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ARMORED COMBAT VEHICLE TECHNOLOGY (ACVT) PROGRAM MOBILITY/AGILITY FINDINGS (U)

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PART I: INTRODUCTION

Background

The ACVT program was a joint Army and Marine Corps project to develop technology for designing and building armored vehicles in the post-1985 time frame. The program examined potentials for improving weapon systems, armor, and mobility/agility performance particularly as advances in these areas could be combined to produce combat vehicles of greater battlefield lethality and survivability. This paper is concerned only with the mobility and agility part of the program, which consisted of three closely related activities:

a. Careful testing of two special test chassis, plus the General Motors XM1 automotive test rig (ATR), the M113A1 Armored Personnel Carrier (APC), and the M60A1 Main Battle Tank (MBT), to develop quantitative data relating various measures of performance to a wide range of vehicle design parameters and terrain conditions and to driver behavior;

b. Development or refinement of analytical models for predicting vehicle performance, and validation of these models using the data base derived from a above, and

c. Use of the validated analytical models to conduct broad parametric studies, to support war games which integrated mobility/agility, weapon systems, and armor considerations, and to evaluate concept designs for lightweight combat vehicles based on present and near-future component technology.

The principal special test chassis was the HIMAG vehicle whose gross weight, center of gravity, suspension spring and damping rates, and wheel travels could be widely varied. The HIMAG was used for ride and shock tests, dash tests, and traverse tests with various drivers. The second special test chassis was the twin-engine M113 developed for research purposes by the U. S. Army Engineer Waterways Experiment Station (WES) and referred to as the M113 HOTROD. The M113 HOTROD (86 gross horsepower per ton (hp/ton) and the ATR (36 gross hp/ton) were used in special tests to examine the effects of high speeds on the motion resistance offered by soils.

Objectives and Issues

The long-range objectives of the ACVT mobility/agility program were to develop an extensive, reliable data base on combat vehicle performance and an array of validated analytical models to make these data readily available to vehicle designers and evaluators.

The immediate objectives were to address the following issues:

a. What are the effects of various vehicle chassis design parameters upon the attainment of high mobility/agility?
b. Are there any risk areas associated with high-speed travel in the area of vehicle-soil physics?
c. What is the fraction of available mobility used by a crew?
d. What is the M1 MBT level of mobility?
e. What is the mobility/agility performance of the HIMAG test bed versus that of conventional armored vehicles, the M1 MBT, and lightweight concept vehicles?
f. Can lightweight combat vehicles be designed with mobility/agility equal to or greater than that of the M1 MBT?
g. Does the attainment of high mobility/agility provide a payoff in survivability?

Mobility/Agility Tests

The test work was designed to develop quantitative data relating specific measures of vehicle performance to the engineering characteristics of a vehicle configuration and of the terrain and to driver behavior. Emphasis was placed upon obtaining a wide range of variations in vehicle and terrain so that trends could be seen clearly and analytical models could be checked as broadly as possible.

More than 1900 mobility/agility tests were conducted with 21 high-performance and 2 contemporary vehicles. Eighteen distinct configurations of the HIMAG variable high mobility/agility test bed were tested to explore mass and suspension effects on performance. Tests were also conducted with the ATR with and without the 13.5-ton turret, the M113 HOTROD and two contemporary vehicles, the M60A1 MBT, and the M113A1 APC. The test vehicles provided a range in gross vehicle weight from 9 to 52 tons, in gross hp/ton ratios from a low of 14 for the M60A1 MBT to a high of 86 for the M113 HOTROD, and in sprocket hp/ton ratios from a low of 8.4 for the M60A1 MBT to 28.9 for the M113 HOTROD. The vehicles were appropriately instrumented to measure and record the data of interest in each test.

Seven types of tests were conducted in quantitatively defined test areas to produce the desired data base and vehicle-terrain-driver relations (1). Five principal types of engineering tests were run--acceleration-deceleration (dash), ride dynamics, obstacle-impact response (shock), turning, and controlled-slalom (maneuver). Two types of tests were conducted to test tactical performance--a 20-km traverse test through many quantitatively defined terrain types for vehicle speed and driver response evaluation, and hit-avoidance tests to determine the survivability attributed to vehicle mobility/agility. The majority of tests were conducted at Fort Knox, Kentucky, with some special soft-soil tests conducted in a floodplain near Vicksburg, Mississippi. In these latter tests, trafficability, mobility, and agility data were obtained from cross-country and soft-soil tests at speeds more than twice those ever before achieved.

Mobility/Agility Models and Simulations

Concurrently with the field tests, turning, maneuver, and traverse models were developed to describe the mobility/agility performance along any specified path through any terrain (2). Field test results validated these new models (3) and revalidated the basic Army Mobility Model (AMM) (4), and its dynamics module VEHDYN (5) as well. The several validated models provided the analytical tools needed to predict mobility/agility performance and to conduct meaningful parametric studies.

These models were used to compare the performance in quantitatively defined German and Middle East terrains of more than 30 concept combat vehicles designed by the engineers at the U. S. Army Tank-Automotive Command to meet specific Army and Marine Corps requirements, plus the M1 MBT, the M3 Cavalry Fighting Vehicle (CFV), the M60A1 MBT, and the M113A1 APC.

PART II: RESULTS OF HIMAG CHASSIS TESTS

Mobility/agility performance depends on design balance, terrain, weather, and a specified mission profile. It cannot be assessed on the basis of a single vehicle parameter.

Figure 1 illustrates the principal factors that affect mobility/agility performance. The results of the ride and shock tests showed that the effects of suspension jounce travel (i.e., the vertical travel of a roadwheel from its static equilibrium position to the bump stop) depended on the degree of suspension damping, suspension spring rate, vehicle weight, and surface roughness. Reduced jounce travel combined with soft springs and low damping caused a progressive increase in suspension "bottoming" (roadwheels striking the bump stops) as the surface roughness or obstacle

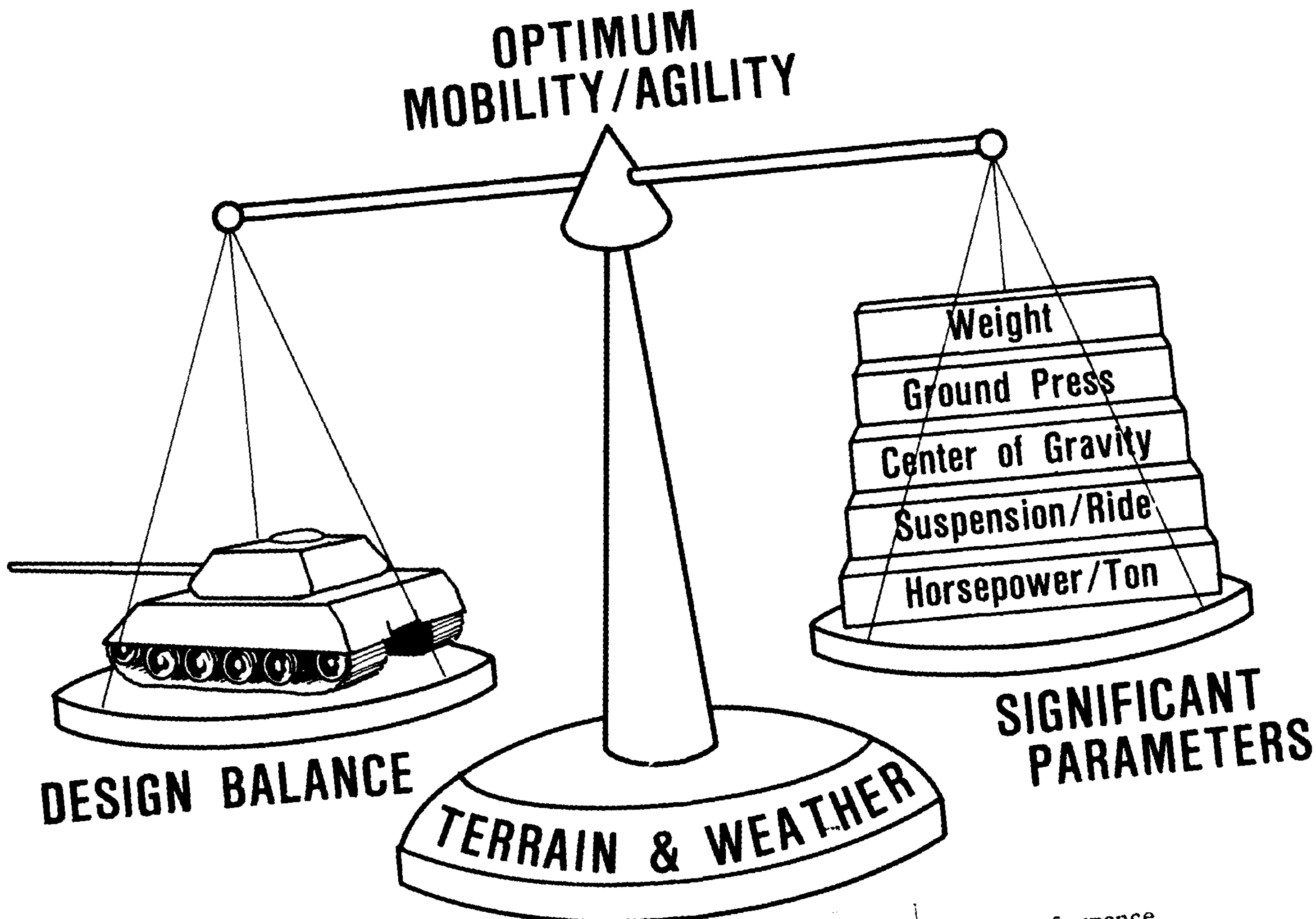

Figure 1. Principal factors that influence mobility/agility performance

height increased. This condition became worse for this type of suspension if the vehicle weight was increased. However, the shock effects caused by suspension bottoming could be effectively reduced with increased damping. The test results showed that light damping provides the best ride on smoother terrains and progressively heavier damping is required as the surface roughness increases. The performance patterns demonstrated the potential value of adaptive suspensions that could sense changing conditions and automatically alter the damping levels to optimize the ride over all terrain.

Ride performance is a function of surface roughness, and shock performance is a function of obstacle height. Consequently, the distribution of surface roughness and of obstacles in the area of operation is a significant factor on overall ride and shock performance. It is wasted time and money to design a vehicle to perform well in very rough terrains and over high obstacles if such conditions are only rarely found in the intended operating areas.

Sprocket horsepower per ton is definitely a prominent factor in mobility/agility performance. Yet it is obvious that a vehicle with high sprocket horsepower per ton and poor suspension will be able to use that power only on smooth terrain surfaces where ride and shock are not limiting factors. Likewise, the mobility/agility advantages of high horsepower per ton are quickly diminished in deformable soils if the vehicle's ground pressure does not provide sufficient flotation to prevent excessive sinkage and soil motion resistance; or in curves and sharp turns during evasive maneuvers if the vehicle's center of gravity is too high for stability; or if the vehicle's dimensions prevent effective maneuvering in the dense forests, such as those found in Germany and certain tropical areas of military interest.

There are no risk areas with vehicle-soil physics.

A principal concern was to determine if the soil motion resistance increased significantly at high speeds in a manner similar to the exponential increase in resistance offered by water to high-speed boats. If the increase was significant, there would be practical limits on power trains beyond which large increases in motion resistance would largely offset power increases, resulting in only small gains in speed. Until this program, power trains in cross-country vehicles had not permitted speeds where such soil resistance rate effects, if they existed, were encountered.

Figure 2 illustrates the effects of soil motion resistance on speeds. The plots depict the motion resistance coefficients R/W (motion resistance to gross vehicle weight ratio) as a function of speed for two distinct soil conditions. The total resistance, the resistance on a firm, level surface, and the resistance due solely to the soil are shown for both the measured and predicted relations. The most important observation from these data

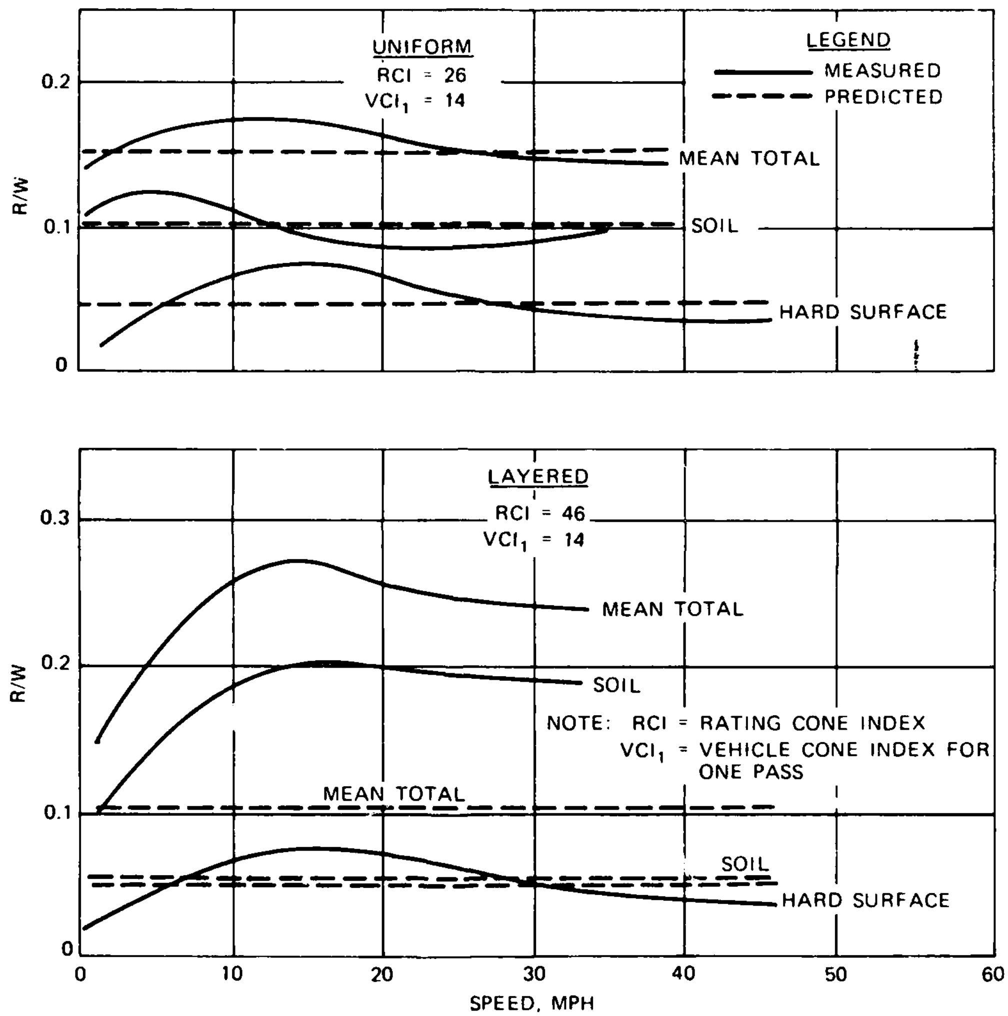

Figure 2. Comparison of measured and predicted motion resistance coefficients versus speed for two soil types (M113 HOTROD)

is that over the speed range from 10 to 30 or 40 mph there appears to be no significant increase in motion resistance; i.e., up to at least 40 mph there is no evidence that increased power will not provide proportionally increased speeds in normal weak soil conditions. The upper plot in Figure 2 shows the average results of four tests run in a soft, sticky soil (rating cone index (RCI) = 26) and compares with the prediction made using the present vehicle cone index (VCI) methods and relations (6). The correlation is good. It is not good for the medium-strength layered soil condition (RCI = 46) shown in the lower plot. It is predicted that R/W = 0.10 . The test logs note that in addition to a firm layer about 5 in. below the surface, the soil in these tests was extremely sticky and tended to clog the tracks and that the test area (continuously flooded for several months just before testing) was "spongy," suggesting that some viscoelastic response of the soil was absorbing substantial energy. These factors would increase the actual measured motion resistance.

Trained military tank drivers will use the increased mobility available in high-performance tracked vehicles.

A comparison of the performance between the professional WES drivers and military drivers was used to determine the degree that trained military drivers would exploit the increased mobility capability of the HIMAG chassis. It would be wasted effort and money to design and build vehicles with 50 or 60 percent increase in mobility capability if military drivers only use 10 or 15 percent of the increased capability. Because the WES professional drivers had been driving the HIMAG vehicle in the previous engineering tests for more than five months just before these tests, they were considered able to exploit the maximum performance capability of the vehicle. Their performance was used as the reference for comparing performance of the military drivers. The evaluations were made from tests with two of the best HIMAG configurations, along with the M60A1 MBT and M113A1 APC for reference, over a rugged 20-km test course, which was composed of 189 distinctly different segments of terrain and 5 general terrain types. There were two groups of military drivers--a group that was familiar with the test course and a group that had never seen the course. All were equally well trained in driving the HIMAG chassis.

The following tabulation shows a comparison of the percent of the WES drivers' speeds achieved by the drivers familiar with the course and the drivers unfamiliar with the course in each terrain type and over the entire 20-km course. For the two HIMAG configurations the familiar drivers reached 90 to 95 percent of the speeds achieved by the WES drivers over the entire course. The unfamiliar drivers achieved 87 percent for the HIMAG 5, but the somewhat unstable behavior of the lighter, tail-heavy HIMAG 2 had a significant influence on those drivers not familiar with the course and they achieved only 79 percent of the WES drivers' speeds.

Percent of WES Drivers' Speeds Achieved
by Familiar and Unfamiliar Drivers

Vehicle	Secondary Road		Dirt Trails		Hog Hollow		Pipe-line		Tank Trails		Entire Course	
	F	U	F	U	F	U	F	U	F	U	F	U
HIMAG 5	95	85	92	78	94	79	98	81	98	80	95	79
HIMAG 2	96	99	99	83	88	83	92	85	82	80	90	87
M113A1 APC	97	95	90	90	68	68	89	83	89	84	89	86
M60A1 MBT	95	92	88	81	92	82	86	76	79	75	88	81

The relative performance results show that the military drivers actually exploited more of the available mobility capability from the two HIMAG configurations than from the two contemporary vehicles. These results clearly illustrate that trained military drivers (familiar with the area) will use 90 to 95 percent of the available HIMAG level mobility in tracked vehicles.

Level of mobility is a multiparameter definition.

Level of mobility is a multiparameter definition. The single parameter definition, horsepower-per-ton, often misused to describe the M60A1 MBT, M1 MBT, and HIMAG levels of mobility, is not adequate. Eleven principal factors that include both vehicle and terrain characteristics have been identified that limit mobility. These factors listed below are also used by the AMM to predict speed (4).

a. Insufficient soil strength.
b. Insufficient traction.
c. Obstacle interference.
d. Combination of terrain factors.

(a–d: NOGO factors)

e. Ride (surface roughness).
f. Soil/slope resistance.
g. Visibility.
h. Maneuverability (through forests or around obstacles).
i. Vegetation (override resistance).
j. Shock (obstacle negotiation).
k. Linear features (streams, ditches, embankments, etc.).

An example of specifying a given level of mobility based on seven performance criteria that involve the eleven factors above is shown in Table 1. Comparisons of performance between the M1 MBT and the HIMAG 5 are shown for those criteria where data were available. A specified level of mobility, such as the M1 MBT mobility and the HIMAG mobility, can be rather accurately defined in terms of the combined minimum acceptable levels for each of the seven performance criteria, but not by using any single criterion.

PART III: RESULTS OF MODEL SIMULATIONS

Lightweight combat vehicles can be designed with mobility/agility equal to or greater than that of the M1 MBT.

Tables 2 and 3 compare the relative performance of eight selected vehicles for four distinct types of mobility in both dry and wet conditions in West Germany and Middle East terrains, respectively. The vehicles are ranked in each case according to performance. The four mobility types--dash, traverse, maneuver, and cross-country--are representative of those often encountered in tactical situations. The relative performance of the vehicles varies according to the type of mobility, the area of operations, and the terrain conditions. The variations show no particular pattern with respect to gross vehicle weight or sprocket horsepower per ton. Observe that:

- a. Generally the HIMAG was a top performer except in the German cross-country terrain where its size severely restricted maneuverability through the denser German forests. The M1 MBT encountered the same problem.
- b. In most cases all the lighter concept vehicles outperformed the M1 MBT.
- c. The M1 MBT demonstrated excellent maneuver performance (in open, level terrain) except in wet German terrain where its performance fell below that of the CFV.
- d. The M113A1 APC and the M60A1 MBT were consistently the worst performers.

These results demonstrate that the M1 MBT always outperforms the two contemporary vehicles but generally falls below the performance levels of the HIMAG and the still lighter concept vehicles. However, subsequent war gaming indicated these differences between the M1 MBT and the concept vehicles were not tactically significant. The results also reflect that vehicle performance depends upon the combined effects of the vehicle, the mission, and the terrain and does not vary directly with weight or horsepower. Consequently, with proper attention to design, a lightweight armored vehicle in the 16- to 20-ton range can achieve or surpass the mobility/agility performance of the M1 MBT.

High mobility/agility provides an increased hit-avoidance capability, but the reduced effectiveness to fire-on-the-move while maneuvering violently may result in only a marginal payoff in survivability.

The results of the hit-avoidance tests revealed that a vehicle capable of performing fast, quick maneuvers can gain an additional measure of hit avoidance (7). The major payoff in high mobility/agility vehicles is in performing fast, dash-to-cover tactics. The principal components in reducing hit probability are the time available to engage the target and the aiming errors. Figure 3 shows a comparison of the dash performance between the M113 HOTROD and the contemporary M113A1 APC in a medium-strength soil (RCI = 46). The maximum speed of the M113 HOTROD was 49 mph compared with 23 mph for the contemporary M113A1 APC. More important is the significant difference in the rate of acceleration. For example, the time required to accelerate from a standing start to 20 mph is only 2.9 sec for the M113 HOTROD compared with 33.0 sec for the M113A1 APC. This quick acceleration permits abrupt speed changes, rapid stops to return fire, and quick starts, and may be more important than the maximum achievable speed per se.

In the simplest sense, against opposing guns, a maneuvering vehicle moves out of the way of a projectile already in flight causing what is referred to as target-induced error. Likewise, a fast, agile target affects the ability of a gunner to accurately track the target in his sight. The gun turret drive and fire-control computer system are also affected. This type of error, which occurs before the round is fired, is referred to as system-induced error. Finally, the fast, agile target reduces exposure time to opposing gunners. These three factors--increased target-induced error, increased system-induced error, and decreased exposure time created by a fast, agile maneuvering vehicle decrease the probability of being hit. Further, a maneuver that minimizes exposure time while maximizing accelerations seen by the firer could be considered optimal (8). However, reduced capability to fire-on-the-move effectively while maneuvering violently may significantly counter the gains in hit-avoidance and result in little net payoff for the latter tactic.

PART IV: CONCLUSIONS

Based on the information presented in this study, it is concluded that:

a. With careful attention to design balance, lightweight combat vehicles can be developed with mobility/agility performance equal to or greater than the M1 MBT.

b. Increases in performance beyond M1 MBT levels, possible with power train components available in the near future, are relatively small and not tactically significant.

c. Increased installed horsepower, up to at least 29 hp/ton at the sprocket, will pay off in increased mobility/agility performance, even in relatively weak soils, provided other design features are kept in balance.

d. Such increases can be achieved in properly designed combat vehicles ranging from 16- to 58-ton gross weight.

e. Properly trained military drivers will achieve more than 90 percent of the mobility available in high-performance tracked vehicles.

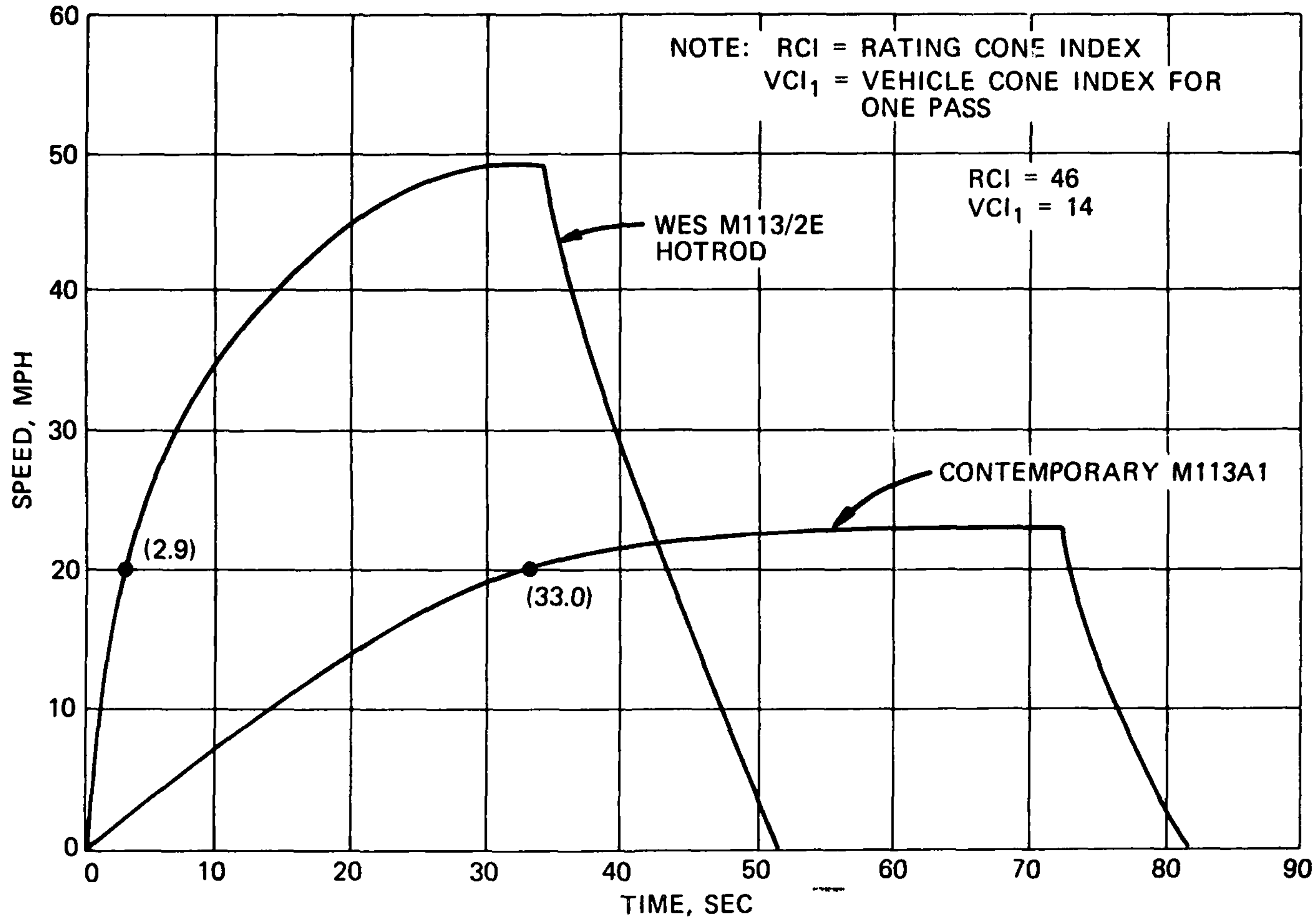

Figure 3. Comparison of acceleration-deceleration performance of WES M113/2E HOTROD and standard M113A1 on the same soil strength

f. A fast, agile maneuvering vehicle provides an increased hit-avoidance capability, but the reduced effectiveness of fire-on-the-move while maneuvering violently may result in only a marginal payoff in survivability.

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Table 1

Minimum Performance Criteria for Specifying a Given Level of Mobility

Principal Vehicle Factors	Performance Criteria	M1	HIMAG 5
Suspension, power train	Ride: Speed, mph, over surface roughness		
	0.5 rms, in.	45.8	55.0
	1.0 rms, in.	45.8	53.0
	1.5 rms, in.	31.5	43.0
Suspension, power train	Shock: Speed, mph, over obstacle height		
	8-in.	45.8	55.0
	10-in.	45.8	55.0
Power train (hp/ton at sprockets)	Dash: Time, sec, for 500-m dash on hard surface	32.4	31.6
GVW, power train, track-ground contact area	Soft-soil: VCI_1	24	18
GVW, power train	Slope: Negotiate a 60% dry slope	Yes	Yes
Vehicle width (1.5 × width = NOGO)	Maneuver (forests): Speed, mph, through forest with 15-ft average spacing	*	*
Center of gravity, tread, track length on ground, power train	Maneuver (agility): Speed-made-good, mph, for maneuver (5 m by 100 m) on hard surface	35	*

Note: GVW = gross vehicle weight; rms = root-mean-square elevations; and VCI_1 = vehicle cone index (minimum soil strength for one pass).

* No experimental data available at this time.

Table 2

Comparison of the Relative Performance of Selected Vehicles at Several Levels of Mobility Based on Speed Predictions in West Germany Terrains

Dry Condition				Wet Condition			
Vehicles	GVW tons	SHP/Ton	Avg Speed mph	Vehicles	GVW tons	SHP/Ton	Avg Speed mph
			Dash (500 m)				
HIMAG 5	42	21	38.0	HIMAG 5	42	21	32.2
CON 22 (PIP)*	21	26	33.6	CON 22 (PIP)*	21	26	30.7
CON 3	16	15	32.7	CON 3	16	15	27.4
CON 22	21	15	32.1	CON 22	21	15	26.8
M1	58	18	31.3	M1	58	18	25.3
CFV	23	16	27.9	CFV	23	16	24.5
M113A1	11	12	26.3	M113A1	11	12	18.9
M60A1	52	8	22.1	M60A1	52	8	16.8
			Traverse (25 km)				
CON 22 (PIP)*	21	26	21.8	CON 22 (PIP)*	21	26	16.4
CON 3	16	15	19.0	HIMAG 5	42	21	14.7
HIMAG 5	42	21	18.9	CON 22	21	15	14.0
CON 22	21	15	18.1	CON 3	16	15	13.4
M1	58	18	17.0	M1	58	18	13.0
CFV	23	16	16.6	CFV	23	16	12.7
M113A1	11	12	14.4	M113A1	11	12	11.4
M60A1	52	8	12.2	M60A1	52	8	9.2
			Maneuver (5 m by 100 m)**				
HIMAG 5	42	21	46.6	CON 22 (PIP)*	21	26	34.3
M1	58	18	43.9	CON 22	21	15	33.0
CON 22 (PIP)*	21	26	41.8	CON 3	16	15	32.5
CON 3	16	15	41.6	HIMAG 5	42	21	32.5
CON 22	21	15	41.2	CFV	23	16	31.6
CFV	23	16	34.0	M1	58	18	29.2
M113A1	11	12	20.5	M113A1	11	12	27.8
M60A1	52	8	21.9	M60A1	52	8	17.8
			Cross-Country (AMM, V_{90})†				
CON 22 (PIP)*	21	26	18.7	CON 22 (PIP)*	21	26	14.8
CON 3	16	15	17.3	CON 22	21	15	13.2
CON 22	21	15	17.1	CON 3	16	15	12.2
HIMAG 5	42	21	16.0	HIMAG 5	42	21	11.9
M1	58	18	13.8	CFV	23	16	8.7
CFV	23	16	13.7	M1	58	18	7.3
M113A1	11	12	10.6	M60A1	52	8	4.1
M60A1	52	8	9.0	M113A1	11	12	2.0

Note: GVW = gross vehicle weight, and SHP/Ton = sprocket horsepower per ton.
* Denotes up-powered version of CON 22.
** Denotes maneuvers of 5-m amplitude and 100-m wavelength on only level terrain with mild to medium surface roughness.
† V_{90} represents the average speed in the area after eliminating the worst 10 percent of the terrain.

Table 3

Comparison of the Relative Performance of Selected Vehicles at Several Levels of Mobility Based on Speed Predictions in Middle East Terrains

Dry Condition				Wet Condition			
Vehicles	GVW tons	SHP/Ton	Avg Speed mph	Vehicles	GVW tons	SHP/Ton	Avg Speed mph
Dash (500 m)							
HIMAG 5	42	21	41.4	HIMAG 5	42	21	38.6
CON 22 (PIP)*	21	26	34.0	CON 22 (PIP)*	21	26	33.2
CON 3	16	15	33.6	CON 3	16	15	32.6
CON 22	21	15	33.3	CON 22	21	15	32.3
M1	58	18	31.5	M1	58	18	30.6
CFV	23	16	28.0	CFV	23	16	27.4
M113A1	11	12	26.4	M113A1	11	12	25.7
M60A1	52	8	22.9	M60A1	52	8	21.9
Traverse (25 km)							
HIMAG 5	42	21	24.5	HIMAG 5	42	21	24.6
CON 22 (PIP)*	21	26	21.9	CON 22 (PIP)*	21	26	22.5
M1	58	18	21.3	M1	58	18	20.9
CON 3	16	15	19.9	CON 3	16	15	19.4
CON 22	21	15	19.5	CON 22	21	15	19.4
CFV	23	16	17.0	CFV	23	16	16.8
M113A1	11	12	14.3	M60A1	52	8	13.6
M60A1	52	8	13.9	M113A1	11	12	13.4
Maneuver (5 m by 100 m)**							
CON 22 (PIP)*	21	26	40.3	HIMAG 5	42	21	40.8
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CON 3	16	15	39.3	CON 3	16	15	37.1
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Cross-Country (AMM, V_{90})†							
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CON 22	21	15	21.0	CON 3	21	15	20.6
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CFV	23	16	16.4	CFV	23	16	16.3
M113A1	11	12	14.1	M113A1	11	12	13.6
M60A1	52	8	13.2	M60A1	52	8	12.6

Note: GVW = gross vehicle weight, and SHP/Ton = sprocket horsepower per ton.
* Denotes up-powered version of CON 22.
** Denotes maneuvers of 5-m amplitude and 100-m wavelength on only level terrain with mild to medium surface roughness.
† V_{90} represents the average speed in the area after eliminating the worst 10 percent of the terrain.