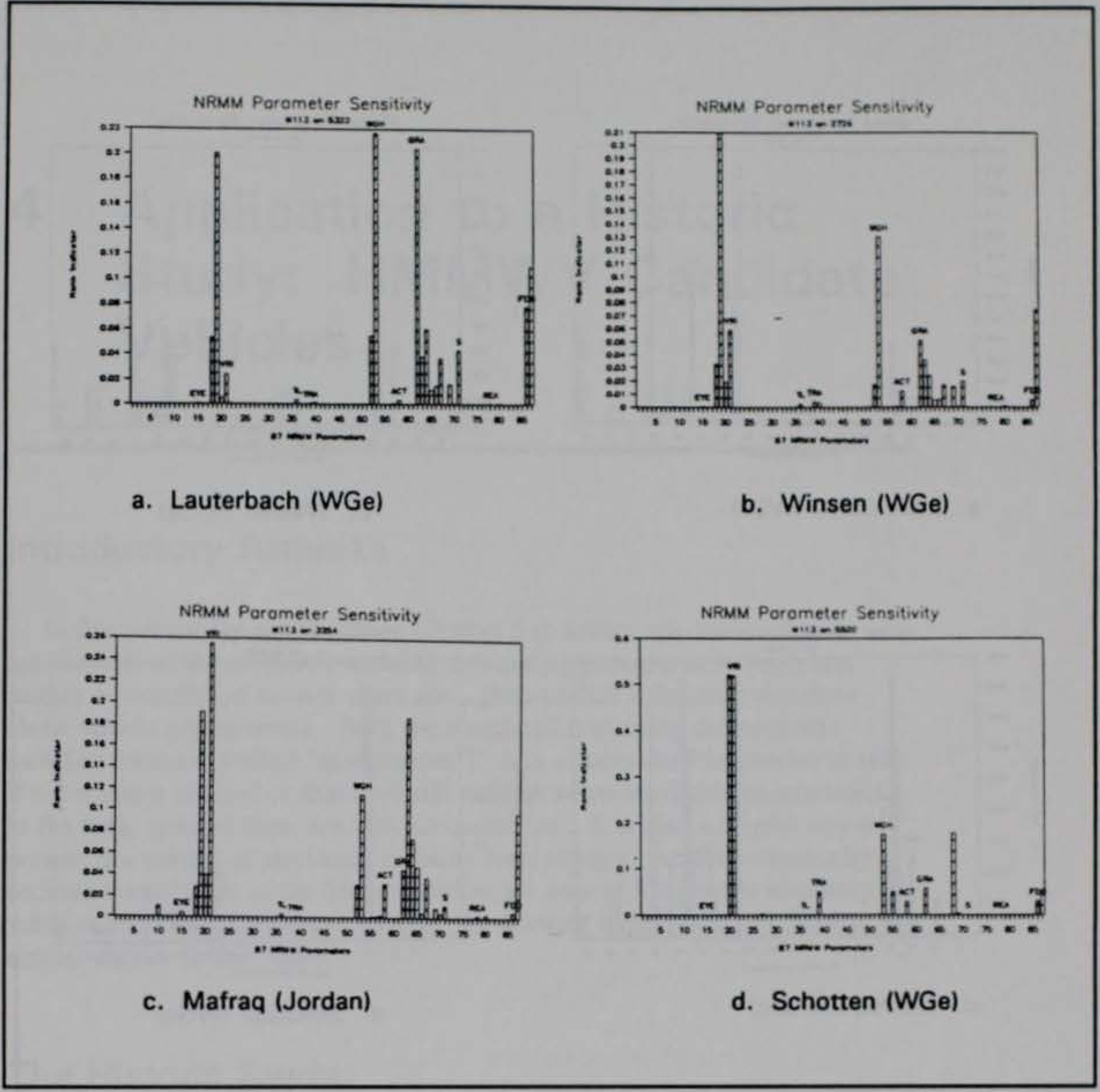


Figure 10. Global view of parameter sensitivity for M113 in four terrains

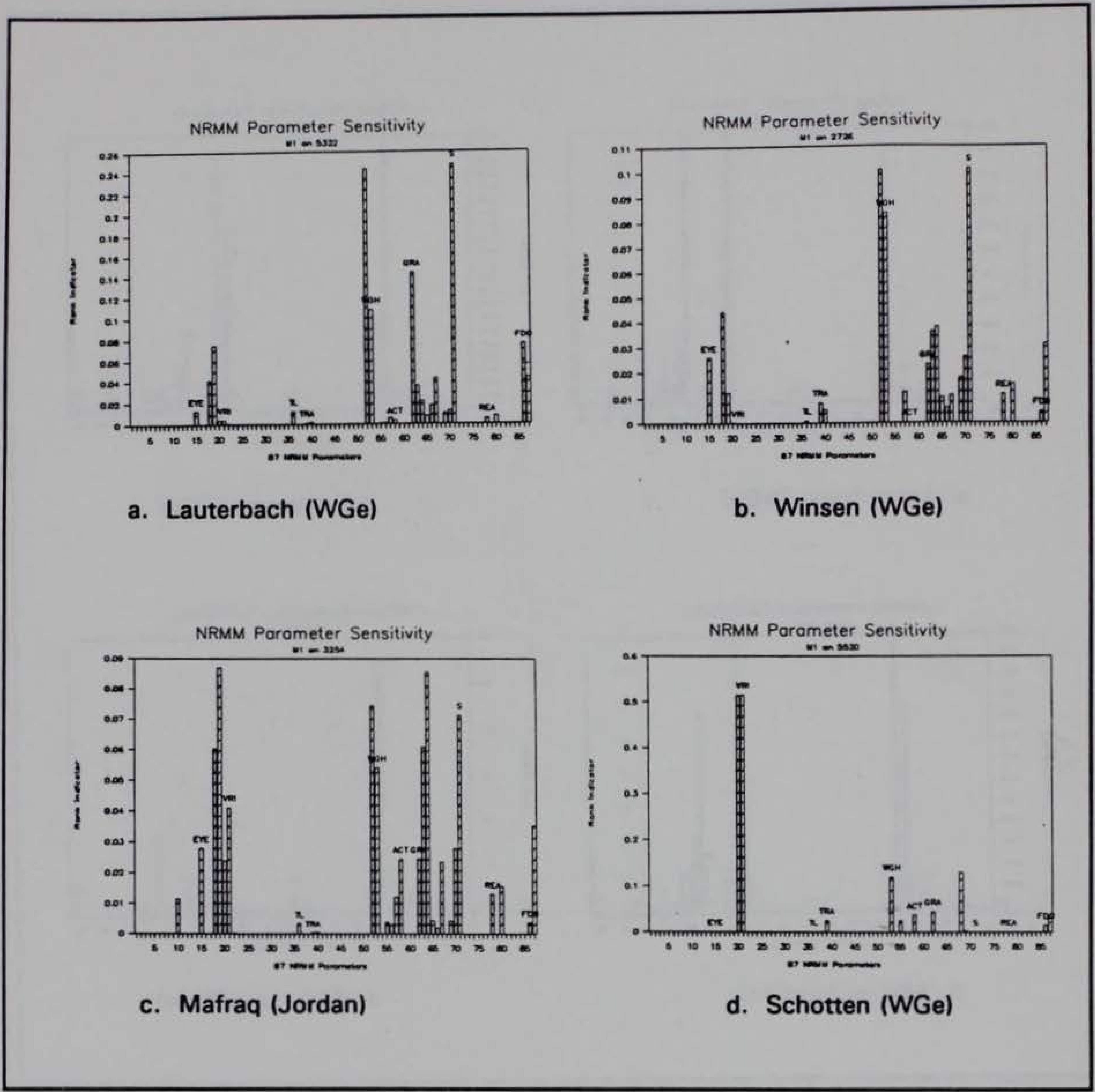


Figure 11. Global view of parameter sensitivity for M1 in four terrains

4 Application to a Historic Study: HMMWV Candidate Vehicles

Introductory Remarks

In this part of the report and in Chapter 5 to follow are discussed two applications of the stochastic mobility forecasting procedures to important studies accomplished several years ago. Both studies influenced decisions about vehicle procurement. Both were accomplished using deterministic mobility forecasts (called "assessments"). It is of considerable interest to see if conclusions reached at that time still hold up when inevitable uncertainties in the data, ignored then, are now accounted for. It is also a helpful way to present the subject of stochastic mobility forecasting to the user community because the subjects of the historic studies are now in the current inventory of vehicles and their replacements are on the drawing boards and will require similar studies in the future.

The Historic Study

This study was part of a report entitled "Ride and Shock Test Results and Mobility Assessment of HMMWV Candidate Vehicles: (Green, Randolph, and Grimes 1983). In 1982, specifications for a "High Mobility Multipurpose Wheeled Vehicle (HMMWV)" called for a common chassis capable of accepting several body configurations to accommodate weapons systems, utility, and ambulance roles. The HMMWV was to be 4x4 wheeled vehicle capable of operating off-road, on trails, and on primary and secondary roads with a 1-1/4 ton payload at speeds comparable to the then-current high-mobility M561 vehicle.

Three military vehicle manufacturers were awarded contracts to build HMMWV prototypes for test and evaluation. Each manufacturer provided 2 prototypes; one was configured as a utility vehicle and the other, as a weapons carrier. For purposes of analytic mobility forecasting using NRMM, vehicle data files were prepared for 11 vehicle configurations: 3 for each of the 3 prototypes and one each for the M151 jeep and M561 (GAMMA GOAT) utility vehicles then in service. The study considered the utility vehicles in both loaded and unloaded conditions and the weapons carriers in loaded conditions.

Study terrains were chosen in the Fulda, Lauterbach, and Schotten areas of West Germany and in the Mafraq and Az Zarqa areas of Jordan. Seasonal conditions included dry, wet, and slippery surfaces, and gave special consideration to snow conditions in Germany and sand conditions in Jordan. Performance assessments were based on mission rating speeds for several standardized and specialized HMMWV mission definitions. Details are spelled out in the original report.

That report did not state a "winner." It did not attempt to formulate a ranking. It merely stated comparative outcomes on a variety of terrains according to a variety of missions. Army procurement specialists accepted such comparisons as advisements during their deliberations. Accordingly, it was unnecessary to completely rerun the study with the stochastic procedures. It sufficed for the purpose of demonstration to deal with just a portion of the original study.

Scope and Methods of the Application

Three vehicle data files were prepared to represent the fully loaded utility configurations of the candidate HMMWV vehicles. The vehicles were designated the AU7 (AM General Corporation), GUF (General Dynamics, Inc.), and TUQ (Teledyne Continental Co.). Photos of the vehicles are presented in Figure 12. Photos of the M151 and M561 comparison vehicles are shown in Figure 13, A listing of geometric characteristics is given in Table 5.

At the outset, each vehicle was studied individually on each of 4 terrains. The terrains were 5322, the Lauterbach off-road quad, and 5520, the Schotten on-road quad in WGe, and 3254A, the Mafraq off-road quad, and 3254R, the Az Zarqa on-road quad in Jordan. In all cases only a "dry, normal" season was used. The sensitivities of each vehicle/terrain combination were determined for the 90 parameters of NRMM whose variability could be controlled at that time. As few as 2 parameters and as many as 12 parameters out of the 90 studied in each case were found to be sensitive. Considered together, only 14 parameters out of 90 were identified as sensitive in any vehicle/terrain context studied. Figures 14 to 18 identify the sensitive parameters. In all cases, the 14 parameters are listed along the horizontal axes. Note that vertical scales differ among the plots. See Tables 1 to 4 to identify the acronyms.

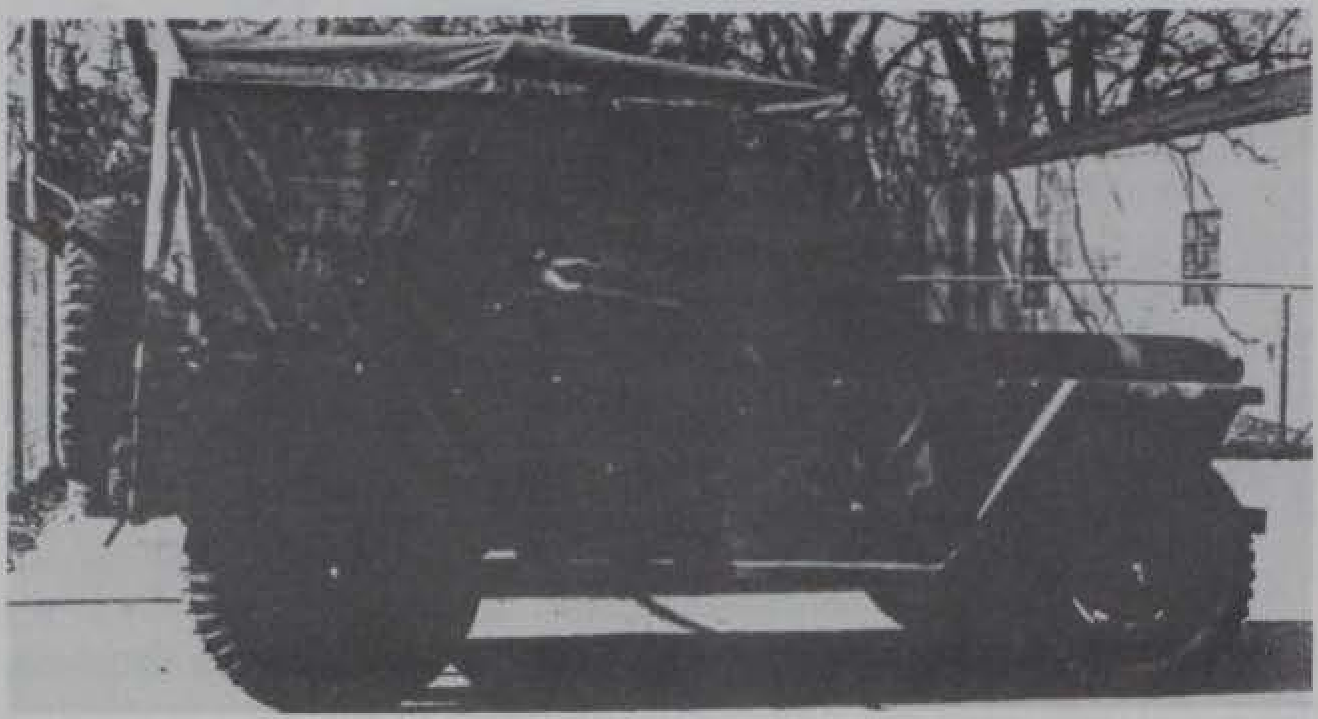
Following the screening of sensitive parameters for all vehicle/terrain combinations, Monte Carlo speed prediction simulations were performed in which the sensitive parameters were treated as random variables and the other parameters were held constant. Error-magnitude scenarios were composed based on judgments of the statistical attributes of the random variables. As in

a. AM General 1-1/4-ton utility vehicle, AU7

b. General Dynamics 1-1/4-ton utility vehicle, GUF

c. Teledyne Continental 1-1/4-ton utility vehicle, TUQ

Figure 12. The candidate HMMWV vehicles

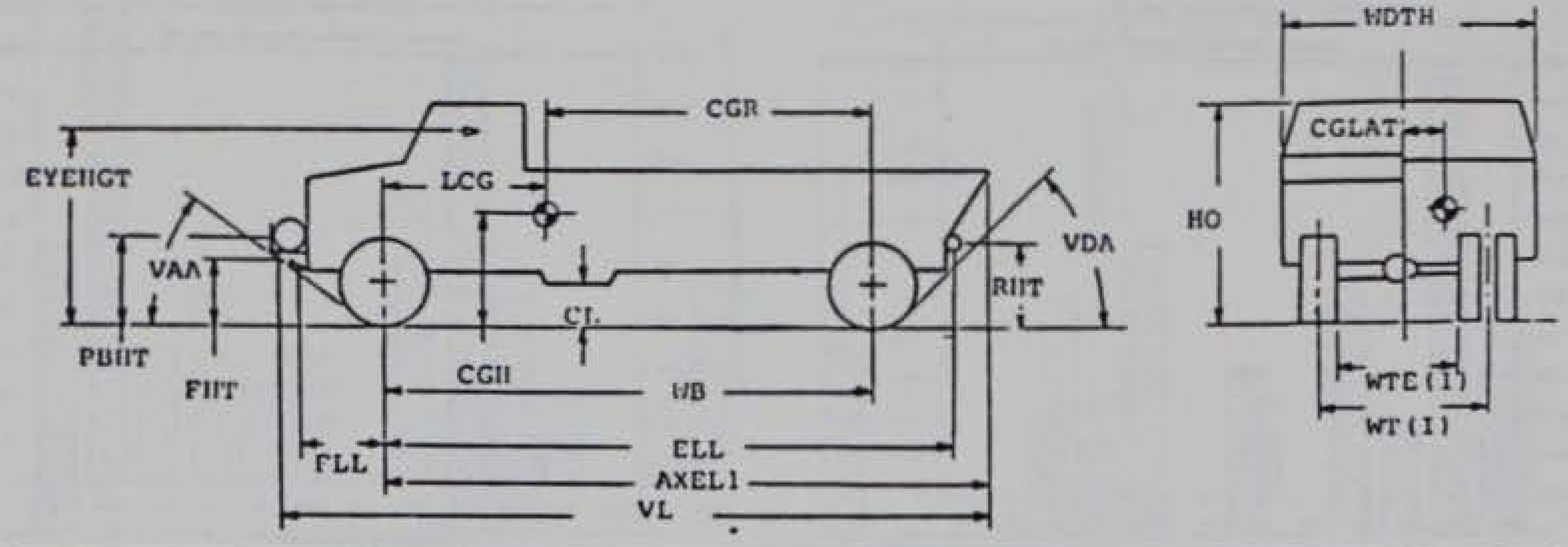


a. M151A2 Truck, utility, 1-1/14-ton

b. M561 Truck, cargo, 1-1/4-ton

Figure 13. The comparison vehicles

Table 5
Vehicle Dimensions



Geometry	Figure Reference	Vehicle AU7	GUF	TUO	M151A2	M561
Vehicle/unit length, in.	VL	185.0	189.0	192.0	132.0	228.0
Front axle to end of vehicle, in.	AXEL1	163.0	163.0	171.0	113.0	203.0
Front hitch to front axle, in.	FLL	22.0	25.0	24.0	19.0	20.0
Front axle to rear hitch, in.	ELL	163.0	163.0	171.0	113.0	203.0
Wheelbase, in.	WB	130.0	134.0	130.0	85.0	165.5*
Front axle to CG, in.	LCG	77.1	74.6	74.7	44.5	90.1
Front axle to driver's station, in.	--	61.0	64.0	63.0	--	--
Vehicle/unit height, in.	HO	71.0	73.0	72.4	71.0	92.0
Driver's eye height, in.	EYEHGT	62.0	68.0	59.0	62.0	64.0
Driver's station height, in.	--	34.5	40.5	30.0	--	--
Front pushbar height, in.	PBHT	24.8	25.5	17.5	18.0	27.0
Front hitch height, in.	FHT	24.8	25.5	17.5	18.0	27.0
Approach angle, deg	VAA	90.0	63.0	61.0	66.0	62.0
CG height, in.	CGH	33.5	33.5	32.25	24.2	34.7
Minimum chassis clearance, in.	CL	11.3	10.0	9.25	8.8	13.5
Rear hitch height, in.	RHT	24.9	25.0	26.25	20.0	15.8
Departure angle, deg	VDA	58.0	51.0	40.0	37.0	52.0
Vehicle/unit width, in.	WDTH	84.0	84.0	82.3	64.0	85.0
Lateral distance: center-plane to CG, in.	CGLAT	0	0.3	0	0	0
If CGLAT ≠ 0 : lateral CG location from center plane looking forward: right (R) or left (L)	--	--	R	--	--	--
Swim speed, mph (0 for nonswimmer)	--	0	0	0	0	2
Fording depth, in. (measured from ground) or swimming depth, in.	--	30.0	30.0	30.0	21.0	49.0
Wheel track, in.	WT(1)	71.6	72.3	69.8	53.0	72.0
Ground clearance under axle, in.	CLRMIN(1)	11.3	10.0	9.25	8.8	13.5
Lateral clearance between inner tires, in.	WTE(1)	59.1	59.8	57.3	46.0	61.0

* First to last axle.

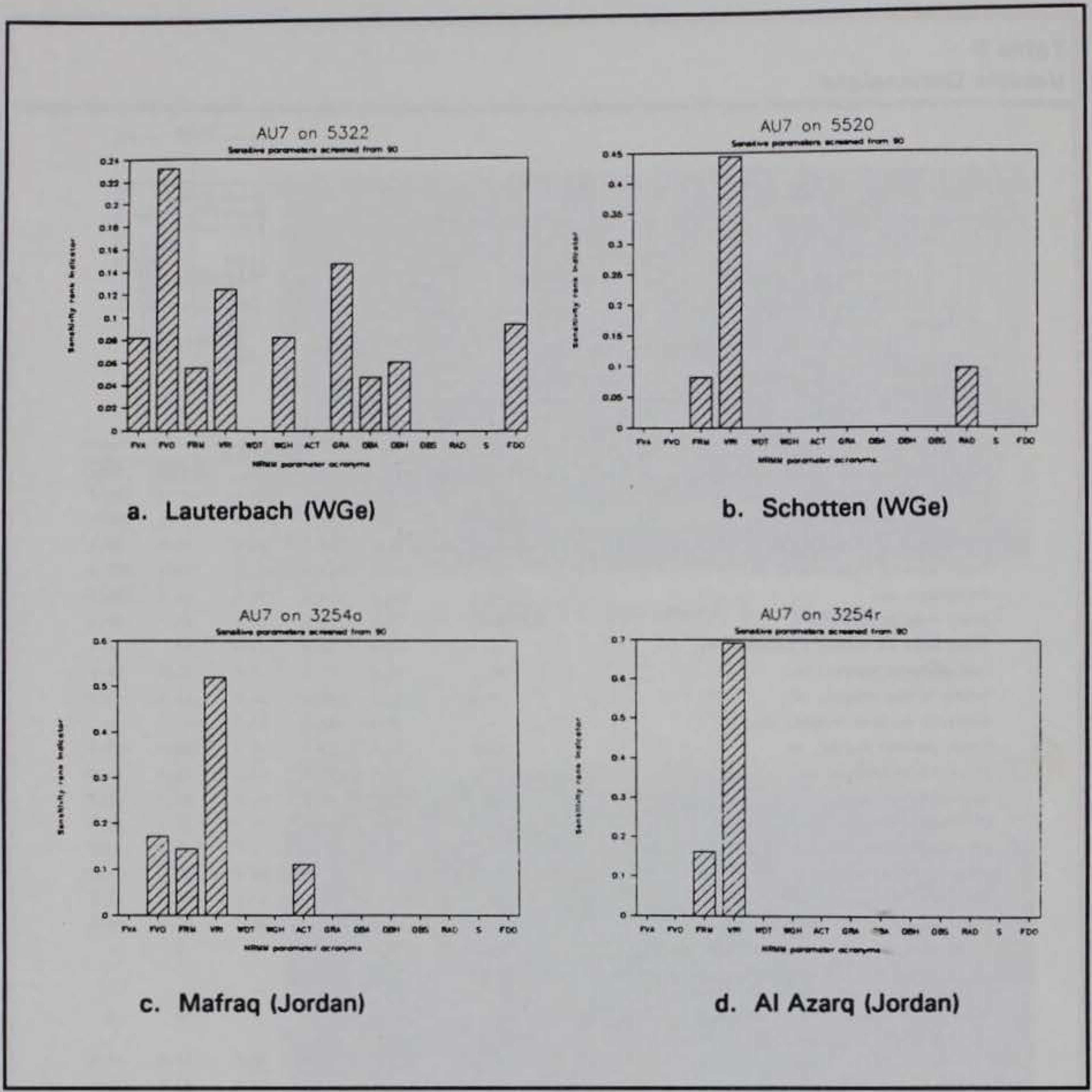


Figure 14. Parameter sensitivity of AU7 in four terrains

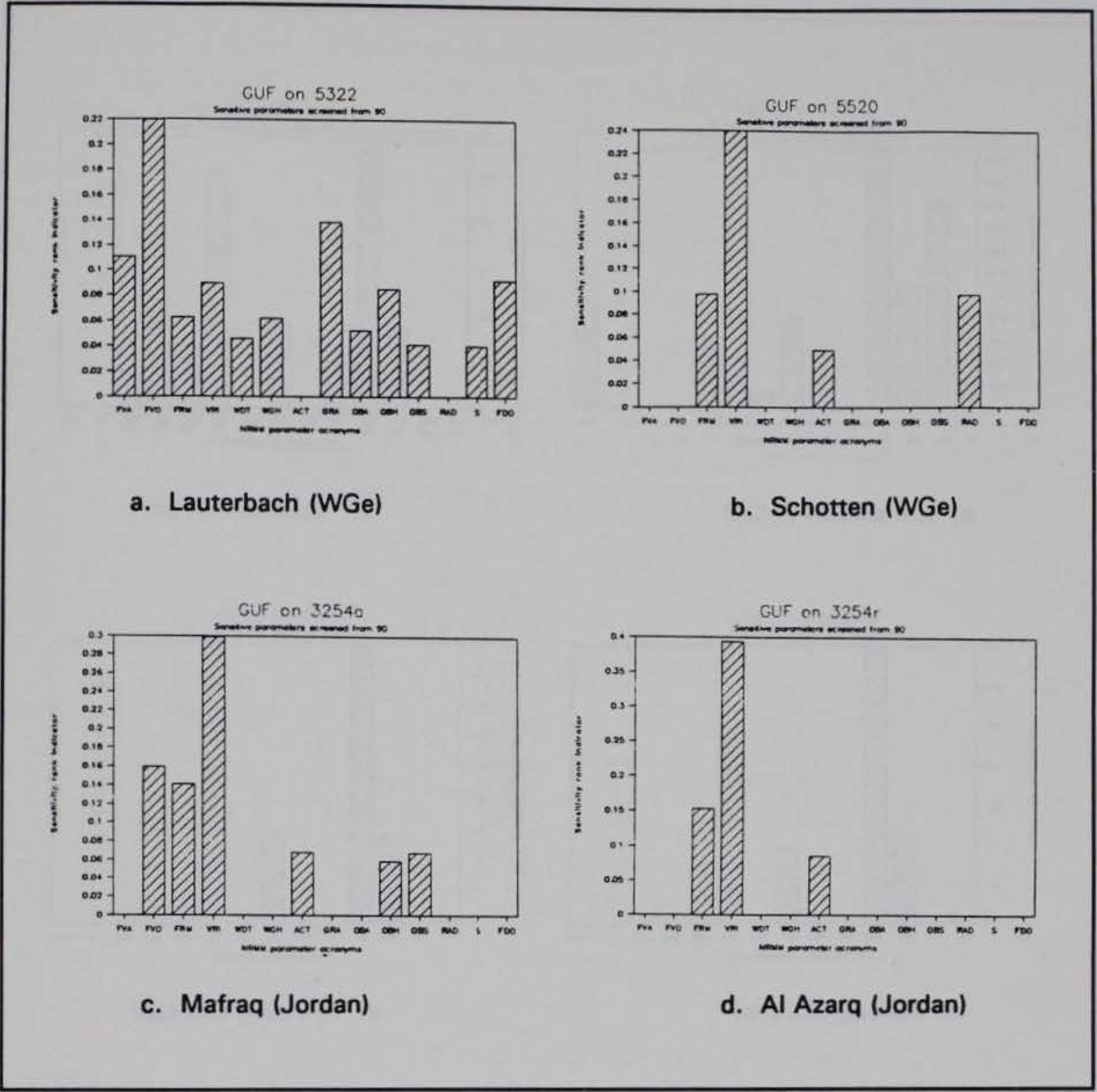


Figure 15. Parameter sensitivity of GUF in four terrains

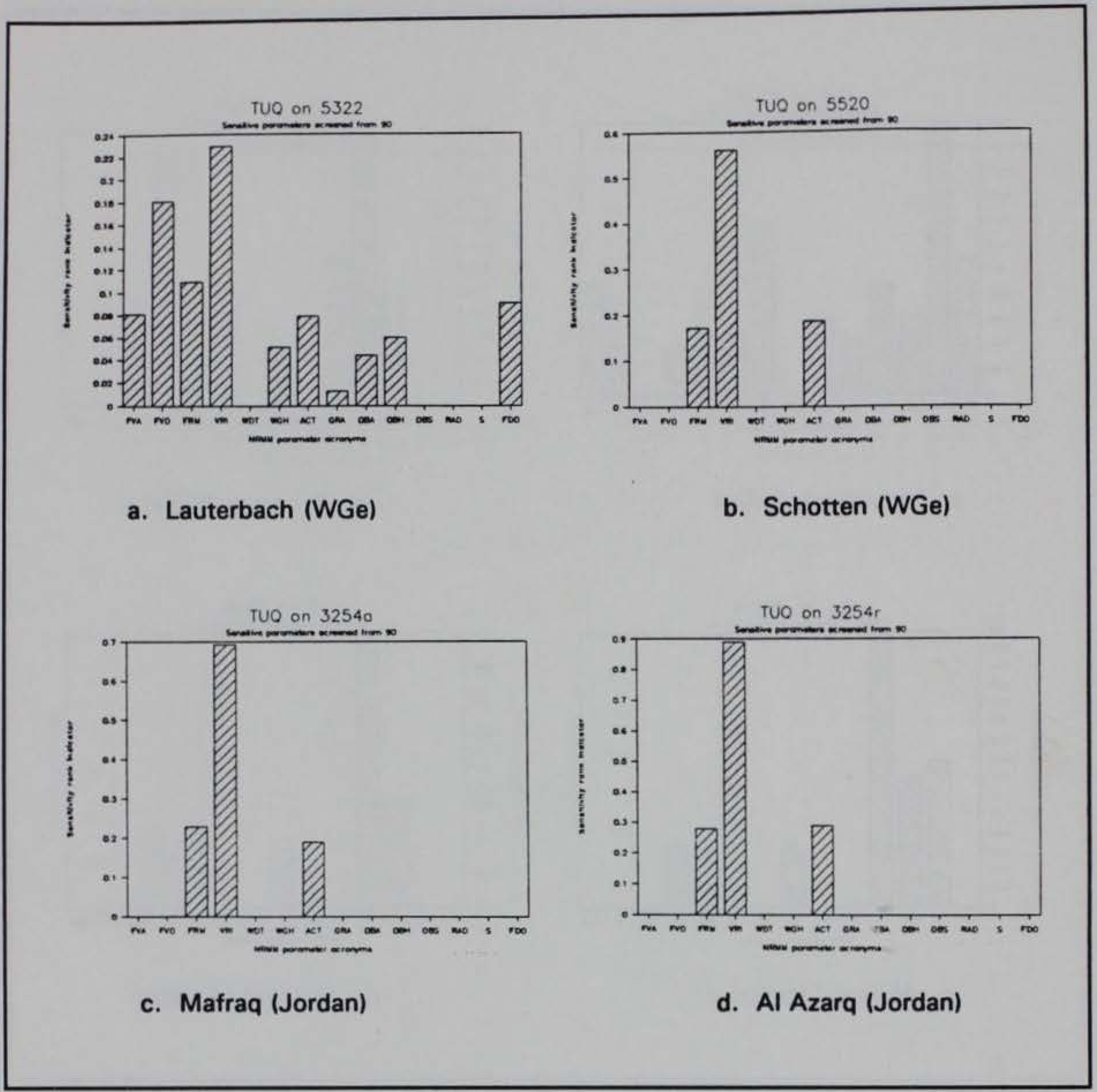


Figure 16. Parameter sensitivity of TUQ in four terrains

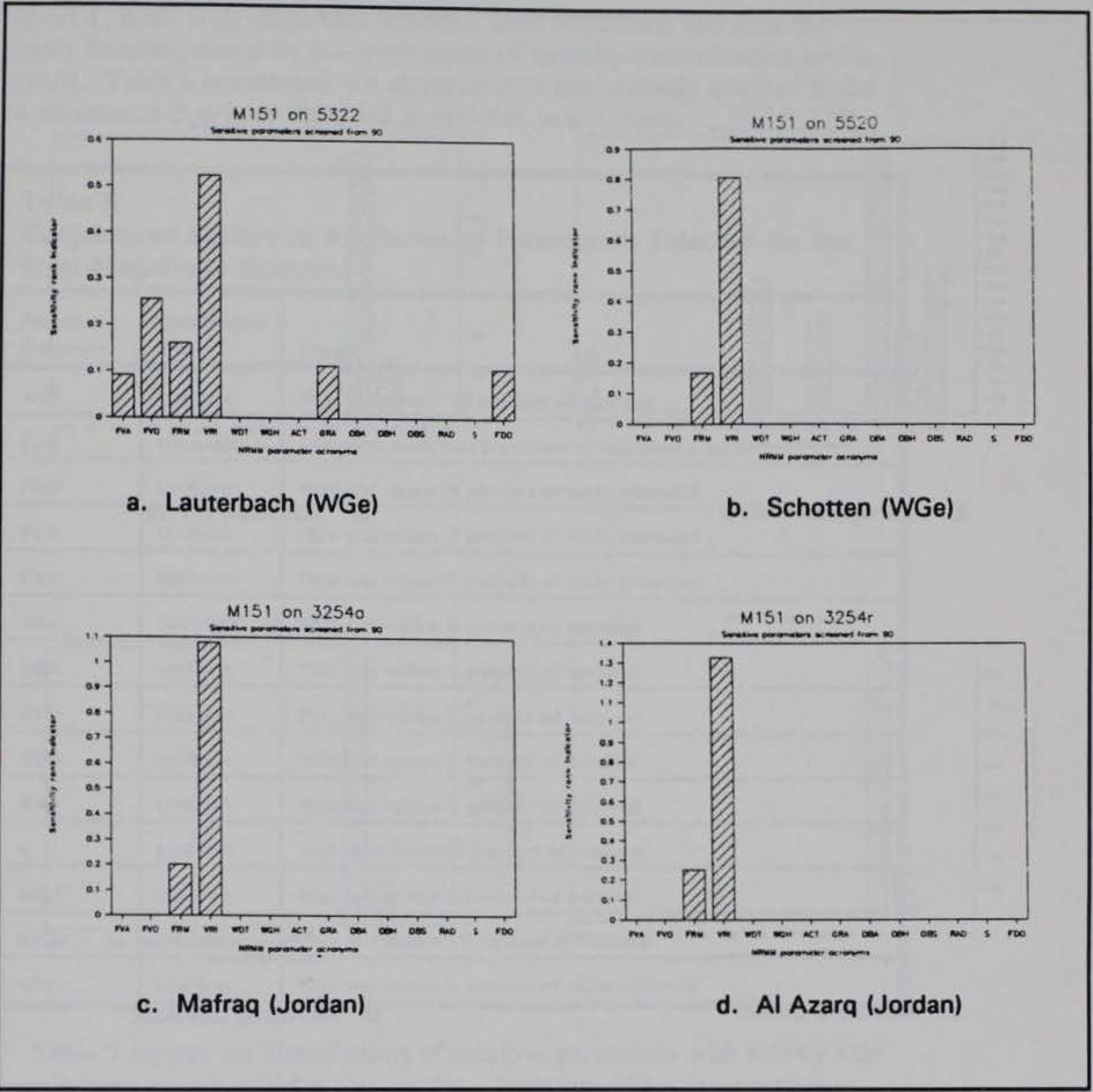


Figure 17. Parameter sensitivity of M151 in four terrains

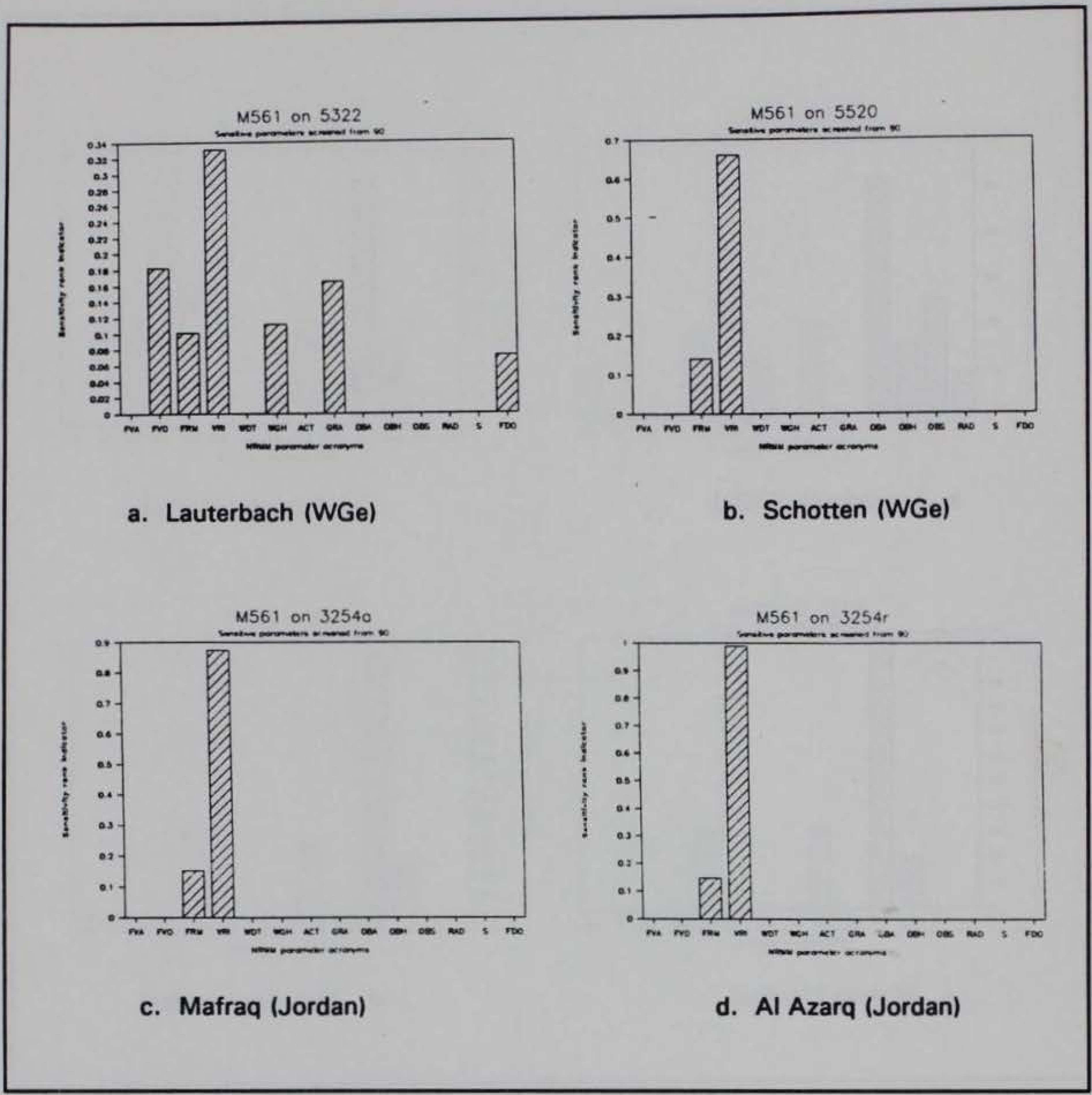


Figure 18. Parameter sensitivity of M561 in four terrains

Report 1, these error-magnitude scenarios were conjectural and must ultimately be strengthened by the involvement of mobility-data-collection professionals. Table 6 summarizes the characteristics speculatively ascribed to the 14 parameters that were identified as sensitive in this study.

Table 6
Conjectured Statistical Attributes of Parameters Selected for the Error-Magnitude Scenario

Parameter Acronym	Distribution Type	Range
ACT	Uniform	Plus and minus 10 percent of nominal
FDO	Gaussian	Standard deviation 5 percent of regression value
FRM	Uniform	Plus and minus 5 percent of table midpoint
FVA	Uniform	Plus and minus 5 percent of table midpoint
FVO	Uniform	Plus and minus 5 percent of table midpoint
GRA	Uniform	Plus and minus 5 percent of nominal
OBA	Uniform	Plus and minus 5 percent of nominal
OBH	Uniform	Plus and minus 5 percent of nominal
OBS	Uniform	Plus and minus 5 percent of nominal
RAD	Uniform	Plus and minus 5 percent of nominal
S	Uniform	Plus and minus 3 percent of nominal
WDT	Uniform	Plus and minus 2 percent of nominal
WGH	Uniform	Plus and minus 10 percent of nominal
VRI	Uniform	Plus and minus 5 percent of table midpoint

Table 7 repeats the identification of sensitive parameters with side-by-side comparisons among vehicles and terrains. Note that where few parameters are sensitive, those parameters are very sensitive and others have been screened out; conversely, where many parameters are sensitive, no one parameter is dominant.

Fingerprints and Speed Profiles

The basic information generated by stochastic mobility forecasts is contained in fingerprints and speed profiles. Postprocessing this information yields mobility rating speeds and speed ranges which are the factors of greatest interest to the user community. In this section are presented numerous figures which show the stochastic NRMM speed predictions for the HMMWV candidates. They are presented as fingerprints, in-unit speed profiles and average speed profiles for each vehicle on the off-road terrains (5322 and 3254a) and as fingerprints, and average speed profiles for primary roads,

Table 7
Identification of Sensitive Parameters

Terrains:

3254r = Az Zarqa
5520 = Schotten
3254a = Mafraq
5322 = Lauterbach

Scenario: Dry, normal

Vehicles: AU7, GUF, TUQ, M151, M561

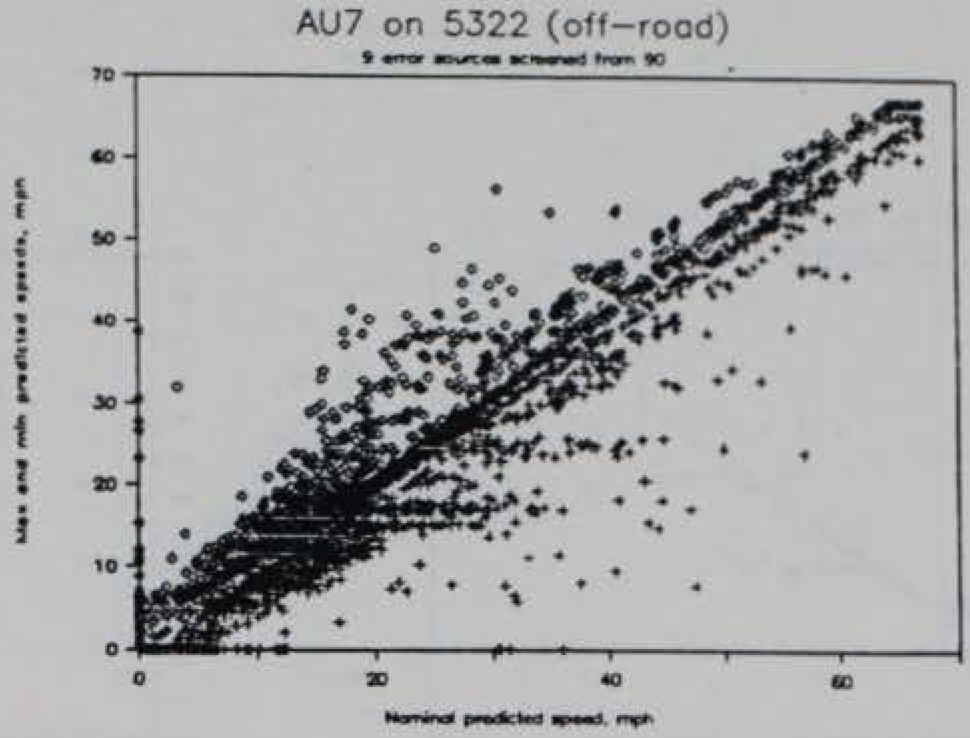
Parameter Acronyms:

Screenings:		FVA	FVO	FRM	VRI	WDT	WGH	ACT	GRA	OBA	OBH	OBS	RAD	S	FDO
5322	AU7	•	•	•	•		•		•	•	•				•
	GUF	•	•	•	•	•	•		•	•	•	•		•	•
	TUQ	•	•	•	•		•	•	•	•	•				•
	M151	•	•	•	•				•						•
	M561		•	•	•		•		•						•
3254a	AU7		•	•	•			•							
	GUF		•	•	•			•			•	•			
	TUQ			•	•			•							
	M151			•	•										
	M561			•	•										
3254r	AU7			•	•										
	GUF			•	•			•							
	TUQ			•	•			•							
	M151			•	•										
	M561			•	•										
5520	AU7			•	•								•		
	GUF			•	•			•					•		
	TUQ			•	•			•							
	M151			•	•										
	M561			•	•										

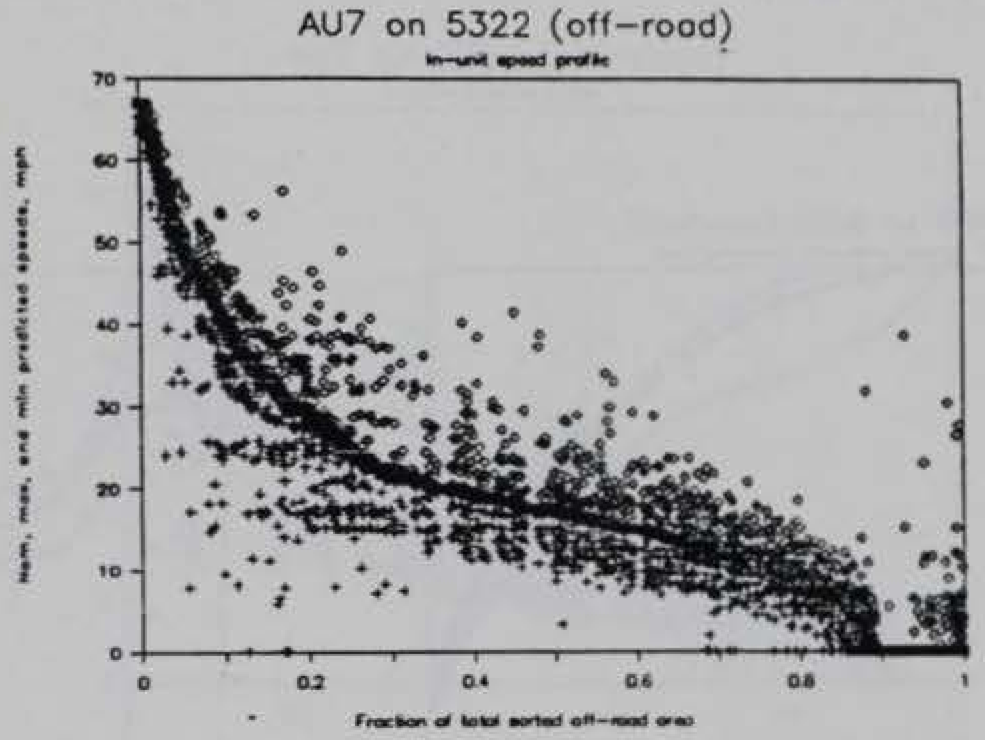
secondary roads and trails for the on-road terrains (3254r and 5520). This information is presented in Figures 19 through 38. It will be helpful to discuss two of these figures in detail as representatives of all the others.

Figure 19 shows fingerprint and profiles for the AU7 on 5322. The fingerprint, remember, conveys a global impression of the impact of data uncertainties in the speed prediction of NRMM for this vehicle, this terrain, and the associated error-magnitude scenario. The greater the departure of the fingerprint from a straight line at unit slope, the greater the effect of the uncertainties. Clusters are characteristics of the vehicle. Note that the density of points gives clues about the importance of the clusters. There are 2707 points in this figure. Above about 20 mph, most of them actually fall close to the unit slope line. Below 20 mph, most points occupy a dense cluster whose width is fairly well defined. Points that can be distinguished individually represent events of relatively infrequent occurrence. In other words, relatively few of the 2707 terrain units are represented by individually distinguishable points.

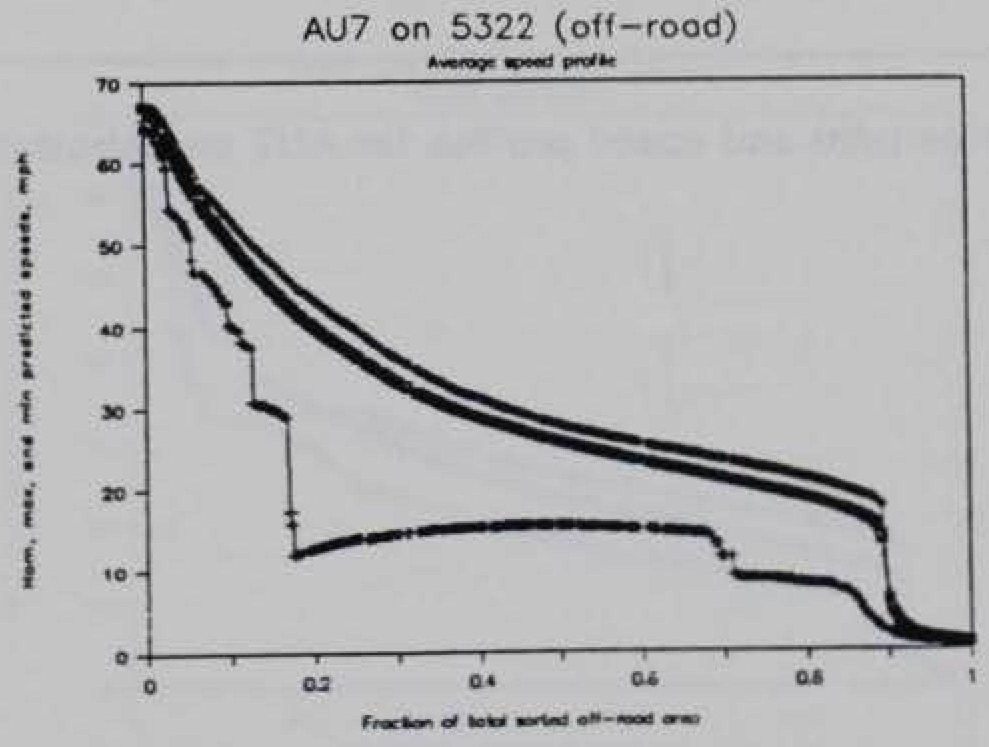
The in-unit speed profile contains the same speed data as the fingerprint but plots speeds versus an area fraction obtained by sorting a list of nominal



a. Fingerprint

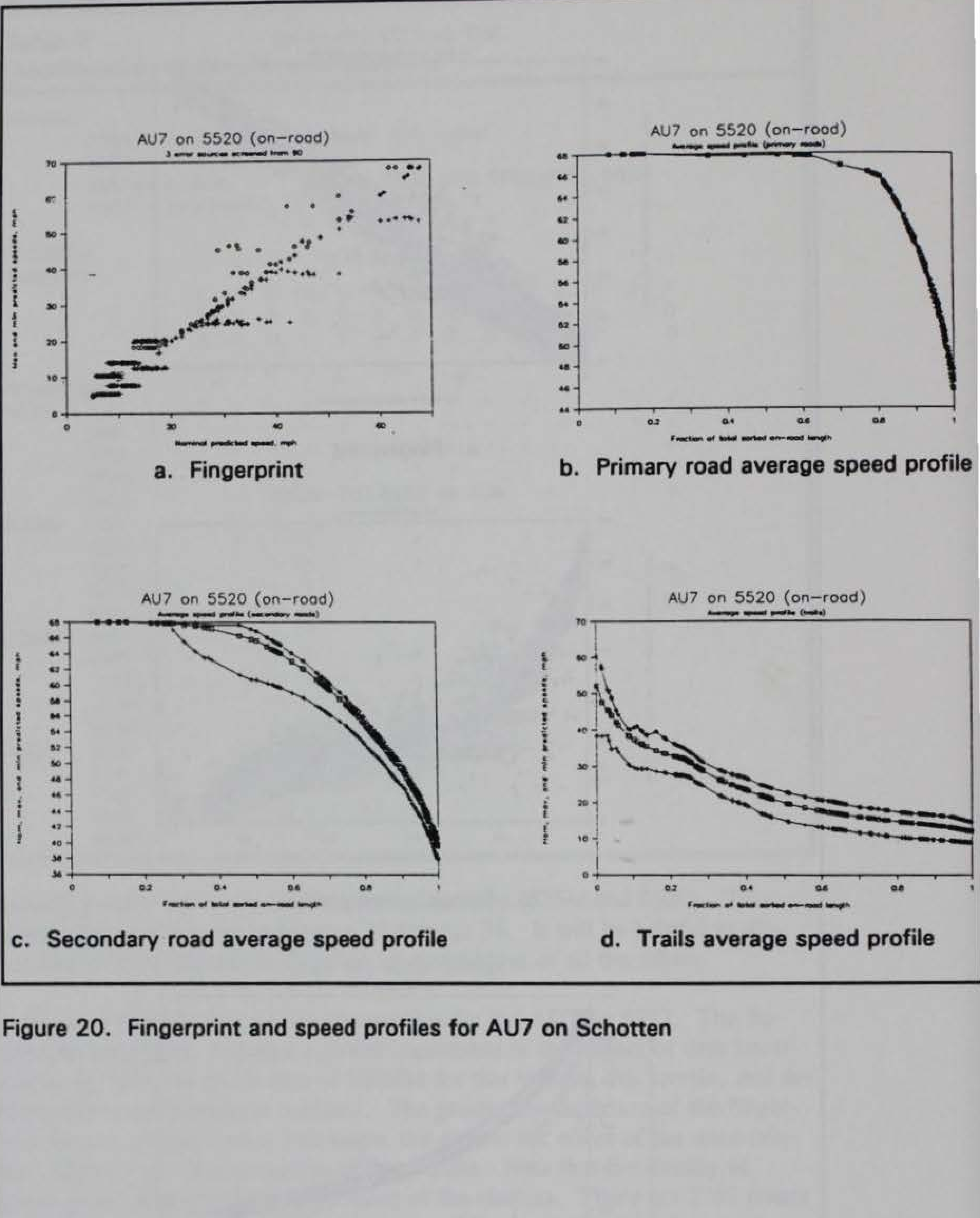


b. In-unit speed profile



c. Average speed profile

Figure 19. Fingerprints and speed profiles for AU7 on Lauterbach



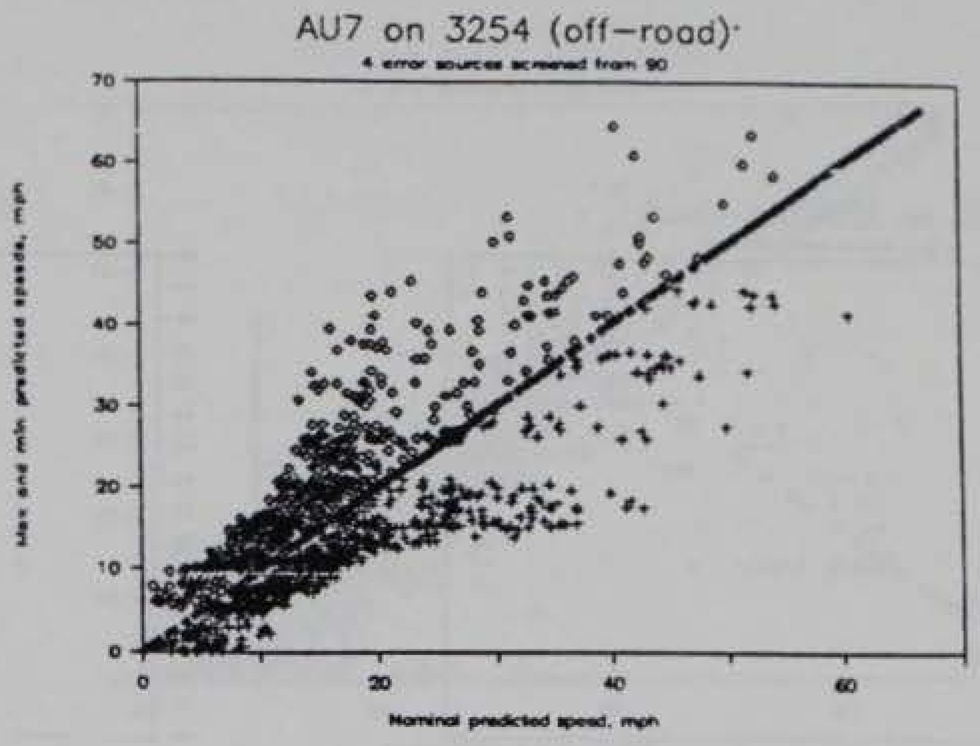
a. Fingerprint

b. Primary road average speed profile

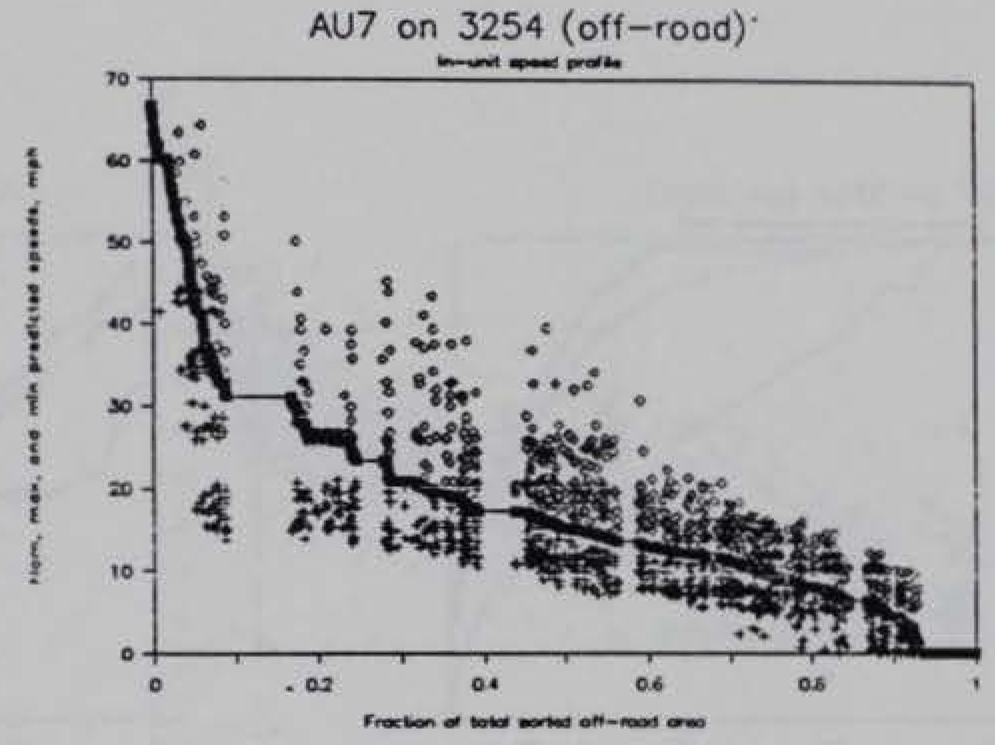
c. Secondary road average speed profile

d. Trails average speed profile

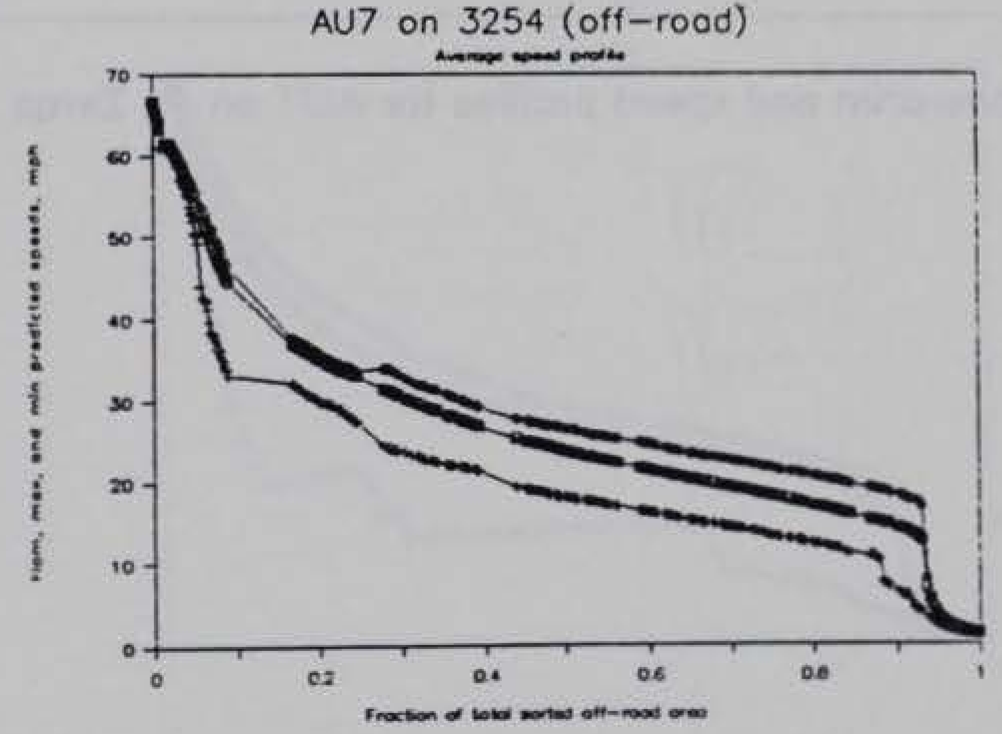
Figure 20. Fingerprint and speed profiles for AU7 on Schotten



a. Fingerprint

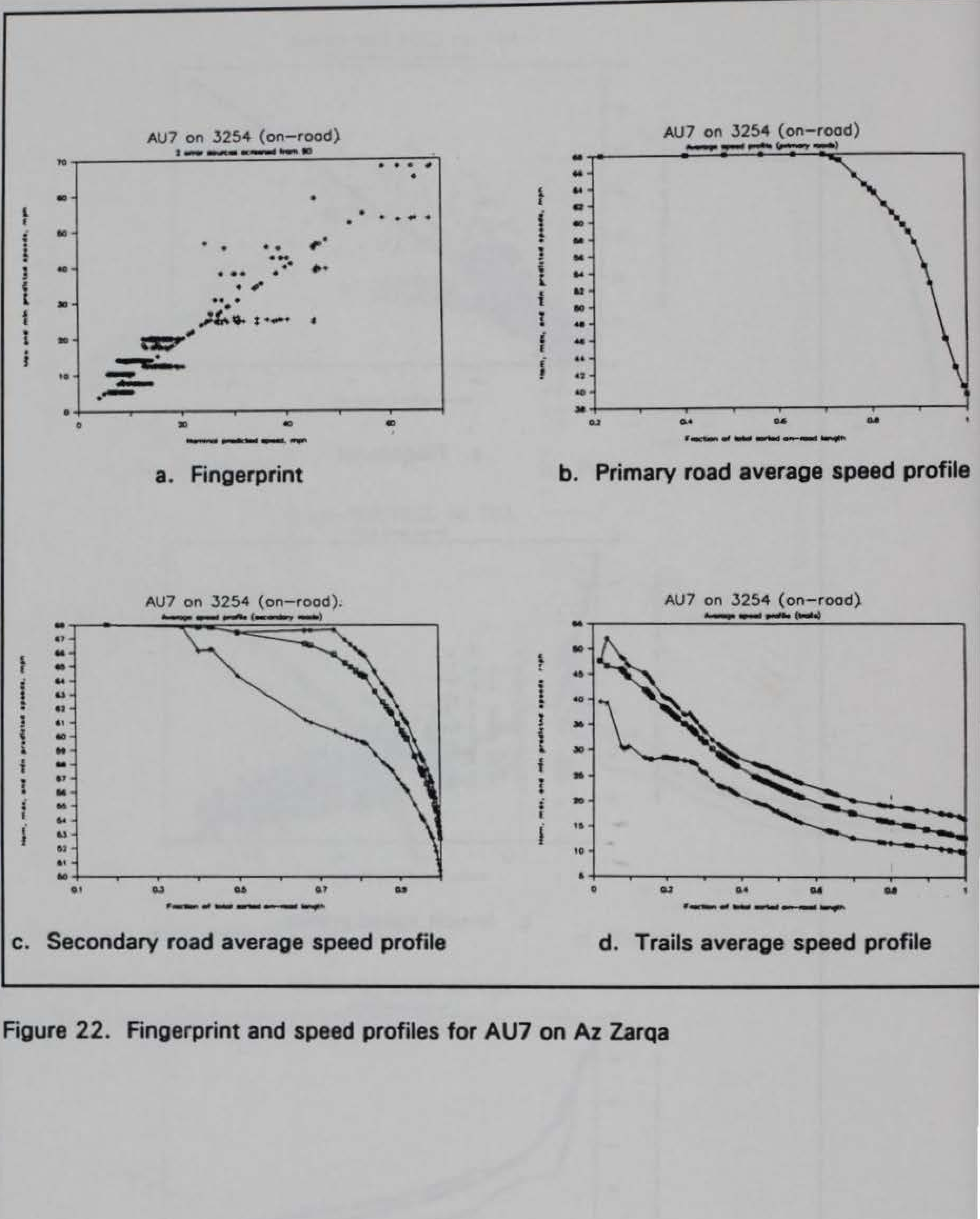


b. In-unit speed profile



c. Average speed profile

Figure 21. Fingerprints and speed profiles for AU7 on Mafraq



a. Fingerprint

b. Primary road average speed profile

c. Secondary road average speed profile

d. Trails average speed profile

Figure 22. Fingerprint and speed profiles for AU7 on Az Zarqa

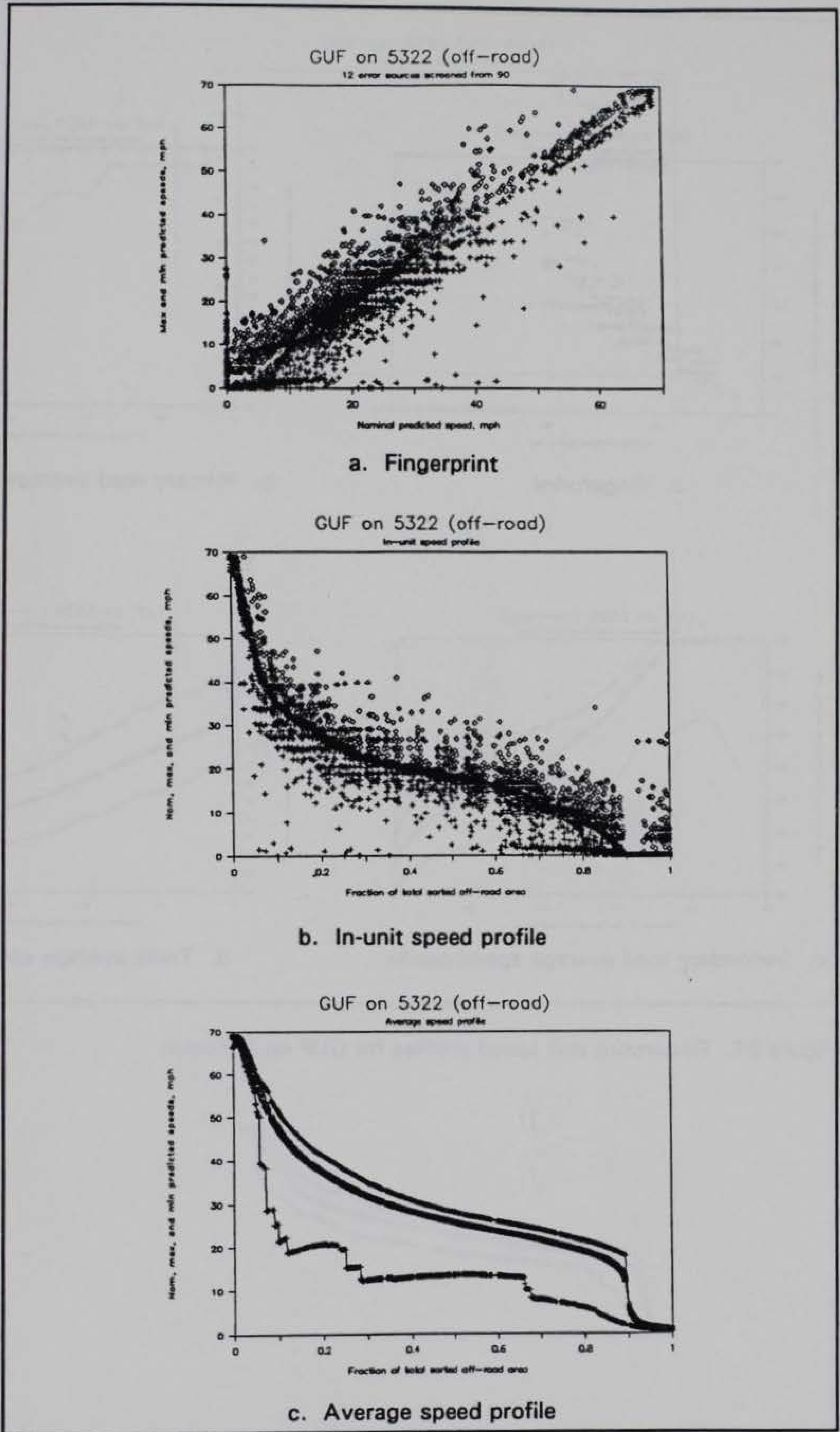
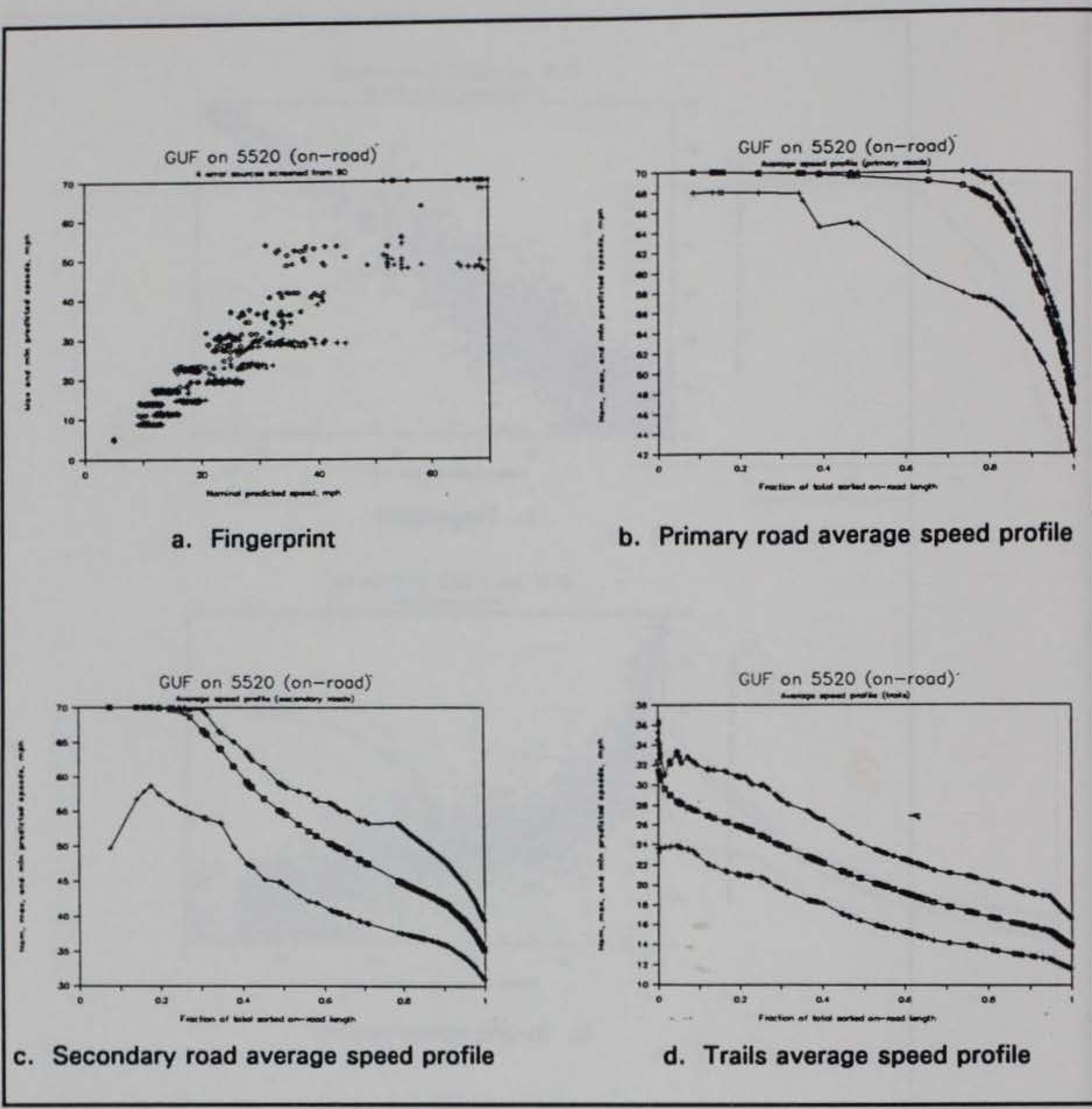


Figure 23. Fingerprints and speed profiles for GUF on Lauterbach



a. Fingerprint

b. Primary road average speed profile

c. Secondary road average speed profile

d. Trails average speed profile

Figure 24. Fingerprint and speed profiles for GUF on Schotten

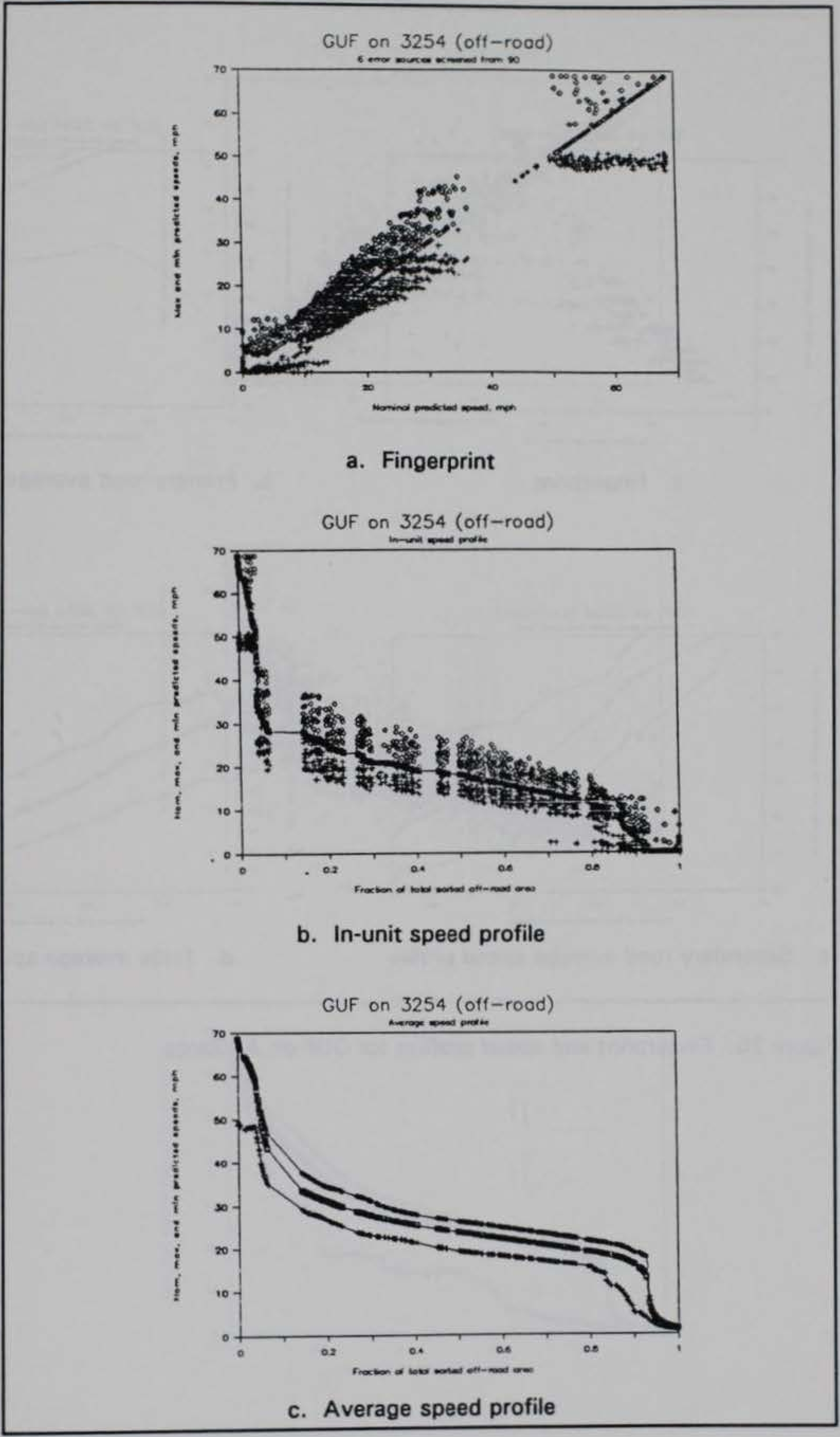
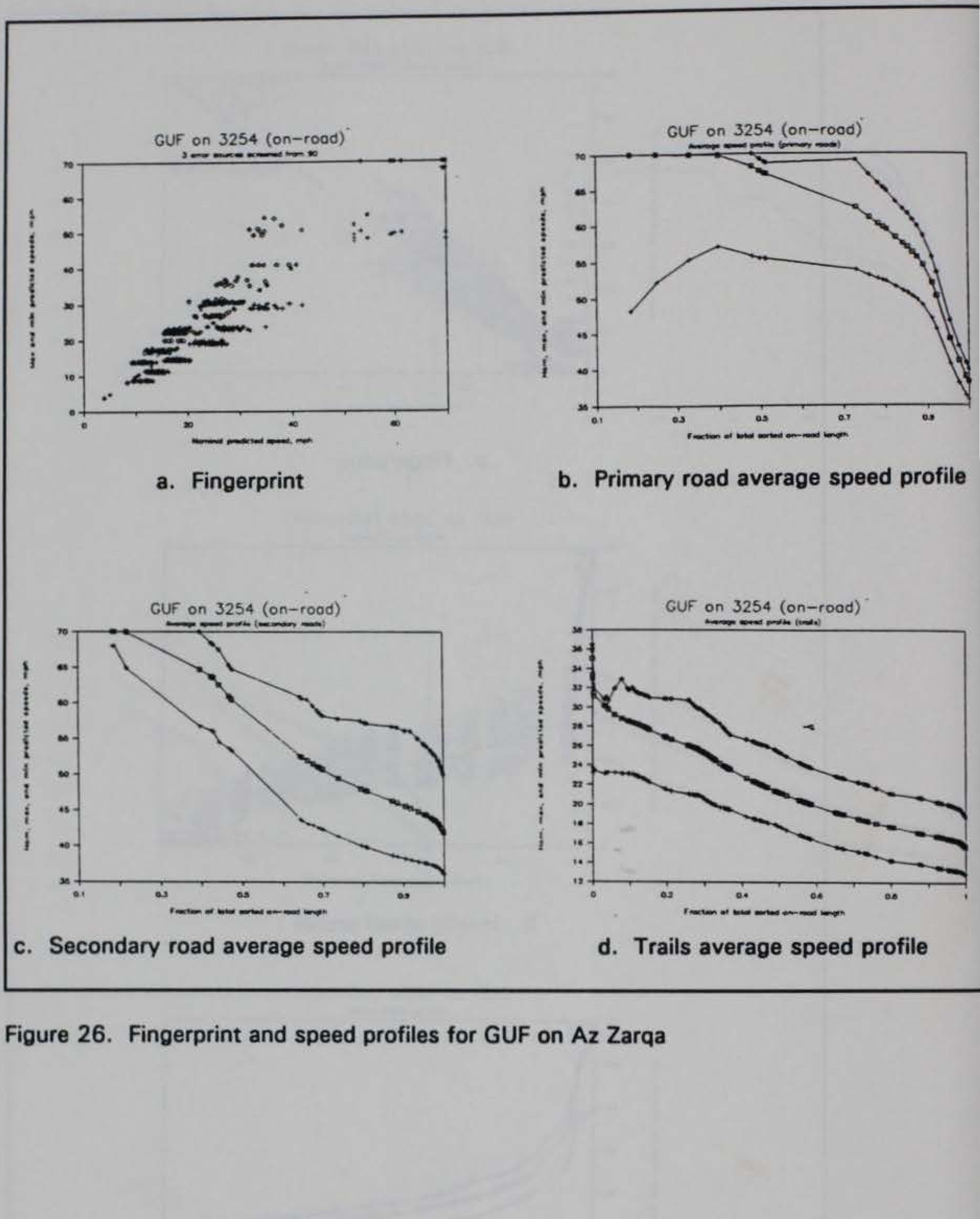


Figure 25. Fingerprints and speed profiles for GUF on Mafraq



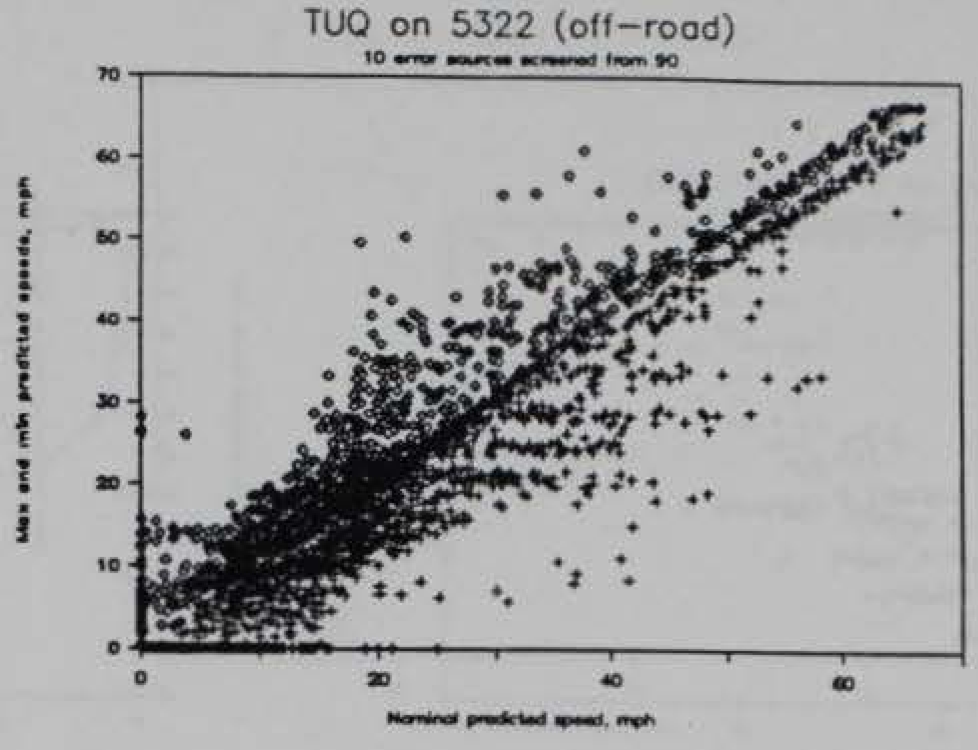
a. Fingerprint

b. Primary road average speed profile

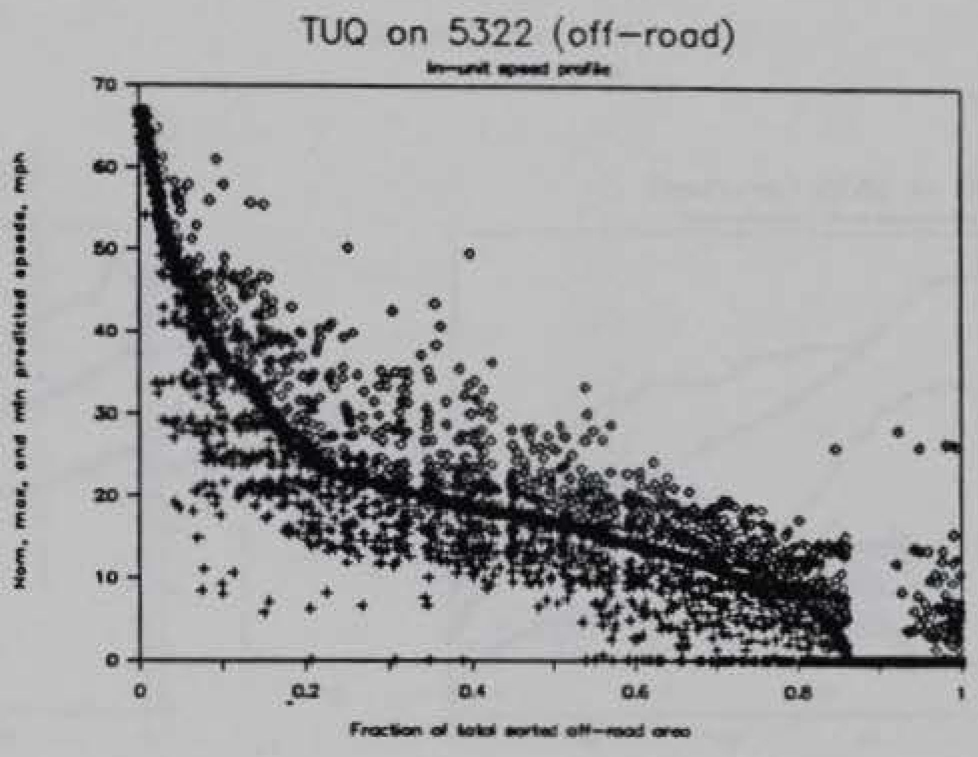
c. Secondary road average speed profile

d. Trails average speed profile

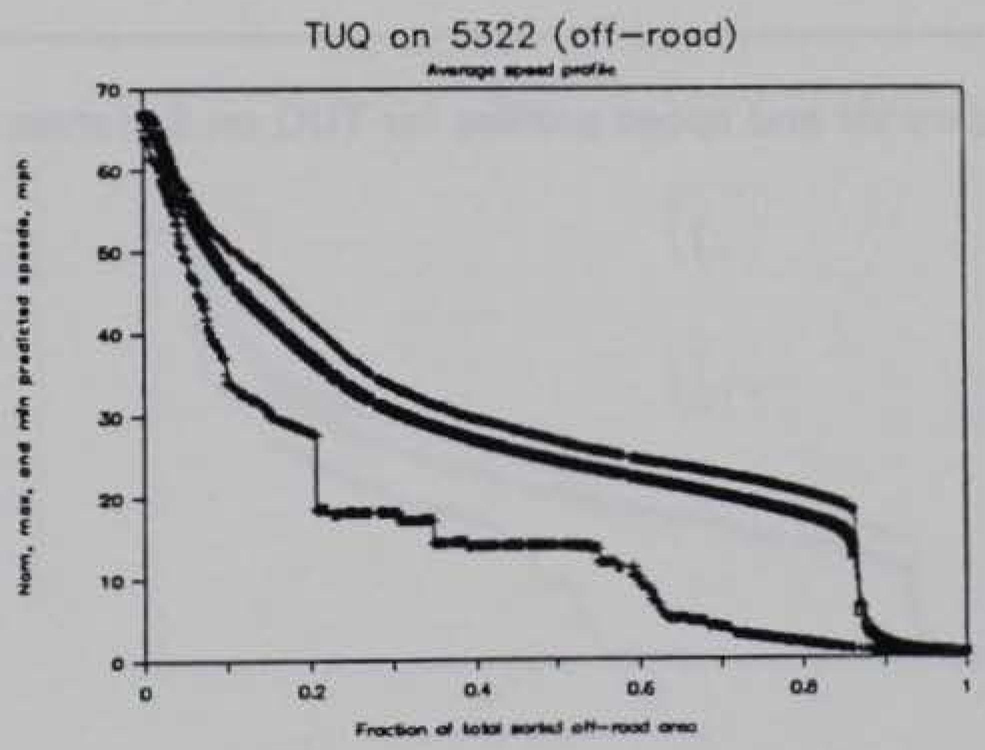
Figure 26. Fingerprint and speed profiles for GUF on Az Zarqa



a. Fingerprint

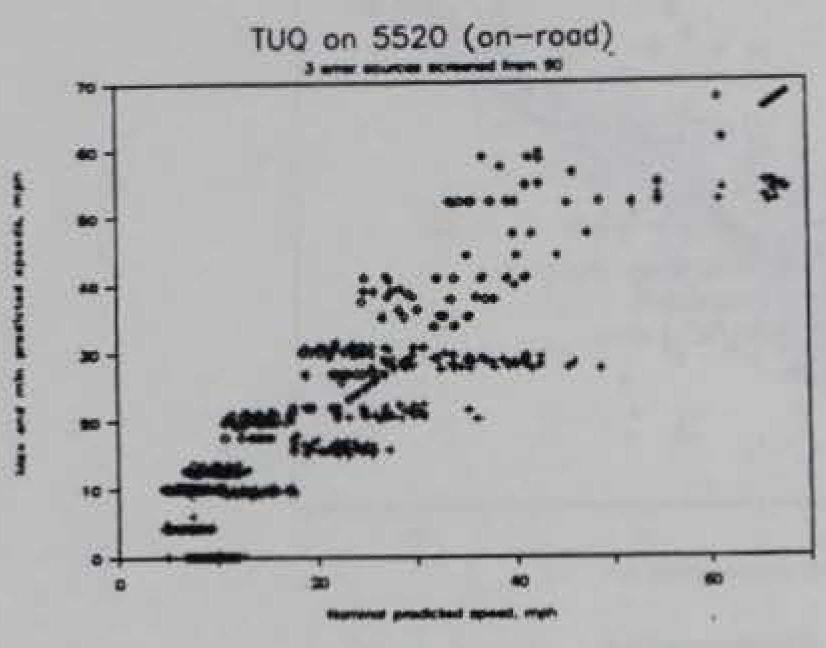


b. In-unit speed profile

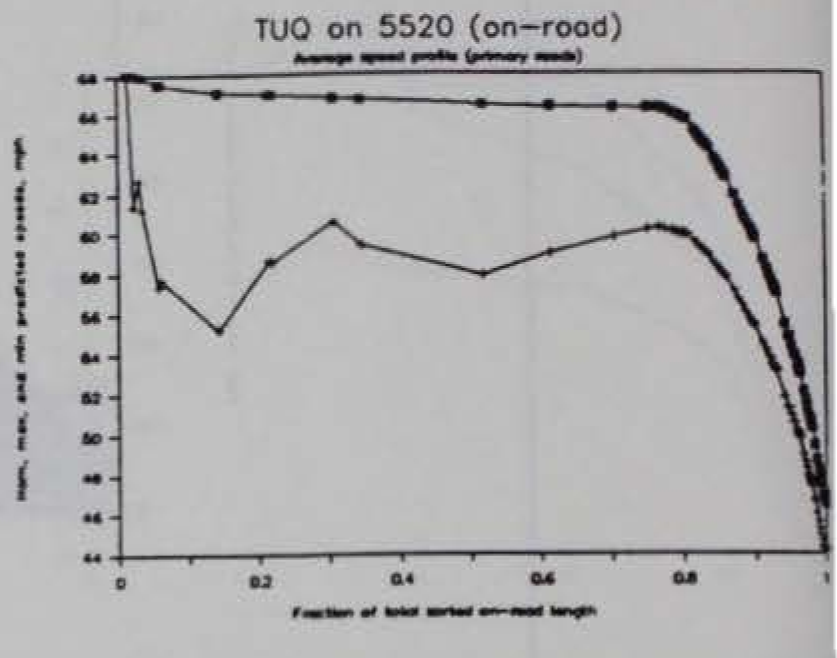


c. Average speed profile

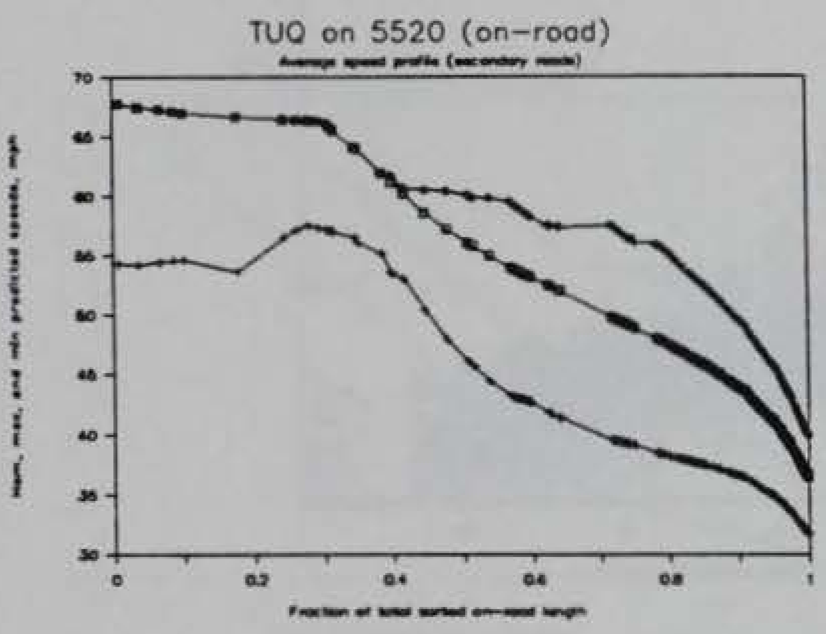
Figure 27. Fingerprints and speed profiles for TUQ on Lauterbach



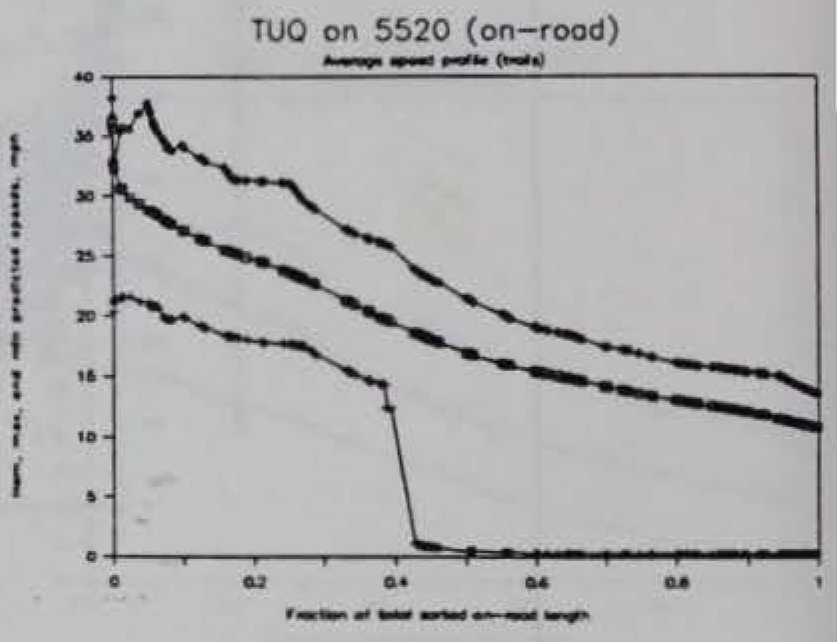
a. Fingerprint



b. Primary road average speed profile

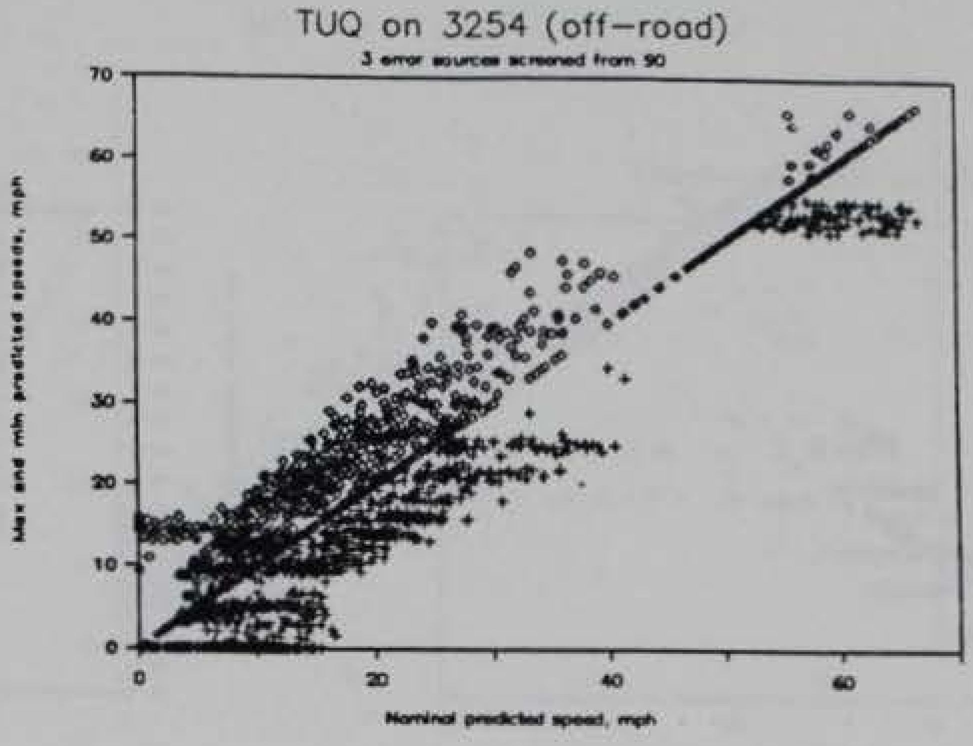


c. Secondary road average speed profile

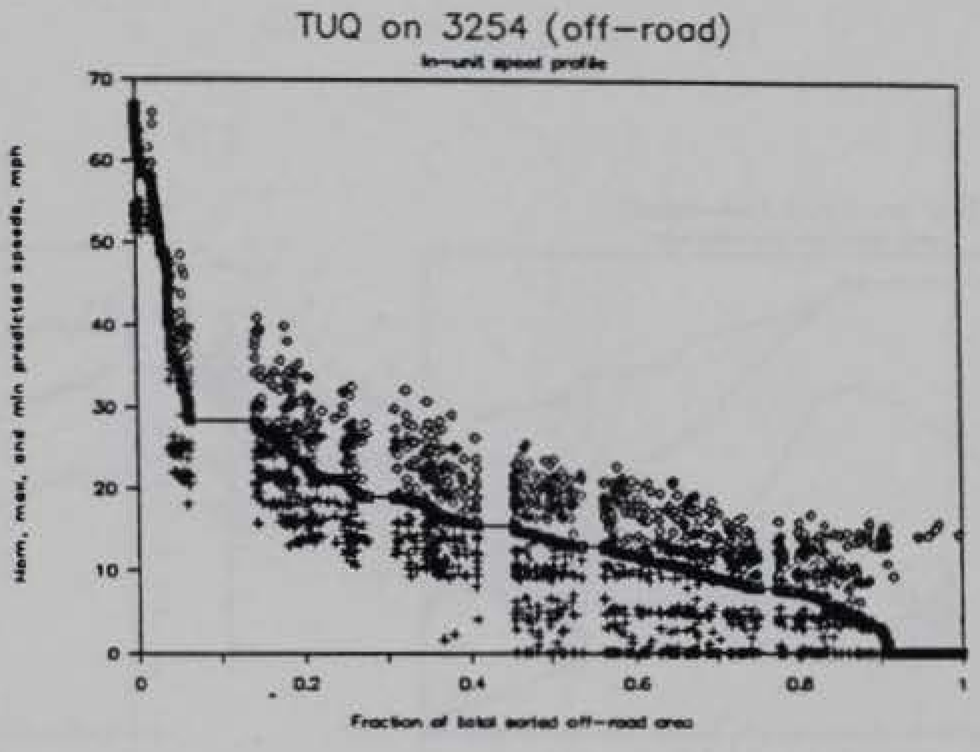


d. Trails average speed profile

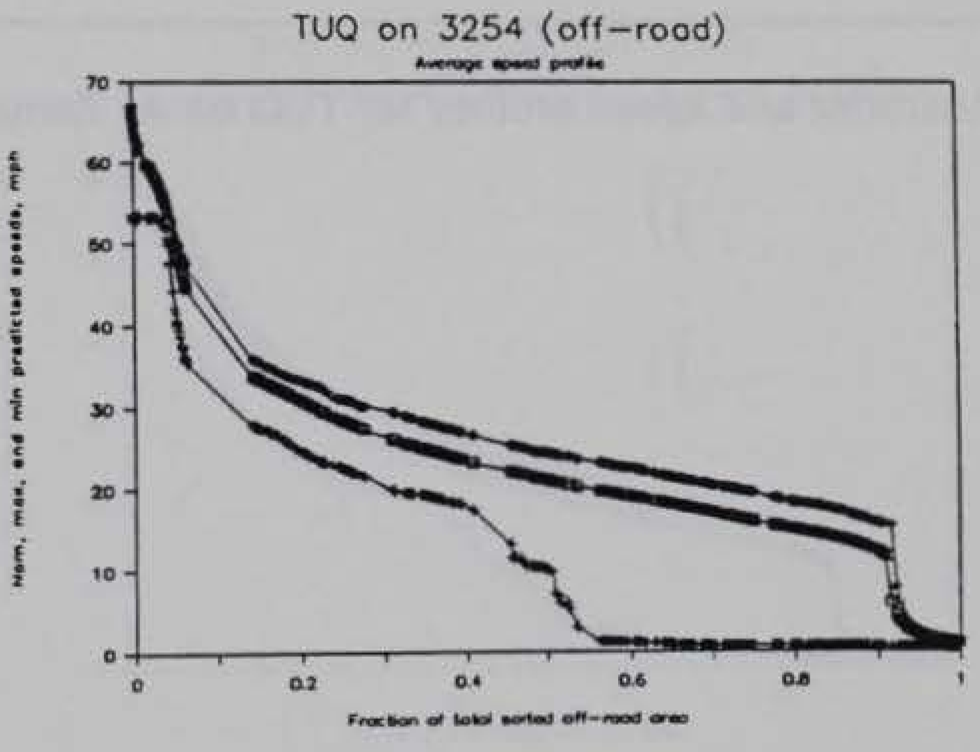
Figure 28. Fingerprint and speed profiles for TUQ on Schotten



a. Fingerprint

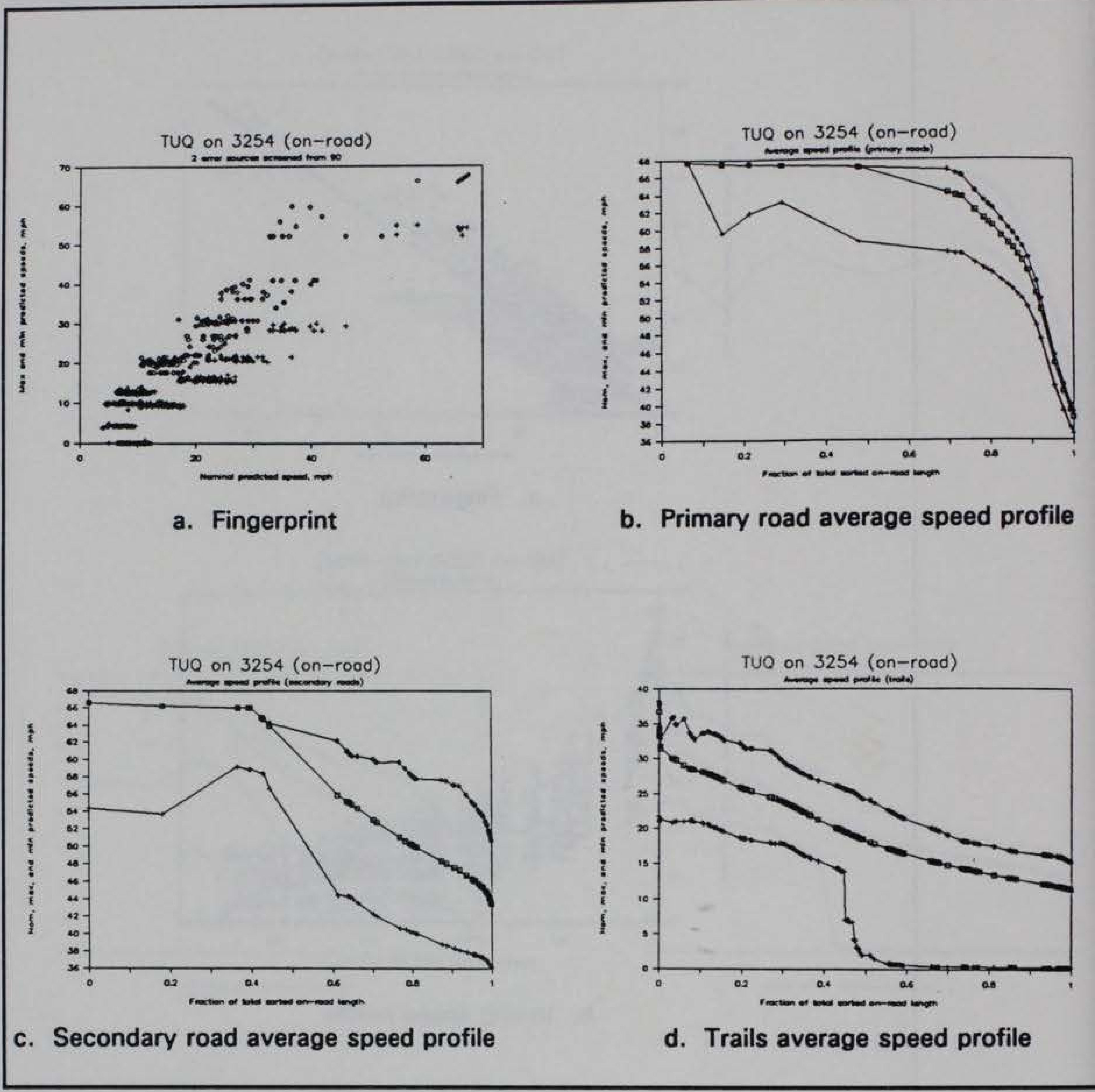


b. In-unit speed profile



c. Average speed profile

Figure 29. Fingerprints and speed profiles for TUQ on Mafraq



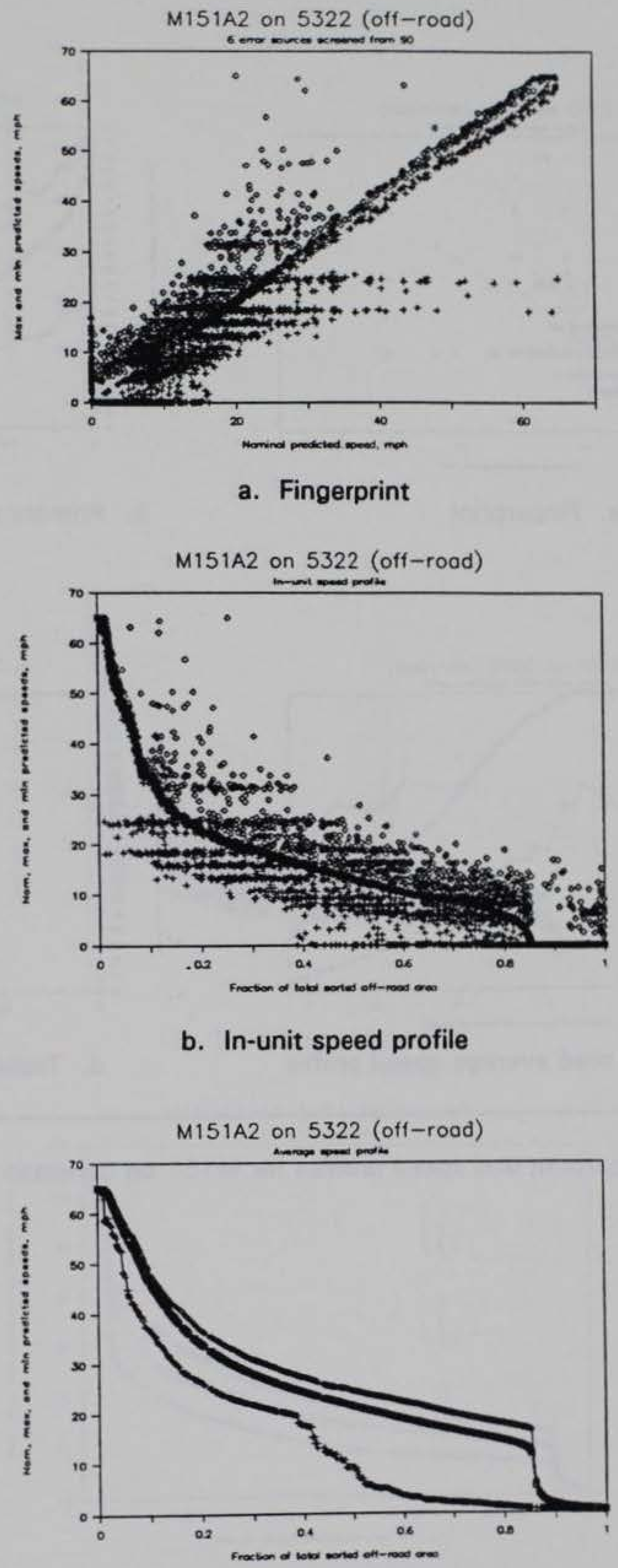
a. Fingerprint

b. Primary road average speed profile

c. Secondary road average speed profile

d. Trails average speed profile

Figure 30. Fingerprint and speed profiles for TUQ on Az Zarqa

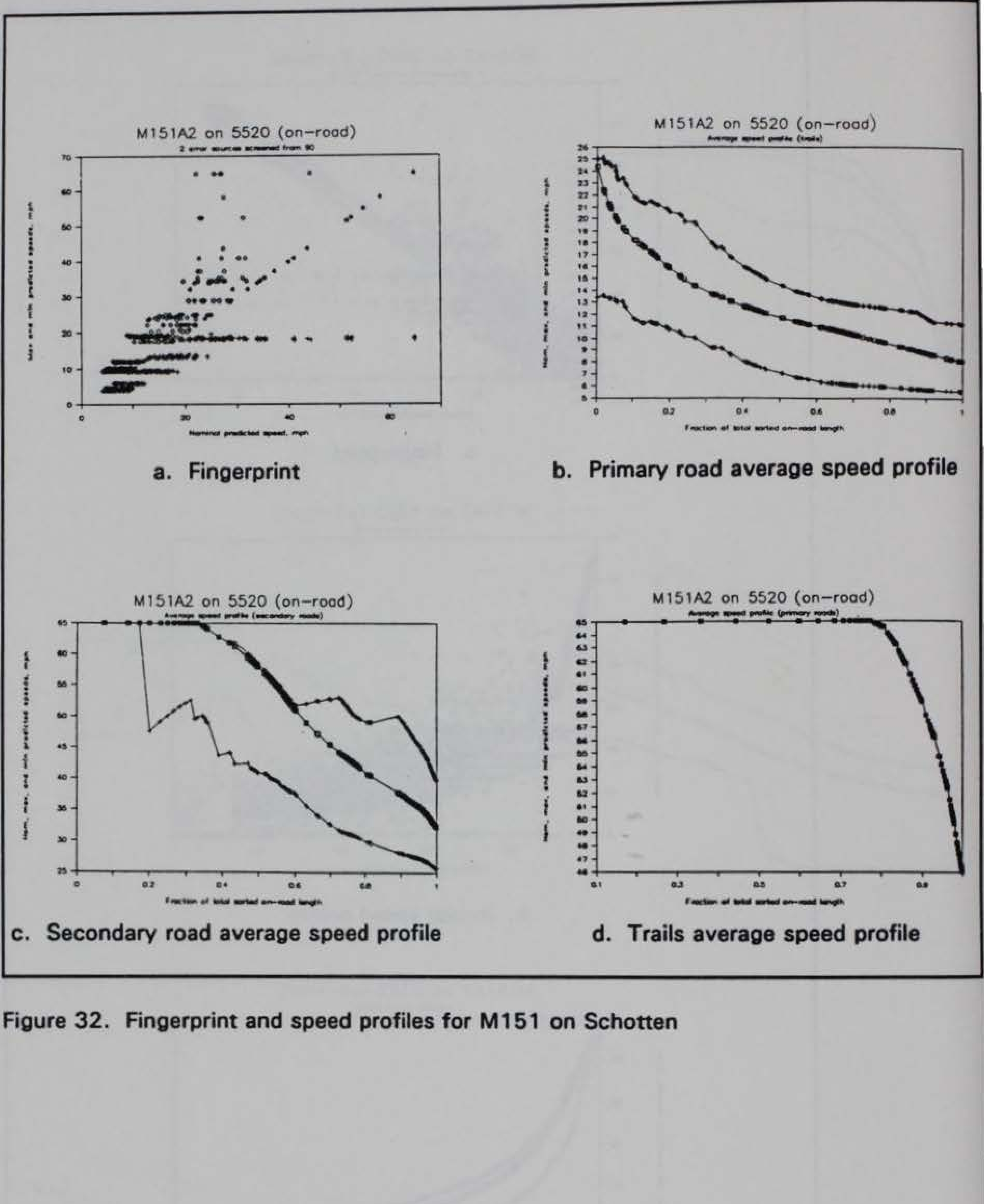


a. Fingerprint

b. In-unit speed profile

c. Average speed profile

Figure 31. Fingerprints and speed profiles for M151 on Lauterbach



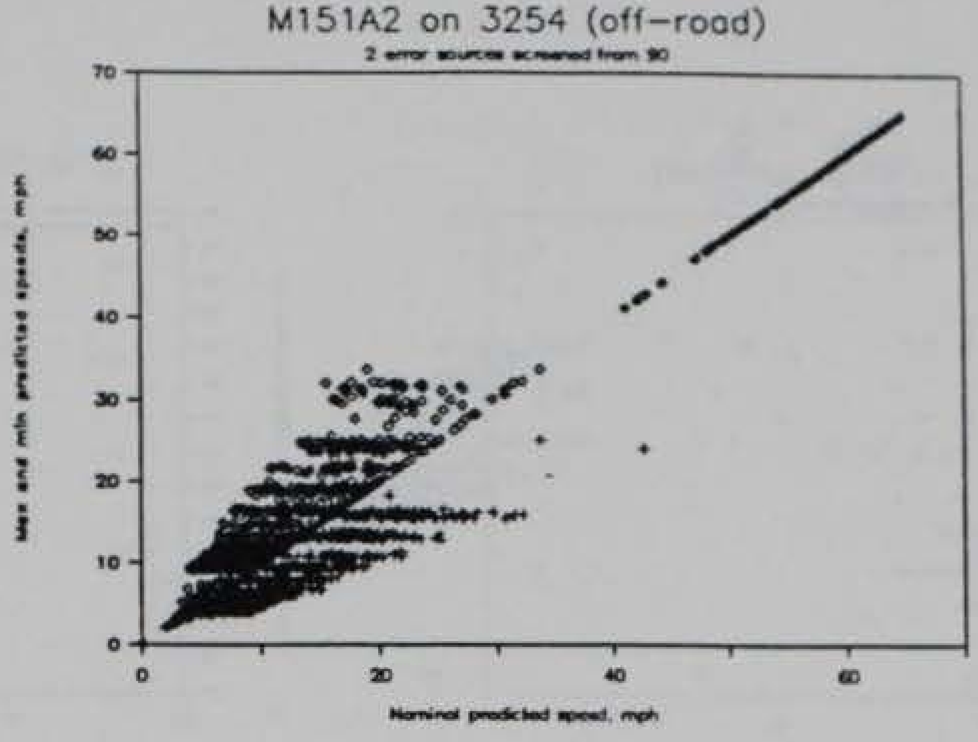
a. Fingerprint

b. Primary road average speed profile

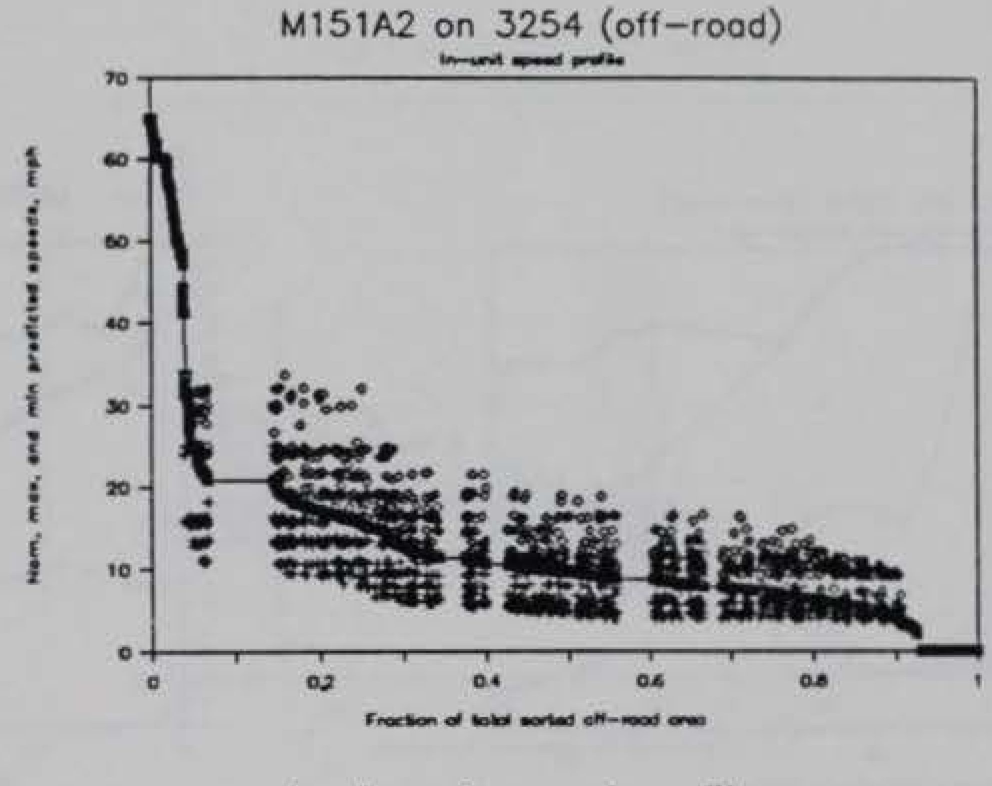
c. Secondary road average speed profile

d. Trails average speed profile

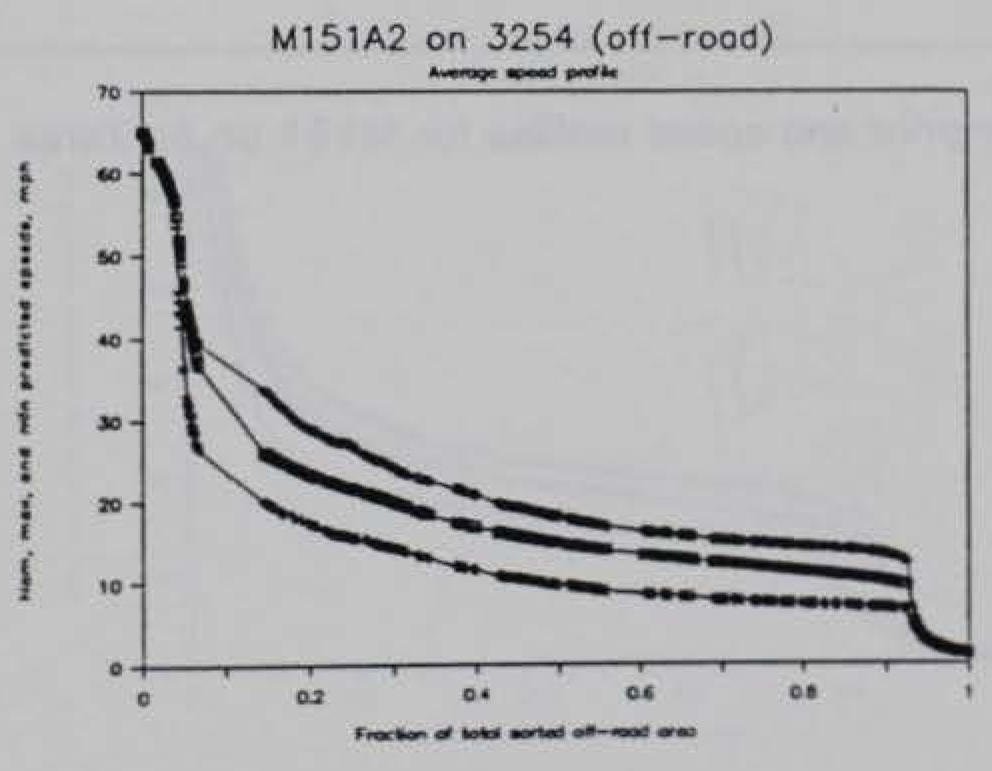
Figure 32. Fingerprint and speed profiles for M151 on Schotten



a. Fingerprint



b. In-unit speed profile



c. Average speed profile

Figure 33. Fingerprints and speed profiles for M151 on Mafraq

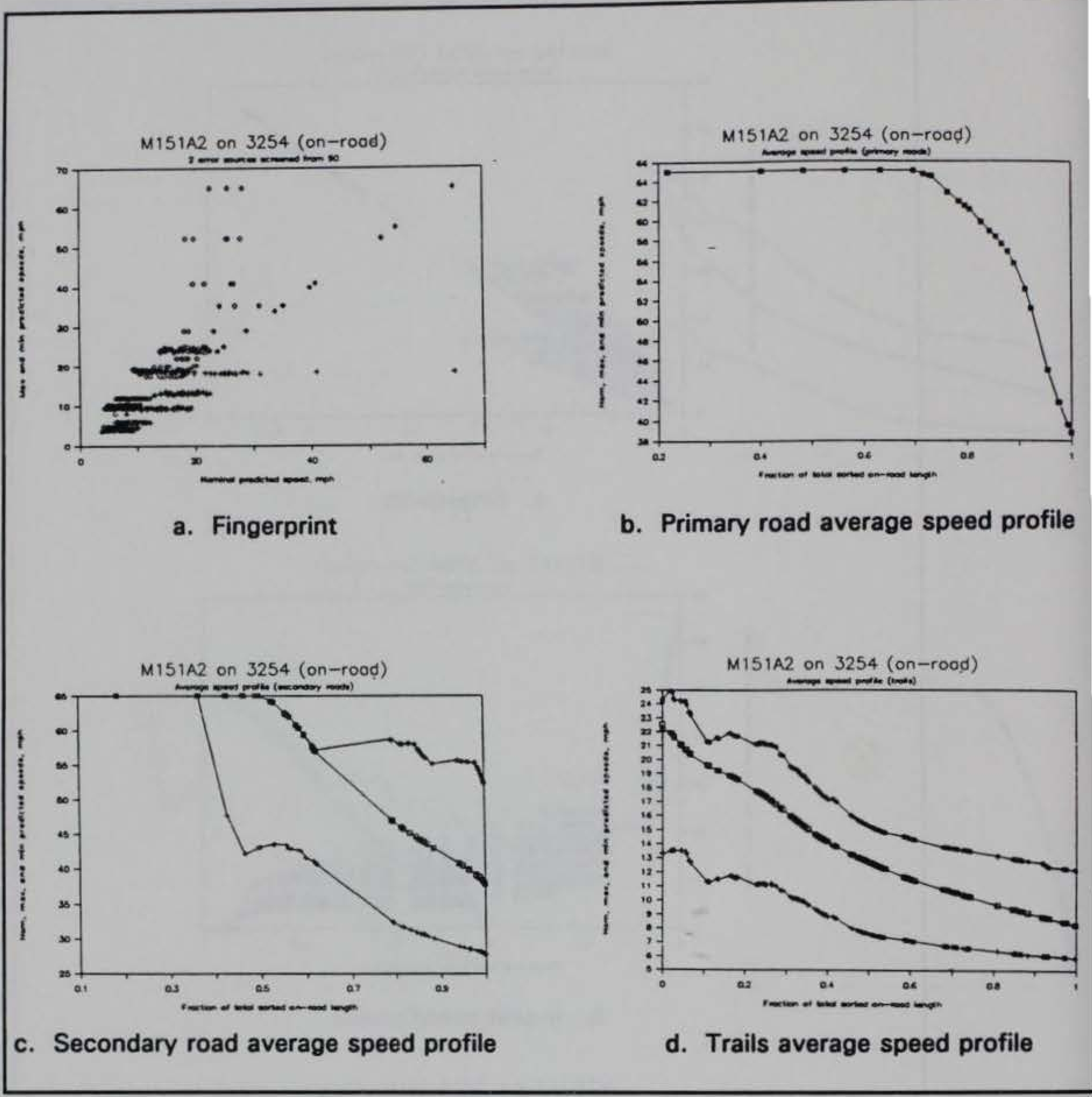


Figure 34. Fingerprint and speed profiles for M151 on Az Zarqa

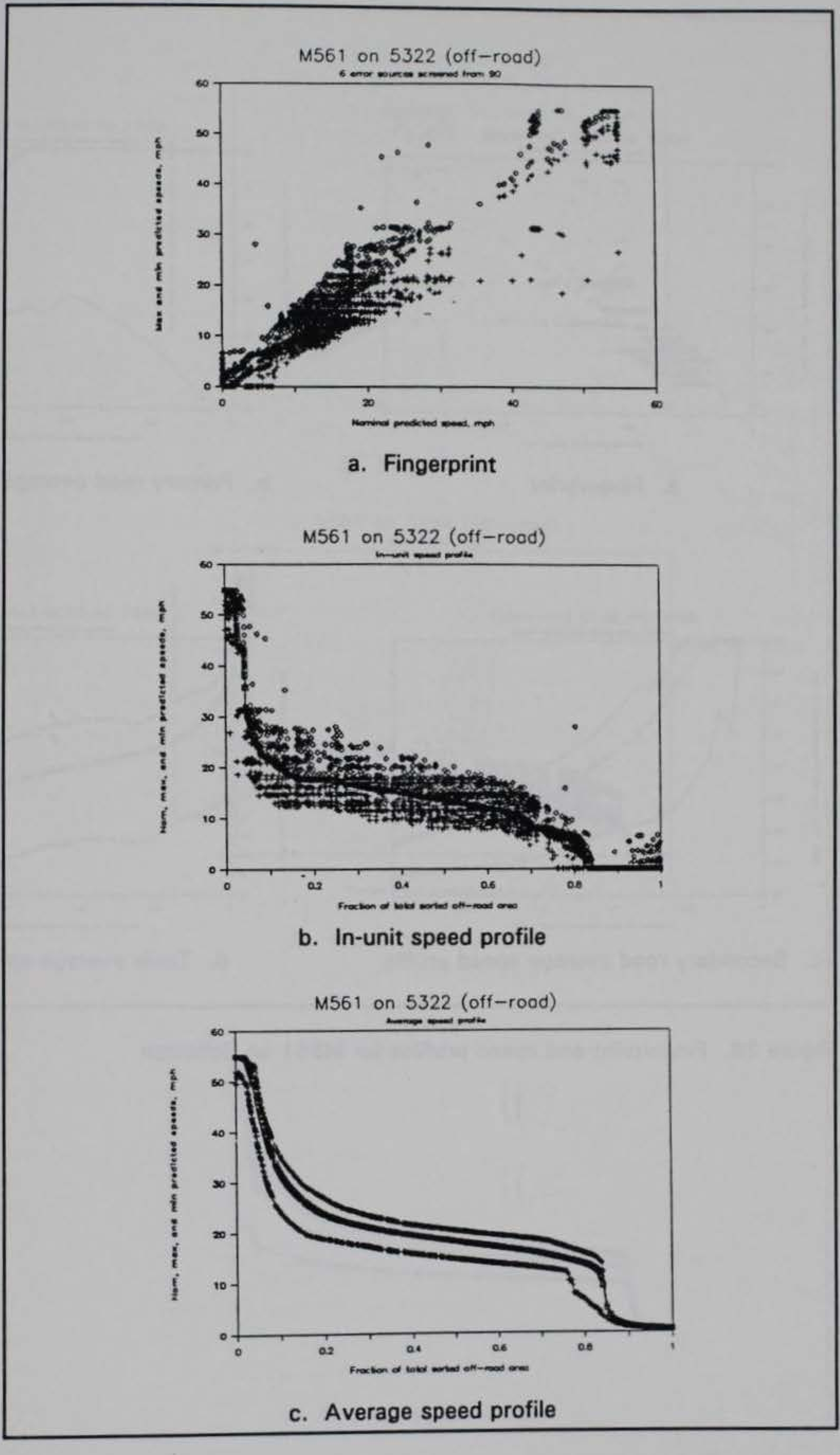


Figure 35. Fingerprints and speed profiles for M561 on Lauterbach

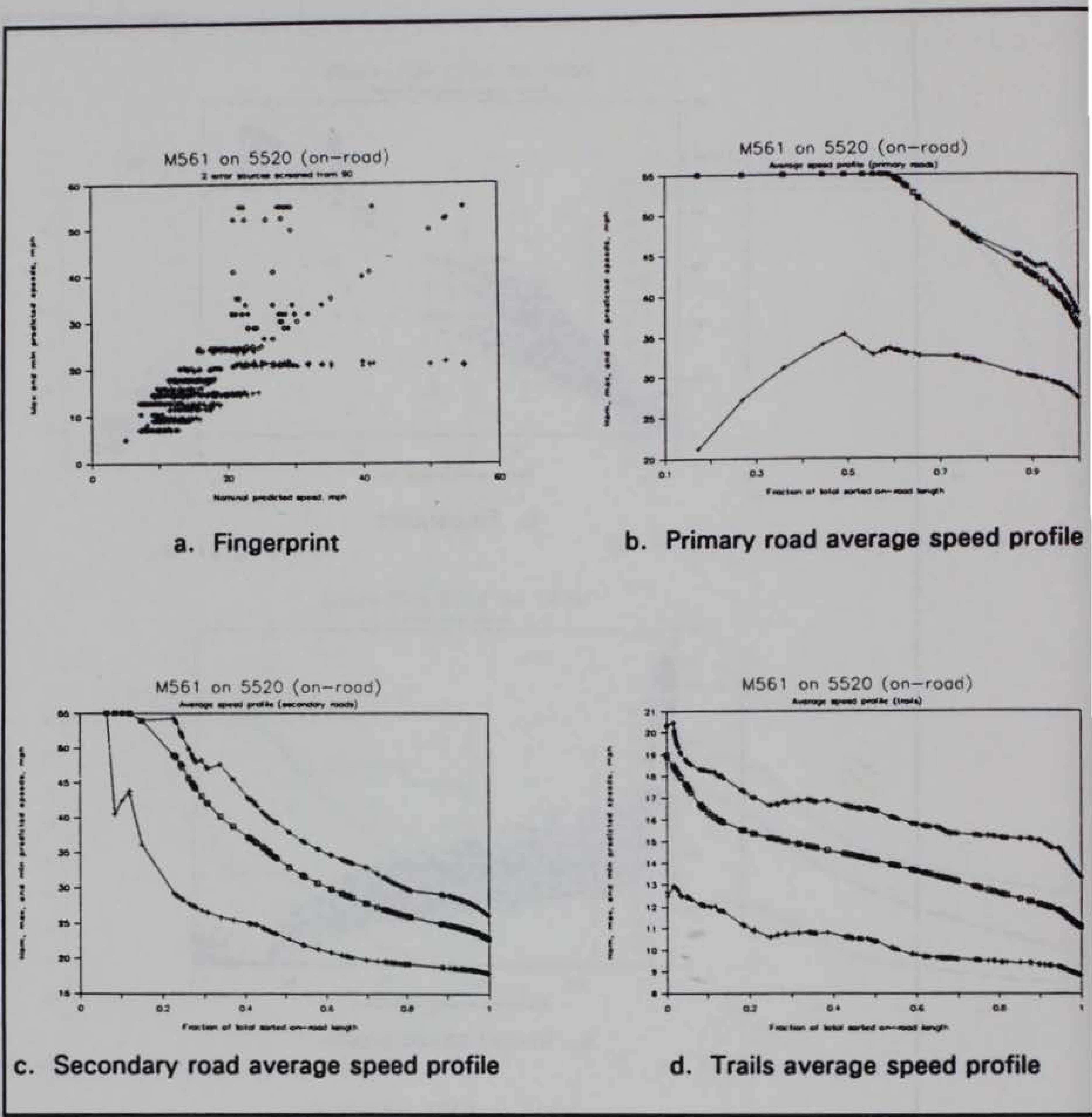


Figure 36. Fingerprint and speed profiles for M561 on Schotten

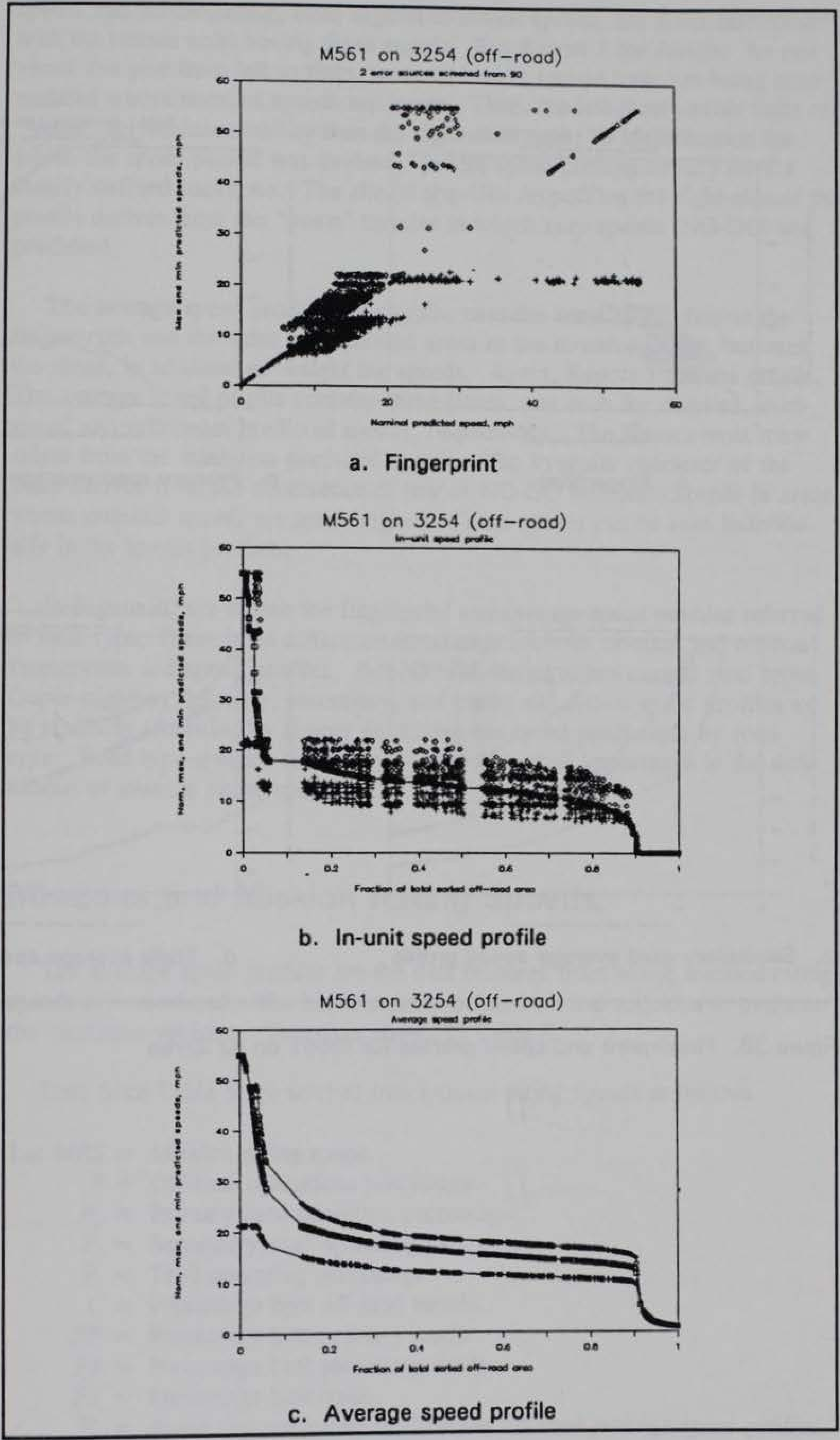
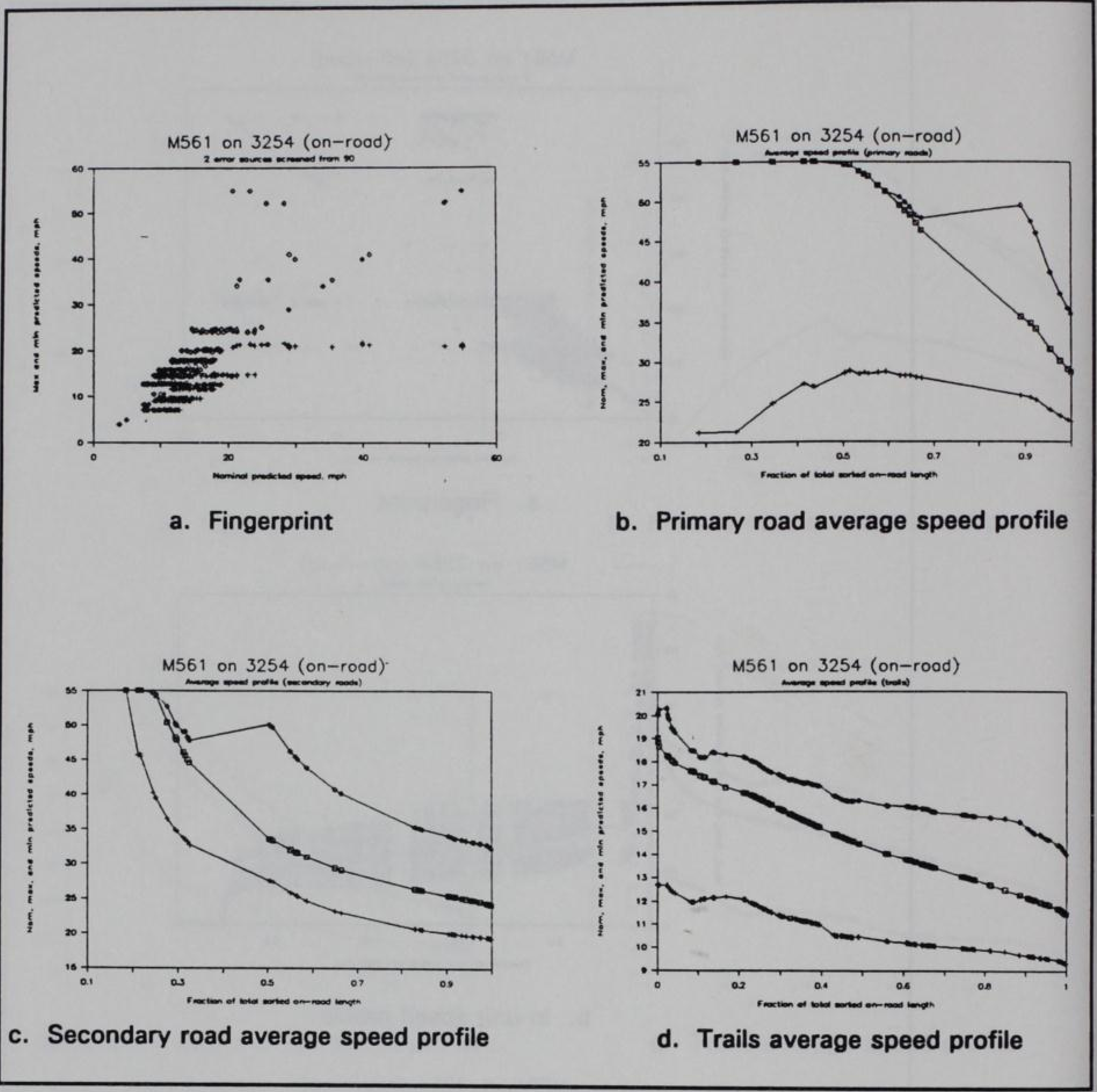


Figure 37. Fingerprints and speed profiles for M561 on Mafraq



a. Fingerprint

b. Primary road average speed profile

c. Secondary road average speed profile

d. Trails average speed profile

Figure 38. Fingerprint and speed profiles for M561 on Az Zarqa

speeds and accumulating, from highest to lowest speeds, the areas associated with the terrain units having those speeds. See Report 1 for details. As one views this plot from left to right, more and more terrain units are being accumulated whose nominal speeds are lower. Thus, the left-most terrain units are "better" for vehicle mobility than the right-most ones, an identification for which the speed profile was devised. In-unit speed profiles usually have a clearly defined backbone. The abrupt step-like dropoff on the right-side of the profile derives from the "worst" terrains in which zero speeds (NO-GO) are predicted.

The average speed profile, once again, uses the same speed data as the fingerprints and the same accumulated areas as the in-unit profiles, but uses the areas, in addition, to weight the speeds. Again, Report 1 has the details. The average speed profile contains three traces, one each for nominal, minimum, and maximum predicted speeds, respectively. The bottom-most trace arises from the minimum predicted speeds. The irregular character of the trace derives from the occurrence of low or NO-GO minimum speeds in areas whose nominal speeds are much higher. These speeds can be seen individually in the in-unit profiles.

In Figure 20 are shown the fingerprint and average speed profiles referred to road type, There is no difference in concept between on-road and off-road fingerprints and speed profiles. But NRMM distinguishes several road types (super-highway, primary, secondary, and trails) and allows speed profiles to be similarly identified by simply separating the speed predictions by road type. Road-type-specific speed profiles are of central importance in the definitions of mission rating speeds.

Missions and Mission Rating Speeds

The average speed profiles are the data resource from which mission rating speeds are calculated. The historic study defined several missions to evaluate the candidate vehicles. These are shown in Table 8.

Data from Table 8 are worked into mission rating speeds as follows.

Let MRS = Mission rating speed.
P = Off-road operations percentage.
P_p = Primary road operating percentage.
P_s = Secondary road operating percentage.
P_t = Trail operating percentage.
C = Percentage best off-road terrain.
PP = Percentage best primary roads.
PS = Percentage best secondary roads.
PT = Percentage best trails.
V_c = Speed corresponding to C on the off-road average speed profile.
V_{pp} = Speed corresponding to PP on the primary road average speed profile.

V_{ps} = Speed corresponding to PS on the secondary road average speed profile.
V_{pt} = Speed corresponding to PT on the trail average speed profile.
T_x = Average time in hours spent crossing gaps and steams per mile of off-road terrain traversed (0.101 in Germany and 0.025 in Jordan under dry, normal conditions).

then

$$MRS = \frac{100}{\frac{P}{V_C} + P*T_X + \frac{P_P}{V_{PP}} + \frac{P_S}{V_{PS}} + \frac{P_T}{V_{PT}}} \qquad (1)$$

Table 8
HMMWV Evaluation Missions

Mobility Level	Percent Total Operating Distance				on Percent of "Best" Terrain/Road Units			
	Primary Roads	Secondary Roads	Trails	Off-Road	Primary Roads	Secondary Roads	Trails	Off-Road
Federal Republic of Germany								
Tactical High	10	30	10	50	100	100	100	90
Tactical Standard	20	50	15	15	100	100	100	80
Tactical Support	30	55	10	5	100	100	50	50
On-Road	35	60	5	0	100	100	10	--
HMMWV	30	30	30	10	100	100	80	80
Jordan								
Tactical High	5	20	25	50	100	100	100	90
Tactical Standard	15	35	35	15	100	100	100	80
Tactical Support	20	40	35	5	100	100	80	50
On-Road	30	40	30	0	100	100	50	--
HMMWV	30	30	10	30	100	100	80	80

The V's are gotten by entering the appropriate speed profiles at the values of the "percentage best" terrains. For example, entering the average speed profile for the AU7 on 5322 (Figure 19) at C = 80 percent (or as the fraction 0.8) gives V_c = 8.0, 18.5, and 21.0 mph as minimum, nominal, and maximum values. Entering at C = 50 percent gives 15.0, 25.0, and 28.0 mph. Finally, entering at 90 percent gives 2.0, 6.0, and 6.0 mph. When values for the V's are taken from the nominal speed profiles, a nominal mission rating speed results. When values are taken from the minimum and maximum profiles, minimum and maximum mission rating speeds are obtained.

Note that the difference, or "range," between minimum and maximum mission rating speeds can be taken as a figure of merit for the performance of the given vehicle on the given terrain against the given mission. Two vehicles having the same computed nominal mission rating speed can be ranked according to range. A smaller range indicates less susceptibility to the influence of data uncertainties.

Mission rating speeds for the 3 candidate vehicles and 2 comparison vehicles are shown in Figures 39 to 43. Nominal, minimum, and maximum values for the mission rating speeds are clustered by vehicle. One can think of the maximum and minimum speeds as defining an error band about the nominal.

Comparison of Historic and Stochastic Mobility Forecasts

The first point of comparison is between the nominal mission rating speeds of the stochastic procedure and the mission rating speeds of the historic study: they should be the same. Figure 44 shows representative comparisons made for the "HMMWV" mission. The comparison is, in fact, favorable. That the historic and nominal values are not identical is reasonable because NRMM has evolved since 1983 (and continues to evolve) as computational refinements are implemented on a continuing basis.

It should be remarked that the three candidate vehicles are actually very much alike. It comes as no surprise that their nominal mission rating speeds are largely the same. This provides an opportunity to see if the stochastic procedures can discriminate among these vehicles.

Consider Figure 43. Of all the missions considered, the HMMWV mission is probably most representative of the demands made on the vehicles. Looking at the nominal speeds, one sees that all candidates outperform the M151 and M561, the high-mobility vehicles of the time. Thus, if scores are being kept, it is clear that the M151 and M561 are out of the picture at the outset. Based on nominal values of the mission rating speed, little would separate the HMMWV candidates. However, when ranges are considered, the TUQ comes up short as the stochastic analysis procedures have captured considerable uncertainty in its mission rating speeds. This means that making speed predictions for the TUQ entails more risk than for the AU7 or the GUF because the predictions cover a wider range of values. Finally, between the AU7 and GUF is seen a classic tradeoff situation. In Figure 43a the vehicle with the higher mission rating speed (good) has the higher range of speeds (bad). Thus, a procurement committee, looking at this scenario only, that might have been tempted to rank the GUF above the AU7 based on mission rating speeds would realize that another factor is at work. The uncertainty in

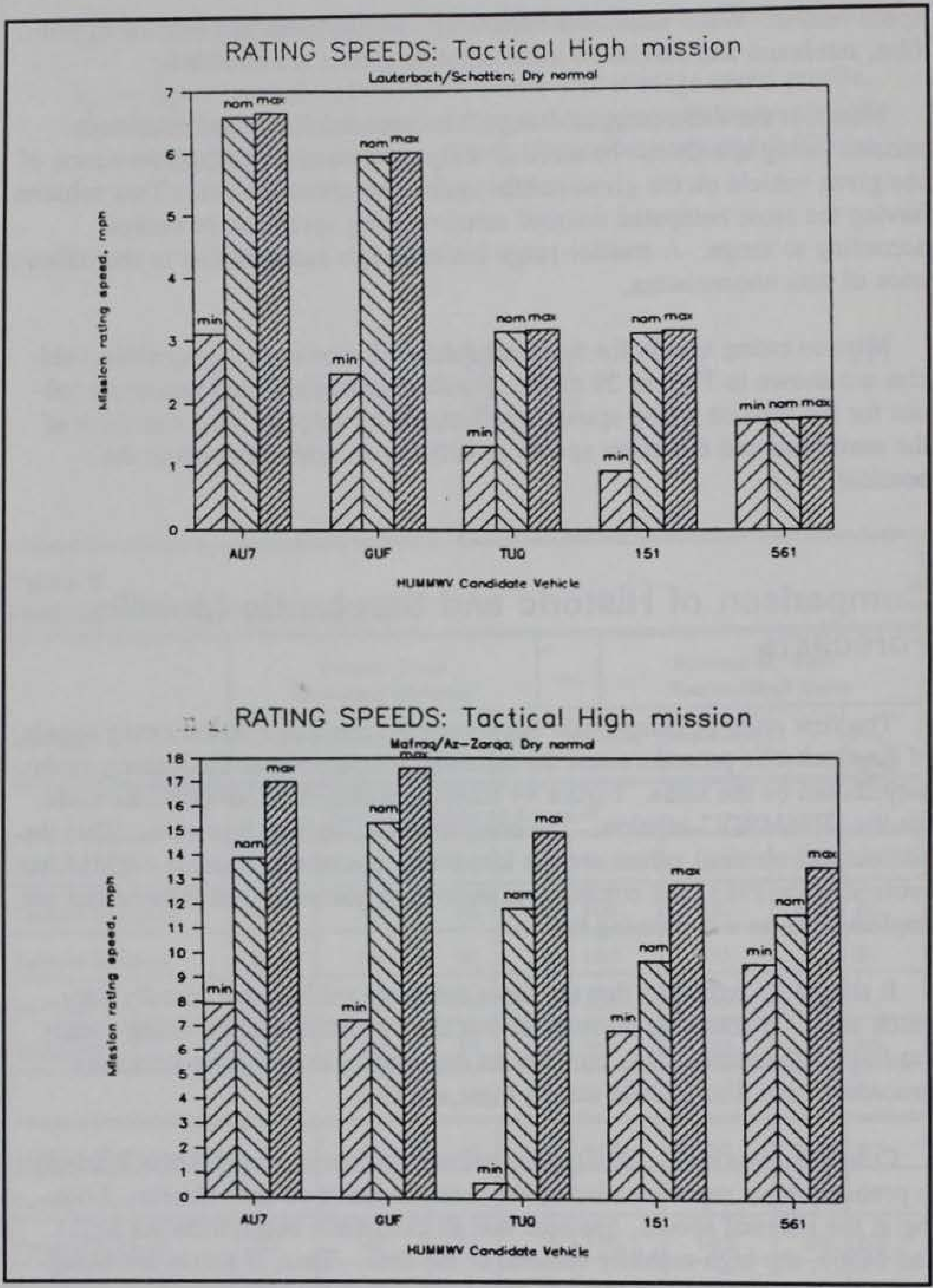


Figure 39. Mission rating speeds for the Tactical High mobility mission

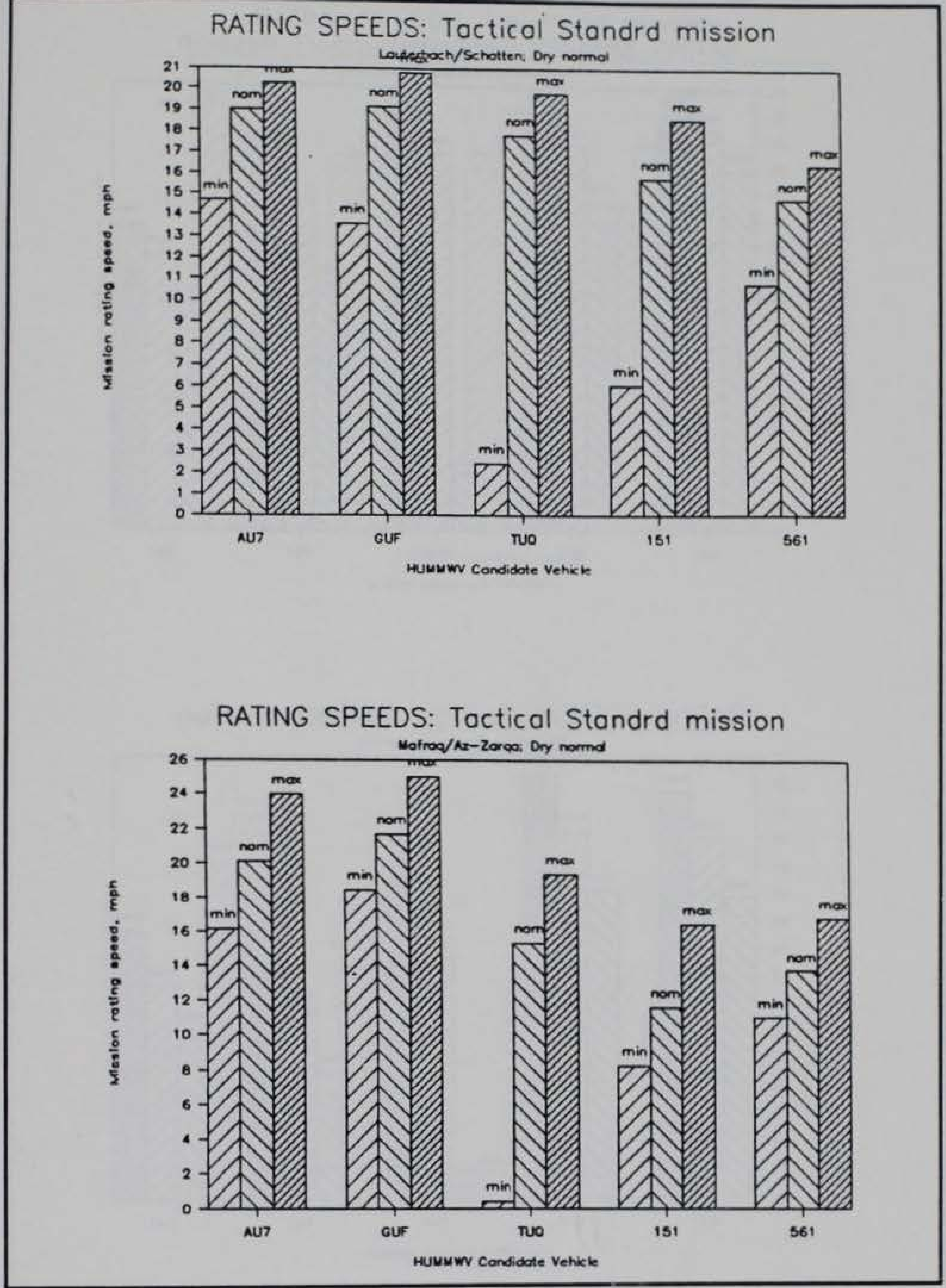


Figure 40. Mission rating speeds for the Tactical Standard mission

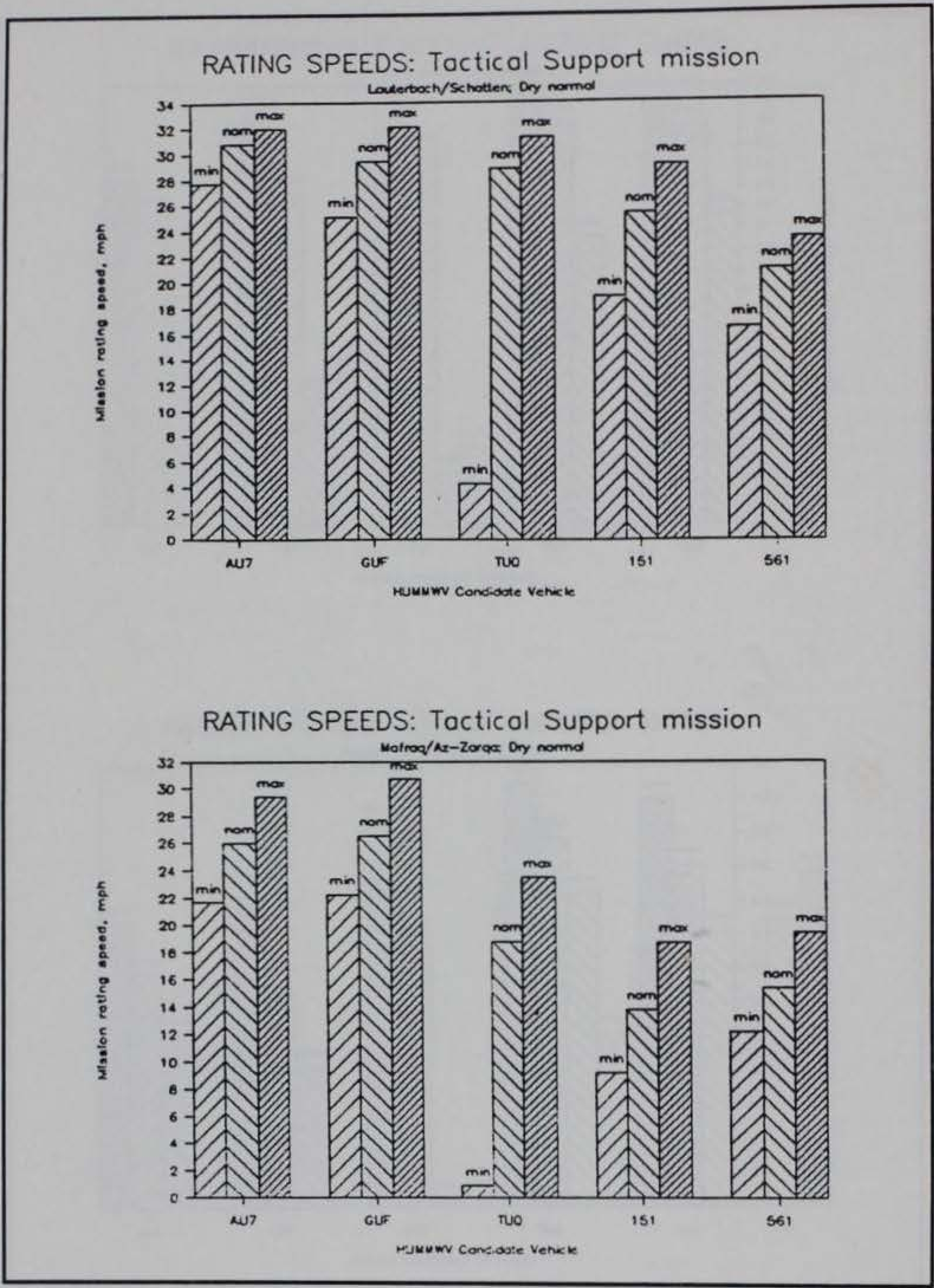
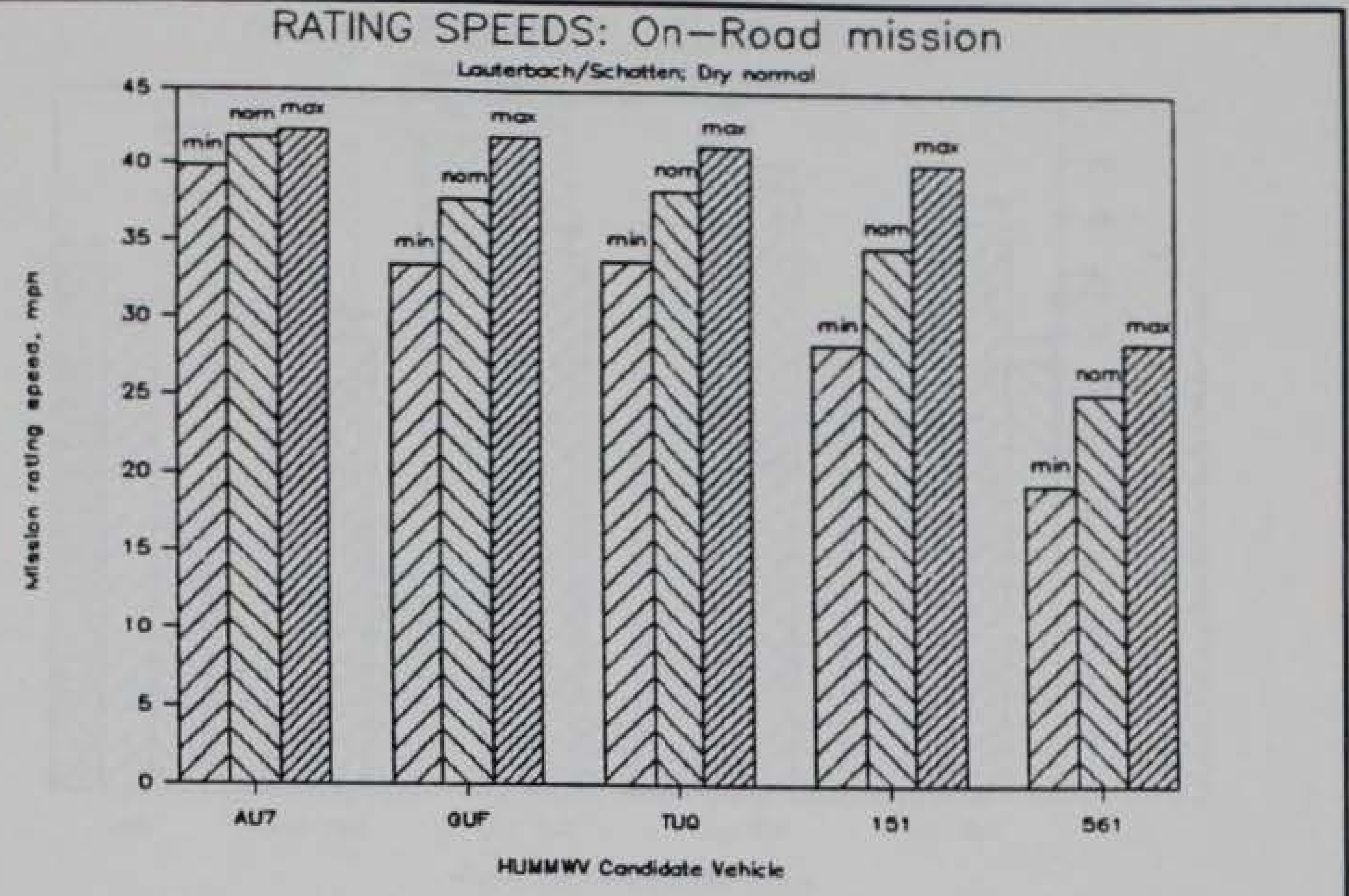


Figure 41. Mission rating speeds for the Tactical Support mission



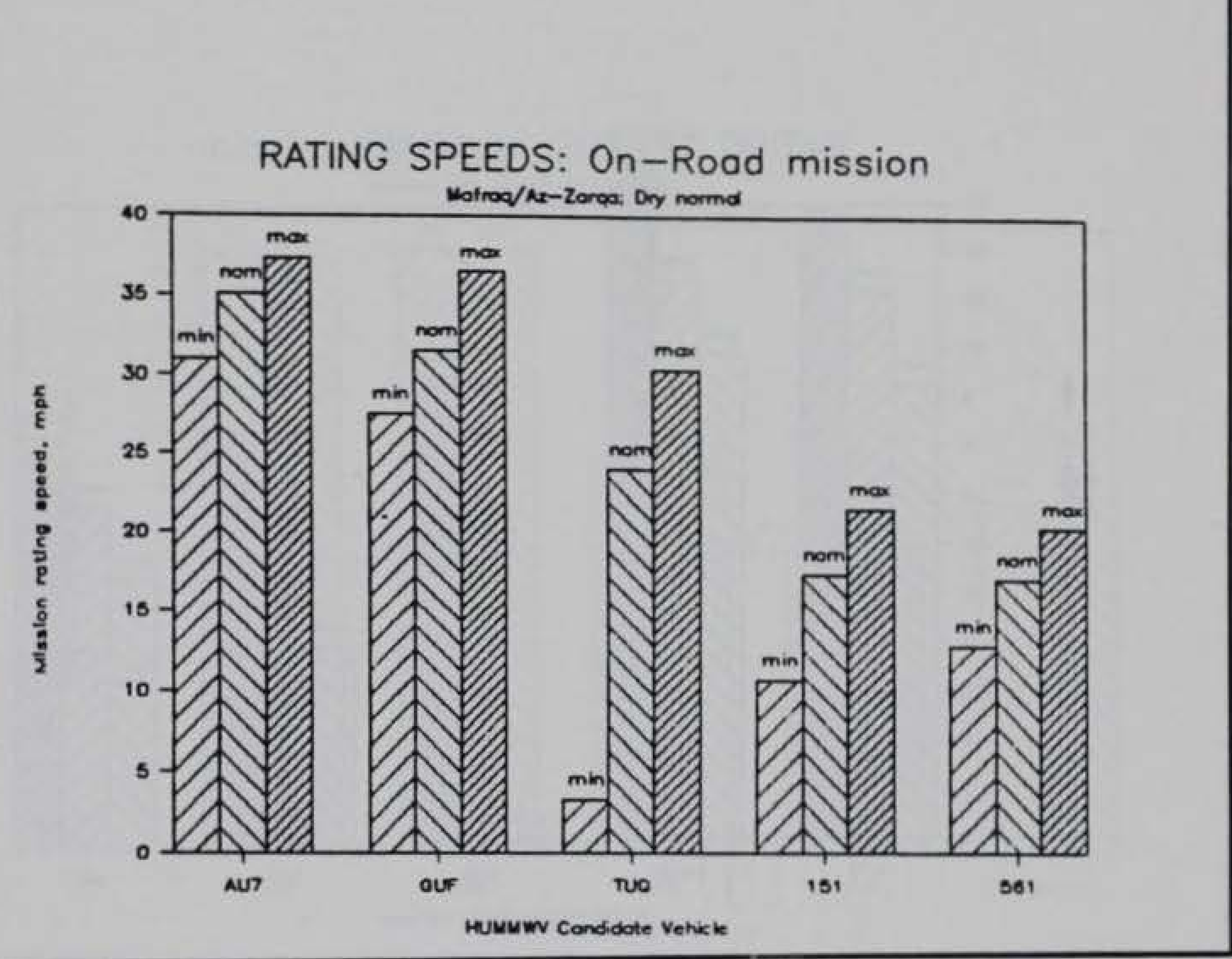


Figure 42. Mission rating speeds for the On-Road mobility mission

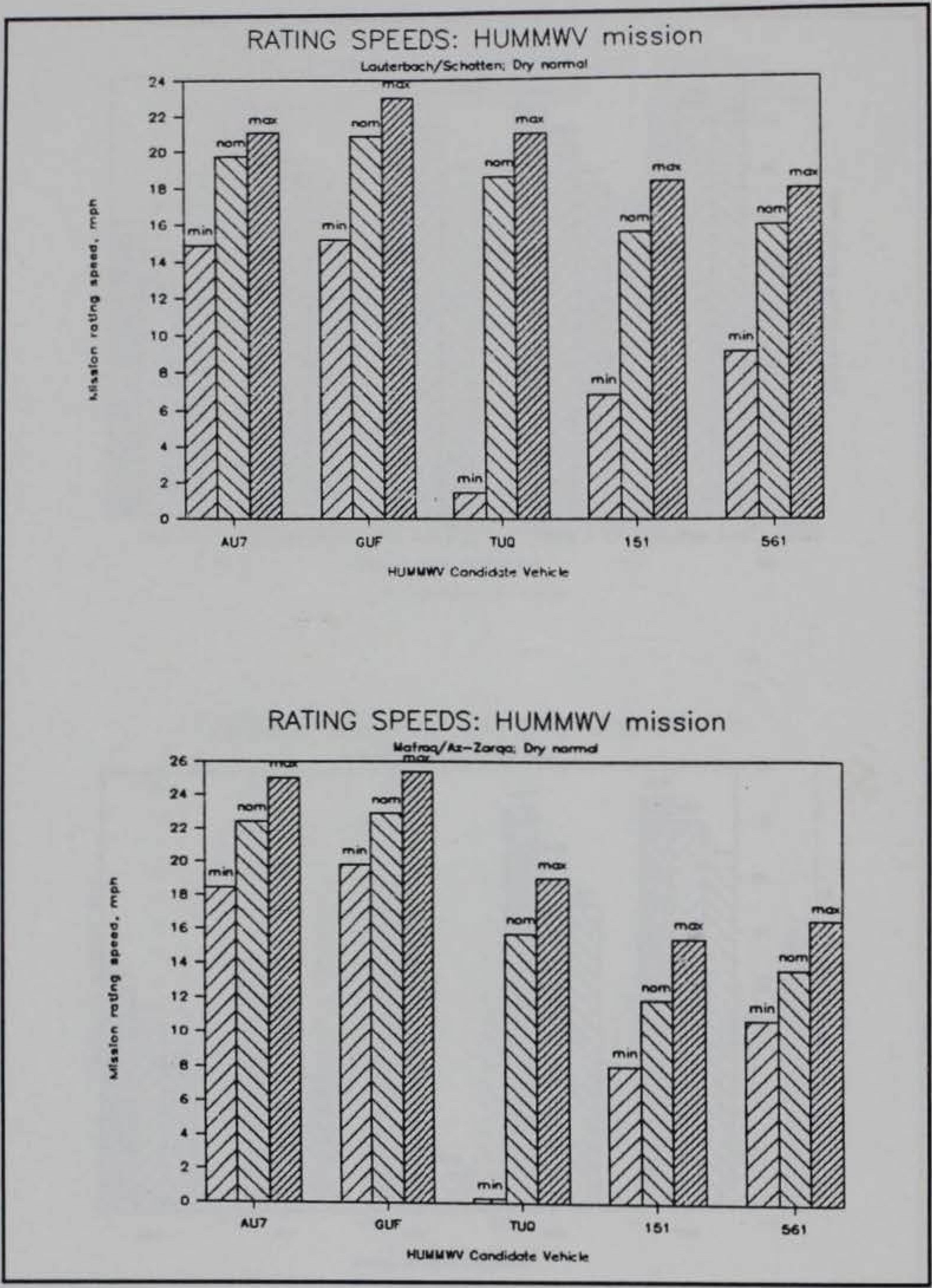


Figure 43. Mission rating speeds for the HMMWV mission

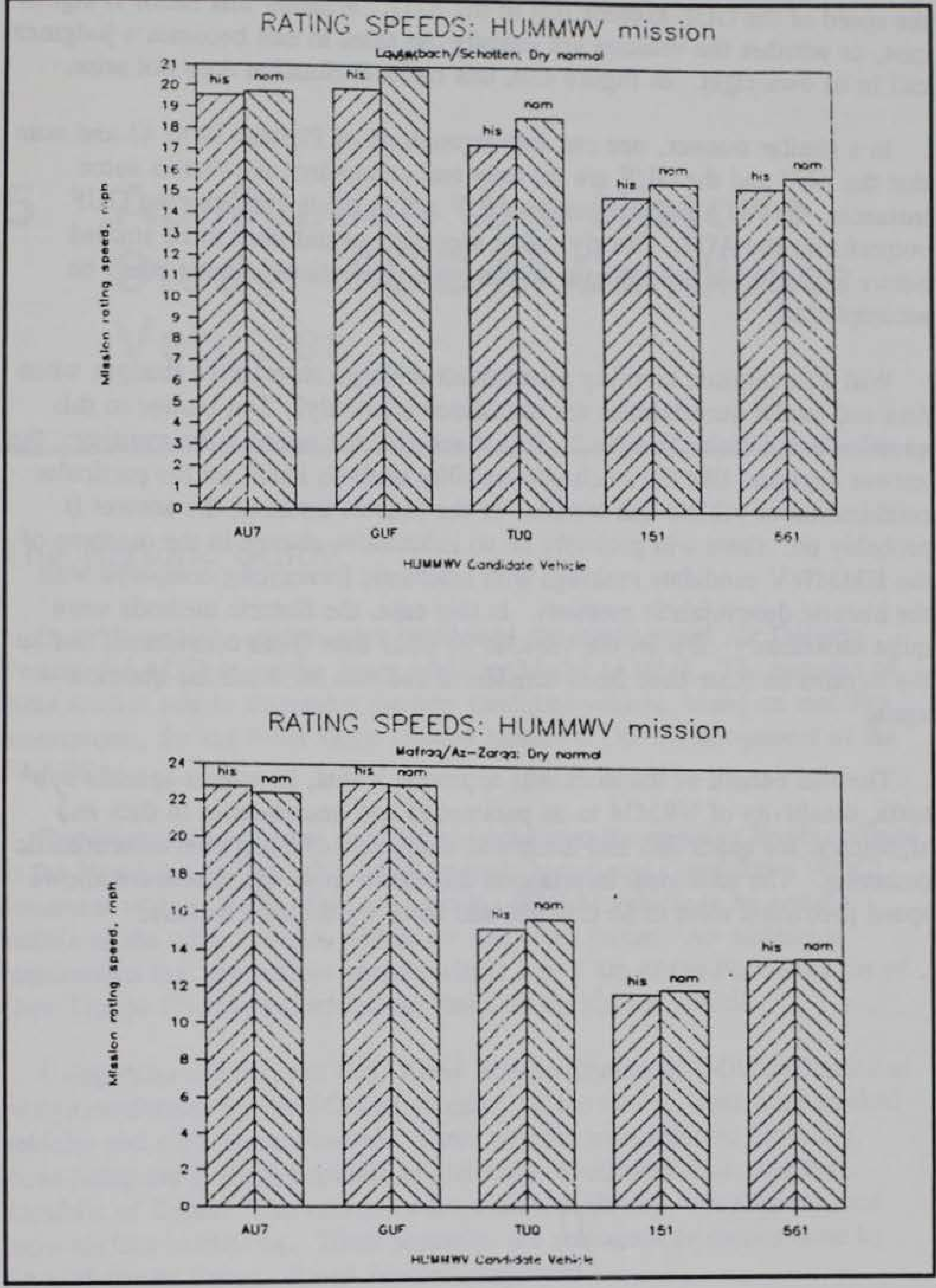


Figure 44. Comparison of historic ("his") and stochastic nominal ("nom") mission rating speeds for the HMMWV mission

the speed of the GUF exceeds that of the AU7. Whether this factor is significant, or whether the vehicles are actually too close to call becomes a judgment call in its own right. In Figure 43b, this tradeoff situation does not arise.

In a similar manner, one can step through all of Figures 39 to 43 and note that the AU7 and the GUF are the only real contenders and that in some instances, the AU7 outperforms the GUF and in other instances the GUF outperforms the AU7. Clearly, other scenarios would need to be studied before a ranking of the vehicles on the basis of predicted speeds could be accomplished.

Will deterministic mobility assessments undergo substantive changes when data and model uncertainties are considered explicitly? The answer to this question is a definite "maybe." This is actually not meant to be amusing: the answer depends, like the stochastic mobility analysis itself, on the particular combination of vehicle and terrain. In the present instance, the answer is probably no: there will probably be no substantive change in the outcome of the HMMWV candidate rankings with stochastic forecasting compared with the historic deterministic methods. In this case, the historic methods were quite satisfactory. But let the vehicles be other than those considered, and let the terrains be other than those considered and one must ask the question again.

The real benefit of the stochastic approach is that, in project-specific contexts, sensitivity of NRMM to its parameters and uncertainties in data and algorithms are quantified and illustrated along side of traditional deterministic outcomes. The additional information that flows from this procedure allows speed prediction risks to be clarified and faced by decision makers.

5 Application to a Historic Study: FOG-M Candidate Vehicles

The Historic Study

In 1987 mobility studies were performed for the Forward Air Defense System (FAADS) using the Army Mobility Model (AMM). The purpose of these studies was to determine the best candidate vehicle, based on mobility assessments, for the Fiber Optic Guided Missile (FOG-M) component of the FAADS.

Candidate vehicles were required to perform at the mobility levels outlined in the Non-Line-of-Sight (NLOS) Required Operational Capabilities (ROC) document of July 1987. This required the FOG-M vehicle to be equally mobile as the other vehicles within the supported forces. An additional requirement that the vehicle operate within 2 to 7 km of the Forward Line of Own Troops (FLOT) put additional limits on the chosen vehicle.

Using these criteria, the U.S. Army Missile Command (MICOM) selected twelve candidates for the FOG-M vehicle. Of the twelve, four were tracked vehicles and eight were wheeled. Three terrains were selected for study, those being the Federal Republic of Germany, Southwest Asia, and the Republic of Korea. The vehicles were evaluated on dry, wet-slippery, and snow surface conditions. These scenarios are analogous to studies done by FAADS for its Ground Based Sensor Component.

Each vehicle in the FOG-M study was evaluated under conditions to approximate the tactical operation requirements of the FOG-M mission. In order to quantify mobility performance, WES, in conjunction with the U.S. Army Training and Doctrine Command (TRADOC) developed five levels of tactical performance. These levels include high-high, tactical high, tactical standard, tactical support, and on-road. Each performance level is based on percentage of travel performed off and on-road, as well as the severity of traveled terrain.

In the FOG-M analysis, the candidate vehicles were required to operate at no less than the tactical high mobility level and many times at the high-high level. In order to select the best performer of the candidate vehicles, the tactical high performance level was averaged over the three scenario areas. Based on this average, the M993 Fighting Vehicle System was selected as the best candidate vehicle for FOG-M applications.

Scope and Methods of Application

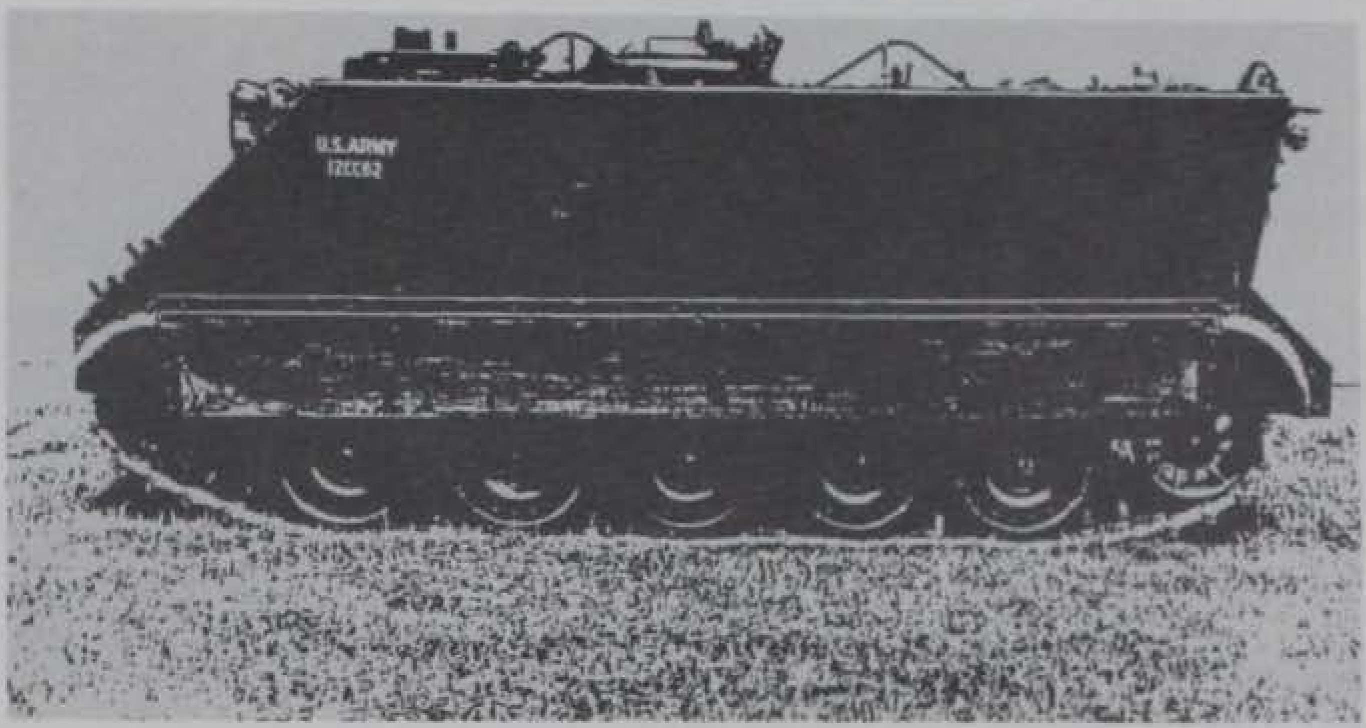
The vehicles used in the stochastic analysis will be limited to the four top performers as determined in the original non-stochastic FOG-M study. These vehicles, in order of their selection, are the M993 (FVS), the M977 (HEMTT), the M113A3, and the M1037. This group consists of two tracked vehicles as well as two wheeled vehicles. As in the original analysis, these vehicles will be evaluated at fully rated combat payload and a 12 watt limiting ride speed.

The M993 is shown in Figure 45 and is a fully-tracked armored carrier, fighting vehicle system (FVS). It is one of the heavier vehicles used in the mobility study with a weight of 56,200 lb. The M993 has a length of 275 in. and a width of 117 in. The tracks themselves are 174 in. long and 21 in. wide. Minimum ground clearance is given as 17 in. This vehicle has a power rating of 17.8 hp/ton which provides it with a maximum velocity of 35.7 mph.

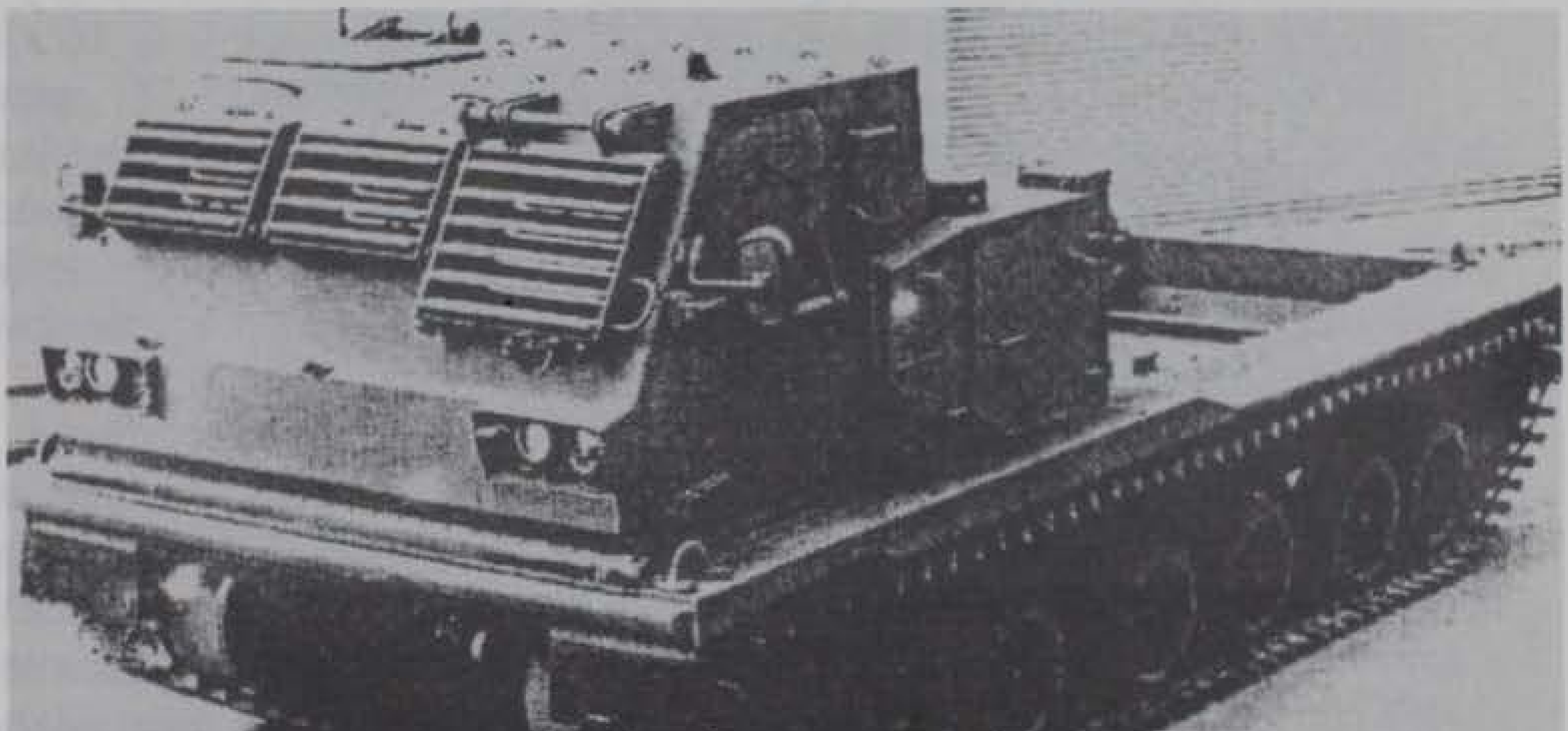
The vehicle rated as second in the original analysis is the M977 Heavy Expanded Mobility Tactical Truck (HEMTT), Figure 46. This, the heaviest vehicle considered, has a gross weight of 60,375 lb. It is one of the two wheeled vehicles considered. The length of the M977 is 361 in., and its width is 96 in. Its wheel base is 210 in., and the minimum ground clearance is 13 in. This vehicle can deliver 14.3 hp/ton and obtain a maximum velocity of 63 miles per hour.

The M113A3 Figure 46, is a fully-tracked, armored, personnel carrier and is one of the lighter vehicles considered. This vehicle weighed 27,200 lb and has a length and width of 205 in. and 106 in., respectively. The track length is 108 in.; and the width, 15 in. The minimum ground clearance required is 16 in. This vehicle is rated for 20.2 hp/ton and obtains a maximum speed of 41 mph.

The fourth vehicle considered in this analysis is the M1037 High-Mobility Multipurpose Wheeled Vehicle (HMMWV), which is pictured in Figure 45. This is one of the wheeled vehicles considered, and it is the lightest with a gross weight of 8,660 lb. The M1037 is 188 in. long and 85 in. wide, and the wheel base is 130 in. The minimum ground clearance is specified as 11.3 in. The M1037 can deliver the most power and highest velocity of the candidate vehicles with a rating of 34.6 hp/ton and a maximum speed of 66.8 mph.

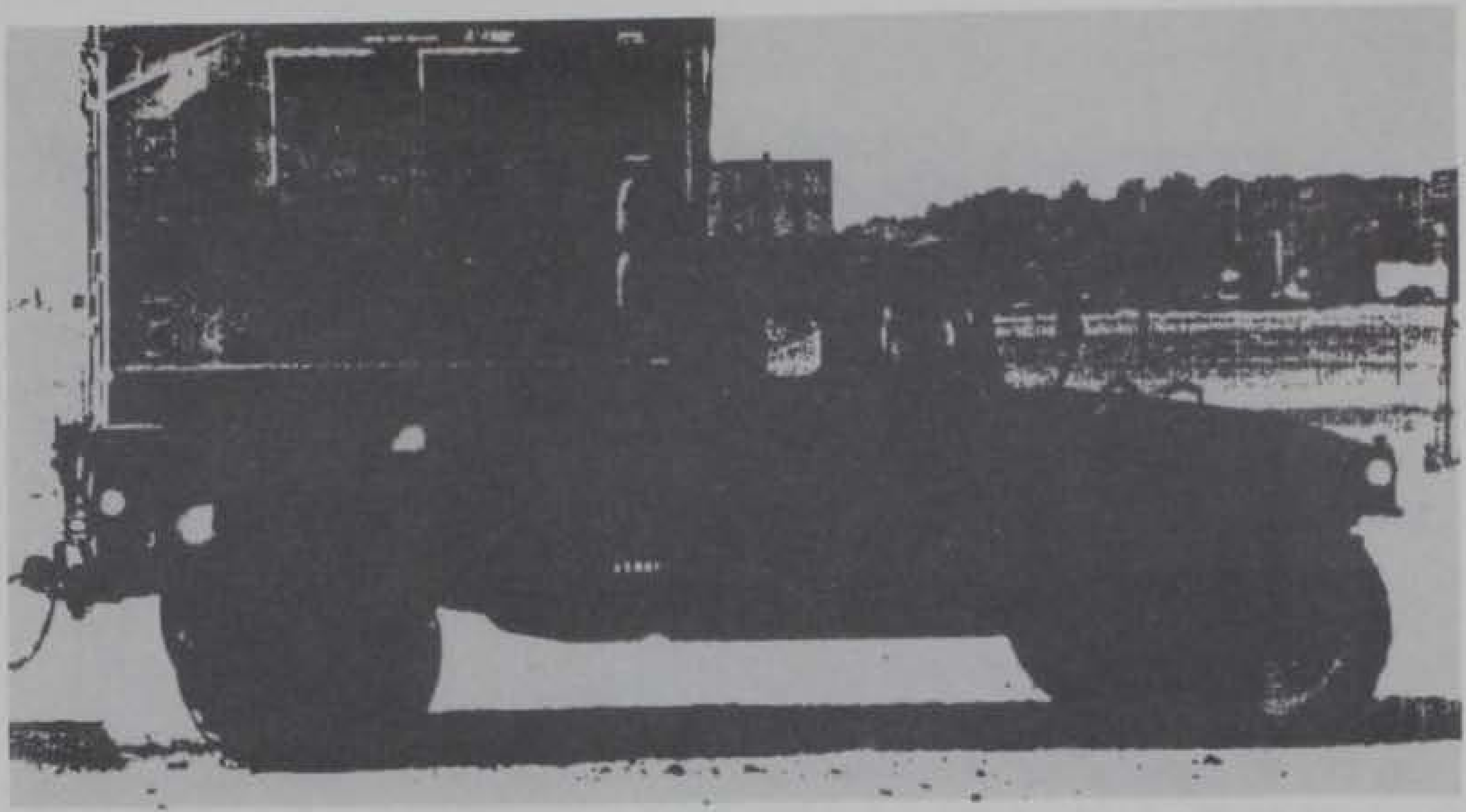


a. M113A3 Armored Personnel Carrier

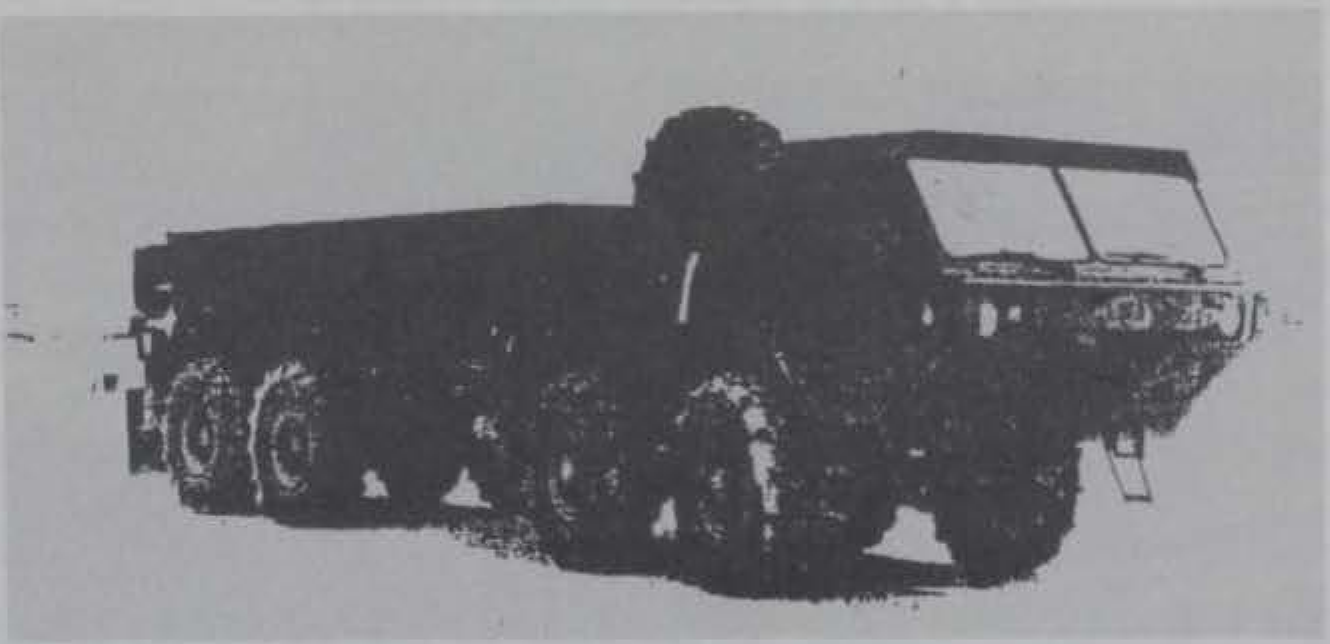


b. M993 Fighting Vehicle System (FVS)

Figure 45. Tracked candidate vehicles for FOG-M



a. M1037 High Mobility Multipurpose Wheeled Vehicle (HMMWV)



b. M977 Heavy Expanded Mobility Tactical Truck (HEMTT)

Figure 46. Wheeled candidate vehicles for FOG-M

The stochastic study is limited to subsets of the three terrains considered in the original FOG-M analysis. These selected terrains represent the typical areal and road conditions that are expected for tactical vehicle deployment. The digital terrain data bases used represent quads in West Germany, Southwest Asia, and the Republic of Korea. In Germany, the Lauterbach Quad provided off-road data; and the Schotten Quad, on-road data. For Southwest Asia, the Arzhan region provided both on and off-road data; and in Korea, Cheorweon areas were used for terrain data. Refer to the original FOG-M report for terrain detail.

In this stochastic study only the dry-normal scenario conditions were considered. The dry-normal condition represents the lowest soil moisture content of the terrain surfaces - thus, the highest soil strength. This condition is representative of the driest 30 day period of an average rainfall year. The assumption that no rainfall has occurred within the last six hours is also inherent to the dry-normal scenario.

The principal tool used in the stochastic mobility analysis is the NATO reference Mobility Model (NRMM). This computer code is based on years of field and lab work and considers terrain factors, road factors, vehicle geometry and human factors in speed predictions. The NRMM analysis provides a speed prediction specific for one vehicle, one terrain unit, and a specific lineal feature of the terrain unit's road network. These speed predictions do not take into consideration any neighboring terrains nor past speed predictions. The NRMM software is an equilibrium code: therefore, there is a unique equilibrium speed for each specific analysis.

This feature of the mobility model allows for each input variable to be varied independently or simultaneously in order to show the influence of data. With the input variables modeled as random, the impact of data and algorithm uncertainties are made very apparent. These results help to quantify the quality of speed predictions by providing a range rather than a single number for predicted speeds. The stochastic approach is clearly advantageous to the making of tactical decisions.

For the stochastic analysis of the FOG-M candidate vehicles, the version of NRMM used was release II. This software was executed under a CRAY system. The first application of the software was the performance of the sensitivity analysis of the input variables. These inputs consisted of 57 vehicle related variables, 15 terrain, 13 scenario, and 5 curve-fit variables, see Tables 1 through 4. Initially these variables were varied independently; and a maximum, minimum, and nominal speed was computed for each terrain unit.

After the computation of these velocity ranges, a second software package was employed on the CRAY to generate rank indicators for each variable on each terrain unit. This program also computed the arithmetic average of the indicators over all of the terrain units. The maximum rank indicator was then determined, and a threshold of 20 percent of its value was established. Any variable with a rank indicator below this threshold was eliminated from further analysis.

With the sensitive variables isolated, the full Monte Carlo component of the NRMM analysis was then performed. In the previous sensitivity calculations, the variation of each variable was plus and minus 10 percent of its nominal value while the curve-fit variables had a range of plus and minus 14 percent. In the Monte Carlo analysis, however, each variable is given a specific variation based on past observations and expert opinions. In this NRMM analysis, each sensitive variable is allowed to vary both independently and simultaneously. In the Monte Carlo routine, 200 velocities are calculated for each terrain unit and a speed probability density is obtained.

The maximum, minimum, and nominal speeds for each terrain unit generated by NRMM was transported to a PC environment to facilitate the generation of the necessary speed profiles and mission rating speeds. Spreadsheets were developed to sort the velocities and terrain units and compute the average cumulative velocities. A separate spreadsheet was created for each vehicle on each terrain set for each road type; therefore, speed profiles were computed for off-road terrain, primary roads, secondary roads, and trails.

Data obtained from the speed profiles was then extracted to compute the applicable mission rating speeds. For the stochastic analysis, the tactical high, tactical standard, and tactical support mobility levels were computed. These mobility levels were developed by representatives of the TRADOC WHEELS study group in the mid-1970's. Each terrain has a different definition of the mission rating speeds for each tactical level as the requirements for tactical mobility change with the environment.

Sensitivity Study

Initial calculations in the stochastic analysis required the determination of variables for which the vehicle performance was sensitive. Sensitivity and screening were performed for the four vehicles studied on each terrain set. Within each terrain, the sensitivity was computed independently for the on-road network as well as for the off-road. Of the 90 variables available for the NRMM forecast, only 21 were determined sensitive in the evaluation of the FOG-M candidate vehicles.

Of these 21 variables, 10 were vehicle variables, 9 were terrain variables, and 2 were regression curve-fit variables. These relevant variables are listed in Table 9 and their speculative statistical distributions in Table 10. These error-magnitude scenarios again were based on judgments of the statistical properties of the random variables, and the conjectural scenarios must be strengthened by mobility-data-collection professionals. All of the distributions used in the FOG-M study are identical to those applied in the HMMWV calculations. Graphs of the sensitivity rank indicators per vehicle per terrain are shown in Figures 47 through 58.

An examination of the sensitive variables for each vehicle on each terrain provides insight into the factors that affect a vehicle's performance. The frequency of occurrence of sensitive variables is given in Table 11, and complete results of parameter screening sorted by terrain and vehicle are shown in Table 12. In comparing the variables that are sensitive for the FOG-M study with those found to be sensitive for the HMMWV, some trends are apparent as all of the variables found to be sensitive for the HMMWV candidate vehicles were found to be sensitive for the FOG-M vehicles as well. Some variables found to be sensitive for the FOG-M analysis, however, were never sensitive for HMMWV vehicles. These variables exclusive to FOG-M include EYE, TL, TRL, WT, OBW, RDA, and FRP; but only FRP was found to be sensitive more than one to three times.

Table 9
Sensitive Parameters for FOG-M Vehicles

	Acronym
Vehicle:	
Driver eyeheight above ground	EYE
Roughness versus speed array	FRM
Obstacle height versus speed array	FVA
Limiting speed for obstacle height	FVO
First to last wheel center distance	TL
Length of track on ground per assembly	TRL
Limiting speed for roughness	VRI
Maximum vehicle width	WDT
Vehicle weight per assembly	WGH
Tread width per assembly	WT
Terrain:	
Surface roughness	ACT
Terrain slope	GRA
Obstacle approach angle	OBA
Obstacle height	OBH
Obstacle spacing	OBS
Obstacle width	OBW
Road radius of curvature	RAD
Recognition distance	RDA
Average vegetation stem spacing	S
Curve-fits:	
Drawbar pull coefficient versus excess rating cone index	FDO
Powered Braked motion resistance coefficient versus excess rating cone index	FRP

A closer examination of the distribution of variables reveals several interesting facts. Although many of the same variables were sensitive for different vehicles and different terrains, there were some exceptions. Two of the variables, for example, driver eye height above ground, EYE, and recognition distance, RDA, were determined to be sensitive for only one vehicle and one terrain--the M1037 on off-road terrain in the Federal Republic of Germany.

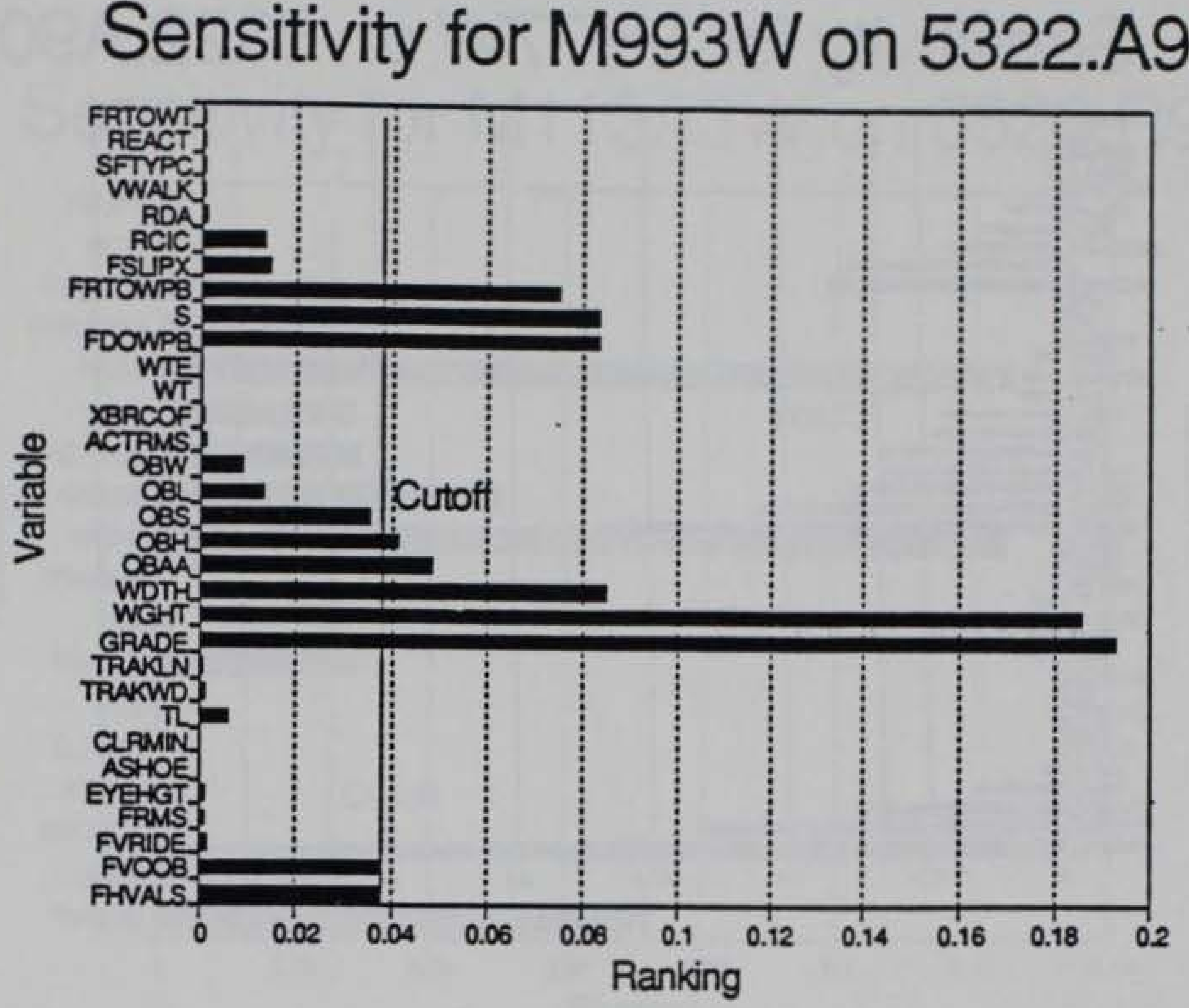
Some other parameters were also determined to be restricted to few vehicles or terrains. One example is the obstacle width, OBW, which was determined to be a sensitive variable only for the M113A3. Other variables that were sensitive strictly for the M113A3 were track length on ground, TRL, and tread width, WT. The variable representing the first to last wheel center distance, TL, was found to be sensitive exclusively for the analysis of the M1037. These two vehicles, the M113A3 and the M1037, the lightest of the four study vehicles, were also the only vehicles to exhibit sensitivity to surface roughness, ACT, and obstacle spacing, OBS. Two variables were found to be sensitive for all vehicles but on only one terrain, the off-road areas of the West Germany. These parameters were the maximum vehicle width, WDT, and the vegetation stem spacing, S.

Table 10
Conjectured Statistical Attributes of Parameters Selected for the Error-Magnitude Scenario

Parameter Acronym	Distribution Type	Range
ACT	Uniform	Plus and minus 10 percent of nominal
EYE	Uniform	Plus and minus 5 percent of nominal
FDO	Gaussian	Standard deviation 5 percent of regression value
FRM	Uniform	Plus and minus 5 percent of table midpoint
FRP	Gaussian	Standard deviation 5 percent of regression value
FVA	Uniform	Plus and minus 5 percent of table midpoint
FVO	Uniform	Plus and minus 5 percent of table midpoint
GRA	Uniform	Plus and minus 5 percent of nominal
OBA	Uniform	Plus and minus 5 percent of nominal
OBH	Uniform	Plus and minus 5 percent of nominal
OBS	Uniform	Plus and minus 5 percent of nominal
OBW	Uniform	Plus and minus 10 percent of nominal
RAD	Uniform	Plus and minus 10 percent of nominal
RDA	Uniform	Plus and minus 10 percent of nominal
S	Uniform	Plus and minus 3 percent of nominal
TL	Uniform	Plus and minus 10 percent of nominal
TRL	Uniform	Plus and minus 10 percent of nominal
VRI	Uniform	Plus and minus 5 percent of table midpoint
WDT	Uniform	Plus and minus 2 percent of nominal
WGH	Uniform	Plus and minus 10 percent of nominal
WT	Uniform	Plus and minus 10 percent of nominal

Fingerprints and Speed Profiles

Following the isolation of sensitive variables and the establishment of their error magnitude scenarios, a measure of their influence on the vehicle's performance can be determined. This determination is done by Monte Carlo analysis in which the sensitive variables are treated as random variates and the insensitive ones are held constant. Speed predictions are repeated 200 times in each terrain unit. When the maximum and minimum speeds are plotted versus the nominal speeds, a fingerprint of the vehicle is generated for a given vehicle on a given terrain.



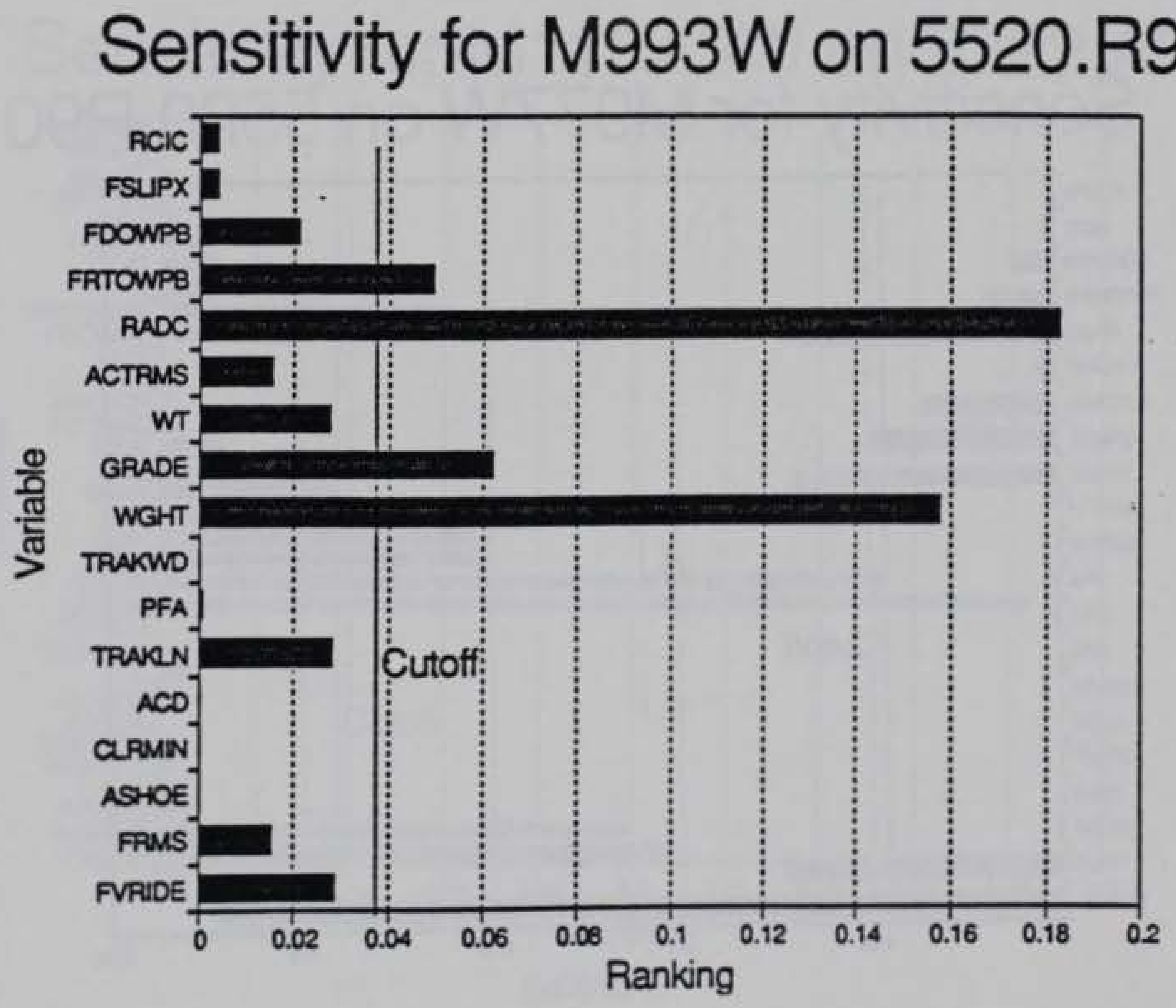


Figure 47. Sensitivity analysis for M993 on WGe terrain

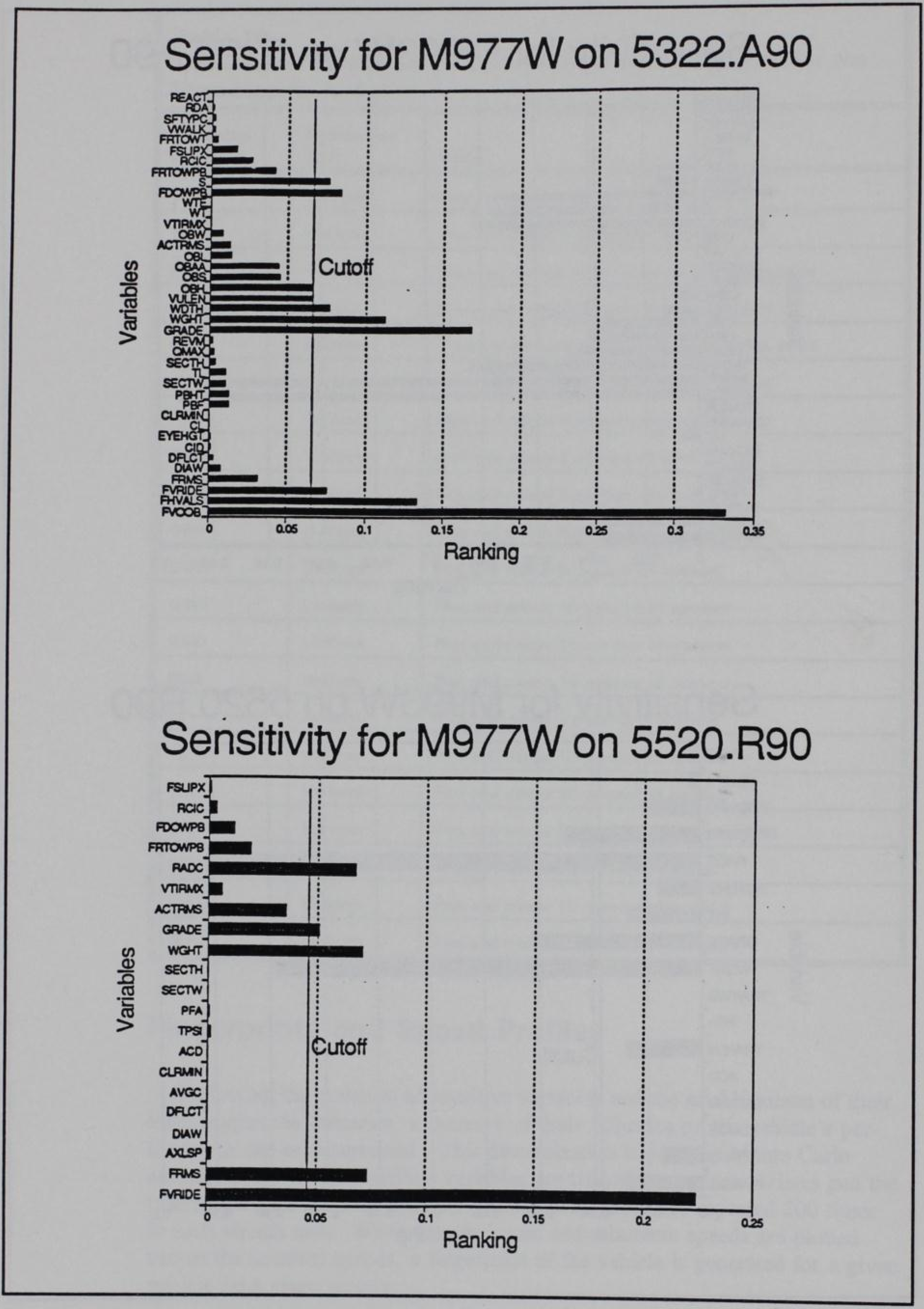


Figure 48. Sensitivity analysis for M977 on WGe terrain

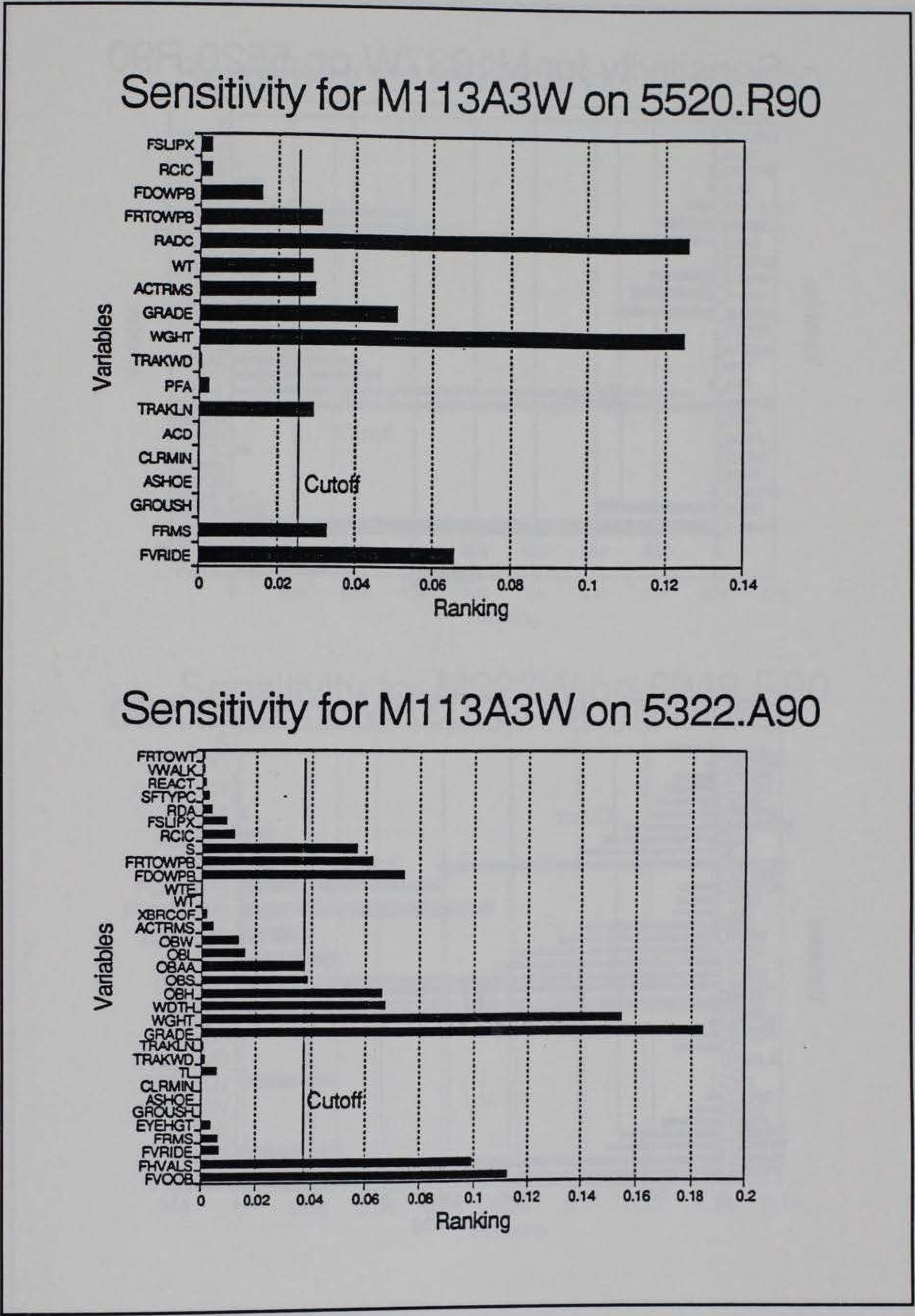


Figure 49. Sensitivity analysis for M113A3 on WGe terrain

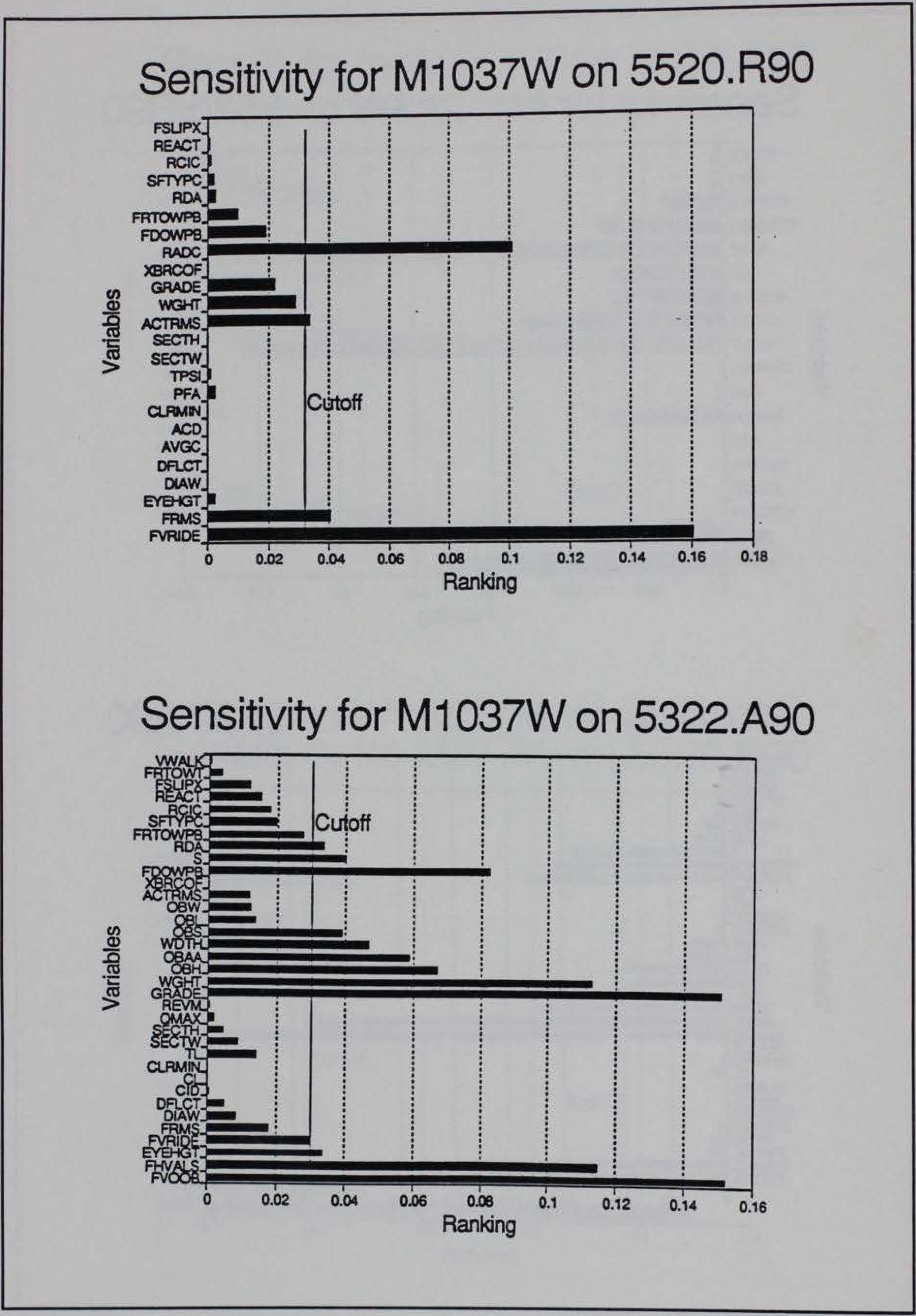


Figure 50. Sensitivity analysis for M1037 on WGe terrain

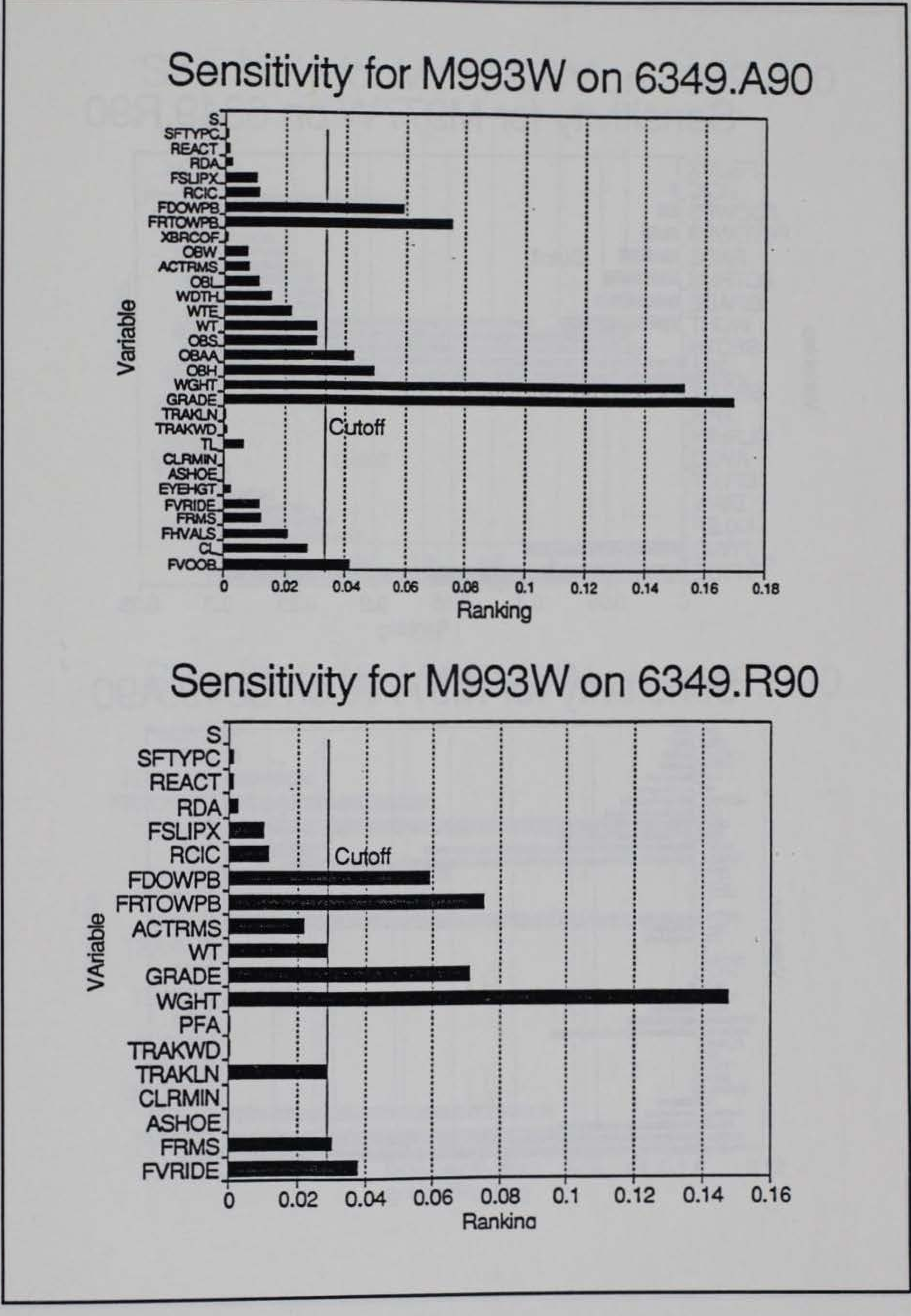


Figure 51. Sensitivity analysis for M993 on SWA terrain

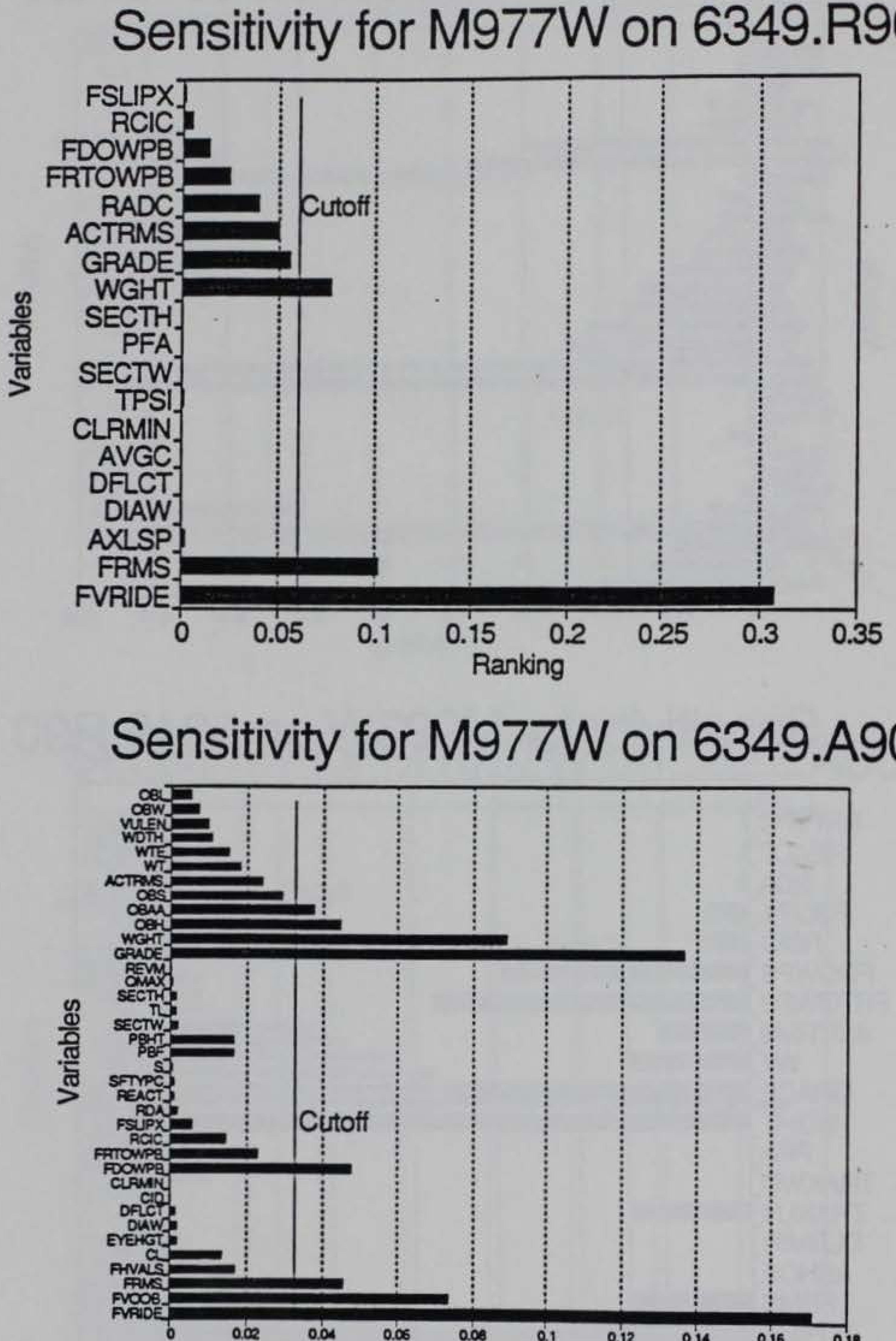


Figure 52. Sensitivity analysis for M977 on SWA terrain

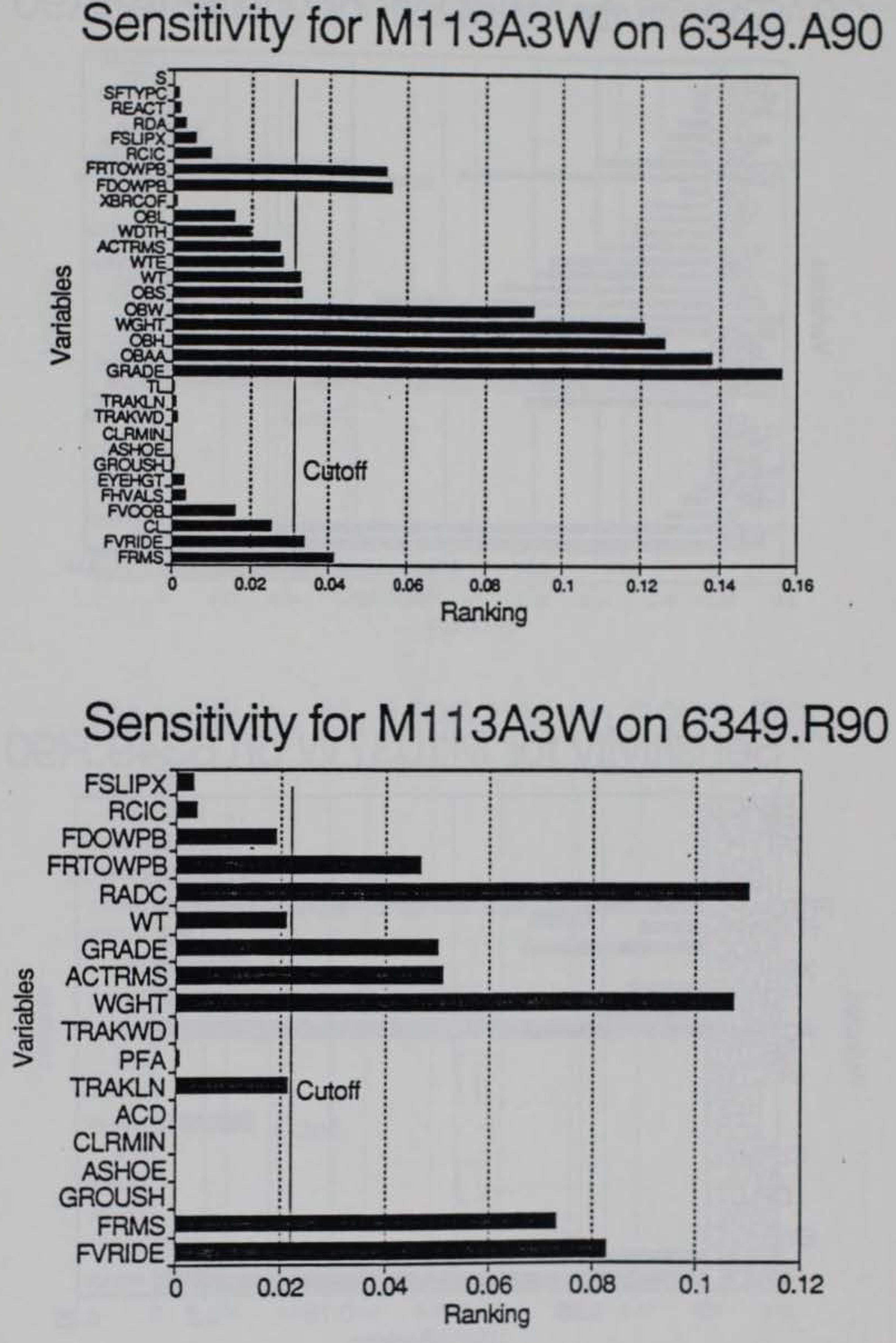


Figure 53. Sensitivity analysis for M113A3 on SWA terrain

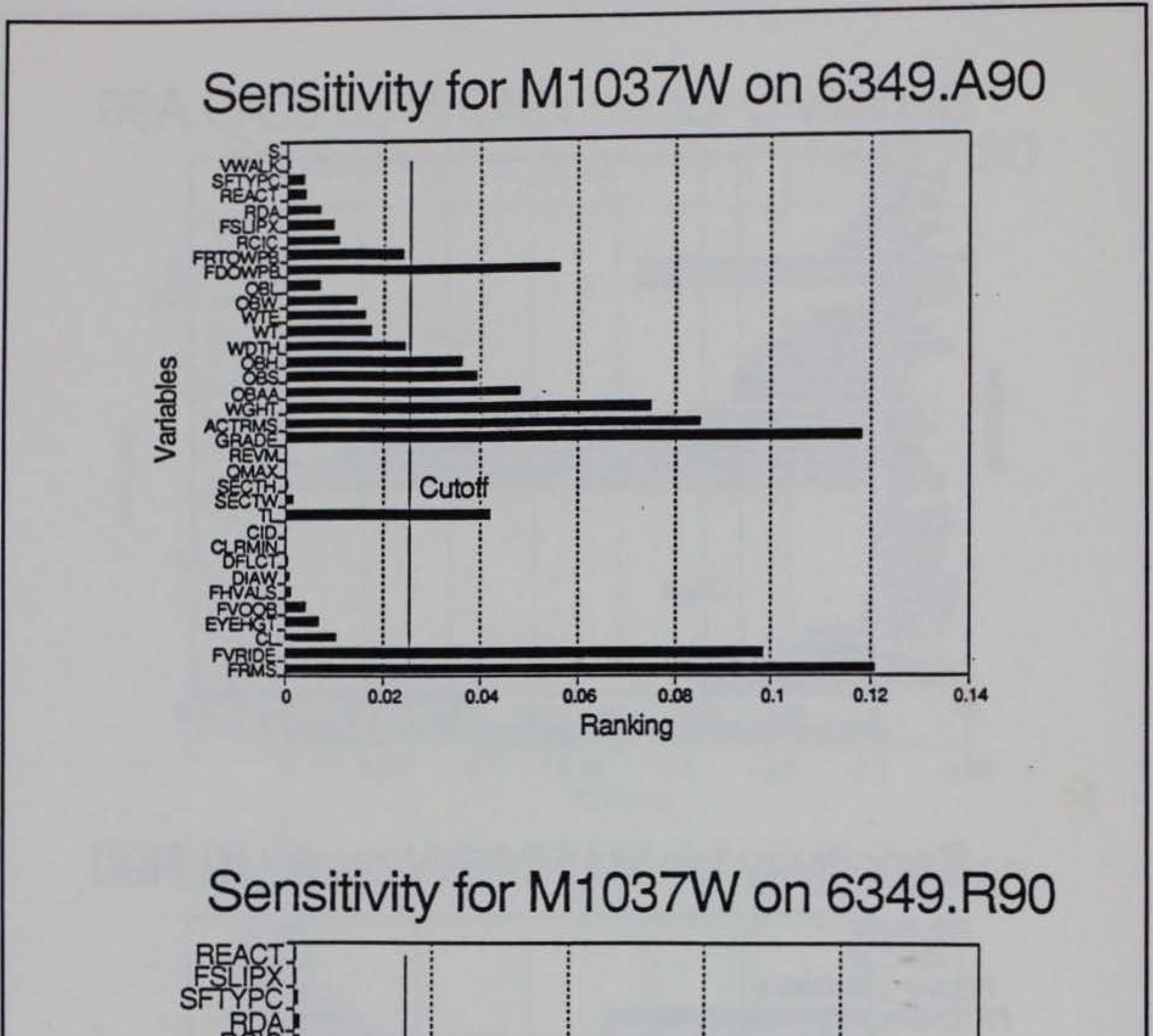


Figure 54. Sensitivity analysis for M1037 on SWA terrain

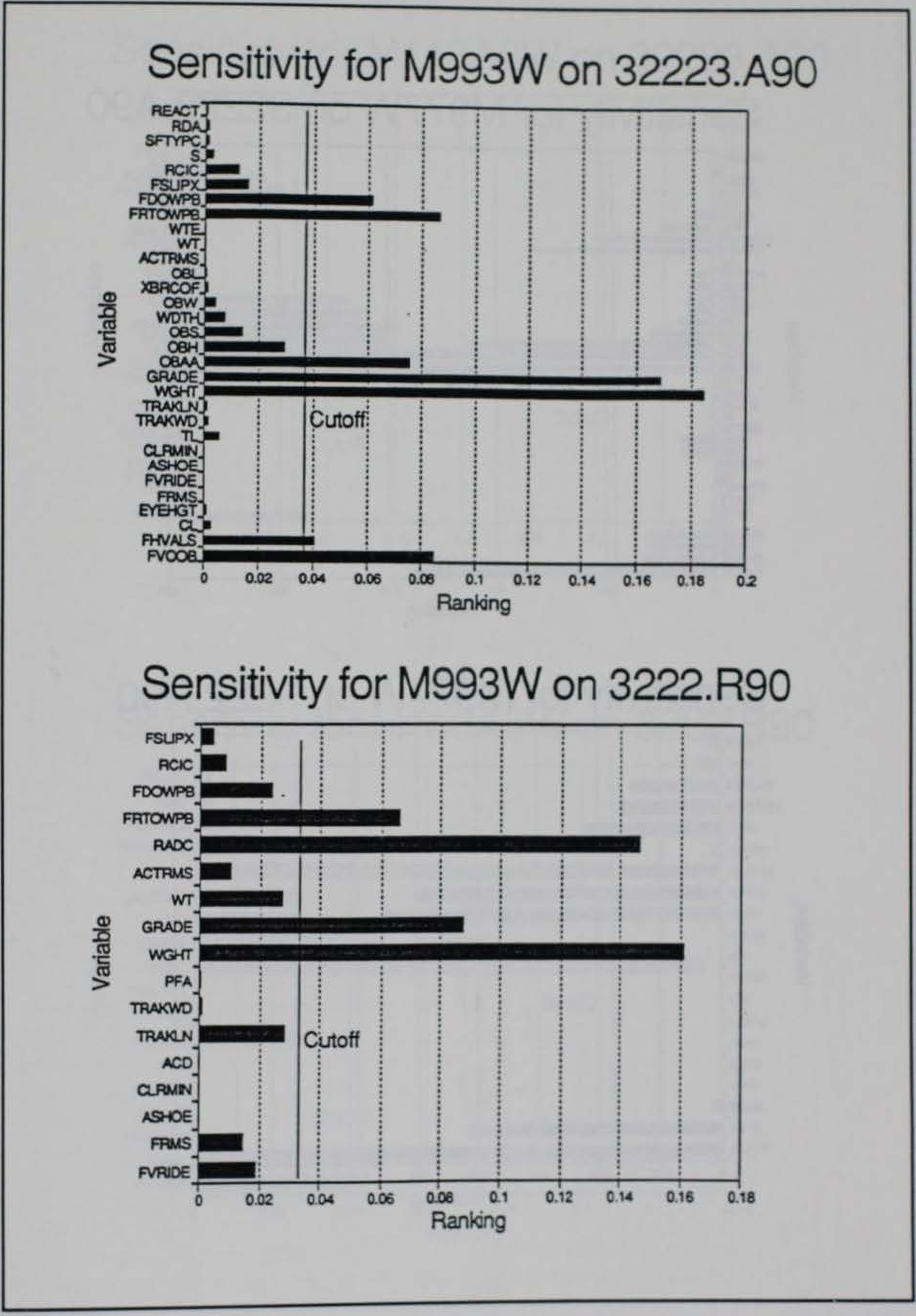


Figure 55. Sensitivity analysis for M993 on ROK terrain

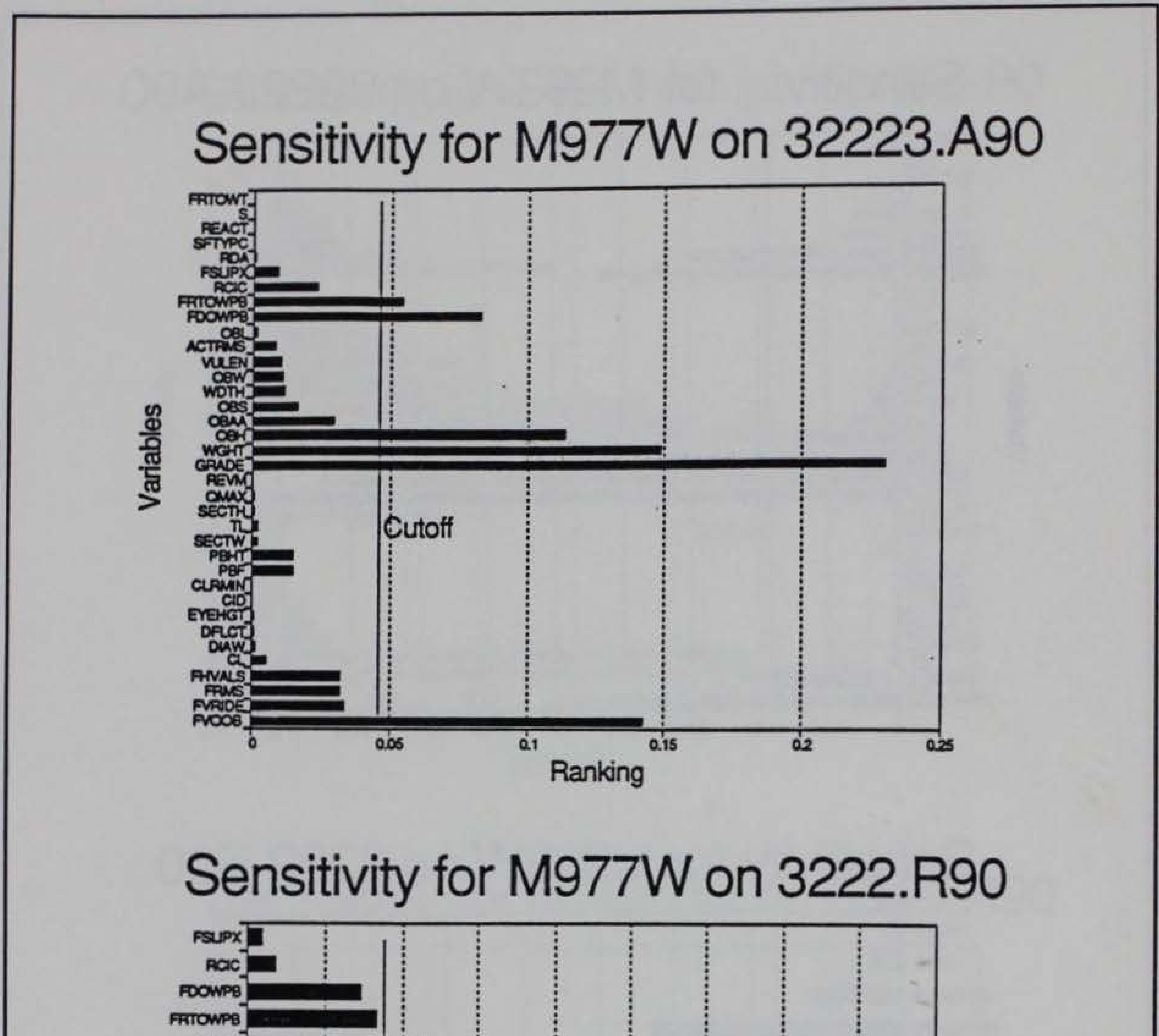


Figure 56. Sensitivity analysis for M977 on ROK terrain

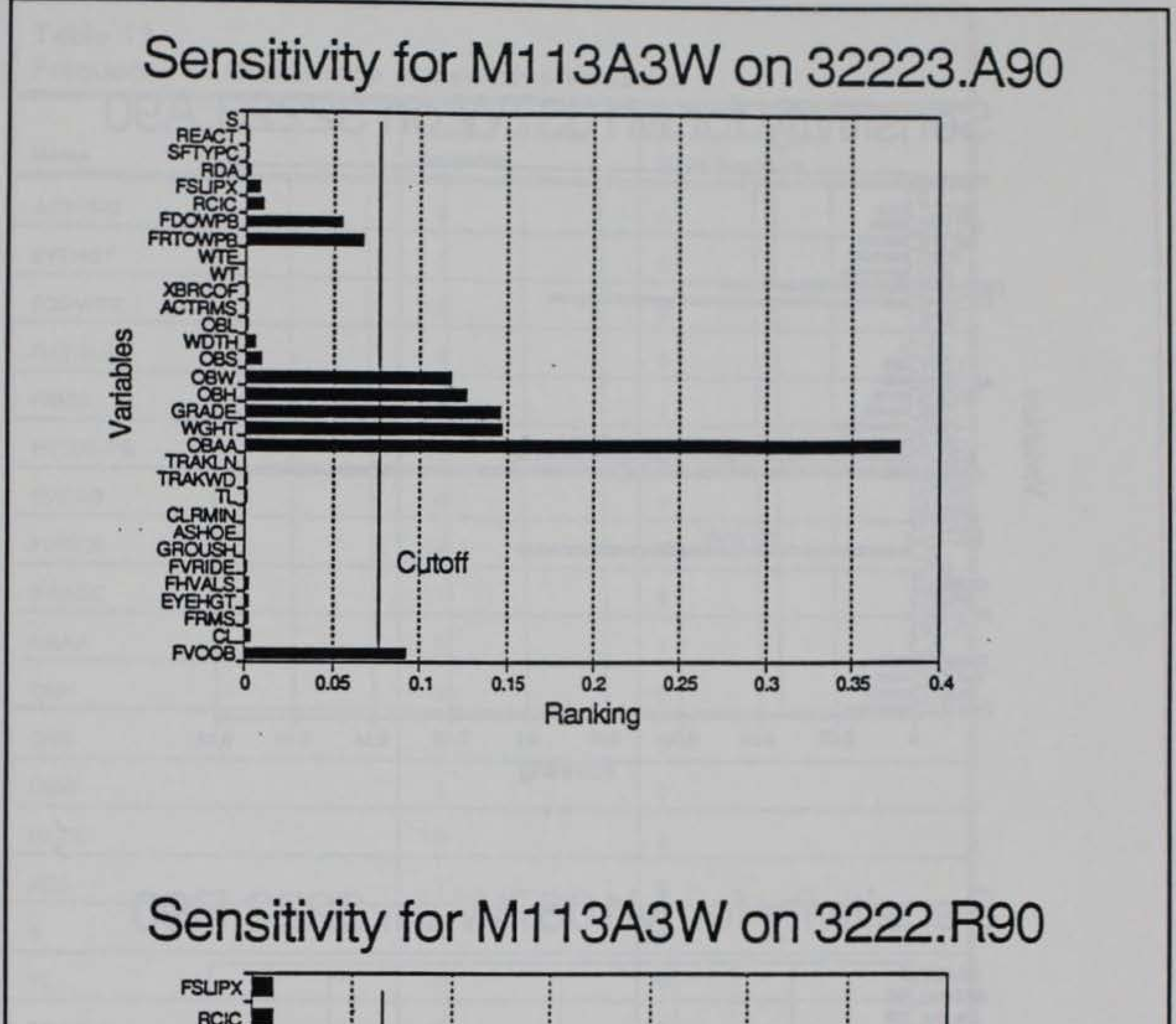


Figure 57. Sensitivity analysis for M113A3 on ROK terrain

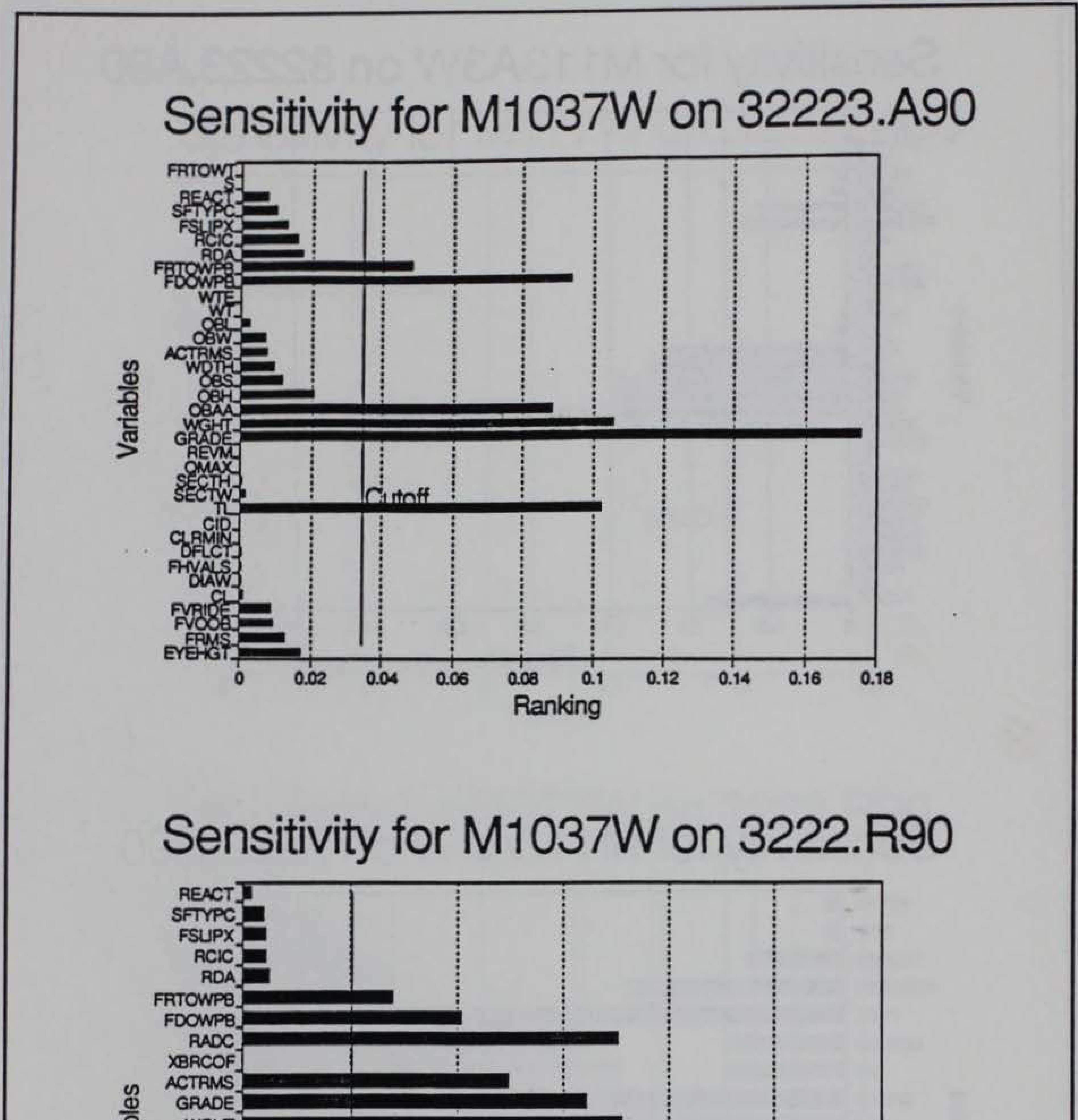


Figure 58. Sensitivity analysis for M1037 on ROK terrain

Table 11
Frequency of Occurrence of Sensitive Variables

Name	Number of Times Sensitive	Number of Times Most Sensitive
ACTRMS	6	0
EYEHGT	1	0
FDOWPB	13	0
FHVALS	4	0
FRMS	14	1
FRTOWPB	13	0
FVOOB	8	2
FVRIDE	14	7
GRADE	21	6
OBAA	9	1
OBH	9	0
OBS	4	0
OBW	2	0
RADC	10	3
RDA	1	0
S	4	0
TL	2	0
TRAKLN	2	0
WDTH	4	0
WGHT	23	4
WT	3	0

These fingerprints are shown for each vehicle for each terrain and road type in Figures 59 through 102. This graph is important as it gives a view of the error performance of the given vehicle on the specified terrain. If no errors were present in data and algorithms, the fingerprint would merely be a straight line. Deviations from a straight line indicate the effects of variations of the input parameters.

For the four vehicles studied, some general patterns were found in the fingerprints. In most cases, the data points were clustered or certain bulges and spikes appeared indicating the nonuniform error performance of NRMM for the range of vehicle speeds. The few cases in which data points can be individually identified indicate rare occurrences in the overall performance.

Table 12
Identification of Sensitive Parameters

Terrains: 5322 = Lauterbach
5520 = Schotten
6349a = Arzhan
6349r = Arzhan
32223 = Cheorweon
3222 = Cheorweon

Scenario: Dry, Normal

Vehicles: M993, M977, M113A3, M1037

Screenings		EYE	FVA	FRM	FVO	TL	TRL	VRI	WDT	WGH	WT	ACT	GRA	OBA	OBH	OBS	OBW	RAD	RDA	S	FDO	FRP
5322	M993								•	•			•	•	•					•	•	•
	M977		•		•			•	•	•										•	•	
	M113A3		•		•				•	•			•	•	•	•				•	•	•
	M1037	•	•		•				•	•			•	•	•	•			•	•	•	
5520	M993									•			•					•				•
	M977			•				•		•			•					•				
	M113A3			•			•	•		•		•	•					•				•
	M1037			•				•				•						•				
6349a	M993				•					•			•	•	•						•	•
	M977			•	•			•		•			•		•						•	
	M113A3			•				•		•	•		•	•	•	•					•	•
	M1037			•				•		•		•	•	•	•	•					•	
6349r	M993			•				•		•			•								•	•
	M977			•				•		•												
	M113A3			•				•		•		•	•					•				
	M1037			•				•		•		•						•				
3223	M993		•		•					•			•	•							•	•
	M977		•		•					•			•		•						•	•
	M113A3				•					•			•	•	•		•					
	M1037					•				•			•	•							•	•
3222	M993									•			•					•				•
	M977			•				•		•			•					•				•
	M113A3			•			•	•		•	•		•					•				•
	M1037			•				•		•		•	•					•			•	•

When the fingerprints were analyzed for the M993 on off-road terrain, however, the deviation between maximum and minimum speeds was not as great as with the other three vehicles on this type of terrain. This indicates that the M993 is not affected as greatly by data errors as are the other candidates. Similar results were found for the M1037 on all on-road terrains; hence, the effect of uncertainty for on-road performance of the M1037 is less dramatic.

The same data shown in the fingerprints can be more clearly defined by an in-unit speed profile. These in-unit profiles Figures 59 through 102, are obtained by plotting speeds versus percentage of total area or distance crossed. This percentage is based on a list sorted by nominal speed from best to worst and accumulating the terrain corresponding to each speed. These plots show

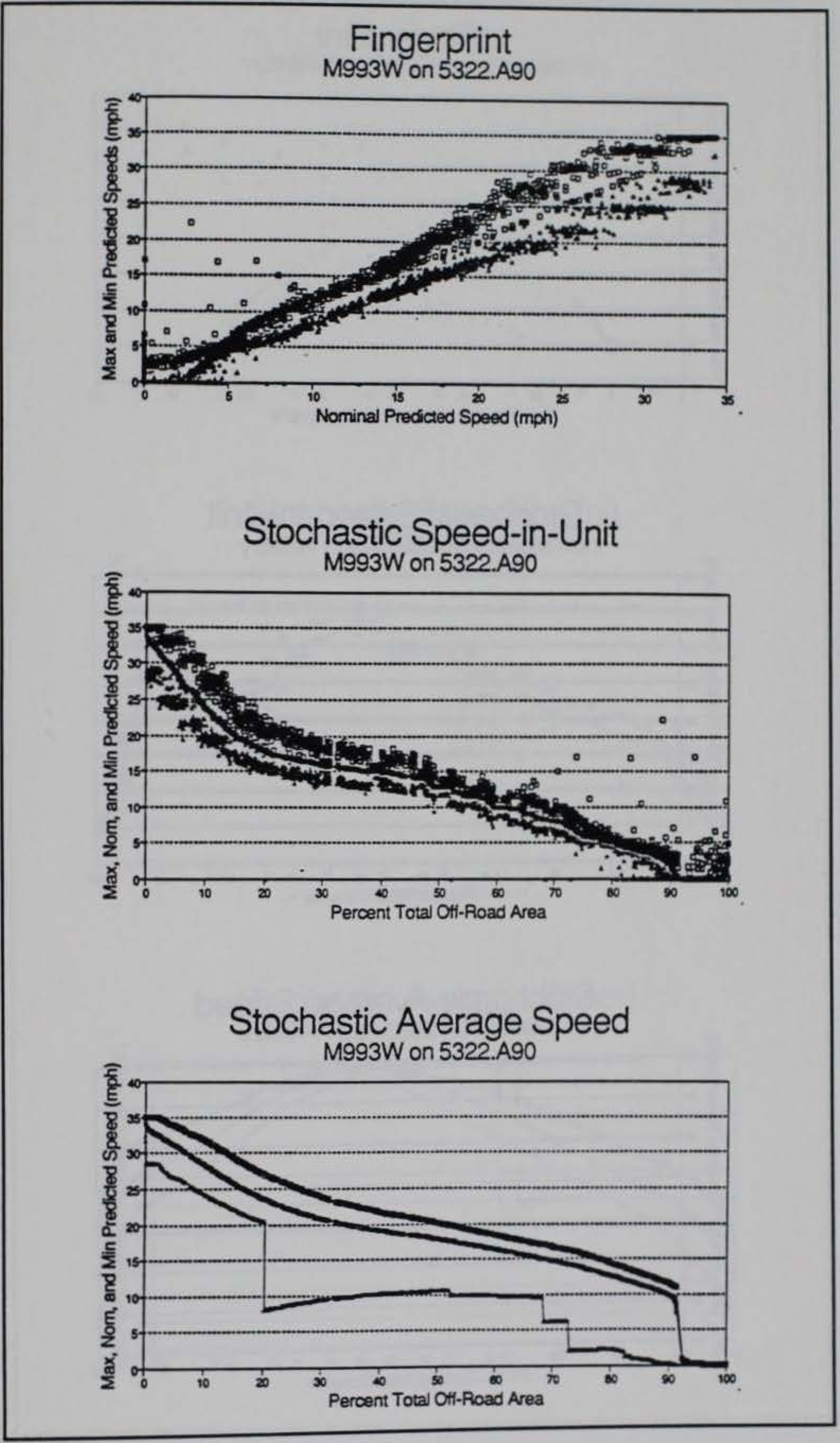


Figure 59. Fingerprint and profiles for M993 on WGe off-road

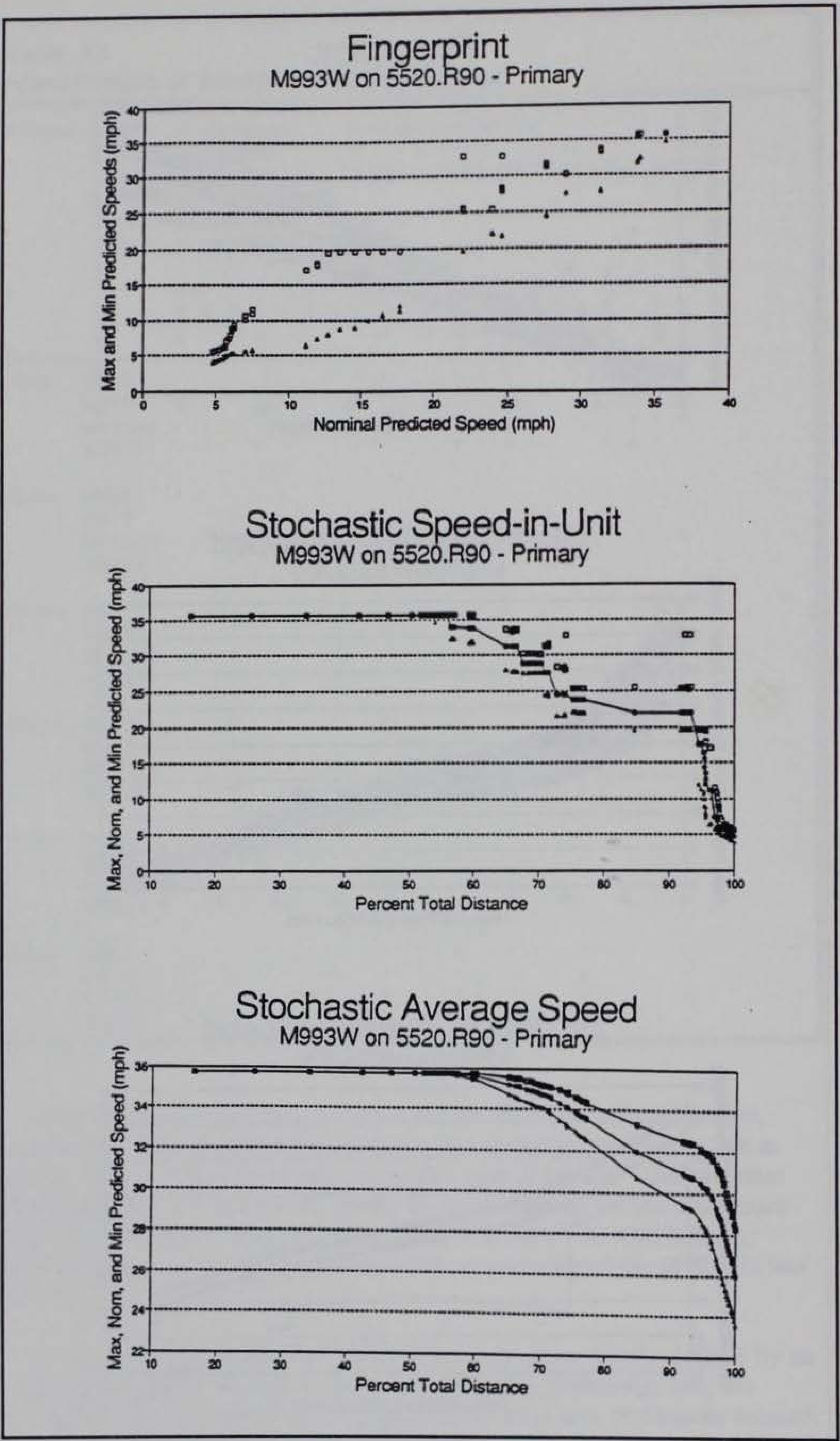


Figure 60. Fingerprint and profiles for M993 on WGe primary roads

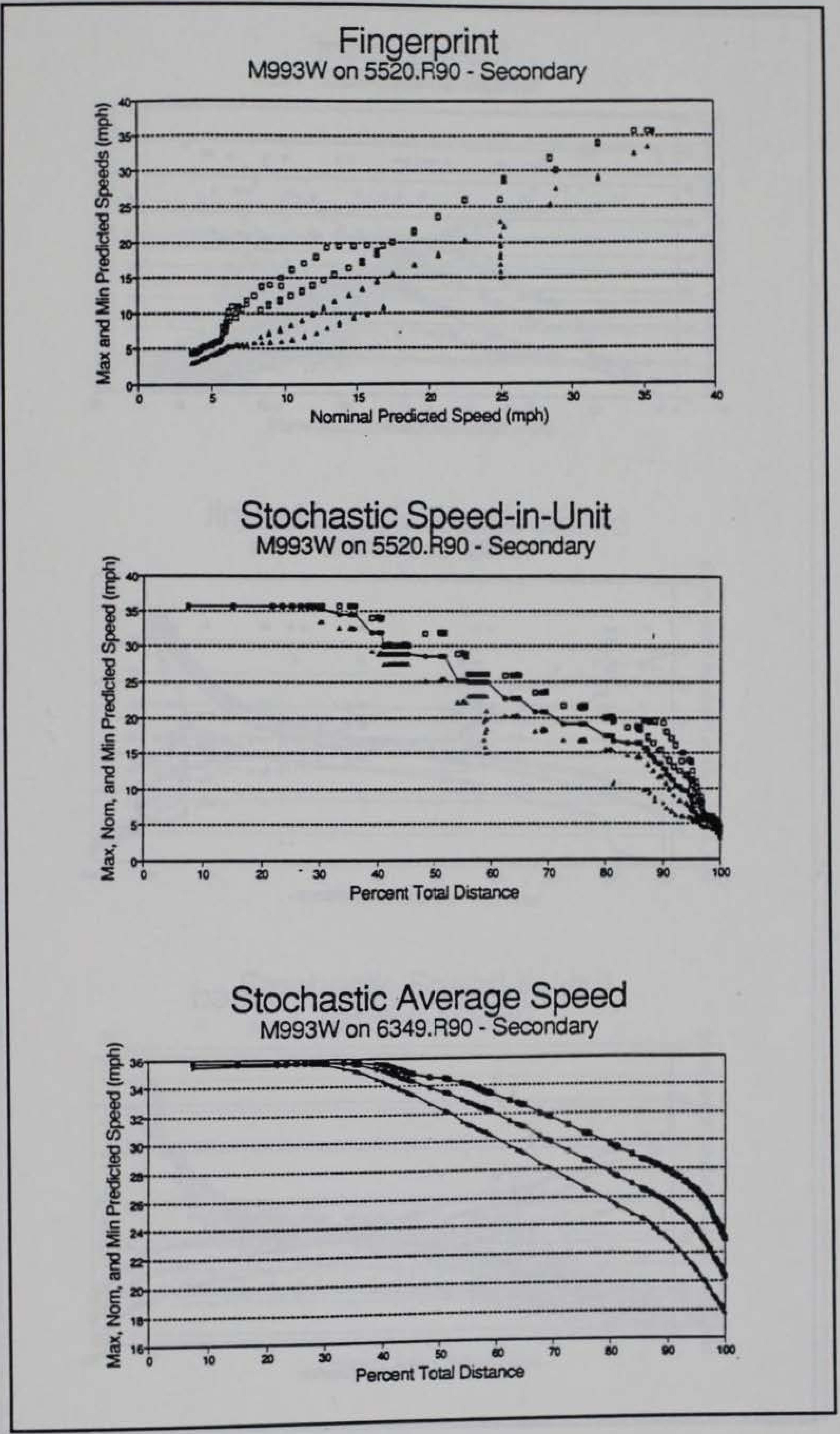


Figure 61. Fingerprint and profiles for M993 on WGe secondary roads

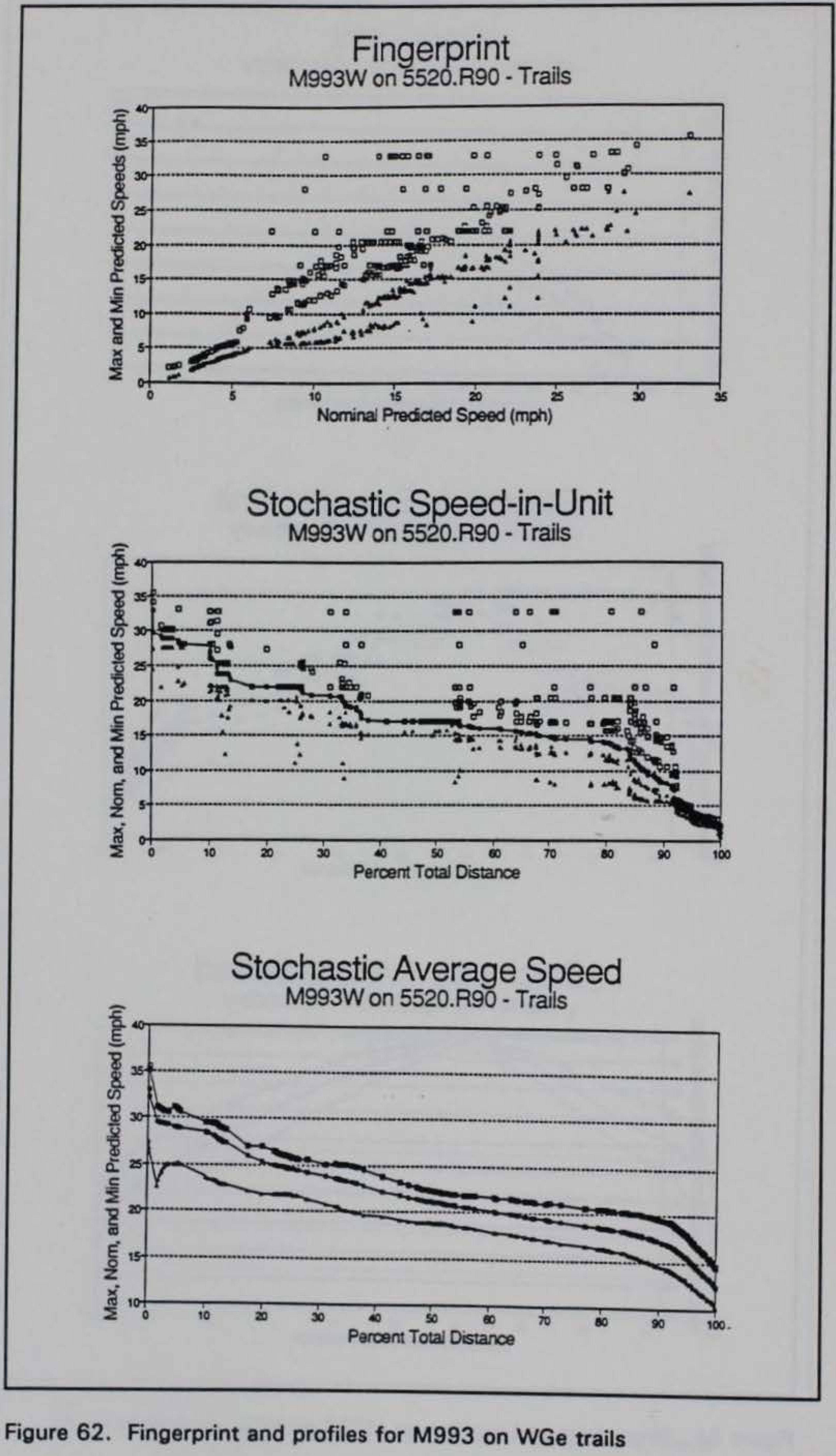


Figure 62. Fingerprint and profiles for M993 on WGe trails

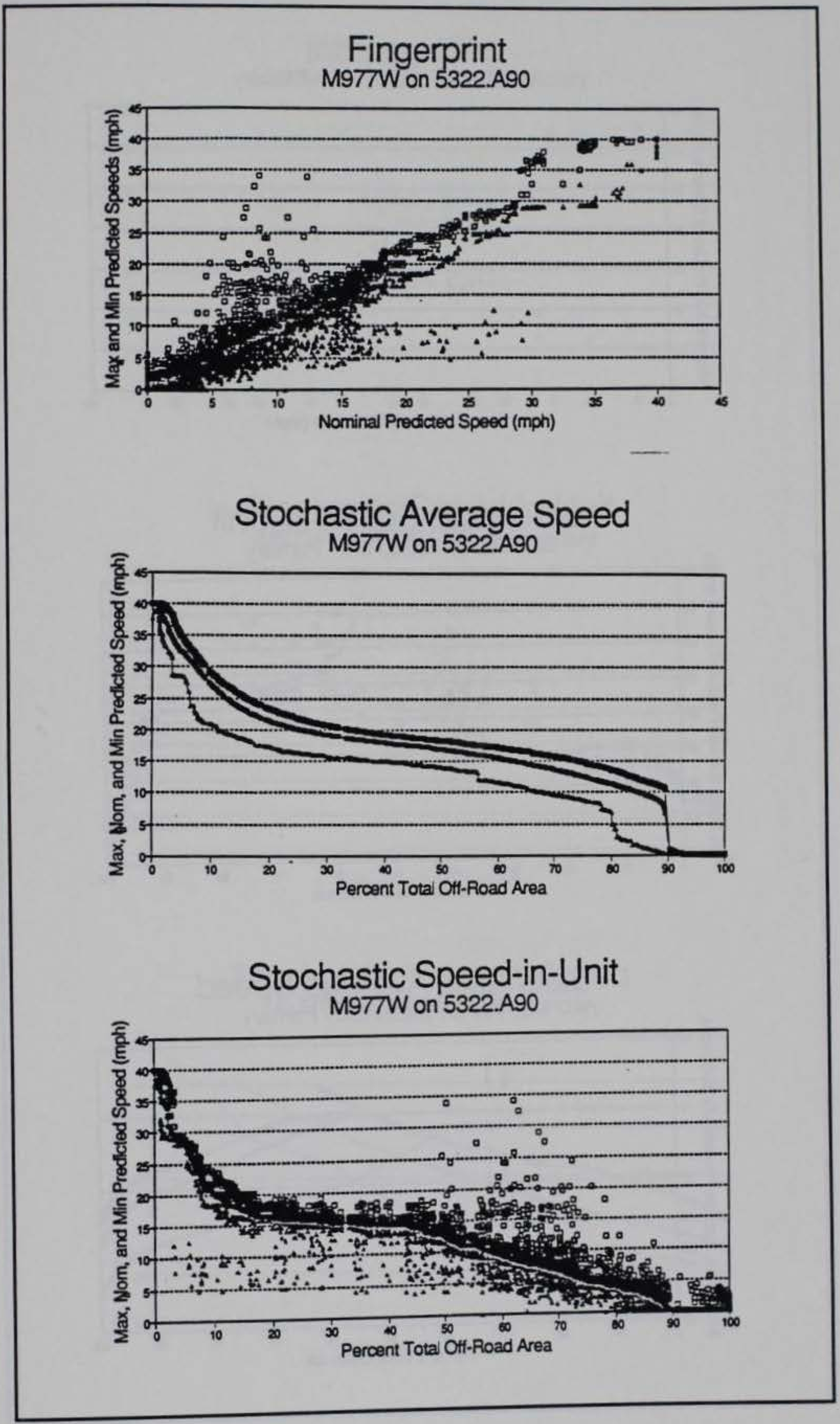


Figure 63. Fingerprint and profiles for M977 on WGe off-road

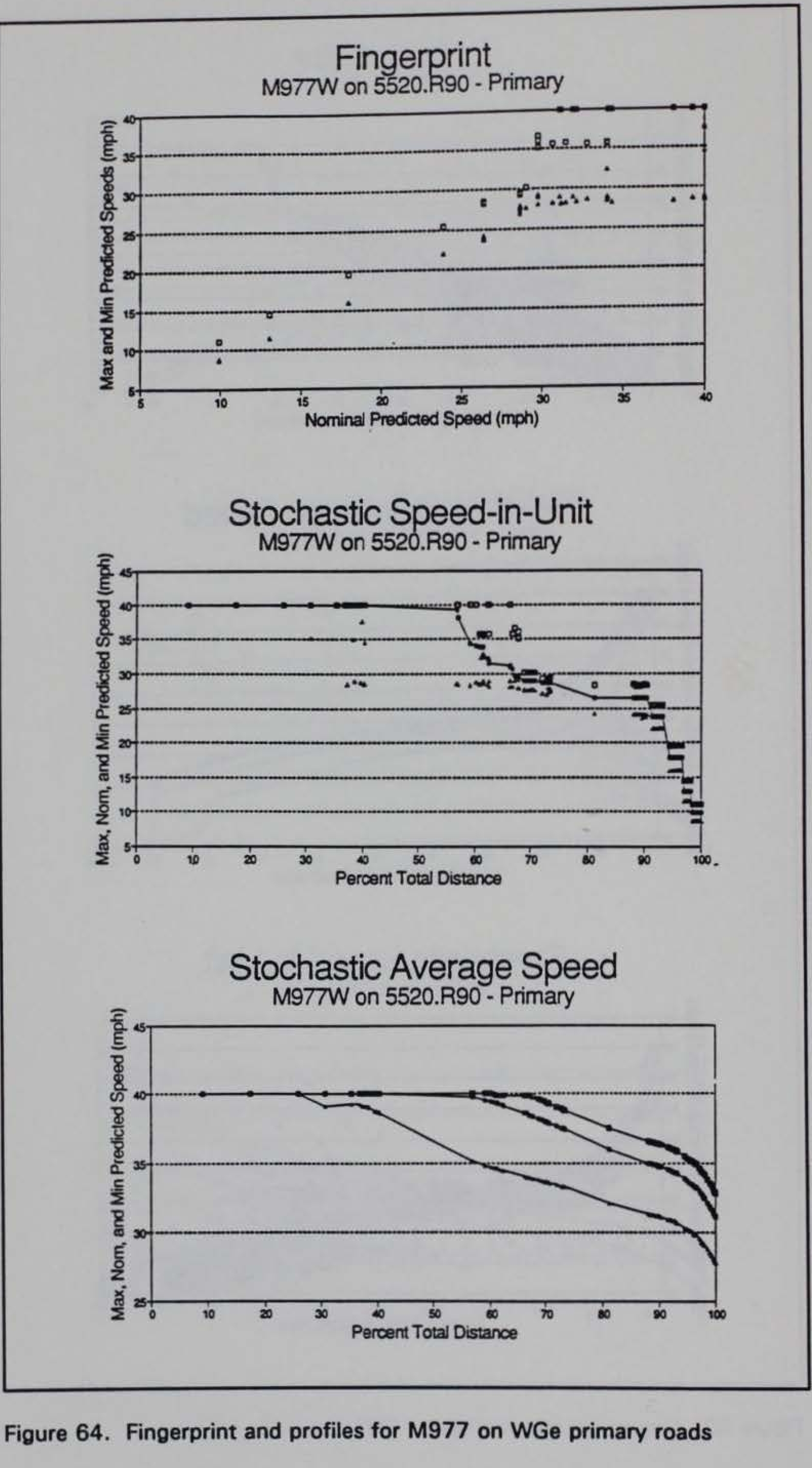


Figure 64. Fingerprint and profiles for M977 on WGe primary roads

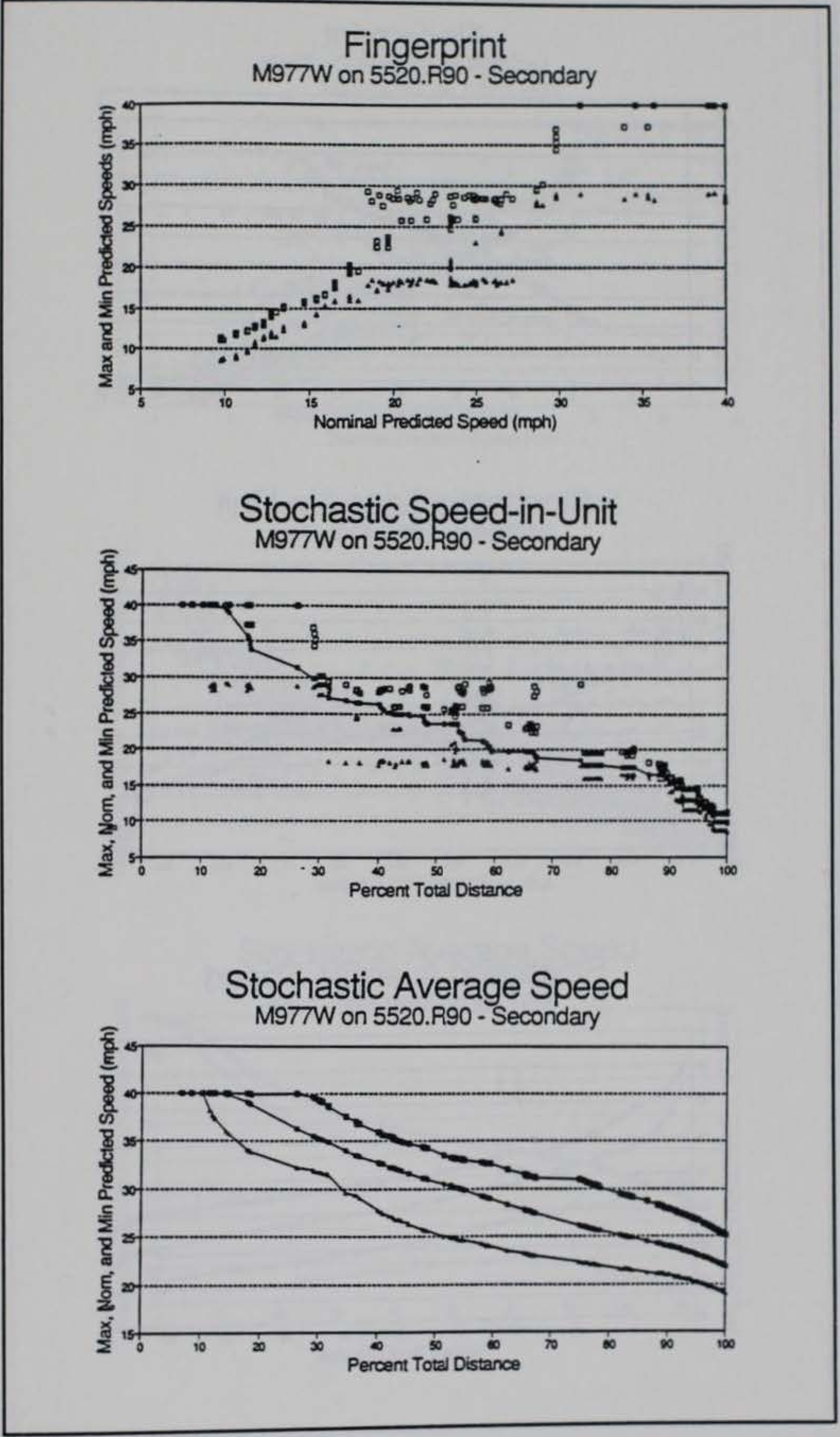


Figure 65. Fingerprint and profiles for M977 on WGe secondary road

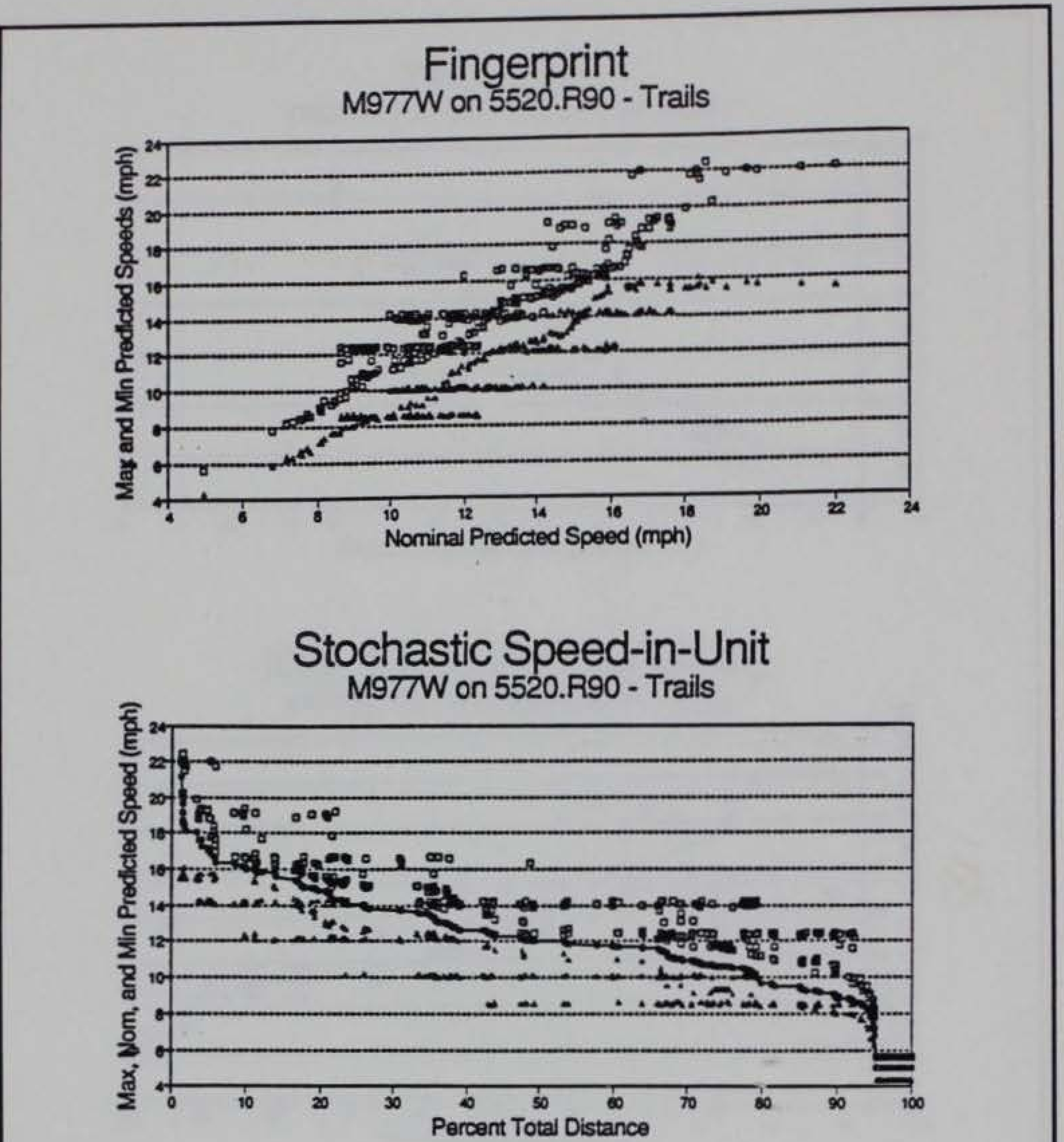


Figure 66. Fingerprint and profiles for M977 on WGe trails

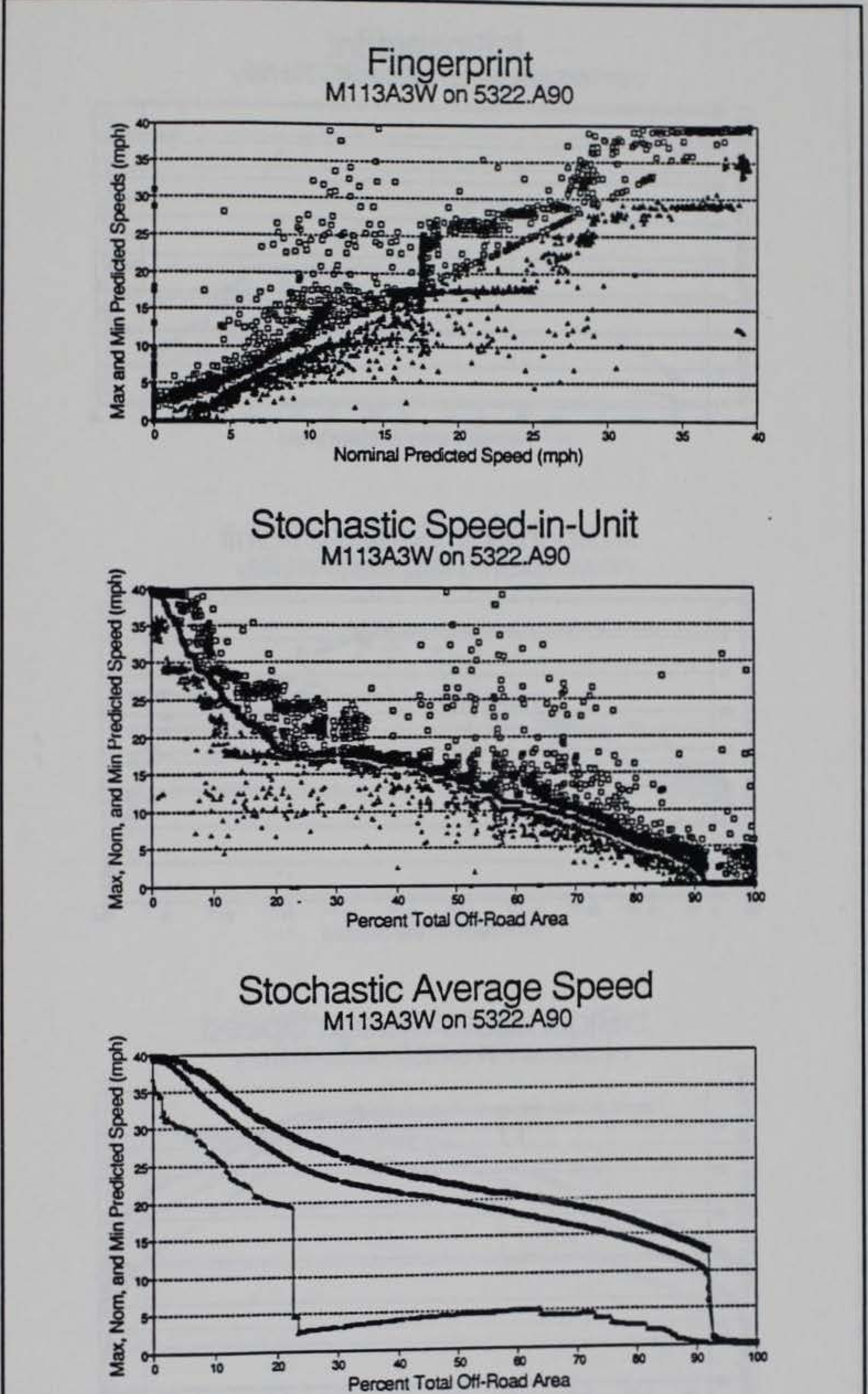


Figure 67. Fingerprint and profiles for M113A3 on WGe off-road

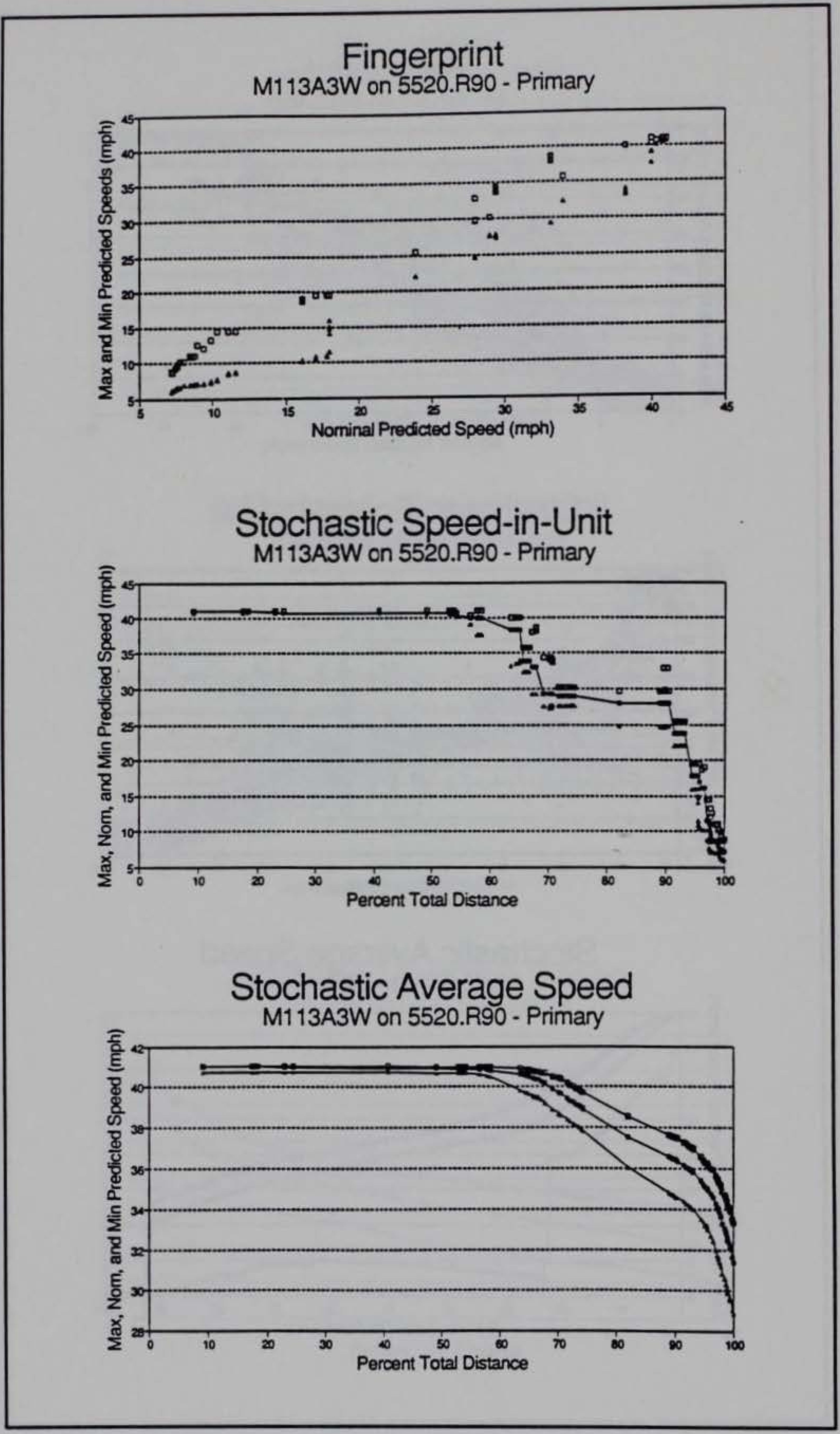


Figure 68. Fingerprint and profiles for M113A3 on WGe primary roads

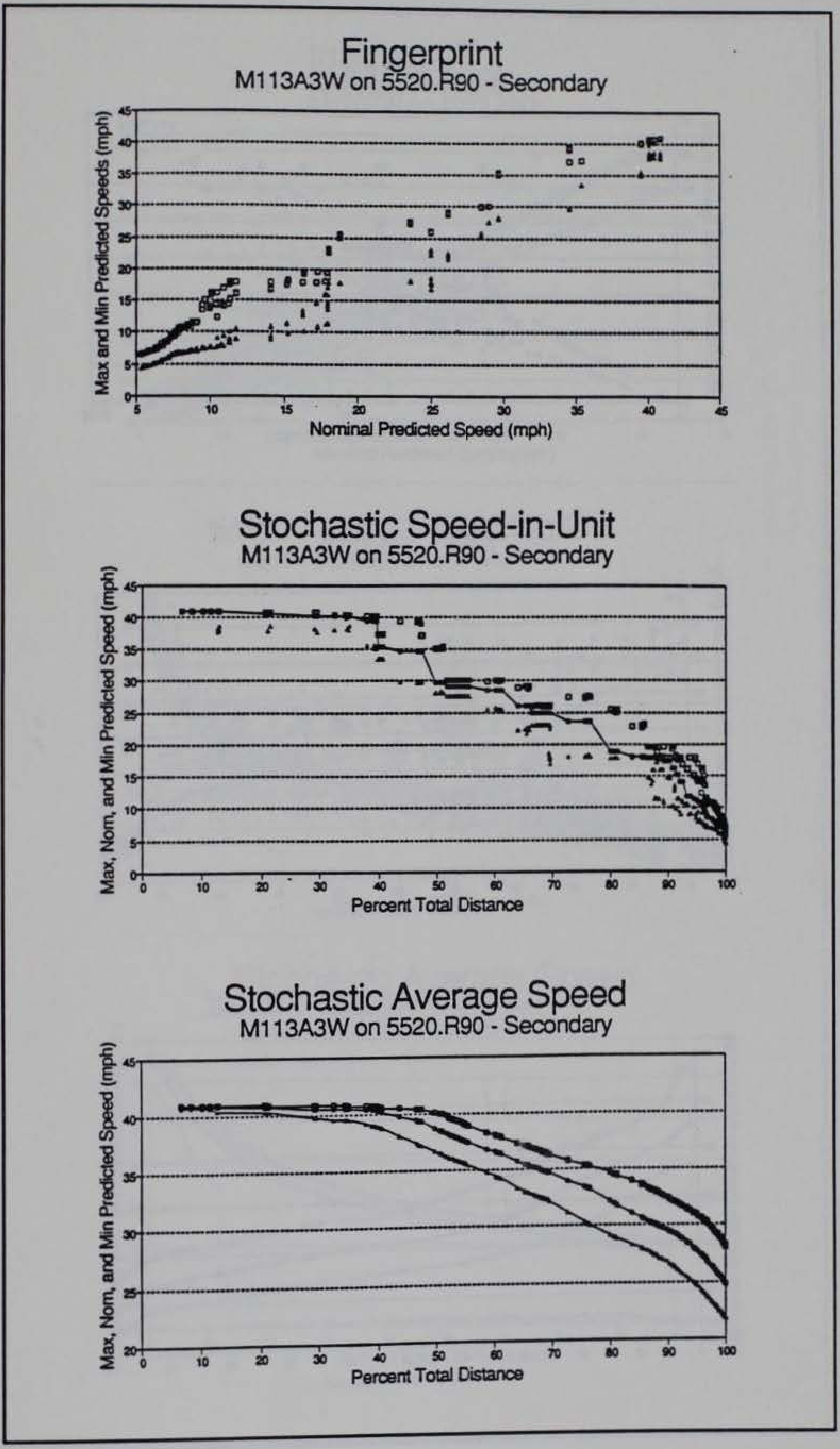


Figure 69. Fingerprint and profiles for M113A3 on WGe secondary roads

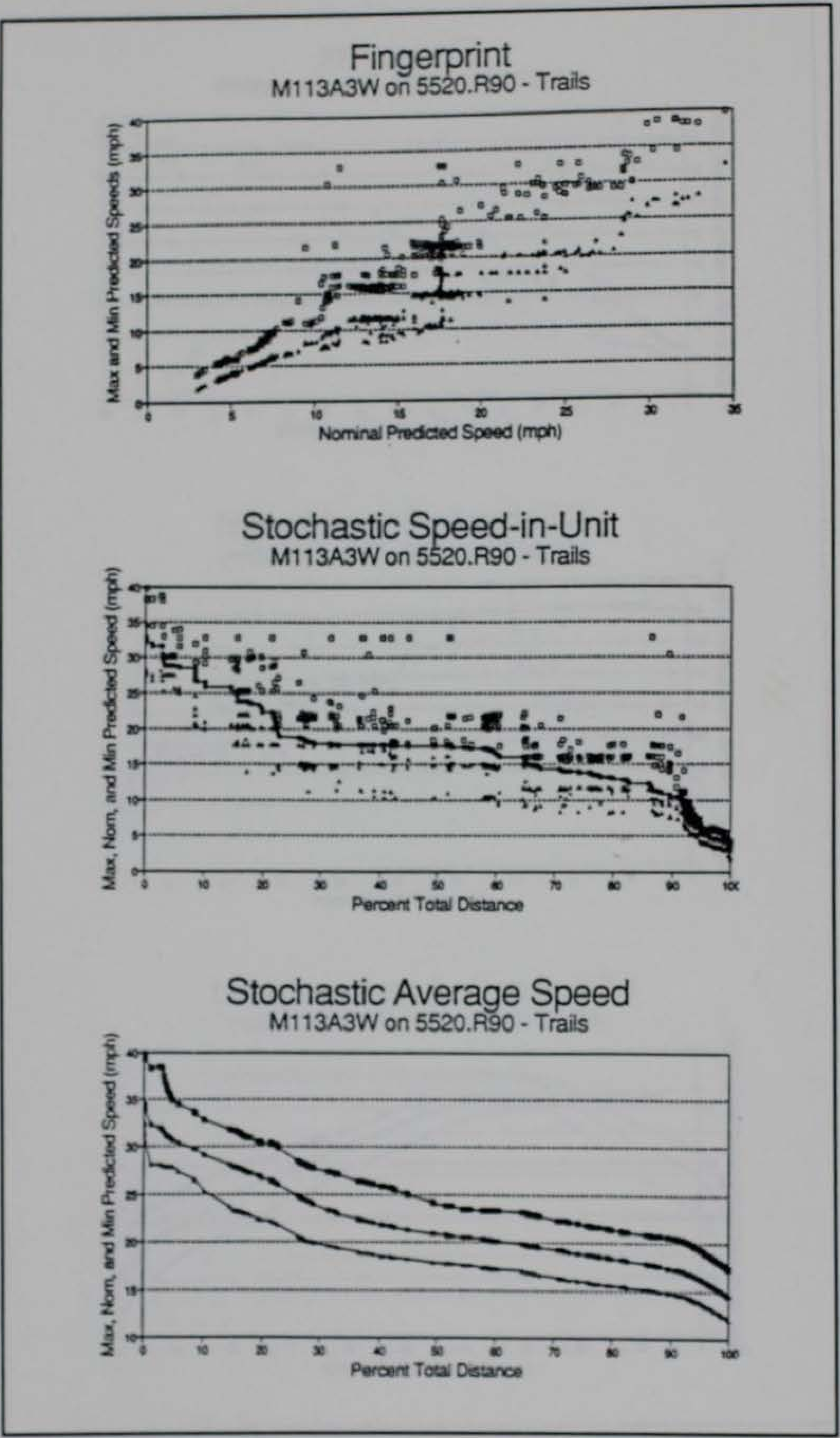


Figure 70. Fingerprint and profiles for M113A3 on WGe trails

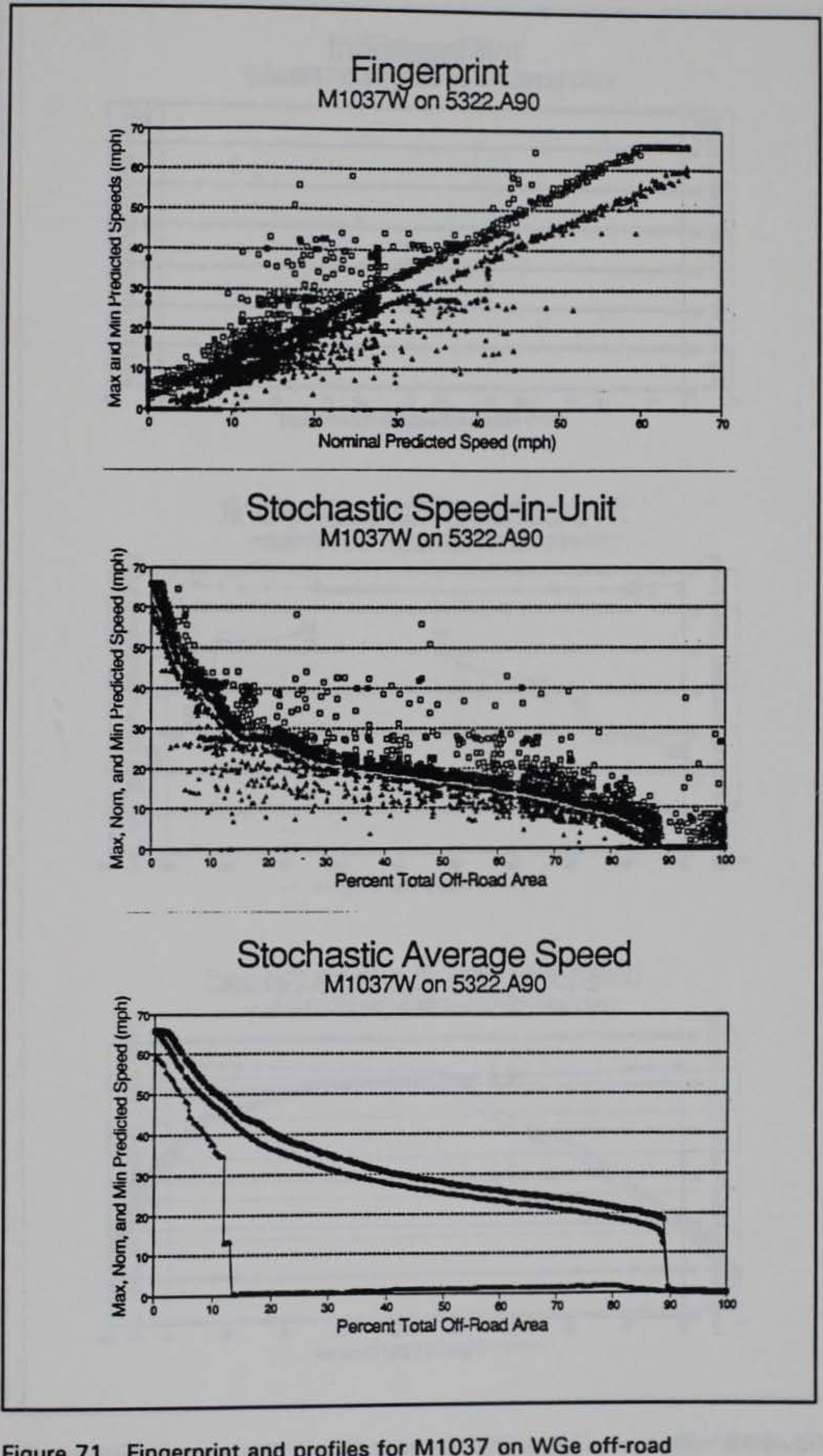


Figure 71. Fingerprint and profiles for M1037 on WGe off-road

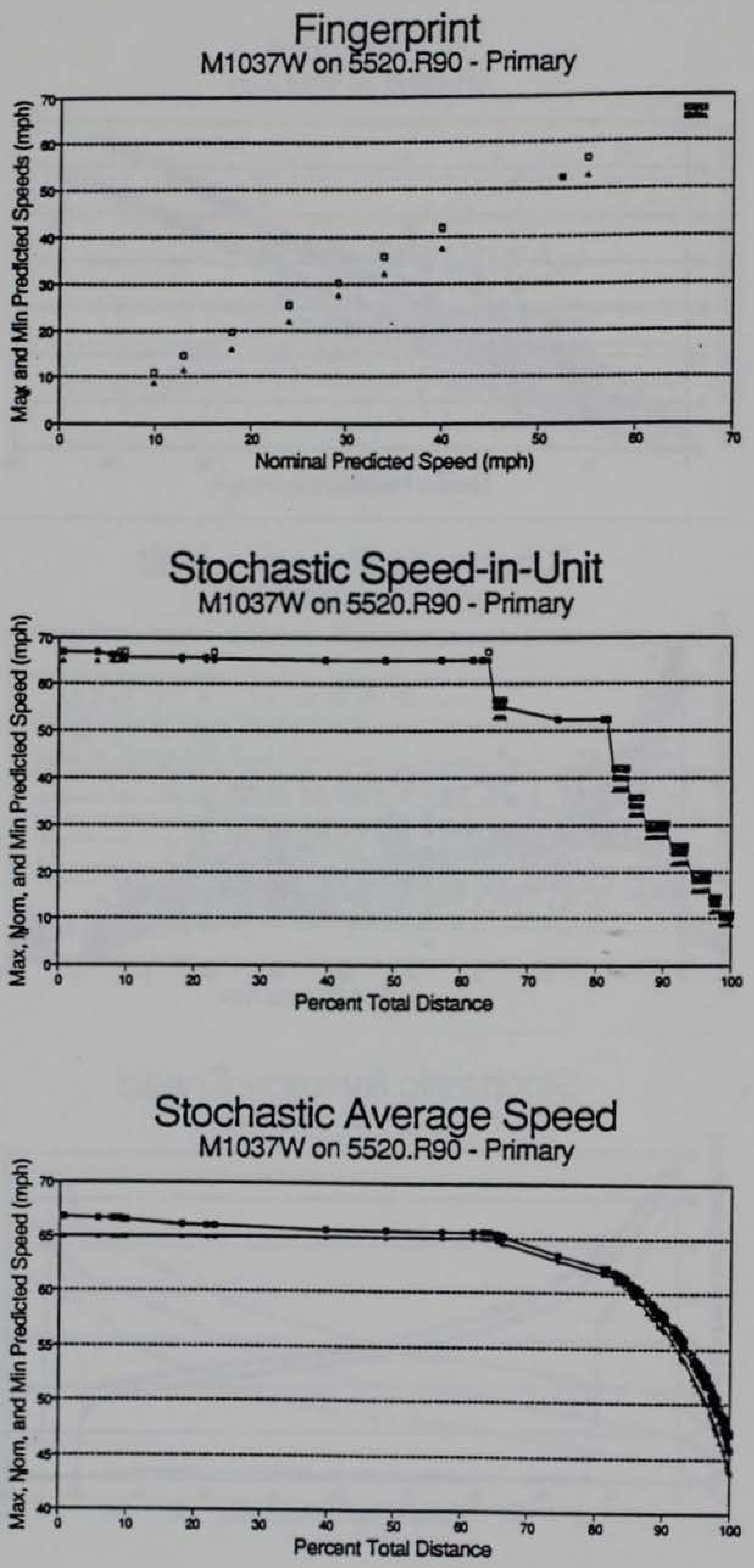


Figure 72. Fingerprint and profiles for M1037 on WGe primary roads

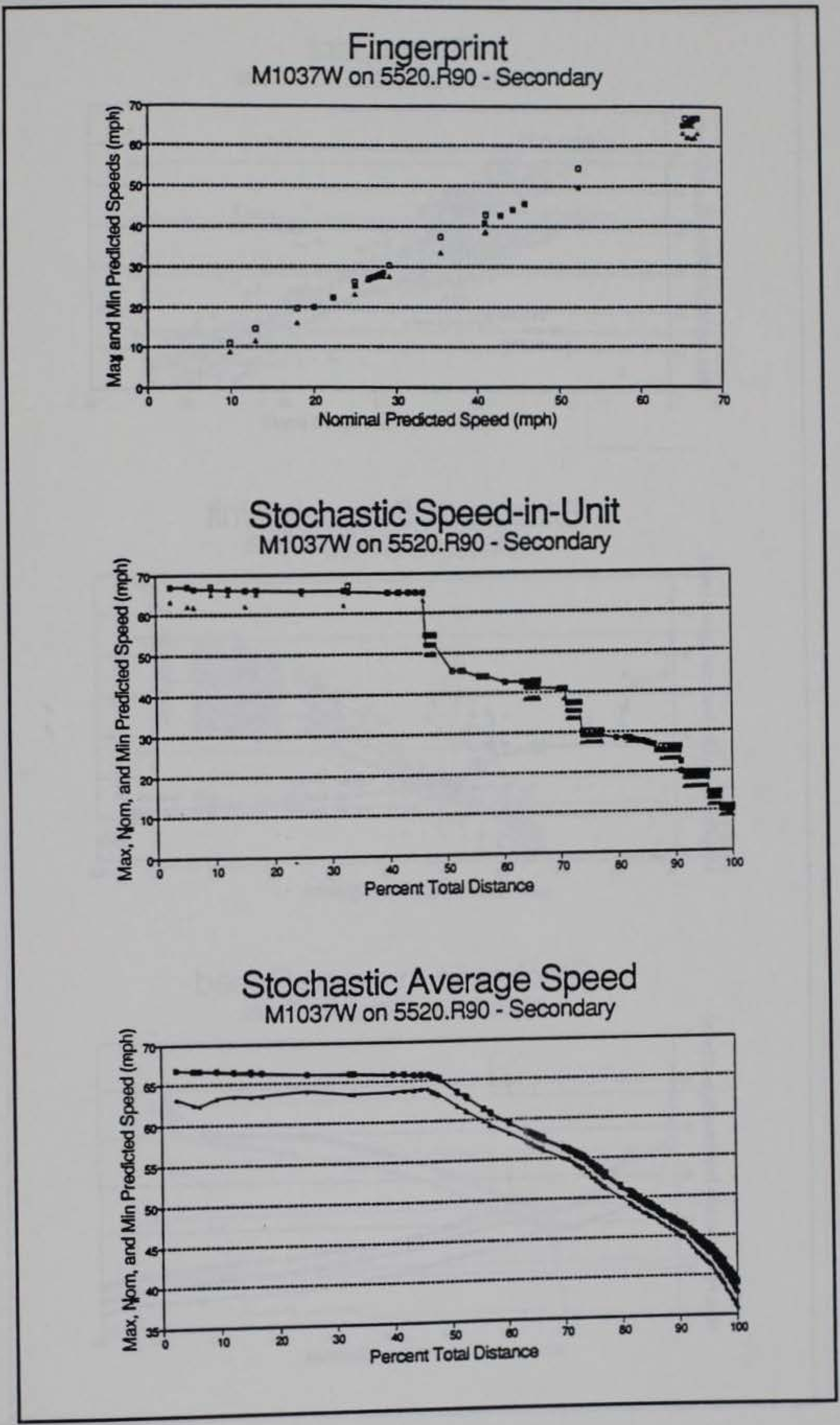


Figure 73. Fingerprint and profiles for M1037 on WGe secondary roads

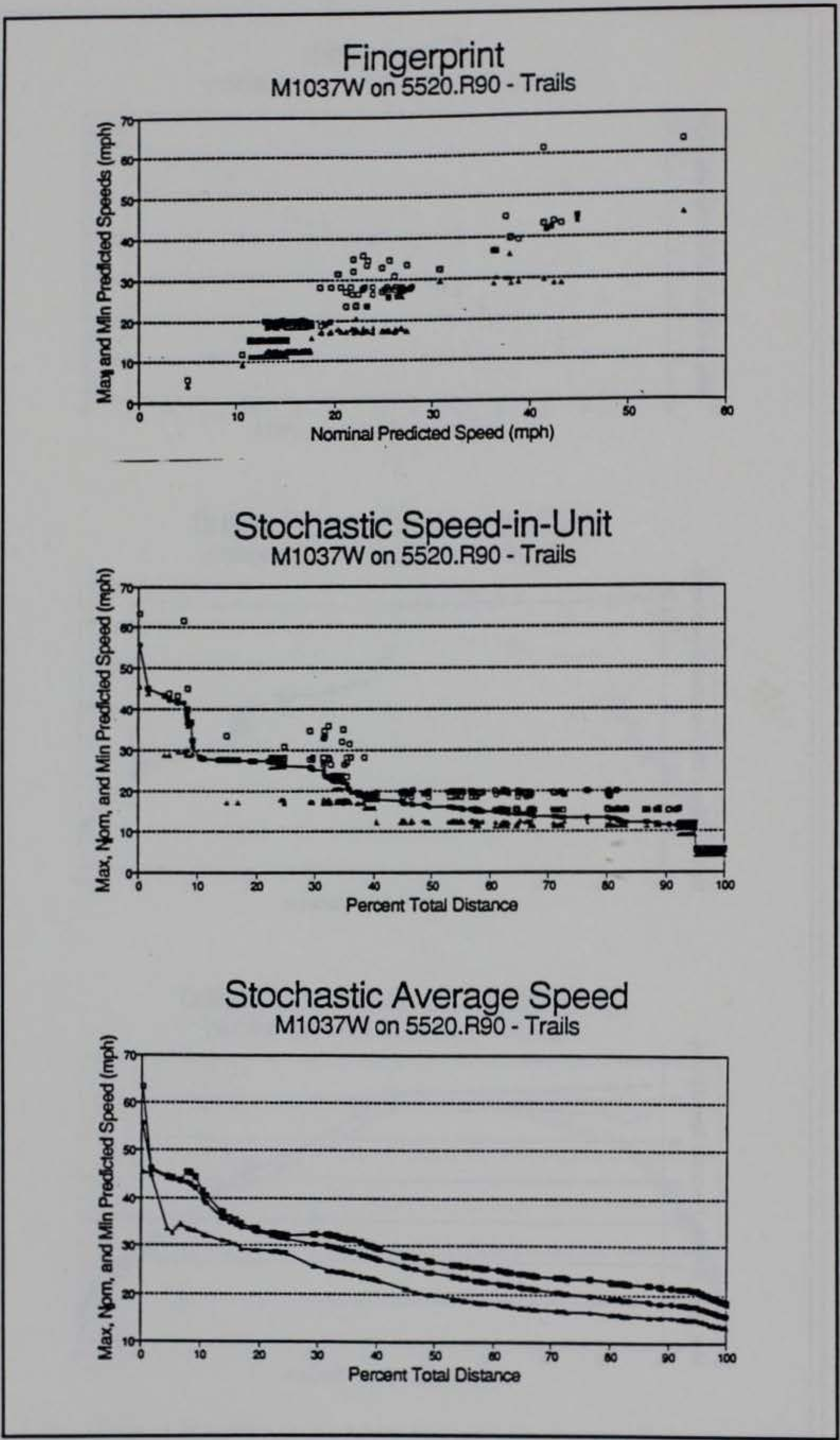


Figure 74. Fingerprint and profiles for M1037 on WGe trails

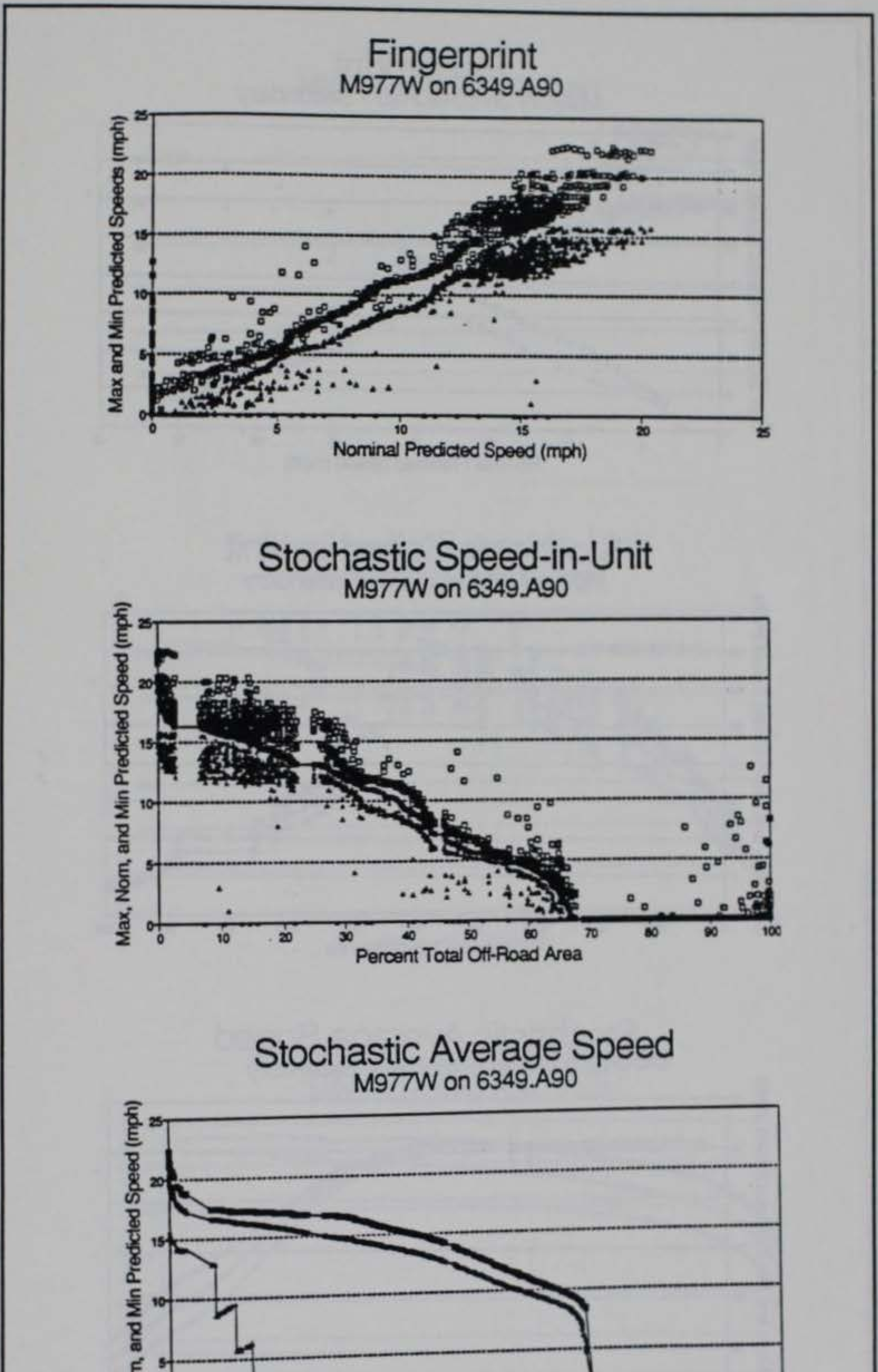


Figure 75. Fingerprint and profiles for M993 on SWA off-road

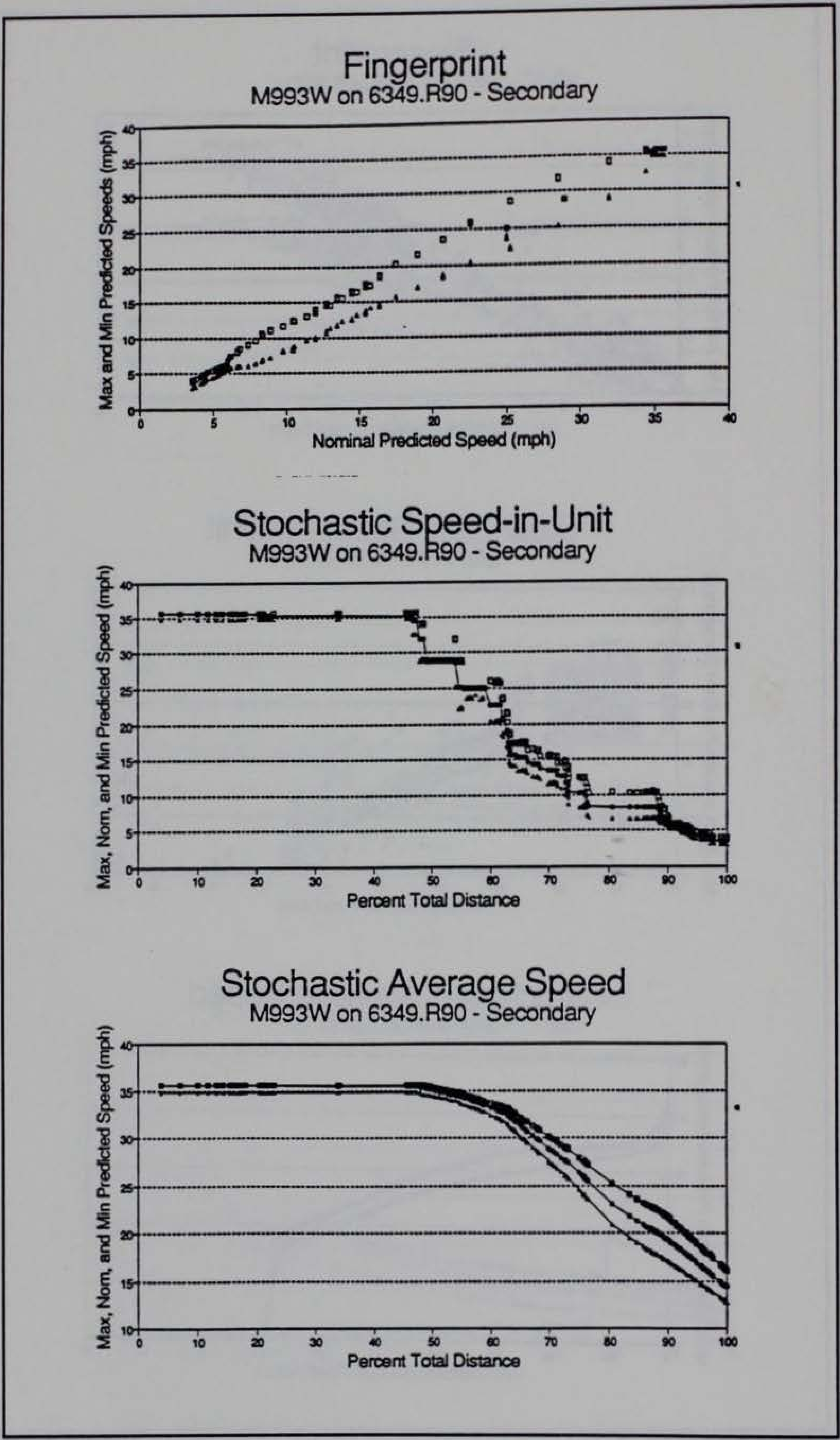


Figure 76. Fingerprint and profiles for M993 on SWA secondary roads

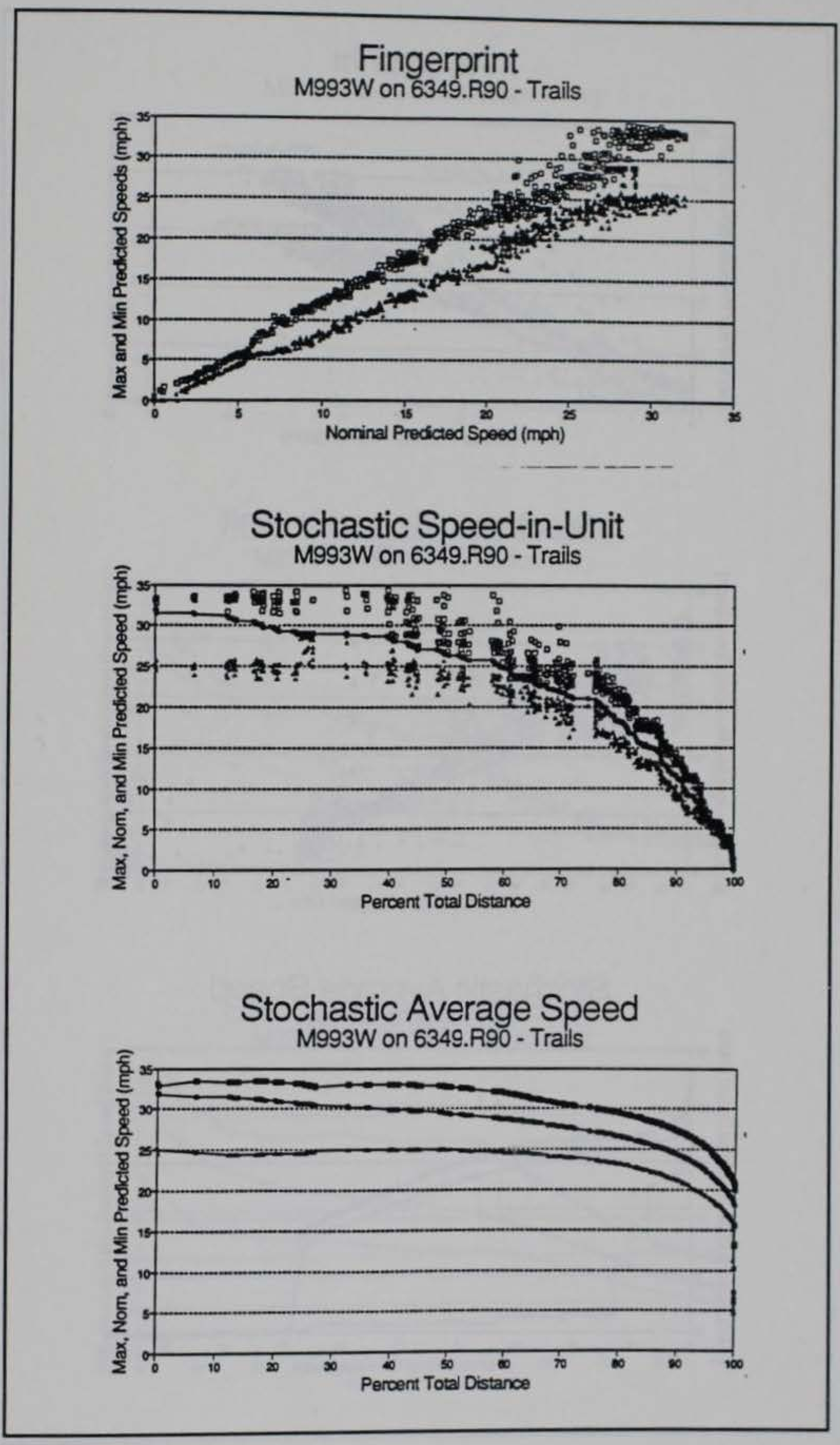


Figure 77. Fingerprint and profiles for M993 on SWA trails

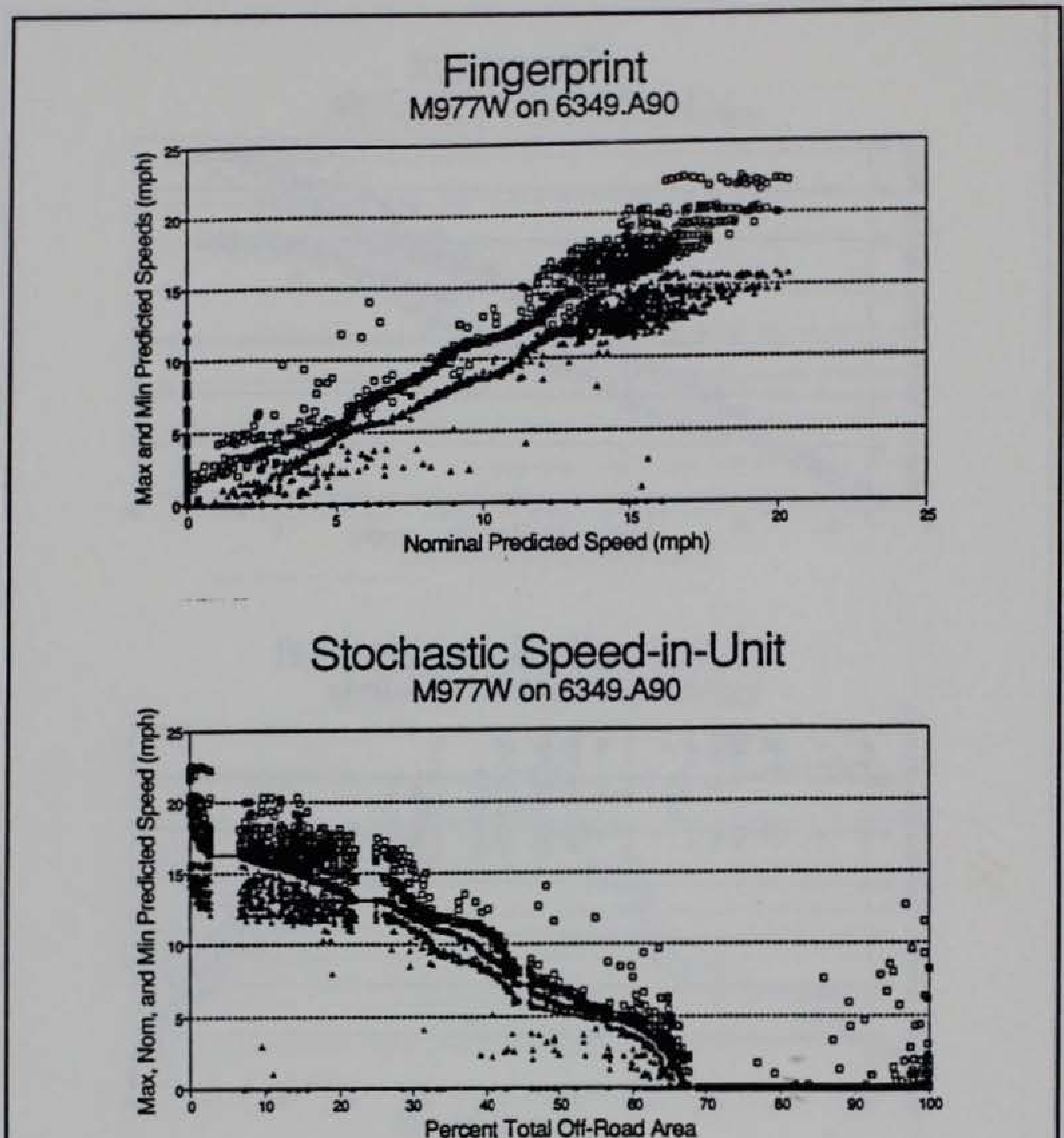


Figure 78. Fingerprint and profiles for M977 on SWA off-road

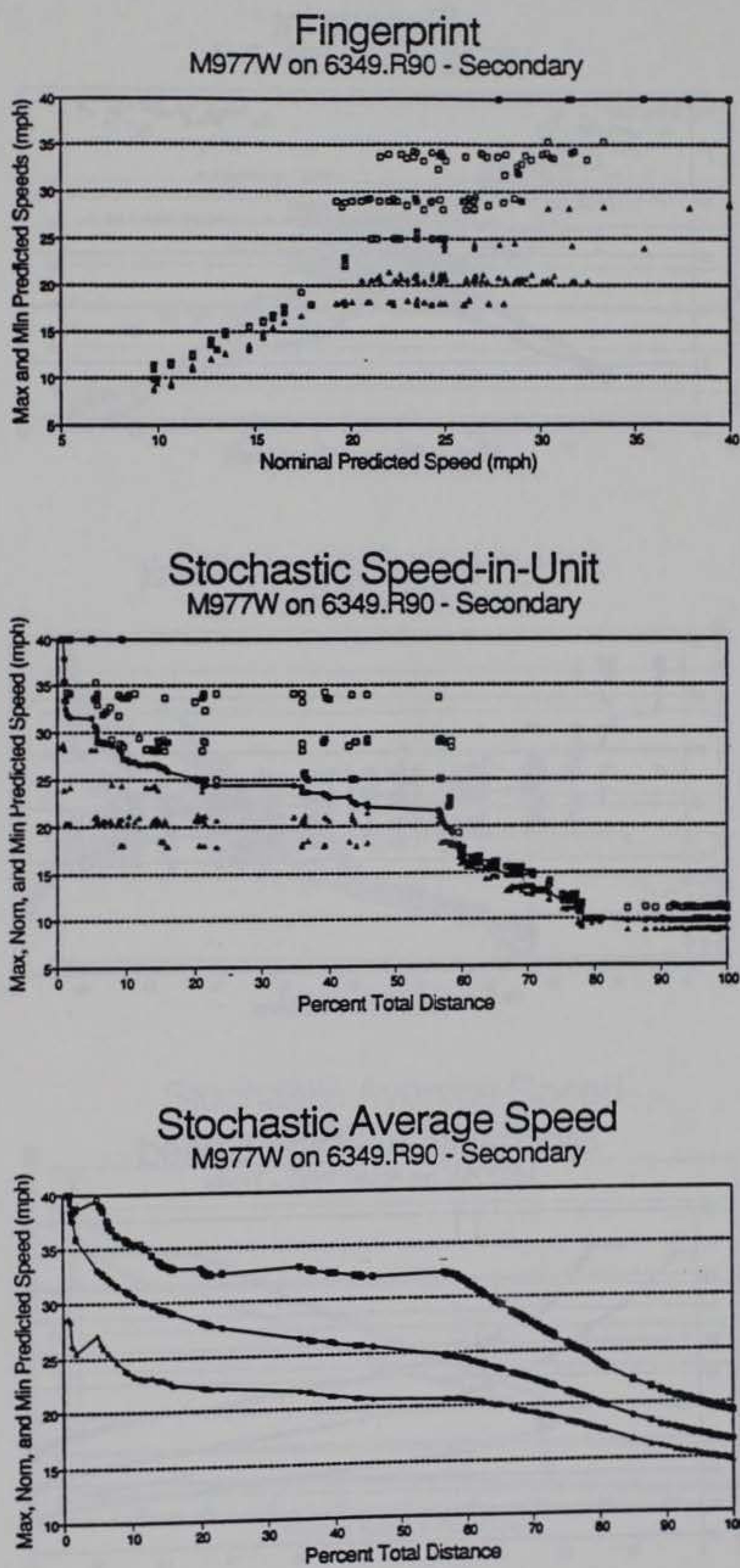


Figure 79. Fingerprint and profiles for M977 on SWA secondary roads

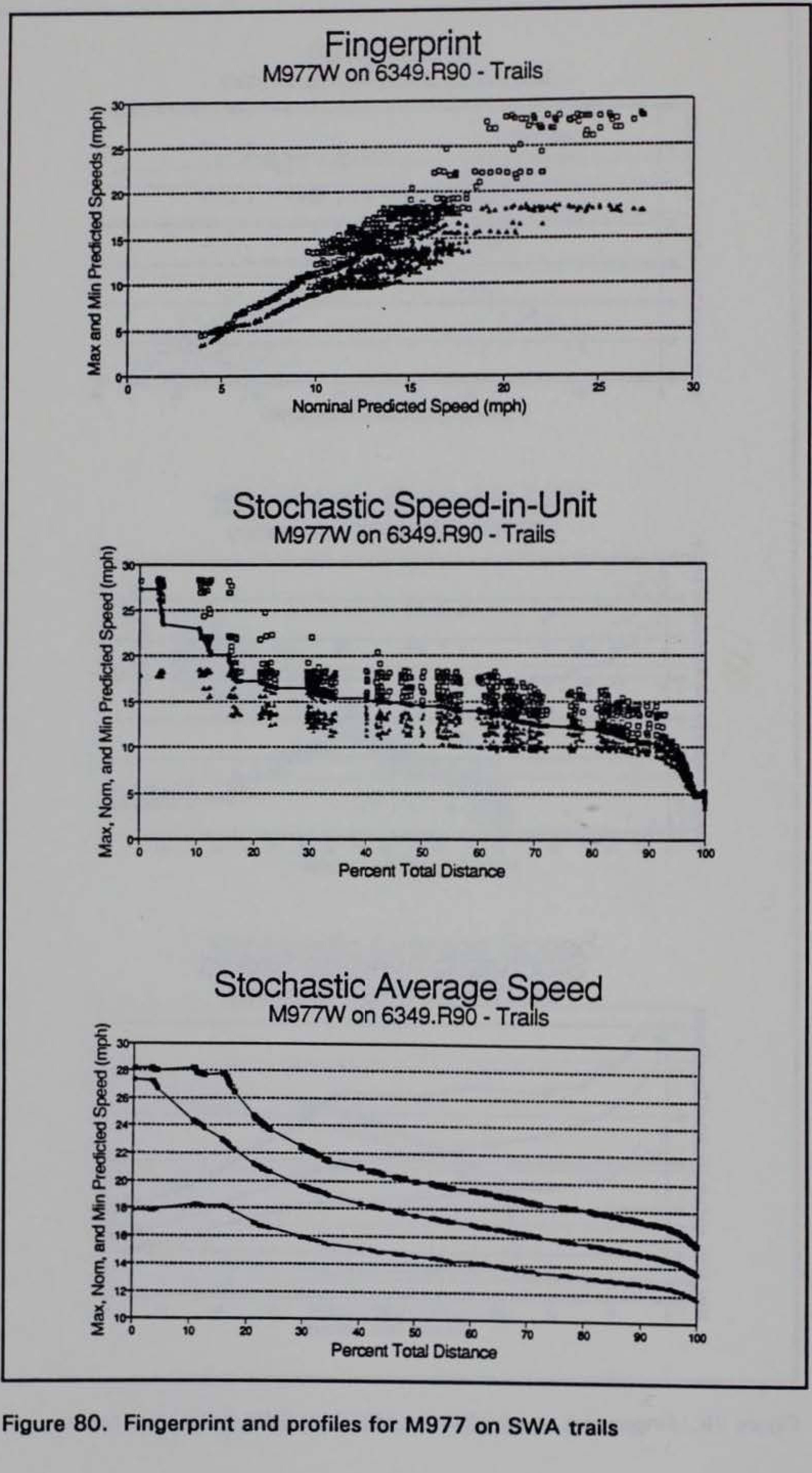


Figure 80. Fingerprint and profiles for M977 on SWA trails

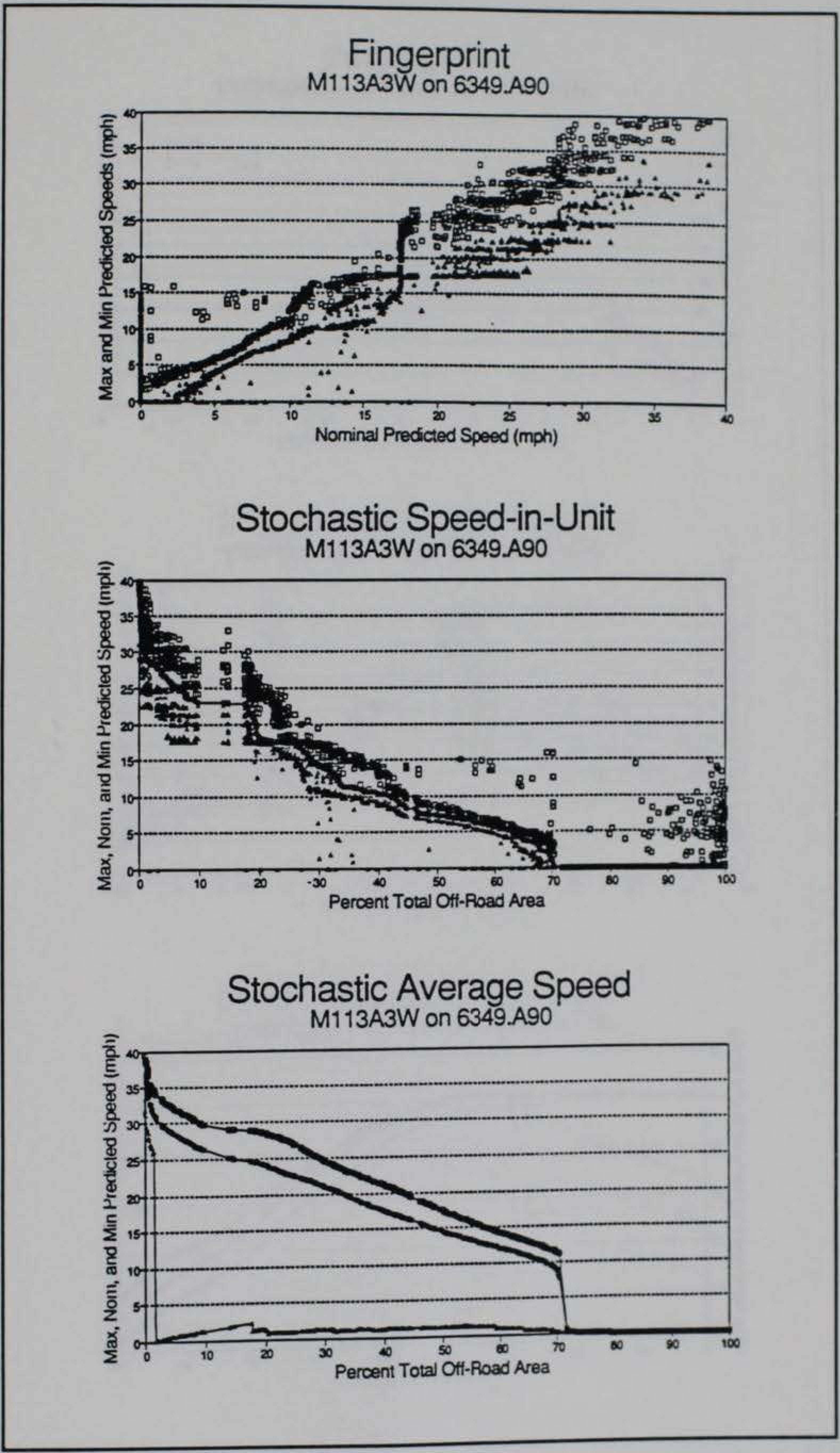


Figure 81. Fingerprint and profiles for M113A3 on SWA off-road

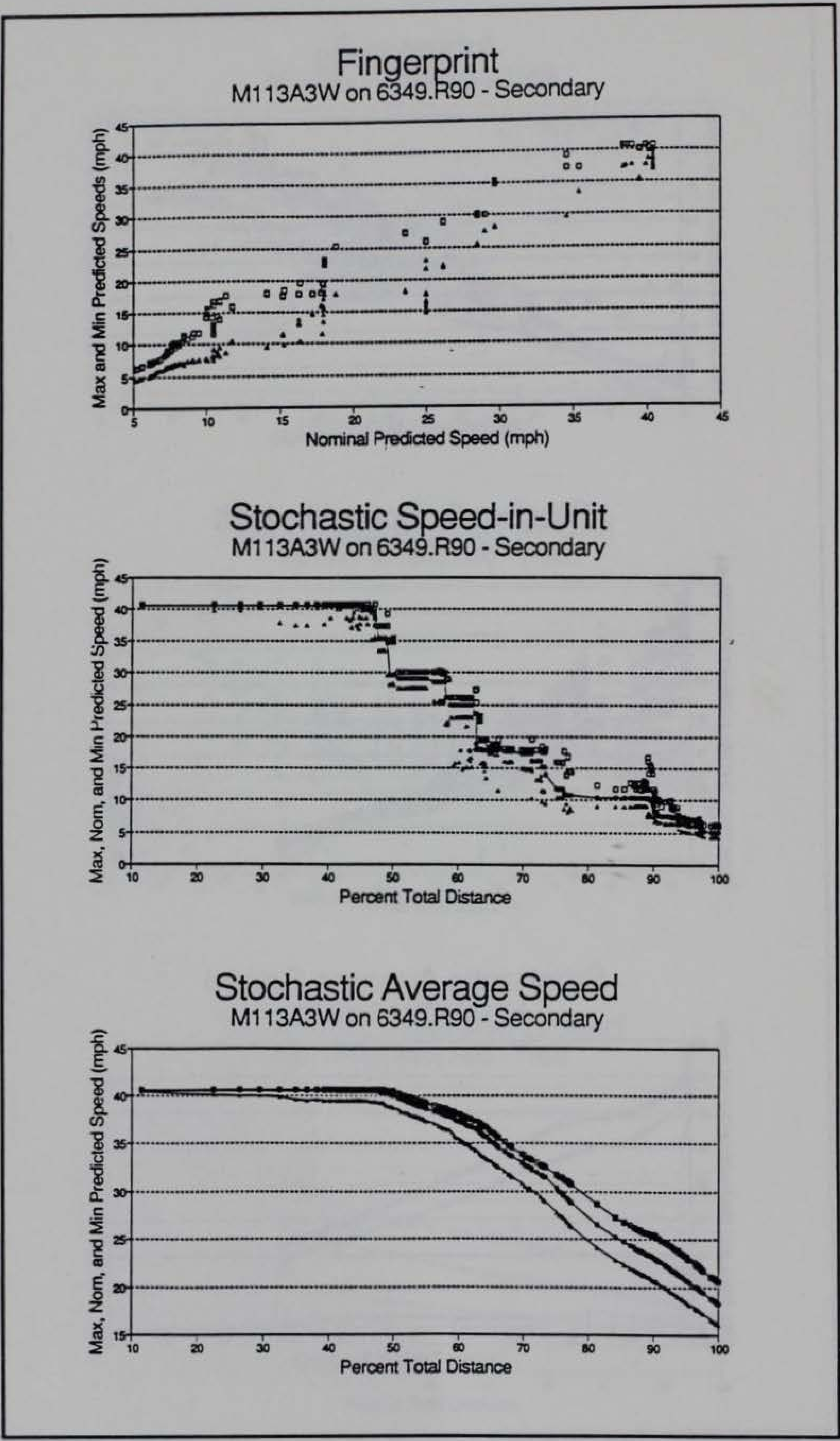


Figure 82. Fingerprint and profiles for M113A3 on SWA secondary roads

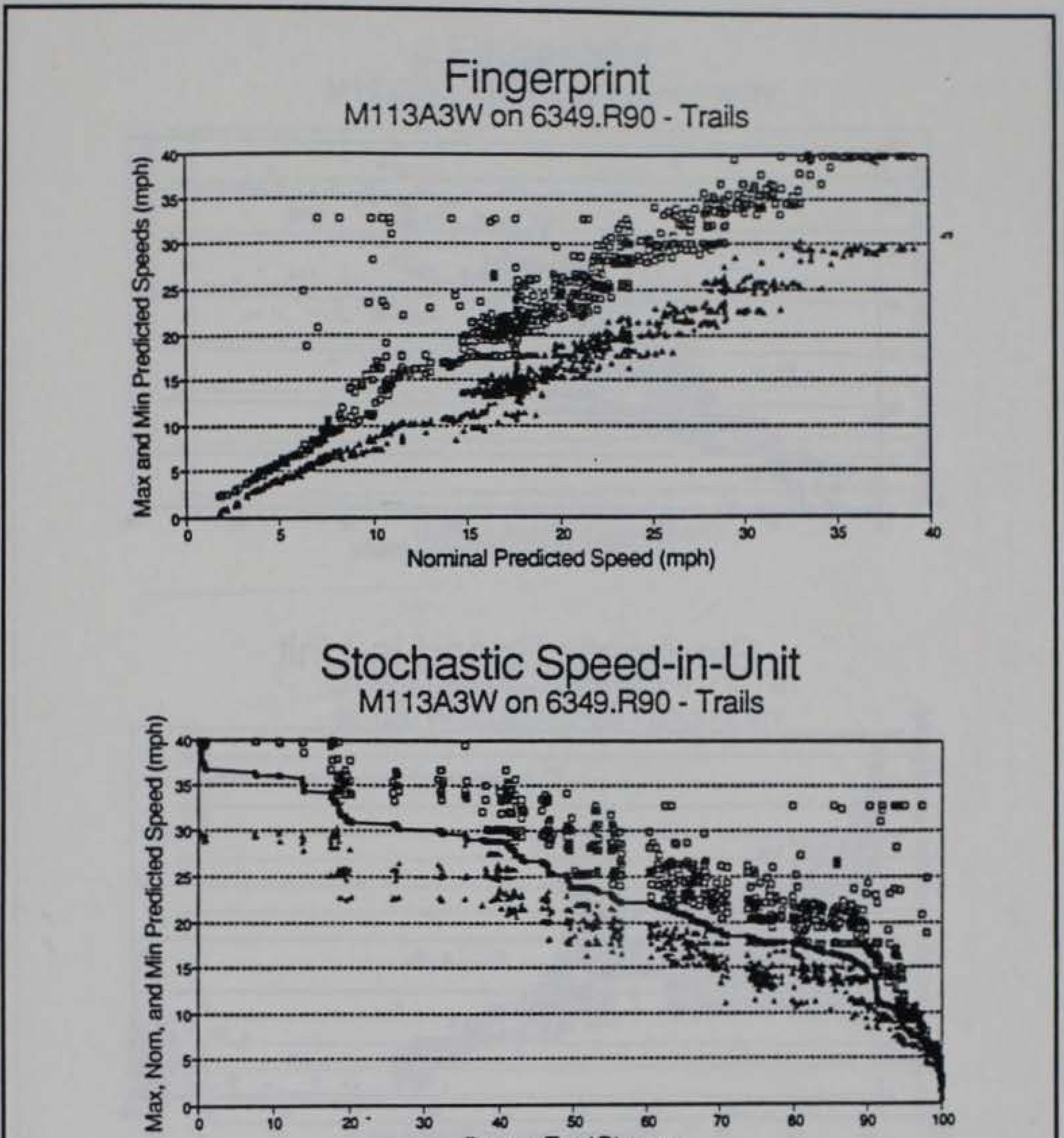


Figure 83. Fingerprint and profiles for M113A3 on SWA trails

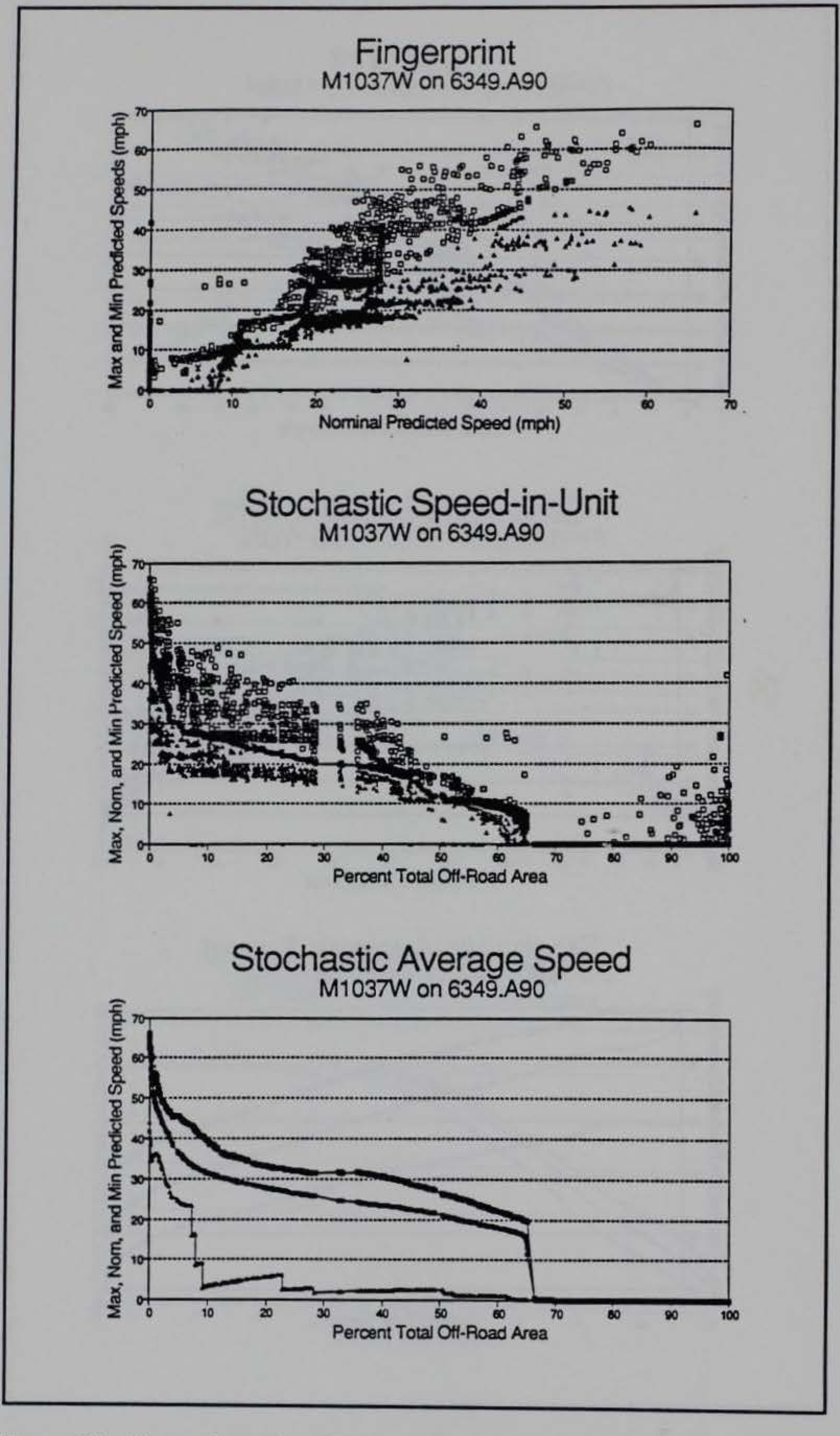


Figure 84. Fingerprint and profiles for M1037 on SWA off-road

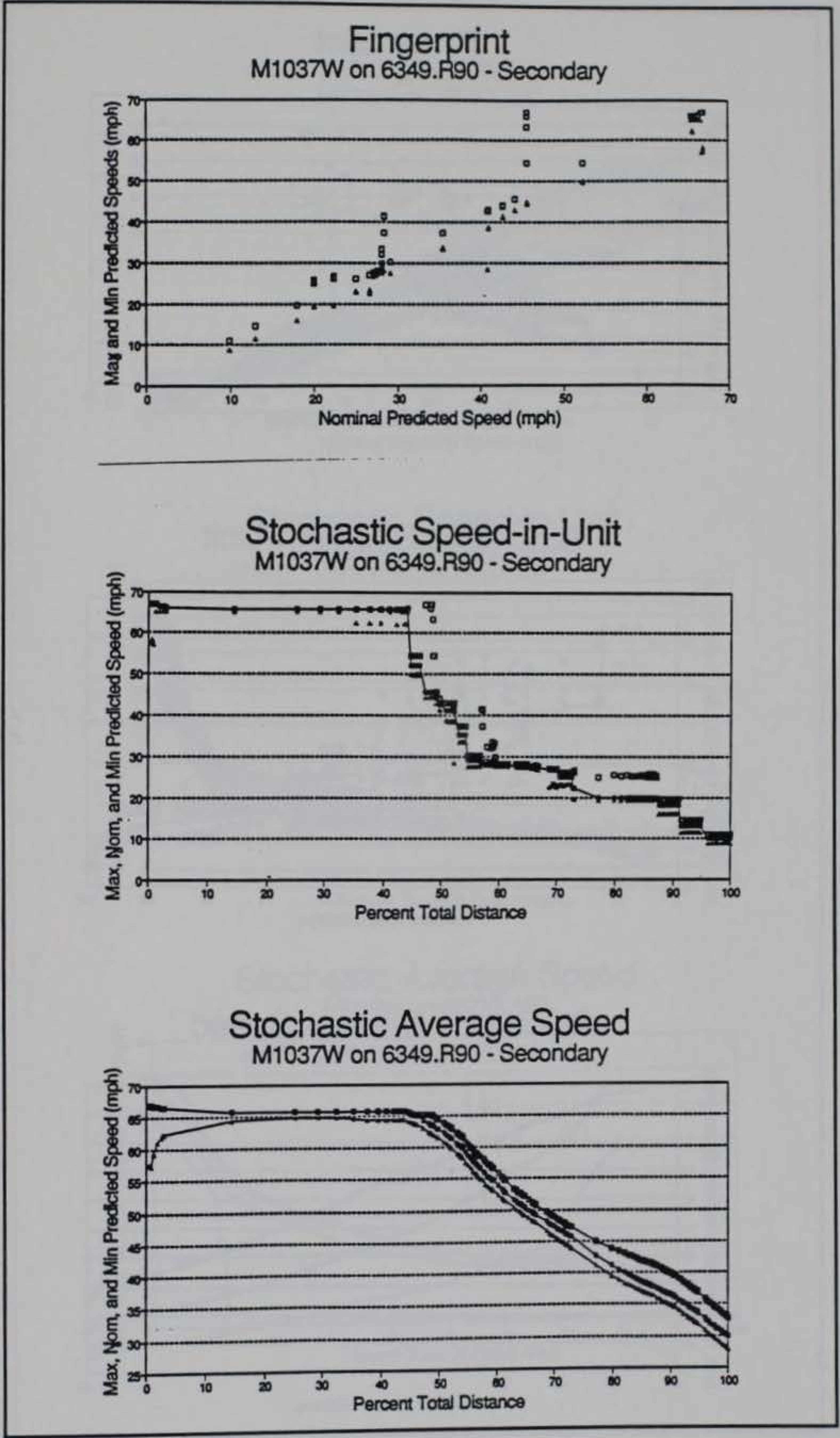


Figure 85. Fingerprint and profiles for M1037 on SWA secondary roads

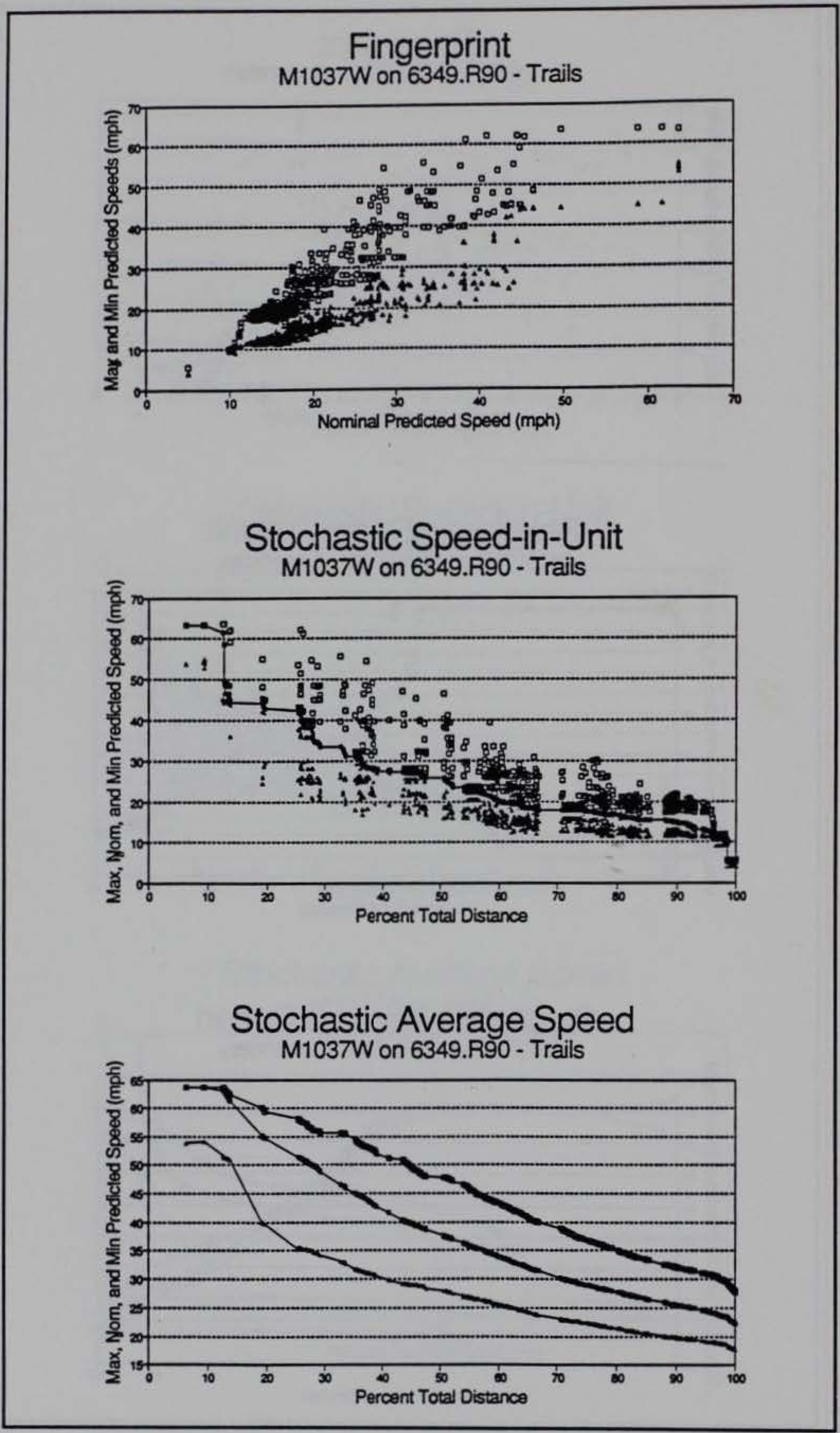


Figure 86. Fingerprint and profiles for M1037 on SWA trails

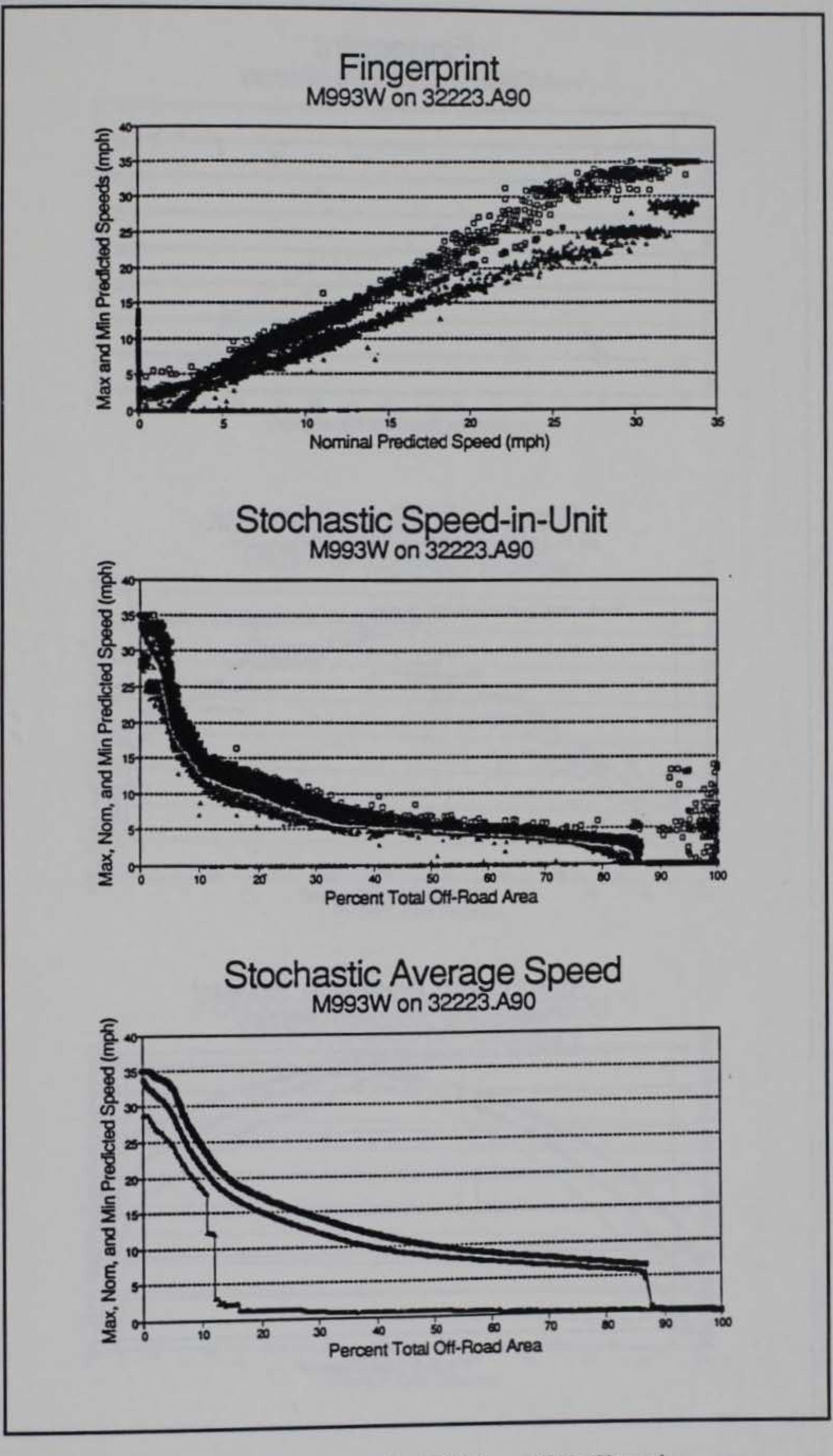


Figure 87. Fingerprint and profiles for M993 on ROK off-road

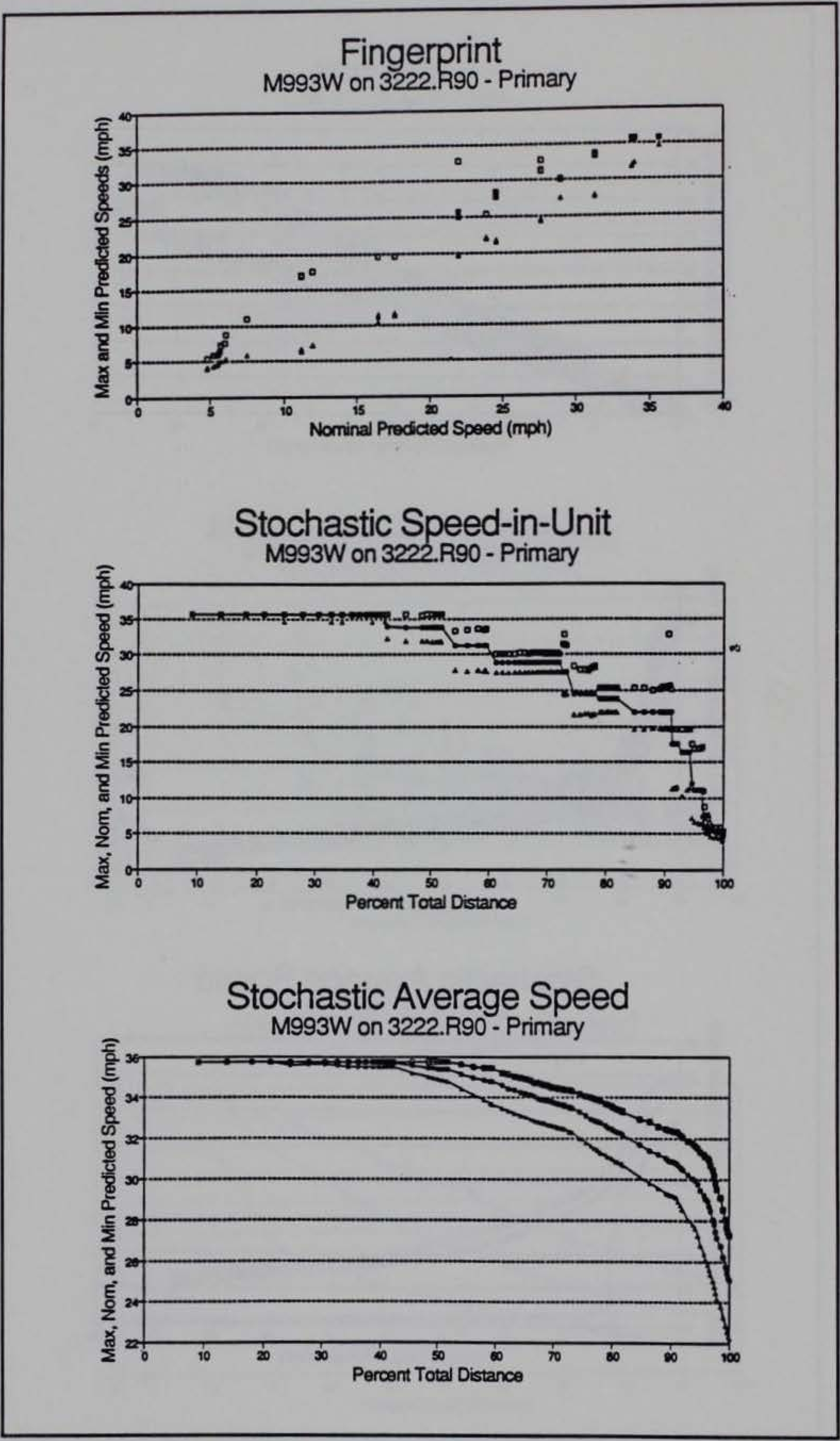


Figure 88. Fingerprint and profiles for M993 on ROK primary roads

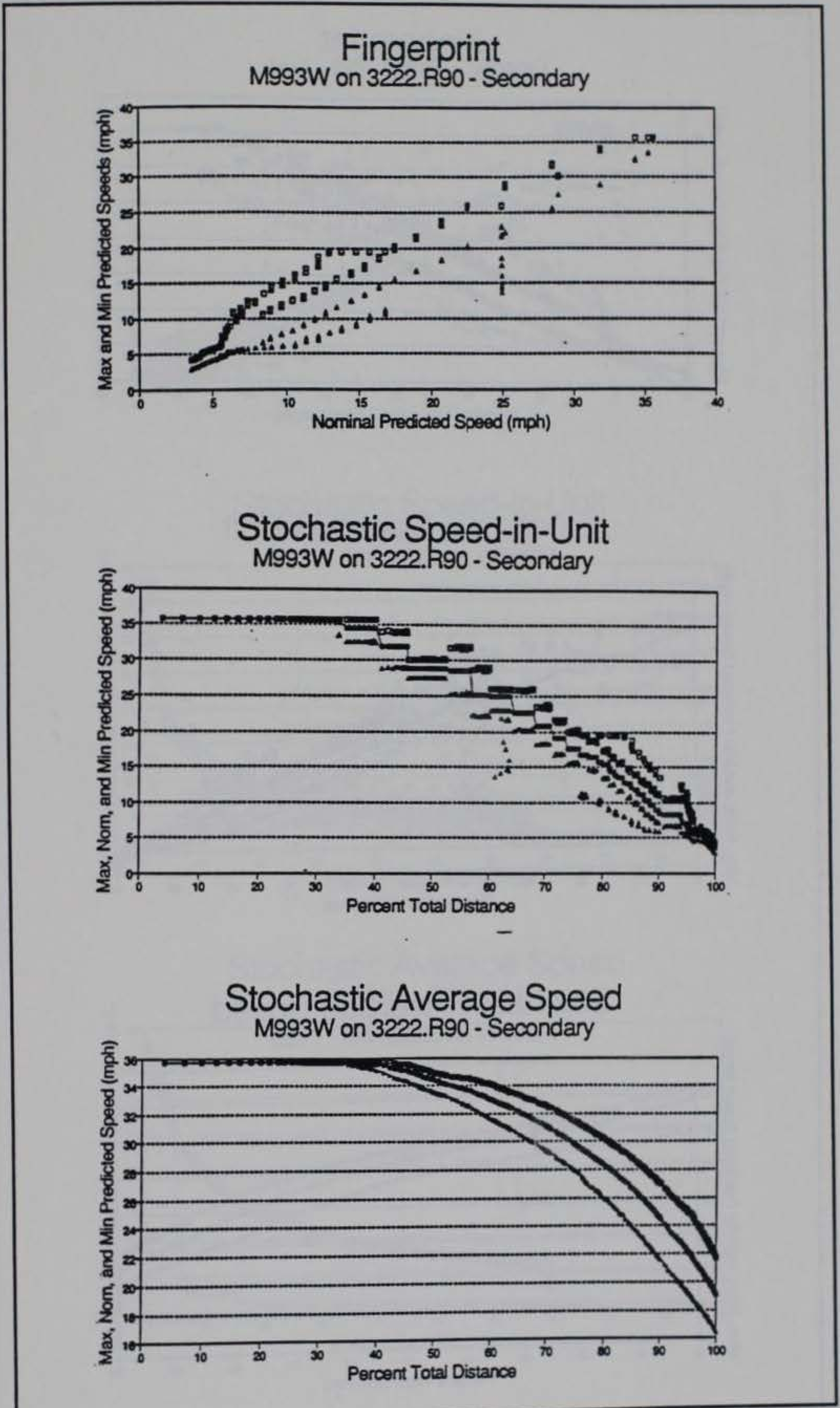


Figure 89. Fingerprint and profiles for M993 on ROK secondary roads

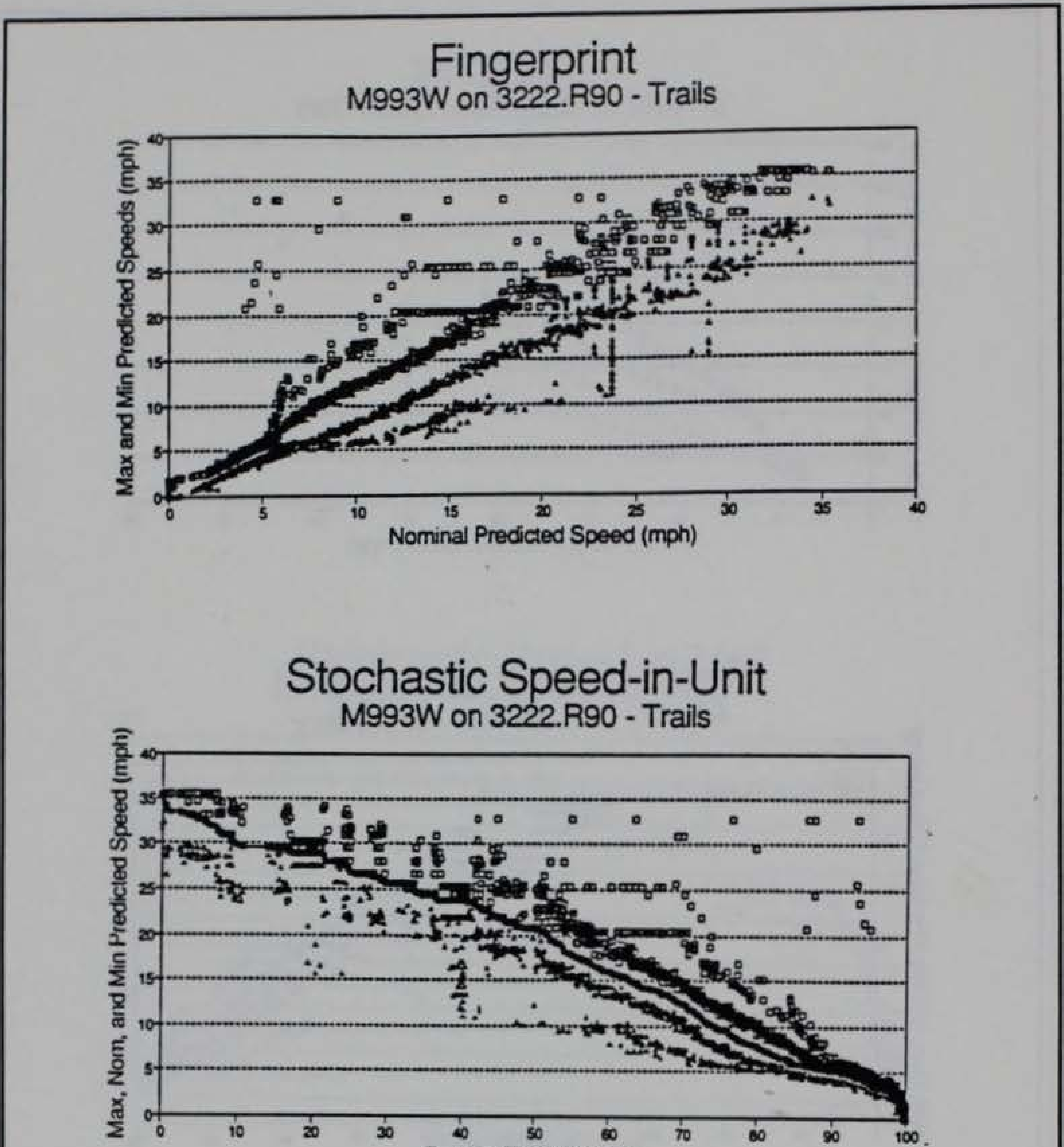


Figure 90. Fingerprint and profiles for M993 on ROK trails

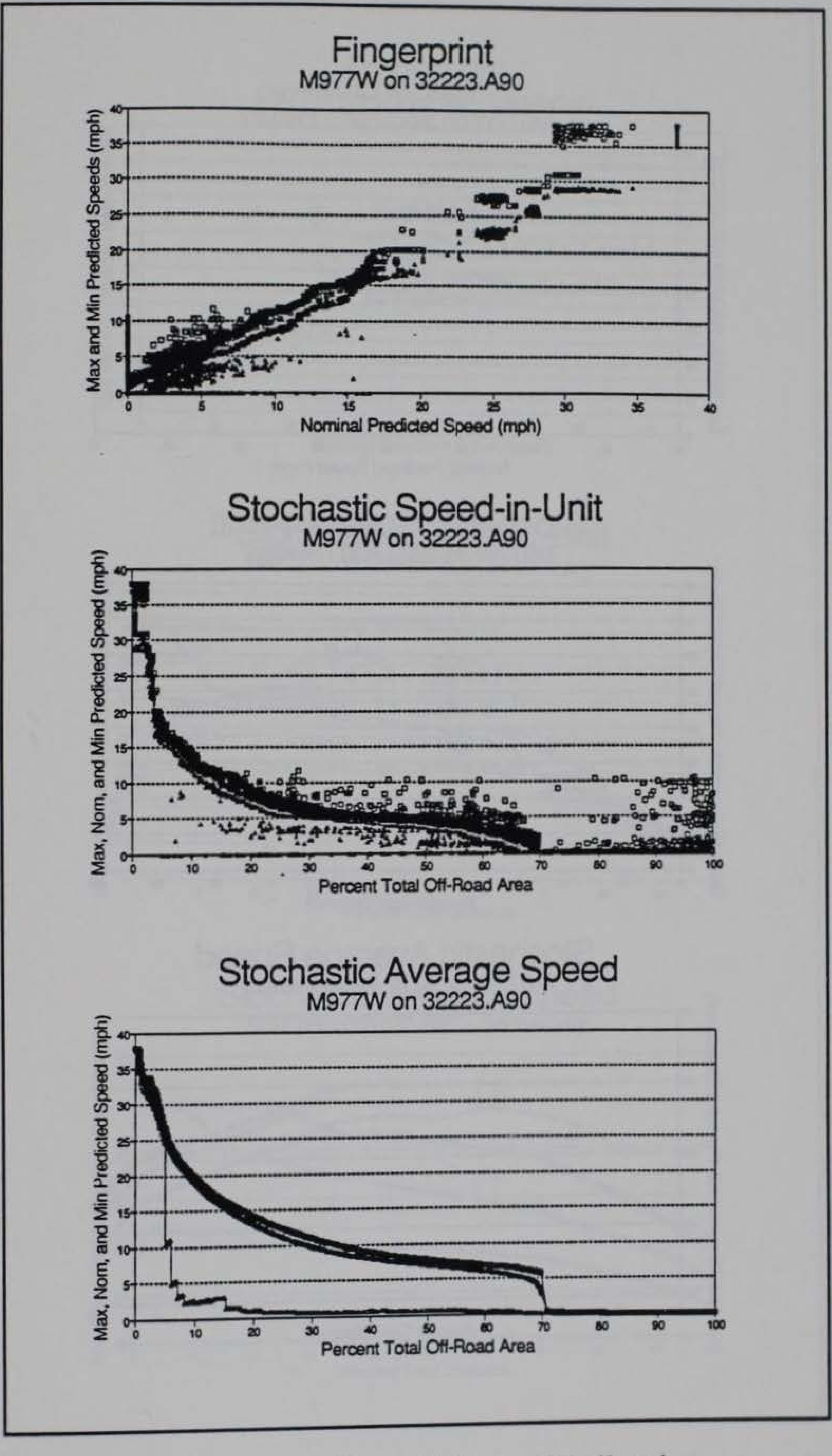


Figure 91. Fingerprint and profiles for M977 on ROK off-road

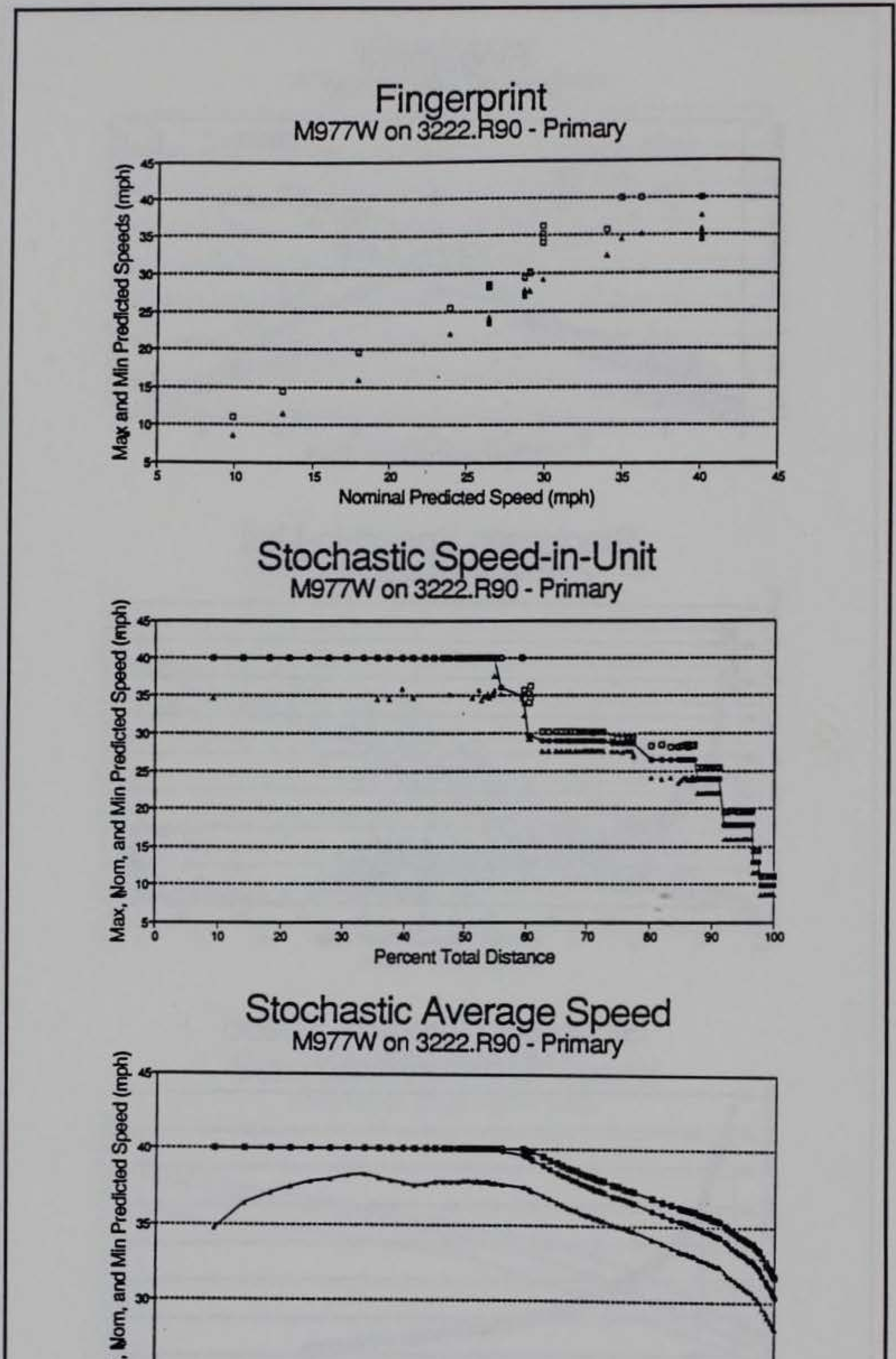


Figure 92. Fingerprint and profiles for M977 on ROK primary roads

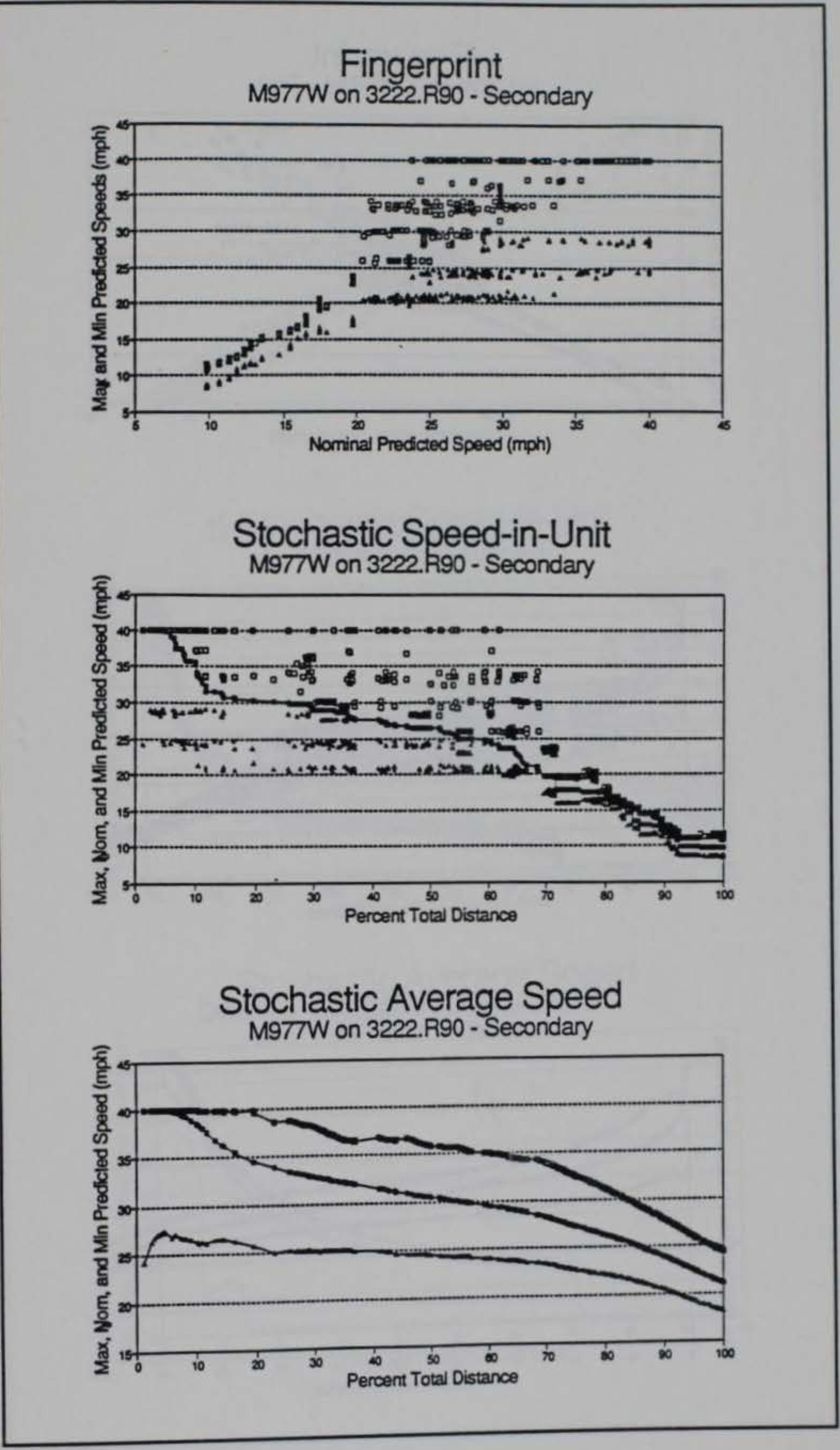


Figure 93. Fingerprint and profiles for M977 on ROK secondary roads

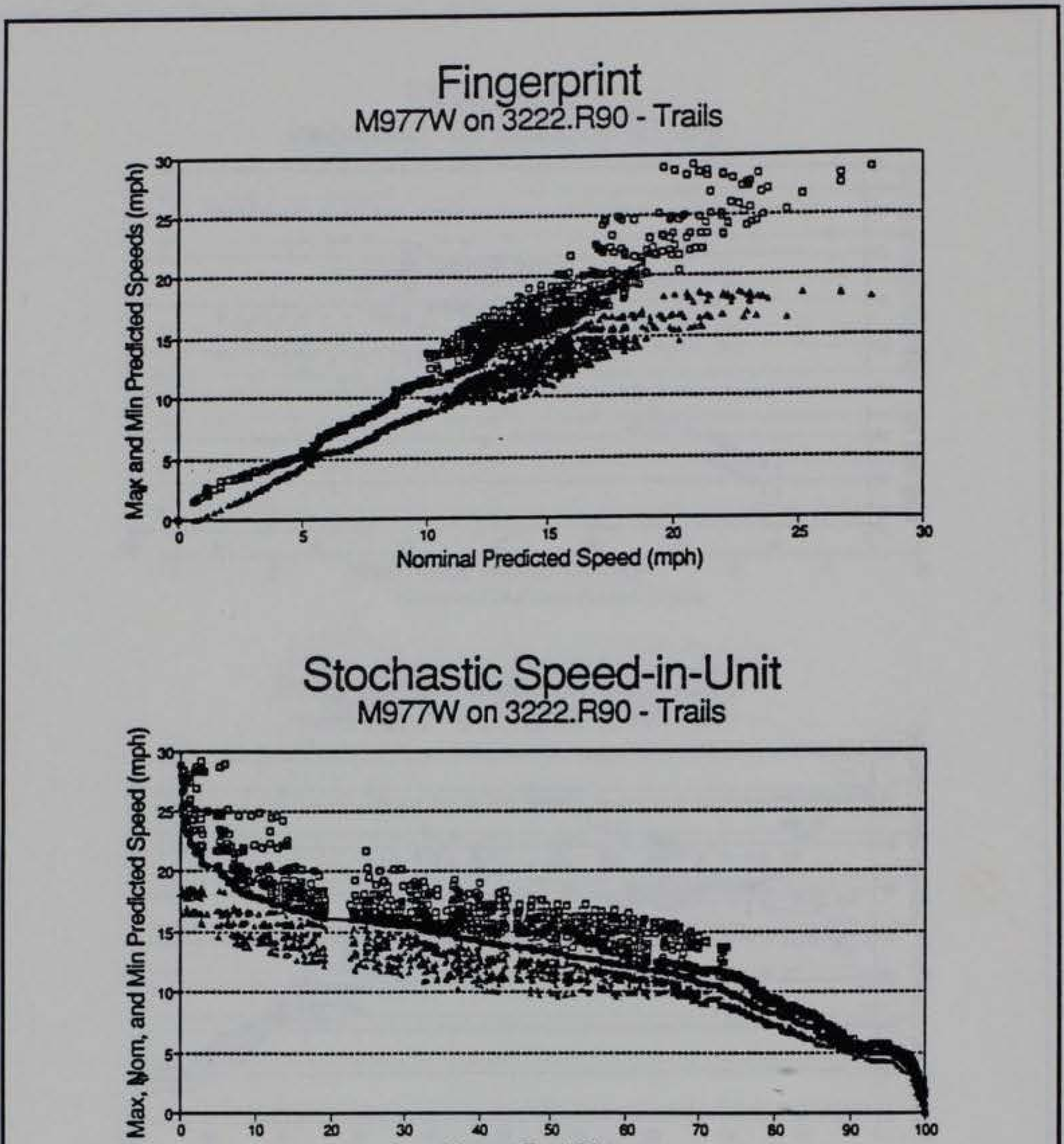


Figure 94. Fingerprint and profiles for M977 on ROK trails

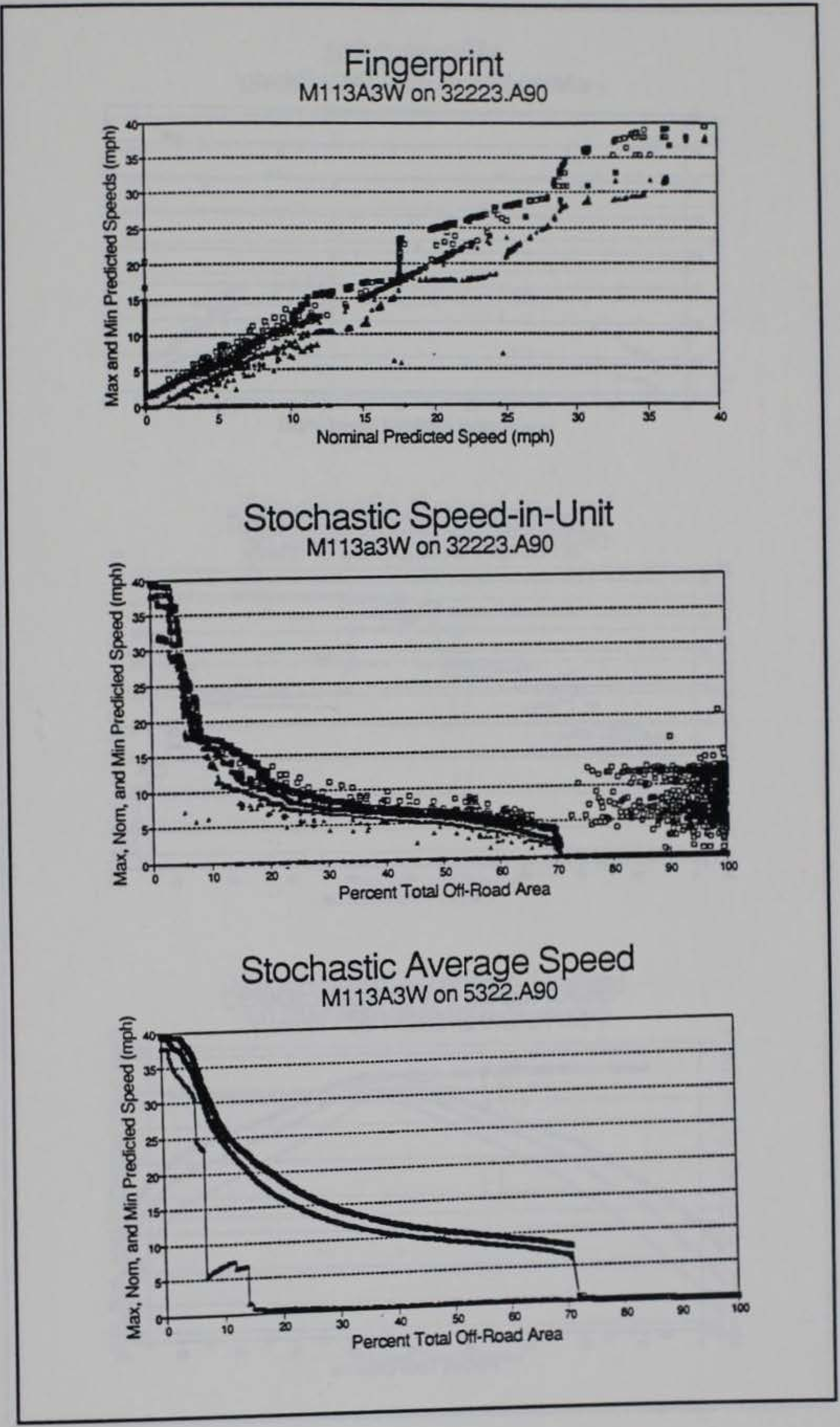


Figure 95. Fingerprint and profiles for M113A3 on ROK off-road

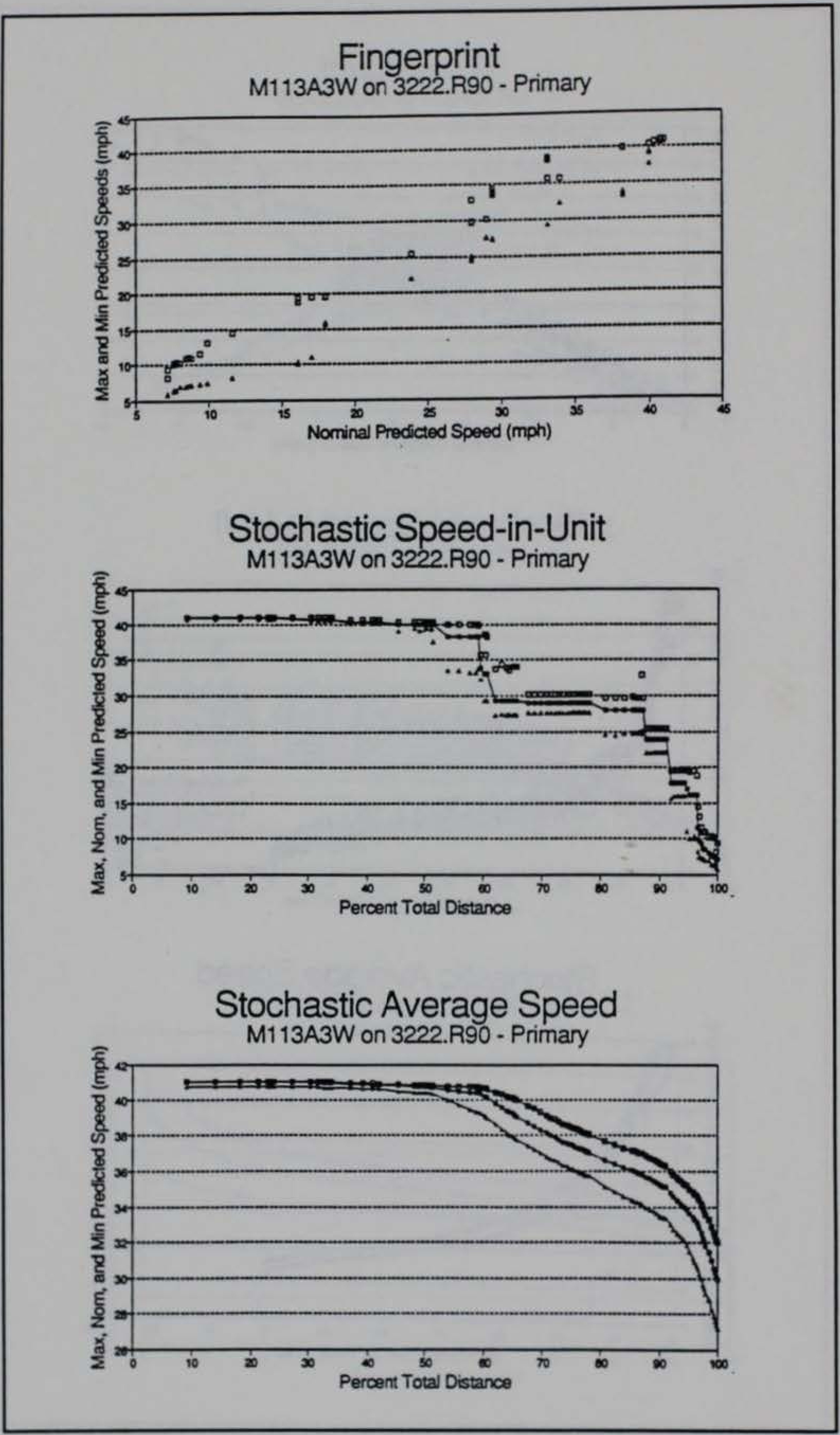


Figure 96. Fingerprint and profiles for M113A3 on ROK primary roads

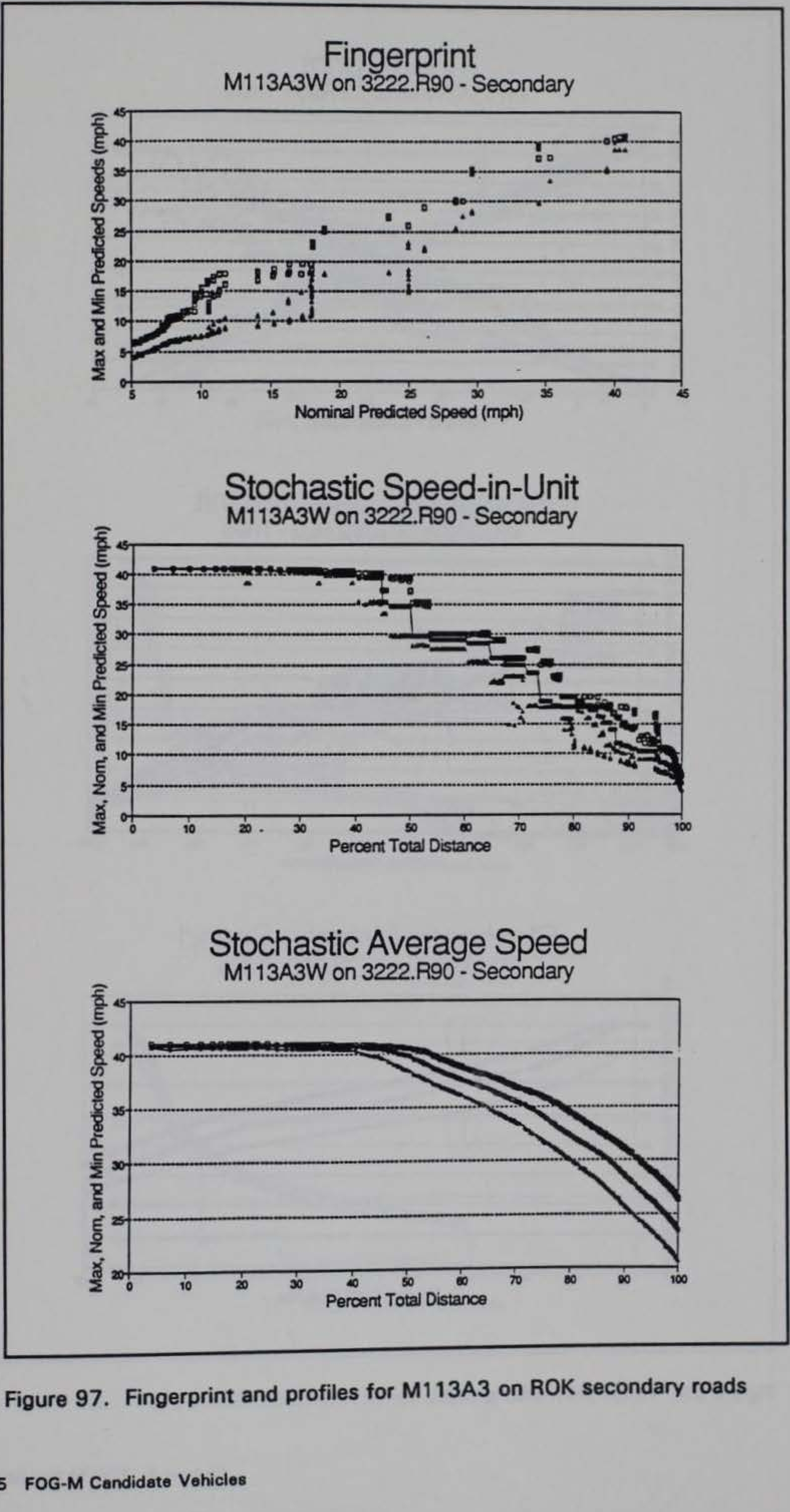


Figure 97. Fingerprint and profiles for M113A3 on ROK secondary roads

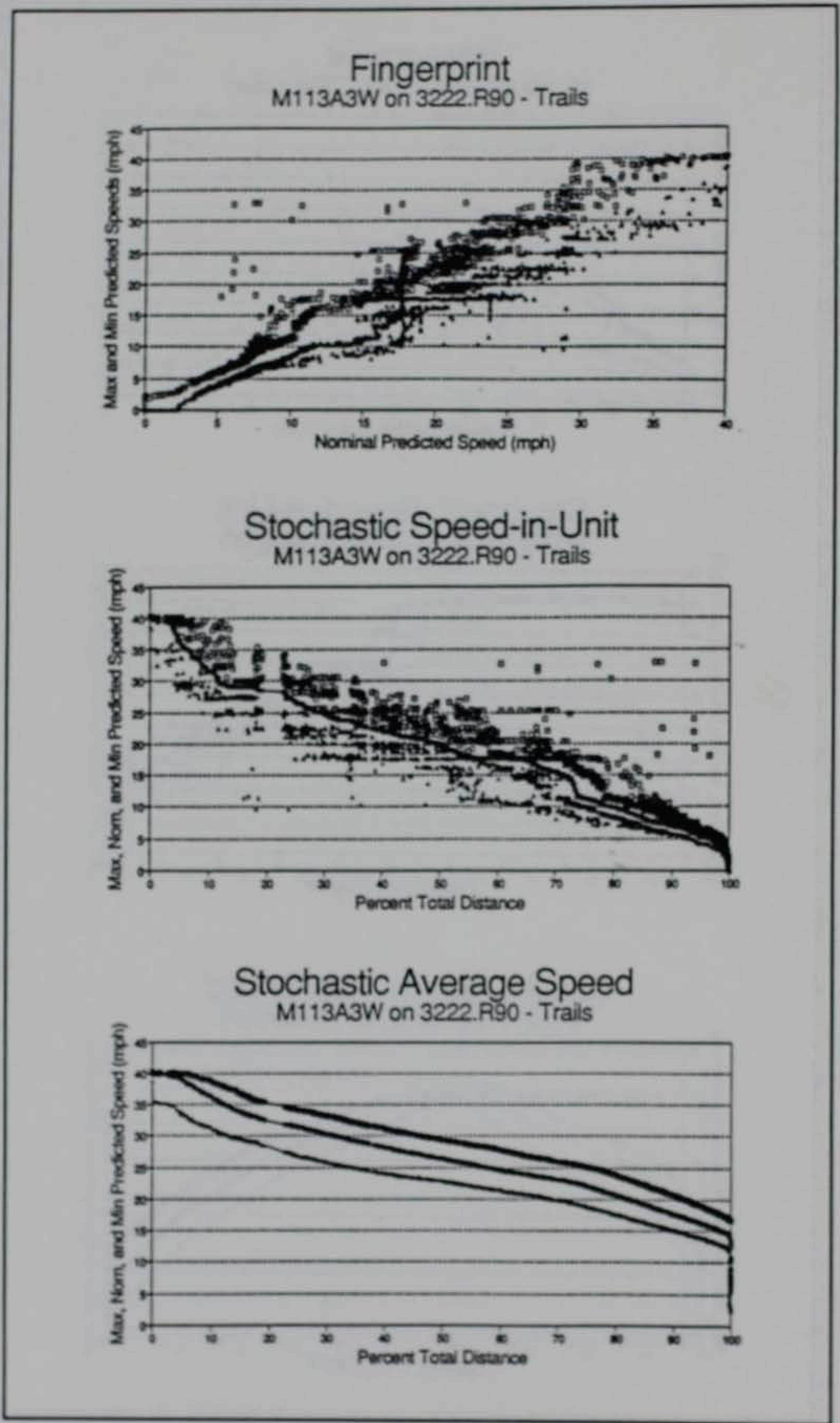


Figure 98. Fingerprint and profiles for M113A3 on ROK trails

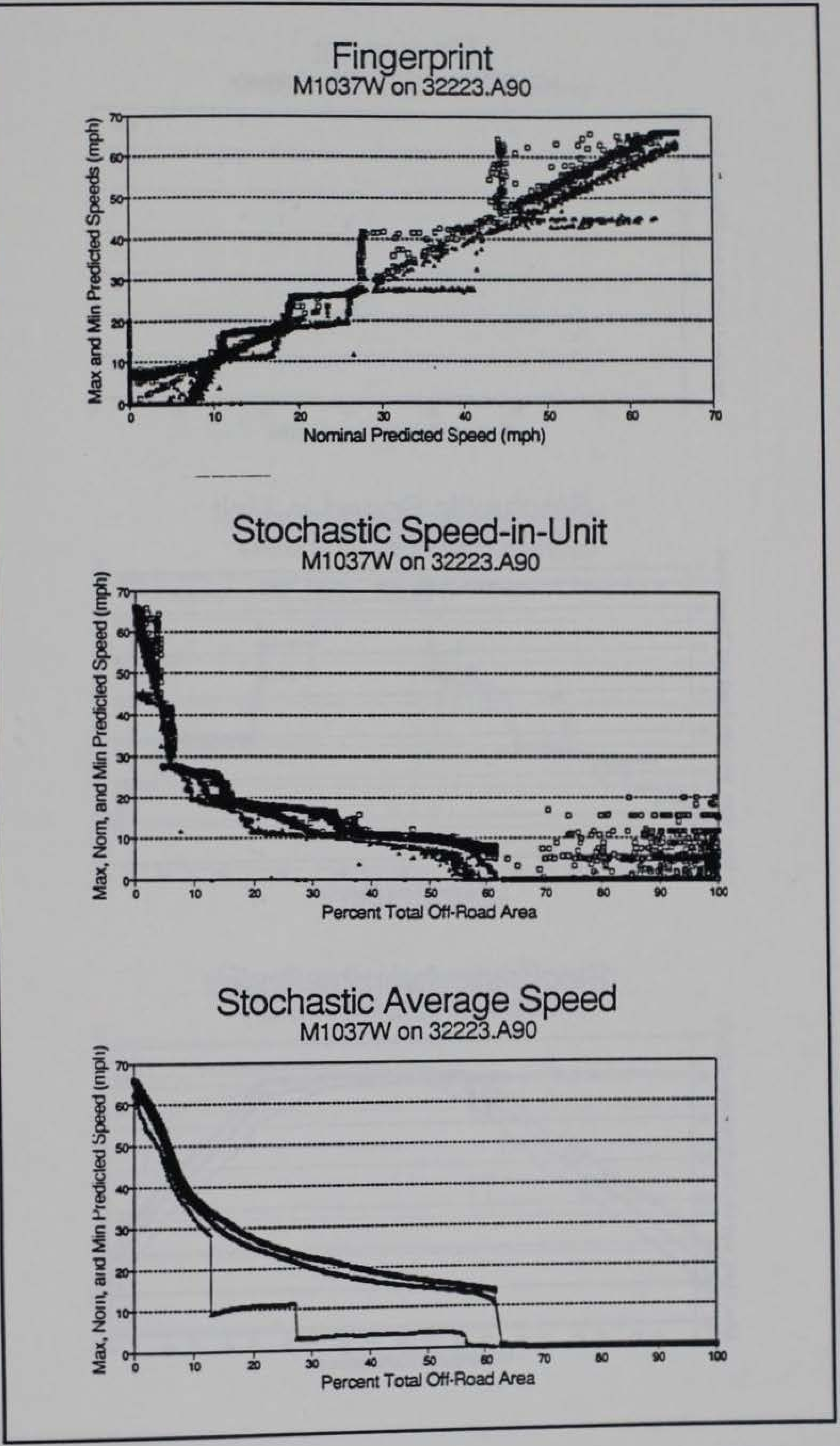


Figure 99. Fingerprint and profiles for M1037 on ROK off-road

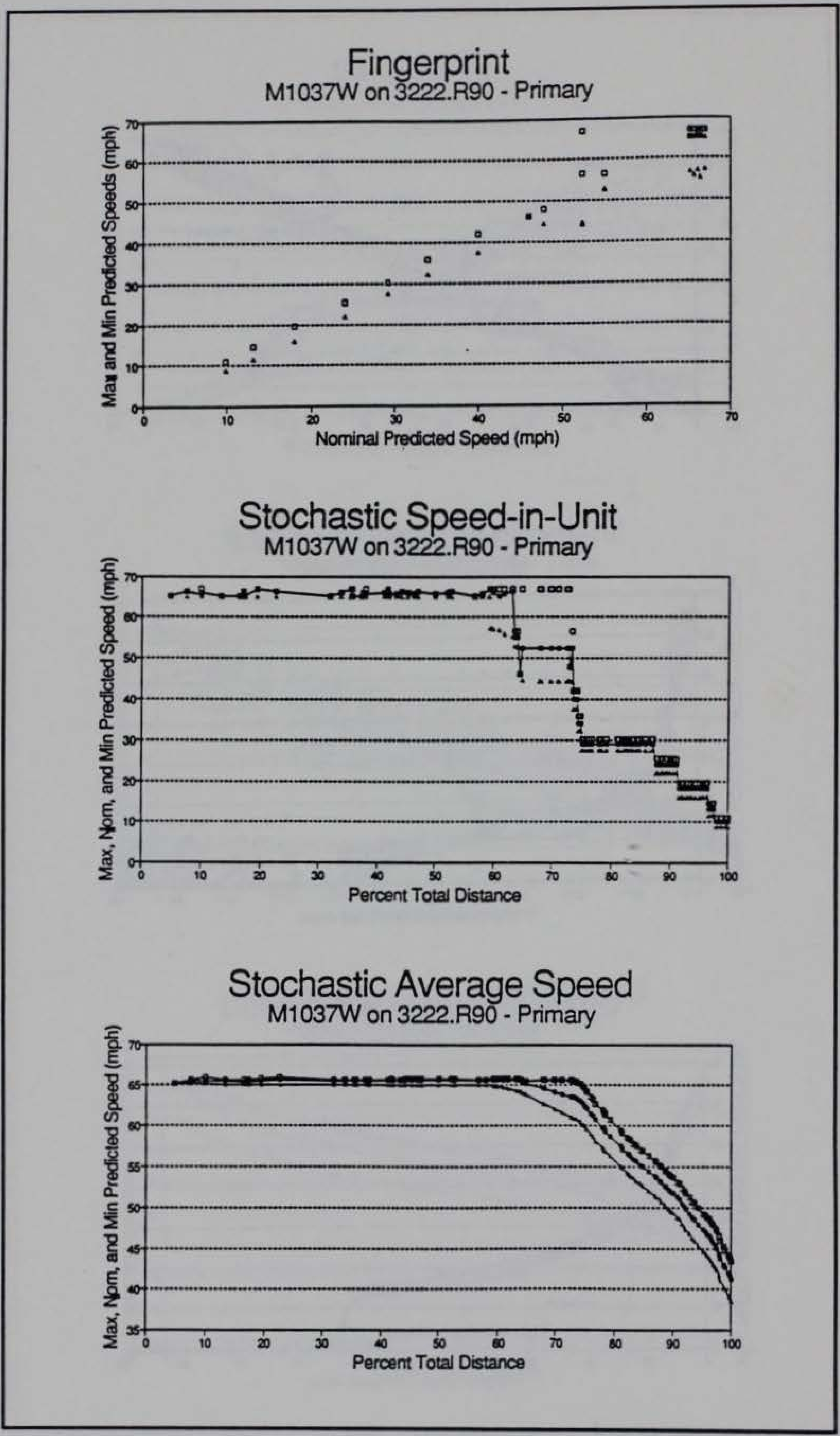


Figure 100. Fingerprint and profiles for M1037 on ROK primary roads

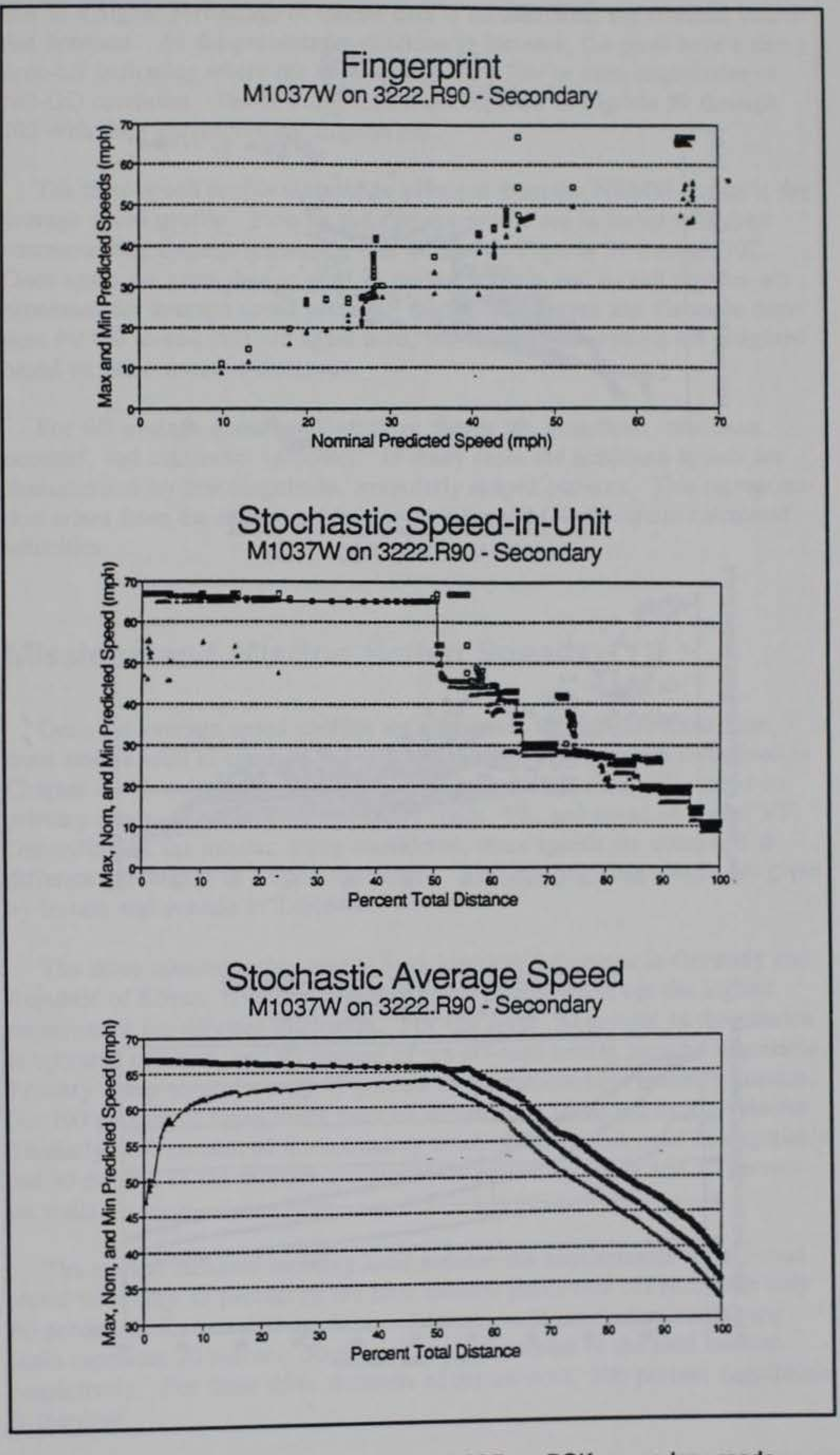


Figure 101. Fingerprint and profiles for M1037 on ROK secondary roads

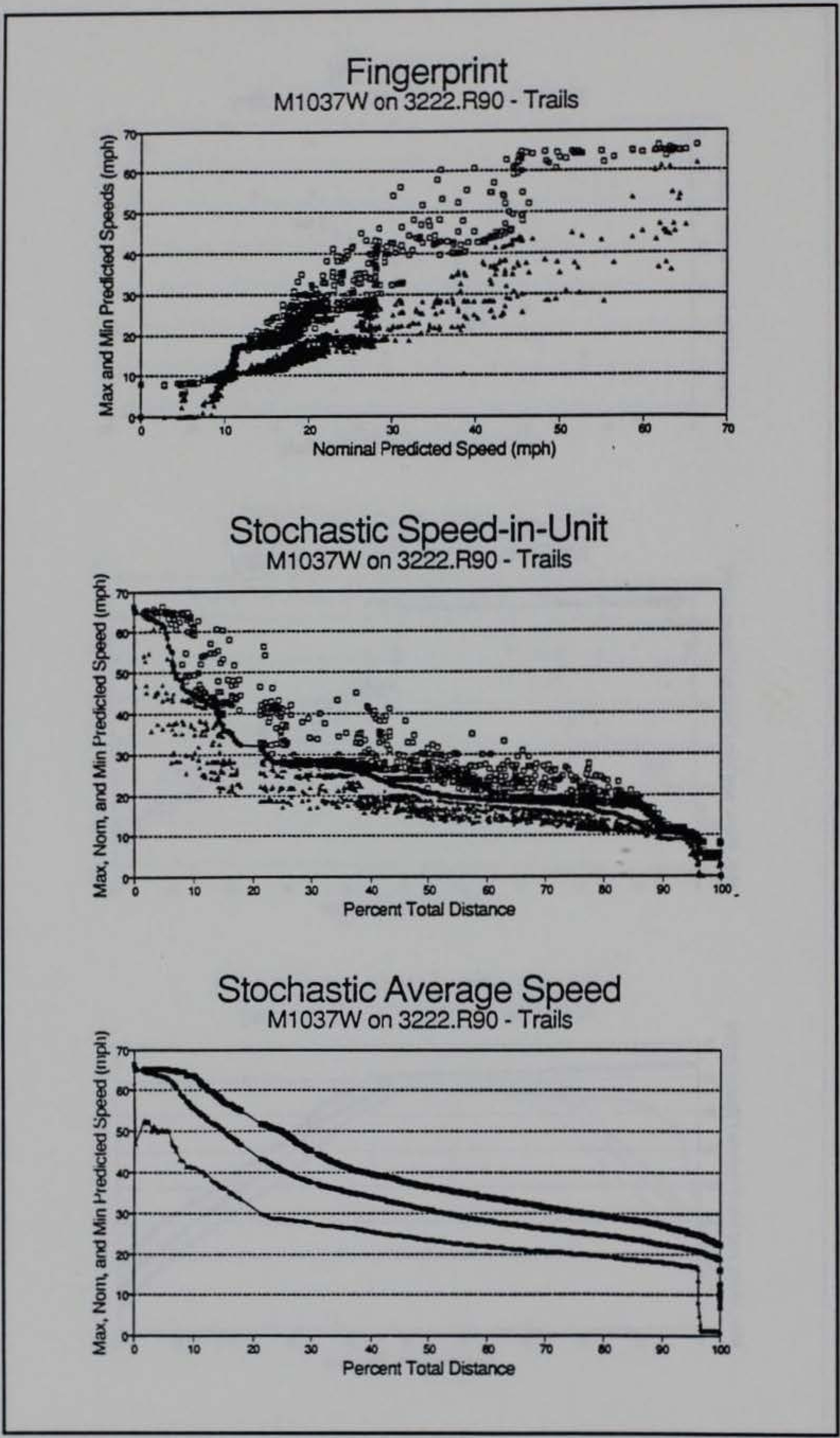


Figure 102. Fingerprint and profiles for M1037 on ROK trails

that as a higher percentage of terrain data is accumulated, the nominal velocities decrease. As the percentages continue to increase, the plots have a sharp drop-off indicating where the speeds reach very low or zero magnitudes--a NO-GO condition. The in-unit profiles are depicted in Figures 59 through 102 with their corresponding fingerprints.

The third speed profile that can be obtained from the NRMM output is the average speed profile. Plots of the average profile are included with their corresponding fingerprints and in-unit profiles in Figures 59 through 102. Once again the same data as used in the fingerprints and in-unit profiles are processed for average speed profiles. Accumulated areas and distances compute for the in-unit data are again used, but this time the speeds are weighted based on these areas or distances.

For the average speed profiles, three curves are generated: minimum, nominal, and maximum velocities. In many cases the minimum speeds are characterized by low-magnitude, irregularly shaped patterns. This representation arises from the occurrence of very low or NO-GO minimum calculated velocities.

Missions and Mission Rating Speeds

Once the average speed profiles are generated, the data extracted from them can be used to compute the required mission rating speeds as defined in Chapter 4. Required average speeds include speed off road, VC, speed on primary roads, VP, speed on secondary roads, VS, and speed on trails, VT. Depending on the mission being considered, these speeds are computed at different percentage of terrain challenged. These appropriate speeds are given by terrain and vehicle in Table 13.

The three mission rating speeds have identical definitions in Germany and Republic of Korea. The first mobility level, tactical high, has the highest requirement for off-road utilization. For this level, 50 percent of the mission is operated off road, and 90 percent of the off-road terrain must be negotiable. Primary roads comprise only 10 percent of the tactical high mobility mission, but 100 percent of these roads must be successfully traversed by the vehicles. Similarly, 100 percent of the secondary roads and the trails must be negotiable but 30 percent of the mission is assumed on secondary roads and 10 percent on trails.

The tactical standard mobility level reduces the requirements for off-road travel with only 15 percent of the total mission performed off road with only 80 percent of the terrain negotiable. Primary roads, secondary roads, and trails represent 20 percent, 50 percent, and 15 percent of the total mission respectively. For these three elements of the network, 100 percent negotiation is required.

Table 13
Summary of Stochastic Average Speeds - MPH

West Germany							
Minimum							
Vehicle	VC90	VC80	VC50	VT100	VT50	VS100	VP100
M993	0.351	2.327	10.626	10.316	18.809	17.735	23.589
M977	0.347	4.974	13.998	9.751	12.219	19.116	27.814
M113A3	0.485	2.942	4.705	12.021	17.854	21.794	28.871
M1037	0.221	1.730	1.203	13.166	19.681	35.966	43.780
Nominal							
Vehicle	VC90	VC80	VC50	VT100	VT50	VS100	VP100
M993	9.906	12.632	17.890	12.456	21.114	20.289	25.970
M977	2.864	11.300	16.960	11.316	14.322	21.817	31.073
M113A3	10.914	13.983	19.708	14.394	20.884	24.759	31.399
M1037	0.673	18.697	25.149	15.502	24.313	37.774	45.694
Maximum							
Vehicle	VC90	VC80	VC50	VT100	VT50	VS100	VP100
M993	11.549	14.446	20.184	14.633	22.304	22.968	28.264
M977	4.230	13.565	18.296	13.088	15.903	25.096	32.809
M113A3	13.523	16.559	21.979	17.285	24.099	28.112	33.333
M1037	0.686	21.453	27.776	18.283	26.684	38.993	47.170
Southwest Asia							
Minimum							
Vehicle	VC90	VC80	VC50	VT100	VT80	VS100	
M993	0.0538	0.118	0.509	4.778	23.288	12.785	
M977	0.0352	0.0517	0.768	11.805	13.230	14.767	
M113A3	0.0407	0.0659	1.354	16.463	21.533	16.173	
M1037	0.0323	0.0445	2.801	17.629	21.341	28.000	
Nominal							
Vehicle	VC90	VC80	VC50	VT100	VT80	VS100	
M993	0.0688	0.260	13.019	5.882	26.594	14.393	
M977	0.0400	0.0646	11.415	13.544	15.611	16.546	
M113A3	0.0454	0.0812	14.547	19.968	25.950	18.289	
M1037	0.0362	0.0530	21.156	22.062	27.661	29.895	
Maximum							
Vehicle	VC90	VC80	VC50	VT100	VT80	VS100	
M993	0.0709	0.262	15.299	13.113	29.483	16.147	
M977	0.0424	0.0676	12.893	15.542	18.076	19.242	
M113A3	0.0520	0.0892	17.471	23.678	30.099	20.583	
M1037	0.0391	0.0574	26.838	27.663	34.962	32.866	

(Continued)

Table 13 (Concluded)							
Republic of Korea							
Minimum							
Vehicle	VC90	VC80	VC50	VT100	VT50	VS100	VP100
M993	0.128	0.405	0.800	1.755	24.196	16.477	22.220
M977	0.0355	0.052	0.739	3.503	13.544	18.145	28.284
M113A3	0.0402	0.0645	0.397	2.415	22.847	20.679	27.251
M1037	0.0274	0.0351	3.769	0.994	23.481	32.772	38.565
Nominal							
Vehicle	VC90	VC80	VC50	VT100	VT50	VS100	VP100
M993	0.252	6.605	8.453	2.332	26.694	19.023	25.048
M977	0.0438	0.0756	7.050	6.148	16.013	21.058	30.386
M113A3	0.0465	0.0854	9.150	5.533	26.395	23.401	29.929
M1037	0.0318	0.0436	14.569	6.981	30.840	35.374	41.249
Maximum							
Vehicle	VC90	VC80	VC50	VT100	VT50	VS100	VP100
M993	0.269	7.109	9.849	3.184	28.118	21.647	27.293
M977	0.0556	0.100	7.817	6.805	17.945	24.368	31.708
M113A3	0.0901	0.187	10.401	6.981	29.415	26.326	32.044
M1037	0.0438	0.0631	16.283	9.423	36.489	38.312	43.503

The tactical support mobility level in WGe and ROK is only slightly influenced by off-road performance as only 5 percent of the mission is required to cover such terrain with 50 percent of the area successfully traveled. Primary roads represent 30 percent of the support mission with 100 percent negotiation required, and trails comprise only 10 percent of total scenario with 50 percent of the trails negotiable.

With no primary roads in the Southwest Asia terrain, secondary roads become increasingly important. For the tactical high mobility level, 50 percent of the total mission is assumed to be off-road with 90 percent of the area required to be negotiable. Tactical high mobility weighs the secondary roads and trails equally with each comprising 25 percent of the mission at 100 percent successful negotiation.

For the tactical standard level of mobility, the off-road requirements are reduced. In this case only 15 percent of the total mission occurs over off-road terrain with 80 percent of the terrain negotiated. This time, secondary roads make up 50 percent of the mission and trails, 35 percent. Both the secondary roads and trails must be negotiable 100 percent.

The influence of off-road operation is minimized while secondary-road travel is maximized for the tactical support mission rating. In this case, only 5 percent of the mission is required to operate on off-road conditions with only 50 percent of the terrain negotiable. The secondary roads, however, contribute 60 percent of the total travel required for support operations. Of the secondary road distance, 100 percent must still be successfully traveled. Trails in this computation represent 35 percent of the total mission with an 80 percent negotiation of the terrain required.

With the available data from NRMM, a maximum and minimum rating speed was computed for each vehicle on each terrain in addition to the nominal. This gives an indication of the mission rating speed range to provide a clearer picture of the vehicle's performance on the given terrain. The mission rating speeds are depicted in Figures 103 through 105 by terrain and tactical mobility level.

In order to facilitate comparisons of the vehicles, a global mission rating speed was developed. This global speed is computed as a weighted average for each tactical mobility level based on the percentage of time the vehicles would be expected to operate on the examined terrains. The global scenario assumed 50 percent of the vehicle's use would be on terrain approximated by the Southwest Asia conditions, 30 percent on terrain similar to the Republic of Korea, and only 20 percent on areas resembling those in West Germany. These global mission rating speeds are shown by mobility level in Figure 106.

Comparison of Historic and Stochastic Forecasts

In the historic evaluation of the FOG-M candidate vehicles, the vehicular performance and ranking was based on studies of many different terrain types as well as scenarios. The percentage of distance which the vehicle could not travel, a NO-GO condition, was also used in making final decisions. In comparing the stochastic results with the previous analysis, only the total area with the dry-normal condition will be used. These comparisons are made based on individual terrain performance as well as overall performance.

Within West Germany, the two vehicles, of the four considered, found to be dominant in the original study were the M993 and the M1037. For all of the on-road travel, the M1037 was found to obtain the highest average speeds. For the off-road transportation, the M1037 also obtained the highest speeds except for the challenge level of 100 percent of the terrain negotiated for which the M993 had a slight advantage. Taking the computed average speeds into consideration, the M1037 was chosen as the best candidate for tactical support missions. Although the M1037 maintained the highest average speeds throughout this region, the percent NO-GO's led to the selection of the M993 as the best vehicle for tactical high and tactical standard levels of performance.

In the stochastic analysis of the candidate vehicles in West Germany, similar results were found. The M1037 clearly outperformed all other vehicles, in respect to minimum, nominal, and maximum speed, on nearly all terrain types. The only exception was for the off-road terrain. At the 90 percent challenge level, the M113A3 maintained the highest minimum, nominal, and

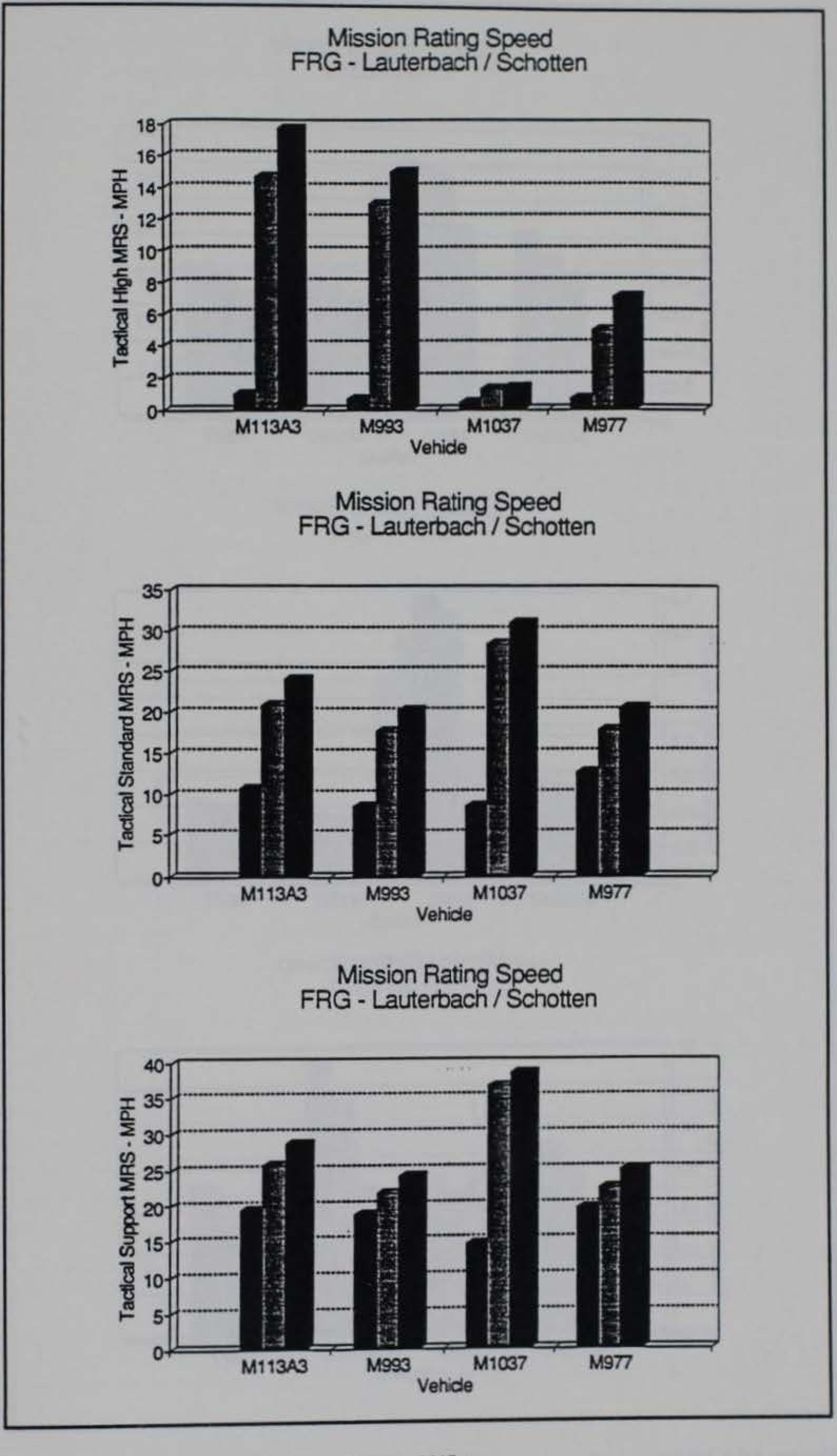


Figure 103. Mission rating speeds for WGe

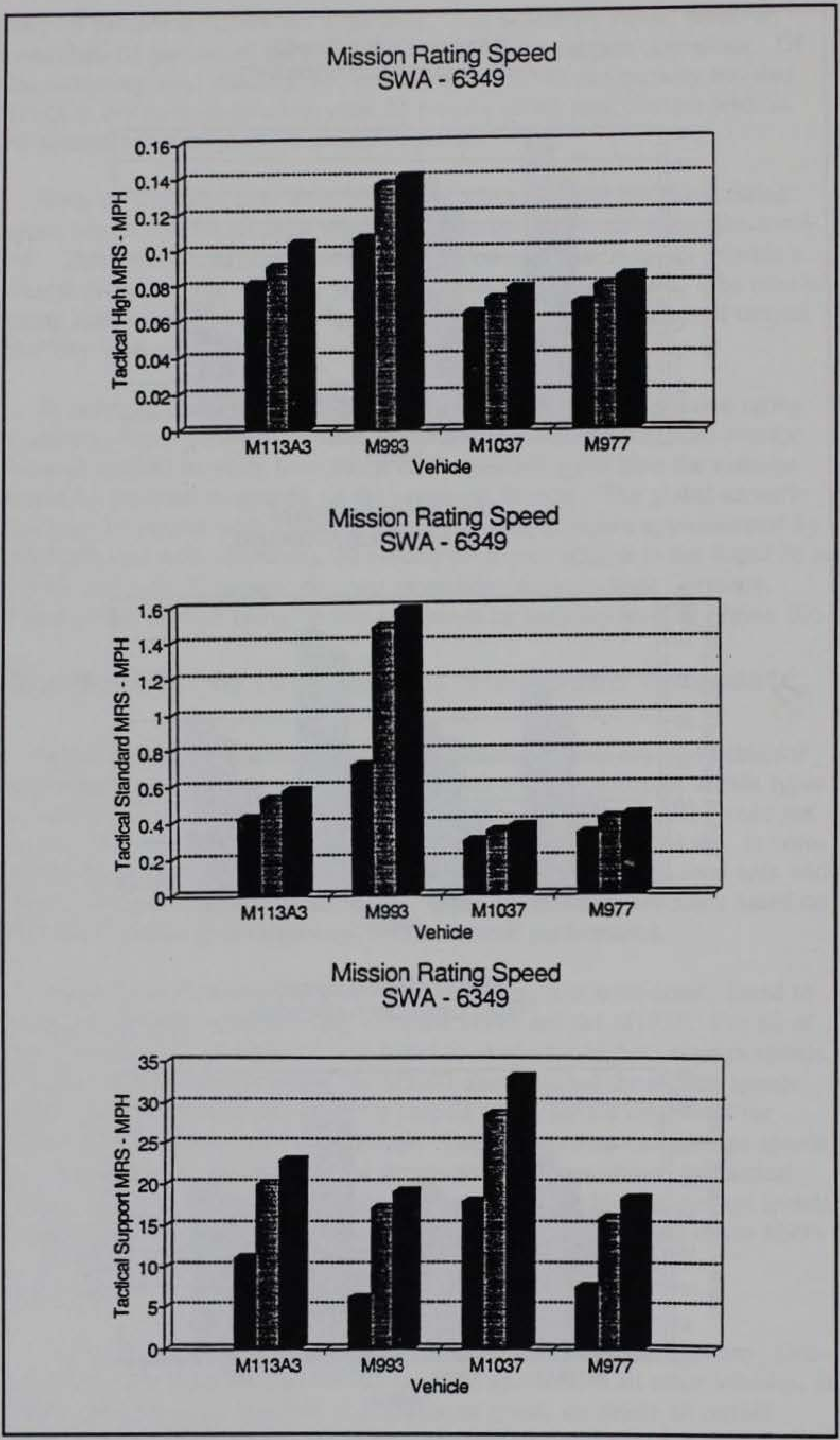


Figure 104.Mission rating speeds for SWA

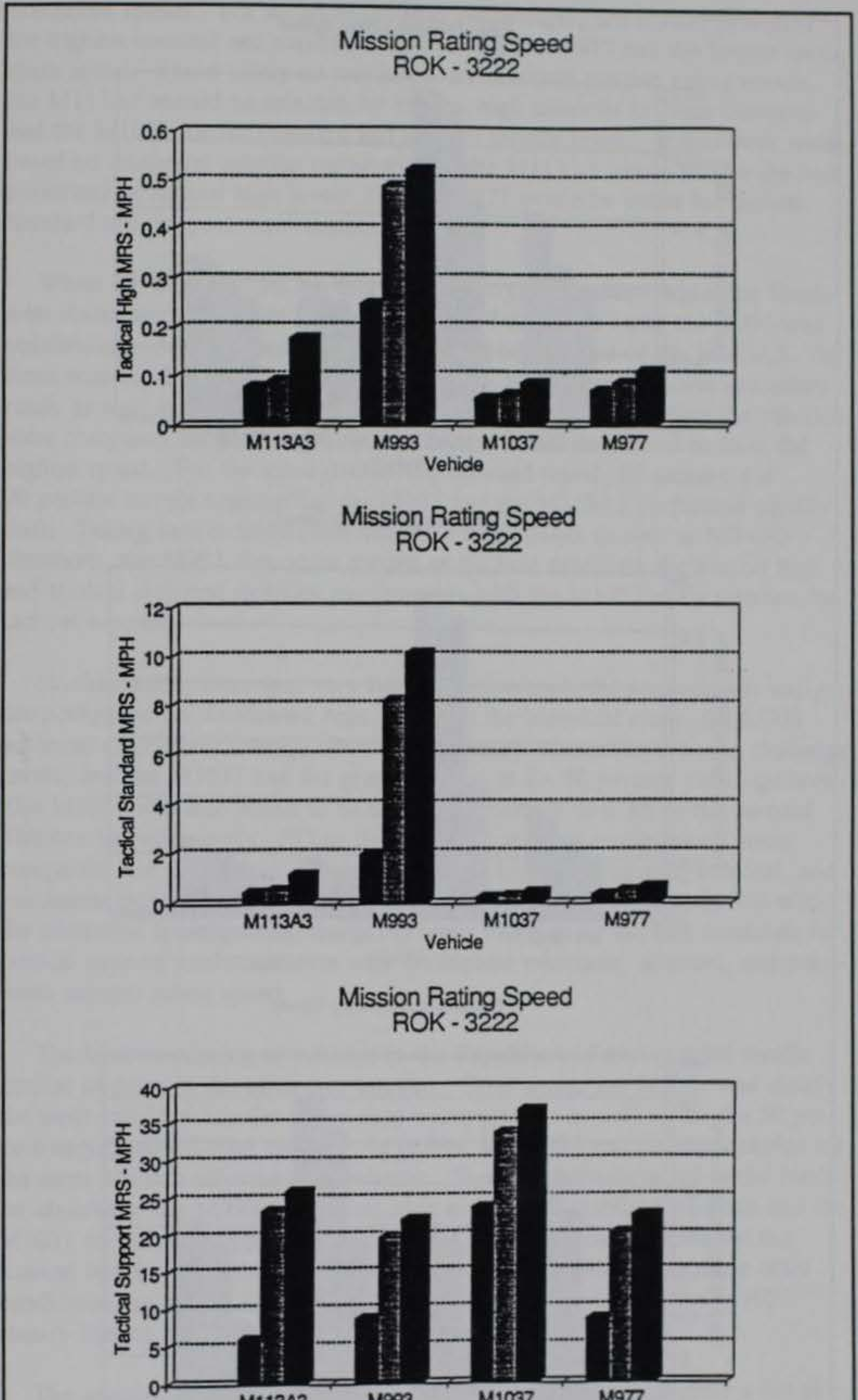


Figure 105. Mission rating speeds for ROK

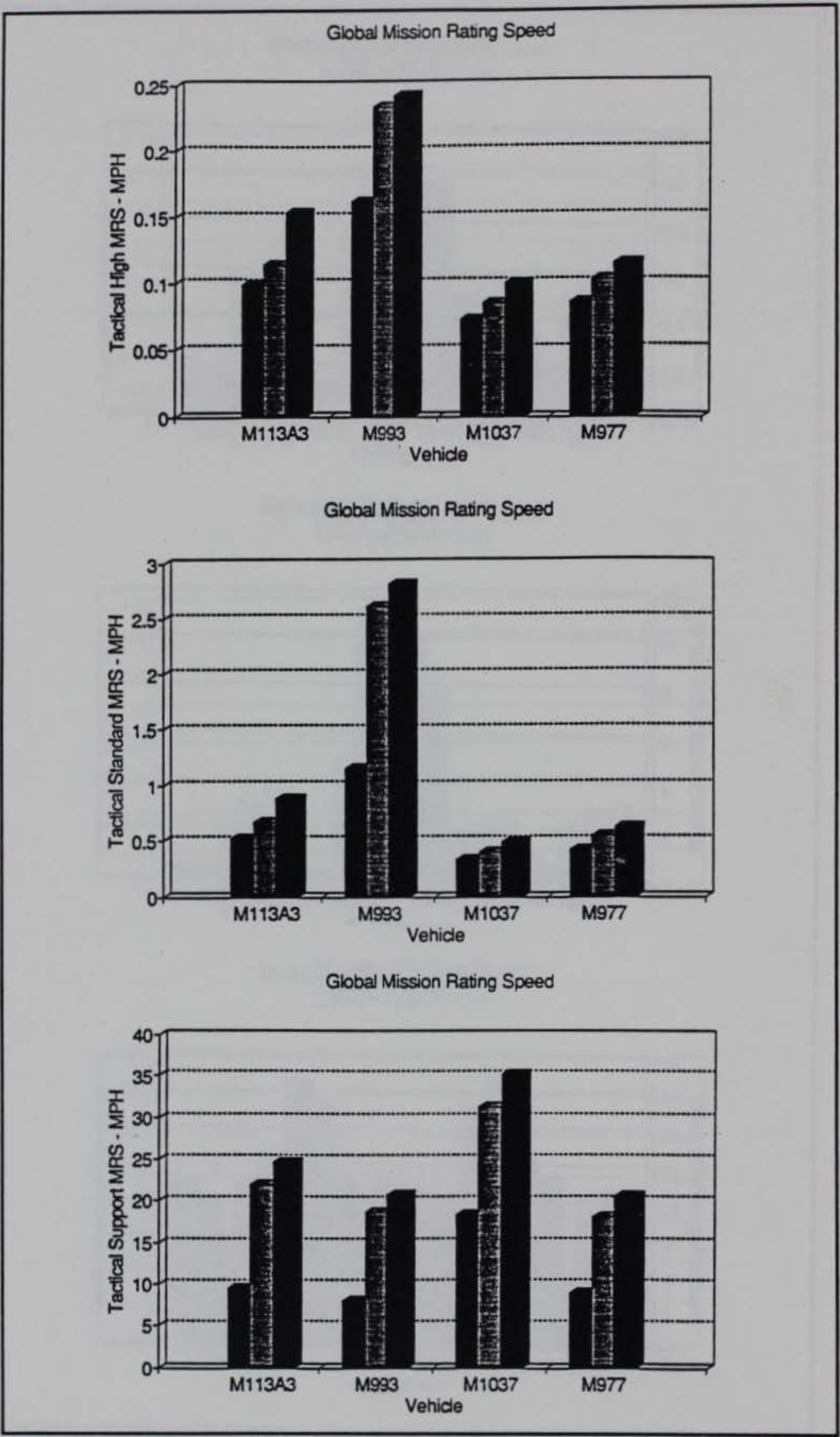


Figure 106. Global mission rating speeds

maximum speeds. For all other off-road percentages, the M1037 produced the highest nominal and maximum speeds, but the M977 had the largest minimum speed. Based solely on maximum and nominal mission rating speeds, the M113A3 should be selected for tactical high missions in West Germany and the M1037 for the standard and support tactical levels. If decisions were based on minimum mission rating speeds, the M113A3 would still be the best performer at tactical high levels, but the M977 would be better for tactical standard and support requirements.

When the four vehicles of interest were originally compared on the Southwest Asian terrains, again the performance of the M1037 and the M993 was outstanding. Also evident this time was the performance of the M113A3. In these studies, the M1037 obtained the highest average speeds over secondary roads as well as off-road at the 50 percent challenge level. When the vehicles were compared for performance on trails, the M993 was found to have the highest speed. For the more demanding off-road travel, 80 percent and 90 percent terrain negotiation, the M993 and the M113A3 performed equally well. Taking into consideration mission rating speeds as well as NO-GO situations, the M993 was again chosen as the best candidate for tactical high and tactical standard mobility requirements with the M1037 again selected for tactical support.

Stochastically, there was very little deviation from the deterministic analyses performed for Southwest Asia. As with the historical study, the M993 achieved the highest average speeds on the more demanding off-road challenge levels, and the M1037 had the greatest speed at the 50 percent challenge level. The M1037 was also found to be the best performer over all of the on-road distance including trails. When the stochastic mission rating speeds were compared, not surprisingly the M993 had the highest minimum, nominal, and maximum tactical high and tactical standard rating speeds. Also in line with the computed speed profile, the M1037 was found to be the best candidate for tactical support implementation with the highest minimum, nominal, and maximum support rating speed.

The historic ranking of vehicles in the Republic of Korea yielded results similar to those in the other two terrains. Once again, the M1037 was clearly the most rapid vehicle for all on-road transportation as well as for the 50 percent negotiated off-road terrain. As before, the M993 was the clear choice for the most difficult off-road manipulation. These performances led to the familiar choices of the M993 for tactical high and tactical standard missions and the M1037 for tactical support implementation. The stochastic results for the Korean terrain led to the same conclusions with the M993 dominating other candidates for tactical high and tactical standard missions, and the M1037 clearly besting the other vehicles for tactical support.

The goal of the original study was to select the best vehicle from a list of candidates to be utilized in the FOG-M component of the Forward Air Defense. Since the historic study was based on several terrain subtypes and surface conditions, the vehicles could be ranked by examining the frequency of their selection as best candidate for tactical-high mobility on each type of condition. This criterion was further restricted by using the high-high mobility level as the determining factor in similarly performing vehicles.

The best vehicle selected in accordance with these stipulations was the M993 FVS followed in order by the M977 HEMTT, the M113A3, and finally the M1037 HMMWV. Since only the dry-normal surface condition and total area were analyzed in the stochastic analysis, the vehicles' performance in this scenario is used for ranking. To clarify the overall performance of the vehicles, the results of the global mission rating speed calculations will be used.

When comparing the computed global mission speeds, the M993 is still the candidate of choice for tactical-high mobility performance, and hence the vehicle of choice for the FOG-M application. The second choice of the four studied vehicles is the M113A3 followed in order by the M977 and the M1037. Although the vehicle of choice from the stochastic analysis is consistent with that of the deterministic study, the order of selection is modified. This is the result of evolutions in the deterministic NRMM between the original study and the present. The stochastic approach has added depth to the FOG-M mobility study by revealing the range of velocities the candidate vehicles can be expected to achieve. This adds confidence to the ranking of candidate vehicles.

Table 14
Stochastic Mission Rating Speeds - MPH

	Tactical High			Tactical Standard			Tactical Support		
	Min	Nom	Max	Min	Nom	Max	Min	Nom	Max
West Germany									
M993	0.69	12.96	14.99	8.65	17.77	20.21	18.60	21.65	24.08
M977	0.68	4.99	7.10	12.68	17.89	20.60	19.49	22.32	24.99
M113A3	0.95	14.69	17.72	10.71	20.96	24.08	19.28	25.58	28.58
M1037	0.44	1.32	1.34	8.58	28.32	31.00	14.54	36.73	38.44
Southwest Asia									
M993	0.110	0.140	0.140	0.72	1.49	1.59	6.24	17.04	19.12
M977	0.070	0.080	0.085	0.34	0.42	0.44	7.56	15.86	18.37
M113A3	0.081	0.091	0.104	0.43	0.53	0.58	11.08	20.11	22.91
M1037	0.065	0.072	0.078	0.29	0.35	0.38	17.96	28.50	33.19
Republic of Korea									
M993	0.251	0.489	0.524	2.02	8.24	10.14	8.81	19.78	22.21
M977	0.071	0.087	0.111	0.34	0.49	0.65	8.63	20.27	22.73
M113A3	0.080	0.093	0.179	0.41	0.55	1.18	5.96	23.38	26.00
M1037	0.055	0.063	0.087	0.23	0.29	0.42	23.76	33.90	36.95
Global Mission Rating Speeds									
M993	0.162	0.233	0.242	1.16	2.61	2.82	8.01	18.61	20.85
M977	0.086	0.103	0.116	0.42	0.55	0.62	9.00	18.09	20.65
M113A3	0.099	0.114	0.154	0.52	0.67	0.89	9.44	21.97	24.78
M1037	0.073	0.085	0.100	0.33	0.40	0.49	18.44	31.41	35.23

6 Conclusions and Recommendations

Conclusions

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

a. Extension of stochastic mobility forecasting procedures to encompass realistic quantities of data requires intense computation. The procedures described in this report call for a supercomputer environment and, while capable of satisfactory service in a research setting, would be unsuitable for the tactical setting that motivated their development.

b. A potential breakthrough was glimpsed that may provide an order-of-magnitude reduction in computational overhead. This involves the development of stochastic mobility forecasting products using far fewer than the full complement of terrain units contained in current maps.

c. Unrelenting advances in computational speed and capacity of portable desk-top machines makes the final attainment of tactical stochastic mobility forecasting highly probable.

d. Application of the procedures to two historic studies confirmed the earlier outcomes attained with the deterministic form of NRMM and illustrated how the stochastic components provided additional information useful in ranking candidate vehicle designs against specified operating missions.

Recommendations

The following recommendations are made:

a. By means of analysis of existing data for the independent variables, personal interviews or by the convening of a panel of expert mobility data acquisition personnel, obtain and use better information on the uncertainty of the independent variables to more closely focus on sensitivity thresholds and error-magnitude scenarios.

b. Follow up on the lead reported here suggesting that the products of a stochastic mobility forecast for a quad can be obtained with far less terrain data units than used heretofore. Transfer operations from the supercomputing environment to a desktop machine at the cutting edge of technology. Upgrade that machine as technology advances. Convert software from its present "breadboard" state to one of refinement, uniformity, and friendliness.

c. Document as Report 3 in the current series the many new and intricate elements of code used to convert NRMM to a stochastic model. Document also the postprocessing software used in both the supercomputing and personal computing environments to create the products of the stochastic mobility forecast.

d. Create tactical offensive and defensive localized scenarios, prepare stochastic estimates of (1) travel time for several avenues of approach and (2) areas which must be defended against a mechanized attack. Explore means of expressing tactical decision parameters in stochastic terms.

e. Prepare and conduct classroom and field exercises using the military personnel who would be responsible for deploying the stochastic version of NRMM in a tactical setting. Learn from these activities how stochastic outputs are best presented to their intended audience.

f. Undertake a limited program of field validation of these methods. This would involve selection of several terrain units, characterizing them by measurements repeated at many different physical locations and traversing them with a vehicle many times using different physical paths. In this way, probability density functions can be developed for the terrain data and the recorded vehicle traversal speeds. Comparisons would follow with NRMM responses to the same inputs.

g. Extend stochastic forecasting methods to all applications that use NRMM as a foundation.

h. The mission rating speed ranges, based as they are on minimum and maximum predicted speeds, depict worst-case error performance by NRMM. Users should be alert to the possible need to resolve NRMM error performance more selectively by appealing to analysis of the mission rating speed probability densities rather than the ranges. This would allow the use of well-known and accepted statistical procedures for the formulation of confidence intervals and for the testing of the significance of differences among vehicles.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1993

3. REPORT TYPE AND DATES COVERED
Report 2 of a Series

4. TITLE AND SUBTITLE
Stochastic Vehicle Mobility Forecasts Using the NATO Reference Mobility Model

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

6. AUTHOR(S)
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Paul Mlakar, William Stough, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. 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-93-15

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

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
This report is available from the 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 is the second in a series that documents the conversion of the NATO Reference Mobility Model from a deterministic code to a stochastic one. The first report described basic concepts and procedures and dealt with relatively small quantities of data as methods were "bootstrapped" into existence. This report describes the extension of the procedures to realistic quantities of data.

In addition, the methods are applied to two historical mobility assessments that were influential, years ago, in the procurement of some Army vehicles now in the inventory. When the studies were originally done, NRMM was used in a completely deterministic way and no consideration was given to the perturbing effects of uncertain data and of scatter associated with field-data-based algorithms. The analyses were repeated (albeit with greatly limited scope) using stochastic mobility forecasting methods as a means of introducing the NRMM user community to these methods in an inherently interesting way.

14. SUBJECT TERMS
Mobility modeling
Stochastic modeling

15. NUMBER OF PAGES
156

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	UNCLASSIFIED	

NSN 7540-01-280-5500

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