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A REEVALUATION OF THE 60% GRADEABILITY REQUIREMENT

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JANUARY 1975

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ABSTRACT

The requirement that all military vehicles be capable of ascending a 60% slope is reexamined to determine if vehicles have been designed to meet this requirement or if the specification is inherently satisfied based on other performance requirements. An analysis of the geometry and performance of a cross section of military vehicles indicates that 60% gradeability is, for the majority of vehicles, inherent. Future vehicles thus could not be designed at lower cost should the gradeability requirement be lowered. Vehicles would still need to satisfy other performance parameters; these in turn would assure 60% gradeability.

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I. INTRODUCTION

Current Army specifications require that all tactical and combat military vehicles be capable of ascending a dry concrete grade of 60% in forward and reverse gears, and maintain braking ability on this slope. The origin of this gradeability requirement is undeterminable, but it dates at least to 1960. Reasons for requiring a gradeability of 60% are similarly unknown, and the requirement is difficult to support on the basis of military operational requirements.

Highways in mountain areas are graded below 7%, while the steepest known mountain slopes have a 32% grade. Any slope approaching 60%, therefore, will only be encountered in off-road operations. Many factors which affect a vehicle's gradeability, however, are not affected by the type of surface the vehicle is traveling on. Gradeability can thus be tested on a steep concrete slope, although this condition will never be experienced during actual vehicle operation.

The ability of a vehicle to ascend a given grade is determined by various design characteristics of the vehicle. Each of these characteristics, however, are also determining factors in vehicle operational characteristics other than gradeability. In a re-evaluation of the gradeability requirement, any design characteristic affecting gradeability must be examined in light of its affect on other vehicle performance requirements. By analyzing each of these characteristics, the affect of a reduced gradeability requirement on overall vehicle performance can be determined. Conversely, by maintaining essential performance requirements, a minimum gradeability can be calculated.

Utilizing the above approach, the gradeability-related design characteristics of ten military vehicles were analyzed to determine the essentiality of maintaining a 60% gradeability requirement and the effect of a reduced requirement on overall vehicle performance.

II. ASSUMPTIONS

The analyses conducted in this study are not to be interpreted as quantitative proof that Army vehicles will ascend a 60% slope regardless of the requirement. Many of the parameters used in the equations are estimates only, and slight variations in them can alter the results. By using good estimates on the selected cross section of vehicles, however, the trend towards a common conclusion is evident. The use of equations and extensive data enabled the analyses of the vehicles to be conducted on a common ground so that any assumptions or oversights would equally affect all the vehicles.

Some vehicle characteristics affecting gradeability were not analyzed. Data on braking ability on slopes were not readily available. As with engine horsepower, however, braking ability on level ground will dictate slope braking performance. The shifting of fluids essential to operation was also not analyzed, although the maximum tilt the engines could sustain was investigated. In all cases, the engines could operate on slopes steeper then 60%.

III. CONCLUSIONS AND RECOMMENDATIONS

The results of the analysis indicate that the majority of the vehicles analyzed were capable of meeting the grade requirement on the basis of other operational specifications. A reduction in the 60% requirement would not lead to a reduction in slope climbing ability because other performance characteristics must still be met.

Because 60% gradeability appears inherent in the design of most vehicles, the usefulness of the requirement is questionable. Elimination of the requirement should not, however, be considered. Military vehicles must be capable of ascending slopes, and even if this capability is inherent, the inclusion of the requirement would help assure it. The value of 60% seems arbitrary, but because the requirement already exists and can be met inherently, the question is not so much, "what should the gradeability be," as "is it worth changing the requirement." As previously stated, changing the requirement would not alter vehicle performance. It would, though, require considerable time and cost to change all the necessary specs. Thus, maintaining the current 60% gradeability requirement appears the best alternative.

Although testing is performed on an artificial slope never encountered in nature, the test procedure could not be significantly improved. The primary difference between concrete and dirt or grass is traction. Testing on slopes of these surfaces would provide a check on the track or tire material, but this test could certainly be done at the plant where the rubber is formulated. The current test procedure is satisfactory, and therefore need not be changed.

Although this study does not recommend any changes to the current gradeability requirement or test procedure, it is hoped that the reason for not suggesting new specifications has been borne out. The interdependency of gradeability with total system performance has been stressed and demonstrated. Gradeability cannot be treated as an isolated performance characteristic; any further research efforts on the subject must bear this fact in mind.

IV. DISCUSSION OF DESIGN CHARACTERISTICS - VEHICLE GEOMETRY

Minor changes in the geometry of a vehicle will not limit the maximum grade it can negotiate. The limiting characteristics are the angles of approach and departure, the location of the center of gravity, and, for wheeled vehicles, the ground clearance. Failure to negotiate slopes due to these parameters is called nose-in failure, critical angle failure, or hang-up failure, respectively. The vehicle parameters referenced in the following section are illustrated in Figure 1.

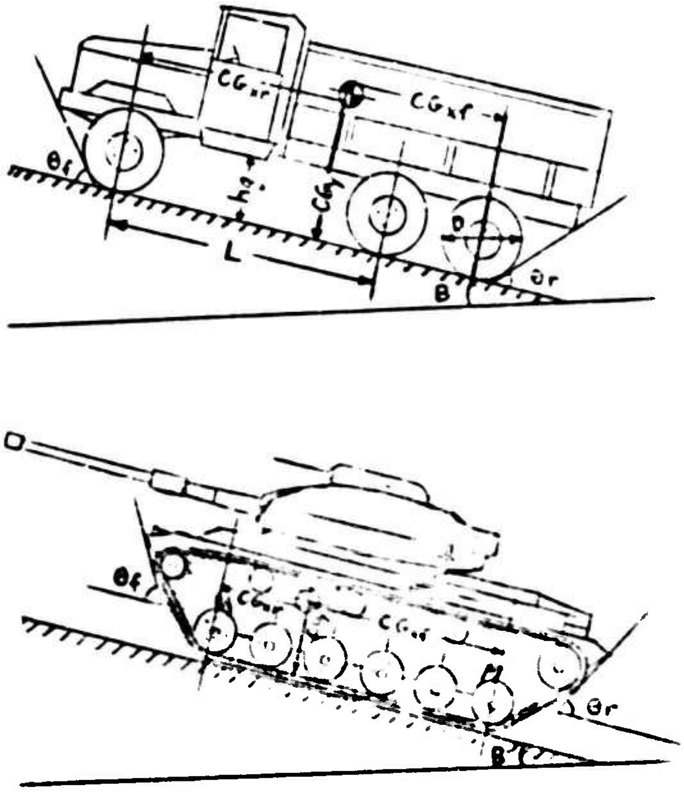

Figure 1

Nose-in Failure

Nose-in failure will occur when the angle of approach (θ_f) or angle of departure (θ_r) of a vehicle exceeds the angle of the slope (B). This failure mode will be most significant on the test slope, because slopes in nature will generally not begin so abruptly. (See Figure 2).

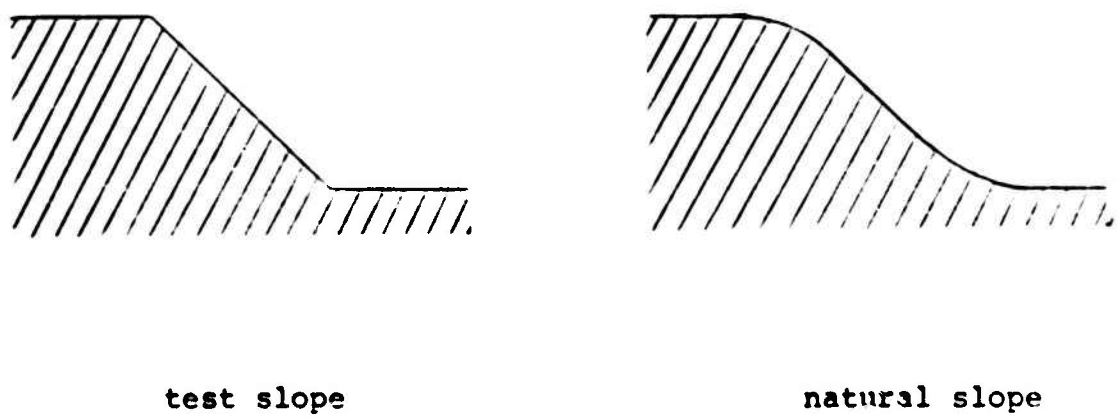

Figure 2

A vehicle can exhibit nose-in failure in four different ways. These ways are illustrated in Figure 3. On examination, modes A and D are identical, as are ways B and C. The illustrations are similar for tracked vehicles.

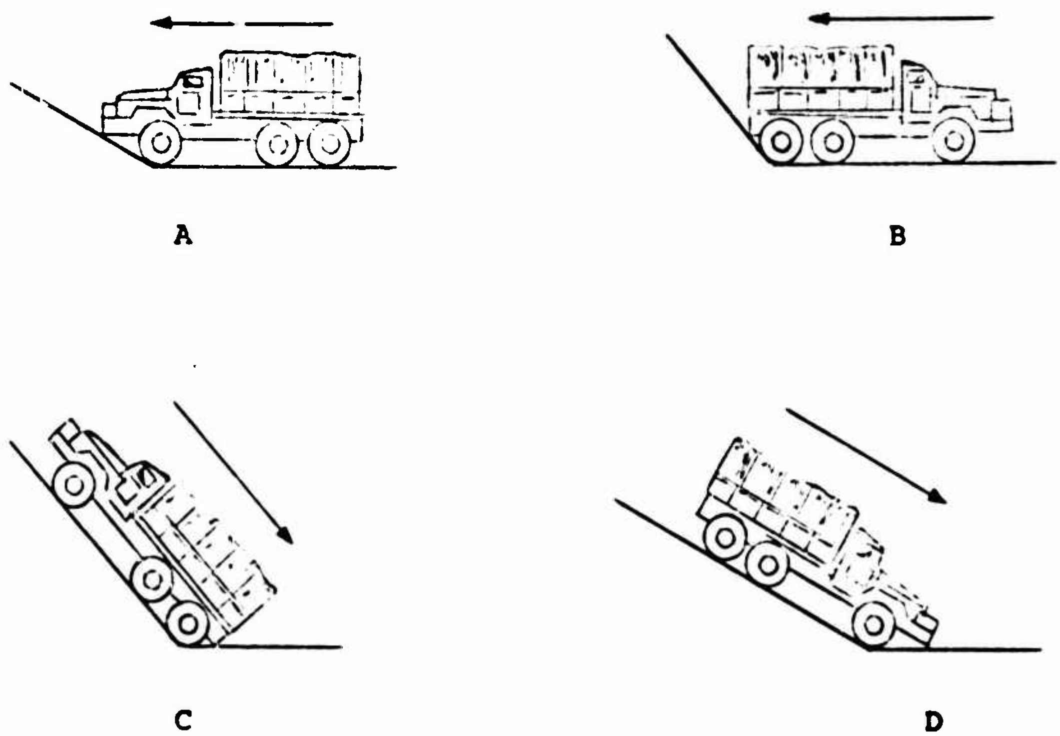

Figure 3

For the ten vehicles analyzed, the angles of approach and departure were recorded and compared to the 60% requirement. The vehicles listed were selected on the basis of their familiarity to Army personnel, their variety, and the availability of data. The results of the analysis of nose-in failure are tabulated in Table 1.

Vehicle	Class	θ_f deg.	θ_f %	θ_r deg.	θ_r %
M151A2	1/4 T truck	66°	224.6%	37°	75.4%
M561	1-1/4 T truck	71.5°	298.9%	43°	93.3%
M36A2	2-1/2 T truck	40°	83.9%	24°	44.5%
M54A2	5 T truck	37°	75.4%	34.5°	68.7%
M520E1	8 T truck	35°	70.0%	37°	75.4%
M746/747	HET	30°	57.7%	29°	55.4%
M60	battle tank	60°	173.2%	60°	173.2%
M109	howitzer	60°	173.2%	50°	119.2%
M113A1	pers carrier	60°	173.2%	40°	83.9%
M548	cargo carrier	57°	154.0%	35°	70.0%

Table 1

It is apparent that the design of the front and rear ends is not a critical factor in determining the gradeability of a vehicle. The HET requirement calls for a gradeability of only 15%. Only the M36A2 then, will exhibit nose-in failure, with the rear bumpers, on a 60% test slope. On a natural slope, however, this bumper would probably clear the ground. The bumpers on any future military vehicle would probably be designed along lines similar to present configurations. To reduce θ_f and θ_r would require lowering the vehicle chassis, thus reducing ground clearance, or extending the nose and rear further from the wheels. The first alternative would affect any ground clearance requirement more than it would affect the gradeability. The rear section of the trucks could be lengthened, to an extent, t permit greater carrying capacity, without lowering the vehicle's gradeability. Similarly, the engines on most of the wheeled vehicles could be moved forward, to permit a better weight distribution, without causing a nose-in failure at 60% slope. Minor configuration changes would therefore not decrease vehicle gradeability. Conversely, any reduction in the gradeability requirement would not affect this design characteristic.

<u>Critical Angle Failure</u>

The location of the center of gravity of a given vehicle imposes a theoretical limitation on the gradeability of that vehicle. As the slope increases, the center of gravity shifts downhill, until it is directly over the rear pivot point of the truck, or over the front point if the vehicle is ascending the slope in reverse. The geometry of this situation is illustrated in Figure 4. Any further increase in slope will cause the vehicle to flip backwards and thus fail to negotiate the slope. From Figure 4, the theoretical critical angle, in forward operation, has a tangent of CGxf/CGy, and in reverse, a tangent of CGxr/CGy. Since the slope is by definition the tangent of the angle multiplied by 100%, the critical slopes are (CGxf/CGy)X100% and (CGxr/CGy)X100%.

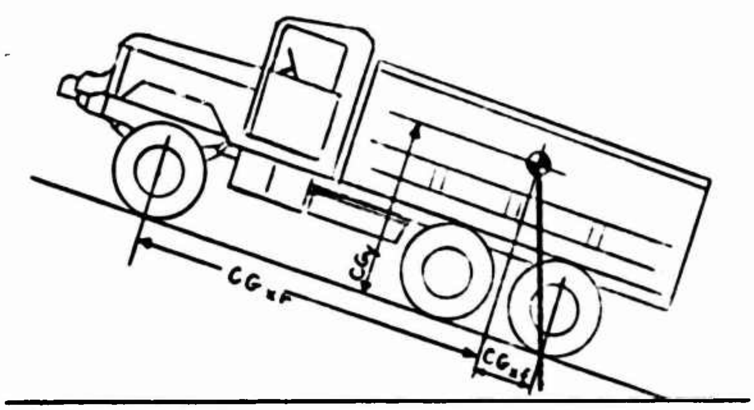

Figure 4

In reality, the actual critical angle will be smaller than the theoretical critical angle due to static and dynamic considerations of the vehicle. When the vehicle is stationary on the slope, the downhill suspension members will sag, causing a downhill shift in the center of gravity. During operation, torque in the drive train will increase this weight shift, as will acceleration uphill. Considering for the moment the theoretical critical angle, the ten selected vehicles were analyzed to determine their maximum gradeability based on this parameter alone. The results are indicated in Table 2.

Vehicle	Distances (In Inches) CGxf	CGxr	CGy	Theoretical Critical Slope (%) in forward	in reverse
M151A2	36.5	48.5	25.6	142.6	189.5
M561	75.4	90.1	34.8	216.7	258.9
M36A2	80.0	134.0	40.8	172.0	288.2
M54A2	71.0	135.0	54.0	131.5	250.0
M520E1	122.4	112.6	48.8	250.8	230.7
M746/747	*	*	*	-	-
M60	91.0	76.0	54.3	167.6	140.0
M109	62.0	94.0	45.0	137.8	208.9
M113A1	52.8	52.2	39.0	135.4	133.8
M548	70.9	40.1	29.0	244.5	138.3

Table 2

*see text below

The large values of the theoretical critical slopes indicate that the critical angle failure mode is not a restriction on the performance of a vehicle. Even allowing for a downhill weight shift from acceleration, torque, and suspension sag, the listed vehicles will fail to negotiate slopes, due to other characteristics, long before they will flip backwards. The location of the center of gravity of the HET was not calculated because of the various loading configurations possible. The long length of this vehicle, however, would yield an extremely steep critical angle. For all the vehicles, the possibility exists that the rear (or front) axle could not withstand the loading it would be subjected to if the vehicle were held at or near the critical angle.

Traction

The maximum grade a vehicle can ascend will be limited by the traction between the tires and the road surface. Failure to maintain traction will dictate a vehicle's gradeability long before the critical angle would. Regardless of the number of driving axles or the number of track pads contacting the ground, the traction of the vehicle is determined by the static coefficient of friction between the rubber and the road. The dynamic coefficient of friction is not employed because the tire or track pad does not slip on the road surface, rather, one area at a time maintains contact until it is lifted off.

The coefficient of friction, μ, is a function of the types of surfaces in contact. This parameter is also the tangent of the angle at which the surfaces will slip, in other words, the maximum gradeability. A coefficient of friction of .90 indicates that an object will not slip on a slope up to 90%. The value of μ for rubber on dry concrete or asphalt is .8-.9, on a dry earthen road, .68, and on gravel, .6. Other performance characteristics permitting, a vehicle will be able to ascent 60% slopes composed of these surfaces. On surfaces with poorer traction, slippage will occur on grades of less than 60%.

The technology of constructing tires and roads will only improve. Military vehicles will therefore always be capable of ascending good roads with slopes of 60% without slipping. A reduced gradeability requirement would permit vehicles to meet the specification on slopes with less traction, e.g., a wet earthen road (μ=.55). Because gradeability tests are conducted on dry concrete slopes, however, a reduced gradeability requirement would be meaningless as far as traction is concerned. If a reduced requirement were supplemented with a new test procedure to specify testing on off-road hills, the gradeability requirement would be an important specification to consider when fabricating new tires or track pads.

<u>Hang-up Failure</u>

If a vehicle does not have sufficient ground clearance, it will fail to clear the ground after ascending a steep slope. The geometry of this failure mode, called hang-up failure, is illustrated in Figure 5. As with nose-in failure, this type of failure will be most prevalent on a test grade, where the slope will end abruptly (see Figure 2). Tracked vehicles are not subject to hang-up failure, as the track will always contact the lip of the slope, and the vehicle cannot get hung up.

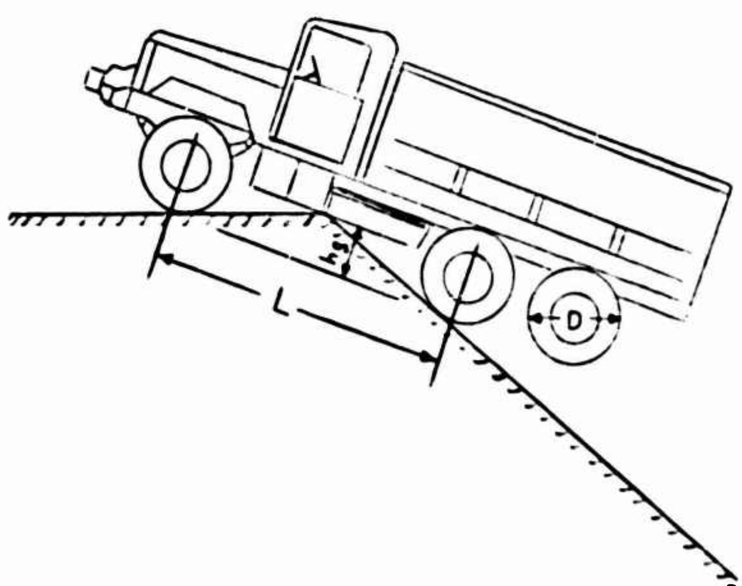

Figure 5

The following equations define the minimum ground clearance required to clear a slope of B degrees. The variable Dr is a dummy parameter used to connect the two formulas. Its value by itself is not required for solution of the ground clearance requirement.

$$D+Dr = \frac{1}{4\, L^2 \sin^2 B - D^2(1-\cos^2 B)} \left\{ 2\, L^2 D \cos B \; (1-\cos B) + \sqrt{\left[2L^2\; D \cos B \;(1-\cos B)\right]^2 + 4L^4\left[4L^2 \sin^2 B - D^2(1-\cos^2 B)\right]} \right\}$$

$$h = 1/2 \left[(D+Dr)^2 - \sqrt{(D+Dr)^2 - L^2} \right]$$

For each vehicle, the wheel base, tire diameter, and ground clearance are fixed. By varying B until h equals the ground clearance hg, the maximum angle that can be cleared is determined. This iterative procedure is best solved through use of a computer program, since the equations are obviously complex and time consuming to solve by hand. By inserting 60% (31^{o}) for B, the required ground clearance to meet the gradeability requirement can be calculated. The results of this analysis of the hang-up failure mode are shown in Table 3.

	Dimensions (in Inches) L	D	hg	B%	h for B = 60%
M151A2	85.0	28	13.4	75	11.3 in.
M561	84.8	38	15.0	91	11.0
M36A2	166.0	41	19.0	50	22.2
M54A2	152.0	41	21.0	63	20.3
M520E1	235.0	69	30.0	57	31.3
M746/747	*	*	*	78/51	*

*Maximum clearance angles indicated in vehicle specifications; no calculations performed.

Table 3

The M36A2 and the M520E1 fail to meet the design criteria for passing the gradeability requirement (the HET requirement is 15%). The M36A2 in particular could get hung-up on a steep slope that abruptly levels off.

The test procedure for determining gradeability does not stress that the vehicle must be capable of approaching and leaving a 60% slope; rather it emphasizes performance on the slope. The only geometric characteristic which must be considered while the vehicle is on the slope is the location of the center of gravity, and this characteristic was determined to be non-critical. While some vehicles failed the nose-in criteria and/or the hang-up failure criteria, no vehicle came close to failing the critical angle criteria. Thus, the physical dimensions of each vehicle are not limiting factors in determining the vehicle's gradeability on the test slope, although some may exhibit difficulty getting on or off the slope. In the field, all the vehicles should be capable of ascending their maximum grade if the slope does not start or level off abruptly. A change in the geometric design of a vehicle is not likely to be reflected in a reduction in gradeability because the center of gravity would not be drastically shifted. From the viewpoint of physical dimensions, then, a change in the gradeability requirement does not appear to be warranted.

V. DISCUSSION OF DESIGN CHARACTERISTICS - POWER CONSIDERATIONS

The previous chapter indicated that all Army vehicles are capable of ascending a 60% slope (15% for the M746/747) if the necessary power is available. To determine if the required power would be available regardless of the gradeability requirement, a key performance characteristic, acceleration, was studied. Test results relating acceleration to drawbar horsepower (dhp) were analyzed to find the minimum horsepower needed to accelerate each vehicle through the gear shifts. For most vehicles, this horsepower was very close to the maximum available horsepower of each engine. Based on these minimum required horsepowers, most vehicles were still capable of ascending 60% slopes, indicating that satisfaction of the acceleration requirement will usually assure compliance with the gradeability requirement. The assumption is made that the proven acceleration rates are necessary performance specifications which cannot be compromised.

Acceleration Requirements

Test data are available for vehicles similar or identical to the ten vehicles analyzed in this report. Among the test results are charts which show drawbar horsepower as a function of vehicle velocity and gear selection. Ideally, gear shifting is done at a specified rpm value which corresponds with maximum net horsepower. By shifting the vehicle at this engine speed, full use is made of the available power. The test results indicate that most available power was used by shifting at the proper time. Table 4 lists the vehicles tested, the minimum horsepower required for maximum acceleration, and the maximum horsepower available. Brake horsepower is converted to net horsepower by dividing by the indicated efficiency factor.

Vehicle	Vehicle Tested	Required bhp	e	Required net hp	Available net hp
M151A2	M151	40	.82	49	61
M561	M561	70	.80	88	91
M36A2	M35A1E1	96	.80	120	130
M54A2	M54A2	155	.80	194	198
M520E1	XM520E1	130	.76	171	176
M746/747	XM746/747	420	.80	492*	492
M60	M60	460	.72	639	643
M109	M109	180	.72	250	345
M113A1	M113A1	90	.72	125	161
M548	M548	100	.72	139	161

*Actual computed value is greater than 492 hp

Table 4

As stated, the Table shows that the horsepowers required to accelerate the vehicles are close to the maximum available horsepower. If acceleration takes precedence over gradeability, then 60% gradeability will be inherent if the vehicles can ascend 60% slopes using the horsepower required for acceleration.

Torque and Horsepower Limitations

The maximum net torque and horsepower of a vehicle will affect its gradeability. The following Table lists those parameters which must be considered in an analysis of gradeability based on torque and horsepower.

	W	V	e	r	R_L	Rr	hp	T
M151A2	3,200	8	.82	14	27.76	36.44	61	119
M561	10,345	4.3	.80	19	70.39	67.60	91	210
M36A2	20,740	4	.80	20.5	66.79	65.20	130	320
M54A2	30,915	3.5	.80	20.5	95.33	95.59	198	440
M520E1	42,810	2	.76	34.5	164.53	148.37	176	494
M746/747	182,000	2	.80	21.2	41.55	41.55	492	1310
M60	101,000	3	.72	12.3	60.96	85.85	643	1575
M109	51,672	3	.72	9.8	85.02	101.52	345	895
M113A1	23,380	3	.72	9.8	58.56	66.81	161	425
M548	26,450	3	.72	9.8	64.22	73.27	161	425

W - gross vehicle weight, lb
V - uphill velocity, mph
e - drive line efficiency
R_L - overall drive ratio-low
Rr - overall drive ratio-reverse
r - tire radius, inches
hp - maximum net horsepower
T - maximum net torque, lb-ft

Table 5

An additional required parameter is the coefficient of rolling resistance for each vehicle. For the low velocities involved, a value of fr = .015 lb/lb for all the vehicles will suffice.

To ascend a given grade, a vehicle must develop enough tractive effort (TE) to overcome grade resistance (Rg), rolling resistance (Rr), and aerodynamic drag. At low velocities, the drag can be ignored, thus leaving the equation,

$$TE = Rg + Rr \quad . \quad (Eq.1)$$

These three terms are defined by the following equations, where all parameters are explained in Table 5.

$$TE = \frac{12\ T\ R\ e}{r} \qquad (Eq.2)$$

$$Rg = W \sin B \qquad (Eq.3)$$

$$Rr = W\ fr \qquad (Eq.4)$$

Substituting Equations 2 through 4 into Equation 1 and solving for sin B yields

$$\sin B = \frac{12\ T\ R\ e}{Wr} - fr \quad (Eq.5)$$

Converting sin B to Tan B gives an expression for maximum gradeability in terms of maximum net engine torque and overall drive line ratio. Because each vehicle must ascend the slope in forward and reverse, calculations are performed twice, using the different gear ratios. Results indicate a maximum theoretical grade, since the engine may not be developing maximum torque due to the speed it is operating at for the slope climbing.

Torque is converted to horsepower by the expression,

$$T = \frac{hp\ 375\ r}{12\, V\, R} \quad .$$

Substituting this expression into Equation 5 gives,

$$\sin B = \frac{375\ hp\ e}{WV} - fr \ . \quad \text{(Eq.6)}$$

This equation relates maximum gradeability to maximum net horsepower and the velocity up the slope. The results are again theoretical, as the operating speed of the engine may not be that at which maximum horsepower is produced. Additionally, this equation is extremely sensitive to the slope velocity; this parameter could very slightly, with a resultant great effect on sin B. Table 6 shows the maximum grades possible based on the solutions of Equations 5 and 6 for each vehicle. Because Equation 6 does not involve the gear ratio, this expression yields the same result for both forward and reverse operation. The Table also shows the solution of Equation 6 for the horsepower required to accelerate each vehicle, as given in Table 4.

	maximum grade based on torque & ratio		maximum grade based on horsepower and velocity	
	forward	reverse	max. hp	req. hp
M151A2	101.0%	269.3%	103.1%	69.5%
M561	100.0	92.3	74.7	70.3
M36A2	55.1	53.4	53.3	46.1
M54A2	79.1	79.5	63.2	61.2
M520E1	55.7	48.7	69.5	66.6
M746/747	12.1	12.1	42.4	42.4
M60	86.8	251.4	67.2	66.6
M109	*	*	72.3	46.3
M113A1	240.7	*	75.9	52.7
M548	200.3	*	63.0	51.5

*indeterminate; $\sin B > 1.00$

Table 6

Among wheeled vehicles, only the M36A2 fails to meet the grade requirement based on horsepower and velocity. A slight reduction in the 4 mph climbing speed, however, would enable the vehicle to easily ascend the 60% slope. Similarly, different values for the efficiencies of the M36A2 and the HET could increase the torque - limited gradeability values.

Tracked vehicles are designed to meet power requirements other than acceleration. They may require ditch climbing ability, or be capable of ascending steep grades (under 60%) at specified speeds. For these reasons, the horsepower required to accelerate is not sufficient to climb a 60% grade, although even steeper slopes are passable utilizing all available power.

From Equations 5 and 6, if horsepower and torque are unchanged, vehicle gradeability would be lessened by reducing the gear ratio used in climbing, thus increasing vehicle velocity. Lowering the gear ratio, however, would reduce the drawbar pull of the vehicles. Thus all the power requirements of each vehicle are interrelated, and a reduction in the slope climbing capability would be reflected in other reduced performance characteristics. Conversely, the ability of each vehicle to maintain its current acceleration and towing characteristics assure that vehicle of being capable of climbing a 60% grade. Any reduced gradeability requirement would not lead to reduced slope climbing capabilities in future vehicles unless other performance features were reduced from current levels. A reduced gradeability requirement, then, does not appear to be justified from the viewpoint of vehicle power considerations.

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