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Vehicle Barriers: Emphasis on Natural Features

Kenneth G. Adams, Benjamin J. Roscoe

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Kenneth G. Adams
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Sandia National Laboratories
Albuquerque, NM 87185
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for the
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ABSTRACT

The recent increase in the use of car and truck bombs by terrorist organizations has led NRC to evaluate the adequacy of licensee security against such threats. As part of this evaluation, one of the factors is the effectiveness of terrain and vegetation in providing barriers against the vehicle entry. The effectiveness of natural features is presented in two contexts. First, certain natural features are presented. Second, the effectiveness of combinations of features is pre- sented. In addition to the discussion of natural features, this report provides a discussion of methods to slow vehicles. Also included is an overview of man-made barrier systems, with particular attention to ditches.

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EXECUTIVE SUMMARY

The Nuclear Regulatory Commission (NRC) has since its inception been concerned with the adequacy of security at licensed facilities. The recent increase in the use of car and truck bombs by terrorist organizations has led the NRC to investigate the adequacy of licensee security against such threats. If present security is deemed inadequate in the context of the perceived threat, then methods to enhance security will be necessary. This report, provides information on methods to slow down or stop wheeled vehicles used on land.

This report primarily discusses the effectiveness of natural terrain and vegetation that might be indigenous to a particular site in providing natural or passive security barriers against vehicle entry and hence against the vehicle bomb threat. Naturally occurring features may be capable of stopping vehicles without assistance. In other cases, these features may only slow down approaching vehicles and therefore will need to be augmented by man-made obstacles. The effectiveness of natural features is presented in two contexts. First, certain natural features are discussed separately, and data on their effectiveness are presented. Second, the effectiveness of combinations of features is presented.

In addition to the discussion of natural features, this report also provides a discussion of methods to slow vehicles. Slowing of vehicles at normal entrance points is of particular importance, because barriers at such points are in most cases less effective than fixed barriers, and, without constraints, a vehicle can attain higher speeds because plant entrance normal roads are paved at such points. Also included is an overview of fixed barrier systems, with particular attention to ditches.

The efficient and economical design of vehicle barriers requires information on the expected maximum speeds at which specific vehicles may be moving when a barrier is encountered. The graphs of maximum vehicle speed versus terrain slope presented in this report can be used as input data in the design of vehicle barriers at licensed sites. Estimates are provided of the speeds of three classes of vehicles as a function of those parameters of natural terrain which have the most significant effects on vehicle speeds. Additional factors which limit vehicle speed, such as vegetation, visibility, and other obstacles, were not included in the parameter study because the benefits they afford are temporary and not generally predictable. The data developed in this study can be utilized to estimate the worst case vehicle threat for use by the vehicle barrier designer.

Streams and ditches constitute natural barriers to vehicles. The data on stream- and ditch-crossing performance presented

in this report can be used to evaluate the efficacy of natural or man-made ditches of specified geometry in preventing threat vehicles from reaching a target. This data can be used to qualify a large number of real-world situations into "GO" or "NO-GO" or "NEED-MORE-DATA" categories.

In order to define the actual limitations to vehicle mobility and speed over terrain adjacent to a specific plant site, it is necessary to make measurements of terrain characteristics adjacent to that site. Practical, inexpensive methods to make limited measurements are available, but the number and type of each measurement may be very large. The data in this report should be useful in reaching decisions on which further measurements (if any) need to be made.

1. INTRODUCTION

The Nuclear Regulatory Commission (NRC) has since its inception been concerned with the effectiveness of security and physical protection systems at licensed facilities. The recent increase in the use of car and truck bombs by terrorist organizations has led the NRC to investigate the adequacy of licensee security against such threats. If present security is deemed inadequate, then methods to enhance security will be necessary. This report, in conjunction with "Security Vehicle Barriers,"[1] provides information on methods to slow down or stop wheeled vehicles used on land.

This report primarily discusses the effectiveness of natural terrain and vegetation that might be indigenous to a particular site in providing natural passive security barriers against vehicle entry and hence the vehicle bomb threat. Naturally occurring features may be capable of stopping vehicles without assistance. In other cases, these features may only slow down approaching vehicles and therefore will need to be augmented by man-made obstacles. Any diminution in an approaching vehicle's speed in general increases the effectiveness of subsequent barriers. The effectiveness of natural features is presented in two contexts. First, certain natural features are discussed separately, and data on their effectiveness are presented. Second, the effectiveness of combinations of features is presented.

In addition to the discussion of natural features, this report also provides a discussion of methods to slow vehicles. Slowing of vehicles at normal entrance points is of particular importance, because barriers at such points are in most cases less effective than fixed barriers, and, without constraints, a vehicle can attain higher speeds because normal plant entrance roads are paved at such points. Also included is an overview of fixed barrier systems, with particular attention to ditches. A more detailed discussion of man-made barriers is contained in Reference 1.

2. NATURAL FEATURES AS BARRIERS

The U.S. Army Waterways Experiment Station (WES), located in Vicksburg, Mississippi, has been involved for many years in the analysis of vehicle mobility problems for the military. In support of this effort, models have been developed that allow the calculation of vehicle performance over specified terrain features and vegetation. Some of these models, along with work reported on by M. G. Bekker,[2] are used to develop the terrain effects described in this report.

McKenzie discusses modeling of vehicle-terrain systems.[3] It is pointed out that the speed a vehicle can attain in a particular situation may be limited by a single factor or by several factors acting in combination. These factors may include

- The maximum pitch or bounce passengers can tolerate
- The inability to overcome or to avoid obstacles
- Inadequate traction in relation to motion resistance from vegetation or soil
- Inadequate vehicle power
- Poor handling by driver

The interaction among these factors is complex; useful estimates of vehicle speed are best made through computer simulation.

The external forces acting on a vehicle include

- Air resistance
- Traction force
- Resistance because of vertical soil displacement
- Resistance because of forward soil displacement
- Slope resistance
- Inertia resistance
- Vegetation resistance

In addition to these environmental factors, the characteristics of the vehicle's power train affect vehicle performance. (The power train, which consists of the engine, transmission, and differential, provides and transmits power to the vehicle's

drive wheels.) The vehicle is often limited by the torque developed by the engine and transmission. The power delivered to the drive wheels as a function of vehicle speed is fundamental to the determination of vehicle performance.

The drawbar pull DBP (lb) of a vehicle is defined as

$$DBP = H - R \tag{1}$$

where

H = soil thrust (lb)

R = motion resistance (lb)

Motion resistance is resistance to movement of a vehicle provided by the surface on or through which it moves. Brief descriptions of several models that can be used to calculate some of these factors are included below. The interaction of the results from these or similar models, including the effect of soil characteristics, is being studied in the WES program discussed above.

2.1 Representative Vehicle Data

In the study "Mobility Performance of 1/4- to 10-ton Tactical Trucks and Cargo Carriers in the HIMO West Germany Study Area," 44 vehicles were analyzed to determine their performance in European terrain.[4] (Only 41 of these wheeled vehicles are listed in Table 1, because 3 tracked vehicles were also included in the study.) Besides the vehicles in the 1/4- to 10-ton range, several tractor-trailer combinations are included. In order to determine vehicle performance, the vehicle tractive force as a function of vehicle speed must be specified. This relationship for some of the vehicles in the 1/4-, 5-, and 10-ton classes is shown in Figures 1 through 3. Major breaks in each curve's shape are due to gear shifting. It is clear that vehicles in the same weight class can have quite different performances solely on the basis of the tractive force available at a specified speed.

The vehicle's ability to overcome obstacles in its path is dependent on the force available to the vehicle at that moment. This force is in turn dependent on the speed of the vehicle and the nature of the surface over which the vehicle is traveling. The tractive-force-versus-speed curves indicate that the tractive force available to the vehicle increases as the vehicle speed decreases; however, the kinetic energy of the vehicle is a function of the square of the vehicle's speed. Thus, for any given situation, the vehicle's performance is based on the tractive force available to the vehicle and its kinetic energy.

Table 1

Vehicle Characteristics

Vehicle	Class*	GVW (lb)	Power-to-Weight Ratio (hp/ton)	Minimum Ground Clearance (in.)	Approach Angle (°)	Departure Angle (°)	Wheel-base (in.)	Center of Mass to Front Wheel (in.)	Width (in.)	Length (in.)
M151A2 4x4	A	3200	44.4	9	66	37	85	45	64	133
TARADCOM 3/4-ton HMTT 4x4	A	6762	51.2	12.2	90	60	124	68	91	178
Dodge Ramcharger 4x4	A	6740	41.5	8.8	43	29	106	52	79	184
American Motors CJ5 4x4	A	4475	67	9	54	43	84	48	60	139
FMC XR311 4x4	A	5890	73	13	69	56	121	68	74	168
M880 4x4	B	7748	42	7	37	28	131	83	80	210
M890 4x4	B	7317	38.8	7	37	28	131	83	80	219
M561 6x6	B	9172	22.5	14.6	62	52	125	90	84	230
M35A2 6x6	C	17980	36.8	11	48	40	155	102	96	268
M35 PIP 6x6	C	19450	21.6	14	46	40	154	101	96	268
Ford Ln8000 4x4	C	19200	22.3	11	46	36	163	96	96	252
Dodge W600 4x4	C	18920	22	10.5	52	47	174	93	96	259
International Harvester IH1750 4x4	C	20500	18.5	10	61	33	170	101	96	271
M49A2C 6x6 (fuel Servicing)	C	20025	14	12.9	40	40	154	93	93	277
German Unimog 416 4x4	C	13450	16.3	17.3	45	46	111	67	123	200
Ford LMT8000 6x4	D	27300	16.1	10	34	49	176	123	96	279
Ford LMT8000 6x6	D	27960	15.7	10.8	44	47	176	118	96	281
International Harvester IH1850 6x4	D	28320	15.5	10	46	58	180	123	96	272
International Harvester IH1850 6x6	D	29380	15	10	62	65	180	123	96	272
TARADCOM 5-ton HMTT 8x8	D	28000	21.4	15	50	73	148	100	98	282
German 5-ton MAN 4x4	D	31394	16.9	15.9	45	40	169	93	98	313
M813A1 6x6	D	32080	15.6	11.5	46	32	181	126	96	300
M813 PIP 6x6	D	34200	14.6	10.5	54	34	178	118	96	326
M656 8x8	D	25835	16.3	12	50	62	148	110	96	276
M816 6x6 (wrecker)	D	43529	11.5	11.6	35	38	179	151	98	345
M813A1 6x6 (Fuel Pods)/M105A2 (Fuel Pod)	D	38990	12.8	11.5	35	32	179	121	102	480
TARADCOM 10-ton HMTT 8x8	E	46500	18.9	14	55	53	190	124	96	339
TARADCOM 10-ton HMTT 8x8 (Wrecker)	E	42500	20.7	14	55	35	[illegible]	138	98	366
TARADCOM 10-ton HMTT 8x8 (Tanker)	E	44000	20	14	55	53	190	124	96	348
Lockheed TDW902 8x8	E	52800	16.3	14	54	54	214	138	112	376
German 10-ton MAN 8x8	E	51455	13.7	16.5	40	45	211	48	98	394
M520E1 GOER 4x4	E	43210	9.9	24	35	35	235	111	108	375
M559 GOER 4x4 (Tanker)	E	46370	9.2	24	35	35	235	117	112	395
M559 GOER 4x4 (Wrecker)	E	46540	9.2	24	35	35	235	109	108	408
British Vauxhall MMLC 4x4	E	35935	11.2	13.9	41	35	170	96	98	265
M757 8x8/M870 (12-ton)	F	55935	7.5	12	50	45	148	116	96	694
M916 6x6/M870 (12-ton)	F	65470	12.2	11.6	42	45	186	149	98	704
M818 6x6/M127A1C (12-ton)	F	58930	8.5	11.5	35	90	167	122	146	525
M818 6x6/M271 Modified (22-1/2-ton)	F	83355	6	11.5	35	90	167	115	97	612
M818 6x6/M127A1C (22-1/2-ton)	F	79930	6.3	11.5	35	90	167	125	97	525
M920 8x6/M871 Modified (22-1/2-ton)	F	89768	8.9	11.6	42	45	181	168	151	646

*Explanation of vehicle classes: A = Cargo 1/4 to 3/4 ton; B = Cargo 1-1/4 ton; C = Cargo 2-1/2 ton; D = Cargo 5 ton; E = Cargo 8 to 10 ton; F = Tractor/Trailer

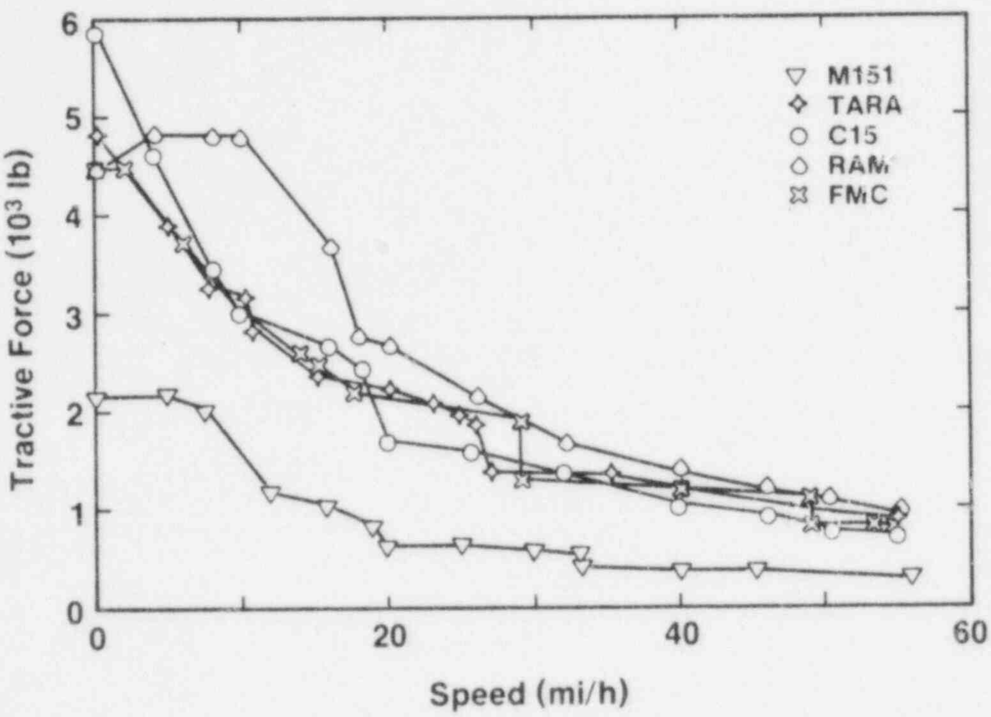

Figure 1. Tractive Force vs Speed: Light Trucks

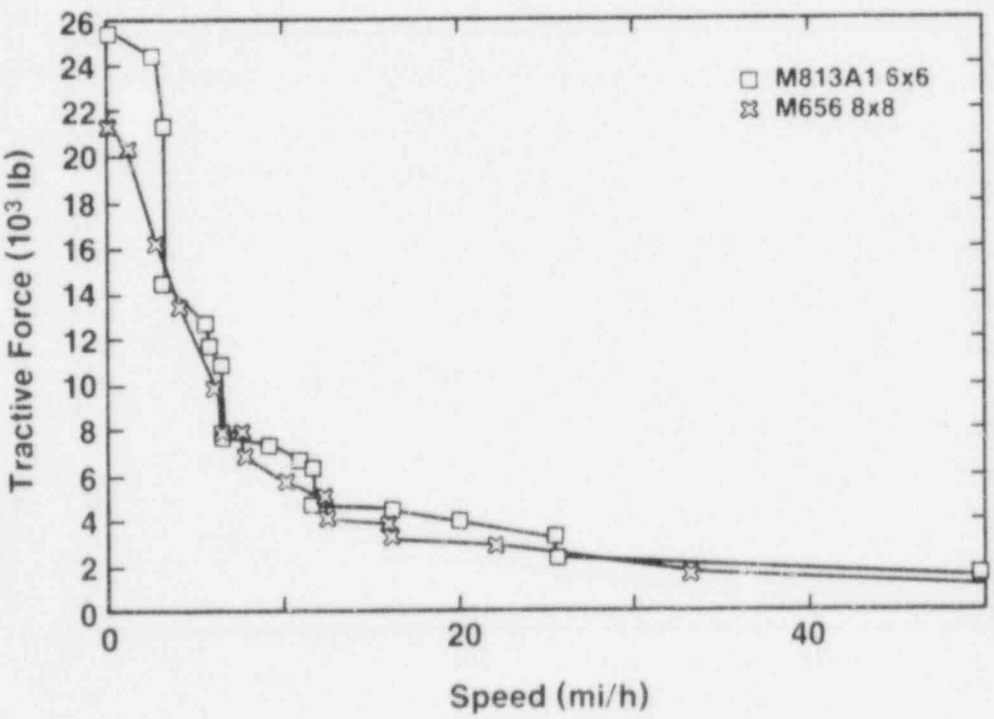

Figure 2. Tractive Force vs Speed: Medium Trucks

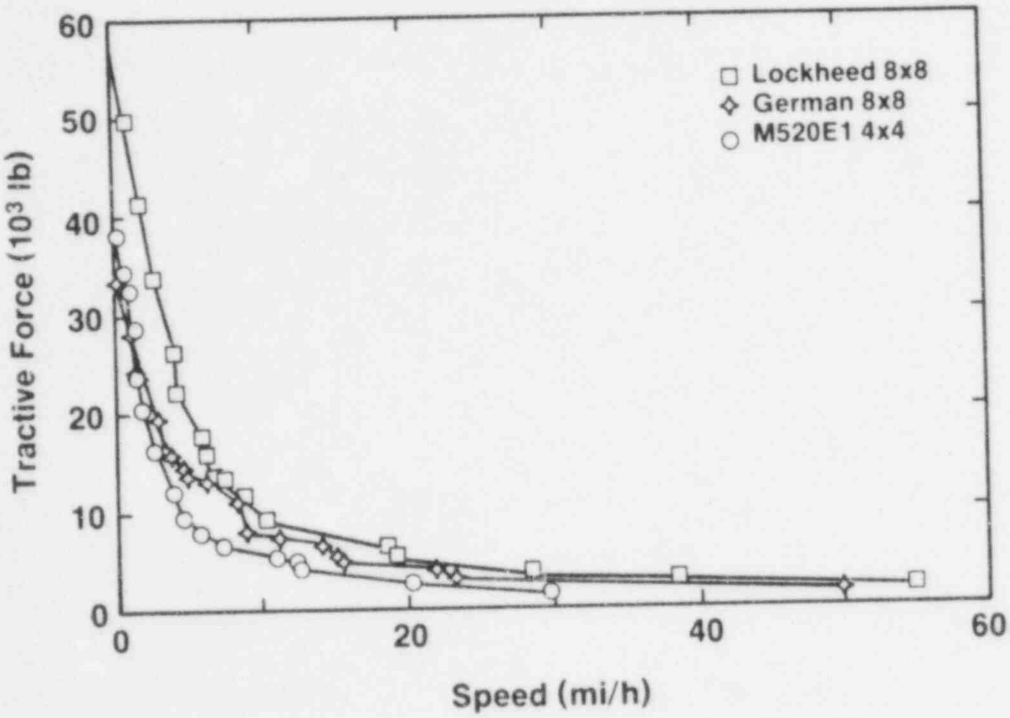

Figure 3. Tractive Force vs Speed

2.2 Trees as Barriers

The use of natural vegetation as a means of stopping, or at least slowing down, vehicles has several attractive features. The cost of using existing vegetation would be small and would be reasonable if new vegetation were planted. The aesthetics of the site would not be degraded and possibly even improved. The main problem associated with use of such barriers is the nonpermanence of vegetation. Unless the vegetation is under the control of the licensee, it could be removed without the licensee's consent. The time required to install compensatory barriers might result in an unacceptable vulnerability. This would be true particularly if the vegetation were removed as a result of malevolent action. Nevertheless, vegetation may be useful and should be considered.[5]

A determination of the minimum force required to fail a single tree is used to establish whether the strength of the leading edge of the vehicle or the driver's tolerance to horizontal acceleration will be exceeded. An empirical equation derived from test results is used to determine the force F_n (lbs) required to fail a single tree:

$$F_h = \frac{40 - H_p}{2} D_s^3 \qquad (2)$$

where

D_s = tree stem diameter (in.)

H_p = pushbar height of vehicle (in.)

This force is compared to the strength of the vehicle's leading edge to estimate whether failure might occur. In addition, the number of g's the driver will experience is estimated by dividing this force by the weight of the vehicle. Figures 4 through 6 contain curves showing the force required to fail trees with diameters from 1 to 20 in. The effect of bumper height is also considered.

If the vehicle and driver can survive the force required to fail a tree, the vehicle may be able to override the tree. The speed at which a vehicle can override a single tree is a function of the force resisting the override. This resisting force should be added to other resisting forces acting on the vehicle. The average force F_o (lbs) required to override a single tree is

$$F_o = W_t/D_x \qquad (3)$$

where

W_t = work required to override single tree (ft-lb)

D_x = average distance between trees (ft)

The work W_t (ft lbs) required to override a single tree is

$$W_t = 100(D_s)^3 \qquad (4)$$

where D_s is as defined above for Eq. 2. This is an empirical relationship derived from field work. The total resistant forces acting on a vehicle are used with the vehicle's tractive force-speed curve to determine the vehicle's maximum speed. Figures 7 and 8 indicate the force required for several values of distance between trees (D_x) and for tree diameters from 1 to 20 inches.

The force with which a tree resists overriding is added to other resistant forces acting on the vehicle, so as to allow determination of whether the tractive force available to the vehicle is capable of continuing vehicle motion. For the vehicle to continue, the tractive force available plus the vehicle's kinetic energy must equal a force greater than that required to fail a single tree.

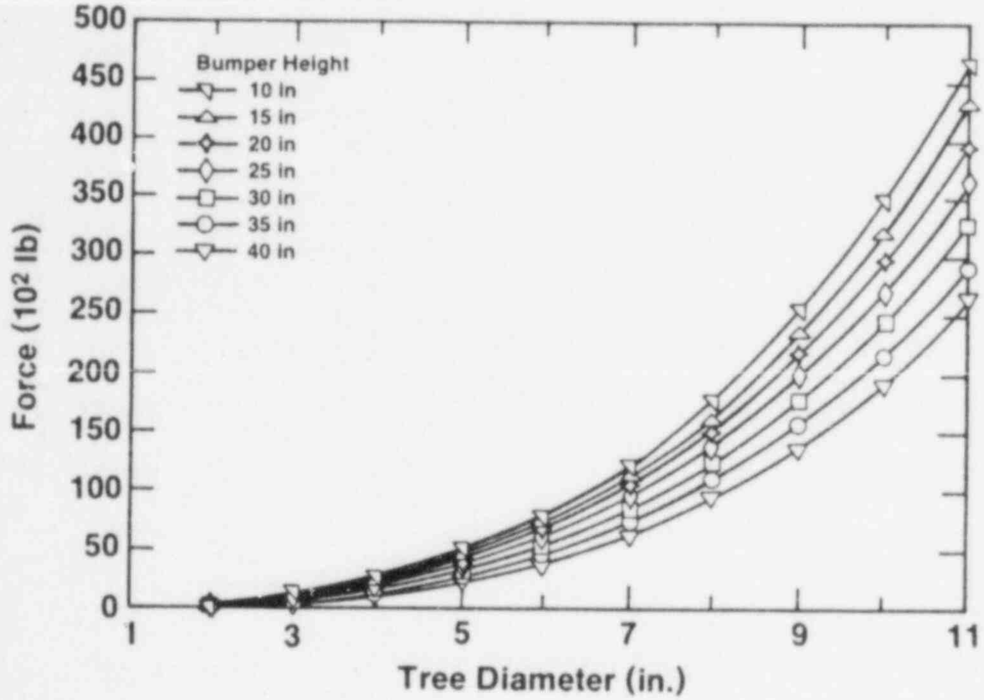

Figure 4. Force to Fail Single Tree vs Tree Diameter: 1- through 11-in. Diameter; Various Bumper Heights

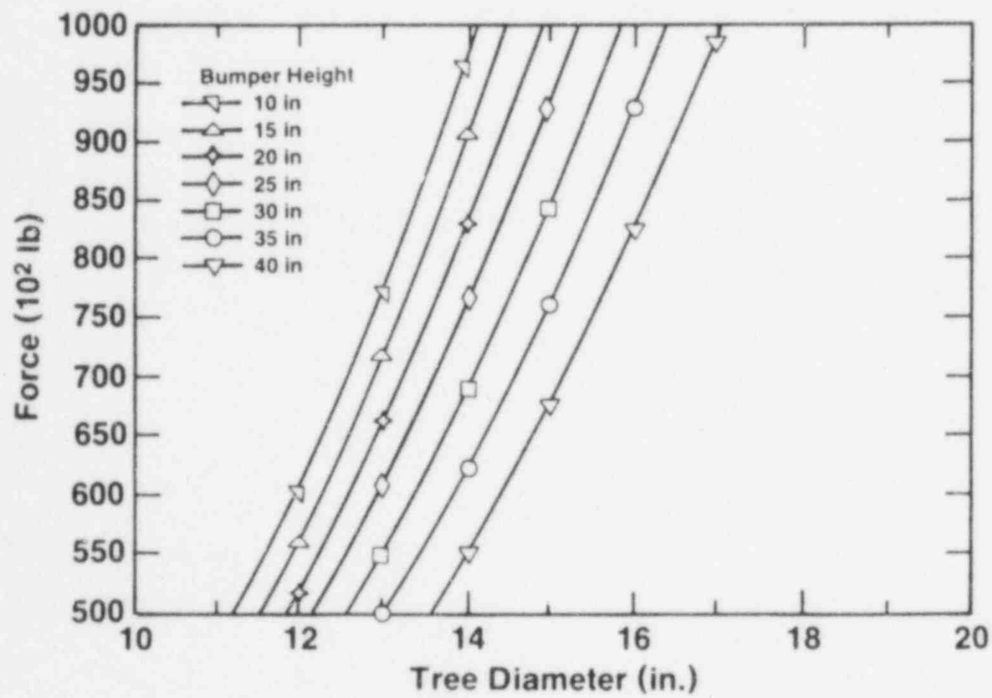

Figure 5. Force to Fail Single Tree vs Tree Diameter: 10- through 20-in. Diameter; 50000- to 100000-lb Force; Various Bumper Heights

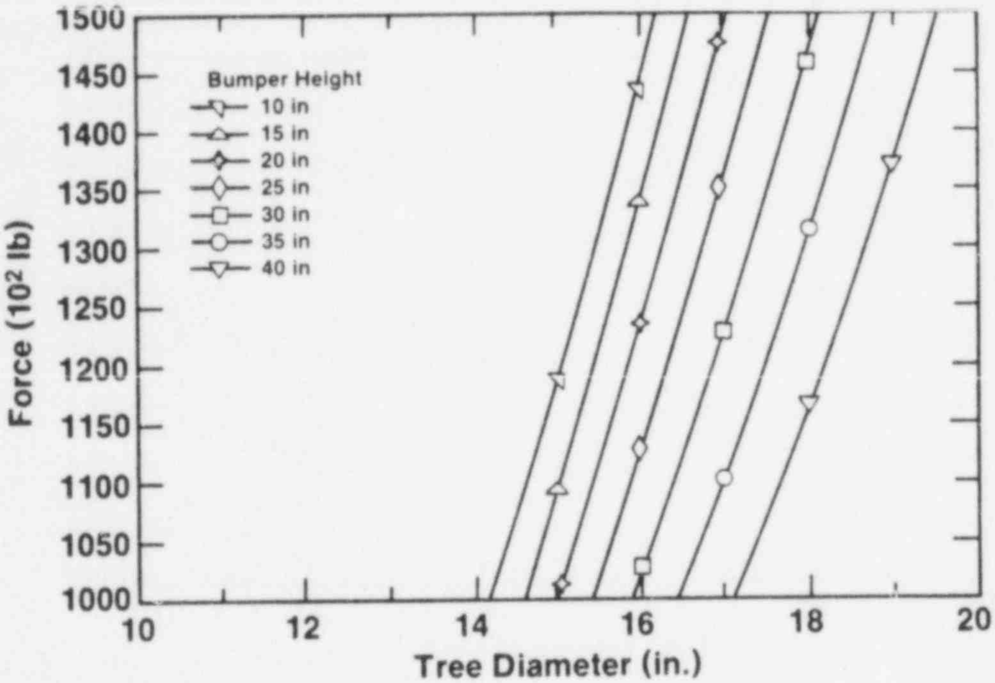

Figure 6. Force to Fail Single Tree vs Tree Diameter: 10- through 20-in. Diameter; 100000- to 150000-lb Force; Various Bumper Heights

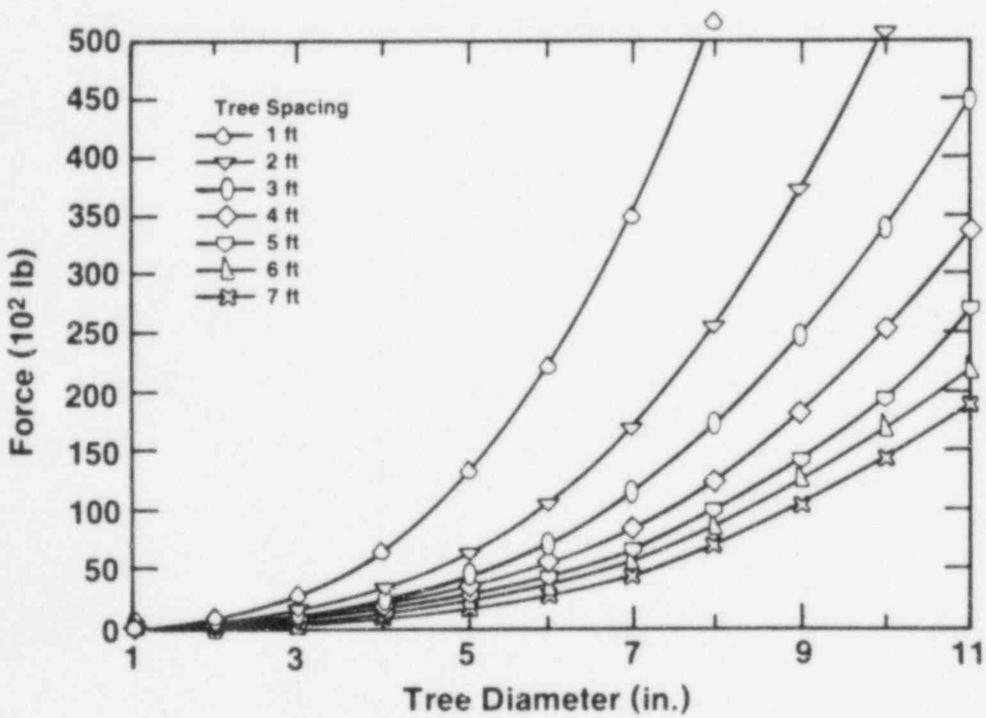

Figure 7. Override Force vs Tree Diameter: 1- through 11-in. Diameter; Various Tree Spacings

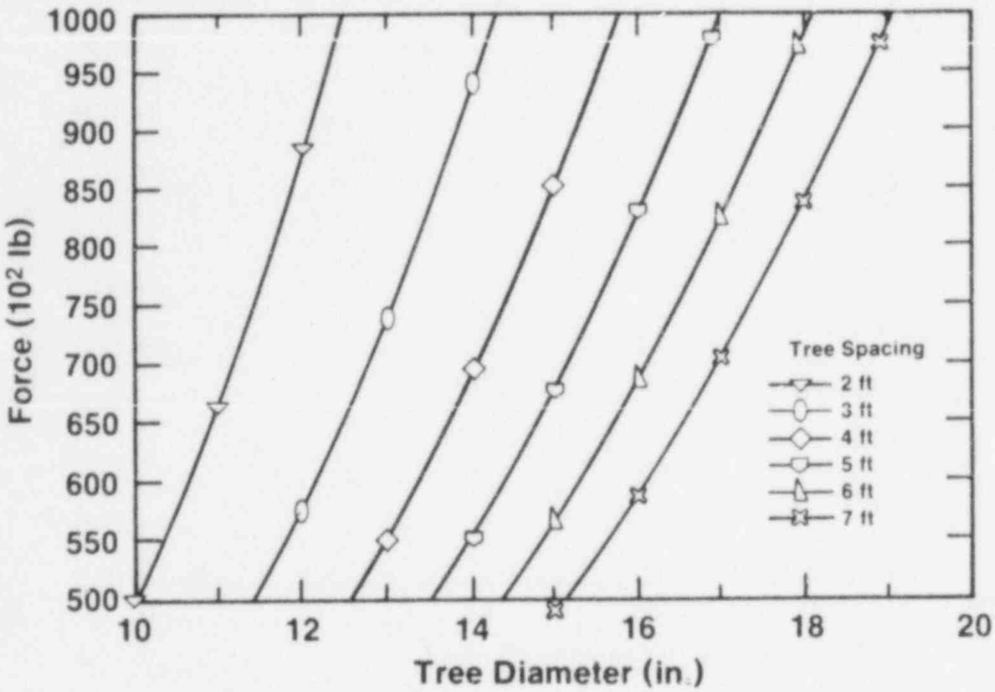

Figure 8. Override Force vs Tree Diameter: 10- through 20-in. Diameter; Various Tree Spacings

The relation for the minimum tractive force T (lbs) required to override a single tree is

$$T = \frac{W_p}{5.8} - \frac{W}{11.6gV^2} \tag{5}$$

where

W_p = work required to fail a tree (ft-lb)

W = weight of vehicle (lb)

g = gravitational constant (ft/s^2)

V = vehicle speed (ft/s)

The value of 5.8 is the assumed average distance (in feet) a vehicle travels to fail a tree. The work W_p (ft lbs) required to fail a tree is

$$W_p = 56(D_s)^3 \tag{6}$$

where D_s is the tree stem diameter in inches. In order for a vehicle to fail a tree, the tractive force available to the

vehicle must be greater than T. Figures 9 and 10 give the value of T for vehicles weighing 5000 and 30000 lbs, respectively. Each figure shows tractive force for several values of speed. The tree stem diameters vary from 3 to 21 in.

2.3 Natural Slopes as Barriers

Natural slopes available around the licensee site could be either an advantage or a disadvantage for protection against vehicle threats. If the site has a slope leading up to the buildings, the slope could limit the vehicle's speed; however, if the slope leads down to the building area, it could accelerate a vehicle. A commonly used slope-climbing model treats a vehicle on a soil slope as a problem in simple static friction.[5] The coefficient of friction is considered to be the drawbar-pull-to-weight ratio the vehicle can develop in the same soil on level ground. Drawbar pull is defined as the force available for external work in a direction parallel to the surface of the soil over which the vehicle is moving. Under these assumptions, the DBP developed by a vehicle on a slope DBP_s (lb) is given by

$$DBP_s = \frac{DBP_\ell}{W} W \cos \theta - W \sin \theta \quad (7)$$

where

DBP_ℓ = drawbar pull on level (lb)

W = vehicle weight (lb)

θ = angle of slope (°)

Values of DBP_s for vehicles weighing 5000, 30000, and 60000 lb, respectively, are shown in Figures 11 through 13. The slope angles are between 0° and 50°, and the DBP on level ground is as indicated for each vehicle.

The maximum negotiable slope angle (θ_{max}) corresponding to DBP_s = 0 is then

$$\theta_{max} = \text{aictan}\left(\frac{DBP_\ell}{W}\right) \quad (8)$$

2.4 WES Obstacle-Traction Model

The obstacle-traction model can be used when it has been determined that a vehicle is not prevented from traversing the obstacle because of the interplay of vehicle-obstacle geometry.[5] The wheelbase, front and rear overhang, and ground clearance of the vehicle will determine, in conjunction

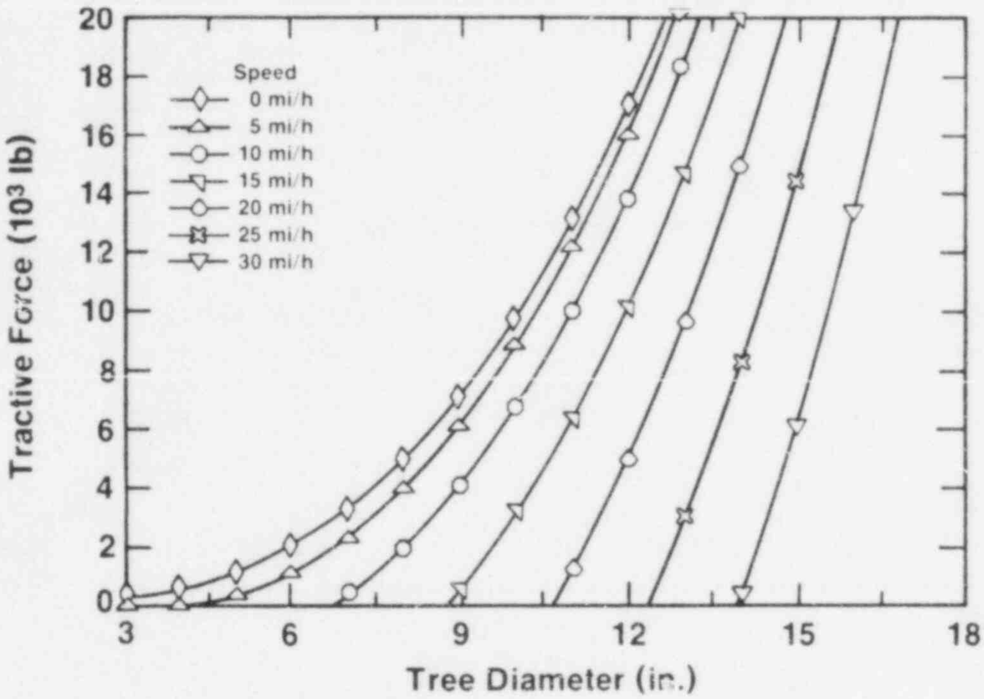

Figure 9. Tractive Force vs Tree Diameter: 5000-lb GVW; Various Speeds

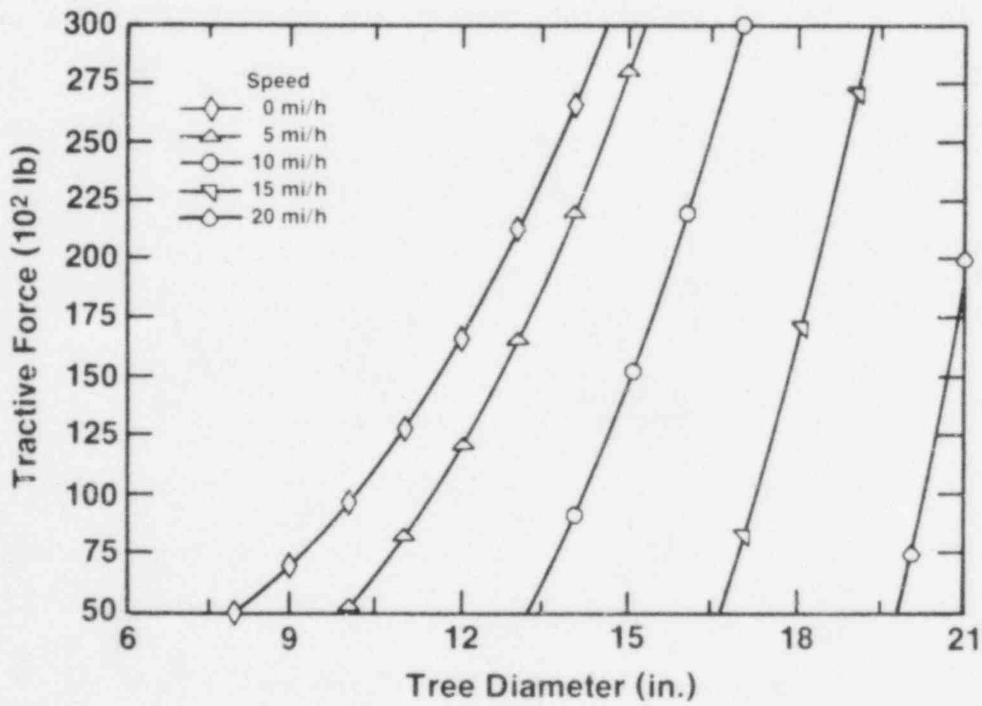

Figure 10. Tractive Force vs Tree Diameter: 30000-lb GVW; Various Speeds

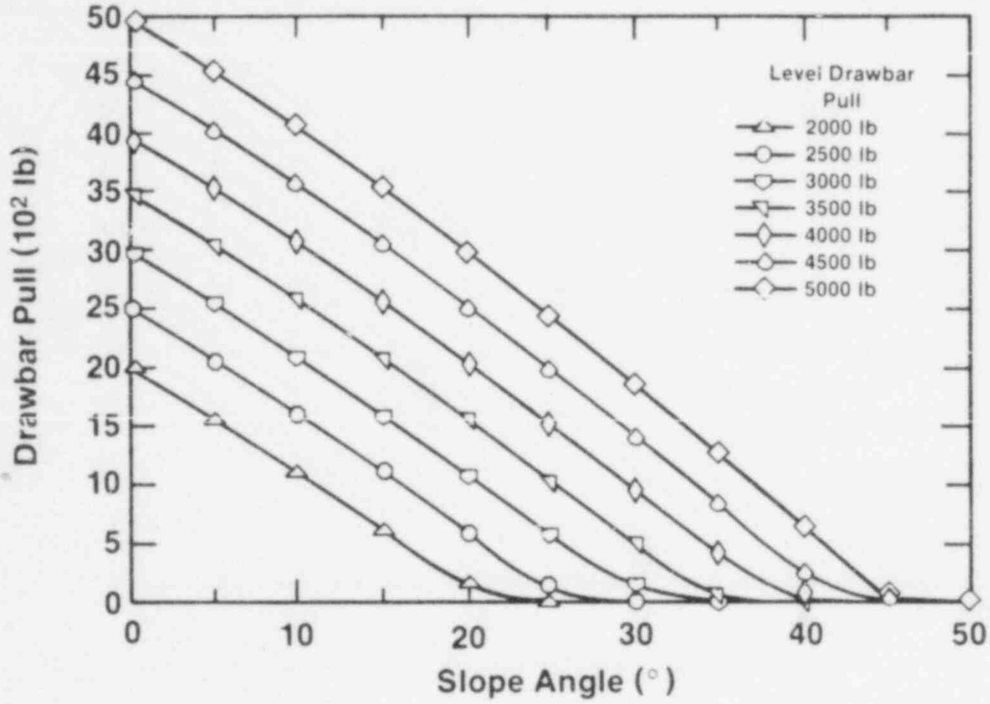

Figure 11. Drawbar Pull vs Slope Angle: 5000-lb GVW; Various Level Drawbar Pulls

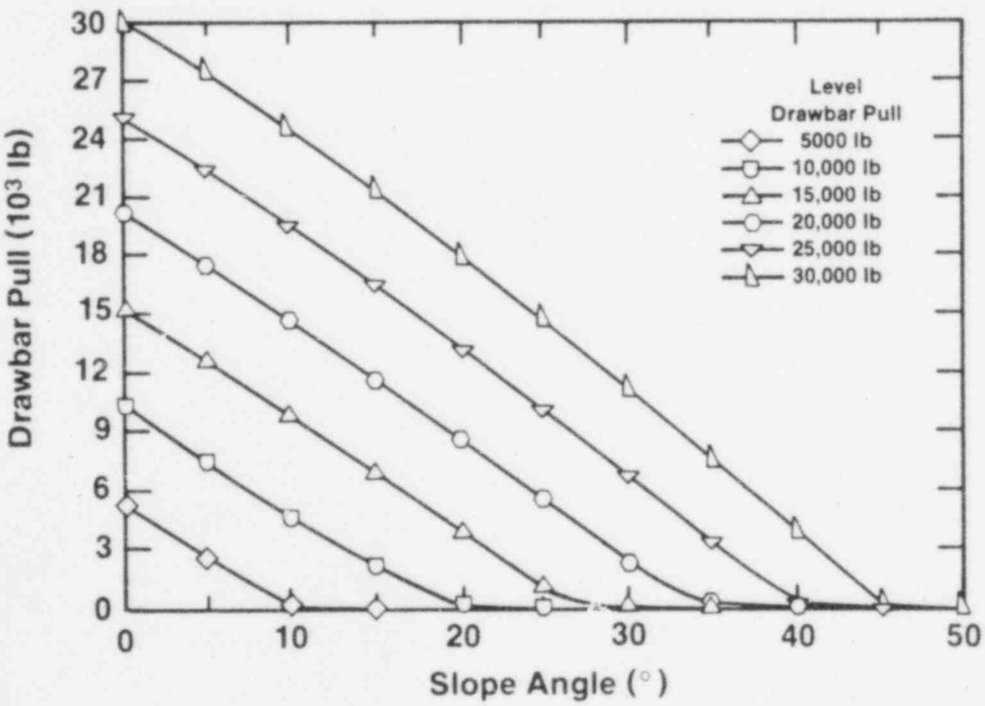

Figure 12. Drawbar Pull vs Slope Angle: 30000-lb GVW; Various Level Drawbar Pulls

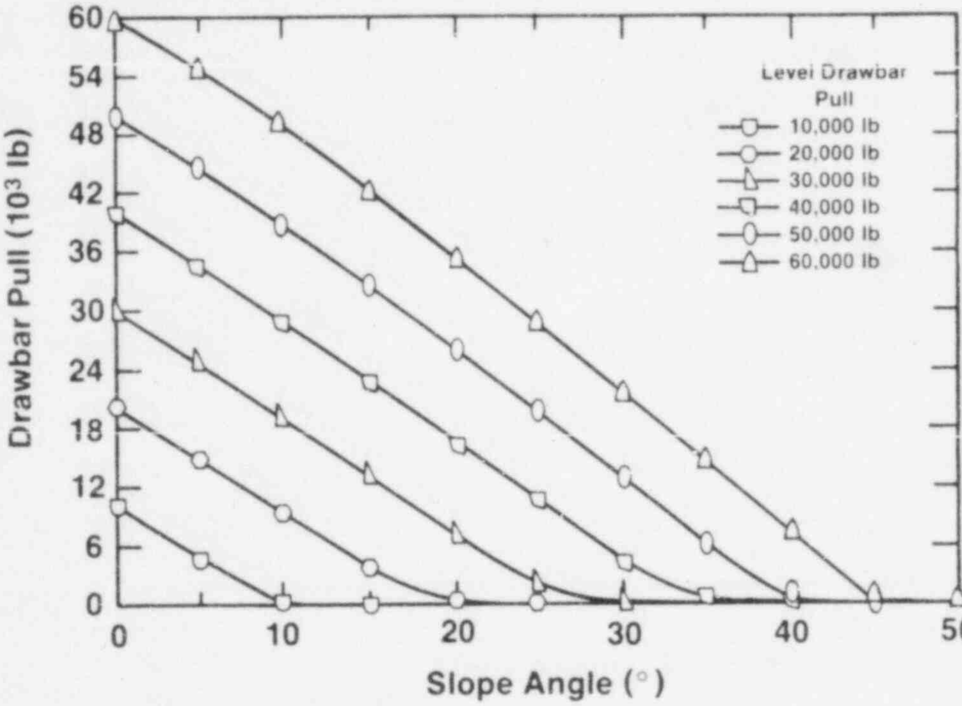

Figure 13. Drawbar Pull vs Slope Angle: 60000-lb GVW; Various Drawbar Pulls

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with the obstacle's dimensions, whether the vehicle will be unable to cross the obstacle (see Hang-Up and Nose-In Failure, Sections 2.7 and 2.8). The minimum force required and the maximum force a vehicle can develop crossing an obstacle at maximum attitude angle are given by the following equations:

$$F_{mr} = \frac{W}{n \sin \alpha} \quad (9)$$

where

F_{mr} = minimum force required (lb)

W = gross vehicle weight (lb)

n = number of axles

α = maximum attitude angle attained in crossing obstacle (°)

$$F_{md} = DBP_{\ell}(\cos \alpha) \quad (10)$$

where

F_{md} = maximum force that can be developed (lb)

DBP_{ℓ} = maximum drawbar pull on level surface (lb)

If the minimum force required is greater than the maximum force available, the vehicle will be unable to cross the obstacle. (Note the similarity to the slope model.)

2.5 WES Override Speed Model

The speed at which a vehicle can override an obstacle is determined by the force resisting the override. This force resisting override can be added to other resisting forces, all of which act on the vehicle. The override force is determined by dividing the work required to override the obstacle by the average distance between obstacles.[5] The equation used is

$$F_{om} = \frac{WH_o}{12D_o} \qquad (11)$$

where

F_{om} = average force required to override obstacles (lb)

W = weight of vehicle (lb)

H_o = height of obstacle (in.)

D_o = average distance traveled between obstacles (ft)

The average distance traveled between two obstacles is D_o determined by counting the number of obstacles in a circular area and then using the following relation:

$$D_o = \frac{\pi D^2}{4wn} \qquad (12)$$

where

D = sample cell diameter (ft)

w = vehicle width (ft)

n = number of obstacles in sample

2.6 Ditch/Mound-Vehicle Interaction

There is a great variety in the forms and sizes of features that may stall a vehicle. Bekker points out, however, that by looking only at pertinent obstacle elements that produce given modes of failure, it is possible to analyze the problem.[2] If one ignores vehicle failure due to problems in stability or traction, then the vehicle's possible failure can be due only to the interrelation between the vehicle and obstacle

geometry. There are two basic modes of failure to clear an obstacle. The first is hang-up failure, where the bottom of the vehicle interferes with the obstacle. The second is nose-in failure, where the nose or rear end of the vehicle interferes with the obstacle (Figure 14).

Any conceivable concave or convex obstacle can be seen to consist of intersecting two-surface configurations. Furthermore, obstacles can be either of two types: step-down or step-up. These two types combined form either an embankment or a ditch. The vehicle dimensions in relation to those of the obstacle determine the obstacle's effectiveness. The most significant vehicle dimensions are

- Wheel diameter
- Wheelbase
- Ground clearance
- Front/rear overhang

2.7 Hang-Up Failure

Hang-up failure (HUF) occurs when a vehicle fails to clear an obstacle because of lack of ground clearance. Relationships to determine the interplay of vehicle and terrain parameters were developed by Bekker (Ref. 2), using the following definitions (Figure 14):

W_b = wheelbase of vehicle (in.)

W_d = diameter of vehicle wheels (in.)

H_g = ground clearance of vehicle (in.)

β = slope of bank (°)

If the vehicle's ground clearance is less than or equal to the encroachment H_e (in), then HUF will occur.

$$H_e = \frac{W_d + D_r}{2} - \left[(W_d + D_r)^2 - W_b^2\right]^{1/2} \qquad (13)$$

where

$$D_r = \text{Num/Den} + \left(\text{Num/Den} + \frac{4W_b^4}{\text{Den}}\right)^{1/2}$$

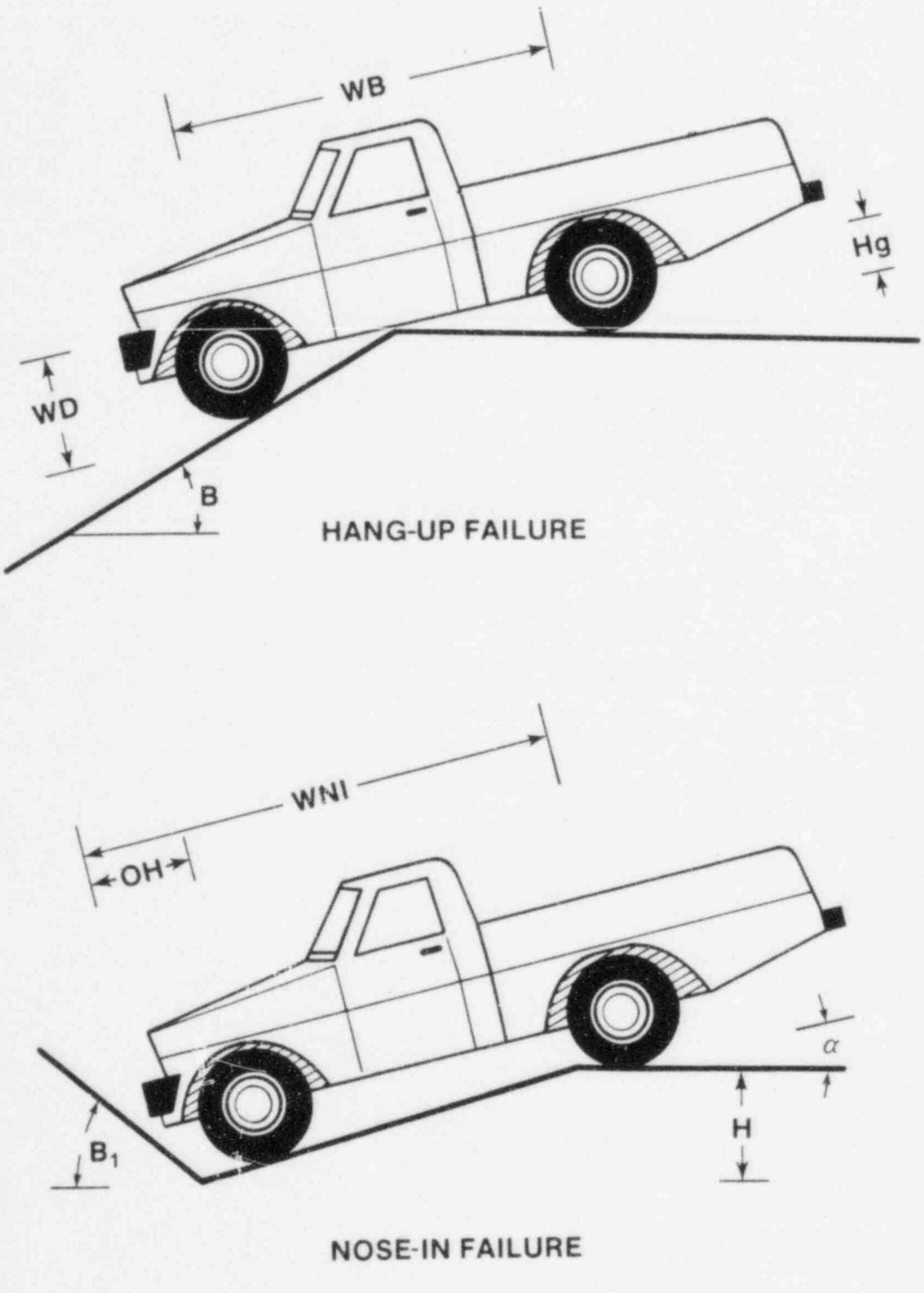

Figure 14. Hang-Up and Nose-In Failures

$$Num = 2W_b^2 W_d^2 (\cos \beta)(1 - \cos \beta)$$

$$Den = 4W_b^2 (\sin \beta)^2 - W_d^2 \left[(\cos \beta)^2 - 2 \cos \beta + 1 \right]$$

The curves in Figures 15 through 19 show the values of encroachment (H_e) for wheelbases of 100, 120, 140, 160, and 200 in. The wheel diameters are 30, 40, 50, and 60 inches. Slope angles vary between 10° and 60°. Using the ground clearance of a vehicle, the degree of slope that will cause HUF for that vehicle can be determined. For instance, a vehicle with a wheelbase of 120 in., a wheel diameter of 40 in., and a ground clearance of 15 in. will suffer HUF on a slope of 30° (Figure 16).

2.8 Nose-In Failure

A vehicle entering a ditch will, in general, encounter HUF first. If it successfully avoids HUF and enters the ditch, it may next encounter nose-in failure (NIF). Bekker developed relationships relating vehicle and ditch parameters to determine NIF.[2] NIF will occur if

$$\frac{W_d}{2 \sin (\beta_1 + \alpha)} \leq W_{b1} - W_b$$

where

β_1 = slope of ditch bottom (°)

α = slope of vehicle's longitudinal axis at failure (°)

W_{b1} = distance from rear wheels to front of vehicle (in.)

with the other parameters defined as for HUF (Figure 14). The angle α depends directly on the geometry of the vehicle and the obstacle. It is determined by solving

$$A(\sin \alpha)(\cos \alpha) + B(\sin \alpha)^2 - C(\cos \alpha) - E(\sin \alpha) = 0 \quad (14)$$

where

$A = W_b(\sin \beta_1)$

$B = W_b(\cos \beta_1)$

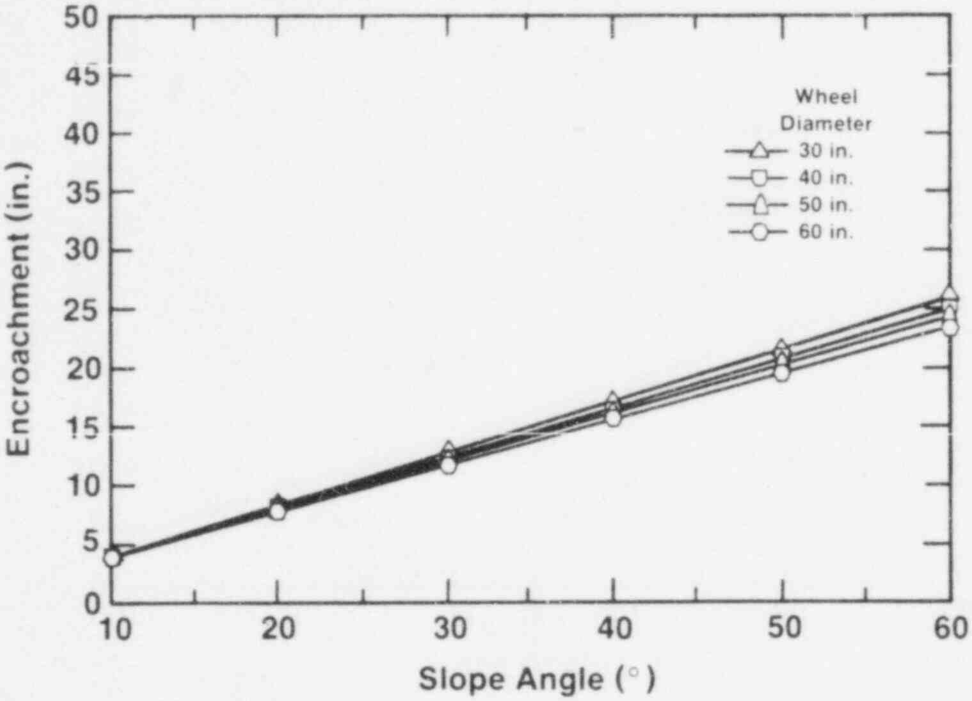

Figure 15. Encroachment vs Slope Angle: 100-in. Wheelbase; Various Wheel Diameters

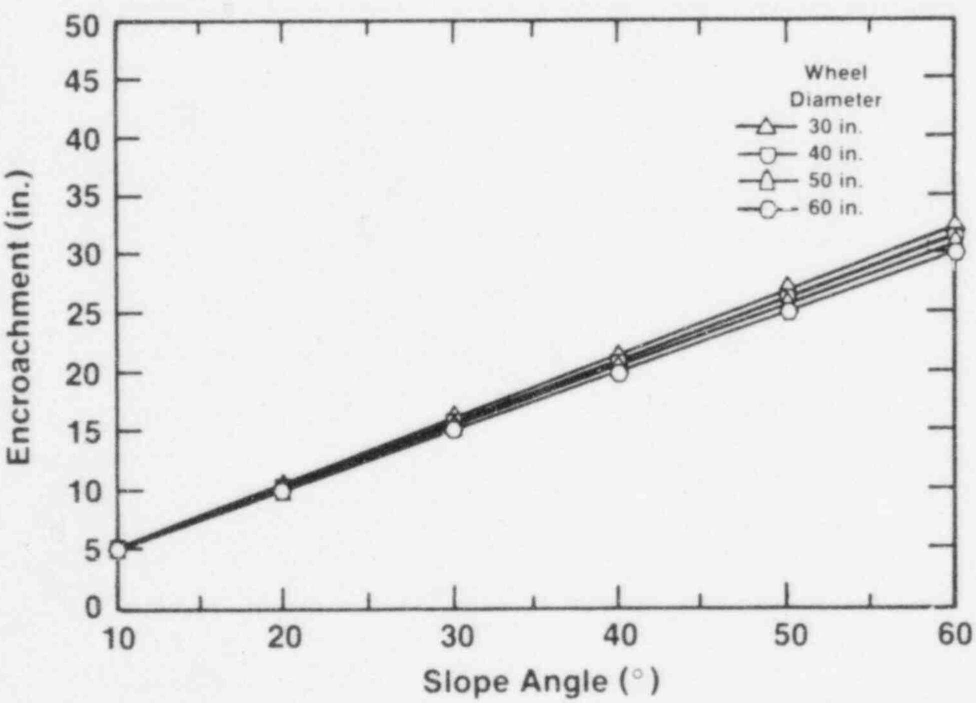

Figure 16. Encroachment vs Slope Angle: 120-in. Wheelbase; Various Wheel Diameters

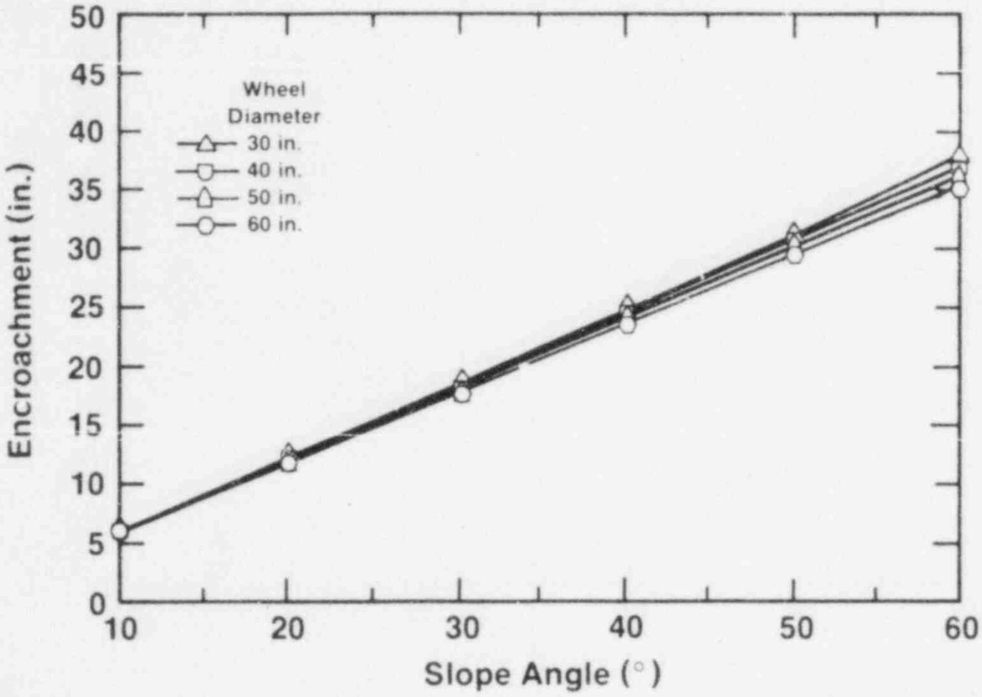

Figure 17. Encroachment vs Slope Angle: 140-in. Wheelbase; Various Wheel Diameters

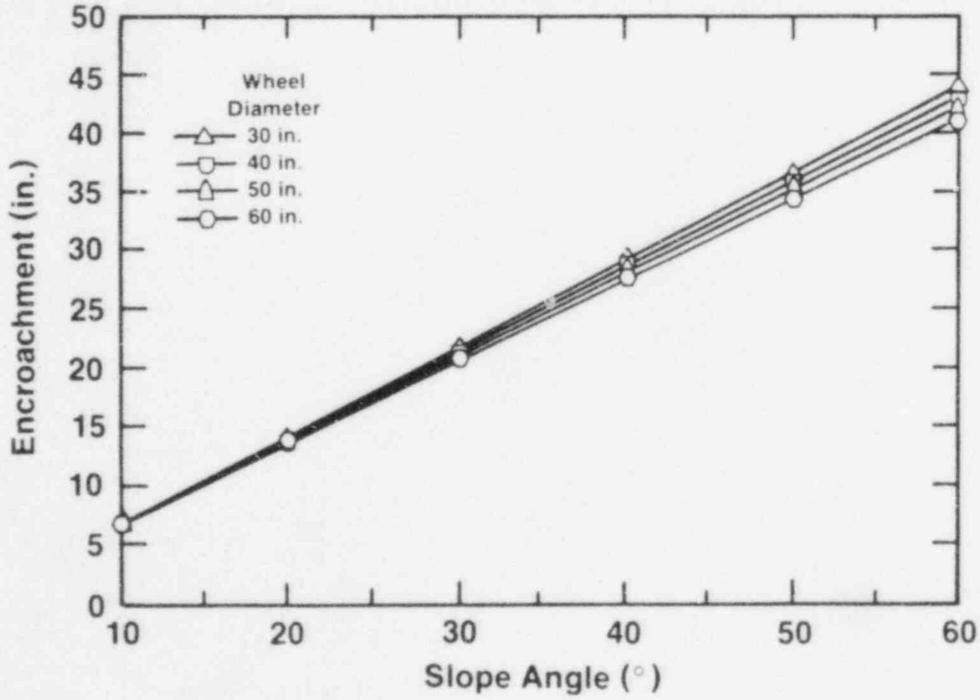

Figure 18. Encroachment vs Slope Angle: 160-in. Wheelbase; Various Wheel Diameters

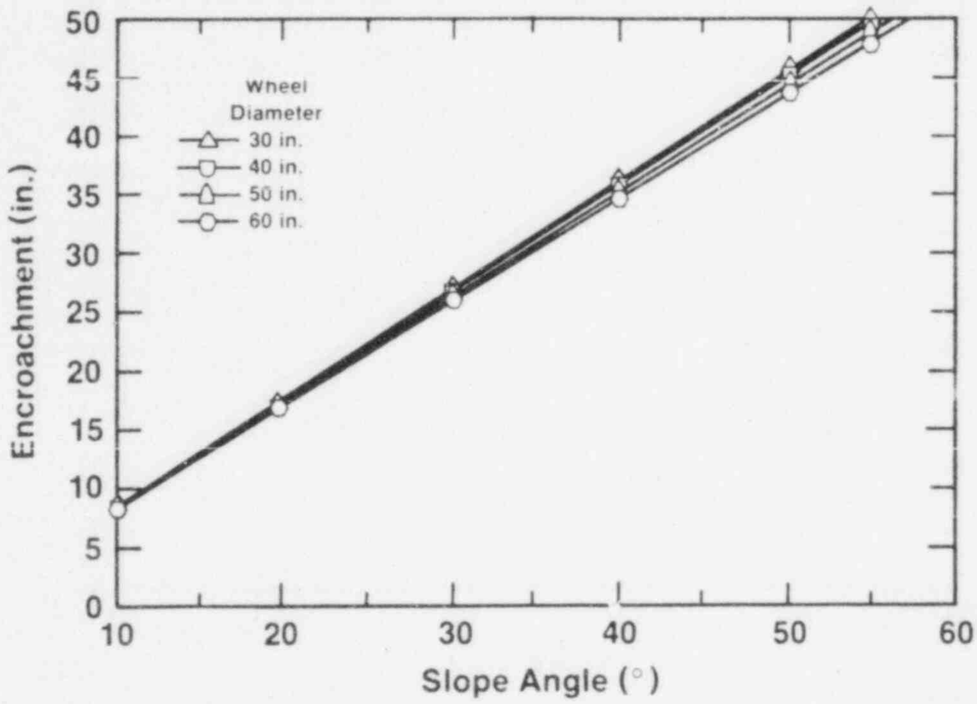

Figure 19. Encroachment vs Slope Angle: 200-in. Wheelbase; Various Wheel Diameters

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$$C = H + \frac{W_d}{2} \sin \beta_1 - \frac{W_d(\tan \beta_1)}{2}$$

$$E = H + \frac{W_d}{2} \cos \beta_1 - \frac{W_d}{2}$$

H = depth of ditch (in.) (Figure 14)

The curves in Figures 20 through 23 show the maximum overhang a vehicle can possess and not be stopped by NIF when negotiating a ditch (bottom slope and height known).

2.9 WES Maneuver Model

Abrupt nondeformable surface irregularities, such as rock outcrops, stumps, boulders, and logs, serve as deterrents to vehicle performance. They will cause the vehicle to slow down to maneuver around the obstacle and perhaps override others. Semiempirical relations have been developed to account for these effects.[5] The area denied to the vehicle by a single obstacle is the area occupied by the obstacle itself plus an area surrounding the obstacle whose width is equal to one-half

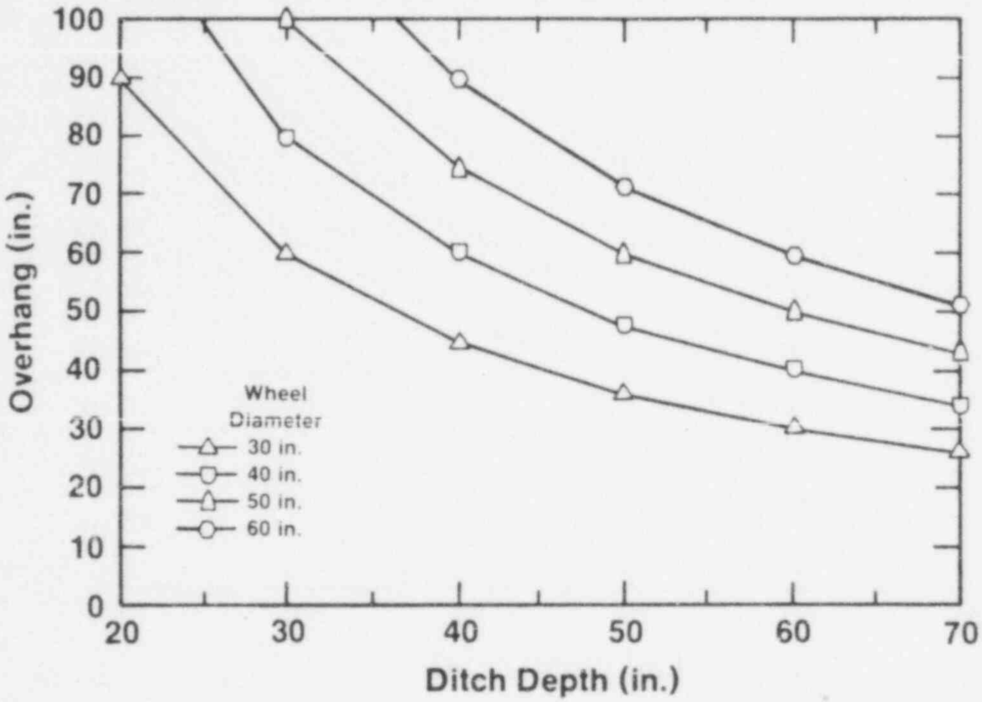


Figure 20. Overhang vs Ditch Depth: 120-in. Wheelbase; 0° Slope; Various Wheel Diameters

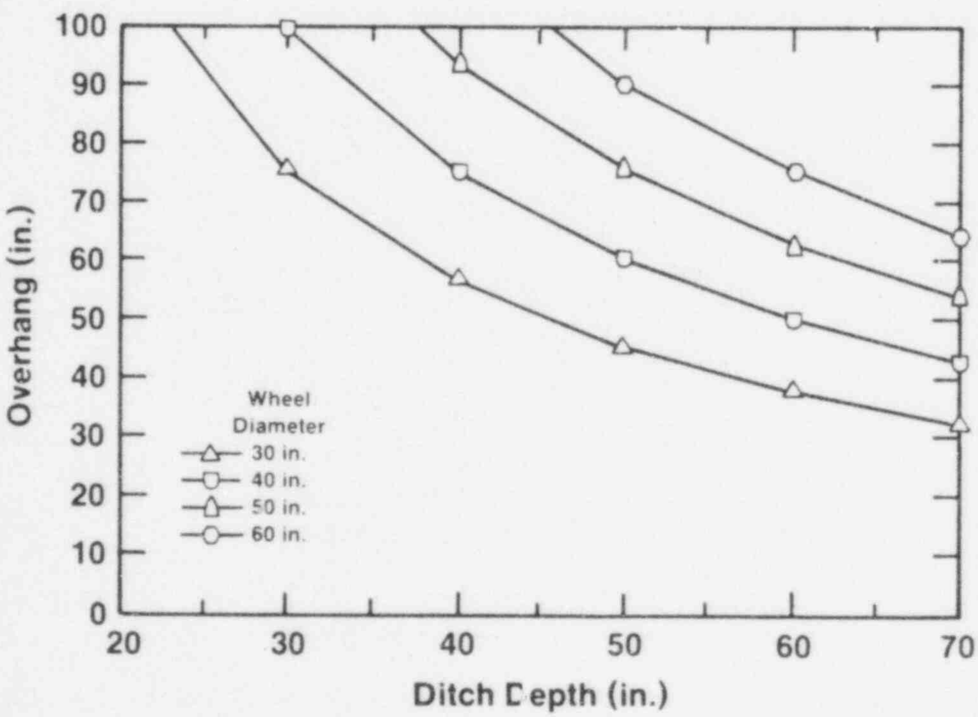


Figure 21. Overhang vs Ditch Depth: 150-in. Wheelbase; 0° Slope; Various Wheel Diameters

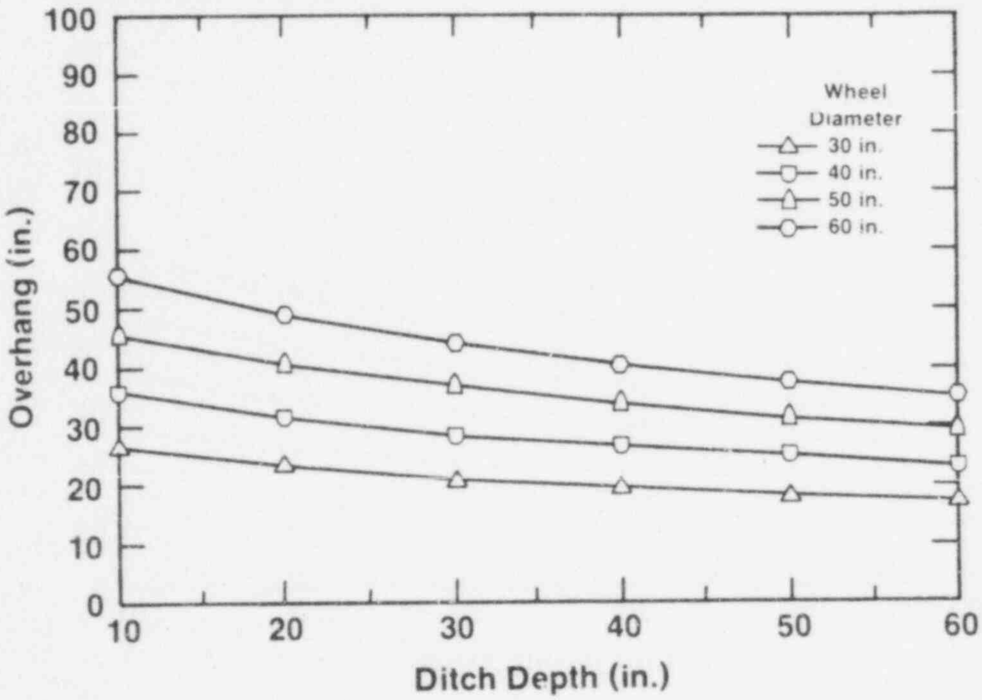


Figure 22. Overhang vs Ditch Depth: 120-in. Wheelbase; 30° Slope; Various Wheel Diameters

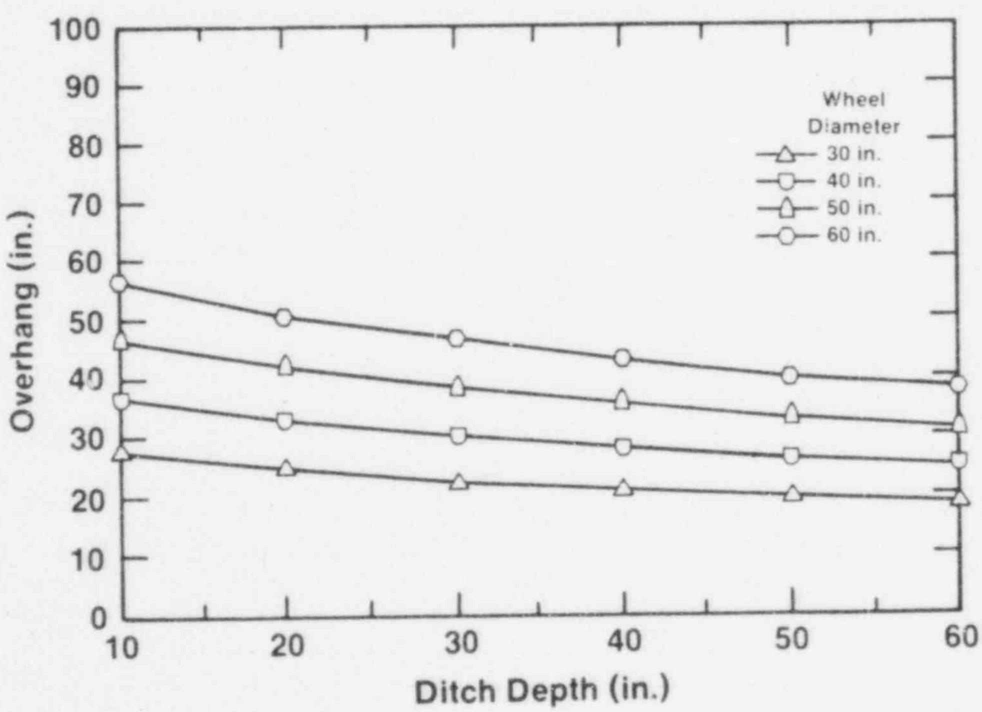


Figure 23. Overhang vs Ditch Depth: 150-in. Wheelbase; 30° Slope; Various Wheel Diameters

the vehicle width (Figure 24). An equation for determining the percentage area denied $\% A_d$ is:

$$\%A_d = \frac{L_o W_o + (L_o + W_o) w + \frac{\pi w^2}{4} n}{A} \times 100 \qquad (15)$$

where

L_o = length of obstacle (ft)

W_o = width of obstacle (ft)

w = width of vehicle (ft)

n = number of obstacles in sample area

A = area of sample (ft^2)

If the vehicle could pass over the obstacle, then twice the width of the vehicle's tractive element is substituted for the vehicle width.

When trees are present, percent area denied is computed by the following equation:

$$\%A_d = \frac{n(D_s + w)^2}{D^2} 100 \qquad (16)$$

where

n = number of tree stems

D_s = stem diameter (ft)

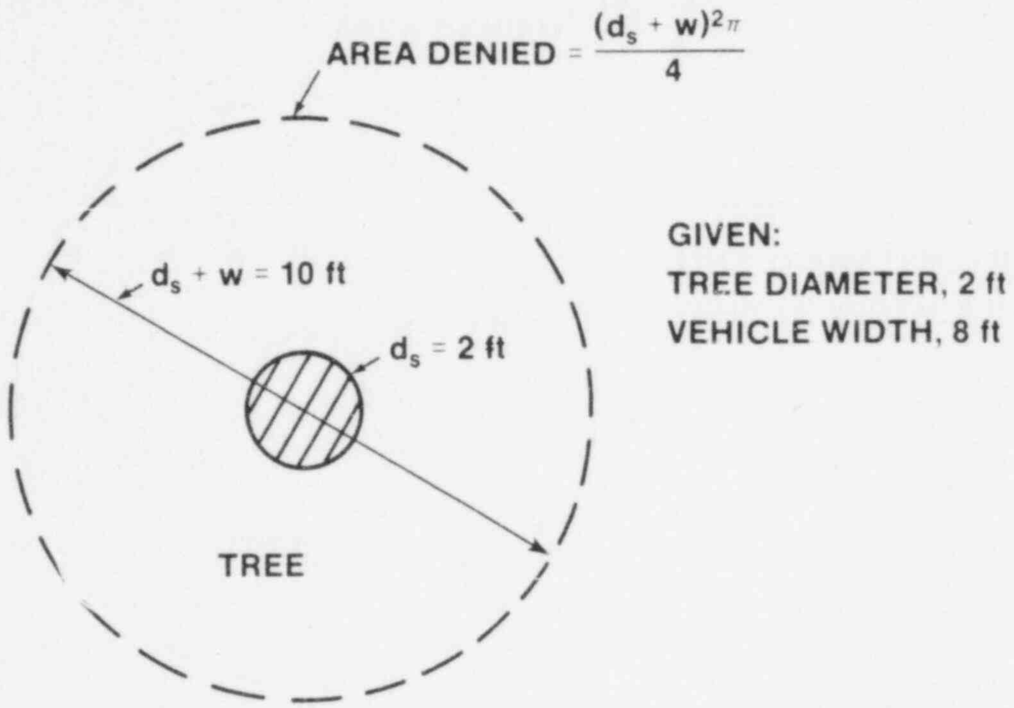
w = vehicle width (ft)

D = sample cell diameter (ft)

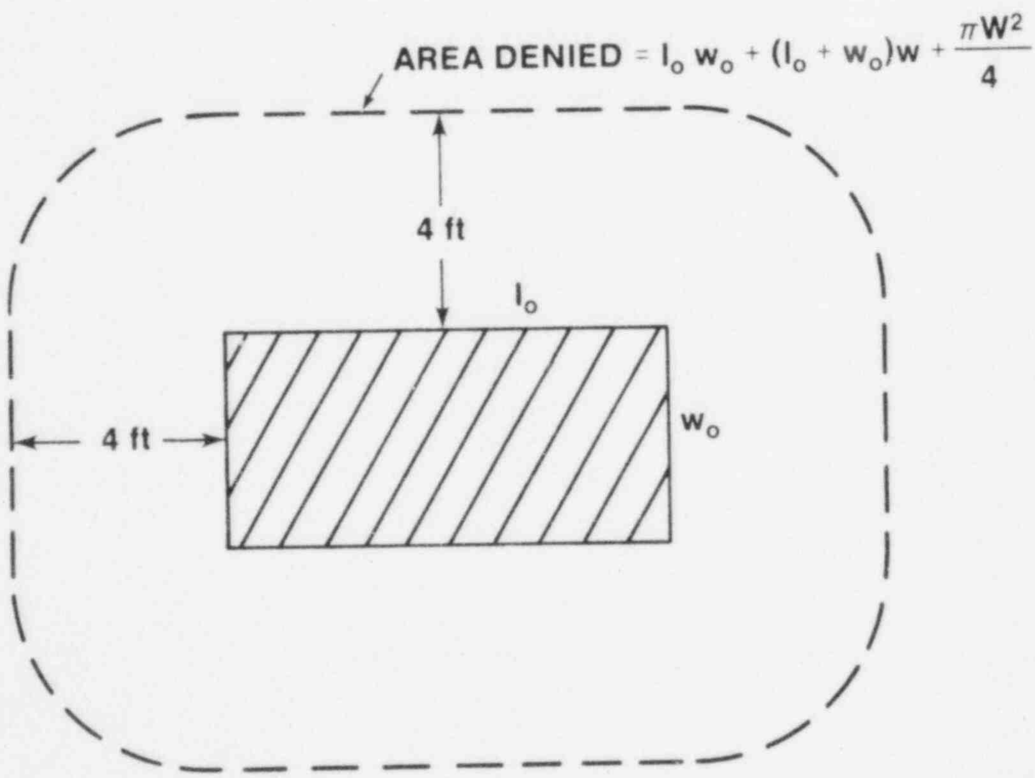
If an area contains a combination of discrete obstacles and trees, the trees in the area of the discrete obstacles are not included in the value of n. The value of n is reduced by the percent area denied by discrete obstacles. The percent areas denied by trees and by other discrete obstacles are added to determine the total percent of denied area.

The vehicle's maneuver speed S_m (mi/h) as a function of percentage of area denied is

$$S_m = \frac{S_o(50 - \%A_d)}{40} \qquad (17)$$



a. TREE



b. OBSTACLE

Figure 24. Examples of Area-Denied Computations for Single Obstacles

where S_o = maximum speed, as controlled by soil, slope, dynamic response, and visibility (mi/h)

Field tests have shown that if the area denied is less than 10%, then the effect on vehicle speed is insignificant. If the area denied is greater than 50%, then the vehicle must override some of the obstacles.

2.10 Ride Dynamics

A ride-dynamics model computes accelerations and motions at the driver's station at a given speed over a specified terrain profile.[6] The profile may be continuously but randomly rough, may consist solely of single discrete obstacles, may contain uniformly spaced obstacles of a specific height, or may be anything in between. The terrain parameters involved are root mean square (rms) elevation and obstacle height and spacing. These are quantified for each spatial area. The driver's tolerance in a continuous roughness situation is a function of the vibrational power being absorbed by the body. The tolerance limit is approximately 6 W of continuously absorbed power for a young American male. However, it has been shown that with sufficient motivation, a young military driver can tolerate more than 6 W for many minutes. The criterion limiting the speed of a vehicle crossing a single discrete obstacle or a series of closely, regularly spaced obstacles is a peak acceleration at the driver's seat of 2.5 g. A driver may be able to tolerate greater accelerations for short periods of time.

The results shown in Figures 25 and 26 are taken from Reference 4. Each pair of bars originating at the horizontal axis represents one of the vehicles listed in Table 1. Figure 25 indicates that for an rms elevation of 3 in., the maximum speed of each vehicle is less than 10 mi/h while satisfying the 6-W requirement. Figure 26 indicates that there is greater variability among vehicles in applying the 2.5-g criterion. A 10-in. obstacle requires most of the vehicles to travel at less than 10 mi/h.

2.11 Soil Dynamics

Soil dynamics is defined as a special body of scientific knowledge that deals with the high rate of strain and resulting large strain failure of off-highway vehicles interacting with soil. The maximum force (DBP) available to a vehicle cannot be greater than the force that can be supported by the surface on which the vehicle moves. The ability of a vehicle to override obstacles is dependent not only on the characteristics of the vehicle but also on the characteristics of the surface. The appropriate characterization of the surface

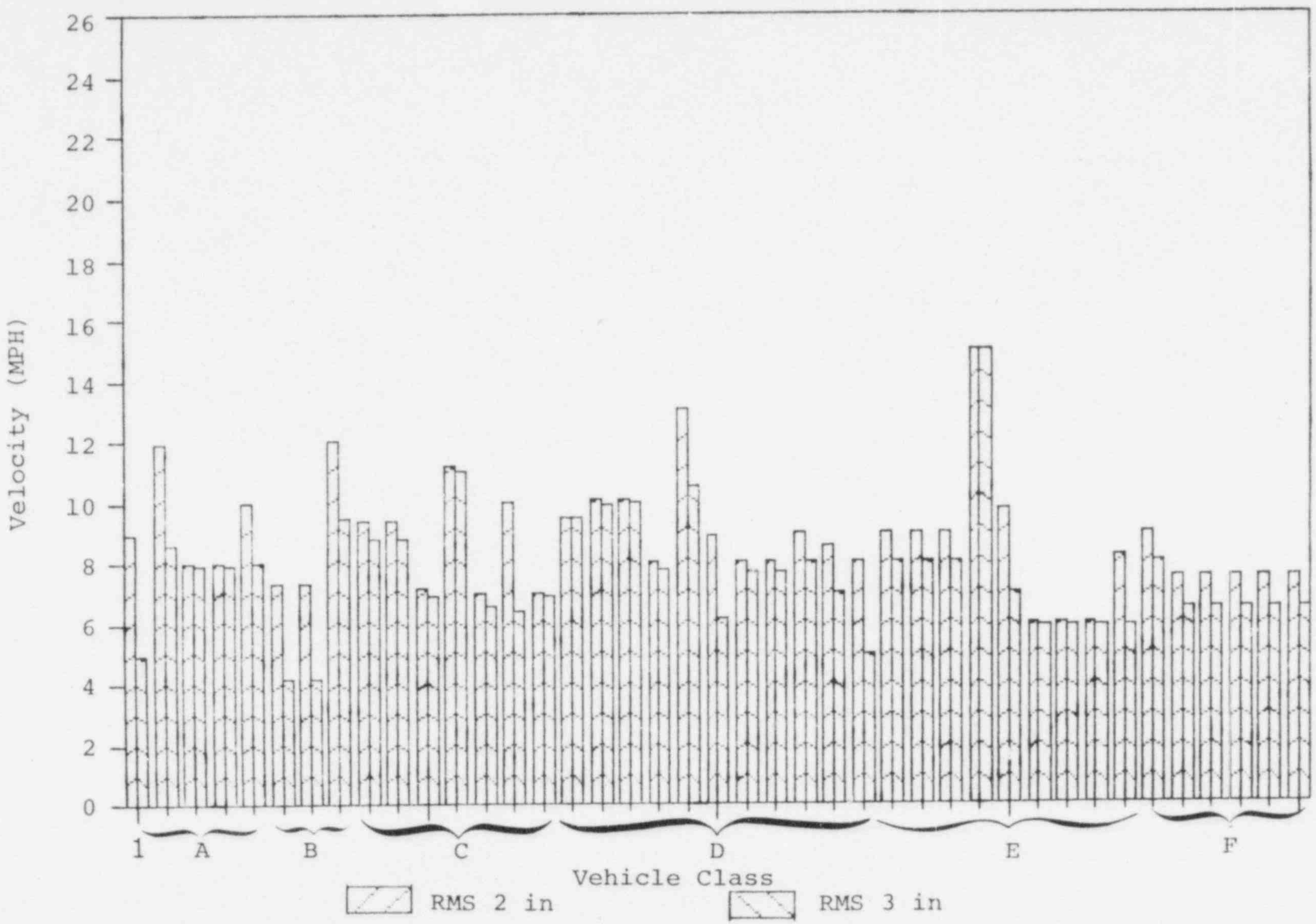


Figure 25. Vehicle Speed vs Root-Mean-Square Elevation to Produce 6 W Continuously Absorbed Power[4]

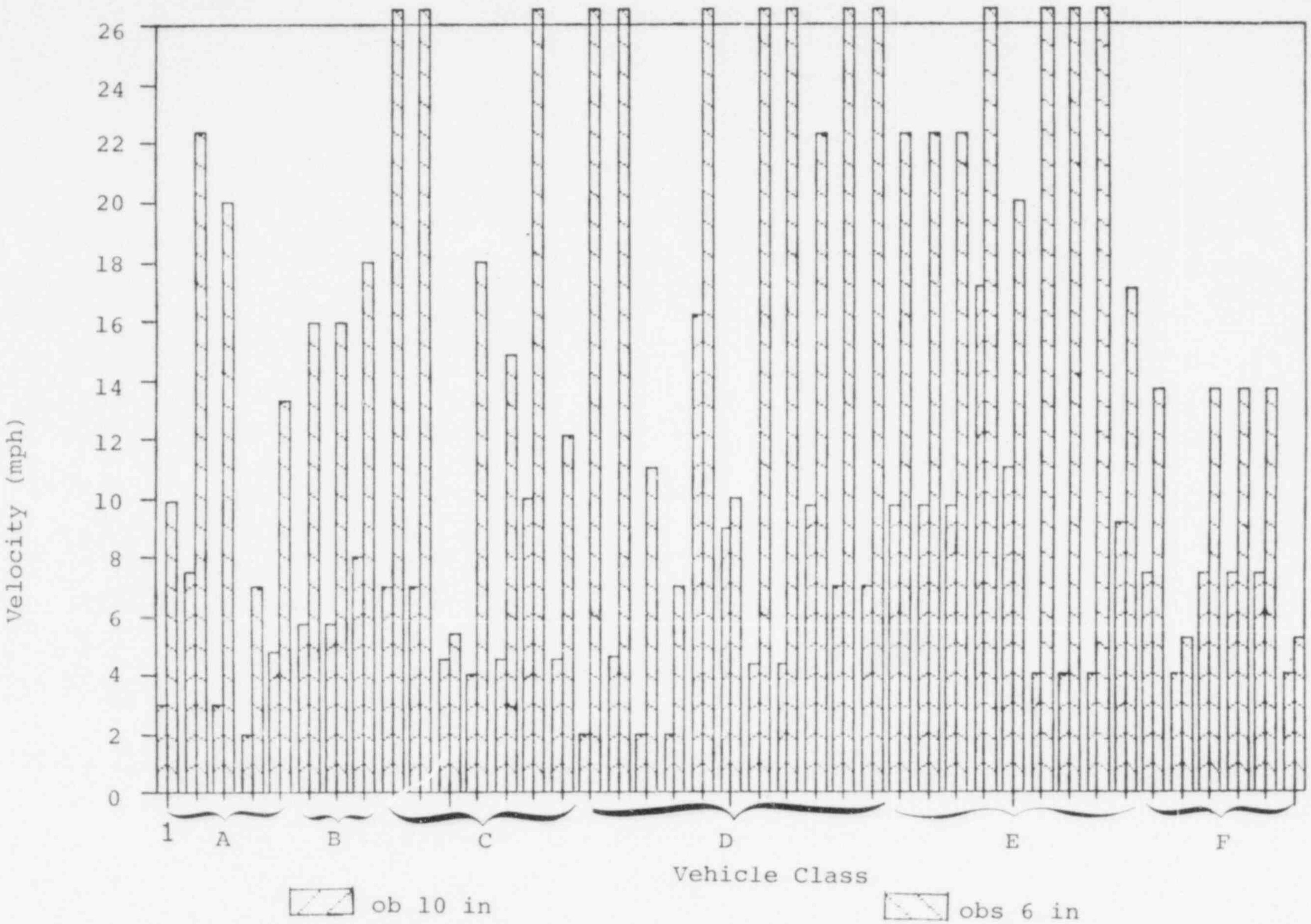


Figure 26. Vehicle Speed vs Obstacle Height to Produce 2.5-g Acceleration[4]

is one of the more difficult tasks in vehicle-terrain modeling.[7]

Bekker (Ref. 8) defined the gross tractive force H (lbs) of a deflecting tire as

$$H = (Ac + w \tan \phi) \quad 1 - \left[\frac{k}{s\ell(1 - \exp \frac{-s\ell}{k})} \right] \tag{18}$$

where

A = contact area of tractive element (in^2)

c = soil cohesion (psi)

w = weight on tractive element (lb)

ϕ = soil internal friction angle (°)

k = tangent modulus of deformation (in.)

s = slip rate = 1 - actual speed/theoretical speed

ℓ = length of contact area (in.)

The values of A and ℓ depend on the tire characteristics of the vehicle. The values of c, ϕ, and k are dependent on the soil characteristics.

3. COMBINATION OF NATURAL OBSTACLES

The discussion thus far has provided models and data dealing with the effect of a single natural feature on a vehicle's performance. Although these results are useful, it is clear that the vehicle does not interact with only one feature at a time. The interaction of several features on the vehicle is of importance. Single-feature models have been combined into a multifeature computer program by the U.S. Army Engineer WES to calculate a vehicle's performance over a specified terrain. In order to provide some preliminary results on the effect of such interactions, the WES was asked to use its model to evaluate the effect of certain representative terrains on three vehicles.[9]

3.1 Discussion of Work Performed

Three vehicles representative of small, medium, and large American-made trucks were selected to be evaluated for their performance on typical terrains adjacent to site boundaries.

Vehicle approach speeds were estimated by utilizing the Army Mobility Model (AMM), a vehicle mobility computer model, with selected vehicle and terrain parameters as input data.[6,10]

Vehicle performance over terrain is presented as the estimated maximum steady-state speed reached by a vehicle as it is driven over terrain with specified constant parameters at an initial speed equal to the vehicle's maximum rated speed. Vehicle performance over obstacles is presented as an estimate of the vehicle's capability to negotiate passage of the obstacles.

3.2 Selected Study Vehicles

Three specific vehicles were selected to represent the vehicle threat in this study.

- The small class vehicle is represented by a Dodge 3/4-ton, 4x4 truck (Figure 27).
- The medium class vehicle is represented by a Ford 4-1/2-ton, 4x2 truck (Figure 28).
- The heavy class vehicle is represented by an International Harvester 7-ton, 6x4 truck (Figure 29).

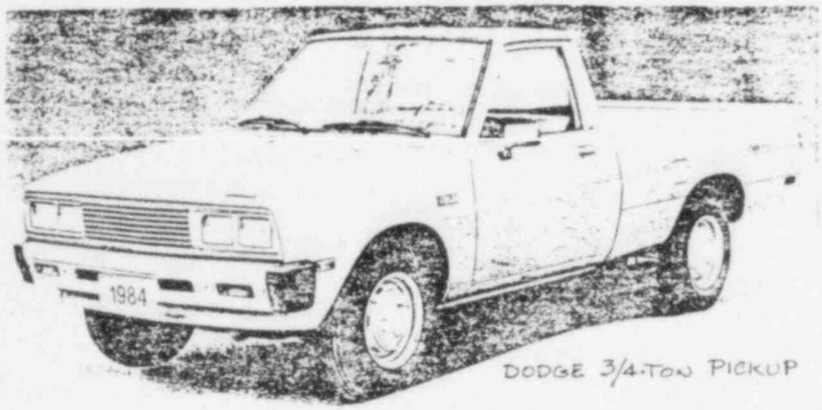


Figure 27. Dodge 3/4-Ton, 4x4 Pickup

Figure 28. Ford 4-1/2-Ton, 4x2 Truck

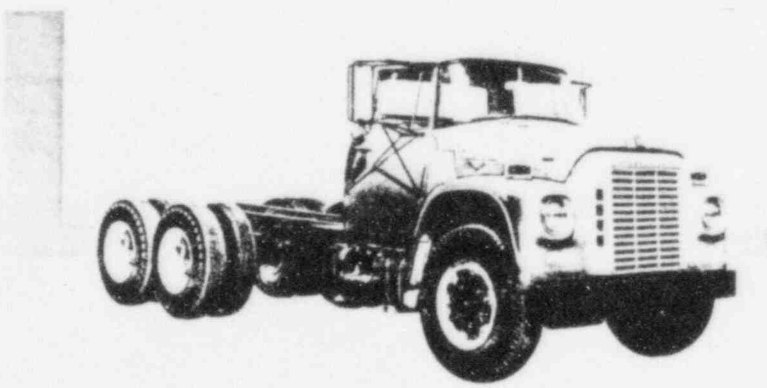


Figure 29. International Harvester 7-Ton, 6x4 Truck

The vehicle characteristics used in the computer calculations include tire size, gross vehicle weight, wheelbase, engine size, ratio of engine power to weight, minimum ground clearance, approach angle, departure angle, transmission type, minimum required soil strength (VCI_1), maximum speed, and dynamic response to surface roughness. Table 2 shows the values of the these parameters for the three study vehicles. The values for VCI_1 indicate the minimum strength of a fine-grained soil that will permit the study vehicles to be driven over the soil. The speeds given for three values of surface roughness in Table 2 are the limiting speeds that can be maintained by a highly determined driver under the maximum tolerable sustained conditions of shock and vibration induced by surface roughness (see Section 2.10, Ride Dynamics).

3.3 Terrain Characteristics

The terrain characteristics used in this study are soil strength, surface roughness, terrain slope, swamp conditions, and stream crossings. The parameters which represent these characteristics were varied over wide ranges in order to define the limits of vehicle performance with respect to each terrain characteristic.

3.3.1 Soil Strength

The ability of a soil to develop adequate bearing and traction capacity under the wheels of a vehicle is primarily a function of the shearing resistance of the soil. The soil model used in the AMM code is the Vehicle Cone Index (VCI) method.[3] This method uses a cone penetrometer to obtain an index of the shear strength of the soil in terms of a single number, the Cone Index (CI). The VCI model is wholly empirical. The soil surface is described in terms of its general nature, namely, fine-grained or coarse-grained, organic, or snow. Its profile of resistance to penetration by a small standardized cone is measured over an appropriate area and depth in terms of pressure on the cone and the rate of sinkage. The resistance measurement obtained in this manner is called the Cone Index. It is functionally related to the soil shear strength differently for the several different soil classes. In the case of soft, fine-grained, inorganic soils, a loss of soil strength occurs as a consequence of remolding of the soil by the weight of the vehicle. Samples of such soils are tested for their remolding index, and the soil strength is then described in Rating Cone Index (RCI), which is the product of the Cone Index and the remolding index. The remolding index is a number less than or equal to unity. As a point of reference, it may be noted that a smooth, dry soil with an RCI of 350 would not noticeably degrade the performance of the Dodge pickup truck in this study; however, the vehicle would be

Table 2

Important Characteristics of Study Vehicles

Vehicle Characteristics	Dodge 3/4-Ton 4x4 Pickup	Ford 5-1/2-Ton 4x2 Truck	International Harvester 7-Ton 6x4 Truck
Tire size	10R-15LT	11.00-22.5	11.00-22.5
Gross vehicle weight (lb)	6,010	23,000	32,000
Wheelbase (in.)	131	162	180
Engine type and size	V8 318 $in.^3$	V8 203 hp	V8 220 hp
Power-to-weight ratio (hp/ton)	50.00	17.66	13.75
Minimum ground clearance (in.)	10	9	10
Approach angle (°)	31	30	46
Departure angle (°)	17	38	58
Transmission type	3-speed auto	5-speed auto	5-speed auto
Minimum required soil strength (VCI_1) (fine-grained soil)	20	40	33
Maximum speed (mi/h)	55	55	55

6-watt speeds, as percentage of maximum speed, over soils of three different surface roughnesses:

Surface roughness (in. rms)			
0.3	100 %	100 %	100 %
0.8	28.0%	10.2%	15.4%
1.0	19.0%	9.1%	11.7%

immobilized if the soil RCI were as low as 15. In this study, soil-strength values of 300, 100, 50, 40, and 15 RCI were used for fine-grained soils. Soil strength values of 250, 100, and 50 CI were used for the coarse-grained soils.

The strength of a given soil varies with its water content and with snow cover. Vehicle performance was determined for each selected soil strength under dry-normal conditions, wet-slippery conditions, and normal snow conditions. The dry-normal surface condition describes the lowest soil strength found during the driest 30-day period for an average rainfall year and assumes that it has been at least 6 hours since the last rainfall. The wet-slippery surface condition describes the highest soil moisture and associated reduced soil strength found during the wettest 30-day period in an average rainfall year. The assumption of continuing rain makes the situation less favorable because of potential slipperiness on soils where strength would otherwise be adequate for flotation. The snow condition assumes that the terrain is frozen and uniformly covered by dry snow to a depth of 10 in. The snow analysis does not assume the use of tire chains.

3.3.2 Surface Roughness

The ride dynamics of a vehicle affect vehicle performance, because vehicle speed is limited by the driver's tolerance to shock and vibration as the vehicle travels over rough terrain and discrete obstacles. The simulation of rough stable ground is normally accomplished by first measuring the actual terrain profile. The measurements constitute an elevation versus distance profile for the area of interest. A terrain profile can be converted to a statistical statement of its frequency components. This is accomplished for a random, stationary segment of terrain by first computing the autocorrelation function of the elevation-versus-distance profile and then calculating the Fourier transform of the autocorrelation function to obtain the power spectral density (PSD) function of the terrain profile. The PSD function is the root-mean-square (rms) value of the terrain profile per cycles per inch as a function of the spatial frequency in cycles per inch. The total area under the PSD function is equal to the rms value of the total roughness for the terrain profile. The area under the PSD function between any two selected spatial frequencies is the contribution to the total roughness from the band of frequencies between these two frequencies. Thus, the frequencies that make the largest contribution to the terrain roughness can be determined from the PSD function.

It has been empirically shown that the PSD function of natural terrain is approximately constant over the spatial frequency bands that excite the natural vibrations of a vehicle, such as the frequency bands specified in the vehicle threat.[11]

Hence, the surface roughness may be specified as a single number, namely, the area under the PSD function between the spatial frequencies corresponding to the natural frequencies of the vehicles. This number is specified in units of inches root-mean-square (in. rms). As a point of reference, a surface of roughness 0.1 in. rms causes negligible degradation in the performance of the Dodge pickup truck, whereas the vibrations caused by a surface roughness of 1.0 in. rms would force the driver to reduce speed to below 20 mi/h. In this study, vehicle performance was evaluated for surface roughness values of 0.3, 0.8, and 1.0 in. rms.

3.3.3 Terrain Slope

Terrain slope affects the speed attainable by a vehicle, in that part of the traction available from the driving wheels and from soil shear strength must first be applied to overcome gravitational forces in the case of a positive terrain slope. In the case of a negative terrain slope, gravitational forces tend to increase vehicle speed; however, this effect is offset by braking action as the driver tries (successfully) to maintain control while the vehicle travels down the slope.

In this study, vehicle performance was estimated for each 5% of terrain slope in the range from +50% to -50%. The calculated speeds are steady-state speeds attained by the vehicles under the assumption that the vehicles were moving at their maximum speeds on level terrain when they encountered the sloping terrain.

3.3.4 Swamp Conditions

Swamp conditions limit vehicle performance primarily because of reduced soil strength due to moisture content of the soil. Several inches of water covering the soil surface of swamps have little effect on vehicle speed. In this study, the slope of the swamp terrain is 0%, and the surface roughness is taken to be 0.8 in. rms. Vehicle speeds were estimated for soil strengths in the range 50 to 15 RCI and for frozen swamp conditions.

3.3.5 Stream Crossings

The factors that affect the capability of a particular vehicle to cross a stream include the bank angles, the height of the bank, the width of the stream bottom, the speed and depth of the stream water, the soil strength, vehicle traction, and the approach and departure angles of the vehicle. The geometry associated with these variables is shown in Figure 30. The stream ditch was taken to be symmetrical, so the left and right

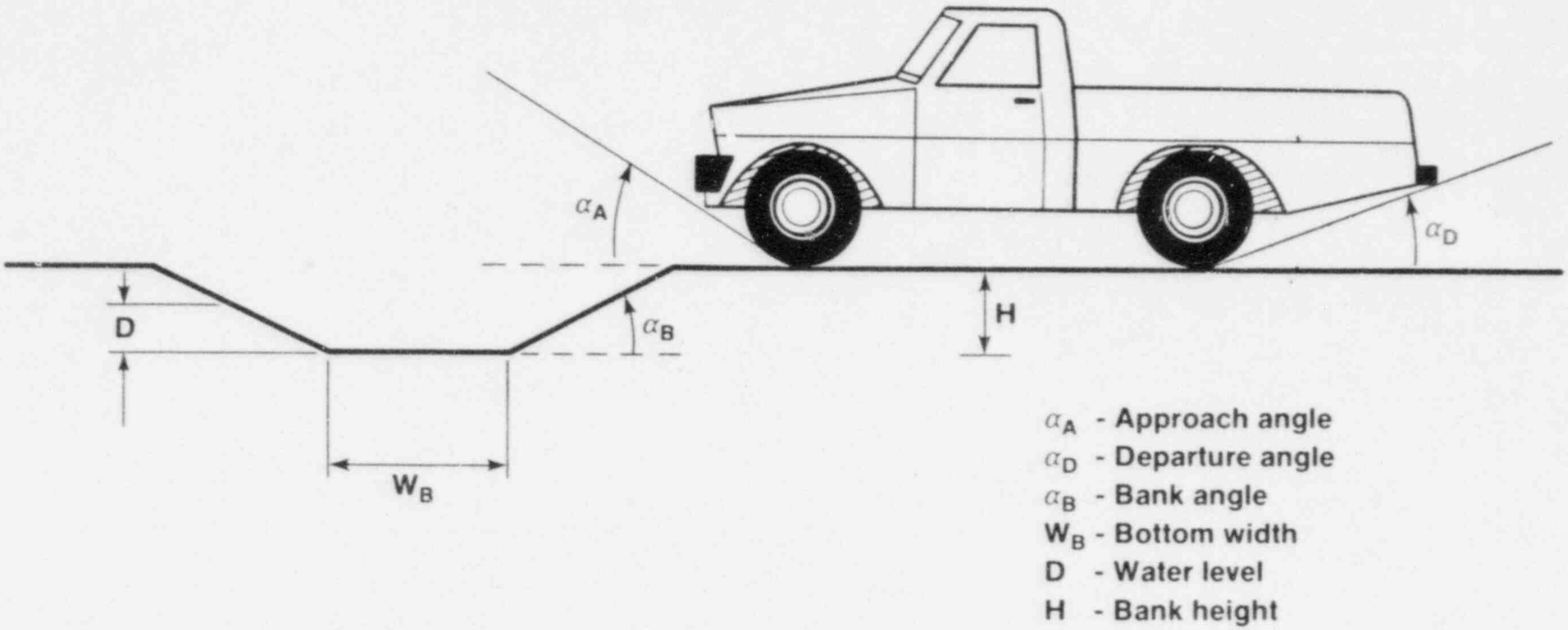


Figure 30. Stream Crossing Geometry

banks are the same. The bank heights were taken to be 10 ft, which permits most of the vehicles to be fully supported on the sloping banks during crossing. The water depth was taken to be 1 ft. This depth is great enough to make the bottom slippery but not so great as to cause swimming or fording problems. Water velocity in the stream was taken to be 1 ft/s, which is low enough not to present problems to the vehicles. The effects of vegetation were eliminated from the calculations. Vehicle performance was determined for bottom widths of 5, 10, 15, 20, 30, and 50 ft. Three bank angles (5°, 8°, and 15°) were examined. The effects of soil strengths were examined by letting this parameter take on values of 300, 188, and 30 CI.

3.4 Vehicle Performance Results

The attainable vehicle speeds over rough, sloping terrain of different soil strengths are shown in the 54 graphs that constitute the appendix to this report. Vehicle performance in swamps is shown as a table of vehicle speed for different swamp soil strengths. Vehicle stream crossing performance is shown in a table of "GO" or "NO-GO" indications as a function of the stream parameters and soil strengths.

3.4.1 Vehicle Speed Over Terrain

In each graph in the appendix to this report, maximum vehicle speed as a percentage of 55 mi/h is plotted against terrain slope in percent for the selected values of soil strength. Each graph is for one value of surface roughness, one type of soil (fine or coarse), one moisture content (dry, wet, snow), and one vehicle. In those cases where there is only a small change in maximum vehicle speed with reduced soil strength, the plot corresponding to the lower soil strength value is omitted from the graph. However, those plots corresponding to the lowest value of soil strength for which a vehicle has a speed greater than zero are not omitted. Since there are three values of surface roughness, two types of soil, and three moisture contents taken into account, there are 18 graphs for each vehicle, for a total of 54 graphs. A sample graph is shown in Figure 31.

3.4.2 Vehicle Performance in Swamps

Swamp conditions were characterized by a terrain slope of 0%, a surface roughness of 0.8 in. rms, and four different soil strengths, including a frozen condition. The corresponding vehicle speeds are shown in Table 3.

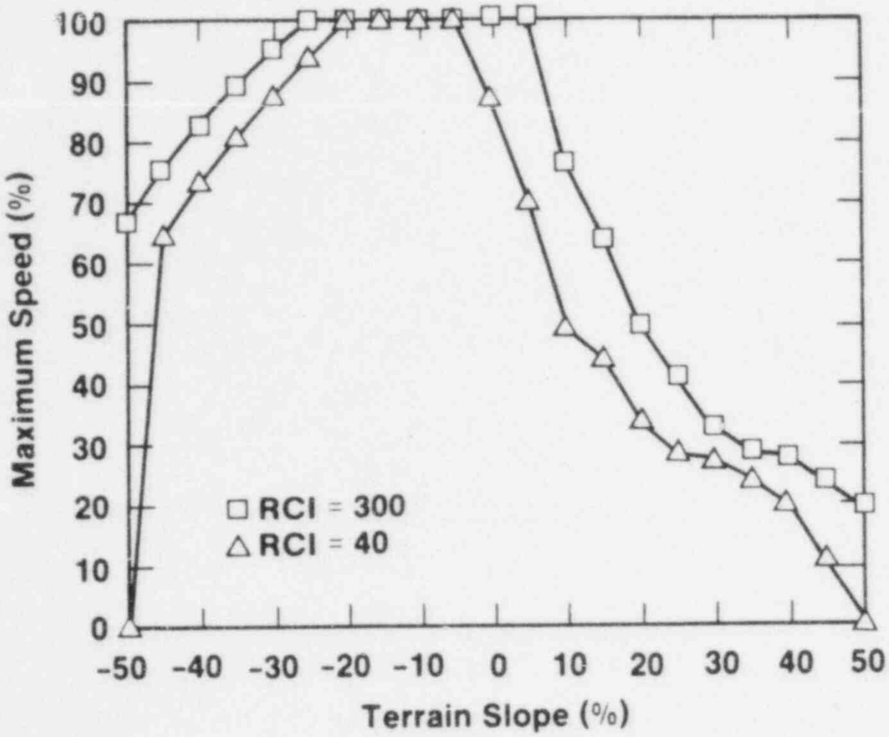


Figure 31. Maximum Speed vs Terrain Slope: 3/4-Ton Truck; Dry, Fine Soil; Surface Roughness 0.3 in. rms (Note: This figure is the same as Figure A-1 in the appendix to this report.)

Table 3

Swamp-Crossing Speeds (mi/h)

Slope 0%
Surface Roughness 0.8 in. rms

Vehicle	Frozen	RCI = 50	RCI = 40	RCI = 15
Dodge 3/4-Ton, 4x4	55	28	28	0
Ford 4-1/2-Ton, 4x2	53	10	0	0
Intl Harvester 7-Ton, 6x4	39	13	7	0

3.4.3 Vehicle Performance in Streams

Stream-crossing performance for the three threat vehicles is presented in Table 4. The variations in bottom width are listed in the left column. The bank angles are shown as column headings in the table. The entries G and S indicate a "GO" or "NO-GO" result for the specific conditions. G indicates the vehicle can go over the stream; S indicates the vehicle is stopped by the stream ditch. The ordered set G,G,G, for example, corresponds to the ordered set of soil strengths 300, 188, and 30, respectively.

Table 4

Stream-Crossing Performance

Dodge 3/4-Ton, 4x4	RCI = 300, 188, 30		
Bottom Width (ft)	Bank Angle 5°	8°	15°
5	G,G,G*	G,G,G	S,S,S**
10	G,G,G	G,G,G	S,S,S
15	G,G,G	G,G,G	S,S,S
20	G,G,G	G,G,G	S,S,S
30	G,G,G	G,G,G	S,S,S
50	G,G,G	G,G,G	S,S,S

Ford 4-1/2-Ton, 4x2	RCI = 300, 188, 30		
Bottom Width (ft)	Bank Angle 5°	8°	15°
5	G,G,S	S,S,S	S,S,S
10	G,G,S	S,S,S	S,S,S
15	G,G,S	S,S,S	S,S,S
20	G,G,S	S,S,S	S,S,S
30	G,G,S	S,S,S	S,S,S
50	G,G,S	S,S,S	S,S,S

Intl Harvester 7-Ton, 6x4	RCI = 300, 188, 30		
Bottom Width (ft)	Bank Angle 5°	8°	15°
5	G,G,S	G,G,S	S,S,S
10	G,G,S	G,G,S	S,S,S
15	G,G,S	G,G,S	S,S,S
20	G,G,S	G,G,S	S,S,S
30	G,G,S	G,G,S	[illegible],S,S
50	G,G,S	G,G,S	[illegible],S,S

*G = Go, Vehicle Can Cross
**S = Stop, Vehicle Cannot Cross

4. MAN-MADE OBSTACLES

4.1 Speed Reduction by Curved Path[12]

A vehicle traveling along a curved path is subject to an outward-directed force. This force, called centrifugal force CF (ft-lbs), is exerted when bodies move rapidly around a curved path. The value is given by

$$CF = \frac{wV^2}{gr} \tag{19}$$

where

w = weight of body (lb)

V = speed of body (ft/s)

r = radius of curve (ft)

g = acceleration due to gravity (ft/s^2)

Radius of curve is defined in terms of the degree of curve D (radians), which is the central angle that subtends a 100-ft arc. That is,

$$r = 100/D \tag{20}$$

The centrifugal force tends to cause overturning or skidding outward from the center of curvature. On a level surface, the outward-directed force is opposed by the inward-directed friction force of the vehicle's wheels. The total force T (ft/lbs) along the radius of curvature is

$$T = CF - fw \tag{21}$$

where f = allowable side friction factor.

The value of f varies greatly with speed, tires, road surface, and weather. New tires on dry concrete may reach a friction factor of 0.5 at low speed with a reduction to 0.35 at high speed. On icy pavement, the friction factor may be reduced to as low as 0.1.

The maximum speed a vehicle can maintain on a flat curved surface is determined by setting the total force along the radius of curvature equal to zero. That is,

$$V = (fgr)^{1/2} \tag{22}$$

Thus, by channeling a vehicle through a curved path, the maximum speed the vehicle can reasonably attain can be

controlled. This method of speed control is attractive for use in normal vehicle entrances to an area.

The effectiveness of barriers designed to stop vehicles increases as the vehicle speed at barrier impact decreases. The speed of the impacting vehicle is of particular concern when movable barriers are to be employed. This concern is based on the fact that movable barriers by their very nature can not be as substantial as permanent barriers, so movable barriers are normally employed at points where surfaces are designed to handle vehicle traffic; therefore, approaching vehicles are more likely to attain high speeds. Methods should be implemented that will force approaching vehicles to decrease their speed.

A vehicle traveling along a curved path has been shown to have a limit imposed on its maximum speed because of centrifugal force acting on it. This force tends to cause outward skidding or, in severe cases, overturning if a turn is attempted at excessive speed. Centrifugal force is opposed by centripetal force provided by the friction between the vehicle's tires and the surface. In addition, when the surface is superelevated (banked), the vehicle's weight component parallel to the surface also opposes centrifugal force. Equating these two forces provides the following relationship:

$$r = \frac{V^2}{15(e + f)} \qquad (23)$$

where

r = radius of curve (ft)

V = vehicle speed (mi/h)

e = rate of superelevation (ft/ft)

f = side friction factor

Since the degree of curve D (degrees) is defined as the central angle that subtends an arc of 100 ft, the above relationship will give the degree of curve if it is written as

$$D = \frac{85900(e + f)}{V^2} \qquad (24)$$

The above relationships indicate that the vehicle speed must decrease as a function of the sharpness of the curve. It also indicates that to optimize this effect, banking should be minimized, and the surface should have as small a coefficient of friction as possible. The graphs in Figures 32 and 33 show the speeds that can be maintained for different curvatures using different coefficient of friction values.

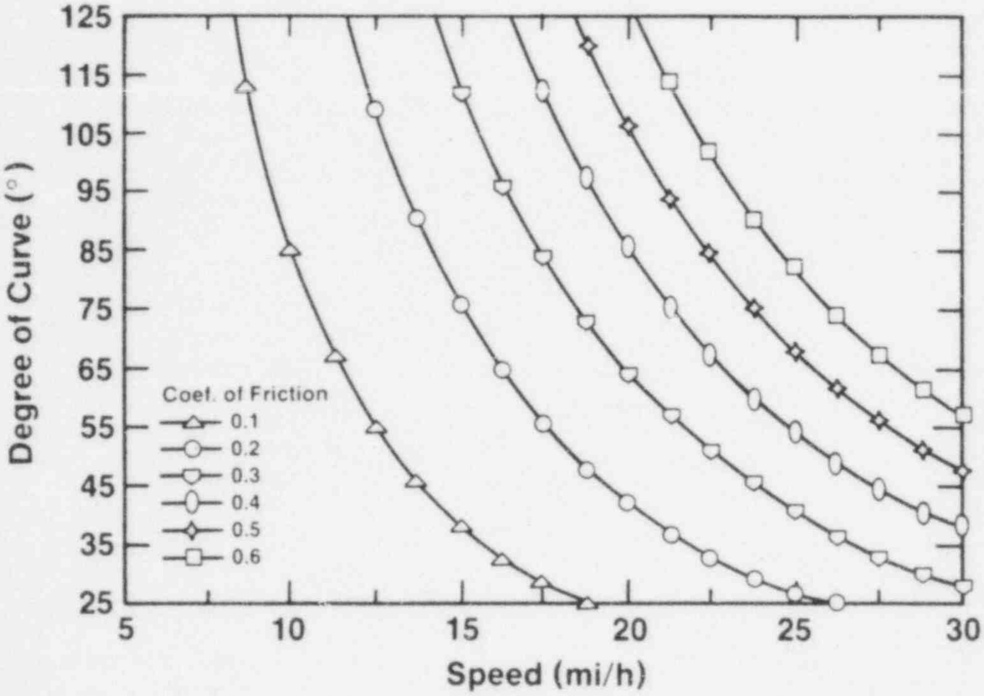


Figure 32. Maximum Speed vs Degree of Curve: Various Coefficients of Friction

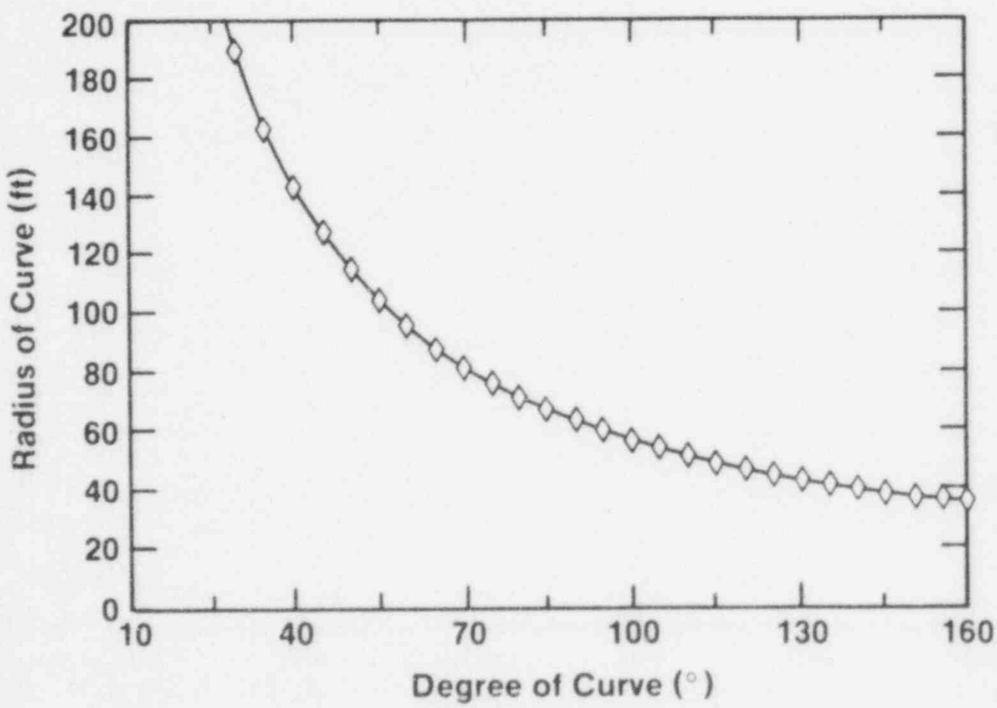


Figure 33. Radius of Curve vs Degree of Curve

There are limits to the degree of curve that can be used. These limits are dependent on the size of the vehicle using the entrance. Figure 34 shows the minimum turning radii for a single-unit truck and a semitrailer, respectively. As can be seen, the minimum practical turning radii for these vehicles are 45 and 50 ft, respectively. Using the curves in Figures 32 and 33, the speeds at these radii would be approximately 10 and 15 mi/h, respectively, depending on the friction factor. It should be noted that on tight curves with little side clearance, driver psychology may limit the speed to values below any theoretical limit.

If the speeds possible at the minimum radius are still considered unacceptable, it is possible to design an approach to the entrance that will require slower speeds. Figure 35 illustrates how this could be accomplished. Such methods require a degree of maneuvering that may be unacceptable for normal operations.

The use of speed bumps before the entrance could also cause vehicles to slow down. However, the effectiveness of speed bumps is dependent on vehicle parameters such as vehicle suspension and driver tolerance to vibration, both of which are subject to some control by an adversary. Thus, the effectiveness of speed bumps cannot be quantified as confidently as can that of curves. The use of speed bumps in conjunction with turns may increase the effectiveness of the curve, because the vehicle friction force will be decreased when the vehicle tires are not in firm contact with the surface.

The relationship of maximum vehicle speed to the rate of superelevation (banking) indicates that by using negative banking, the effective side friction of the vehicle would be decreased and therefore vehicle speed would need to be decreased. The rate of banking possible in a given situation must be determined by site conditions. Slow-moving vehicles, particularly under low-friction (ice) conditions, could leave the driving surface if too much banking were used.

The channeling of vehicles to ensure that they must follow the prescribed path requires the use of barriers similar to those used on the facility's perimeter. The barriers could be continuous, such as concrete median barriers, or discrete, such as filled reinforced-concrete pipe placed in patterns requiring vehicles to execute turns. Whatever methods are used, appropriate foundation and anchoring are required for any fixed barrier.

In the case of an entrance infrequently used by large vehicles, it might be prudent to consider designing the approach so that it could be suitably modified to allow large-vehicle access infrequently. This could be done by having in the approach pattern discrete barriers that could be removed in a reasonable

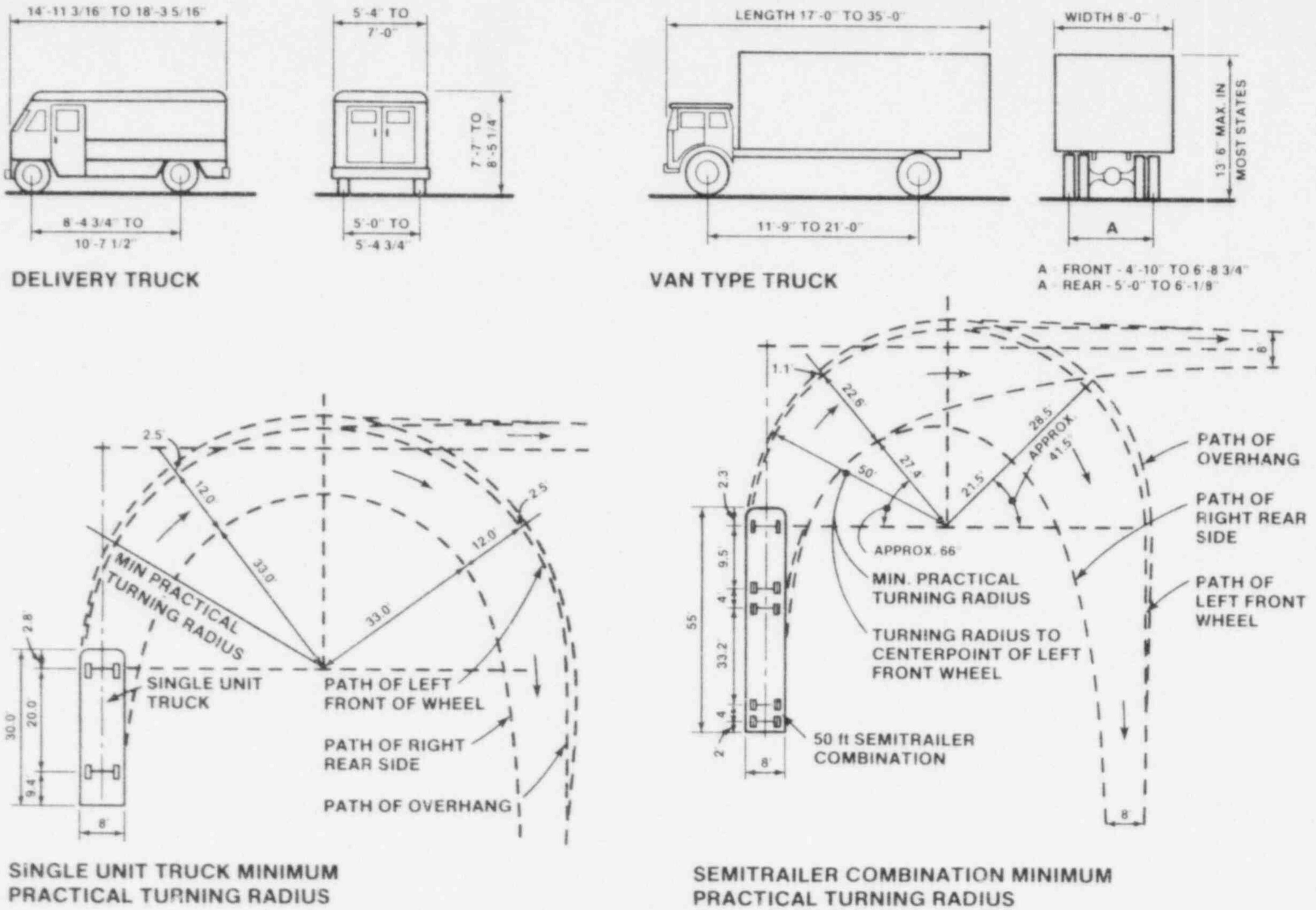


Figure 34. Minimum Turning Radii[13]

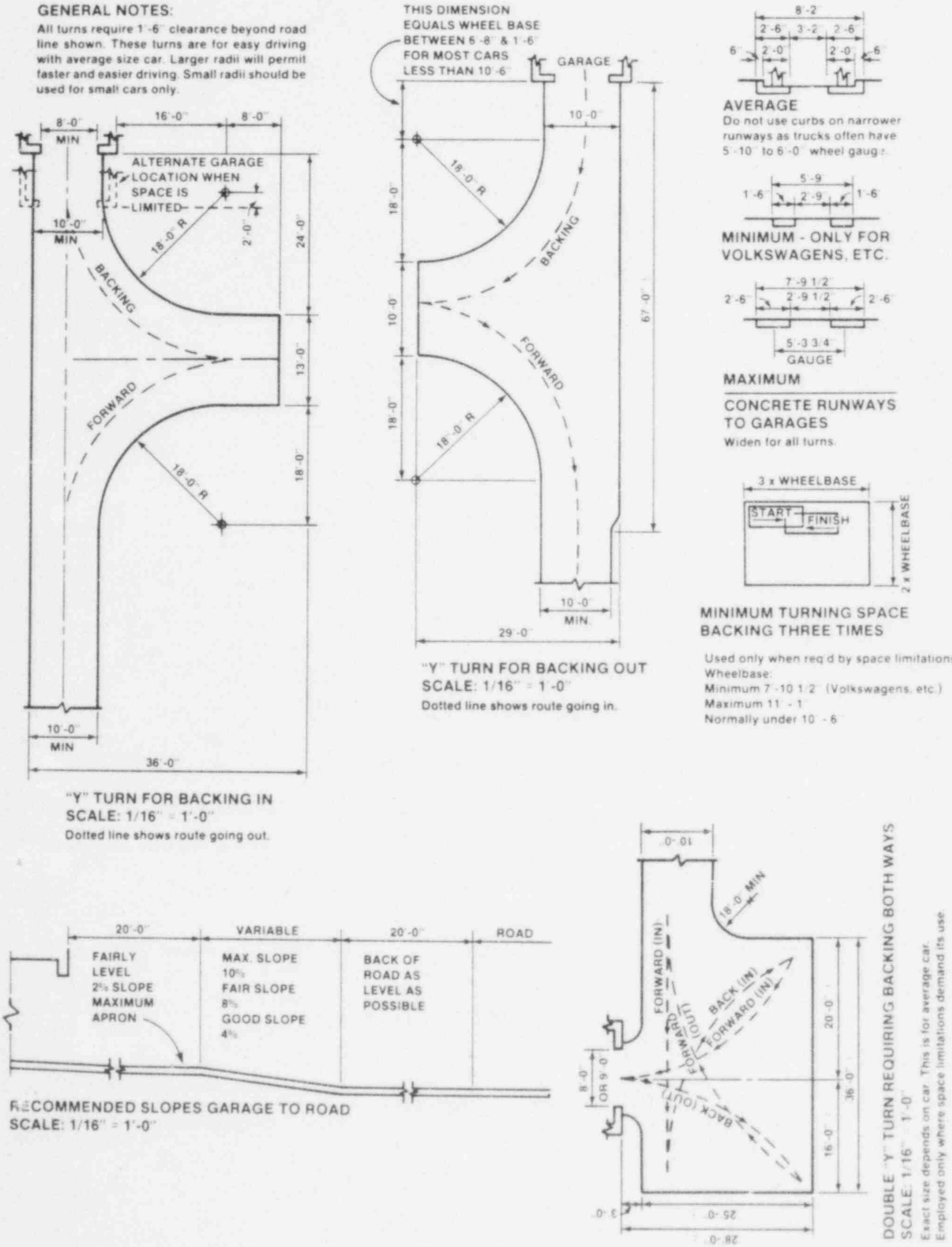


Figure 35. Maneuver Patterns at Entrance[13]

time. During the time such barriers were removed, compensatory security measures would be required.

4.2 Vehicle Barriers

Prevention of vehicle penetration of a protected area requires installation of a barrier system with a high probability of stopping postulated threat vehicles. In the report "Vehicle Access and Control Planning Document," a compilation of possible barriers is presented.[14] Figure 36 illustrates a number of barrier types. It should be remembered that the purpose of a barrier system is not only to halt the vehicle, but also to prevent facility damage. A barrier system should be installed so that halted vehicles could not remain a threat. This requires that the vehicle be halted at a sufficient distance from a vulnerable area to prevent damage if the vehicle cargo of explosives were detonated. This barrier standoff distance depends on the vulnerability of targets to explosives, and the postulated amount of explosives that could be involved. A barrier with a high probability of immediately stopping a vehicle could be installed closer to a target than a barrier that only disables a vehicle, thus allowing it to continue beyond the barrier until its momentum is exhausted.

Each type of barrier has its associated advantages and disadvantages. The less massive types constructed of metal or wood members are more vulnerable to neutralization by explosives than more massive barriers constructed, for example, of concrete. Massive barriers have the disadvantage of providing cover and concealment for any adversary. If an adversary is given enough unhampered time, any barrier can be breached or circumvented; therefore, any barrier system must be under the control and surveillance of the security force.

The report "Security Vehicle Barriers" provides detailed discussion of both fixed and movable barriers.[1] Included for each barrier are a sketch, test results (including photographs), and comments on the barrier's application. A short discussion of barrier types is included here for completeness, but Reference 1 should be consulted for details of specific barriers.

4.3. Impact Load on Longitudinal Barriers

A longitudinal barrier is one of three types: a roadside barrier, a median barrier, or bridge rails. The impact force delivered to an object being struck by a vehicle is a function of such vehicle characteristics as weight and stiffness, and of impact conditions such as speed and impact angle. Any barrier must be able to survive an impact in a sound enough condition to perform its function.

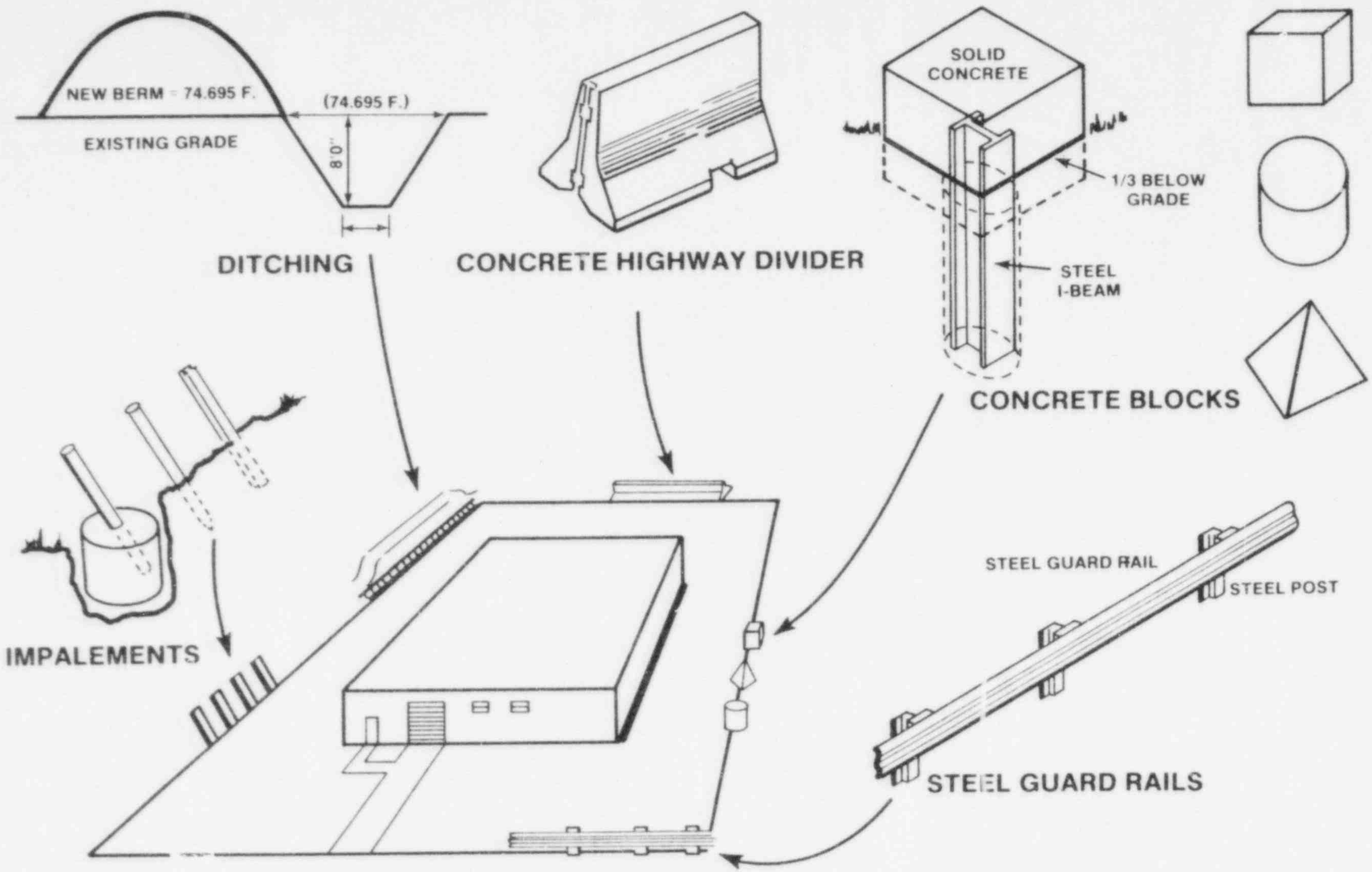


Figure 36. Perimeter Barriers

An expression has been developed that allows the magnitude of the impact force F_{lat} (ft-lbs) to be calculated for a longitudinal barrier.[15] The expression is

$$F_{lat} = WG_{lat} \tag{25}$$

where

W = vehicle weight (lb)

G_{lat} = average vehicle lateral deceleration (ft/s^2)

With G_{lat} given by:

$$G_{lat} = \frac{V_i^2 \sin \theta^2}{2g[A \sin \theta - 0.5B(1 - \cos \theta) + D]} \tag{26}$$

where

V_i = vehicle impact speed (ft/s)

θ = vehicle impact angle (°)

g = acceleration due to gravity (32.2 ft/s^2)

A = distance from vehicle's front end to center of mass (ft)

B = vehicle width (ft)

D = lateral displacement of barrier railing (ft)

This expression calculates the average lateral deceleration over a time that begins at impact and ends with the vehicle being parallel to the barrier line. Tests have shown that peak decelerations can be approximately twice the values calculated. It is assumed that barrier and vehicle stiffness are uniform in the lateral direction and independent of deformation. The inertia of the barrier is also assumed to be negligible. If these assumptions are not valid, the calculated values will be low.

Figures 37 and 38 indicate the sensitivity of the impact force to the vehicle speed at an impact angle of 90°. Figure 37 is representative of a small vehicle while Figure 38 represents a heavy vehicle. Figures 39 through 42 indicate the sensitivity of the impact force to angle of impact. Figures 39 and 40 are for vehicles having a speed of 30 mi/h while Figures 41 and 42 represent impacts at a speed of 60 mi/h.

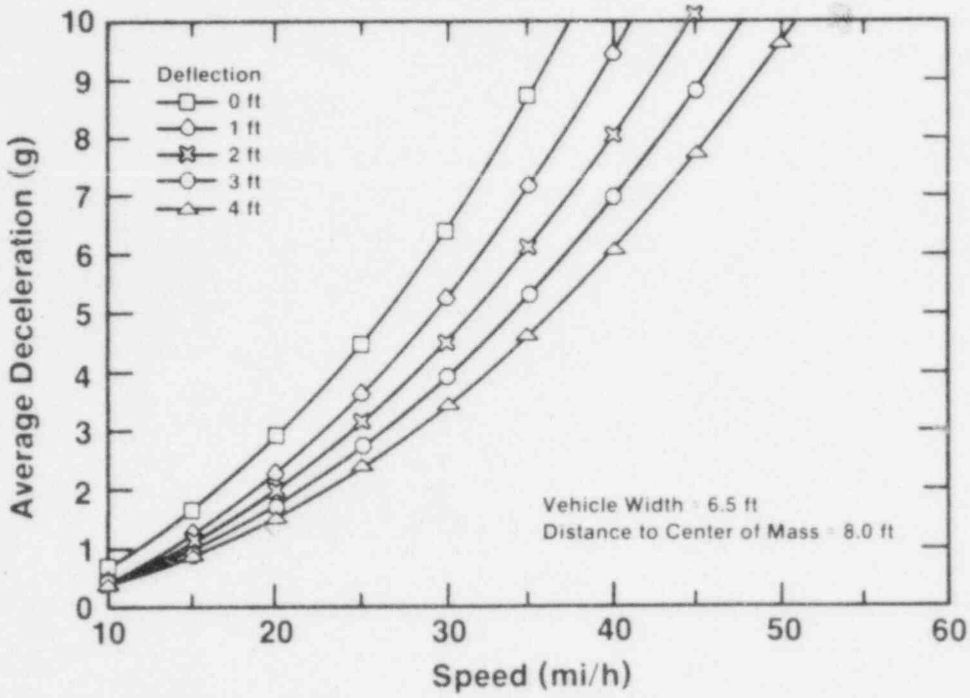


Figure 37. Average Deceleration vs Impact Speed: 90° Impact Angle; Vehicle Width = 6.5 ft; Distance to Center of Mass = 8.0 ft; Various Deflections

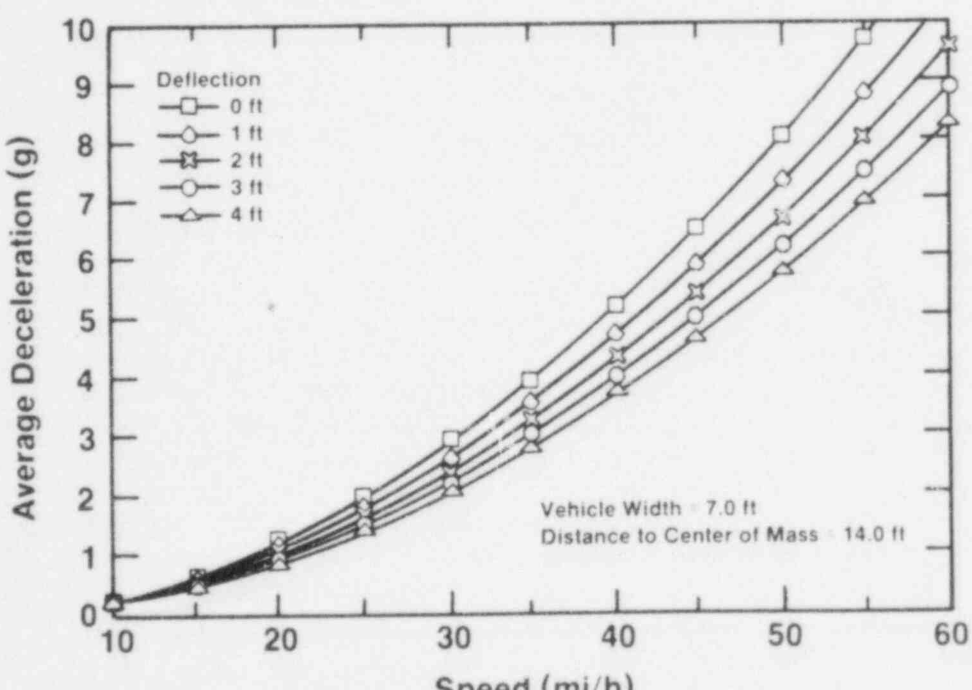


Figure 38. Average Deceleration vs Impact Speed: 90° Impact Angle; Vehicle Width = 7.0 ft; Distance to Center of Mass = 14.0 ft; Various Deflections

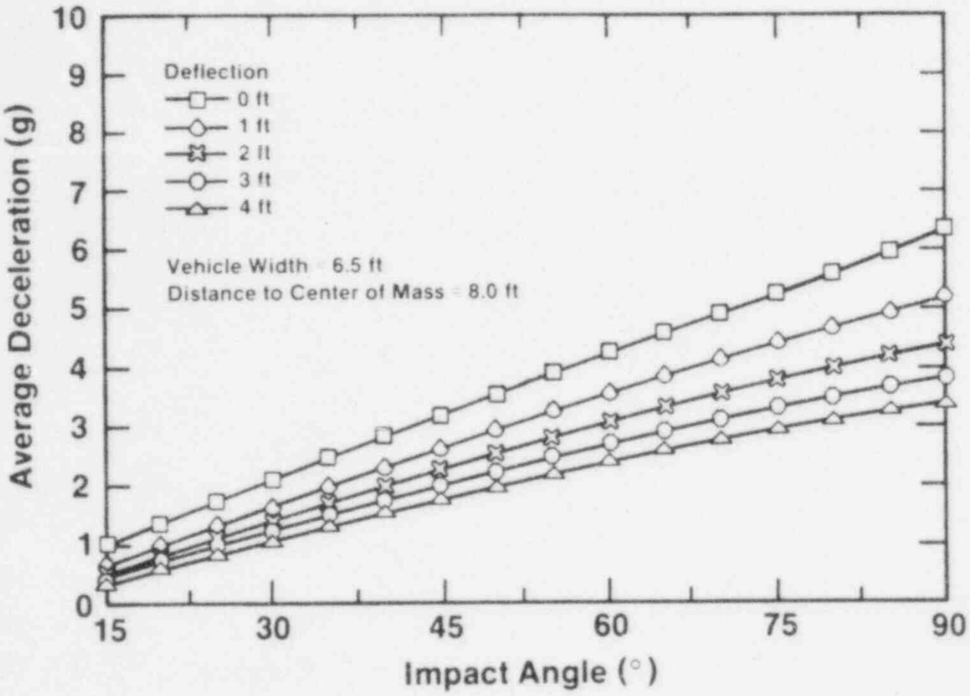


Figure 39. Average Deceleration vs Impact Angle: Speed = 30 mi/h; Vehicle Width = 6.5 ft; Distance to Center of Mass = 8.0 ft; Various Deflections

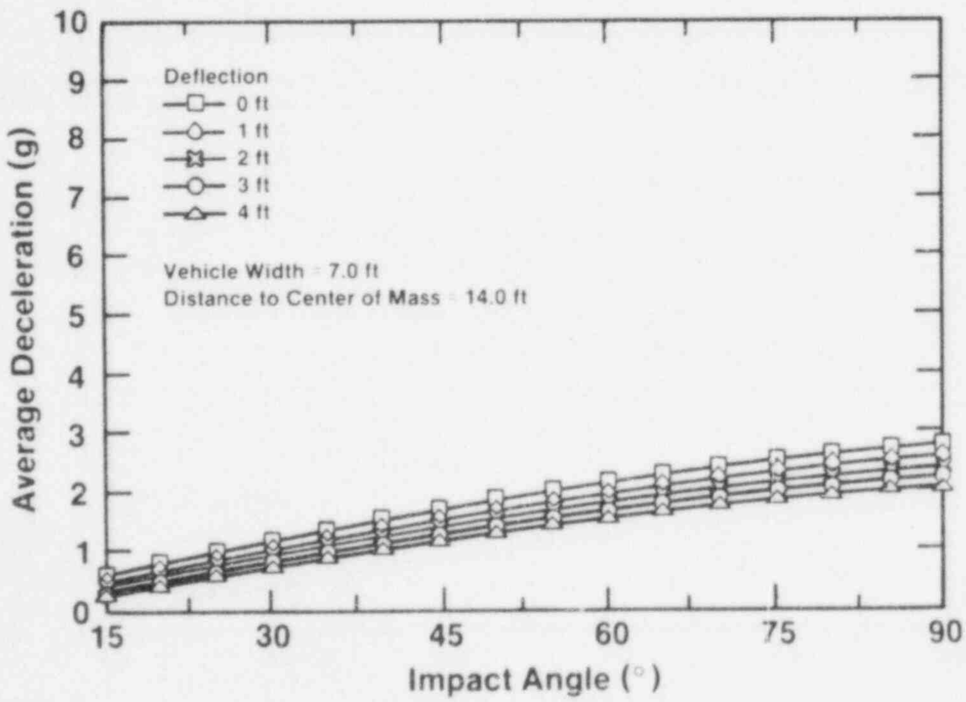


Figure 40. Average Deceleration vs Impact Angle: Speed = 30 mi/h; Vehicle Width = 7.0 ft; Distance to Center of Mass = 14.0 ft; Various Deflections

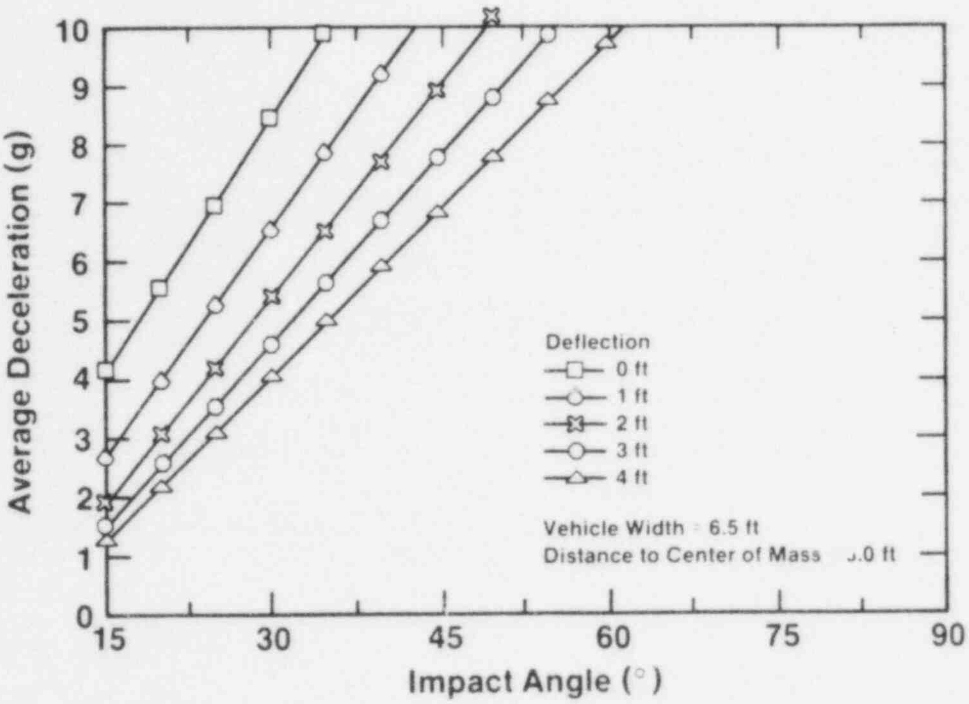


Figure 41. Average Deceleration vs Impact Angle: Speed = 60 mi/h; Vehicle Width = 6.5 ft; Distance to Center of Mass = 8.0 ft; Various Deflections

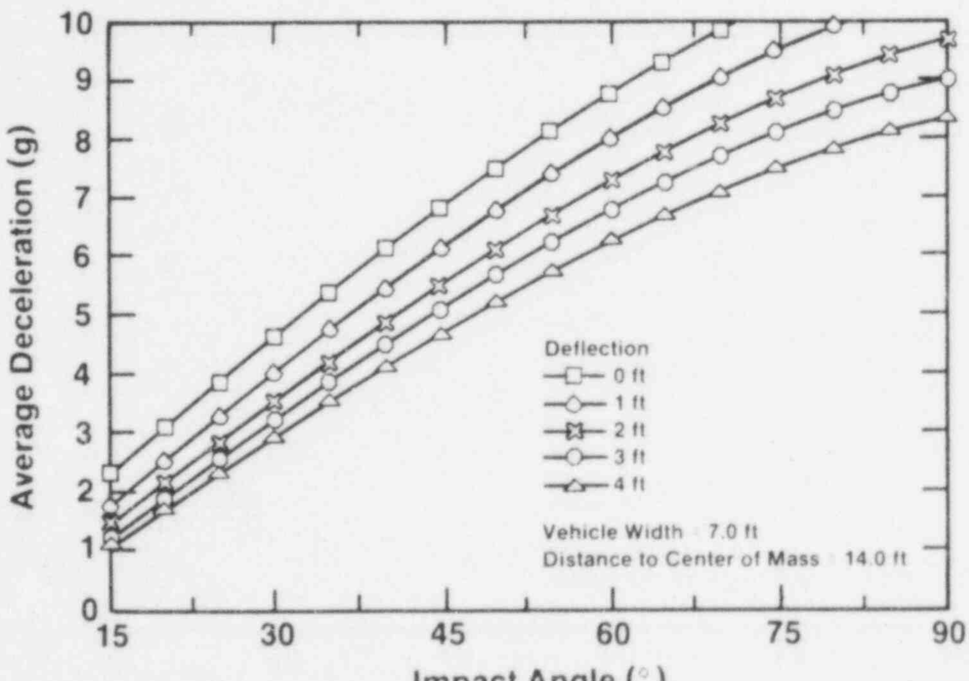


Figure 42. Average Deceleration vs Impact Angle: Speed = 60 mi/h; Vehicle Width = 7.0 ft; Distance to Center of Mass = 14.0 ft; Various Deflections

4.4 Inertial Barriers

Inertial barriers are designed to provide a mechanism for transferring the momentum of the vehicle to the barrier mass. The rate at which the barrier system allows this to occur determines the severity of the interaction and thus the lethality of the interaction to the vehicle's occupants. Assuming that after impact the vehicle and barrier remain together and have the same speed (inelastic collision), a relationship can be developed that gives the average deceleration of the vehicle A_v (ft/s^2) over the depth of the barrier. This relation is

$$A_v = \frac{V_i^2 \left[1 - \frac{W_v^2}{(W_v + W_b^2} \right]}{2D} \qquad (27)$$

where

V_i = Vehicle impact speed (ft/s)

W_v = Vehicle weight (lb)

W_b = Barrier weight (lb)

D = barrier depth (ft)

In addition, the change in speed of the vehicle ΔV_i (ft/s) can be determined by using the relation:

$$\Delta V_i = \frac{V_i W_v}{W_v + W_b} \qquad (28)$$

Consider the expression $W_v/(W_v + W_b)$ to be a scaled weight. Then A_v and Δ_v (Eqns. 27 & 28) can be calculated independent of specific vehicle and barrier weights. Figures 43 through 45 show the deceleration for vehicles traveling at 30, 45, and 60 mi/h as a function of scaled weight for several barrier depths. Figure 46 shows the speed change as a function of scaled weight for these three speeds. For convenience, Figure 47 relates scaled weight to the ratio of barrier weight to vehicle weight. These expressions indicate that for the vehicle to be halted, a barrier of infinite weight would be necessary, which is clearly not the case. Once the vehicle is sufficiently slowed, other forces, ignored in this analysis, bring the vehicle to a stop. The assumptions under which these expressions were developed must be kept in mind. Barriers whose weights are large compared to the vehicle will not affect a vehicle in the above manner as the conditions for inelastic collision will not be satisfied.

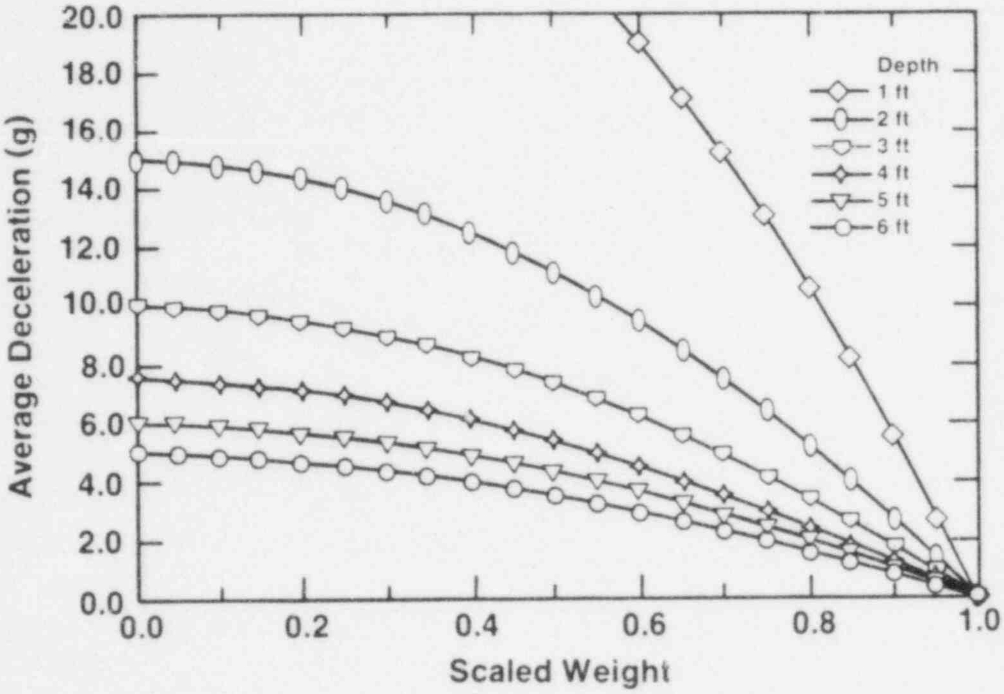


Figure 43. Average Deceleration vs Scaled Weight: Speed = 30 mi/h; Various Barrier Depths

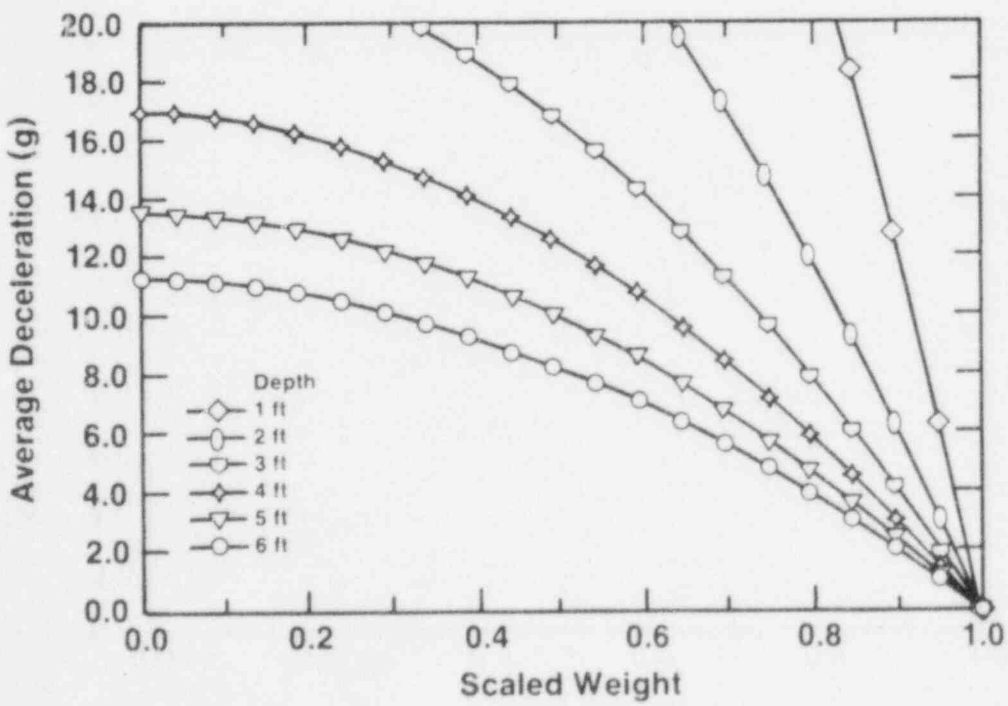


Figure 44. Average Deceleration vs Scaled Weight: Speed = 45 mi/h; Various Barrier Depths

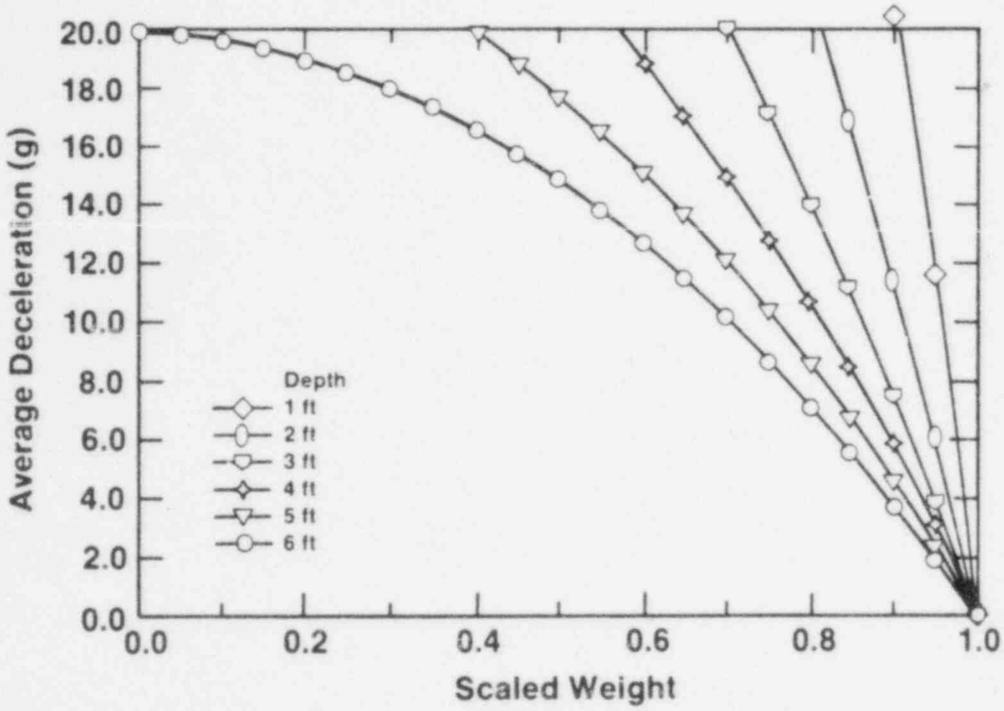


Figure 45. Average Deceleration vs Scaled Weight: Speed = 60 mi/h; Various Barrier Depths

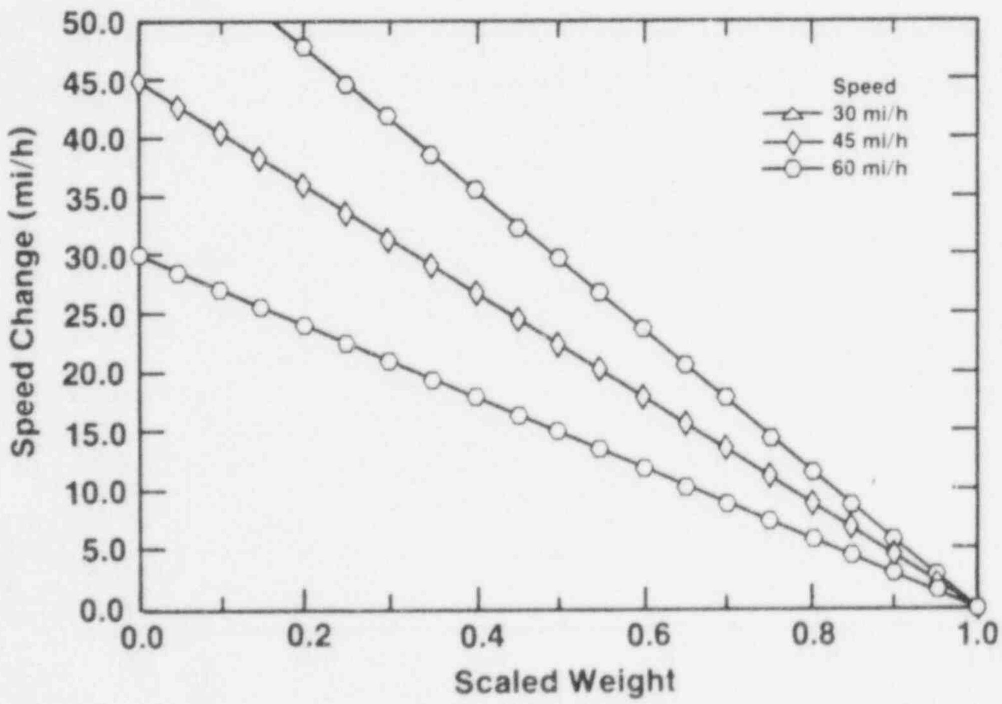


Figure 46. Speed Change vs Scaled Weight: Various Speeds

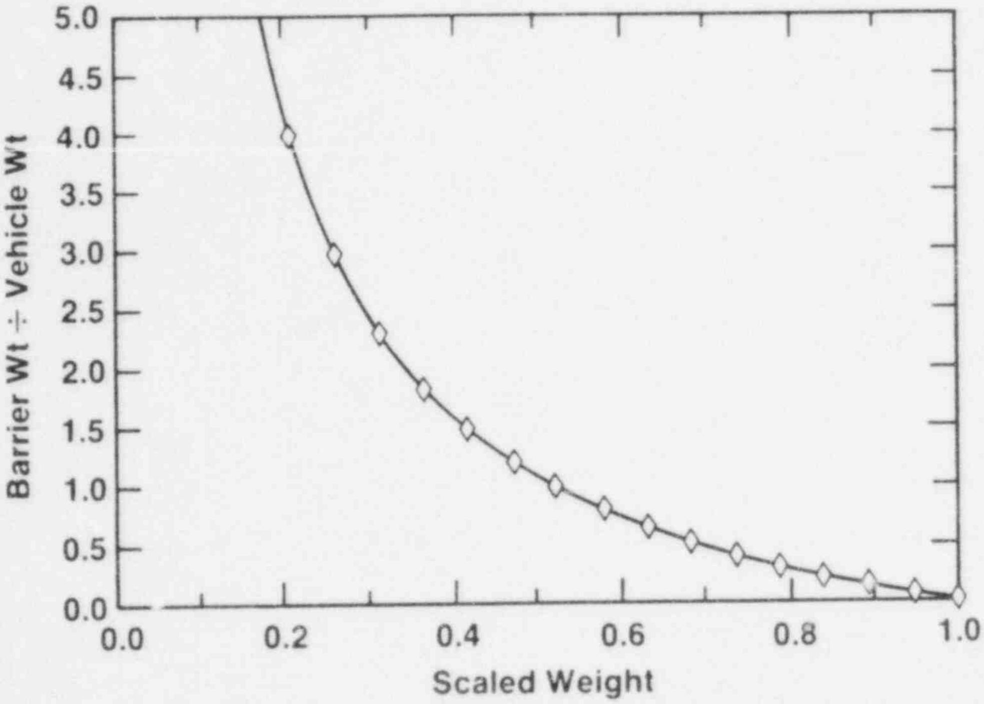


Figure 47. Barrier Weight/Vehicle Weight vs Scaled Weight

4.5 Obstacles to Slow Down or to Halt Vehicles

Barriers that are not substantial enough to halt a vehicle will nevertheless cause a decrease in the speed of the vehicle and thus reduce the vehicle's kinetic energy. The vehicle's encounter with subsequent barriers, assuming it can not regain its original speed, will repeat the process until the vehicle is brought to a stop. The number of barriers necessary to stop a vehicle will determine the distance around the facility required for their installation. Since it may be impossible to design a single barrier that will stop the maximum-threat vehicle without assistance, a series of barriers may be necessary. The cost relationship (tradeoff) between erecting a series of lighter barriers compared to one effective barrier should also be considered.

4.5.1 Crash Cushions

Highway departments have been interested in methods to decelerate vehicles in a smooth manner to prevent injury to the vehicle occupants from impact and rapid deceleration. In highway applications, these crash cushions are used to shield

rigid objects that can be extremely hazardous if struck by a vehicle at road speed. In addition, slowdown devices provide a means of stopping runaway vehicles on steep hills and may have application in perimeter barrier systems.

4.5.2 Structural Systems

Structural systems rely on the friction forces between the anchors and the ground along with the energy of deformation to remove energy from the vehicle. Steel or wooden guard rails anchored to posts along highways are examples of such systems. Concrete median barriers are another structural system, although the mass of such barriers also provides a mechanism for vehicle energy dissipation.

4.5.3 Mass Systems

Mass systems primarily consist of a container, such as steel or plastic drums, empty or filled with sand or water. The energy of the impacting vehicle is dissipated by deformation of the container and the movement of the material contained (see Section 4.3). Most of the systems in use are patented and available commercially. Reference 16 provides a discussion of these systems. Their use in perimeter barrier systems would be in areas that might be susceptible to accidental involvement by the general public. An example would be normal facility entrances. Possible lethal barriers might need to be shielded by crash cushions.

4.5.4 Sand Piles

The slowing and stopping of runaway vehicles on steep slopes is a problem for highway departments. The use of sand piles is one means of mitigating this problem. Although the term "sand pile" is used, the composition can be clean, round gravel. Such a system works on the assumption that the gravel can not support a vehicle traveling on its surface. The vehicle will sink into the material, and the resulting increase in friction will slowly halt the vehicle. In highway applications, it is assumed that the vehicle engine is no longer being used to provide power to the vehicle's wheels, but this would not be the case in perimeter barrier application. However, the loose surface would provide poor traction for any vehicle, thus the effective vehicle tractive power would be low. The use of salt is required in winter to prevent freezing, and periodic litter pickup is required to prevent compaction. A pile in use in Pennsylvania, 328 ft long and consisting of 6200 tons of specially graded gravel 1 ft 4 in. to 13 ft 6 in. deep, stopped a tandem dump truck going 40 mi/h in 110 ft and a 74,450-lb

tractor trailer going 40 to 45 mi/h in 148 ft.[16] Such piles may have some application in perimeter barrier systems.

4.6 Excavations

Vehicle barriers can be constructed by excavations around the area to be protected. A triangular ditch (Figure 48) will stop a vehicle but will allow it to back out. Figure 48 also shows a triangular ditch on a slope. The trapezoidal ditch shown in Figure 48 is a more effective obstacle but requires more effort in construction. In a trapezoidal ditch, a vehicle can be halted by hanging up on the front lip of the ditch or by the front end impacting the bottom or far side of the ditch. This type of failure depends on the dimensions of the ditch as compared to the vehicle dimensions. In order to mitigate erosion of the sides of the ditch, thereby decreasing its effectiveness, revetting of the ditch is necessary. The slope of the ditch sides together with the composition of the excavated material will determine the revetting material. For ditches to remain effective, procedures have to be available to ensure that the attributes that make them effective vehicle barriers are not compromised by natural or human interaction. Natural phenomena, such as heavy rain and snow pack, and litter, such as leaves, could effectively change the depth and/or the slope of the ditch, making it less effective.

Ditch dimensions need to be such that vehicles attempting to cross will be halted. As mentioned above, these dimensions depend on the dimensions of the vehicle the ditch is designed to stop. There are two basic modes of vehicle failure in clearing an obstacle. The first is HUF, when the bottom of the vehicle interacts with the obstacle. The second is NIF, when the nose of the vehicle interferes with the obstacle (see Hang-Up and Nose-In Failure, Sections 2.7 and 2.8). Steepening the side slopes of the ditch and increasing its depth combine to make it more effective as a barrier. The width of the ditch should be such that it cannot be readily spanned by bridging techniques. Widths of 13 to 20 ft at the top with widths of 7 to 10 ft at the bottom are typical ditch dimensions. Slopes greater than 50° with depths greater than 5 ft are capable of stopping most vehicles.

4.7 Structural Obstacles

Vehicle obstacles can be made from any construction materials.[18] The most straightforward use of such materials as timber or steel posts is embedding the structural members in linear arrays around the perimeter of the area to be protected. Wooden posts should be at least 15 in. in diameter. Embedding can be done vertically or at such an angle that approaching vehicles would impale themselves on the structure.

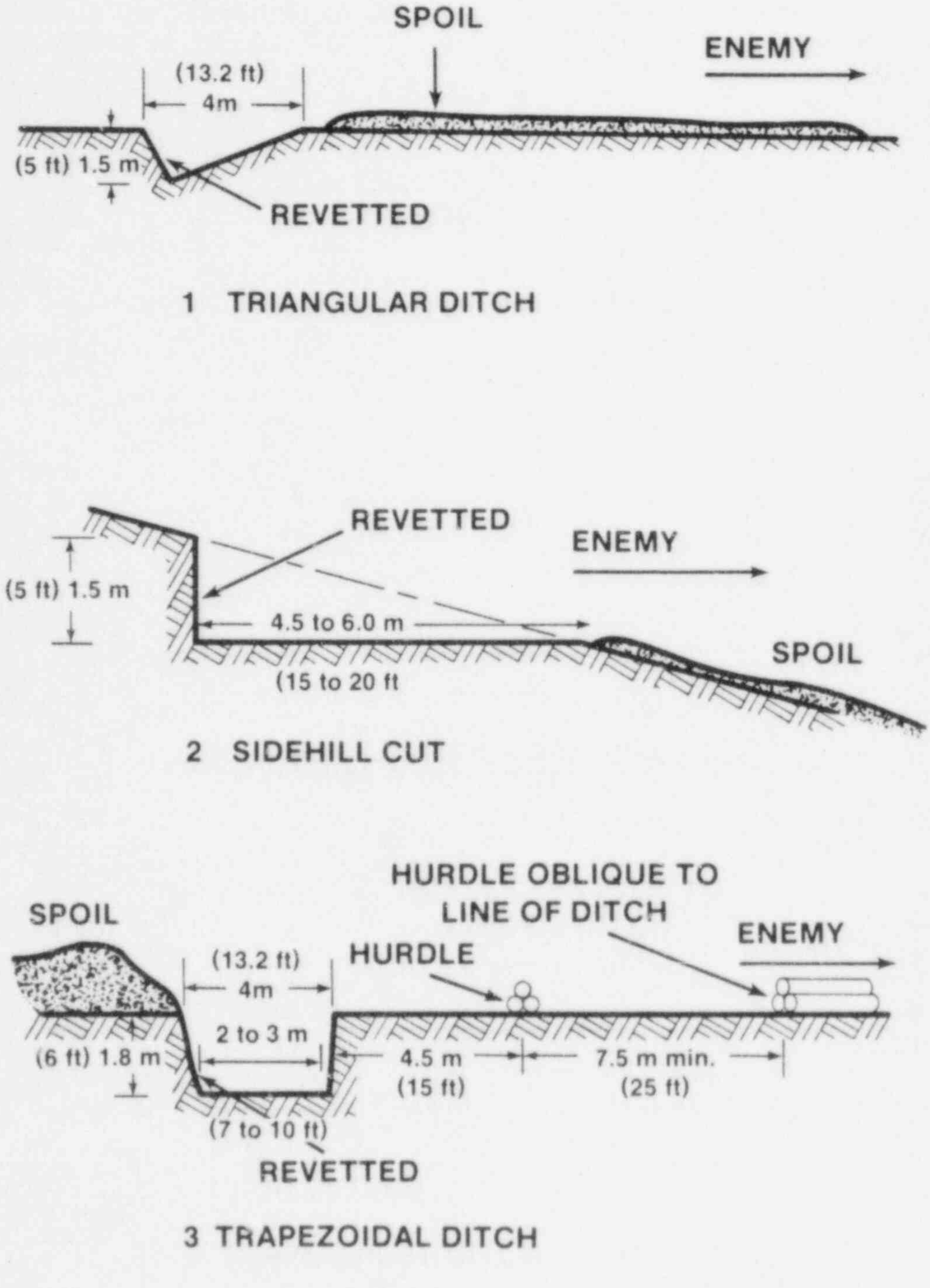


Figure 48. Antivehicle Ditches[17]

The posts should be buried at least 5 ft into the ground and extend 3 to 4 ft above the surface. The minimum acceptable density of posts is 200 posts per 328 ft of perimeter. The spacing should be irregular with at least 3.3 ft and not more than 6.6 ft between posts. By having predug, pipe-lined holes, posts could be inserted in a relatively short time and thus provide a removable barrier.

Steel hedgehogs (Figure 49) are relatively lightweight considering their effectiveness. They are designed to revolve under wheeled vehicles and puncture them. Hedgehogs can be quickly installed or removed and therefore might be considered for backup or temporary use when compensatory barriers are needed. A hedgehog is constructed of three 4x4x0.4-in. 4-ft-long angle steel plate and weighs approximately 160 lb. They are used in rows with at least 150 hedgehogs to each 328 ft of perimeter.

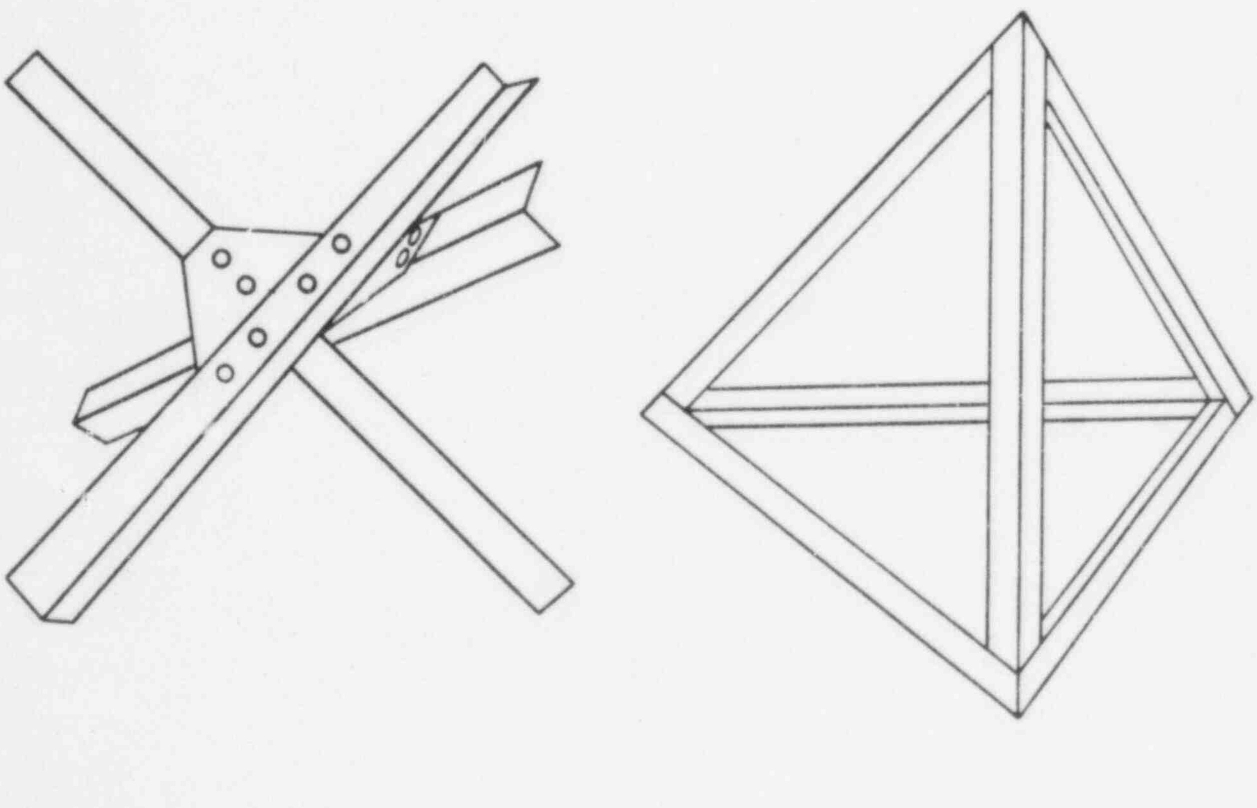


Figure 49. Hedgehogs and Tetrahedrons[17]

Steel tetrahedrons (Figure 49) can be employed in a similar manner. They are usually made of 4x4x0.6-in. angle iron approximately 5 ft on a side. Their finished height is approximately 4 ft.

Concrete shapes such as those used for highway dividers can also be used. They are designed for small-angle impact of light vehicles and may need strengthening for barrier application (see Section 4.3).

Used heavy-equipment tires could be used as vehicle barriers. These large tires, 7 to 8 ft in diameter, are half buried in the soil. Their effectiveness has been demonstrated against light trucks.

The effectiveness of these discrete barriers can be enhanced if they are linked together by cable or chain. This linkage provides a method of distributing the load transmitted to a single obstacle to adjacent obstacles. This linkage also increases the difficulty of narrow vehicles trying to transverse the obstacle field.

4.8 Mass Obstacles

Mass obstacles rely on their inertia to slow or stop impacting vehicles. The transfer of energy and momentum from the vehicle to the barrier mass decreases the vehicle speed. The amount of momentum that can be transferred and the time determine the severity of the crash environment to the vehicle and driver.

Crash cushions that depend on momentum transfer for stopping the vehicle decrease the vehicle's momentum in increments to prevent extreme damage to the driver and the vehicle (see Inertial Barriers, Section 4.4). In addition, the forces involved in the impact can cause vehicle structural damage, making it inoperable. Examples of other mass obstacles are concrete obstacles of various shapes. Depending on their mass they can be utilized to stop or slow down approaching vehicles. A cube of concrete 4 ft on a side requires about 2.4 yd^3 of concrete and weighs approximately 5 tons. A concrete cylinder 3.3 ft in height and with a diameter of 4 ft requires 1.3 yd^3 of concrete and weighs approximately 3 tons. The effectiveness of such barriers can be enhanced if they are anchored to the ground.

4.9 Realism and Uncertainty

The models discussed in Section 2 of this report are either empirically established relations between vehicle/terrain parameters or physically derived relations under a number of limiting assumptions. It is necessary to idealize both the

vehicle and terrain parameters in order to quantitatively describe them. The models presented provide a means of determining the effects of different terrain features on the behavior of vehicles. The results determined by using these models are representative of the vehicle/terrain interaction. They should not be considered absolute in the sense that, for example, a tree with a given diameter will always stop a vehicle with a given kinetic energy. Variations in the tree due to species, age, disease, and soil/root binding will affect the tree's performance. The uncertainty in results due to the characterization of the vehicle and the terrain must be considered when the results are to be used to provide a measure of vehicle performance degradation. The complete vehicle barrier system implemented at a given site must, while giving credit for natural features, be sufficiently robust to provide protection against a postulated vehicle threat.

In addition to the uncertainties due to vehicle/terrain model parameterization, the uncertainties due to this particular application of the models must be considered. The models and the simulation program used in Section 3 were developed primarily to determine safe effective vehicle performance in a military mission context. The driver's physiological and psychological reaction to the terrain's effect is taken into account. The vibration of the vehicle caused by the terrain is used to determine the driver's performance. This tolerance to vibration is not only a function of the degree of vibration but also its duration. In the simulation it is assumed that the surface roughness continues for a long enough distance to incapacitate the driver if the vibration level is sufficiently high. Whenever it is appropriate in the models, driver safety and comfort are explicitly or implicitly considered. The willingness of the driver of the threat vehicle to tolerate a relatively short interval of physiological or psychological discomfort to reach the goal must be considered. Such considerations argue for a robust vehicle barrier system.

5. APPLICATION OF RESULTS

The efficient and economical design of vehicle barriers requires information on the expected maximum speeds at which specific vehicles may be moving when a barrier is encountered.

The graphs of maximum vehicle speed versus terrain slope presented in this report can be used as input data in the design of vehicle barriers at licensed sites. Estimates are provided of the speeds of three classes of vehicles as a function of those parameters of natural terrain which have the most significant effects on vehicle speeds. Additional factors which limit vehicle speed, such as vegetation, visibility, and other obstacles, were not included in the parameter study because the benefits they afford are temporary and not generally predictable. The data developed in this study can be utilized to estimate the worst case vehicle threat for use by the vehicle barrier designer.

The significant result of the swamp-crossing analysis is that crossing speeds are determined primarily by wet soil strength and roughness of the swamp surface. Typically, swamps will have low soil strength, which greatly limits vehicle speed. However, frozen swamp conditions allow the vehicles to attain a speed which is limited primarily by surface roughness.

Streams and ditches constitute natural barriers to vehicles. The data on stream- and ditch-crossing performance presented in this report can be used to evaluate the efficacy of natural or man-made ditches of specified geometry in preventing threat vehicles from reaching a target. The data of Table 4 present the limits of stream-crossing performance for each class of threat vehicle in terms of the relevant geometrical parameters and soil strength. This data can be used to qualify a large number of real-world situations into "GO" or "NO-GO" or "NEED-MORE-DATA" categories.

In order to define the actual limitations to vehicle mobility and speed over terrain adjacent to a specific plant site, it is necessary to make measurements of terrain characteristics adjacent to that site. Practical, inexpensive methods to make limited measurements are available, but the number and type of each measurement may be very large. The data in this report should be useful in reaching decisions on which further measurements (if any) need to be made.

The plan for the selection of terrain measurements at specific sites should have a goal of first classifying all terrains of interest into one of a minimal number of types (e.g., four or five). Then a program for obtaining measurements for each terrain type should be performed. This method has the potential benefit of not requiring extensive terrain measurements

for every plant site. This work would take advantage of the insights gained in the current study.

As with any strategy involving plans and actions to prevent a determined adversary from accomplishing a goal, consideration must be given to the adjustments the adversary may make to the barriers placed before him. Such adjustments by the adversary, termed countermeasures, include modifications to the vehicle that increase its hardness to barriers or increase its mobility over terrain, and modifications to the terrain that reduce the natural obstacles afforded by the terrain. It is recommended that potential countermeasures to planned or existing barriers be identified and evaluated for their feasibility and effect on barrier effectiveness.

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APPENDIX A

GRAPHS FOR SECTION 3

This appendix consists entirely of 54 graphs of maximum speed versus terrain slope, for three classes of vehicle, six categories of soil, and three values of surface roughness. For a discussion of these graphs, refer to Section 3.4 of the basic report.

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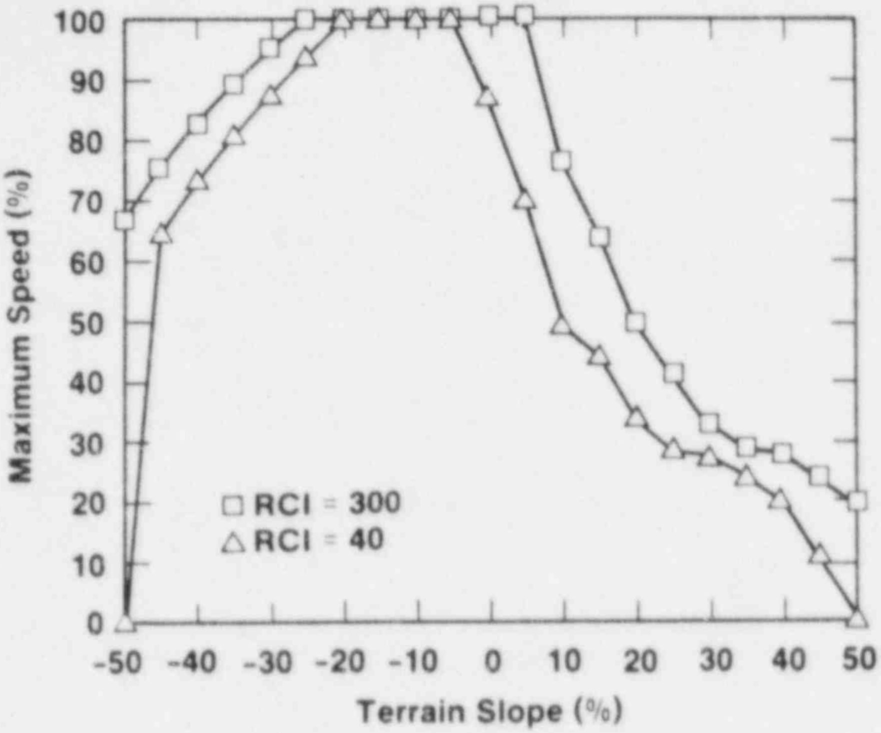

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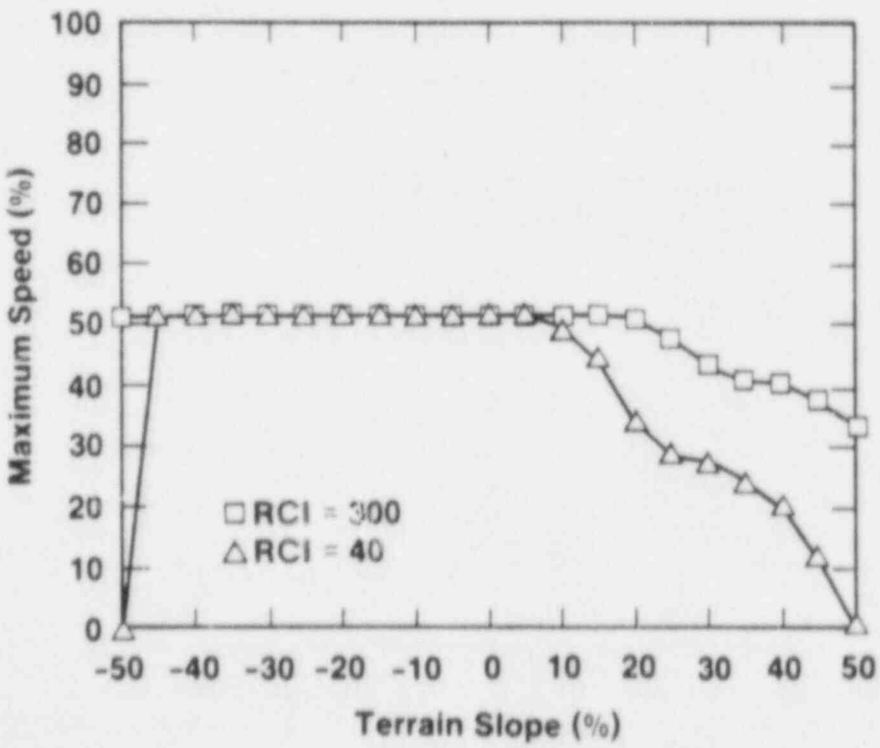

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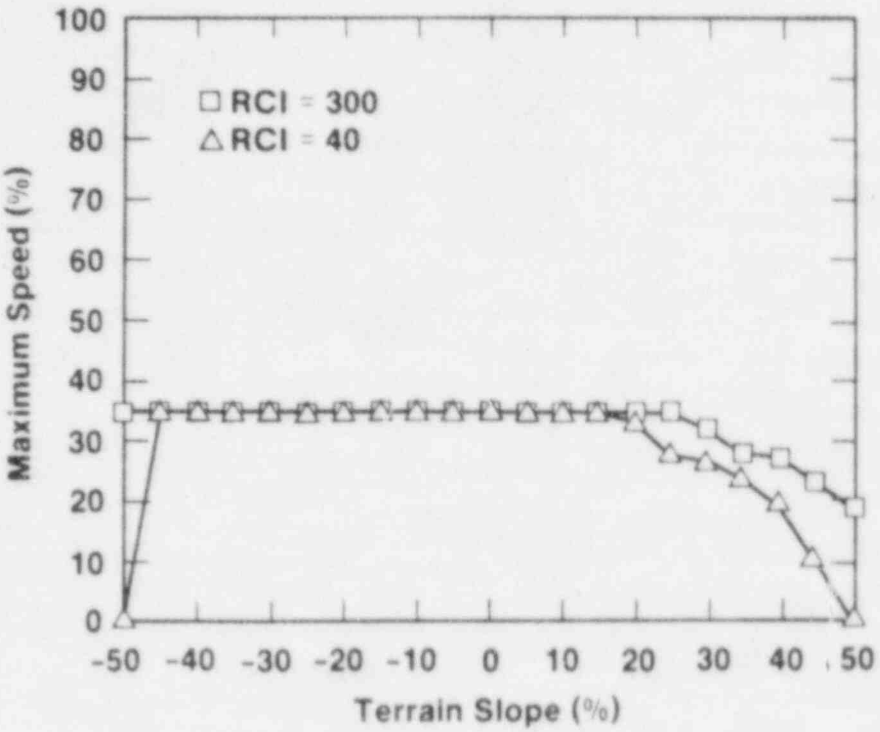

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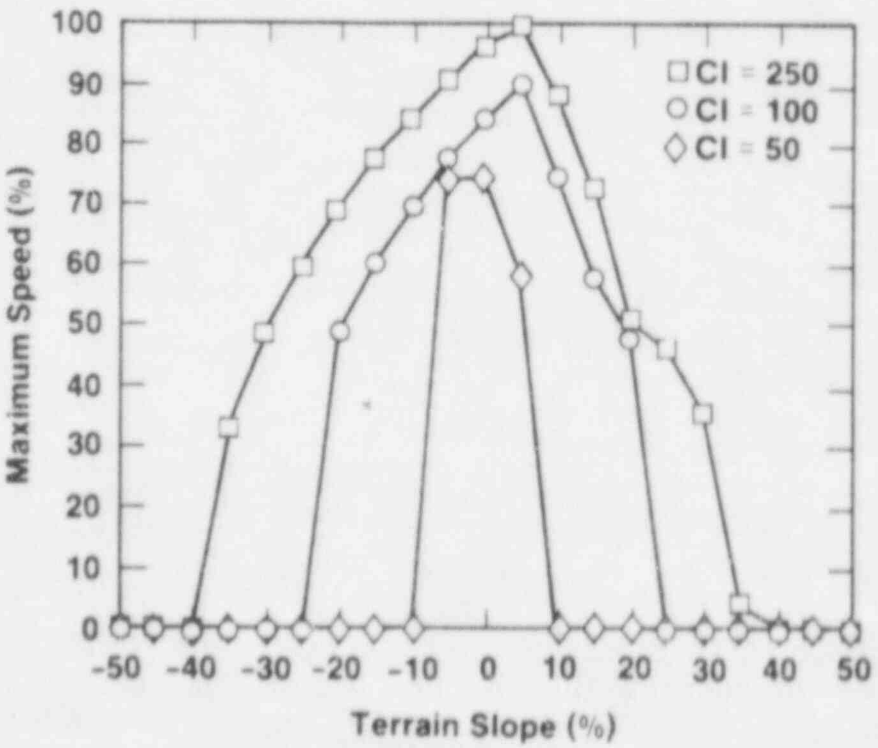

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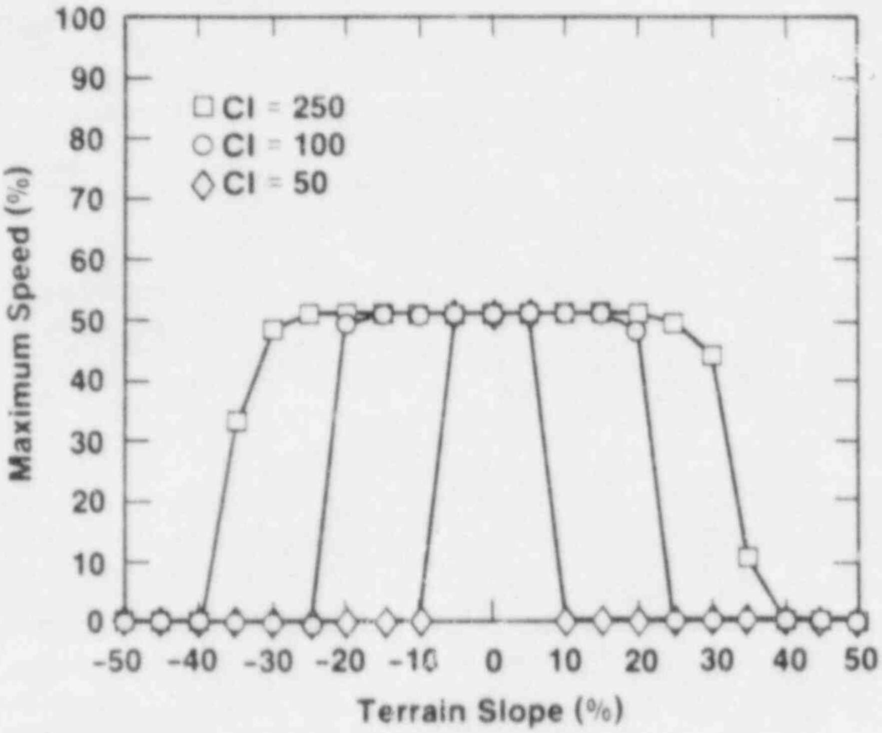

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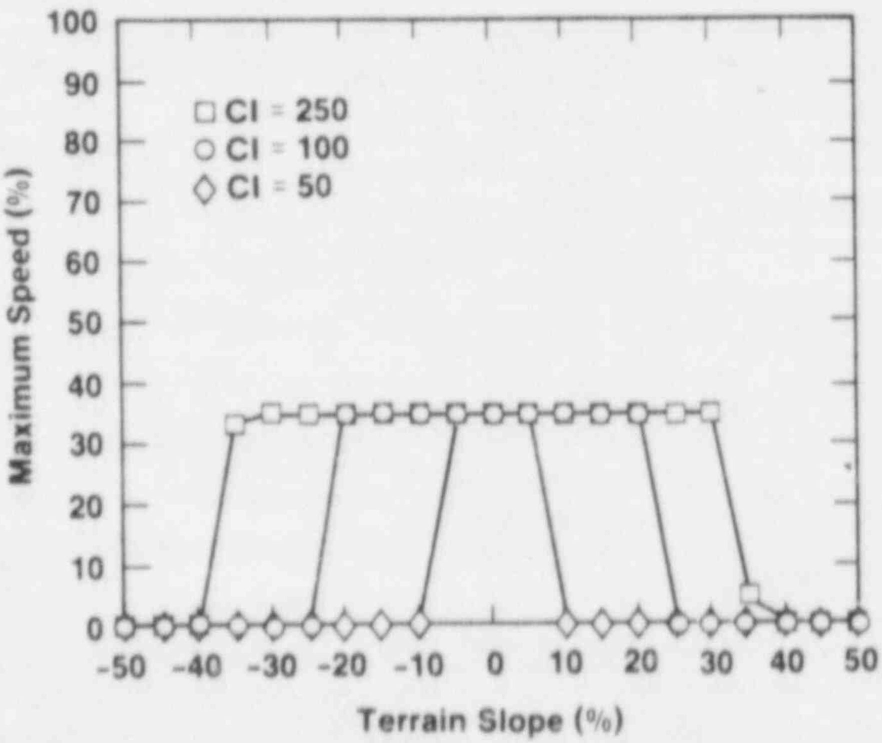

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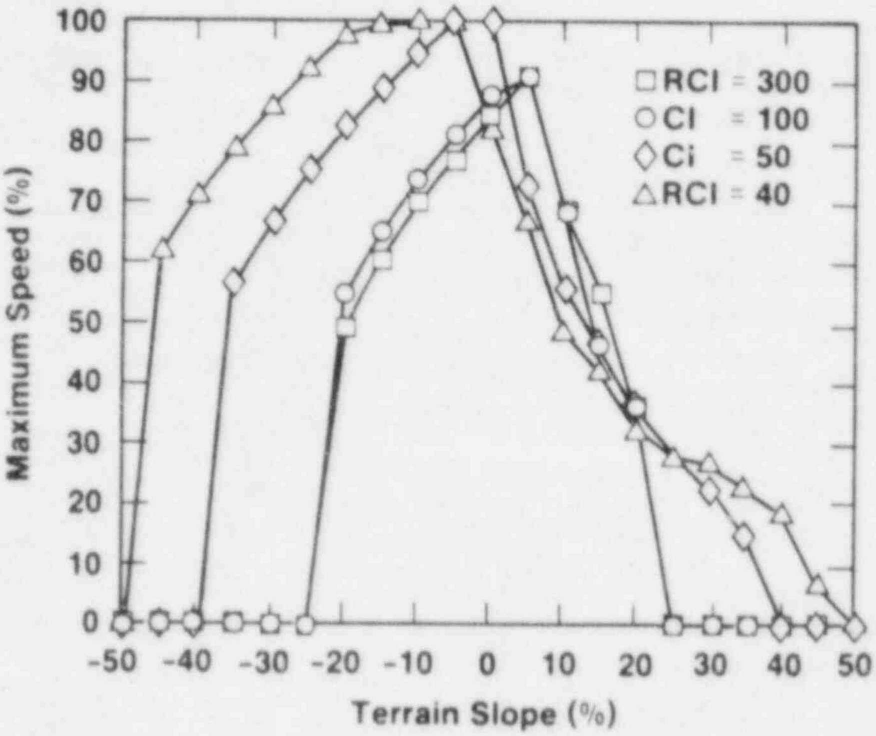

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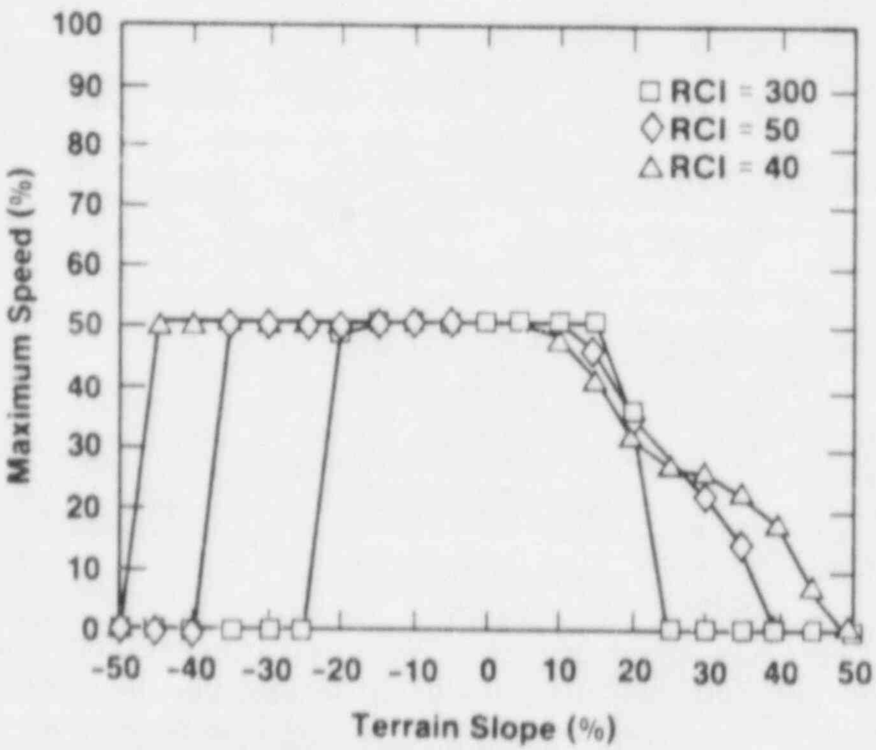

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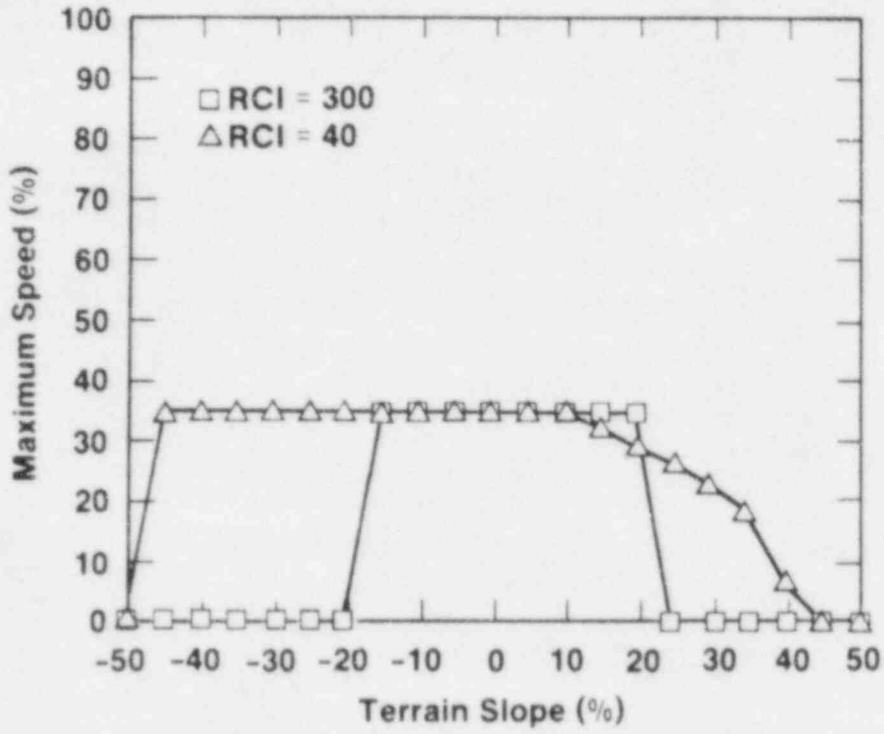

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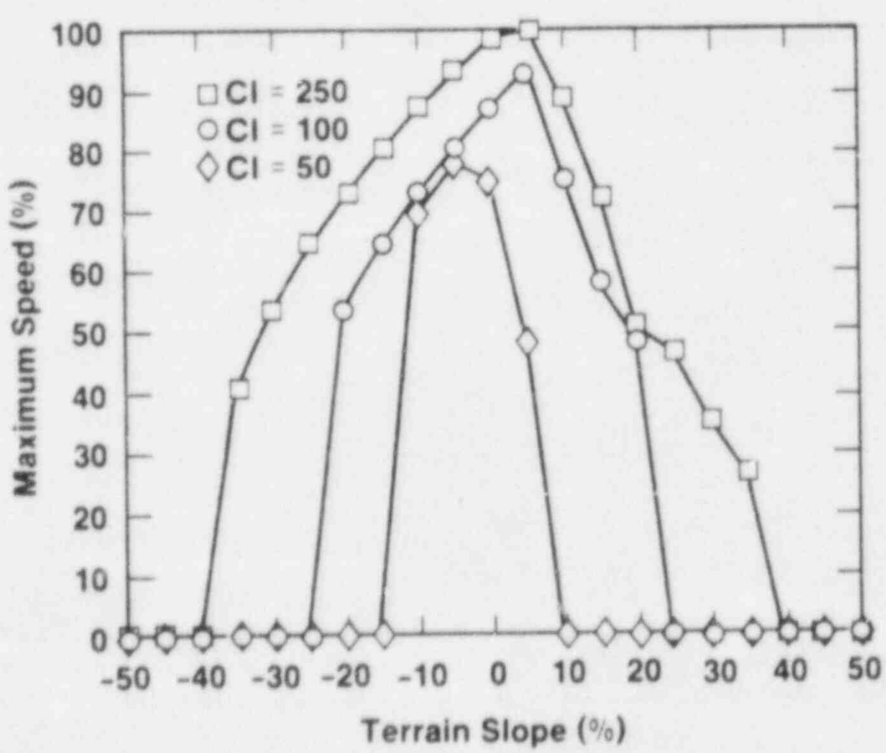

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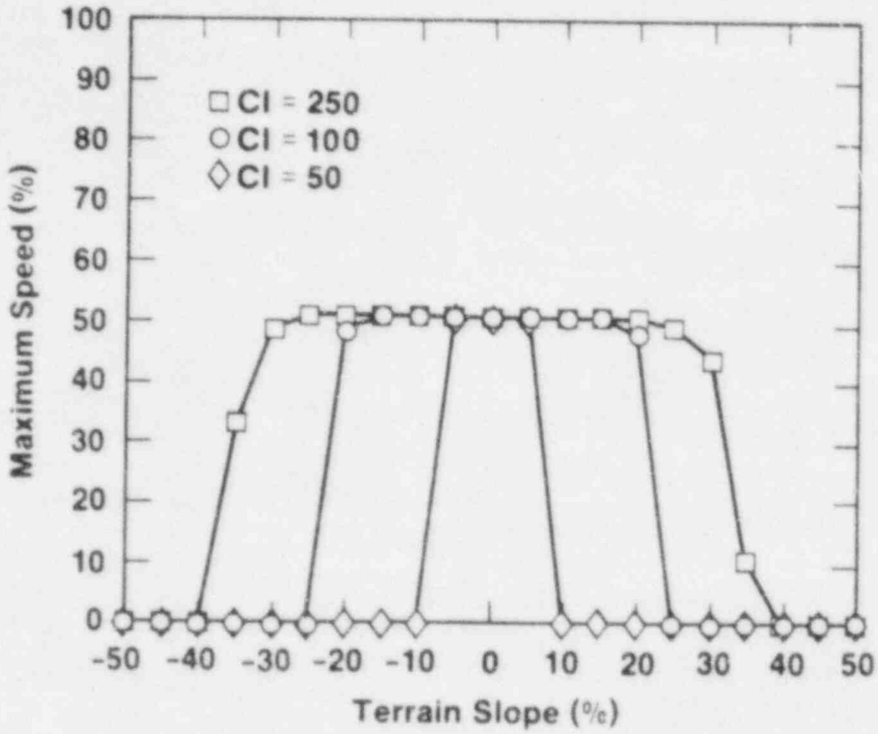

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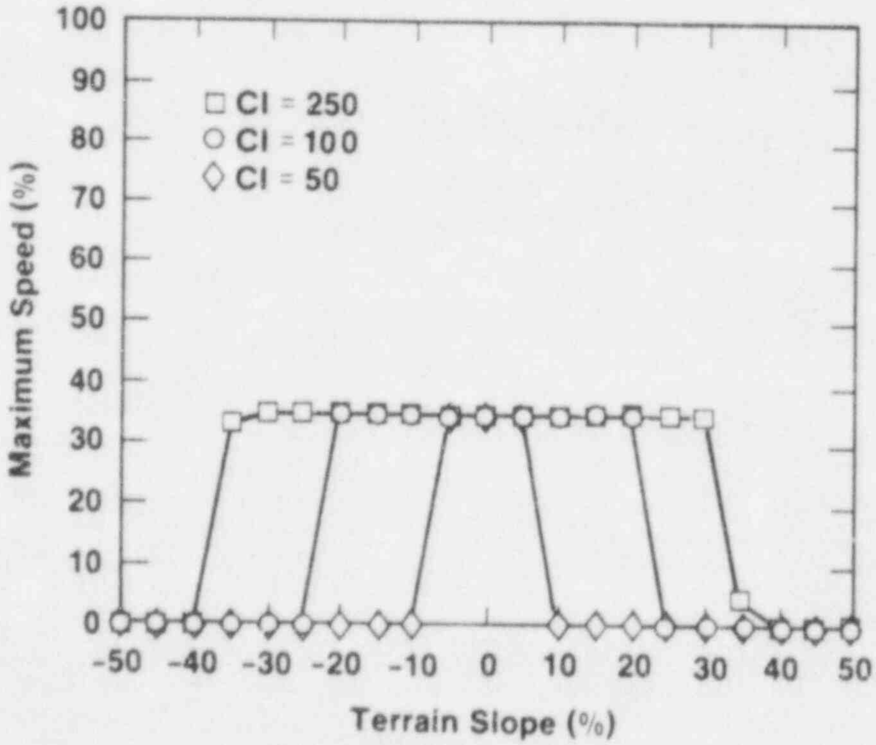

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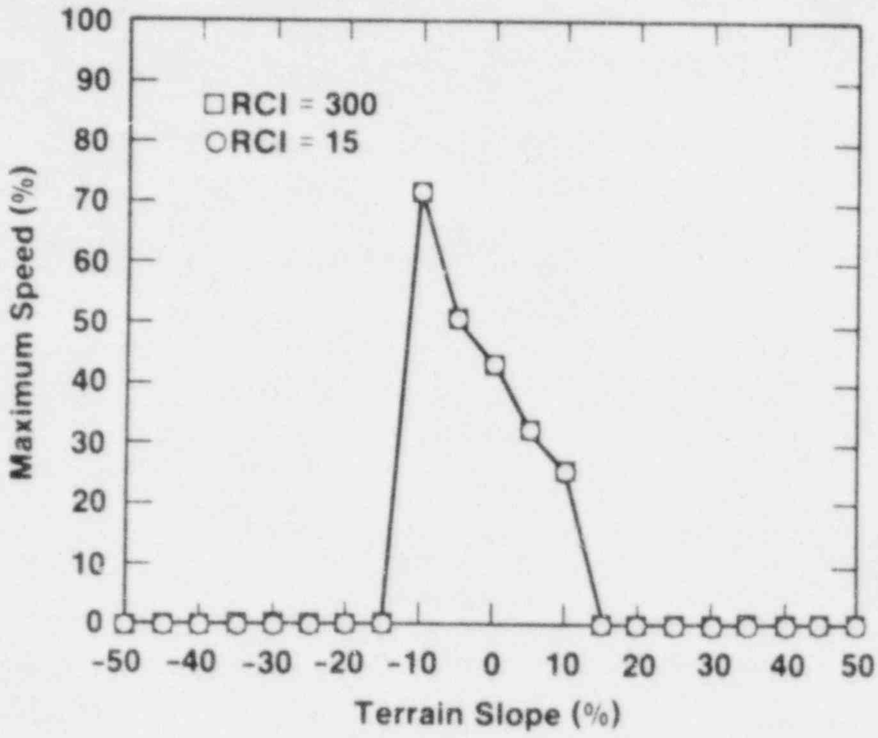

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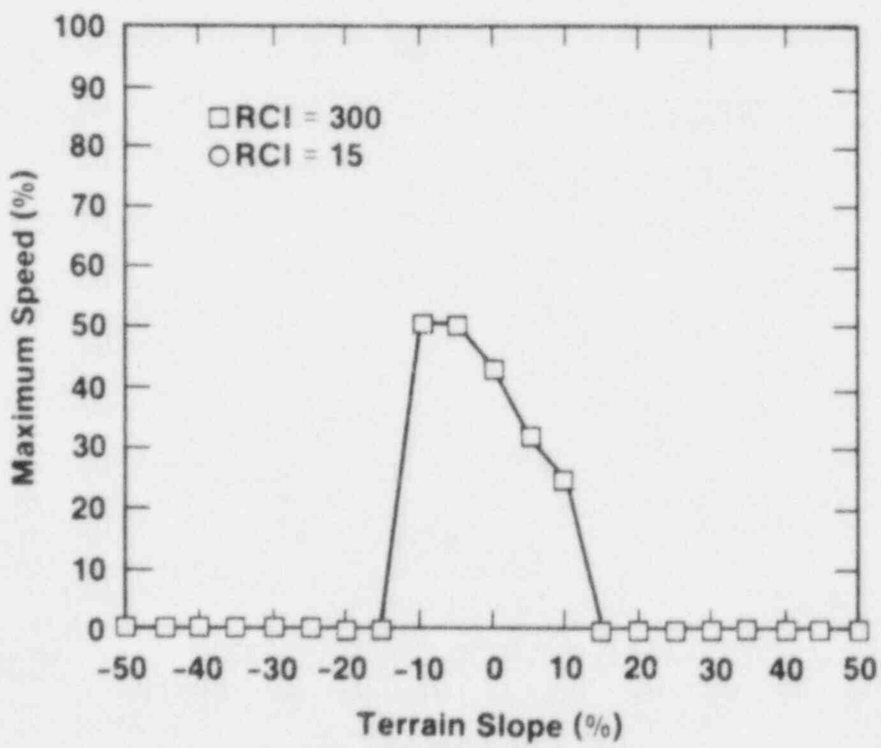

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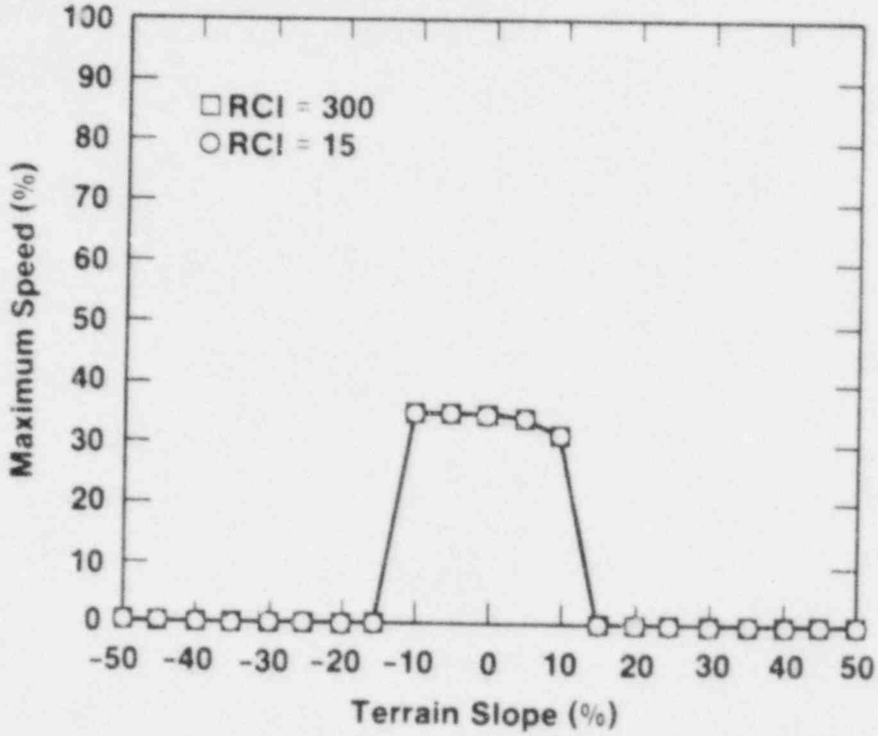

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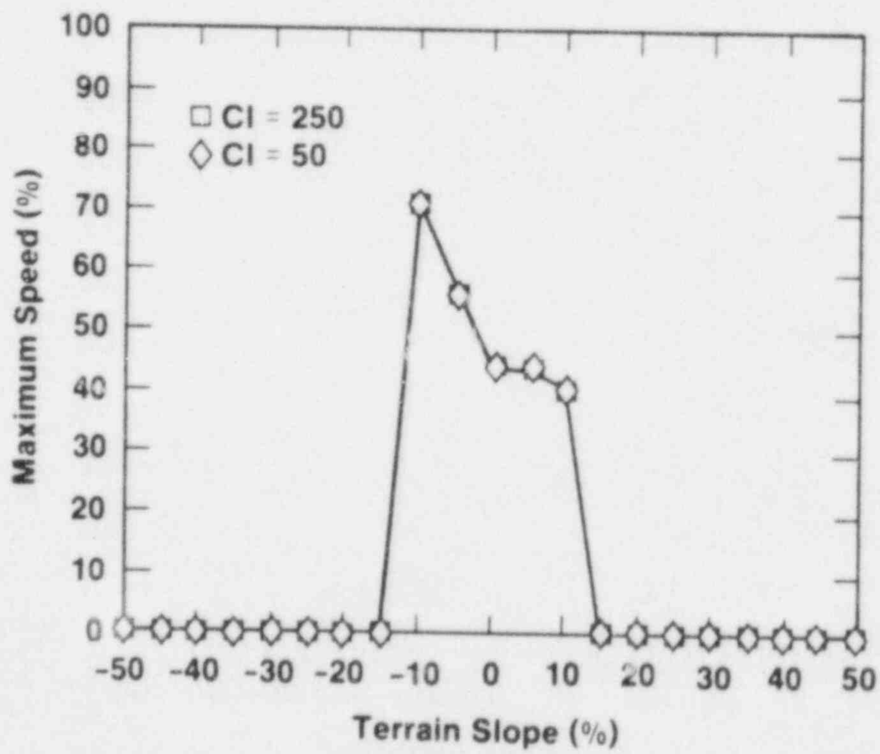

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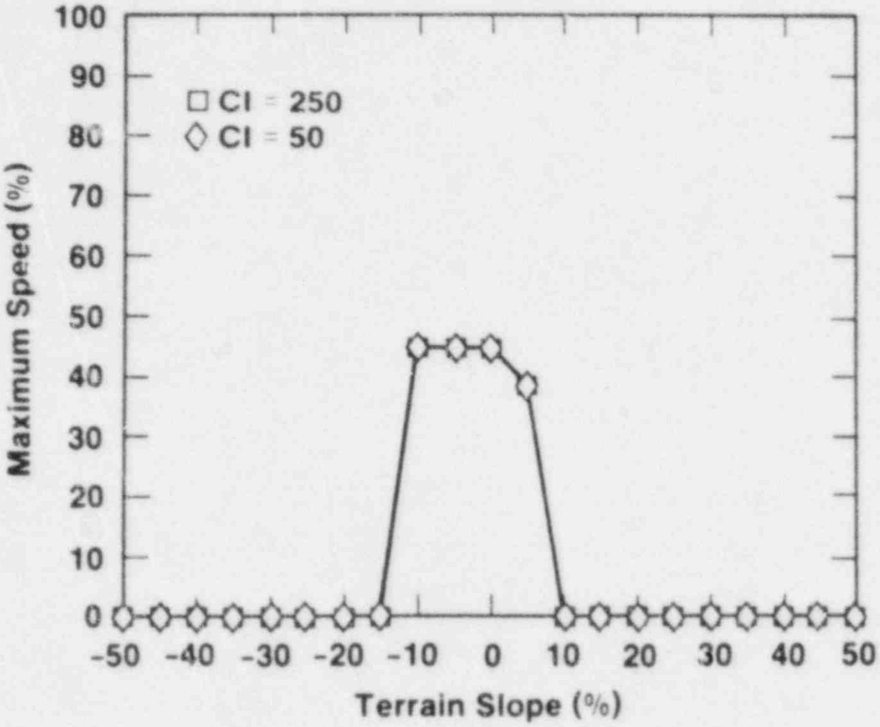

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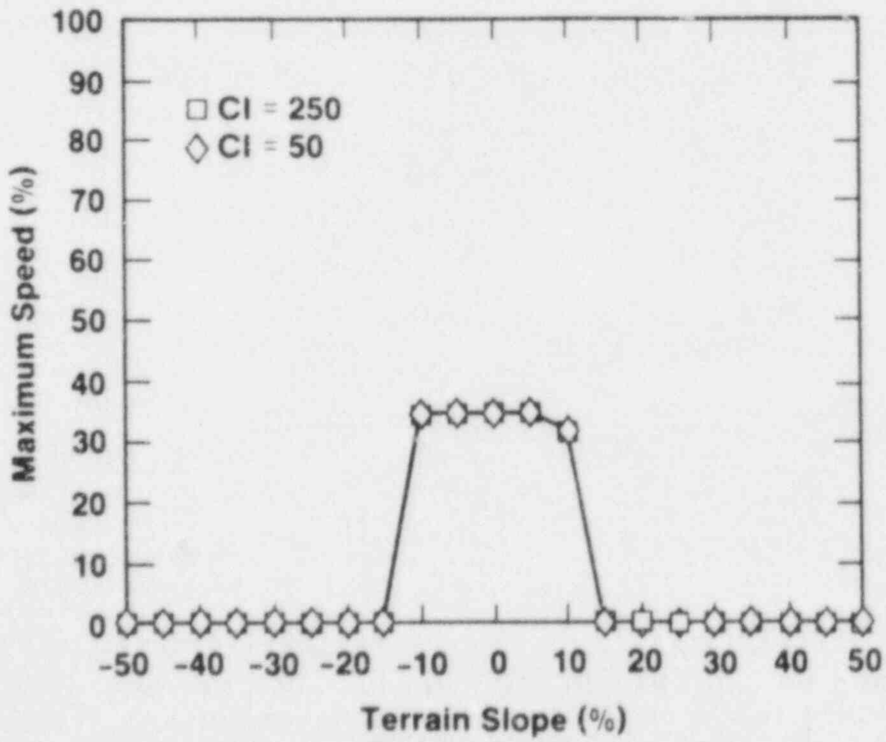

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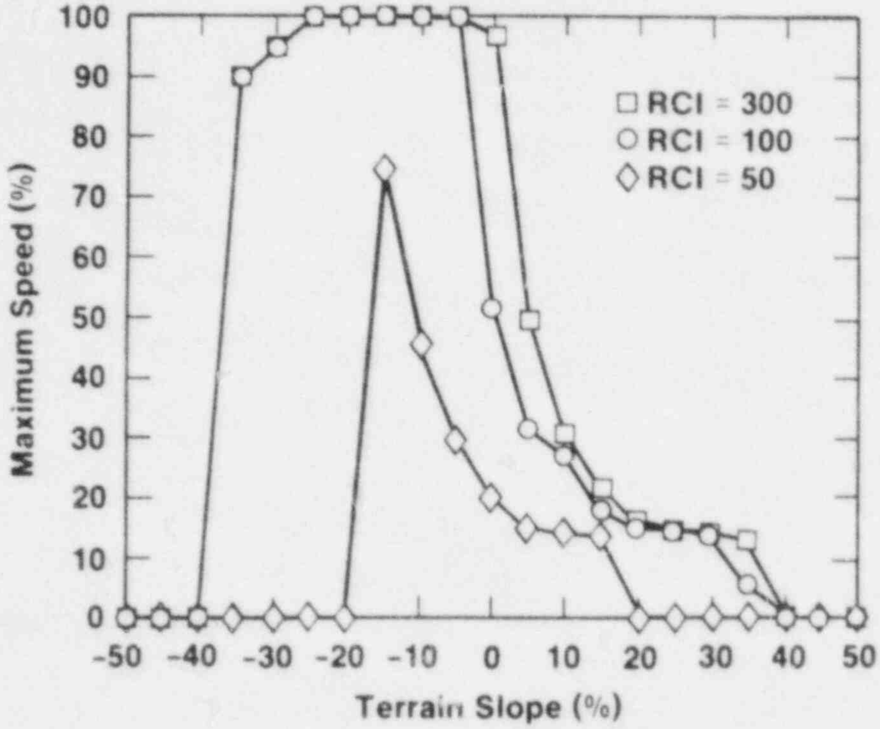

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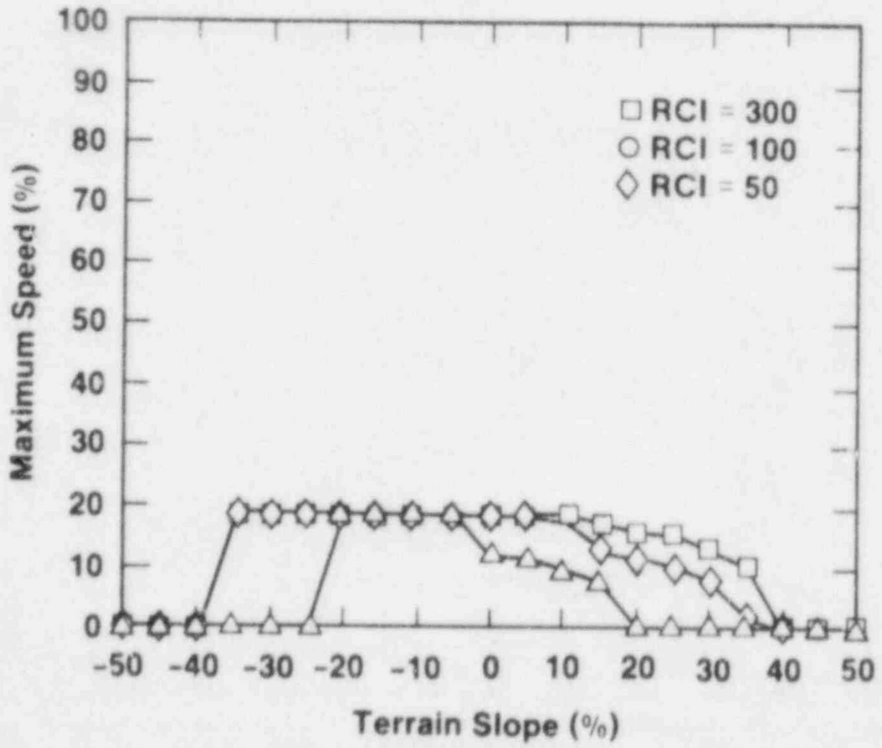

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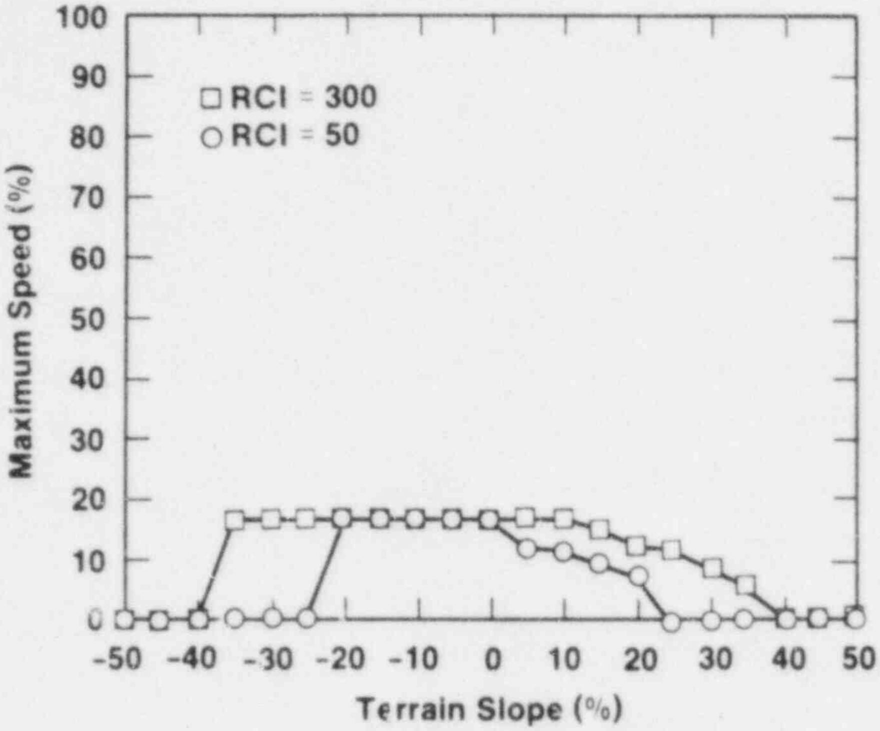

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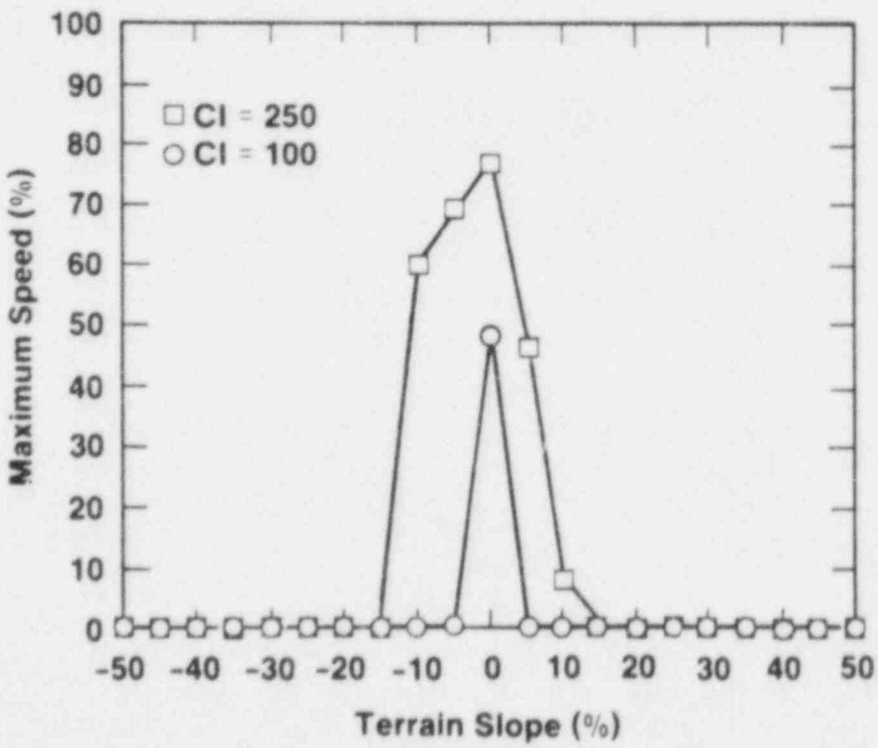
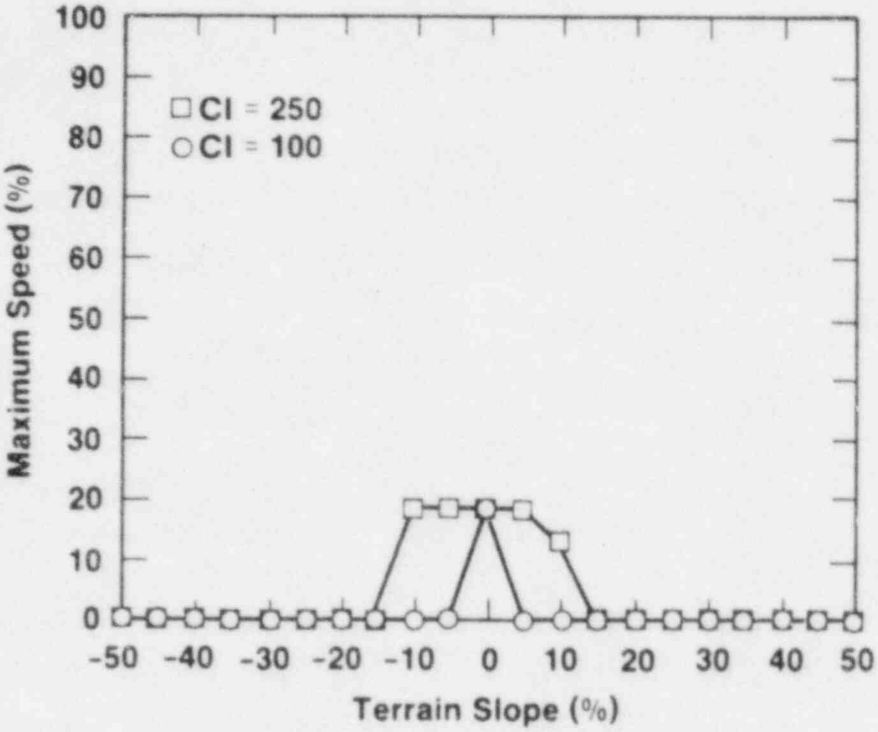


Figure A-22. Maximum Speed vs Terrain Slope: 4-1/2-Ton Truck; Dry, Coarse Soil; Surface Roughness 0.3 in. rms



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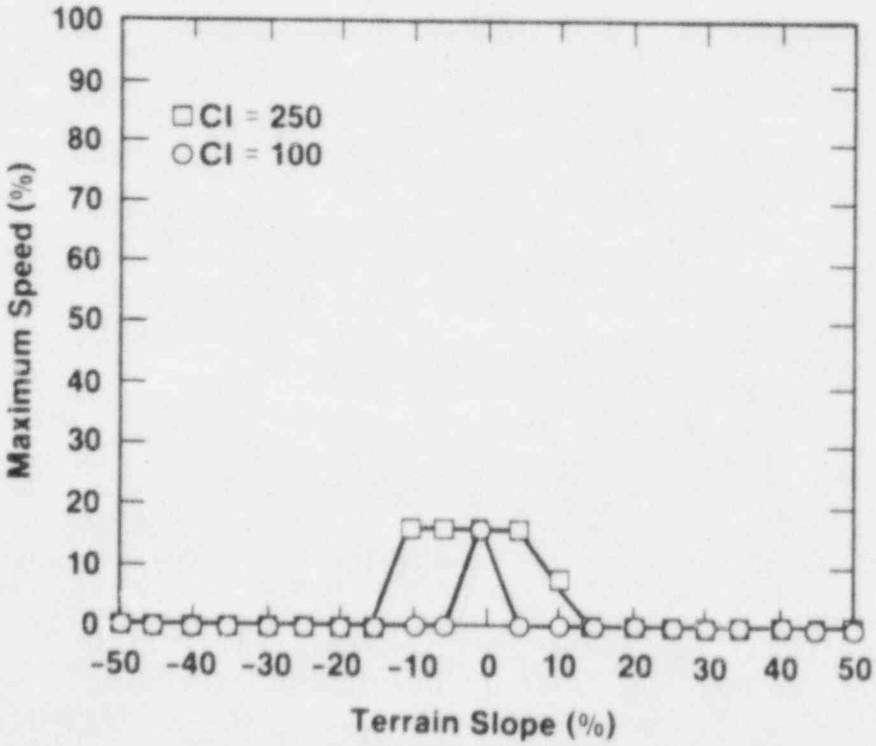

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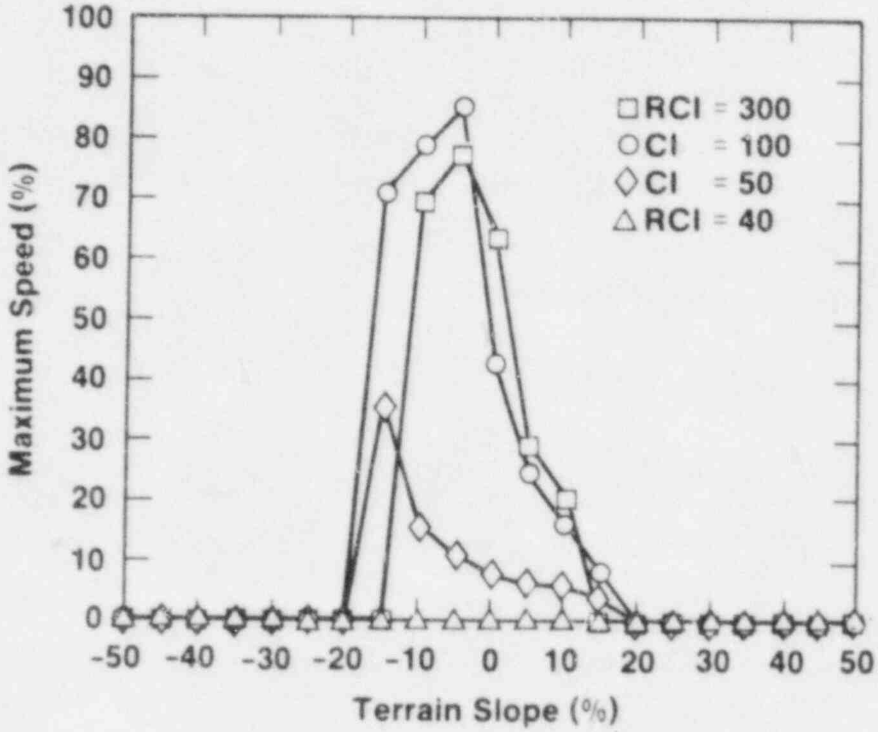

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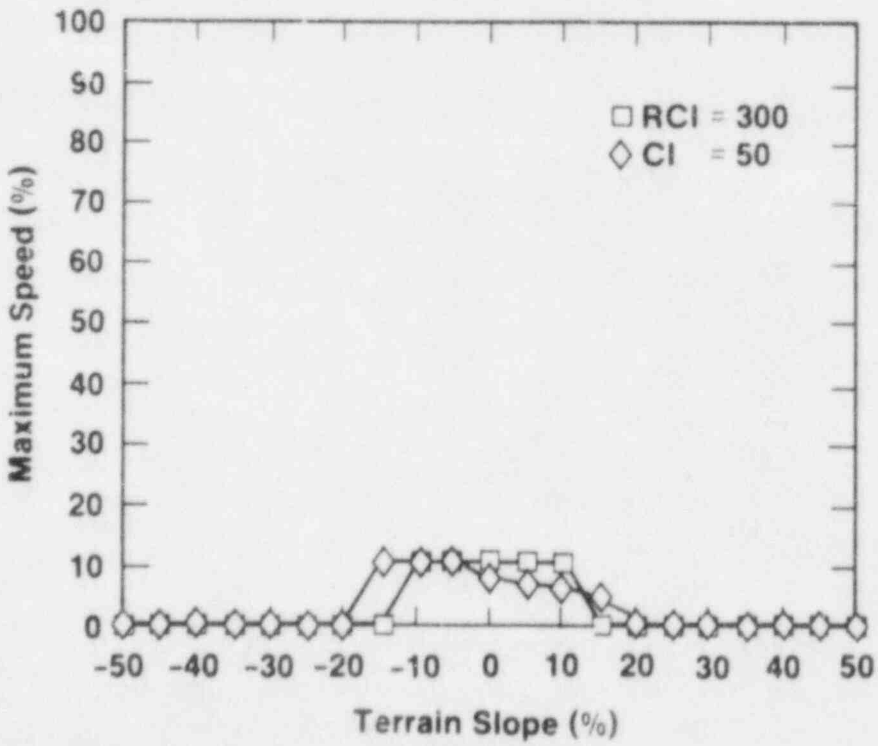

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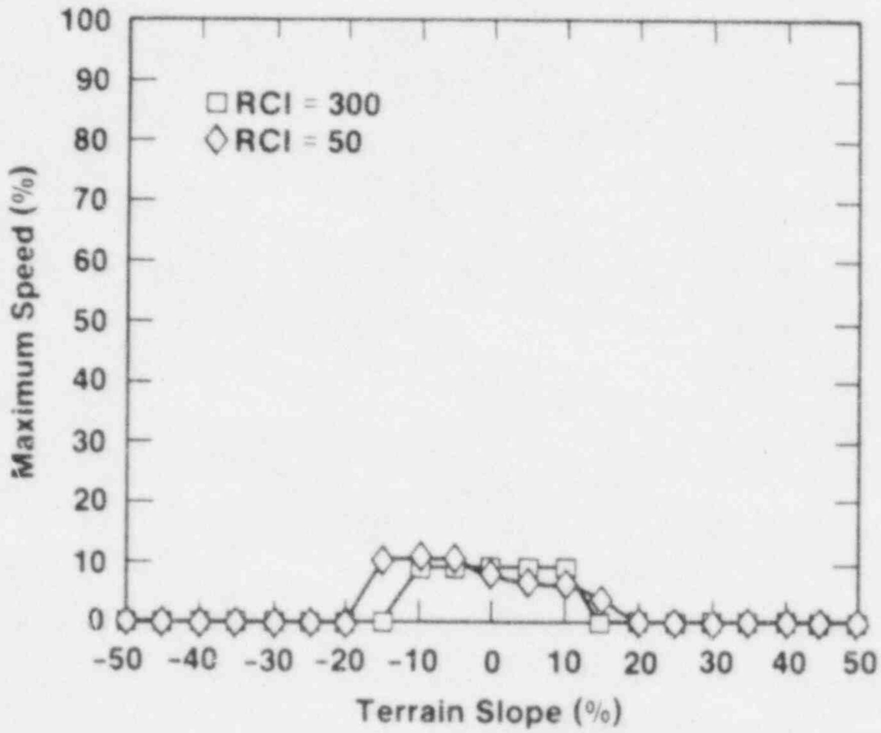

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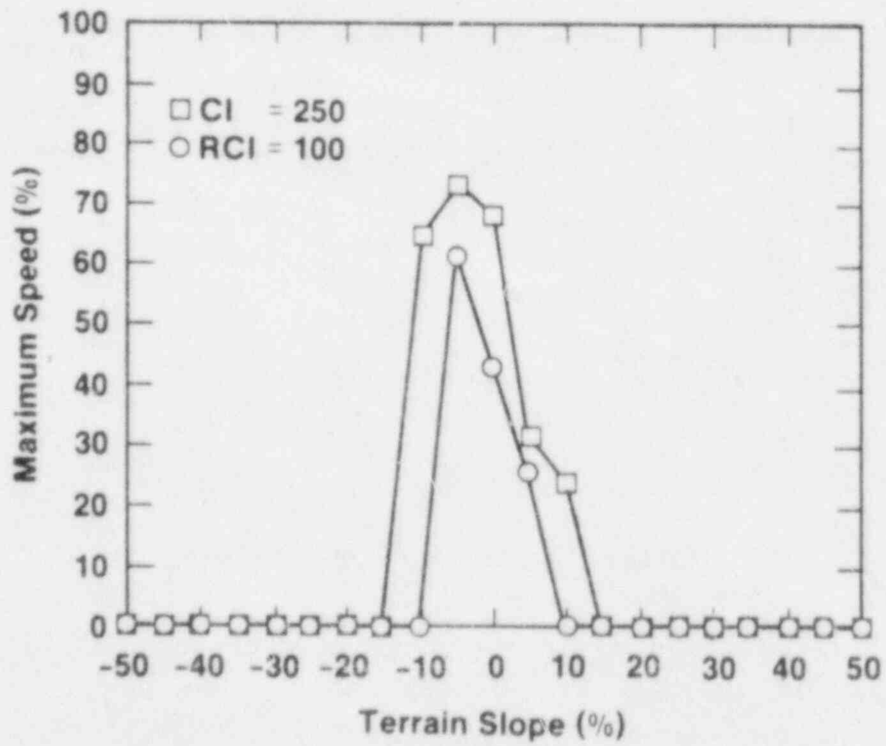

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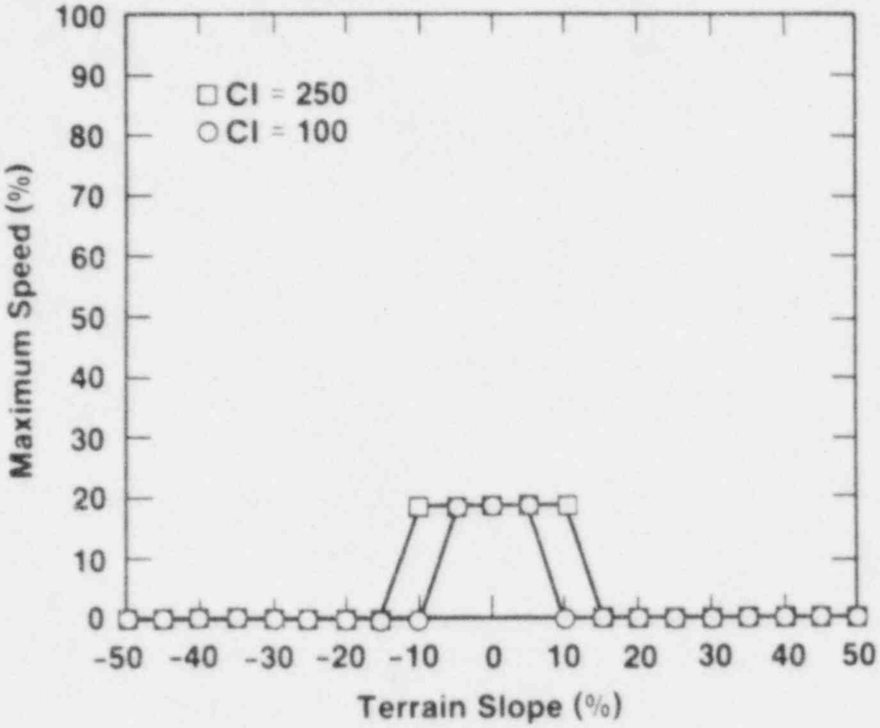

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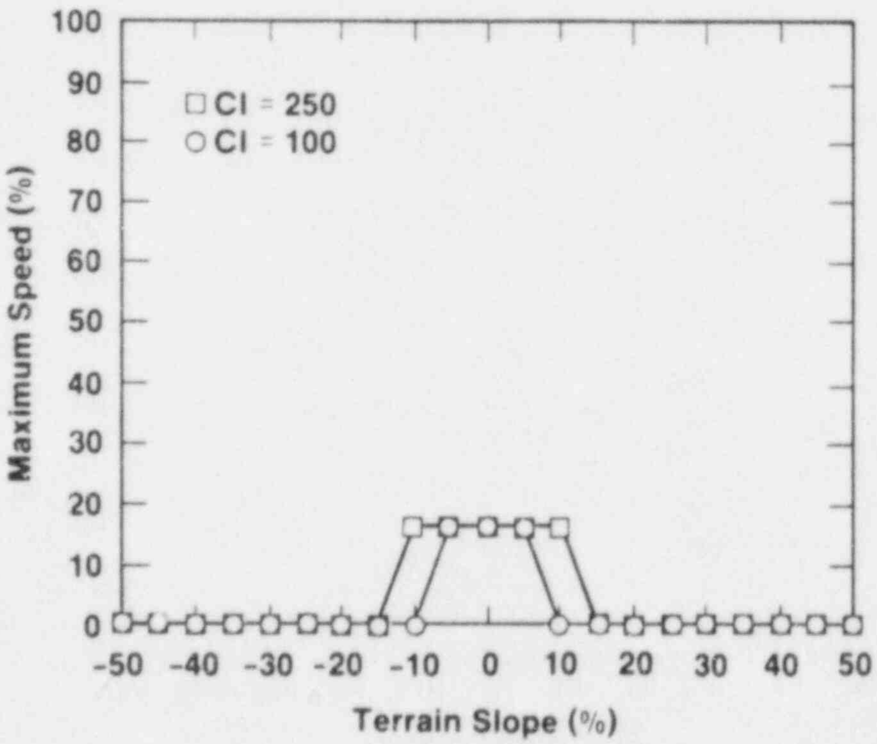

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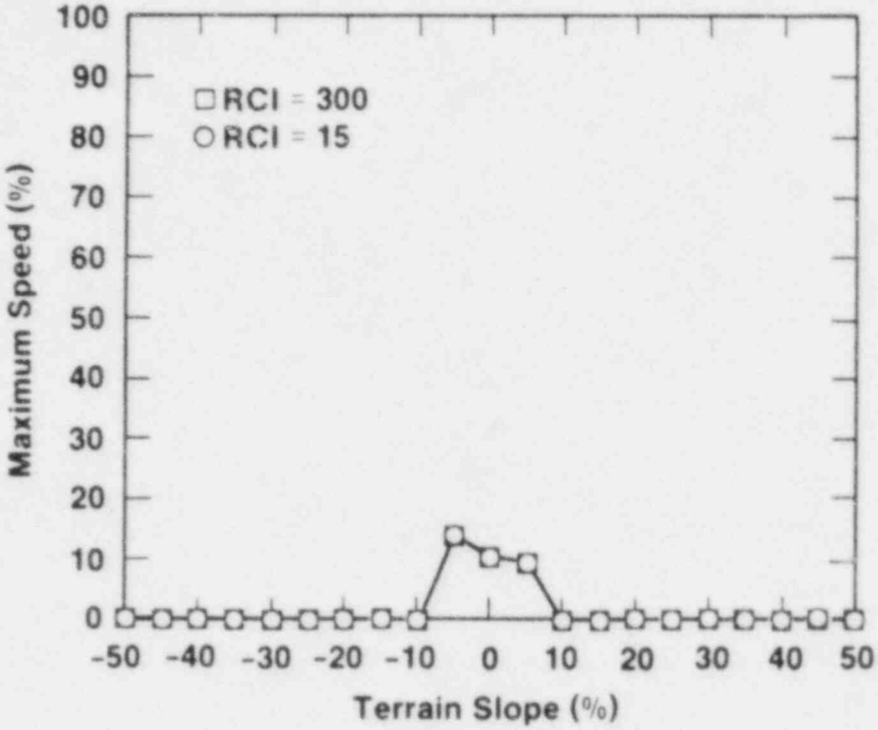

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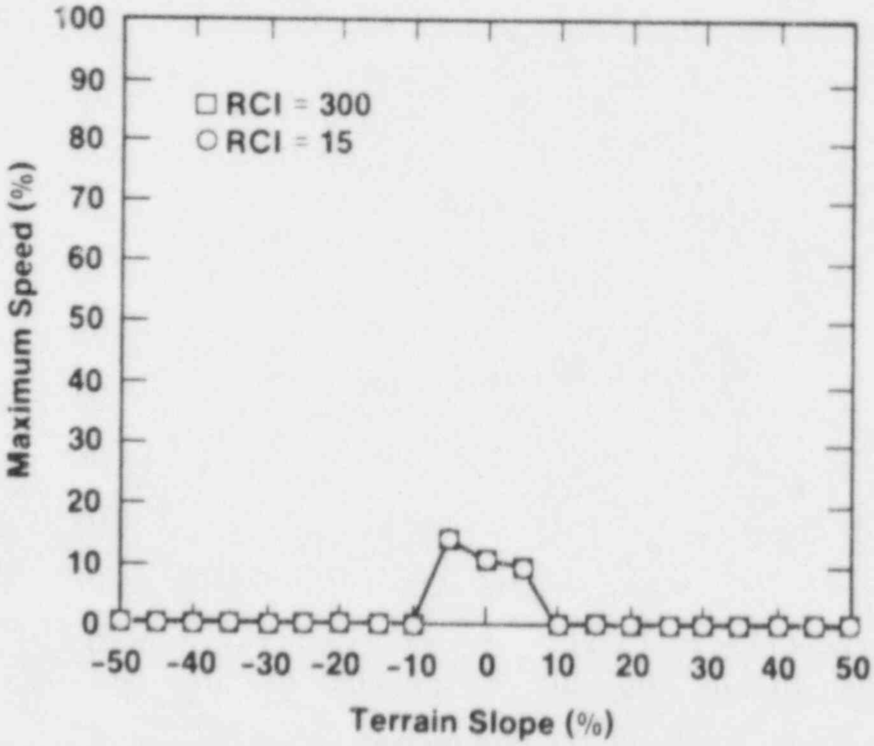

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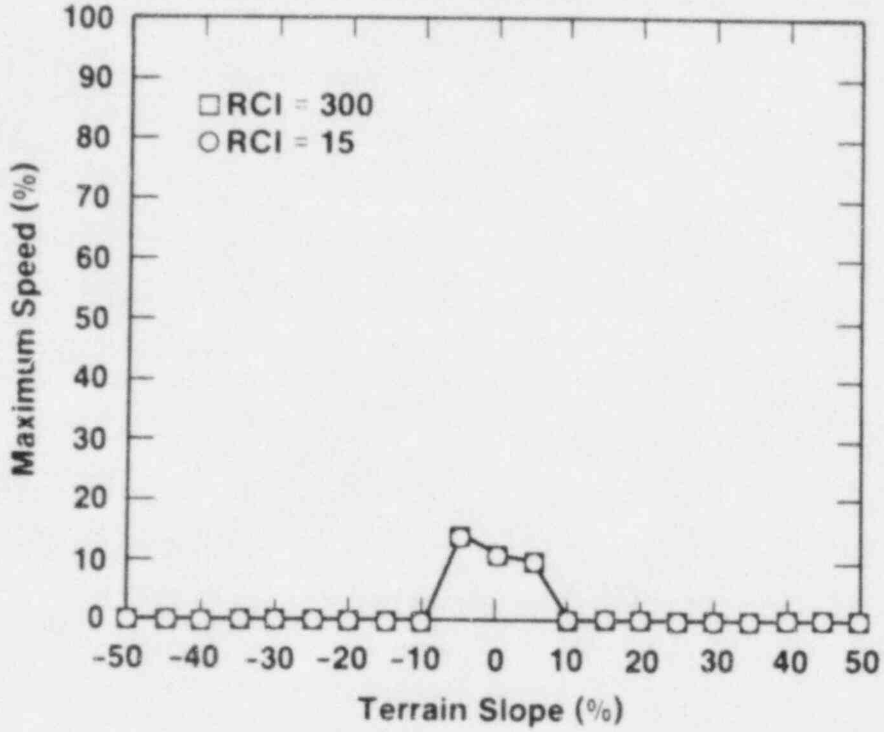

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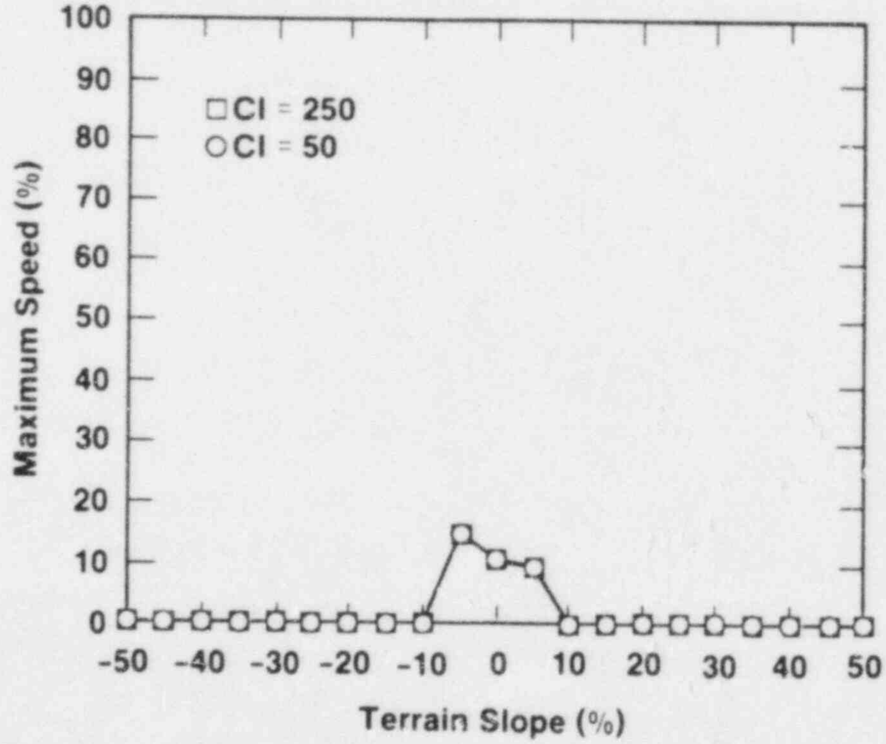

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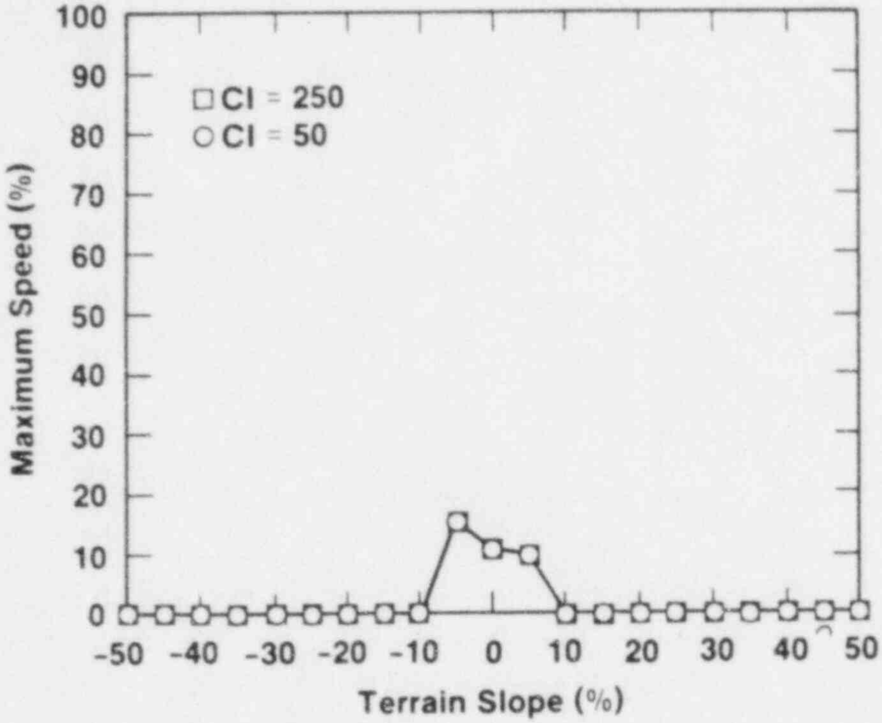

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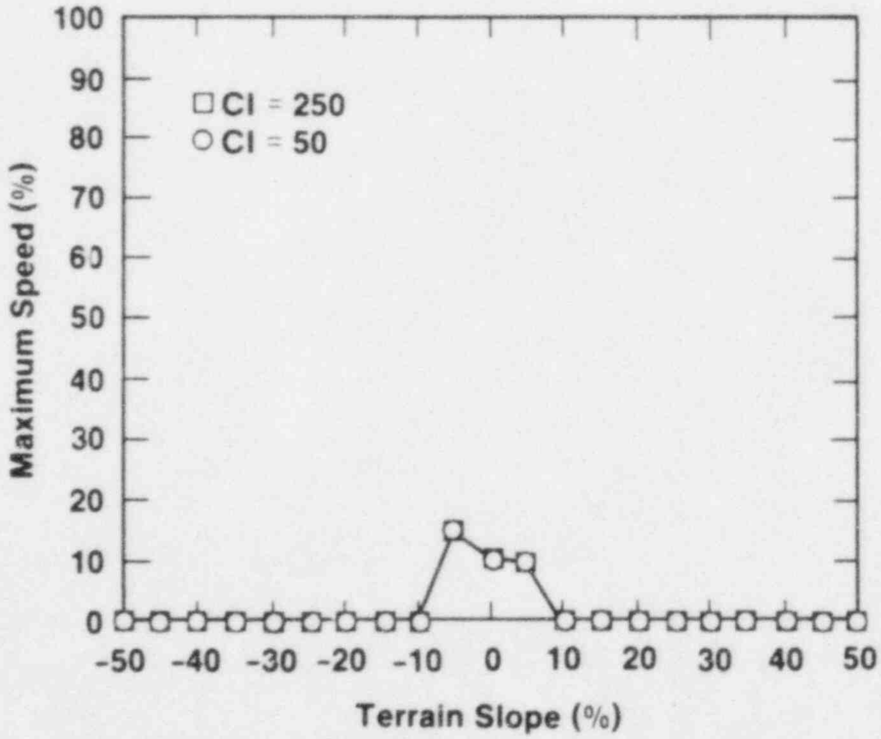

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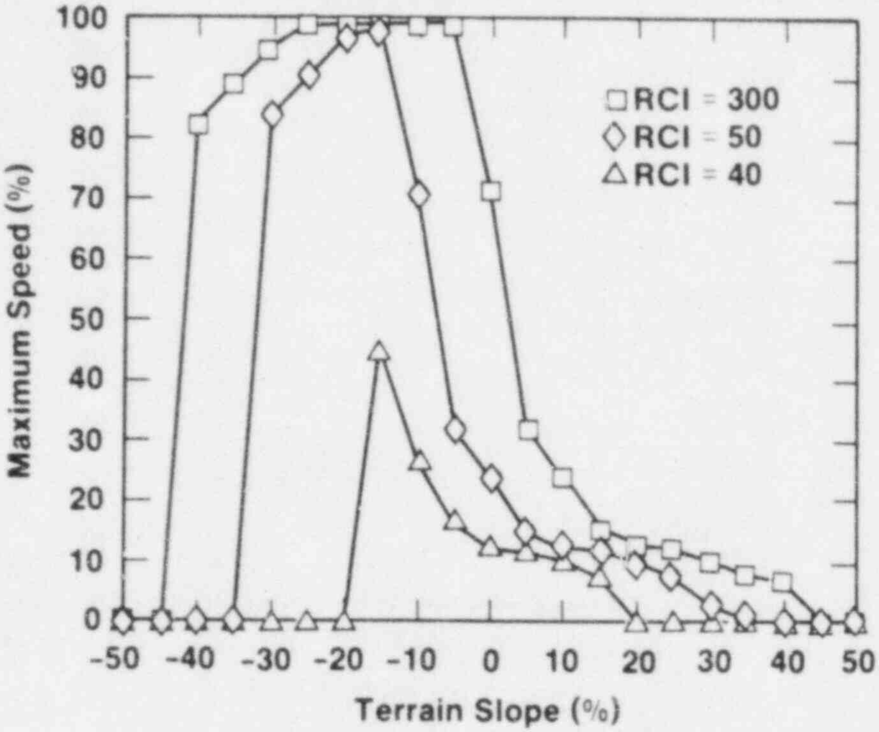

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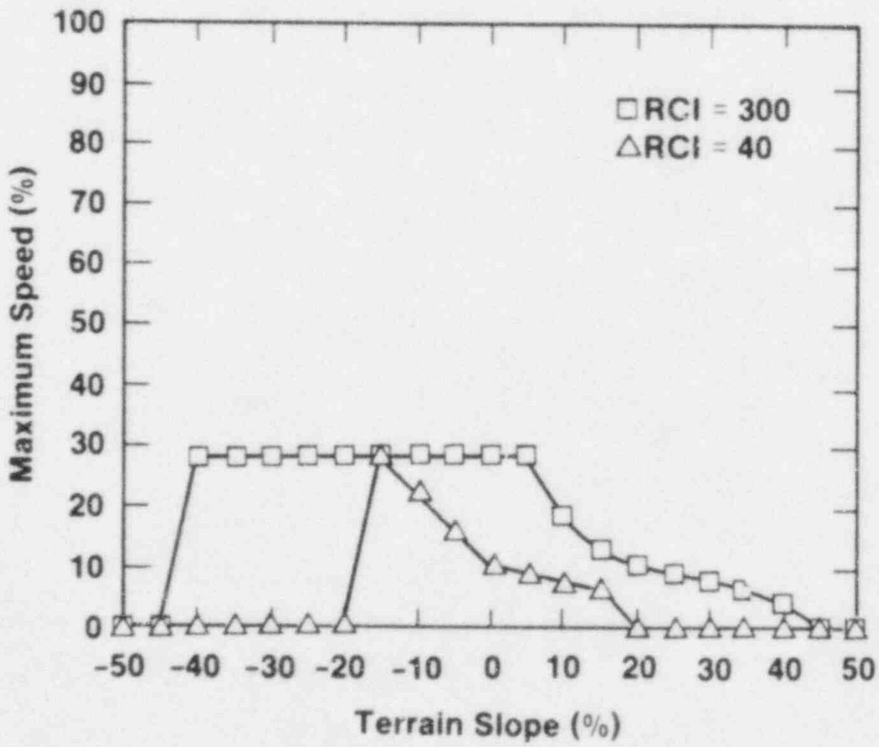

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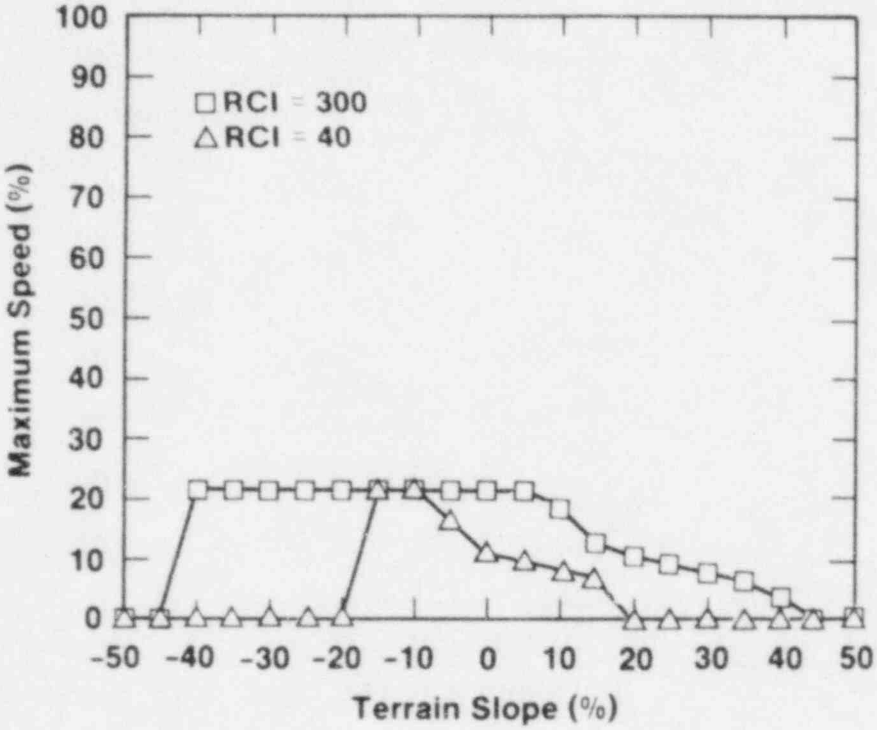

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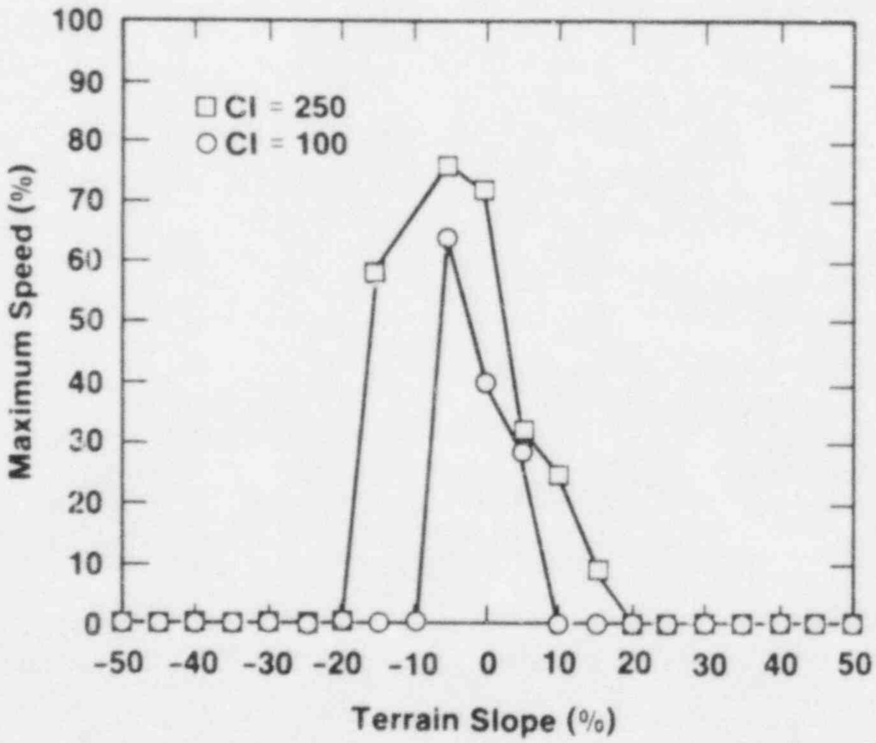

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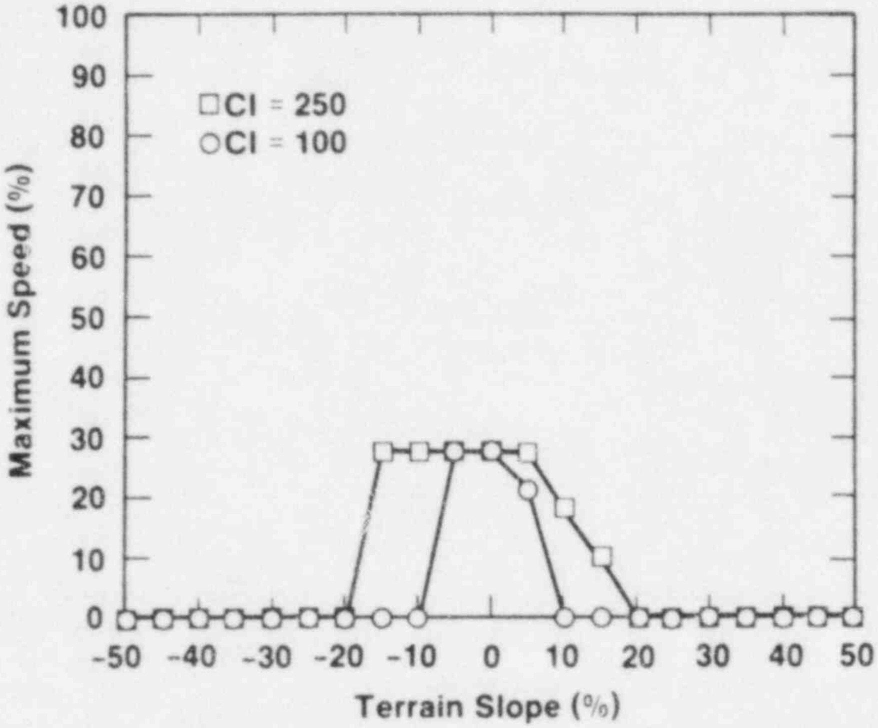

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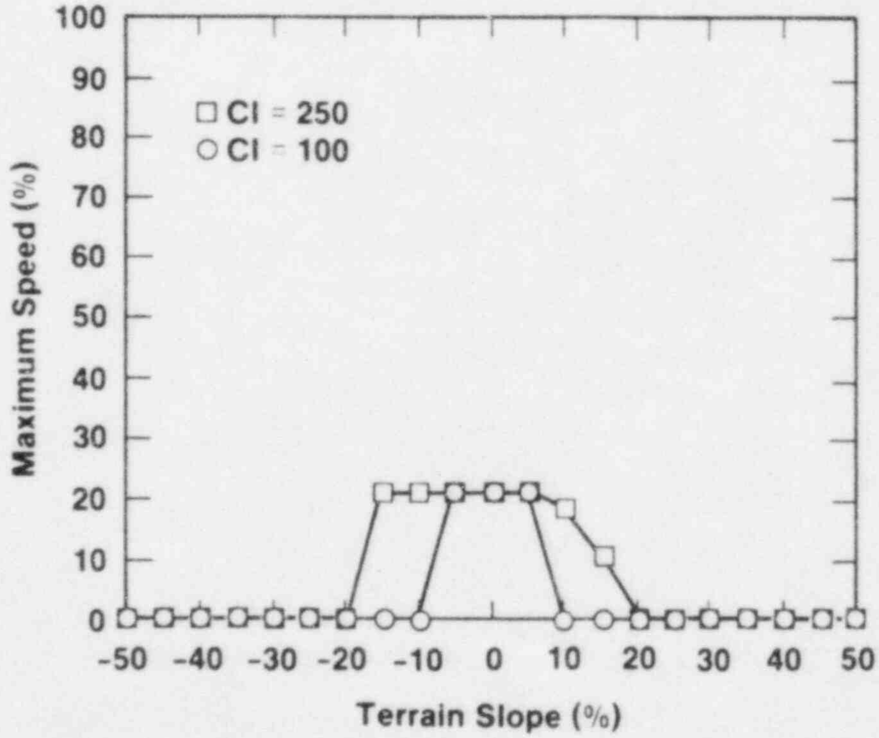

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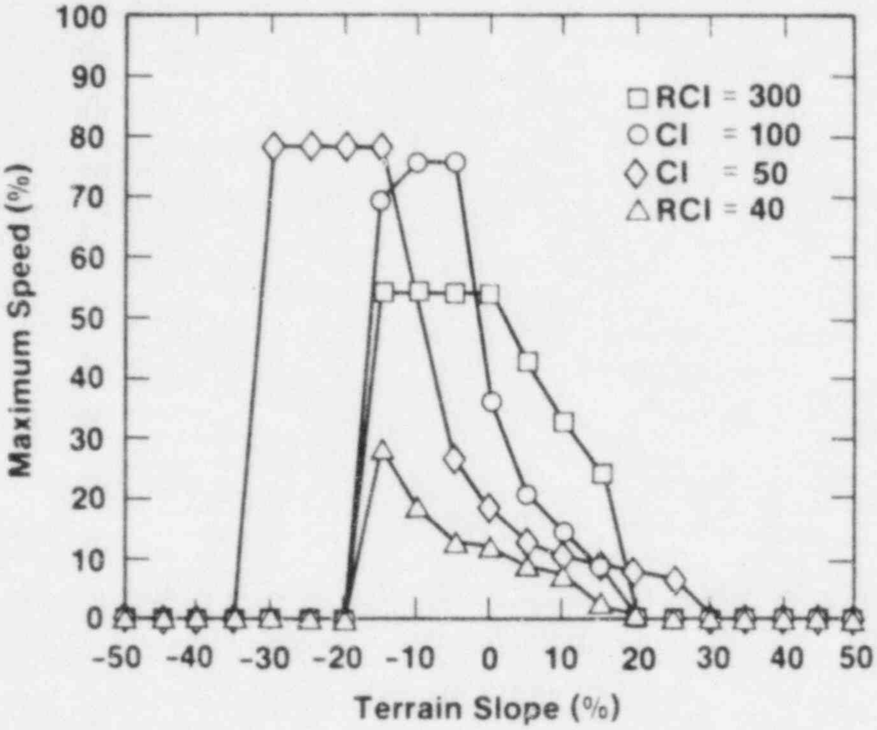

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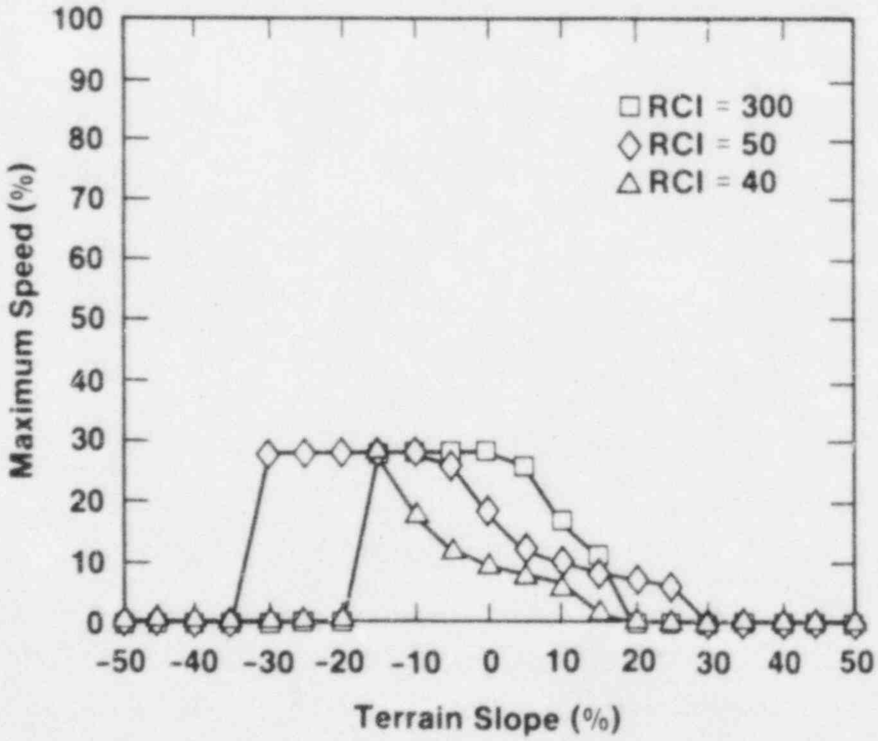

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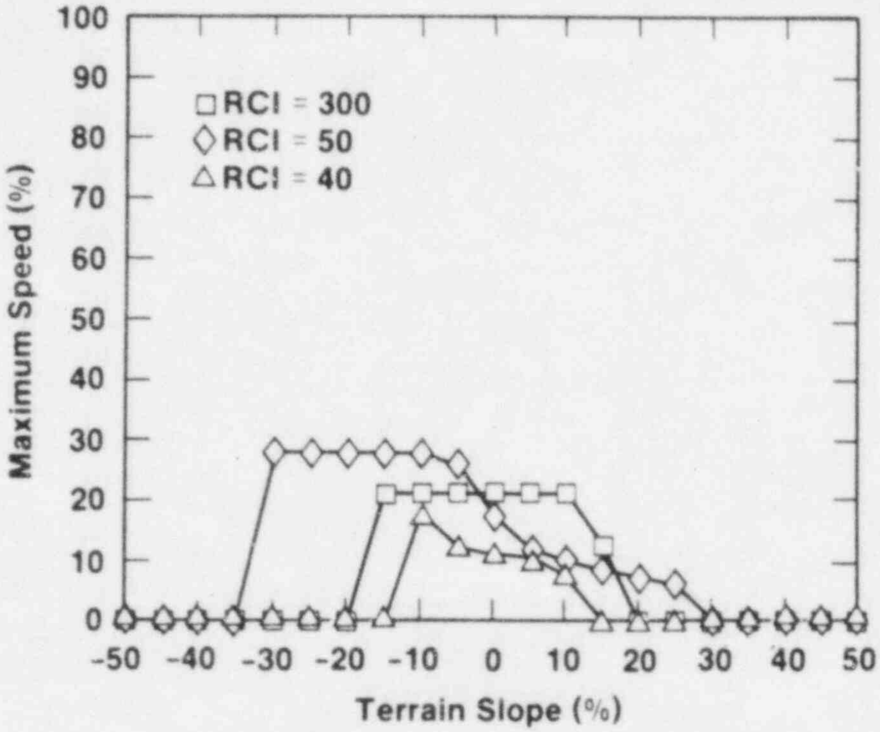

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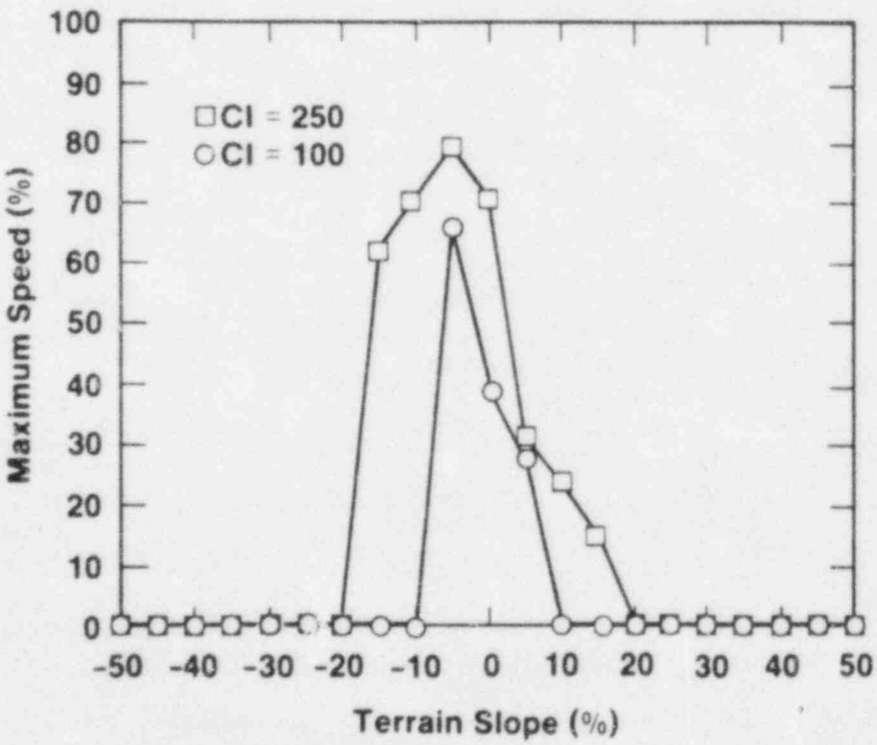

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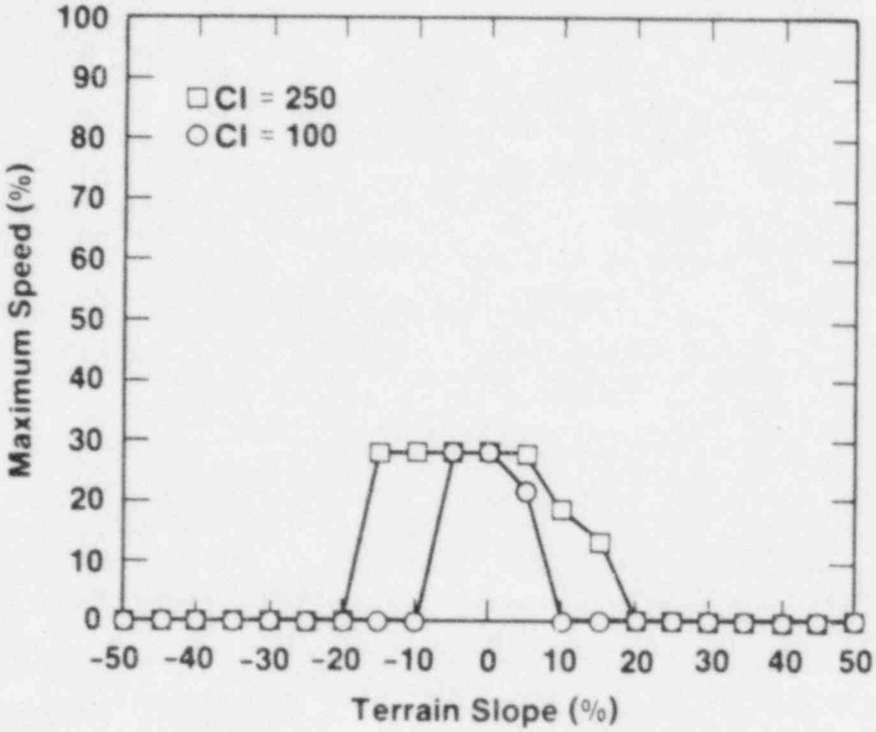

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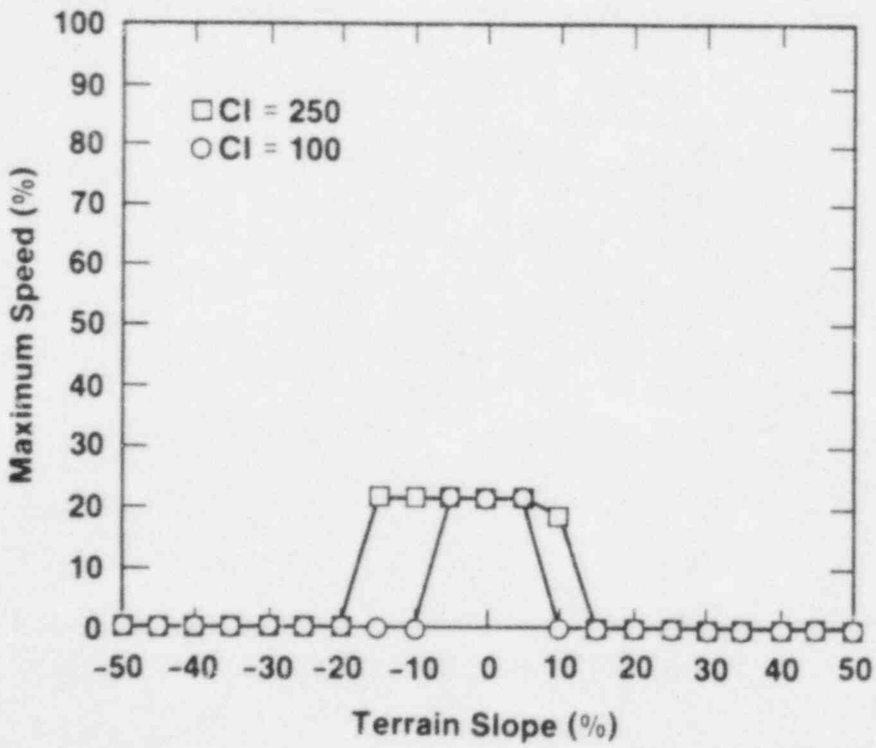

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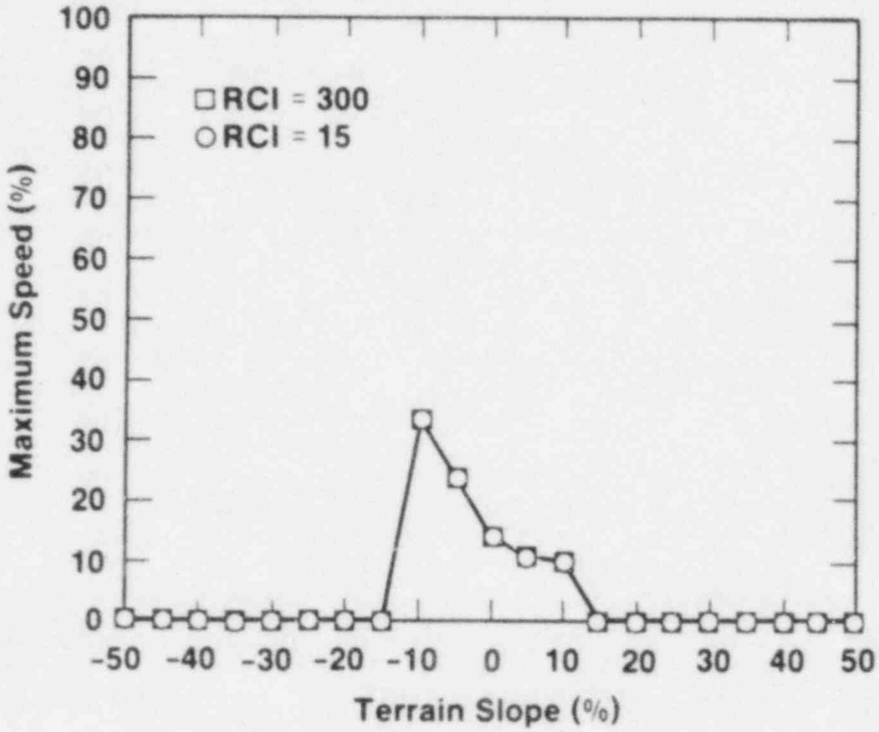

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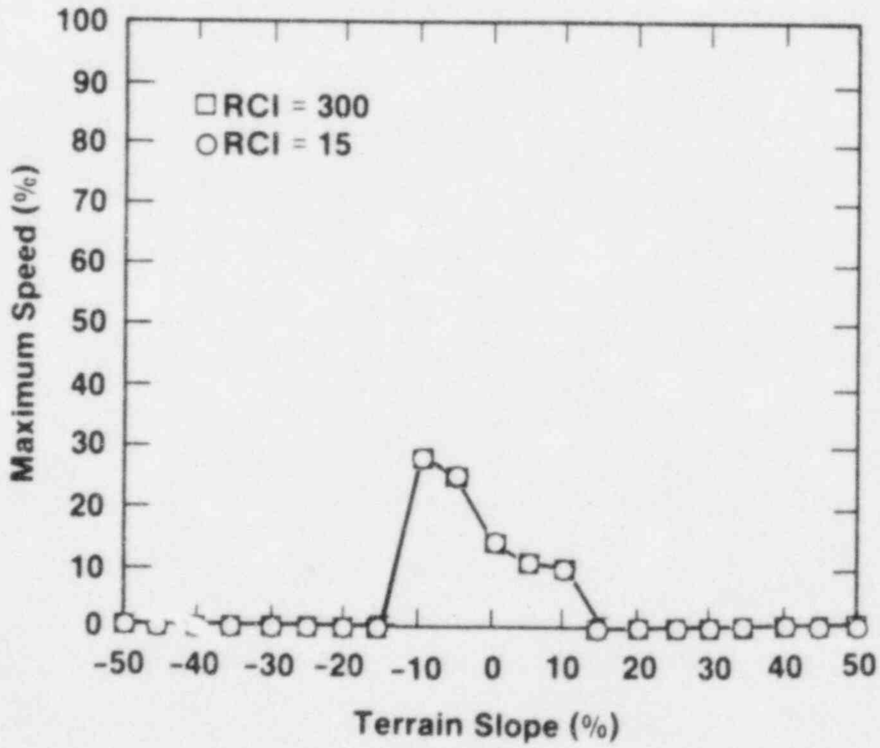

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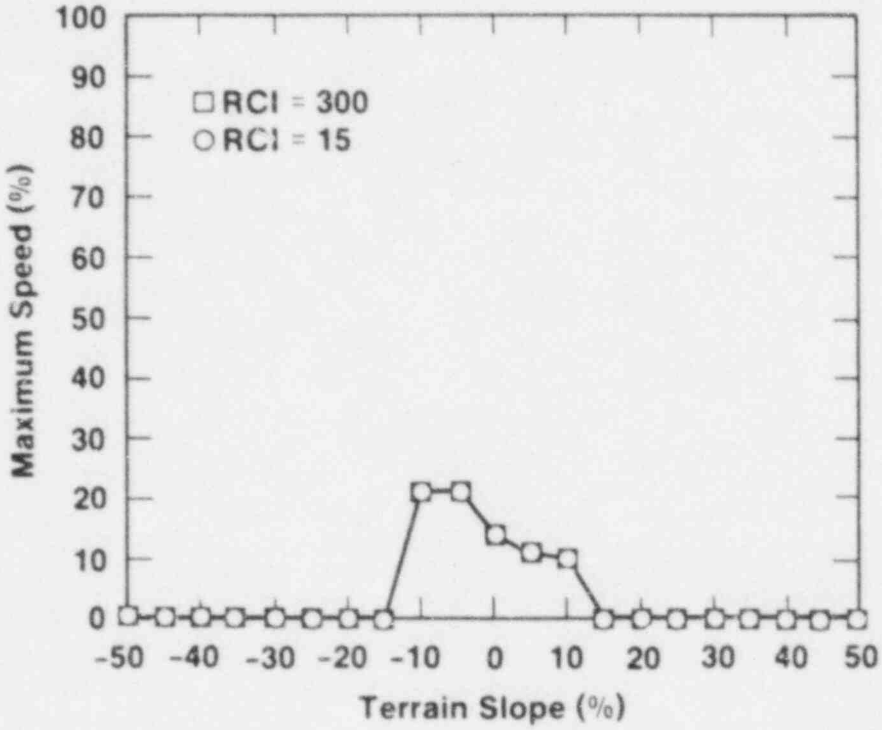

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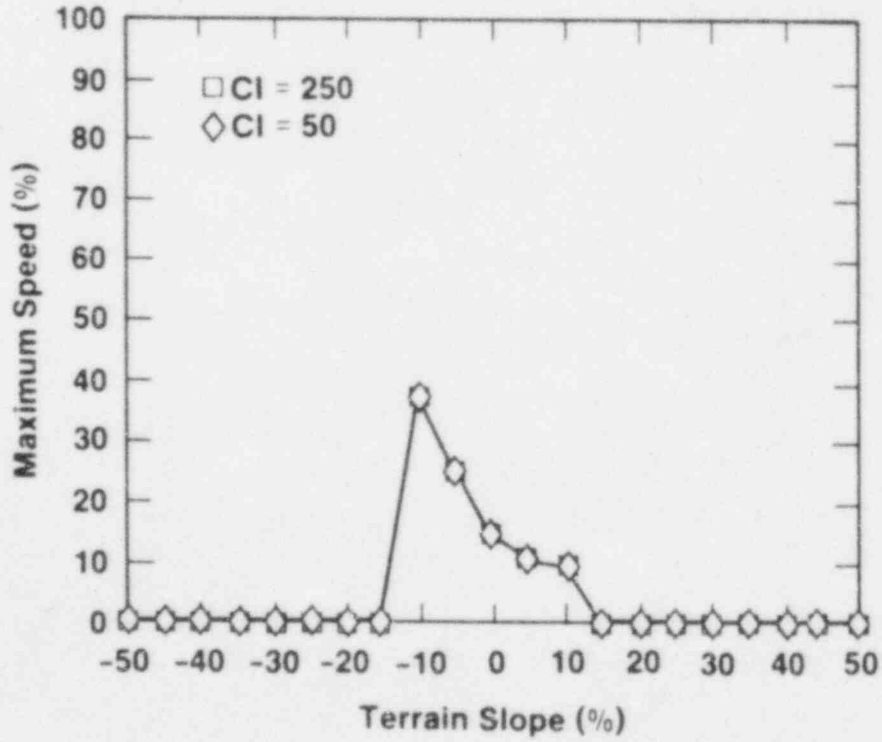

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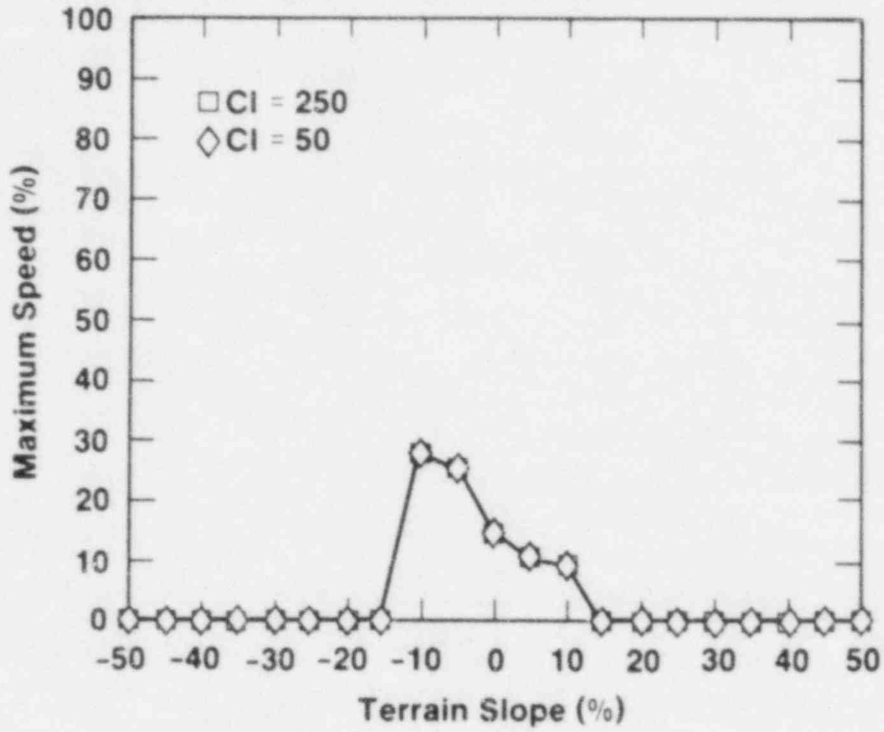

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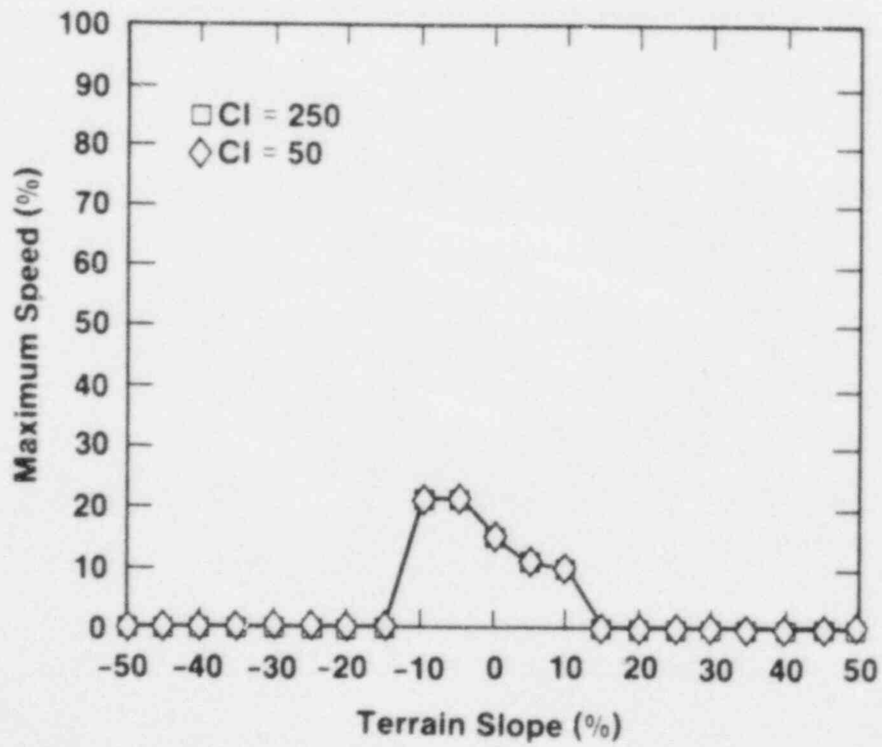

Figure A-54. Maximum Speed vs Terrain Slope: 7-Ton Truck; Snow, Coarse Soil; Surface Roughness 1.0 in. rms

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The recent increase in the use of car and truck boms by terrorist organizations has led NRC to evaluate the adequacy of licensee security against such threats. As part of this evaluation, one of the factors is the effectiveness of terrain and vegetation in providing barriers against the vehicle entry. The effectiveness of natural features is presented in two contexts. First, certain natural features are presented. In addition to the discussion of natural features, this report provides a discussion of methods to slow vehicles. Also included is an overview of man-made barrier systems, with particular attention to ditches.

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