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TRACKS VERSUS WHEELS IN SOFT SOIL AND SNOW

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PREFACE

This paper was prepared by Dean R. Freitag, Chief, Mobility Section, Army Mobility Research Branch, Mobility and Environmental Division, U. S. Army Engineer Waterways Experiment Station, and Zoltan J. Janosi, engineer, Land Locomotion Laboratory, U. S. Army Tank-Automotive Center, Detroit Arsenal, Detroit, Michigan. The paper was presented at the Fourth Meeting of the Quadripartite Standing Working Group on Ground Mobility held in London, England, during the period 24 June through 2 July 1963.

To study an area of common interest, the paper utilizes the data, techniques, resources, and experience of the Land Locomotion Laboratory, U. S. Army Tank-Automotive Command, and of the Army Mobility Research Branch, Mobility and Environmental Division, Waterways Experiment Station.

Besides the individuals listed as authors, the following personnel contributed significantly to the analyses of the data and to the preparation of the paper: Mr. R. A. Liston, Director, Land Locomotion Laboratory; and from the Waterways Experiment Station, Mr. W. J. Turnbull, Technical Assistant for Soils and Environmental Engineering; Mr. W. G. Shockley, Chief, Mobility and Environmental Division; and Mr. S. J. Knight, Chief, Army Mobility Research Branch.

Col. Alex G. Sutton, Jr., CE, was Director of the Waterways Experiment Station during this study. Mr. J. B. Tiffany was Technical Director.

SUMMARY

Each time a new vehicle is proposed the choice of running gear can only be made after a careful consideration of factors such as mission, initial cost, suspension vulnerability, obstacle performance, ridability, fuel economy, reliability, maintenance cost, and soft-soil performance. Of these several factors the most influential one dictating the use of tracks over wheels is that of soft-soil performance.

A detailed examination of the latter aspect reveals that most wheeled vehicles used at the present time have less mobility than tracked vehicles of the same weight. If the mobility of either type of vehicles is to be improved, designs having contact pressure as low as possible must be developed. As far as wheeled vehicles are concerned, this can be achieved by increasing the number of wheels or by increasing the size of the tires, or by a combination thereof.

The analysis seems to indicate that it is more effective to increase the tire size than the number of wheels. The analysis also indicates that the smaller tire sizes are not capable of providing extremely good mobility for heavy wheeled vehicles. While light vehicles could be equipped with available tires that would make them competitive with tracks on soft ground, the analysis indicates that the tracked vehicles have higher pull/weight ratios on firm soil.

Introduction

The phrase "tracks versus wheels" implies that some sort of conflict exists between tracks and wheels. It almost seems as if the problem should be approached in debating-team style with formal arguments pro and con. Therefore, this discussion will be initiated somewhat in this manner. Later, it is intended to endeavor to cast the cold light of experimental data on one facet of the total question.

The problem of tracks versus wheels has been the subject of a wide range of treatments from idle conversations to full-fledged investigations. In almost all cases, there seems to be a desperate seeking for an unassailable conclusive answer that will, once and for all, eliminate future discussion and banish the problem. In all reality, however, it seems evident that a final answer is not possible. Each time that a new vehicle requirement is posed, the problem of wheels versus tracks must be reconsidered. Therefore, this paper will not eliminate the wheel-versus-tracks controversy but it may shed a little more light on one small phase: the relative performance of tracked and wheeled vehicles in soft soils and snow.

Before further discussion, one obvious but pertinent observation should be made. This is that there would be no need for a tracked suspension to have been invented if the same degree of performance could have been realized with a wheeled vehicle, all other factors being equal.

When a decision is to be made whether to use a wheeled or a tracked vehicle, a large number of factors must be considered. A fairly complete list of these factors would include vehicle mission, initial cost, suspension vulnerability, soft-soil performance, obstacle performance, ridability, fuel economy, power losses, reliability, and maintenance cost.[1*] The relative importance placed on these various factors can obviously produce entirely different answers. Thus it happens that one army has selected wheeled armored personnel carriers while another uses only tracked armored personnel carriers. Unfortunately, it does not seem possible to determine which set of weighting factors is more nearly correct until the comparative utility of the two types of carriers in some future war will have been evaluated.

It is rather obvious that the mission of the vehicle must be the first factor to be considered in the evaluation. The mission establishes the size of the vehicle, the general characteristics, and the probable operating environment. Broadly speaking, in the past, vehicle missions have been considered to consist of combat, combat-logistical, and logistical operations. It is proposed that a fourth mission be recognized--remote area operation. If a vehicle has a combat mission, it obviously must be capable of operating in an off-the-road environment with high efficiency. The combat-logistical mission implies an approximately equal split between on- and off-road operations. However, the combat-logistical vehicle has a choice of route selection not available to the combat vehicle. The former vehicle must operate in natural terrain but it can bypass obstacles that the combat vehicle must overcome and it can rely on such crutches as winches or special traction aids that are impractical for the combat vehicle. The logistical vehicle is a highway machine pure and simple and, militarily speaking, may well be a thing of the past. The

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* Raised numbers refer to list of references at end of this paper.

off-road performance required is minimal since it is assumed that time and equipment are available to make the environment sympathetic to the vehicle. The statement that logistic vehicles may be a thing of the past assumes that aerial delivery of supplies may eliminate the necessity for long highway hauls. Unlikely as this may seem to some investigators, tribute must be paid to those planners who have demonstrated the ability of making esoteric plans become hard reality. The remote area mission vehicle must operate in all sorts of exotic environments, even in some that may now seem impossible. A remote area mission must at the outset be assumed to require almost complete operation off the road or else the area would not be remote. It is seen, then, that the vehicle mission establishes the amount of on- and off-highway operation expected for a vehicle and this, in turn, establishes the relative importance of soft-soil performance.

The factor of initial cost can be elaborated upon only vaguely and with difficulty. Obviously a conventional tracked suspension will cost more than a conventional wheeled suspension. The qualifying "conventional" must be included in this statement since, if equal performance with both systems were demanded, the cost of the track would likely be competitive with the wheel. However, it is not an accident that economy-minded off-road construction machinery designers are currently favoring wheeled versions. It can be concluded that the initial cost of tracked vehicles is higher than that of wheeled vehicles.

An examination of the relative suspension vulnerability of tracks and tires indicates that a tracked vehicle holds an advantage over a pneumatic-tired wheeled vehicle. Extensive research and development have been devoted to producting pneumatic tires that would be immune to small arms fire.

Some of the results have been most successful. Unhappily, this success was achieved at the expense of benefits usually associated with a pneumatic tire since the sidewalls were so strong that a rigid wheel resulted. Obviously, a well-placed mine or howitzer round can be very unkind to a track; nevertheless, a considerable force is required to inflict real damage. It thus appears that a track is considerably less vulnerable than a pneumatic-tired wheel.

The factors of fuel economy, power losses, ridability, reliability, and maintenance costs must be analyzed in two sets of circumstances, on-road operations and off-road operations. On the highway the wheeled vehicle is obviously superior in all factors. This is evidenced by the fact that there are no tracked vehicles operating commercially on the highway.

When the off-road situation is considered, the analysis is no longer quite so simple. If fuel consumption is measured between two specific points, the fact that a wheeled vehicle may require a more circuitous route to avoid obstacles or soft soil can greatly reduce the spread between the two vehicle forms. Further, if the wheeled vehicle operates at a high slip rate over much of the terrain, the relative advantage of a wheel is again reduced. Differences in power losses become much less significant when off-road operation is considered, since motion resistance from the soil becomes the dominant factor and slight differences in the loss between the engine and the ground no longer are significant. This factor is, of course, closely related to soft-soil performance which will be examined in detail later in the paper.

The ride of the tracked vehicle is generally considered superior to the wheeled vehicle in off-road conditions. There is no obvious reason why a properly designed wheeled vehicle should not provide a good ride off the road, but the point is that such a "properly designed" vehicle has not been offered for comparison. The tracked vehicle normally benefits from a high sprung-to-unsprung mass ratio and great vertical travel of the bogie wheels. It has often been demonstrated that a tank, for example, could move over rough terrain at a speed several times that of a truck. Furthermore, observations of a tracked 5-ton cargo carrier and a wheeled 5-ton truck indicated that the tracked machine developed a higher speed, but this may have been due as much to driver differences as to vehicle differences. However, in the absence of contrary evidence, it is assumed that a better ride is produced by a tracked vehicle in off-the-road operations.

The relative reliability and maintenance costs for wheels and tracks are difficult to establish since no data on these factors are at hand for examination. It would seem reasonable to expect that a wheeled vehicle especially designed for off-road operation would compete favorably with tracked vehicles. On the other hand, it would seem equally reasonable that a wheeled vehicle designed primarily for highway operation would suffer by comparison in off-road travel, since the suspension would receive frequent loads and impacts considerably in excess of those for which the vehicle was designed.

The factor of obstacle performance has been left untouched primarily because this characteristic is as much dependent on vehicle geometry as on the suspension form chosen. If approach and departure angles, ground clearance, break angle, track or tire grouser configuration, wheel or road wheel spacing, and other factors affecting obstacle performance are carefully considered, good obstacle performance is possible either in wheeled or in tracked vehicles.

As might have been anticipated, it is apparent that the principal reason for the use of tracked vehicles is their superior soft-soil performance. This observation was offered more or less at the outset of the discussion. However, by examining a cross section of the problems involved in selecting wheels or tracks, the field has been cleared to concentrate on this most significant factor.

Comparative Performance of Wheeled and Tracked Vehicles

The extent to which soft-ground mobility presently is dependent upon the type of running gear of a vehicle can be illustrated by comparing the performances of tracked and wheeled vehicles now in operation. Many vehicle-performance tests have been conducted by or under the auspices of the Transportation Corps and the Army Mobility Research Center (AMRC) of the Soils Division, U. S. Army Engineer Waterways Experiment Station (WES). Data from these tests provide direct comparisons of performance and in addition furnish a factual basis for hypothesizing the significance of the vehicle characteristics important to soft-ground mobility.

Before the results of the vehicle tests can be assessed meaningfully, the vehicles themselves, their performance, and the condition of the tests must be expressed quantitatively in a common set of terms.

Several measurable quantities suggest themselves as possibly useful bases for comparison or descriptors of vehicles. They are weight, contact pressure, volume, cargo capacity, power, etc. The first two of these quantities have been selected for this analysis. Their limitations as single vehicle descriptors are obvious and well known. However, gross weight is a measure or an indicator of overall size, and the contact pressure describes in a general way the proportion of the overall vehicle devoted to providing support for the vehicle's weight.

The nominal contact pressure of a tracked vehicle is obtained by dividing the vehicle's weight by the overall area of track in contact when the vehicle is resting on a firm surface. Openings in the track and spacings between links are considered part of the track in computing the area. Similarly, the nominal contact pressure of a pneumatic-tired vehicle is obtained by dividing the vehicle's weight by the area of contact of the tire when at rest on a firm surface. The areas are measured from conventional tire prints by considering the spaces between tread features as part of the overall area.

The nominal contact pressure measurement does not recognize the space occupied by a necessary portion of running gear that is not in contact with a surface. Therefore, to give some consideration to the space required to contain the traction elements, a vehicle descriptor termed "projected contact pressure" has been introduced. To get this descriptor, vehicle weights were divided by the projected area of the space actually occupied by the running gear components. For tracked vehicles, this is the distance from outside the front sprockets to outside the rear sprockets times the track width times the number of tracks. The projected area of a tire is simply the overall tire diameter times the width. The projected areas of all wheels of a wheeled vehicle that come into contact with the ground are summed to get the total projected contact area.

Two different quantities have been used to provide a numerical rating of vehicle performance. One is the conventional pull-weight ratio, P/W.

From the standpoint of the traction elements, this ratio may have a different meaning in sand or snow where frictional properties largely govern behavior than it has in wet, fine-grained soils. Nevertheless, it has frequently been used to describe performance in all types of soils and should at least serve as a basis for comparison of wheeled and tracked vehicles in a particular soil type. As used in this study, the pull is the maximum sustained force the vehicle was able to exert on a tow cable, i.e., the amount of thrust the vehicle's traction system was able to generate over and above that needed to propel itself in the test medium. The weight term in the ratio is simply the total static weight of the vehicle. Refinements such as distribution of load to individual wheels and dynamic loadings were ignored. The other rating of vehicle performance is the vehicle cone index (VCI) which has been developed so far only for fine-grained soils. This value indicates the lowest soil strength that will support the passage of the vehicle it describes. In the evaluation system developed at the WES, it is the soil cone-index value that will just be sufficient to allow the vehicle, with no towed load, to make 50 passes in the same tracks. A soil with a strength of 75 percent of this value is estimated to be just strong enough to permit one or two passes.

Since the purpose of the analysis is to compare performance of vehicles, the numerical ratings supplied are for the same set of conditions. The VCI ratings are the soil-strength levels representing the point of zero pull for all the vehicles. Pull-weight ratios for the various vehicles were obtained, either directly or by interpolation, for the same soil strength. Soil strengths were measured by the cone index in most of the tests but were estimated in the remainder of the tests.

The vehicles considered in the analysis are listed in table 1. Each vehicle has been assigned a number to assist in locating the corresponding plotted points in the graphical presentations. The weight, nominal contact pressure, and projected contact pressure of each vehicle are also listed. The nominal contact pressure of vehicles with pneumatic tires is that obtained at 15-psi inflation pressure. The value of 15 psi was arbitrarily chosen for fine-grained soils as a common datum, as this was the inflation pressure used in most of the actual field tests on such soils. Since inflation pressure affected results of tests on coarse-grained soils and snow much more significantly than on fine-grained soils, various inflation pressures are shown for the former materials. These data are listed in subsequent tables as appropriate.

Fine-grained soils

The vehicles considered in this paper are listed in table 1. The VCI ratings shown were calculated by means of the equations developed by the AMRC. These equations are given and described briefly in Appendix A. The extent to which the calculated VCI compares with experimental results is shown in figs. 1 and 2 for the vehicles actually tested. In these plots, the strength of the soil on which a test was run has been plotted on the X axis, and the computed VCI's have been computed on the Y axis. Thus, for each vehicle, there is a series of plotted points representing "go" or "no-go" tests for that vehicle. Those tests in which the vehicle failed to make 50 passes are plotted as closed symbols. The tests in which the vehicle was not immobilized within 50 passes are shown by an open symbol. If the computed VCI's were absolutely correct, the 1:1 line representing equal vehicle cone indexes and soil cone indexes would completely separate the closed symbols from the open symbols.

It can be seen that the computed VCI's tend to provide a slightly conservative estimate of vehicle performance. In fig. 1, showing wheeled-vehicle data for 226 tests on 27 vehicles, in only five instances was a vehicle immobilized on a soil condition rated stronger than the VCI. On the other hand, there were 17 tests in which the vehicle was able to travel on a soil that would have been expected to cause immobilization, i.e., it had a cone index significantly (more than 2 cone index) lower than the VCI. In fig. 2, the pattern for the 123 tracked vehicle tests on 13 vehicles is seen to be similar. There is just one immobilization on a soil rated adequate, but there are 18 "go" tests on soils having cone indexes that are less than the computed VCI by more than 2 cone index units. Thus, considering both wheeled and tracked tests, the evaluation could be considered to be correct about 88 percent of the time and correct or on the safe side about 98 percent of the time.

It has been apparent from these plots that the vehicle cone index calculation provides a reasonable evaluation of the probable performance of vehicles not tested if the vehicles are not radically different from the vehicles actually evaluated.

The performance of vehicles in wet, fine-grained soil as rated by the vehicle cone index has been plotted against vehicle weight in fig. 3. A line has been drawn on the plot that most nearly separates the wheeled vehicles from the tracked vehicles. The data show that a wheeled vehicle usually has a higher VCI than a tracked vehicle of equal total weight. This means that conventional wheeled vehicles tend to require stronger soils to support them. The data show also that lightweight vehicles, both wheeled and tracked, tend to have better performance than very heavy ones.

There are three wheeled vehicle tests that plot on the tracked side of the line. These vehicles are the 16-ton GOER (empty), No. 1; the Marsh Buggy with 10-ft tires, No. 30; and the XM410, 8x8, No. 37. All three have lightly loaded, relatively large tires. Two tracked vehicles plot well into the region occupied by most of the wheeled vehicles. They are the D4 tractor, No. 51; and the M5 tractor, No. 59. These vehicles have relatively narrow tracks.

Fig. 4 shows the VCI ratings of tracked and wheeled vehicles plotted against their nominal contact pressure. Not all the vehicles in table 1 are represented, as contact pressure data were not available for some of the wheeled vehicles. A line can be drawn that separates completely the wheels from the tracks, but for both wheeled and tracked vehicles there is a fairly consistent trend for performance to be best at the lowest nominal contact pressure. It is somewhat surprising to observe further that wheeled vehicles at a relatively high nominal contact pressure have the same computed VCI as tracked vehicles at lesser nominal contact pressure. However, this observation is not necessarily meaningful in an absolute sense as the nominal contact pressure term for wheeled vehicles is quite arbitrary. Furthermore, it should be recognized that since the nominal contact pressure of a tire normally is not less than the inflation pressure, the lower limit of this descriptor, as used in this plot for wheeled vehicles, is 15 psi. If the tire contact area data for the descriptor had been obtained at a lower inflation pressure, the wheeled vehicle data points (in fig. 4) would all be shifted to the left, more nearly in line with the tracked vehicle points. (A reasonable absolute minimum pressure would be the projected contact area, which will be discussed in a subsequent paragraph.) Nevertheless the data in fig. 4 suggest that the performance of wheels is reasonably good considering that the nominal contact pressures are relatively high.

Observations of vehicles when towing loads and climbing slopes suggest that tracked vehicles are capable of utilizing the available soil strength to better advantage than are wheeled vehicles. This advantage, which may be the result of the more uniform pressure distribution and aggressive grousers, appears to be confirmed by field data. It seems pertinent, therefore, to compare the pulling ability on the basis of the nominal contact pressure descriptor. In fig. 5, the nominal contact pressures of the various vehicles are plotted against an estimated pull/weight (P/W) rating on a cone index of 80. The P/W estimate was obtained using the techniques described in WES Technical Memorandum 3-240, 14th Supplement. Fifty or more passes of the vehicle are assumed. A line can be drawn to separate the wheeled and tracked vehicles primarily because of the differences in nominal contact pressure. Nevertheless, the trend of the data suggests that the wheeled vehicles would do as well as tracked vehicles if the nominal contact pressures were the same. It must be noted, though, that the use of the 15-psi inflation pressure datum limits the nominal contact pressure of the wheeled vehicles to this value (15 psi). To get lower nominal contact pressures, lower inflation pressures must be used. Unfortunately, the data are not adequate to explore this line of reasoning further.

Projected contact pressure has been used as the vehicle descriptor in plotting fig. 6. Not all the tracked vehicles are represented, as the necessary dimensions were not available for some. It is evident that this descriptor is strongly related to the VCI. In fact, as can be noted in the equation for the VCI of wheeled vehicles in Appendix A, the descriptor is exactly twice the most important element of the equation, i.e., $\frac{\text{gross weight}}{(\text{tire diameter}/2) \times \text{tire width} \times \text{No. of wheels}}$. It is of some interest that the projected contact pressures for tracked vehicles are of the same order of magnitude as for wheeled vehicles and with some exceptions imply the same level of performance. A single line would represent all the data in fig. 7 quite well. The M46, M47, and M48 tanks (Nos. 43, 44, and 45) and the M6 tractor (No. 58) are able to achieve a higher level of performance, i.e., lower vehicle cone index, than other vehicles of the same projected contact pressure. The reason for this is not known, but it may be noted that all vehicles are relatively heavy.

In summary, data on existing vehicles show that wheeled vehicles have less mobility at the same weight than tracked vehicles in fine-grained soils. From a careful study of figs. 4 and 5 it appears that the performance of many wheeled vehicles is equal to that of many tracked vehicles. However, in terms of the P/W ratio (fig. 5) it can be seen that the best tracked vehicles perform somewhat better than the best wheeled vehicles. Also, the poorest tracked vehicles have better performance than a number of the wheeled vehicles considered. For both wheeled and tracked vehicles, the trend is for the more mobile vehicles to have contact pressures that are relatively low in comparison to others of their type. Thus the data imply that in wet, fine-grained soil the less-mobile wheeled vehicles can be provided with soft-soil mobility equal to most tracked vehicles by reducing the nominal contact pressure. This could be accomplished by increasing the size and/or number of the wheels.

Coarse-grained soils

The performance ratings given here for vehicles operating in coarse-grained soils are exclusively in terms of the one-pass, pull-weight ratio obtained in tests at one soil-strength level. Adequate data are available on 13 wheeled vehicles and 6 tracked vehicles. These vehicles and the corresponding vehicle numbers are listed in table 2, together with nominal contact pressure and performance data for at least two different tire inflation pressures. One of the inflation pressures was about the lowest considered practicable for the tires tested (usually less than 12 psi), and the other was either a typical "cross-country" pressure (usually in the range of 15-25 psi) or one that allowed only moderate tire deflection.

In fig. 7, the P/W ratios of the vehicles on sand at a cone index of 100 are shown in relation to their weights. At any gross weight it is apparent that tracked vehicles are better performers than wheeled vehicles. Only one wheeled vehicle, No. 33, was as capable as the poorest of the tracked vehicles tested, and this wheeled vehicle was a very lightly loaded "model" without a practical load-carrying ability. All the tracked vehicles developed about the same P/W ratio. It seems apparent from these data that the weight descriptor is not directly related to performance. Part of the spread in the performance of wheeled vehicles at any particular weight is the result of differences in the tire inflation pressure, a factor that greatly influences performance.

Fig. 8 compares vehicle performance with nominal contact pressure. These data show that most of the wheeled vehicles operate with nominal contact pressures that are much higher than the nominal contact pressures of tracked vehicles. This is true even for the lowest inflation pressures tested. Only the unusual vehicles in the Marsh Buggy class were able to develop the performance rating of the poorest of the tracked vehicles at a comparable nominal pressure. These vehicles operate at loads per tire that are quite small in relation to the load conventionally carried by tires of this size. The data show also that the performance of the wheeled vehicles was strongly related to the nominal contact pressure. It will be noted that if a parallel relation is assumed for tracks, the best wheeled vehicles never will be able to operate as effectively as the best tracked vehicles if both have the same nominal contact pressure. It is of some interest to note further that the three tracked vehicles that demonstrated superior performance are the engineer tractors. One of the distinguishing features of these tractors is a relatively rigid track suspension. It seems possible that this may be a factor in the performance level achieved.

The relation of vehicle performance to the projected contact pressure is shown in fig. 9. The implications of this plot are much the same as the nominal contact pressure plot, except that the M5A4 and M4 high-speed tractors (Nos. 54 and 55) appear to fall more nearly in the same class as the engineer tractors. In both contact pressure plots, the M29C (No. 48) has a relative performance rating more comparable to the wheeled vehicles than to the other tracked vehicles.

Overall, the data show that in sand very few existing wheeled vehicles achieve the level of performance of any of the tracked vehicles. However, the data suggest that a P/W performance rating equal to that of the poorer tracked vehicles could be realized if the wheels were operated at an equal value of contact pressure. The general trend of the data is such as to imply that the best wheeled vehicles cannot match the performance of the best tracked vehicles at equal contact pressures. The data show the conventional rigid-tracked engineer tractors to be superior to other types of tracked vehicles in coarse-grained soils.

Snow

The data on the performance of wheeled vehicles in snow are too few to permit a good comparison of track-versus-wheel performance. Generally, wheeled vehicles are considered to be unsuited for use in snow, but some notable exceptions do exist.

Weight is known to influence wheel performance. The Marsh Buggy, carrying 3500 lb on each of its 10-ft-diameter tires, traveled easily on Greenland ice-cap snow. The Sno-train tractor, using somewhat wider 10-ft-diameter tires but carrying a tire load of 8000 lb, was little more than marginally operative in Greenland. The Byrd Sno Cruiser with 17,500 lb on each 10-ft-diameter tire was a complete failure in the Antarctic in the 1930's. The Tournadozer, total weight 31,000 lb, nominal contact pressure about 17 psi, was immobile on the Greenland ice cap; but the M135, 2-1/2-ton truck, total weight 17,000 lb, nominal contact pressure about 27 psi, could just propel itself. All the tracked vehicles tested in Greenland, including the M48 tank at 11.2-psi nominal contact pressure, 93,000 lb total weight, were mobile and able to exert a significant level of pull (P/W approximately 25). It should be recalled that ice-cap snows tend to be much stronger than subarctic and tree-line snows.

A few one-pass, drawbar tests have been conducted with small, wheeled vehicles in deep, soft, subarctic snow. These data provide a few numerical evaluations of wheel performance. Typical results are shown in fig. 10.

Also shown in fig. 10 are the results of some one-pass tests with tracks in a similar snow but which were obtained at a different time and place than the wheeled vehicle data. The trend of the data is somewhat similar to that for the coarse-grained soils. This result is in line with the concept of dry, soft snow acting as a frictional material. The data suggest that lightly loaded wheels can approach the performance level of the poorer tracked vehicles at equal nominal contact pressure but probably cannot match the ability of the better tracked vehicles. It should be noted also that the wheeled vehicles were able to move only when the nominal contact pressure was quite low.

While the snow data are far from conclusive, it seems clear that conventional wheeled vehicles are not capable of performing adequately in most snow. It is likely, too, that wheels will be found to be somewhat inferior to tracks even at equal weights and/or equal nominal contact pressures.

Redesign of Wheeled Vehicles

The intent of the foregoing analysis was to compare the performance of wheeled and tracked vehicles and to note any implication contained in the data. A logical extension of this study is to use this knowledge together with presently available analytical techniques to determine the changes that would be necessary to provide a specific wheeled vehicle with a soft-soil performance level equal to that of an existing tracked vehicle with a closely similar size and mission. This has been done for the three vehicle pairs listed in table 4. In the analysis are included small, medium, and large vehicles of relatively modern design.

To limit the number of possible wheel configurations to be analyzed, only two types of change were studied: (a) the number of wheels required for the desired mobility if the tire size actually used on the vehicles was retained and (b) the size of tires required if the same number of wheels and same tire proportions (i.e., diameter-width ratio) as presently used were retained.

The analysis was carried out using both the technique based on the AMRC cone index system (described in Appendix A) and the equations developed by the Land Locomotion Laboratory (LLL) based on the Bekker soil-value system. These latter methods and equations are described in some detail in Appendix B. The AMRC system permits the direct calculation of the wheel configuration that would just allow the vehicle to complete one or 50 passes on the same soil on which the counterpart tracked vehicle also would just complete one or 50 passes. The LLL equations are used to calculate the pull a vehicle can exert on the first pass over a soil with a given set of values. To make a comparison similar to that afforded by the AMRC system, wheel characteristics were determined that would provide the vehicle with just a little more than zero drawbar pull on the same soil conditions that would almost cause the counterpart tracked vehicle to become immobilized. This was done by developing a series of curves of P/W versus soil consistency "k" for a bracketing number of possible wheel configurations. The combined results of both these calculations are given in table 5.

Interestingly, the two systems yielded the very same redesign conclusions for the problem of providing the necessary number of wheels with tires of the size presently in use. The results of the tire size computations yielded slightly different results. The LLL estimates of the necessary tire size were consistently a few inches greater than the corresponding AMRC estimates. Therefore, the values shown in table 5 are the averages of the two sets of numbers.

The design estimates in table 5 show that wheeled vehicles can be designed to have the same soft-ground mobility as tracked vehicles. However, it is equally evident that the size and/or number of wheels necessary to accomplish this can create the awkward problem of incorporating them in a practical vehicle. From the data, this problem appears to be considerably more acute for the large vehicles than for the small ones.

It must be emphasized that the vehicle redesigns just described provide just sufficient mobility for the wheeled vehicles to traverse the same very soft soil that the tracked vehicle can just barely cross. This is the condition for which the available P/W ratio effectively is zero. If the redesign had been made to meet a requirement that the wheeled vehicle be able to equal the tracked vehicle at a large P/W ratio (i.e., on a relatively strong soil), the wheeled configurations would have been even more extreme and probably impractical to build. This problem will not be dealt with in this paper in the interest of brevity, but a thorough study of the computation systems in Appendixes A and B, and particularly figs. A2, B3, and B4, will confirm this observation. Both the LLL and the AMRC systems imply that the use of a greater number of the present tire sizes probably will not achieve the same P/W performance on strong soils as the better tracked vehicles. This is apparently true, even though the number of tires used becomes absurdly large. On the other hand, the LLL system calculations indicate and recent WES field data tend to confirm that the tracked-vehicle P/W levels can be reached by using tires of heroic proportions.

Conclusions

On the basis of arguments advanced and data presented, the following points are concluded:

a. A general solution to the problem of wheels versus tracks is not feasible.

b. Whether to use wheels or tracks is a question which must be answered each time a new vehicle requirement is posed.

c. The following are the principal factors to be considered in making the decision: mission, initial cost, suspension vulnerability, obstacle performance, ridability, fuel economy, maintenance cost, and soft-soil performance.

d. Soft-soil performance is the principal factor that has motivated the selection of tracks over wheels.

e. A study of actual performance data for existing wheeled and tracked vehicles indicates:

(1) Tracked vehicles can operate on softer soils, pull heavier loads, and climb steeper slopes than wheeled vehicles of the same weight.

(2) Reduction of contact pressure appears to be the most effective, presently feasible way to improve the performance of both tracked and wheeled vehicles.

f. According to existing theoretical or quasi-theoretical knowledge, reduction of contact pressure in wheeled vehicles by increasing the size of tires is more effective in improving vehicle performance than by increasing the number of wheels and retaining the same tire size. This statement is especially applicable if vehicle performance is judged mainly on the criterion of drawbar pull on firm soils.

g. Redesign of wheeled vehicles to endow them with the ability to travel on soil as soft as that upon which "counterpart" tracked vehicles can travel, can be accomplished but only at the expense of adding an awkward or unrealistic number of wheels of the original size or by greatly increasing the tire size while retaining the same number of wheels. Redesign of wheeled vehicles to provide them with P/W ratios on firm soil as high as tracked vehicle "counterparts" will require even a greater number of wheels and/or larger tire sizes, according to the best information available.

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Table 1

Vehicle Data

Fine-Grained Soils

Vehicle No.	Vehicle	Tire Size	No. of Wheels	Weight lb	Vehicle Cone Index	Nominal Contact Pressure psi*	Projected Contact Pressure psi
	Wheeled Vehicles						
1	16-ton GOER XM437E1 (empty)	29.5-25	4	39,300	42	17	4.5
2	16-ton GOER XM437E1 (loaded)	29.5-25	4	71,070	79	--	8.1
3	5-ton GOER XM520	18.00-26	4	26,667	57	17	6.0
4	5-ton GOER XM520	15.00-34	4	26,667	66	19	6.9
5	6x6 Meili Flex-Trac	10.00-20	6	9,100	43	26	3.8
6	4x4 Meili Flex-Trac	10.00-20	4	9,100	55	27	5.7
7	Tournadozer	21.00-25	4	31,209	55	21	6.0
8	2-1/2-ton M135	11.00-20	6	17,700	59	31	6.4
9	2-1/2-ton M34	11.00-20	6	17,500	60	31	6.3
10	3/4-ton M37	9.00-16	4	7,475	60	24	6.1
11	4-ton, 6x6 truck	14.00-20	6	25,100	59	27	6.2
12	6-ton, 6x6 truck	14.00-20	6	34,800	81	35	8.6
13	1/2-ton M274 (mule)	7.50-10	4	1,100	32	15	1.5
14	Bucket loader	14.00-24	4	13,815	48	19	4.7
15	1/4-ton Willys station wagon	7.00-15	4	3,665	53	--	4.5
16	1/4-ton M151 (jeep)	36x20-14	4	3,450	25	15	1.3
17	1-1/2-ton Powerwagon	46x18-16	4	9,500	35	15	2.9
18	Gama Goat	12.4/11-16	6	5,770	34	--	2.4
19	2-1/2-ton M49	9.00-20	10	13,490	48	28	3.9
20	XM409E1 truck	16.00-20	8	46,450	70	--	7.0
21	Rough terrain forklift	16.00-24	4	30,625	77	--	8.5
22	BARC	36.00-41	4	197,000	174	22	12.0
23	5-ton LARC	18.00-25	4	28,000	56	--	6.4
24	15-ton LARC	24.00-29	4	65,060	87	--	8.8
25	2-1/2-ton DUKW	11.00-18	6	20,055	74	27	7.6
26	1/4-ton M38 (jeep)	7.00-16	4	3,250	50	21	4.1
27	5-ton M41	14.00-20	6	30,185	70	27	7.5
28	4x4 Jumbo truck	18.00-26	4	20,100**	54	21	6.3
29	3/4-ton M37 (empty)	9.00-16	4	5,925	52	23	4.8
30	Marsh buggy	33.5-66	4	11,990	22	--	0.7
31	Marsh buggy	18.00-25	4	11,745	35	[illegible]	2.7
32	Marsh buggy (model)	9.00-14	4	180	9	[illegible]	0.2
33	Marsh buggy (model)	6.00-16	4	210	16	15	0.3
34	3/4-ton XM408	7.00-16	6	4,562	44	21	3.7
35	8-ton XM520E1	18.00-33	4	43,410	72	--	7.6
36	3/4-ton FC-170	9.00-16	4	6,920	45	23	4.3
37	2-1/2-ton XM410	16.00-20	8	15,050	33	--	2.3
38	Saracen APC	11.00-20	6	22,400	79	32	8.8
39	2-1/2-ton, 6x6 truck	10.50-18	6	16,300	62	25	6.6
40	GOER, 5000 gal, XM438E2	29.5-25	4	72,000	80	--	8.2

(Continued)

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* Nominal contact pressures are for tire inflation pressure of 15 psi.

** Weight of 14,000 lb used to obtain vehicle cone index.

Table 1 (Concluded)

Vehicle No.	Vehicle	Tire Size	No. of Wheels	Weight lb	Vehicle Cone Index	Nominal Contact Pressure psi	Projected Contact Pressure psi
		Tracked Vehicles					
41	M24 tank			35,800	58	11.3	6.2
42	M26 tank			92,000	64	13.3	---
43	M46 tank			97,000	60	13.2	8.7
44	M47 tank			97,200	62	13.7	8.7
45	T48 tank			98,400	49	11.2	6.9
46	T92 howitzer			124,700	65	12.5	---
47	M8 cargo tractor			49,700	44	7.8	4.8
48	M29 cargo carrier (weasel)			5,640	25	1.8	1.2
49	T41E1 tank			50,800	47	9.4	5.7
50	LVT-4			33,400	52	8.6	---
51	D4 engineer tractor			14,870	57	9.4	5.8
52	D6 engineer tractor			22,670	49	8.2	---
53	D7 engineer tractor			29,500	40	6.9	4.9
54	M5A4 hi-speed tractor			25,230	42	6.3	4.7
55	M4 hi-speed tractor			30,250	45	7.1	4.9
56	M4A1 hi-speed tractor			37,100	37	6.1	4.3
57	T18E1 personnel carrier			42,000	43	8.3	---
58	M6 hi-speed tractor			74,300	53	9.5	7.1
59	M5 hi-speed tractor			27,000	64	10.4	7.1
60	Nodwell RN-200 cargo carrier			67,000	29	5.0	---
61	M113 personnel carrier			22,900	47	7.3	4.3
62	XM571 utility carrier			7,700	27	2.1	---
63	XM548 cargo tractor			25,250	44	8.0	---
64	M59 hi-speed tractor			38,700	41	7.0	4.4
65	M8E2 cargo tractor			41,500	39	6.0	4.0
66	T28 superheavy tank			188,000	52	14.0	---
67	M76 cargo carrier (otter)			12,200	23	2.1	1.2

Table 2

Vehicle Data

Coarse-Grained Soils

Vehicle No.	Vehicle	Tire Size	Nominal Contact Pressure psi	Drawbar Pull/ Weight at 100 CI	Projected Contact Pressure psi
	Wheeled Vehicles				
3	5-ton GOER XM520	18.00-26	14.2 18.2	0.380 0.275	6.0
7	Tournadozer	21.00-25	17.1 24.2	0.346 0.252	6.0
8	2-1/2-ton M135	11.00-20	27.2 35.1	0.283 0.179	6.4
10	3/4-ton M37	9.00-16	21.2 27.2	0.274 0.177	6.1
14	Bucket loader	14.00-24	15.7 22.8	0.316 0.215	4.7
25	2-1/2-ton DUKW	11.00-18	22.4 31.9	0.316 0.195	7.6
26	1/4-ton M38	7.00-16	17.8 24.4	0.329 0.204	4.1
27	5-ton M41	14.00-20	21.8 29.8	0.332 0.234	7.5
28	4x4 Jumbo truck	18.00-26	17.3 24.3	0.305 0.208	6.3
29	3/4-ton M37 (empty)	9.00-16	19.4 22.8	0.274 0.215	4.8
30	Marsh buggy	33.5-66	5.8 3.6	0.400 0.450	0.7
31	Marsh buggy	18.00-25	9.2 12.6 18.0	0.415 0.350 0.345	2.7
33	Marsh buggy (model)	6.00-16	1.6 2.0	0.540 0.480	0.3
	Tracked Vehicles				
48	M29 cargo carrier (weasel)		1.8	0.494	1.2
51	D4 engineer tractor		9.4	0.551	5.8
52	D6 engineer tractor		8.2	0.553	---
53	D7 engineer tractor		6.9	0.527	4.9
54	M5A4 hi-speed tractor		6.3	0.490	4.7
55	M4 hi-speed tractor		7.1	0.502	4.9

Table 3

Vehicle Data

Deep Dry Soft Snow

Vehicle No.	Vehicle	Tire Size	Nominal Contact Pressure psi	Drawbar Pull/ Weight
	Wheeled Vehicles			
32	Marsh buggy (model)	9.00-14	1.8	0.17
			2.8	0.01
33	Marsh buggy (model)	6.00-16	1.9	0.16
			2.9	0.06
			3.9	0.00
	Tracked Vehicles			
48	M29 cargo carrier (weasel)		1.5	0.26
54	M5A4 hi-speed tractor		8.4	0.14
64	M59 hi-speed tractor		7.0	0.24
65	M8E2 cargo tractor		6.2	0.25

Table 4

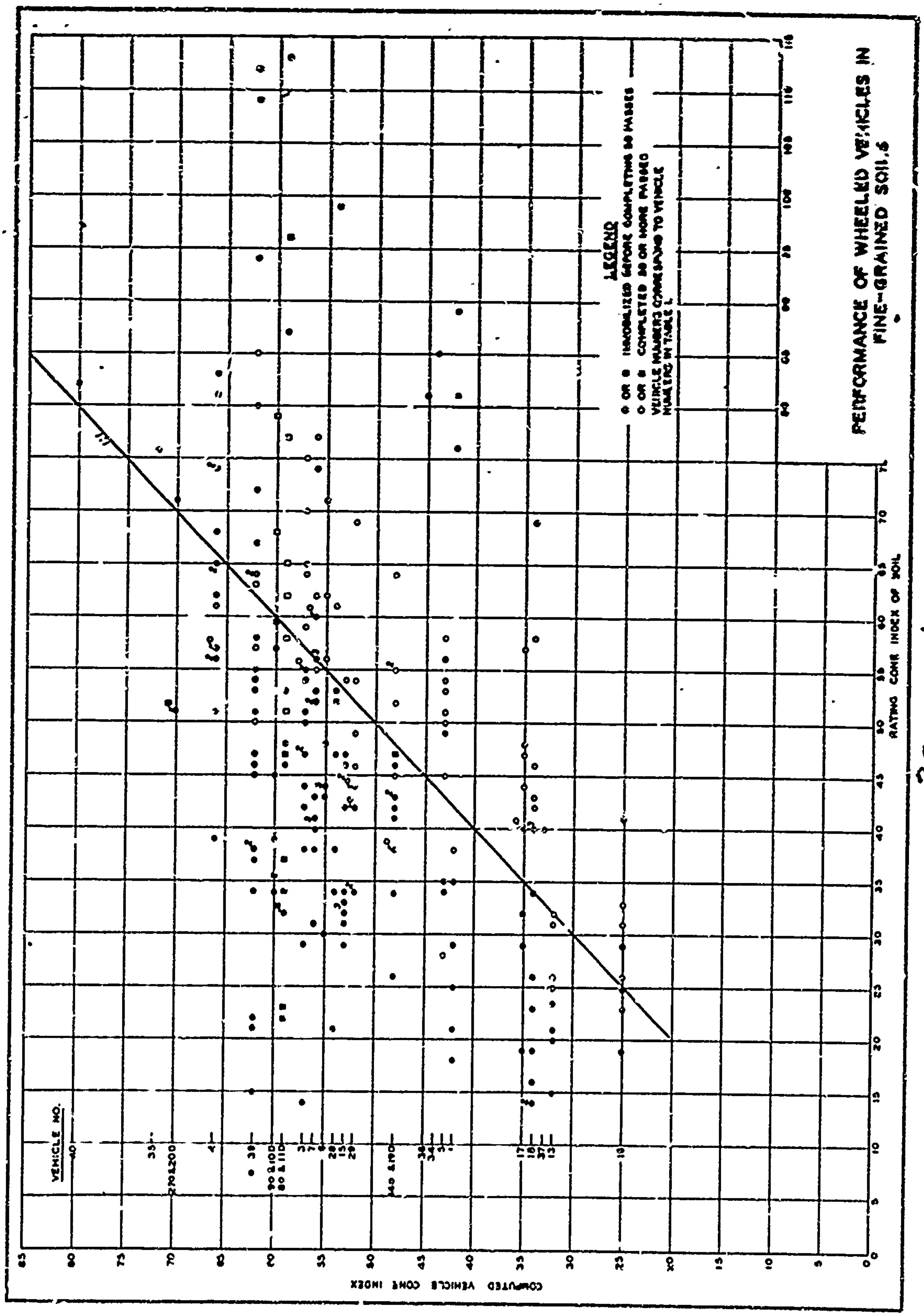
Vehicles Compared in Wheel Redesign Problem

Wheeled Vehicle							Counterpart Tracked Vehicle		
			Tire						
Name	Weight lb	No. Tires	Size	Width in.	Diameter in.	Capacity	Name	Weight lb	Capacity
Gama Goat	5,770	6	12.4/11-16	11.2	36.1	2500 lb	XM571	7,700	2400 lb
Saracen	22,400	6	11.00-20	11.0	42.0	12 troops	M113	22,900	12 troops
GOER XM437E1	71,070	4	29.5-25	29.5	74.0	16 tons	Nodwell RN200	67,000	10 tons

Table 5

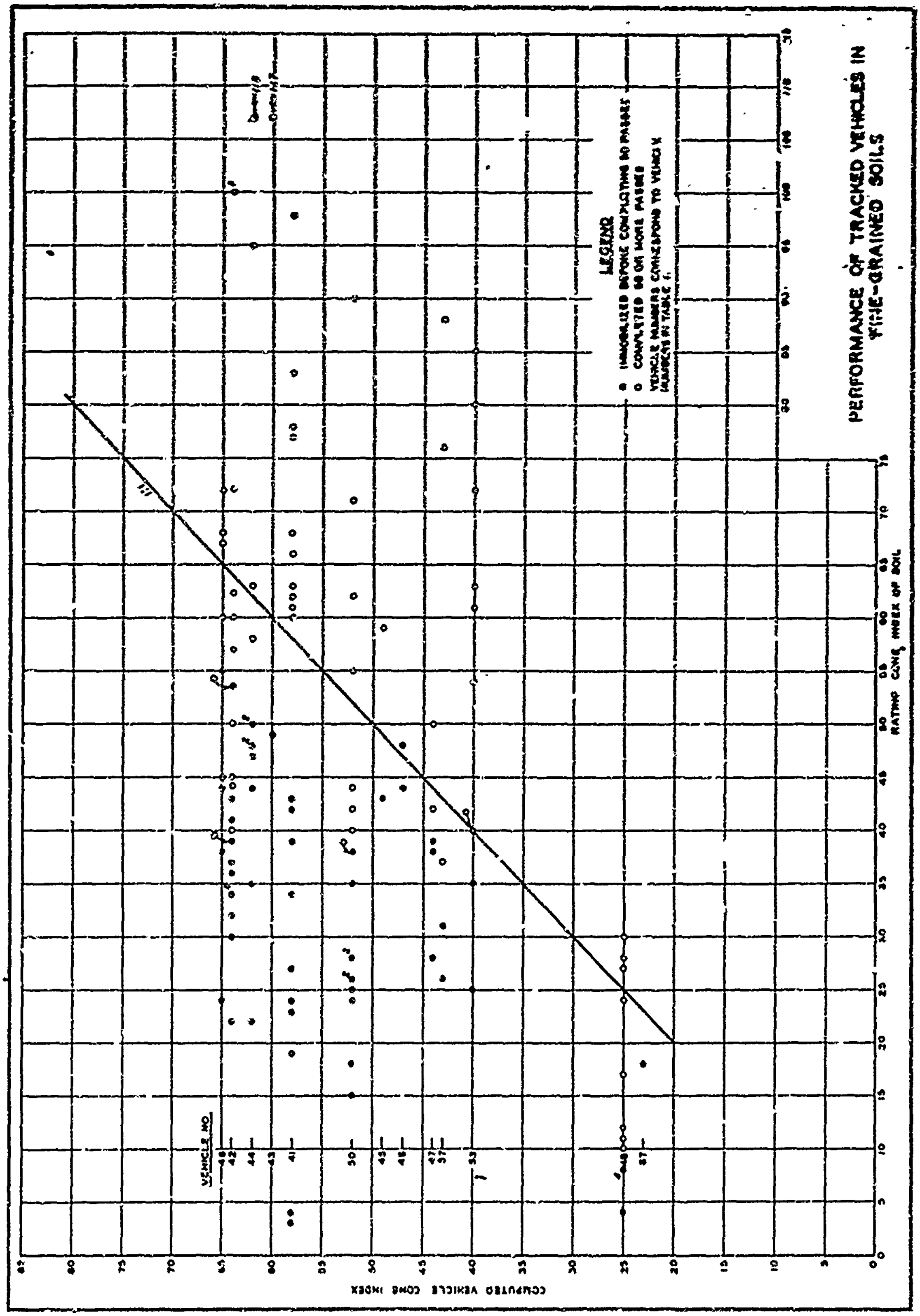
Wheel Configurations Required for Equivalent Mobility to Tracked Counterpart

Wheeled Vehicle	Number of Tires of Present Size	Tire Size for Present Number of Tires	
		Width, in.	Diameter, in.
Gama Goat	10	16	52
Saracen	12	17	65
GOER	20	96	240



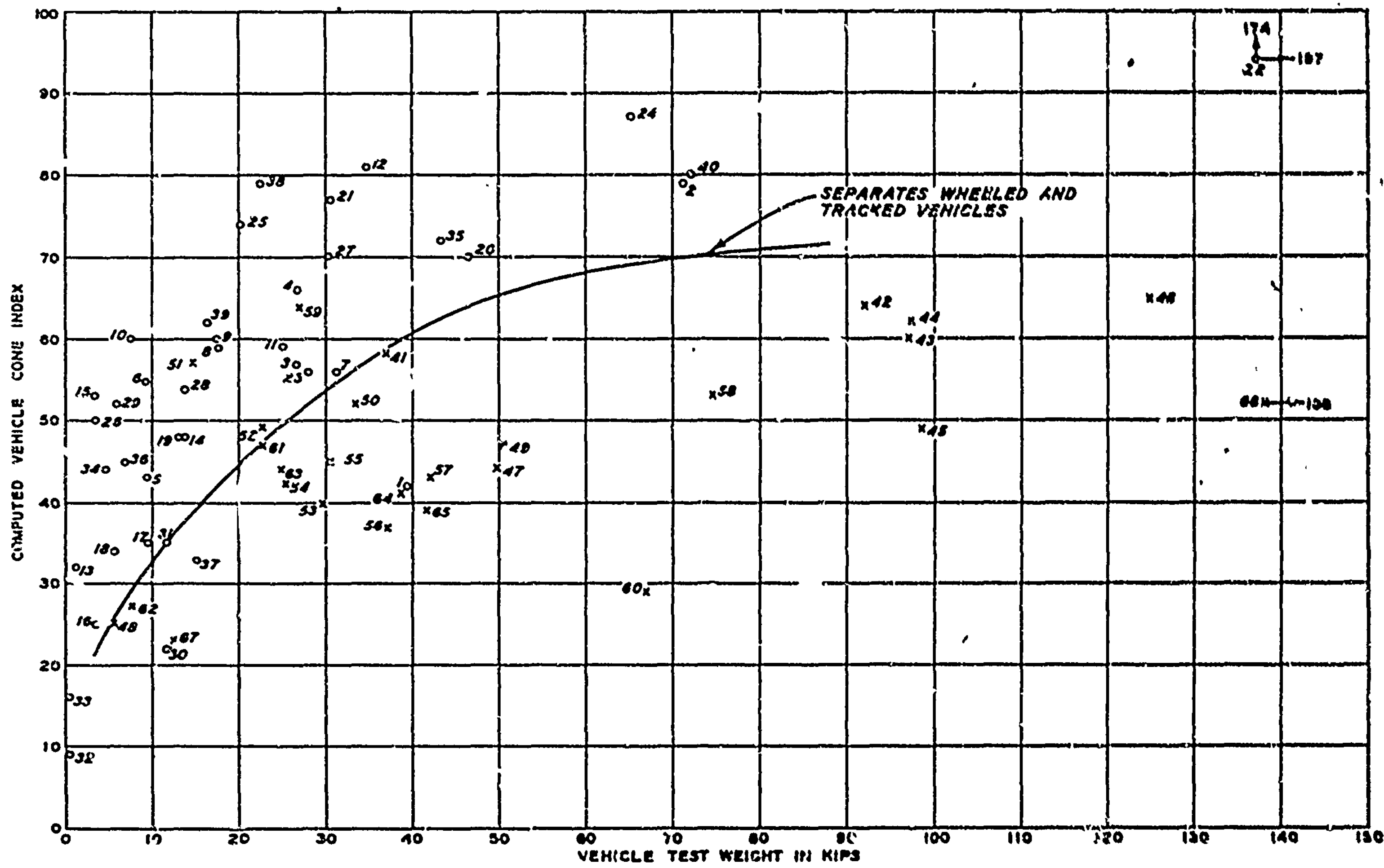
PERFORMANCE OF WHEELED VEHICLES IN FINE-GRAINED SOILS

FIGURE I



PERFORMANCE OF TRACKED VEHICLES IN FINE-GRAINED SOILS

FIGURE 2

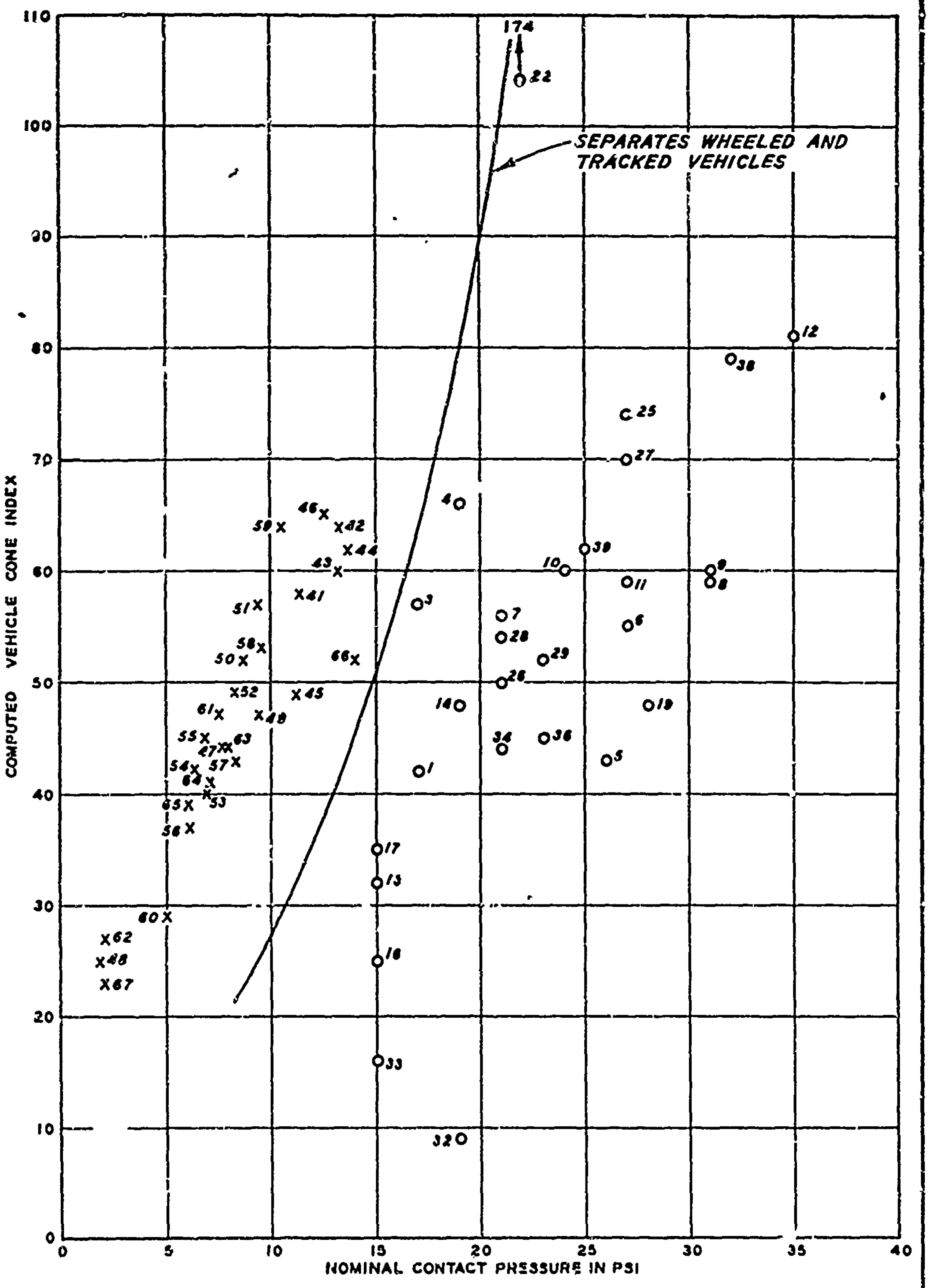


LEGEND
- o WHEELED VEHICLES
- x TRACKED VEHICLES

SLANT NUMBERS BY PLOTTED POINTS CORRESPOND TO VEHICLE NUMBERS IN TABLE I

PERFORMANCE OF VEHICLES IN FINE-GRAINED SOILS

FIGURE 3

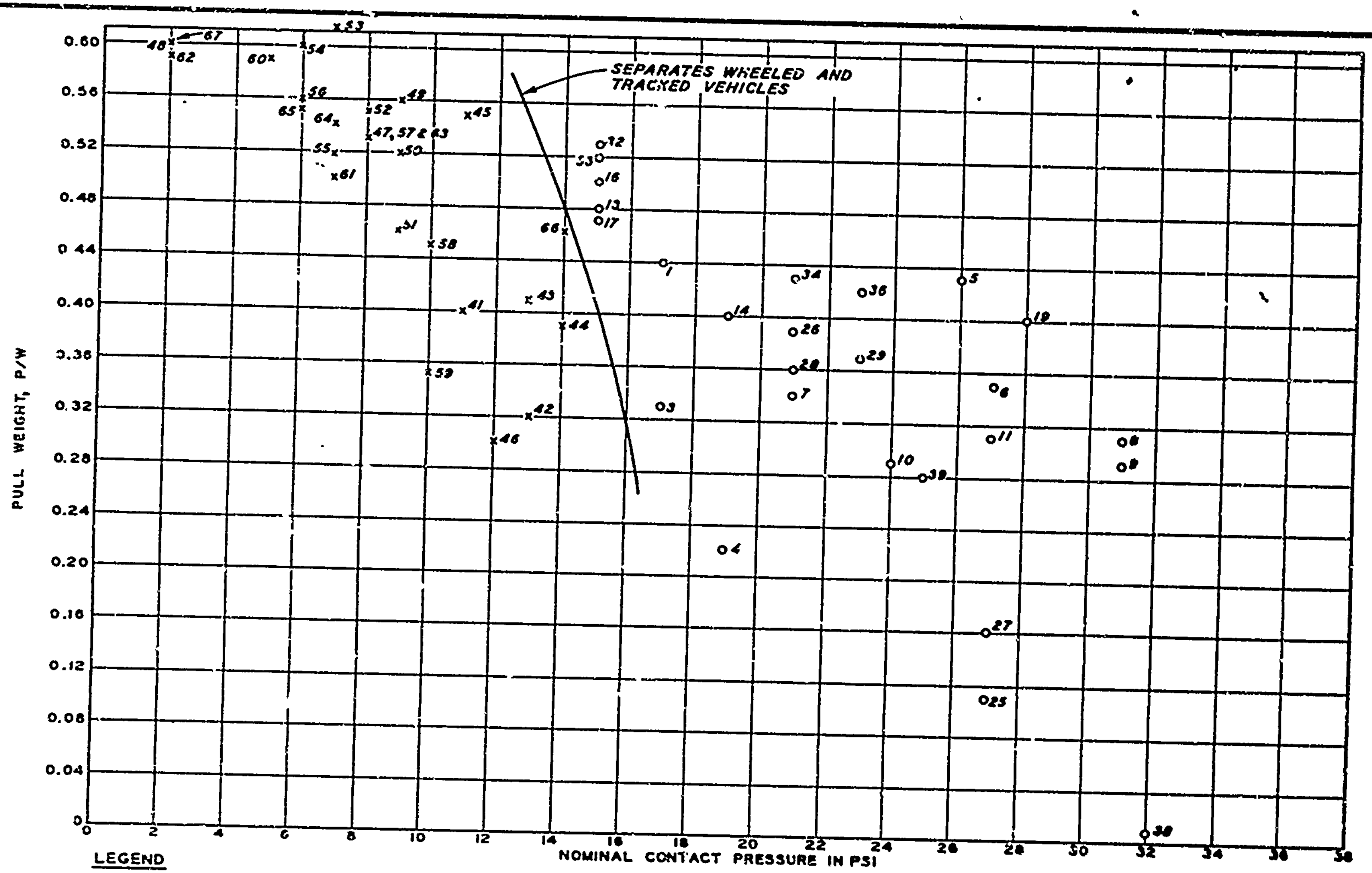


LEGEND

O WHEELED VEHICLES
X TRACKED VEHICLES
SLANT NUMBERS BY PLOTTED POINTS CORRESPOND TO VEHICLE NUMBERS IN TABLE I.

PERFORMANCE OF VEHICLES IN FINE-GRAINED SOILS

FIGURE 4



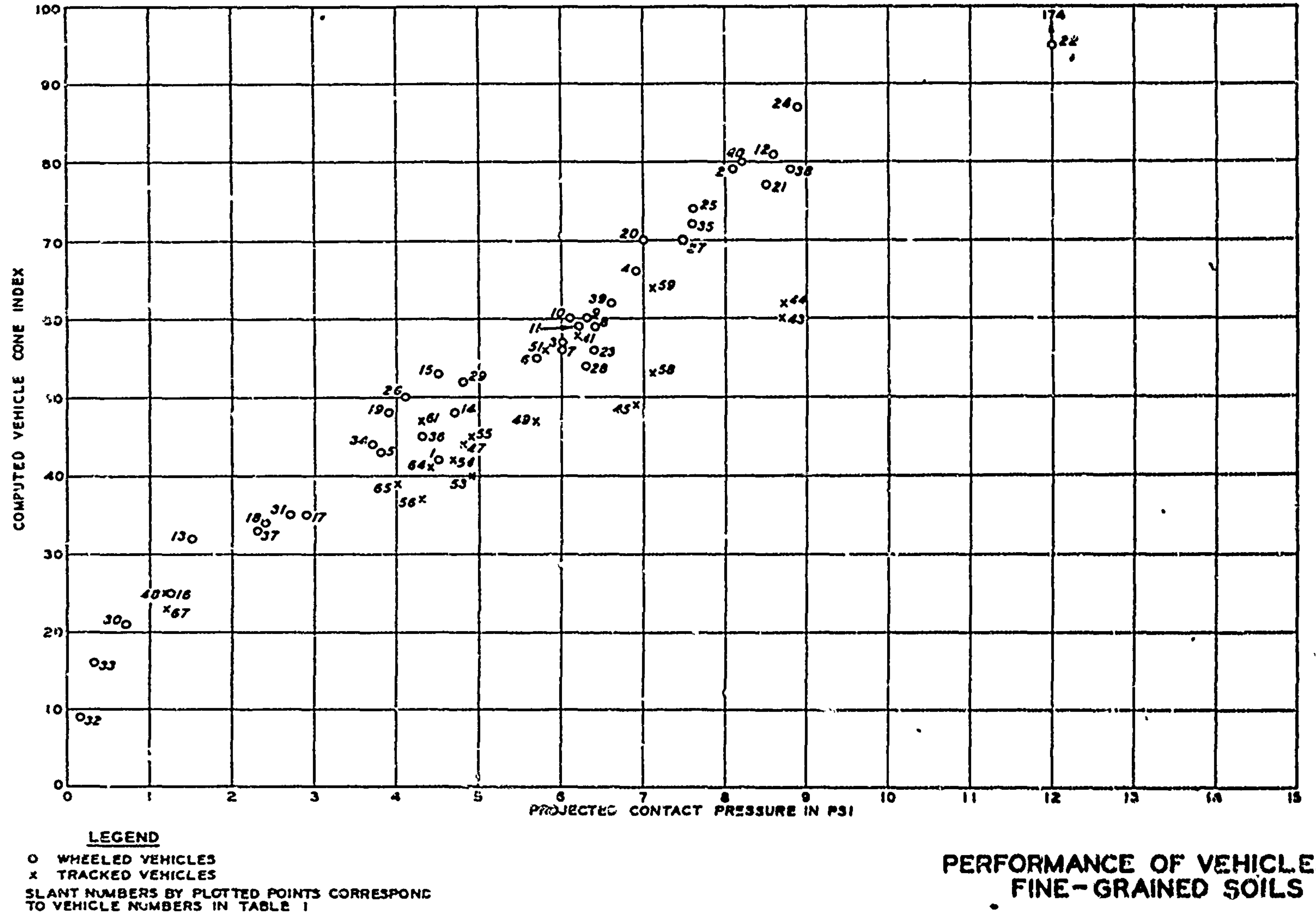
LEGEND

- o WHEELED VEHICLES
- x TRACKED VEHICLES

SLANT NUMBERS BY PLOTTED POINTS CORRESPOND TO VEHICLE NUMBERS IN TABLE I

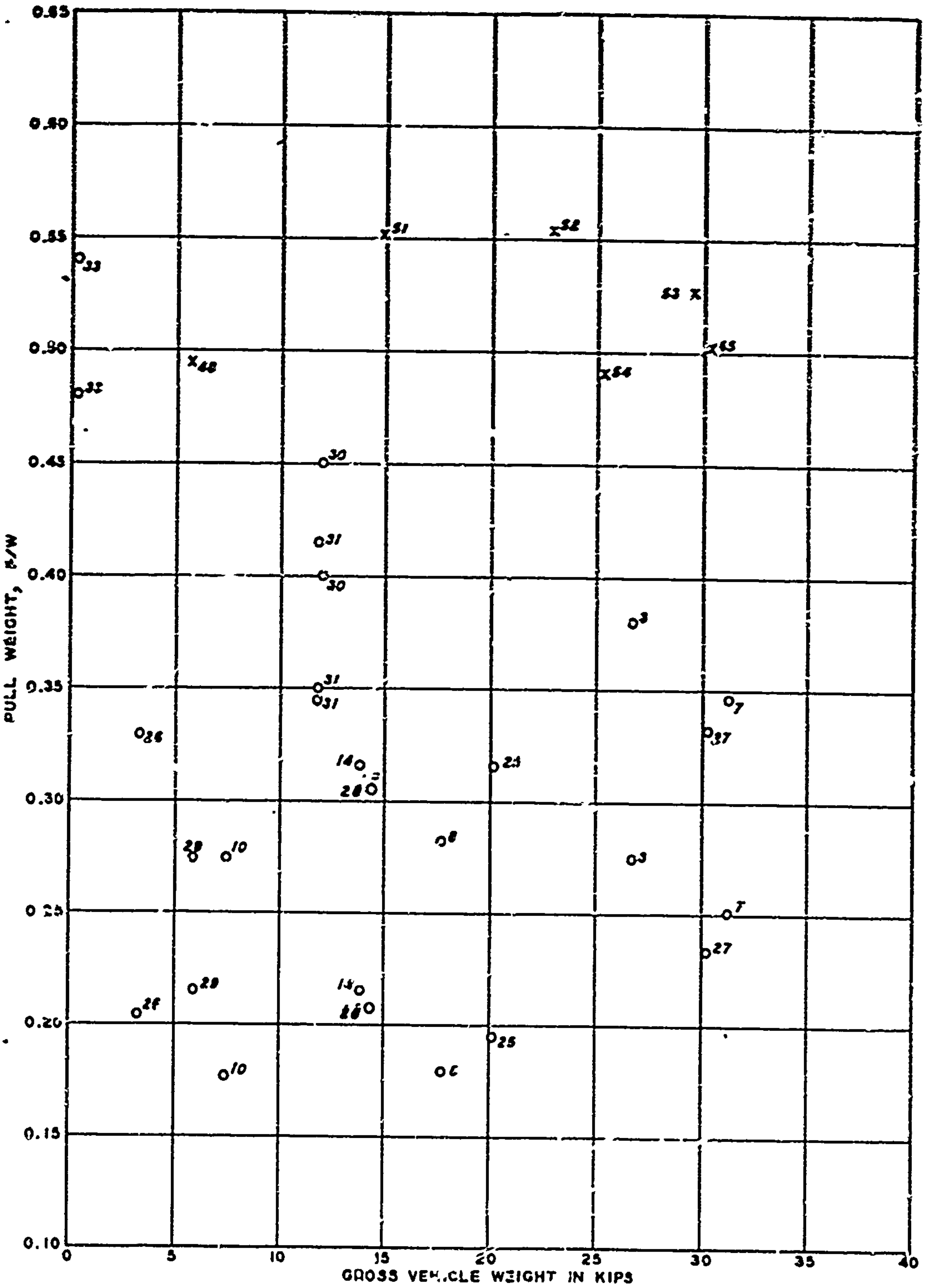
PERFORMANCE OF VEHICLES IN FINE-GRAINED SOILS (CONE INDEX = 80)

FIGURE 5



PERFORMANCE OF VEHICLES IN FINE-GRAINED SOILS

Figure 6

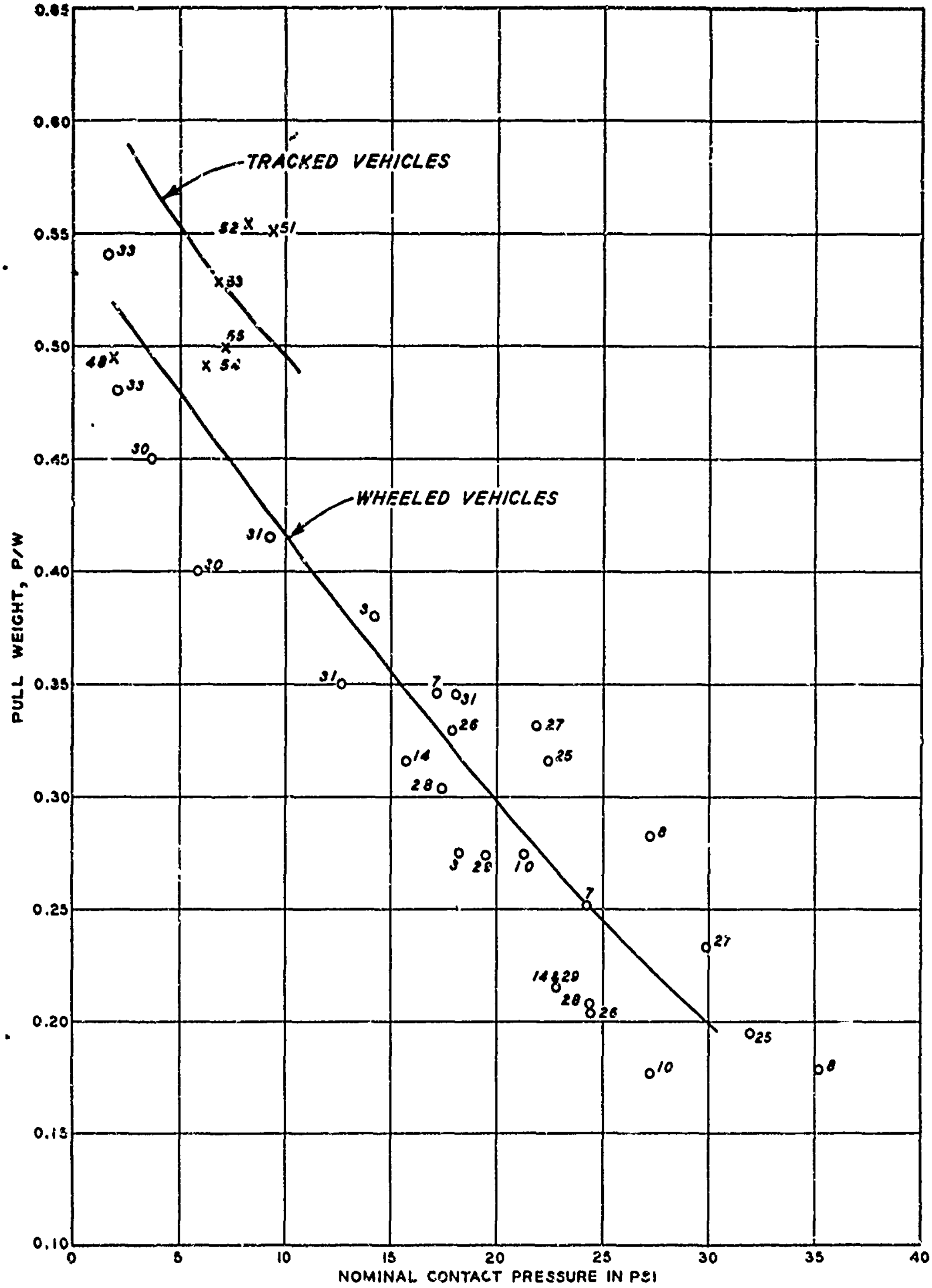


LEGEND

O WHEELED VEHICLES
X TRACKED VEHICLES
SLANT NUMBERS BY PLOTTED POINTS CORRESPOND TO VEHICLE NUMBERS IN TABLE 2.

PERFORMANCE OF VEHICLES IN COARSE-GRAINED SOILS

(CONE INDEX=100)



LEGEND

O WHEELED VEHICLES

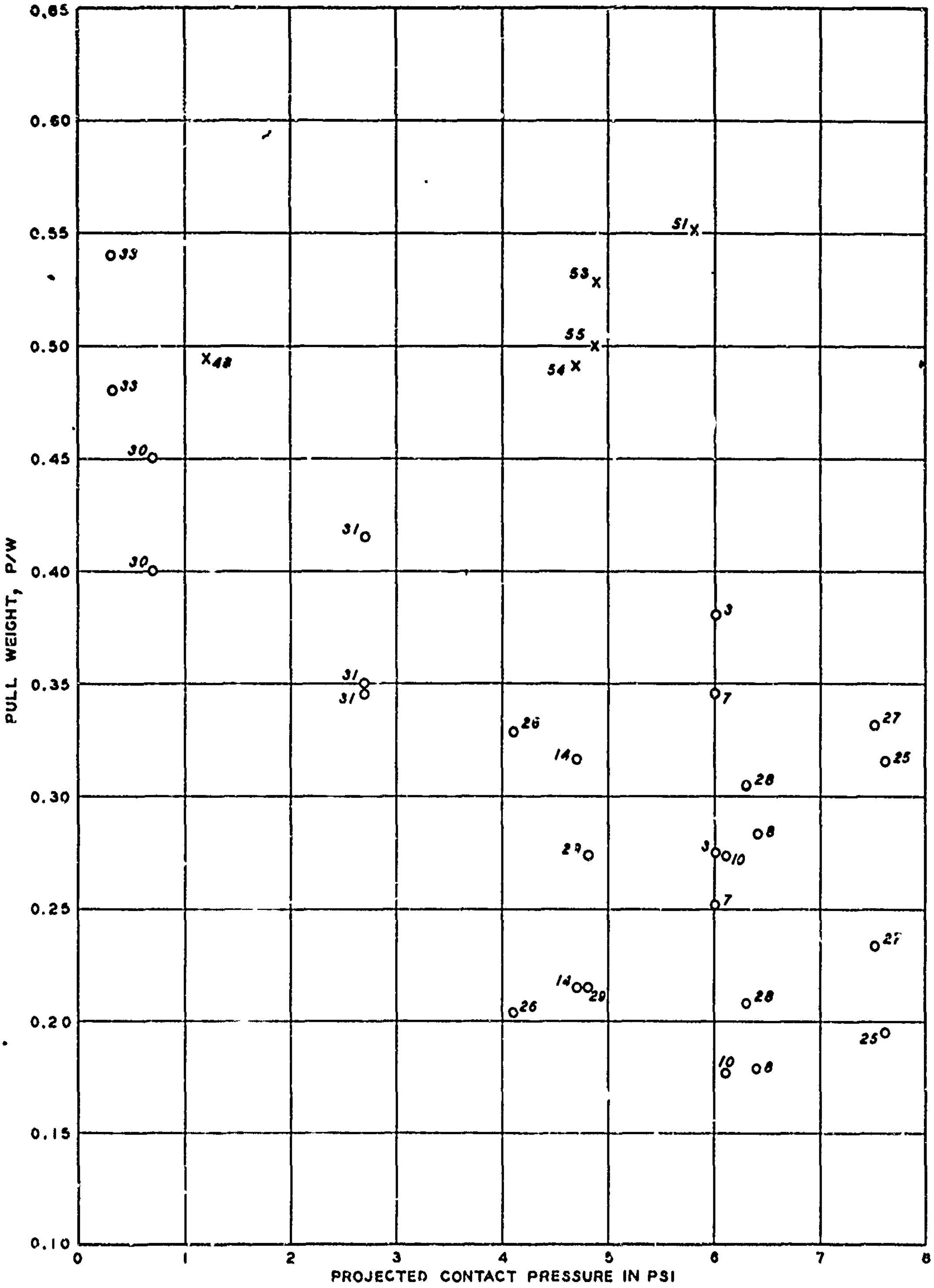
X TRACKED VEHICLES

SLANT NUMBERS BY PLOTTED POINTS CORRESPOND TO VEHICLE NUMBERS IN TABLE 2.

PERFORMANCE OF VEHICLES IN COARSE-GRAINED SOILS

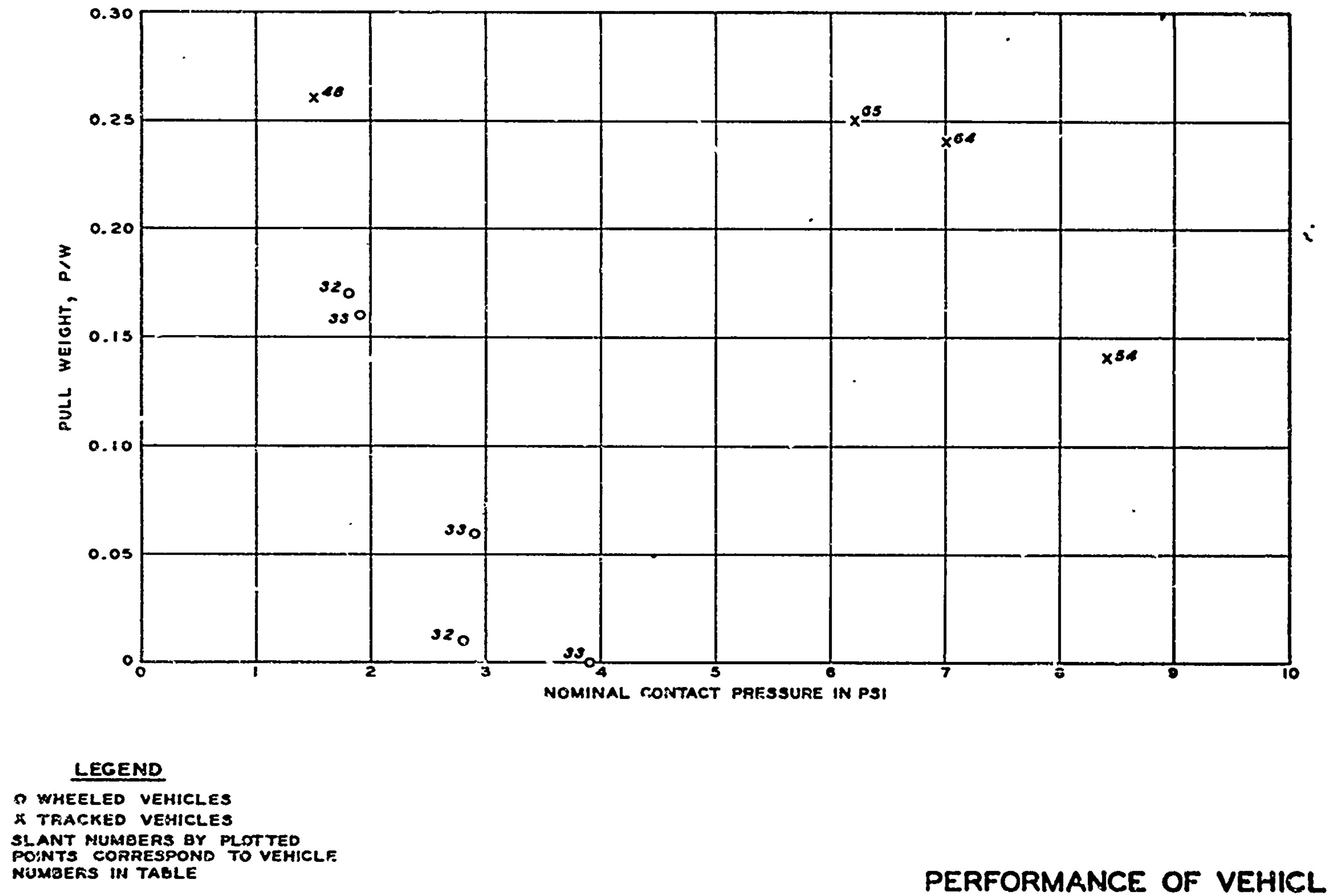
(CONE INDEX= 100)

FIGURE 8



PERFORMANCE OF VEHICLES IN COARSE-GRAINED SOILS
(CONE INDEX=100)

FIGURE 9



PERFORMANCE OF VEHICLES IN DEEP-DRY SOFT SNOWS

Figure 10

APPENDIX A: COMPUTATION OF VEHICLE CONE INDEX

The vehicle cone index (VCI), i.e. the minimum soil strength in the critical layer required to support 50 passes of the vehicle in the same tracks, is determined by first computing a mobility index (MI) and then reading the corresponding value of vehicle cone index from the curve, fig. A1.

The MI is obtained by solution of the following equations:

For wheeled vehicles

$$\text{MI} = \left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor} \times \text{grouser factor}} + \text{wheel load factor} - \text{clearance factor}\right) \times \text{engine factor} \times \text{transmission factor} \times \text{differential factor} \qquad (1)$$

where

$$\text{contact pressure factor} = \frac{\text{gross weight in pounds}}{\text{tire width in inches} \times (\text{overall diameter in inches of wheels}/2) \times \text{No. of tires}}$$

$$\text{weight factor} = 0.02 \times \text{gross weight in kips} + 0.6$$

$$\text{tire factor} = \frac{\text{tire width in inches} + \text{No. of wheels}}{100}$$

$$\text{grouser factor} = \begin{matrix} 1.05 \text{ with chains} \\ 1.00 \text{ without chains} \end{matrix}$$

$$\text{wheel load factor} = \frac{\text{gross weight in kips}}{\text{No. of wheels}}$$

$$\text{clearance factor} = \frac{\text{ground clearance in inches} - 12}{2}$$

$$\text{engine factor} = \begin{matrix} 1.0 \text{ when} > 10 \text{ hp/ton} \\ 1.1 \text{ when} < 10 \text{ hp/ton} \end{matrix}$$

$$\text{differential factor} = \begin{matrix} 0.95 \text{ if lockout type} \\ 1.00 \text{ if conventional type} \end{matrix}$$

For tracked vehicles

$$\text{MI} = \left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{track factor} \times \text{grouser factor}} + \text{bogie factor} - \text{clearance factor} \right) \times \text{engine factor} \times \text{transmission factor} \qquad (2)$$

where

$$\text{contact pressure factor} = \frac{\text{gross weight in pounds}}{\text{area of tracks in contact with ground, sq in.}}$$

weight factor
$< 50{,}000$ lb = 1.0
50,000 to 69,999 lb = 1.2
70,000 to 99,999 lb = 1.4
$> 100{,}000$ lb = 1.8

$$\text{track factor} = \frac{\text{track width in inches}}{100}$$

grouser factor
< 1.5 in. high = 1.0
> 1.5 in. high = 1.1

$$\text{bogie factor} = \frac{\text{gross weight in pounds divided by 10}}{\text{total No. bogies in contact with ground} \times \text{area of 1 track shoe}}$$

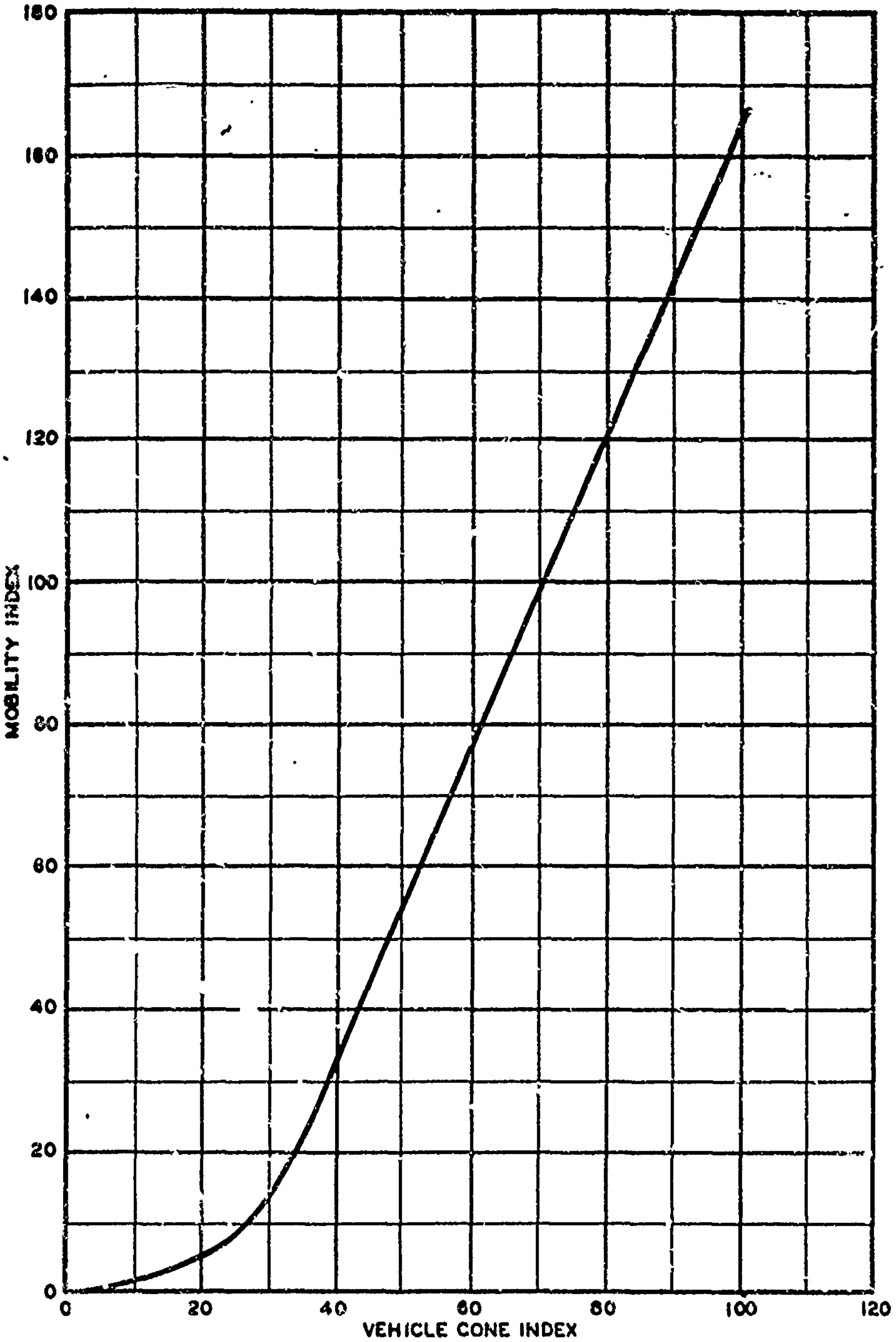
$$\text{clearance factor} = \frac{\text{clearance in inches}}{10}$$

engine factor =
> 10 hp/ton = 1.00
< 10 hp/ton = 1.05

transmission factor
hydraulic = 1.00
mechanical = 1.05

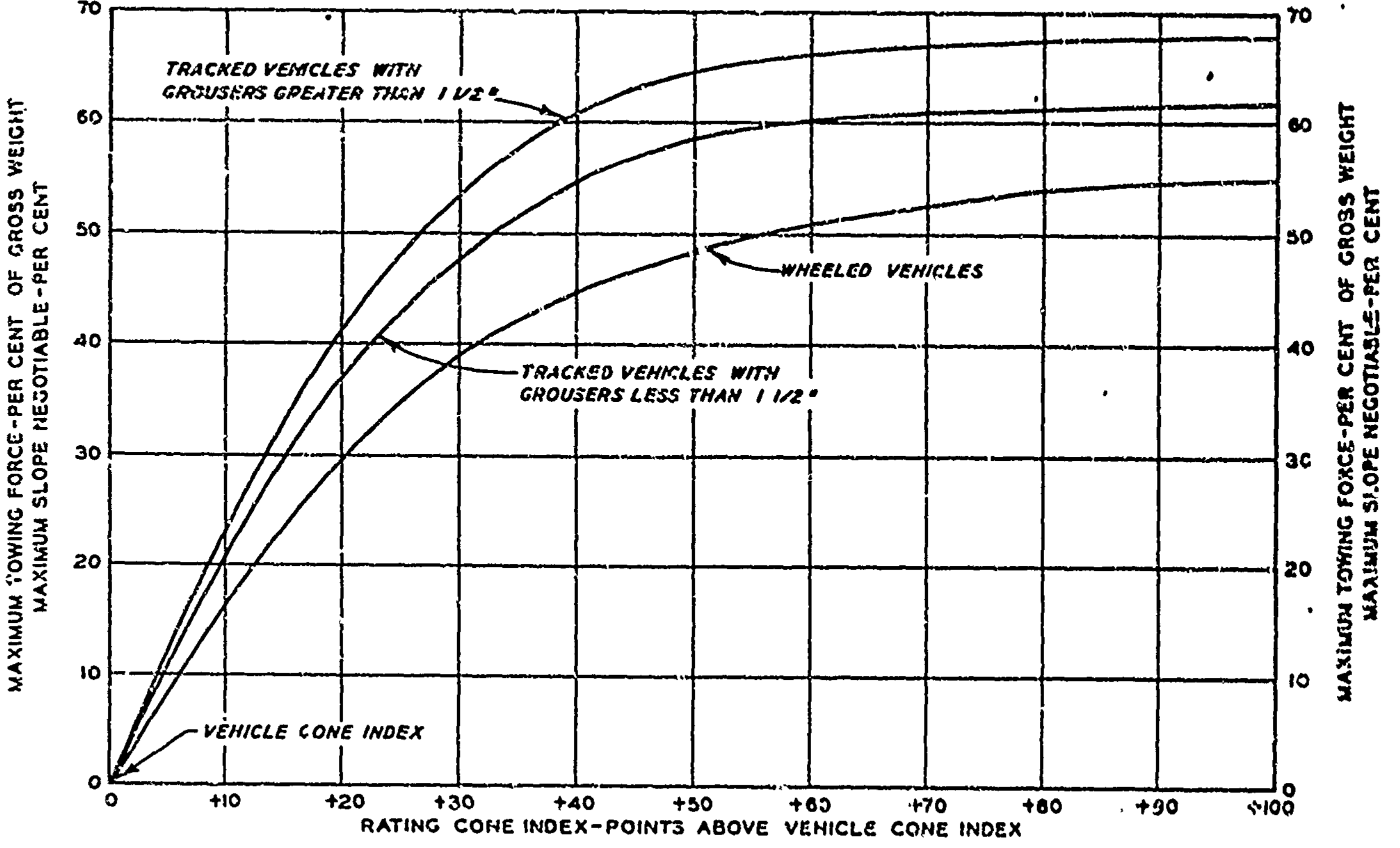
Estimation of Drawbar Pull or Slope Climb

A reasonably accurate estimate of the drawbar pull or the slope a vehicle can climb on a fine-grained soil can be made for "conventional" vehicles using the curves in fig. A2. As can be noted, all vehicles are represented by only three curves, one for wheeled vehicles, one for tracked vehicles with grousers less than 1-1/2 in. high, and one for tracked vehicles with grousers more than 1-1/2 in. high. Note that the ordinate is both towing force or drawbar pull in percent of vehicle weight and slope in percent, and that the abscissa is rating cone index units above the vehicle cone index.



MOBILITY INDEX
VS
VEHICLE CONE INDEX

FIGURE A1



PERFORMANCE CURVES FOR
SELF-PROPELLED VEHICLES ON
FINE-GRAINED SOILS

FIGURE A2

APPENDIX B: COMPUTATION OF VEHICLE PERFORMANCE CURVES

The Land Locomotion Laboratory (LLL) method for assessing the mobility of a vehicle permits the computation of the drawbar pull on any soil strength and thus the development of a pull versus soil consistency curve for that vehicle. When this is done for two vehicles, the performance of the vehicles can be compared readily on the basis of the soil consistency required to just support the vehicles, i.e. that permitting a little more than zero drawbar pull, as well as on the basis of drawbar pulls at any higher soil strength. When the calculated sinkage exceeds the belly clearance, the soil consistency at which this occurs is considered to be that required to permit passage.

The method employed for the calculation of the drawbar pull has been described in a number of publications;[7,8,9] therefore, only a brief outline is given below.

The general expression for the gross tractive effort exerted by a vehicle is:

$$H = \iint_A \overline{\tau} \cdot \overline{j} \, dA \qquad (1)$$

where

H is the gross tractive effort (lb)

$\overline{\tau}$ is the shear stress (lb/in.^{2})

$\overline{j}$ is a horizontal unit vector whose sense is opposite to the direction of travel

dA is a surface element of the entire vehicle-soil interface (in.^{2})

A is the entire interface area (in.^{2})

The right-hand side of equation (1) is the sum of the horizontal components of the shear stresses acting along the interface. It can only be evaluated if the shear stress is known at every point of the surface A.

It is assumed that the shear stress is a function of the horizontal soil deformation due to slip and the normal pressure:

$$\tau = (c_B + p \tan \phi_B) f(j) \tag{2}$$

where

c_B is the cohesion measured by a bevameter[7] (lb/in.^{2})

p is the stress normal to dA (lb/in.^{2})

ϕ_B is the angle of friction measured by a bevameter (deg)

j is the horizontal soil deformation due to slip (in.)

The function $f(j)$ is assumed to be of the following form:

$$f(j) = 1 - e^{-j/K} \tag{3}$$

where

K is the tangent modulus of an experimental shear stress-strain curve (in.)

The normal pressure has been calculated by means of Bekker's equation:

$$p = (k_c/b + k_\phi) Z^n \tag{4}$$

where

k_c, k_ϕ, and n are soil parameters

Z is the sinkage of the element dA (in.)

b is a characteristic dimension of the ground contact area (in.)

The sinkage may be obtained from an equation expressing the equilibrium of the vertical forces:

$$W = \iint_A (\bar{p} \cdot \bar{k} + \bar{\tau} \cdot \bar{k})\, dA \qquad (5)$$

Equations 1-5 permit the evaluation of the gross traction of a track or a wheel as a function of slip, provided that j can be expressed as a function of slip (i_o) and the coordinates of the equation of the path of a point of the running gear.

This is a very simple expression in case of a track:

$$j = i_o x \qquad (6)$$

The mathematics become more involved for a wheel:

For $\beta_v > \beta_o$

$$j = \frac{D}{2}\left\{\sqrt{2i_o - i_o^2}\cos(\beta_v - \beta_o) - \cos\beta + (1 - i_o)[\sin(\beta_o - \beta_v) + \sin\beta + \beta_v - \beta_o - \beta]\right\} \qquad (7)$$

While for $\beta_o > \beta_v$ we also use the following equation:

$$j' = \frac{D}{2}\left[\sqrt{2i_o - i_o^2}(\cos\beta - \cos\beta_o) + (1 - i_o)(\sin\beta_o - \sin\beta + \beta_o - \beta)\right] \qquad (8)$$

where

x is the distance between the front of the ground contact patch of a track and an arbitrary point of the track (in.)

D is the diameter of the wheel (in.)

β_v is the central angle of that point of the wheel perimeter to which a vertical velocity vector belongs (radians)

β_o is the central angle associated with the sinkage (radians)

β is the central angle between β_o and an arbitrary point (radians)

Using the above equations and assuming a uniform normal pressure distribution under a track, the gross tractive effort of a track-laying vehicle becomes:

$$H = (Ac_b + W \tan \phi_B) \left[1 - \frac{1}{J} (1 - e^{-J}) \right] \qquad (9)$$

where

J stands for $i_o l/K$

The gross tractive effort for wheels (assuming that p does not vary in the lateral direction; and that $\tau = 0$ in equation 5) is:

For $\beta_v > \beta_o$

$$H = \frac{bD}{2} \int_{\beta_v - \beta_o}^{\beta_v} \left\{ c_B + k \left(\frac{D}{2} \right)^n [\cos (\beta_v - \beta) - \cos \beta_o]^n \tan \phi_B \right\}$$

$$\times (1 - e^{-j1K}) \cos (\beta_v - \beta) \, d\beta \qquad (10)$$

For $\beta_o > \beta_v$

$$H = \frac{bD}{2} \int_{o}^{\beta_v} (\text{integrand of equation 10}) - \frac{bD}{2} \int_{\beta_v - \beta_o}^{t_o} \left\{ c_B + k \left(\frac{D}{2} \right)^n \right.$$

$$\left. \times [\cos (\beta_v - \cos \beta_o)]^n \tan \phi_B \right\} (1 - e^{-j'1K}) \cos (\beta_v - \beta) \, d\beta \qquad (11)$$

The net tractive effort or drawbar pull is calculated by subtracting the motion resistance from the gross tractive effort.

The motion resistance is

$$R = \iint_{A'} \overline{p} \cdot \overline{J} \, dA \qquad (12)$$

which yields a general solution

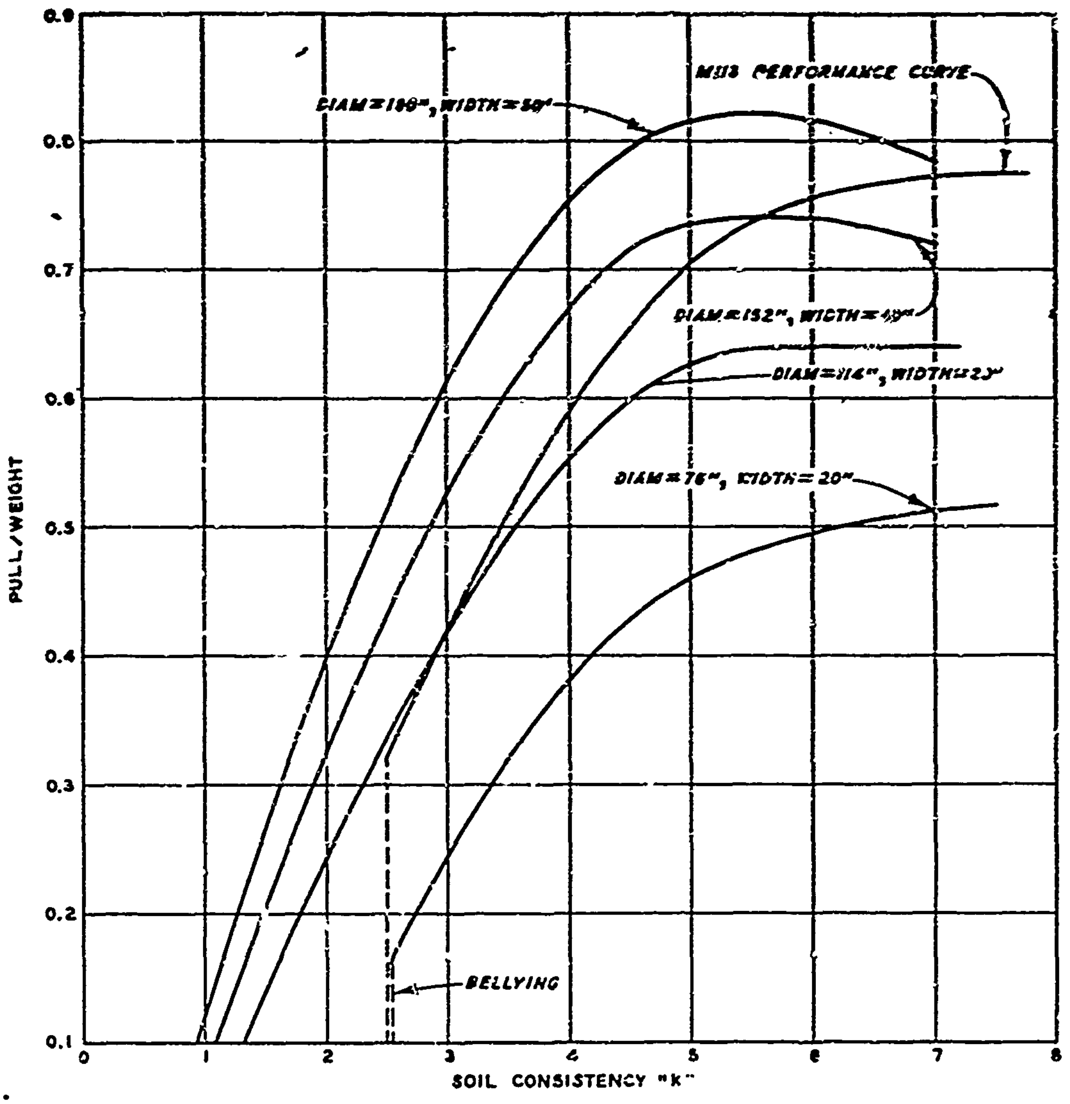
$$R = \frac{b\ k}{n + 1} z_o^{n+1} \tag{13}$$

Drawbar pull calculations by the LLL were carried out for the following six sets of soil values:

Soil No.	k_c	k_ϕ	n	c	ϕ	K
1	17.5	6.60	.530	1.60	29.2	1.0
2	9.5	5.60	.500	1.90	29.5	1.0
3	6.5	4.70	.470	2.05	25.5	1.0
4	4.5	3.75	.425	1.58	23.5	1.0
5	3.3	2.80	.390	1.05	21.5	1.0
6	2.2	1.00	.350	0.82	10.7	1.0

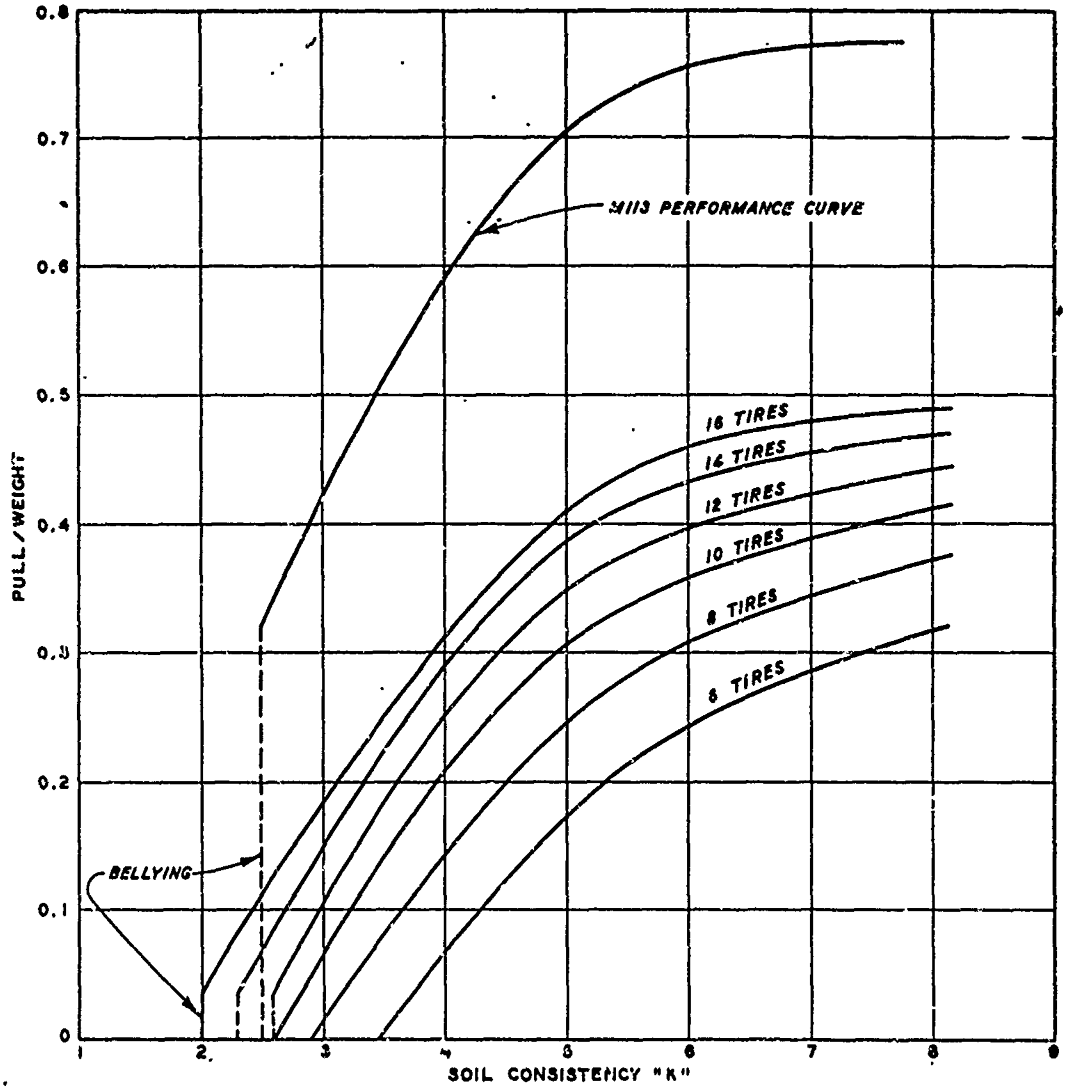
The computations were performed for 80 percent slip, for at this slip the drawbar pull reaches its maximum and K no longer exerts an influence. Therefore $K = 1.0$ was assumed for the sake of simplicity. It was further assumed that all wheels met the same conditions, that is, the effect of the passage of the preceding wheels on the performance of subsequent ones was neglected.

The results of the calculations for one of the vehicle pairs studied (Saracen and M113) are shown graphically in figs. B1 and B4. Fig. B1 is a plot of the calculated pull/weight (P/W) ratio versus the soil consistency parameter k for the 6x6 vehicle with several different tire sizes. In fig. B2 the P/W ratio is plotted against k to show the performance of the vehicle when evaluated with various multiples of wheels of the original size. The P/W ratio of the Saracen on a soil of consistency $k = 5$ is shown in fig. B3 in relation to the number of wheels. In fig. B4 the P/W ratio on a soil of consistency $k = 5$ is plotted against the tire width for tires having a constant diameter/width ratio.



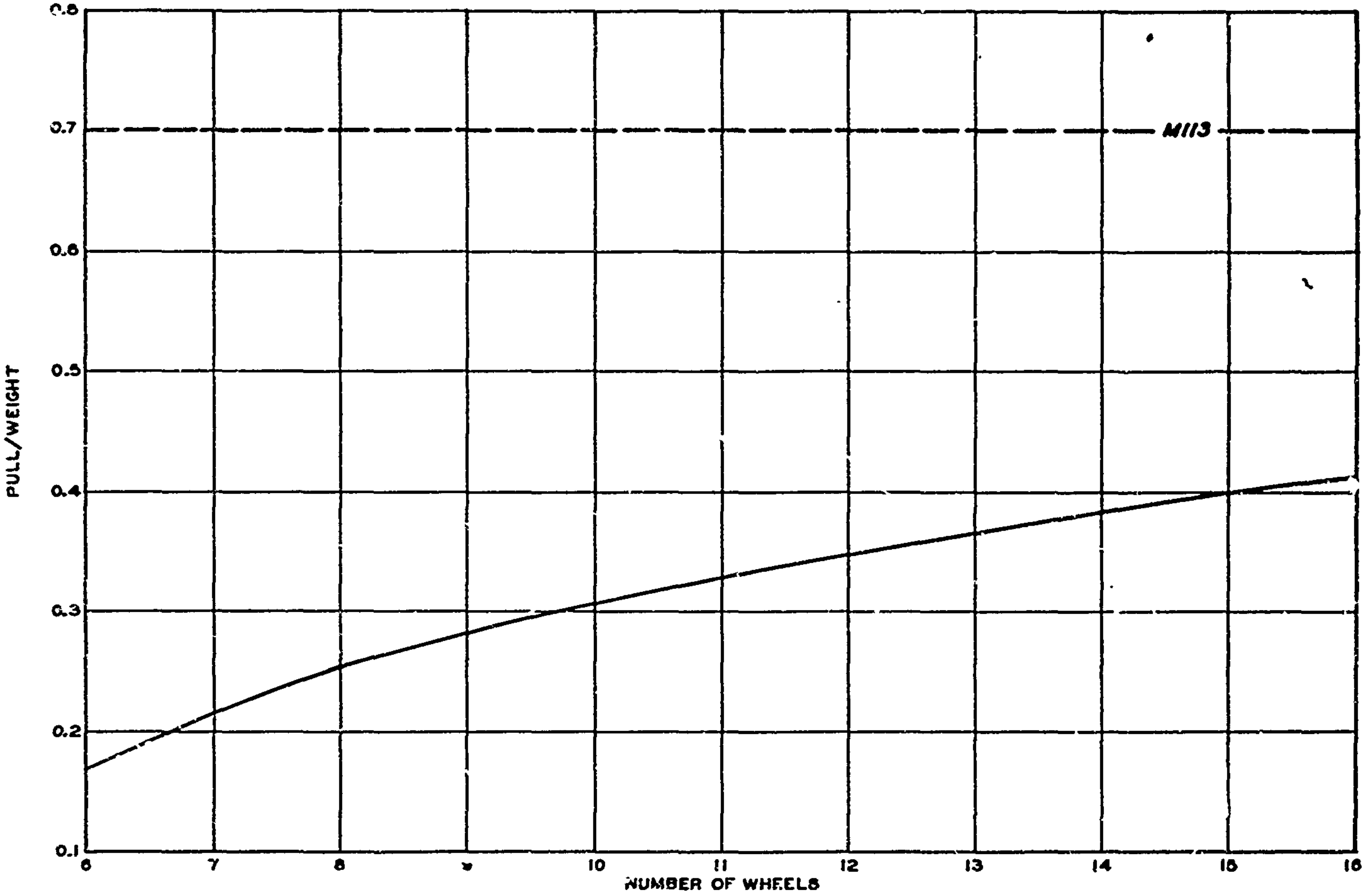
PERFORMANCE CURVES FOR
6 X 6 SARACEN WITH
VARIOUS TIRE SIZES

FIGURE B-1



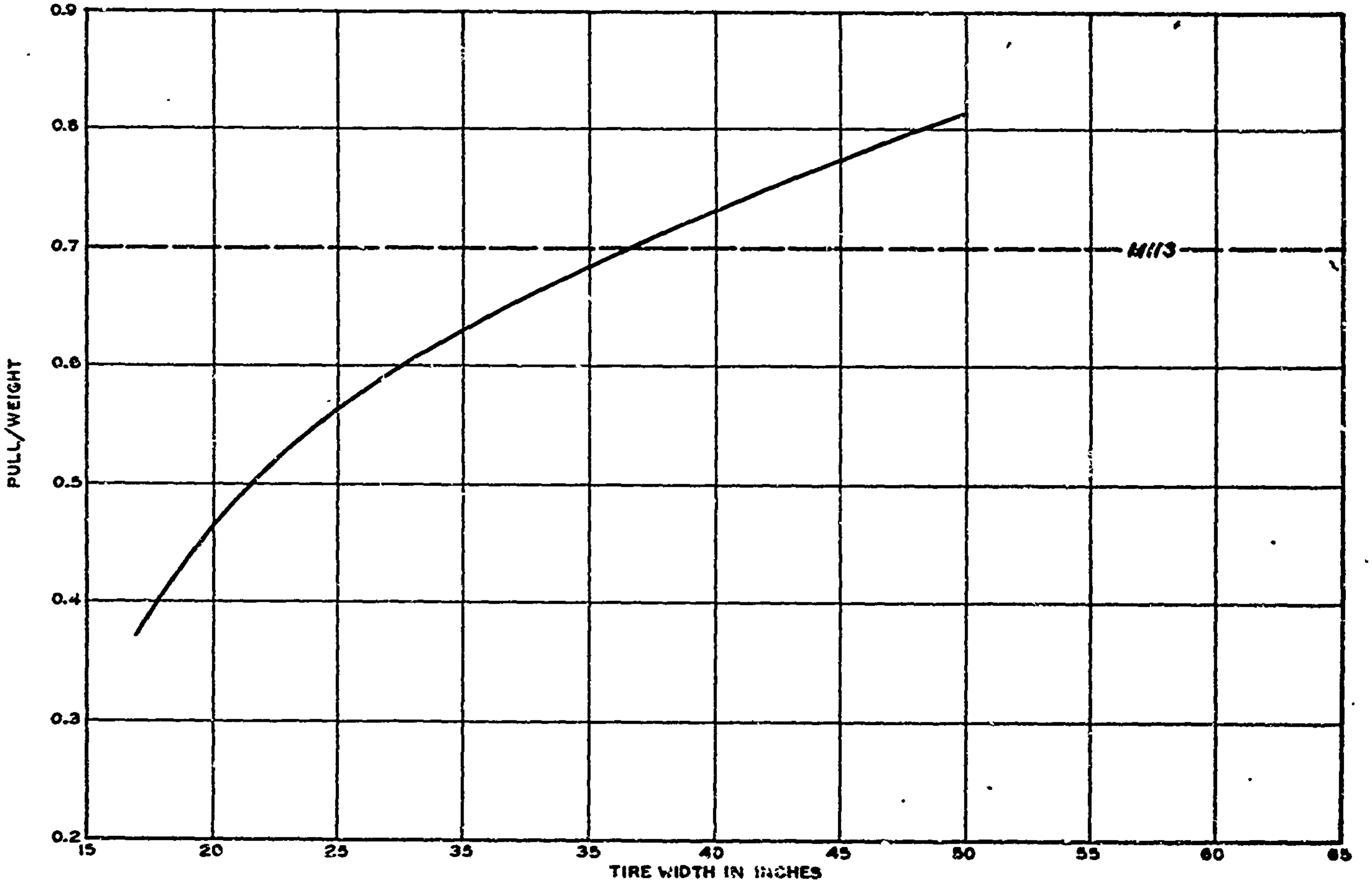
PERFORMANCE CURVES FOR
SARACEN WITH VARIOUS
NUMBERS OF 11:00-20 TIRES

FIGURE B-2



PERFORMANCE OF
6 X 6 SARACEN VS
NUMBER OF 11.00-20 TIRES
(SOIL CONSISTENCY, k=5.0)

FIGURE B-3



NOTE: DIAMETER/WIDTH = 3.8.

PERFORMANCE OF
6 X 6 SARACEN VS
SIZE OF TIRES
(SOIL CONSISTENCY, K=5.0)

FIGURE B-4