MISCELLANEOUS PAPER M-68-2

DESCRIPTION AND COMPARISON OF TIRE PERFORMANCE IN SAND IN TERMS OF ENERGY PARAMETERS

by

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August 1968

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ARMY-MRC VICKSBURG, MISS.

Foreword

The study reported herein was conducted by personnel of the Mobility Research Branch (formerly Army Mobility Research Branch), Mobility and Environmental Division, U. S. Army Engineer Waterways Experiment Station (WES), in a continuing program of research under DA Project 1-T-0-62103-A-046, "Trafficability and Mobility Research," Task 03, "Mobility Fundamentals and Model Studies." This work is under the guidance and sponsorship of the Directorate of Development and Engineering, U. S. Army Materiel Command.

This paper was prepared for and presented at the Second International Conference on the Mechanics of Soil-Vehicle Systems, of the International Society for Terrain-Vehicle Systems, in Quebec, Canada, 29 August-2 September 1966. Only the abstract of the paper was published in the proceedings of that conference.

Director of the WES at the time of the conference was COL John R. Oswalt, Jr., CE, and Mr. J. B. Tiffany was Technical Director. At the time of the publication of this Miscellaneous Paper, the Director was COL Levi A. Brown, CE, and Mr. Tiffany was Technical Director.

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Abstract

Some typical aspects of the rolling motion of pneumatic-tired wheels in dry sand are described in qualitative terms. The positive slip range, between the self-propelled condition and 100 percent slip, is considered. In this range, three phases of the phenomenon are distinguished according to the rate of variation of torque and pull. The parameters used for the description are energy coefficients: torque, pull, and dissipated energy coefficients. Experimental results are given to illustrate this approach.

The first part of the paper describes the three phases of rolling motion with respect to slip and defines the energy parameters. The second part is a discussion of the observed effects of wheel load, sand strength, and tire characteristics upon (a) the rate of increase of torque at low slips, (b) the value of the maximum pull/load ratio, and (c) the rates of increase of torque energy and dissipated energy at medium and high slips.

This discussion illustrates the physical understanding of rolling motion in sand that can be gained from the comparative study of each phase for various tires under various load and soil conditions. Such a comparison provides a means of specifying the differences in performance between different tires. The discussion also questions the agreement between observed facts and existing theories. It is found that important aspects consistently observed in tire performance are not predicted by any present theory.

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Introduction

In selecting tires for military, construction, or agricultural vehicles, there is a continuing need to compare the performances of different pneumatic tires operating in soft soil.

Tires often have been compared simply in terms of the maximum pull/load ratio they can produce on a given soil, but such comparisons are incomplete because they ignore efficiency and effect of soil conditions. At the other extreme, if a complete comparison is to be made, so many sets of graphs, plots, and tables must be developed and evaluated that comparison is no longer straightforward and simple.

What is ultimately needed is a truly theoretic understanding of the interaction of pneumatic tires and sand. However, such an understanding may be a long time in coming because it necessarily depends on a foundation of basic physical laws, such as stress-strain relations in soil, not presently available. Lacking such laws, it is felt that some immediate progress can be made by developing an intellectual framework for describing, in general terms, tire behavior in sand. In the present paper, this is done by considering energy parameters.

Definitions

The concepts on which description of tire behavior in sand is based and the related definitions have been fully explained in a paper published

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in the Journal of Terramechanics.[1*] They are briefly summarized in the following paragraphs.

When a rolling tire has traveled one unit of distance, a certain amount of energy has been delivered to it (or withdrawn if the wheel is braked) through the torque M. Dividing this torque energy by the load W on the wheel yields the torque energy coefficient η, the expression of which is:

$$\eta = \frac{M\omega}{Wv} = \frac{M}{WR}\frac{1}{1 - s} = \frac{M}{WR}(1 + g)$$

where

ω = rotational velocity of the wheel

v = forward speed

R = radius of the wheel

$$s = \text{normal slip} = \frac{\text{theoretical distance - actual distance traveled by the wheel}}{\text{theoretical distance}}$$

$$g = \text{differential slip} = \frac{\text{theoretical distance - actual distance}}{\text{actual distance}}$$

Soil (and possibly tire) deformations dissipate a certain amount of that torque energy, essentially by friction; for one unit of distance traveled and one unit of vertical load, the dissipated energy is represented by the dissipated energy coefficient ρ.

The difference between torque energy and dissipated energy is the energy that can be recovered (or must be supplied) in the form of pull P (or towing force); it is represented by the pull energy coefficient λ. For one unit of distance traveled, the pull energy--that is, the work of the pull--is P. For one unit of distance and one unit of load, the pull energy coefficient λ is equal to $\frac{P}{W}$.

Since $\lambda = \eta - \rho$, the expression for the dissipated energy coefficient is:

$$\rho = \eta - \lambda = \frac{M}{WR}(1 + g) - \frac{P}{W}$$

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* Raised numbers refer to similarly numbered items in References at end of text.

(ρ is also the coefficient of rolling resistance, as proposed by Phillips.[2])

This equation states that the factors controlling the development of pull by a wheel are the torque that can be applied to the wheel under given soil, load, and slip conditions and the energy dissipated because of soil (and possibly tire) deformations necessary for the torque to be developed under these conditions.

Graphical Representations

Energy coefficients can be plotted against either normal slip s or differential slip g. The use of s is more common and permits representation of the full range between 0 and 100% slip. The use of differential slip g is not convenient for high slips since g becomes infinite. However, it can easily be shown[1] that in the case of a rigid wheel on a hard surface--the simplest case to study rolling motion, thus convenient to use as a term of comparison--energy coefficients as defined above vary in a linear fashion when plotted against differential slip g. It is therefore of interest to plot the coefficients measured with actual pneumatic tires in soils against g in order to see in what manner and how much the measured quantities deviate from the reference pattern of the rigid wheel on a hard surface. This will provide a convenient means for describing the particular features of rolling motion of pneumatic tires in soils--sand in the present paper.

As an example, fig. 1 shows the variations of η, ρ, and λ versus g, as obtained experimentally from a programmed-slip test. Test conditions and tire dimensions are given in the figure. Curves for torque and dissipated energy coefficients versus differential slip for several tires and various test conditions are shown in figs. 2 and 3; fig. 4 shows the tires tested.

Phases of Rolling Motion in Sand with Respect to Slip

Several observations can be made from figs. 1, 2, and 3:

a. For g between 0 and approximately 0.25 (normal slip s between 0 and 20%), η (or torque) increases rapidly; ρ increases also, but at a much slower rate. Thus pull energy $\lambda = \eta - \rho$ rapidly increases. This slip range is called phase A of the rolling motion phenomenon. The physical reason for the observed variations is essentially that development of moderate slip mobilizes the shear strength of the sand in the direction of movement without requiring a large amount of energy to be lost by friction.

b. For g between 0.25 and approximately 2 (normal slip s between 20 and 70%) both torque energy coefficient η and dissipated energy coefficient ρ vary linearly as functions of g. Since λ is equal to their difference, $\eta - \rho$, it also varies linearly with g. This is called phase B. Several facts are important to note. First, the rate of variation of η, much lower than in phase A, is a constant for a given tire, without regard to load W and cone index (or firmness) of the sand. For the various tires, the rates of variation of η are very similar. Second, the rate of variation of ρ also is a constant for a given tire, regardless of load and cone index. However, in this respect, there is an important difference between different tires in that the slopes of ρ versus g curves vary from 0.50 to 0.72. Such a difference is significant; for example, at $g = 1$ (normal slip $s = 50\%$) it means a difference in the value of ρ of $0.72 - 0.50 = 0.22$. As $\lambda = \eta - \rho$, it also means, other factors being equal, a difference of 0.22 in the value of λ, which is important.

For a given tire, the relative rates of variation of η and ρ govern the variation of pull energy λ. Pull energy increases in phase A; in phase B, it may increase if the rate of variation of η is still larger than that of ρ, or decrease if the rate of variation of ρ is larger than that of η. In fact, the second possibility was found in all the tests studied, except for the bicycle tire where the rates of variation of η and ρ are practically equal and λ remains constant as slip increases. Thus, λ usually decreases in phase B, as shown in the example in fig. 1. It follows that between phase A and phase B, λ usually reaches a maximum. The physical phenomena prevailing in phase B are that friction in the sand is almost fully mobilized in the direction of movement, preventing a further large increase of torque; and that soil deformations associated with slip values of phase B lead to a dissipation of energy by friction that increases, with respect to slip, at a rate usually a little larger than that of torque energy.

c. The range of g values above 2 (normal slip s greater than 70%) is termed phase C. This slip range is not covered by tests reported in figs. 1, 2, and 3. It is known, however, that at very high slips λ increases again, and for s close to 100% sometimes reaches values larger than the maximum that occurs between phases A and B. It is also known that this pull increase is due to a decrease in the rate of variation of ρ , while the rate of variation of η remains the same. In other words, the observed pull increase is not due to an increase of torque, but to the presence of soil deformation conditions at high slip where torque can be developed with a relatively favorable dissipation of energy.

This description of the various phases that can be distinguished in rolling motion on sand is followed below by a discussion of some special aspects which may be of interest for a further physical understanding of tire performances. Their agreement with current theory will be briefly mentioned.

Rate of Increase of Pull and Torque Energies in Phase A of Rolling Motion

In fig. 2 it can be seen that for a given tire, the rate of increase of torque energy coefficient η with slip, in phase A varies according to load and cone index. No such differences for dissipated energy coefficients are observed (fig. 3). Thus, the rate of increase of pull energy λ also varies in phase A according to load and cone index. As a matter of fact, the rate of increase of torque energy coefficient η in phase A is of direct practical importance, since it determines in part the value that the pull energy coefficient λ has reached when phase B begins and, consequently, the value of the maximum pull that can be obtained in given load and soil conditions.

The rate of increase of torque energy coefficient η with slip in phase A is higher for higher cone index; this is probably because dense sand requires less shear strain to develop shear strength. The rate of increase of torque energy coefficient η is higher when load is lighter, presumably because of the smaller volume of sand under shear.

As far as comparing tires is concerned, the rate of increase of torque energy coefficient η in phase A very much depends upon the tire; η (or torque) increases much faster in tests with the Terra tire than in tests with the bicycle tire. It could be concluded that the rate of increase of η is related to the width/diameter ratio of the tire. However, many other characteristics of the tires, such as absolute dimensions, cross-section shape, or flexibility, also are different; thus, no definite conclusion can be reached at the present time regarding the tire characteristic responsible for the differences observed in the rate of torque increase with slip.

The effect of sand firmness on the rate of increase of torque and pull at low slip appears to be well recognized by present theory. However, current theory does not seem to clearly predict observed facts with regard to the effect of load--namely, the lower rate of increase of torque at higher loads.

Effect of Load and Sand Firmness on Maximum Pull

Fig. 3 shows that when load and cone index vary for a given tire, the difference between the dissipated energy coefficient curves is not the slope of the curve, but their intercept at zero slip. When load increases and cone index decreases, this intercept goes up. If the torque energy curve were unique, this would result in an equal decrease of pull/load ratio, since $\lambda = \eta - \rho$. However, as mentioned in the previous paragraph, the torque energy curves are not the same, but lower when load is heavier and cone index lower. It follows that the variations of λ_{max} (maximum pull/load ratio) observed when load and soil conditions vary are due to both a change of torque and a change of dissipated energy. For instance, typical results at the maximum pull point for two load and sand firmness conditions are:

1. $\eta = 0.6$ $\rho = 0.1$ $\lambda_{max} = 0.5$
2. $\eta = 0.4$ $\rho = 0.3$ $\lambda_{max} = 0.1$

Thus, the lower value of η (or torque) in the second case may be responsible for the lower value of λ_{max} to the same extent as the higher value of ρ (or rolling resistance). This conclusion is valid for performance variations due to both load and sand strength changes. As far as the author knows, this is not explicitly predicted by presently available theory.

Relative Rates of Increase of Torque Energy and Dissipated Energy Coefficients in Phase B

It has been stated previously that there is a small difference between the slopes of the torque energy coefficient curves in phase B for different tires, but that tires differ more distinctly in the slopes of the dissipated energy curves. This difference is responsible for the more-or-less pronounced decrease of pull in phase B. An interesting feature of these curves is that they have the same slope for a given tire under different load and sand strength conditions. Thus, this slope is a characteristic of the tire itself. Such a fact permits a direct comparison between different tires operating in sand without reference to specific test conditions. Evidently, a complete comparison between tire performances requires other elements; however, the fact that parameters specific for a given tire can be found is promising for providing convenient means of comparison.

It would be of interest to know which characteristics of a tire influence the slopes of the dissipated energy curves. Their identification would require tests which have not been performed yet. According to what is presently known, it seems that cross-section shape and flexibility, which determine the shape of the contact area between tire and soil, are the principal factors.

With regard to existing theory, very little can be said because torque and dissipated energies have not been studied separately as such, and furthermore because no decrease of pull with slip has been predicted.

Conclusion

After defining three phases (A, B, and C) of rolling motion of pneumatic tires in dry sand, it has been illustrated that these tires differ essentially in two respects:

a. The rate of increase of torque in phase A (low slip); this rate is higher for denser sand, lower for heavier load, and depends upon the tire itself.

b. The rate of increase of dissipated energy coefficient in phase B (intermediate slip values); this rate does not depend upon load and sand strength; it has a specific value for a given tire.

These differences between tires offer convenient means for comparing them with regard to their performance in sand.

Acknowledgment

This paper was prepared under the guidance and sponsorship of the Directorate of Research and Development, U. S. Army Materiel Command.

References

1. Leflaive, E., "Mechanics of wheels on soft soils; a method for presenting test results." Journal of Terramechanics, vol 3, No. 1 (1966).
2. Phillips, J. R., "The powered vehicular wheel plane-rolling in equilibrium; a consideration of slip and rolling resistance." Mechanics of Soil-Vehicle Systems; Proceedings of the 1st International Conference on the Mechanics of Soil-Vehicle Systems, Turin, Italy (1961), pp 541-554.

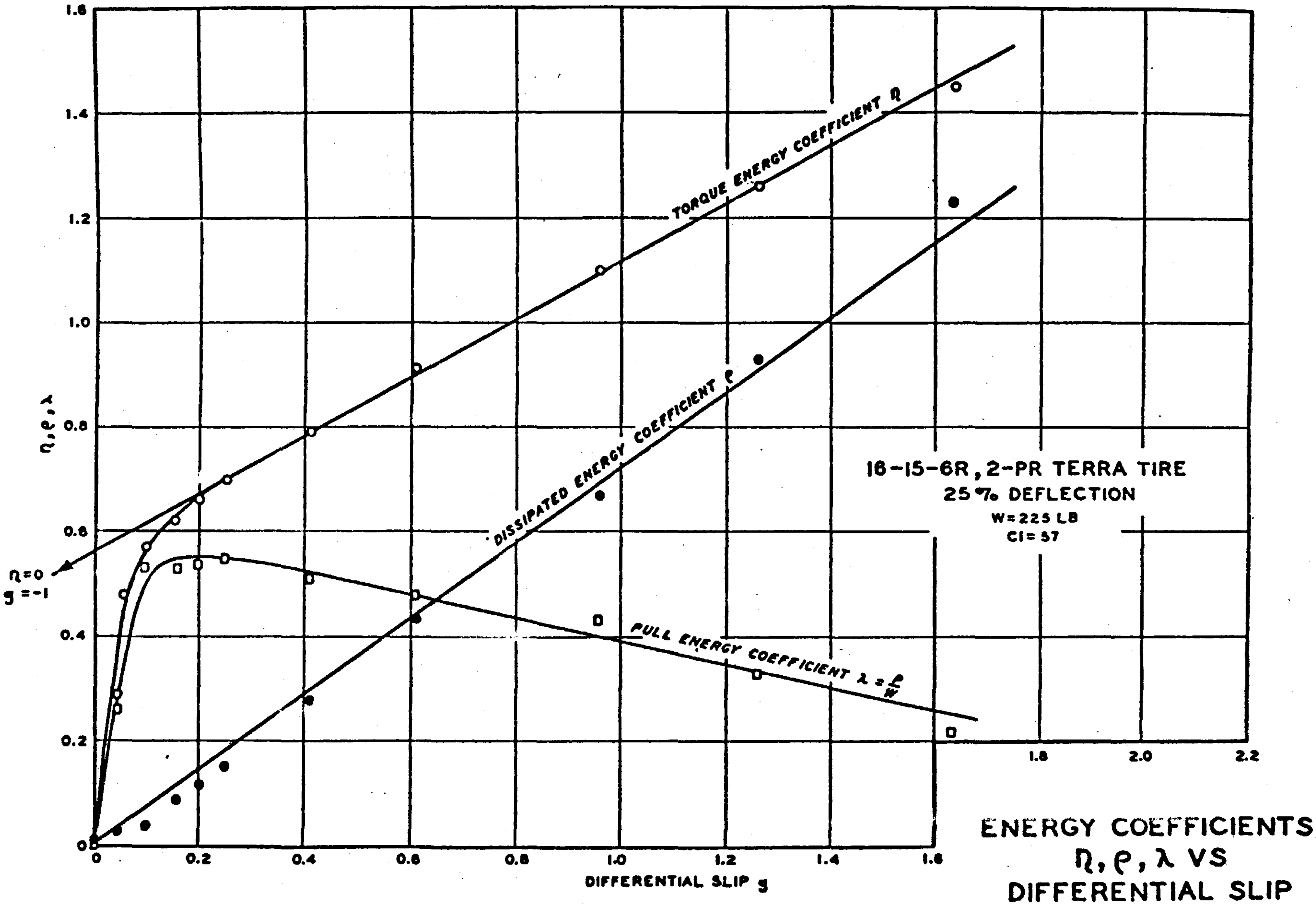
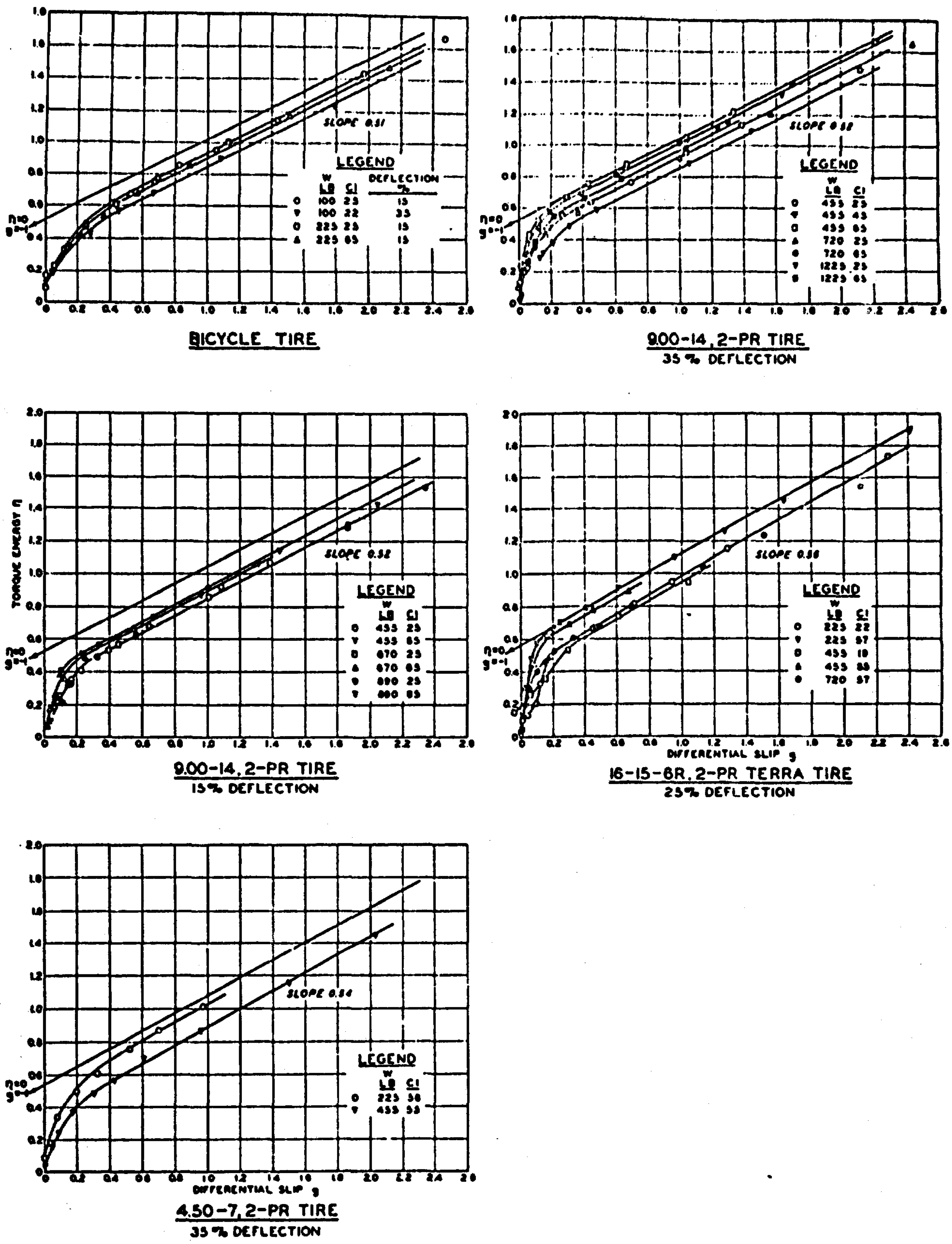
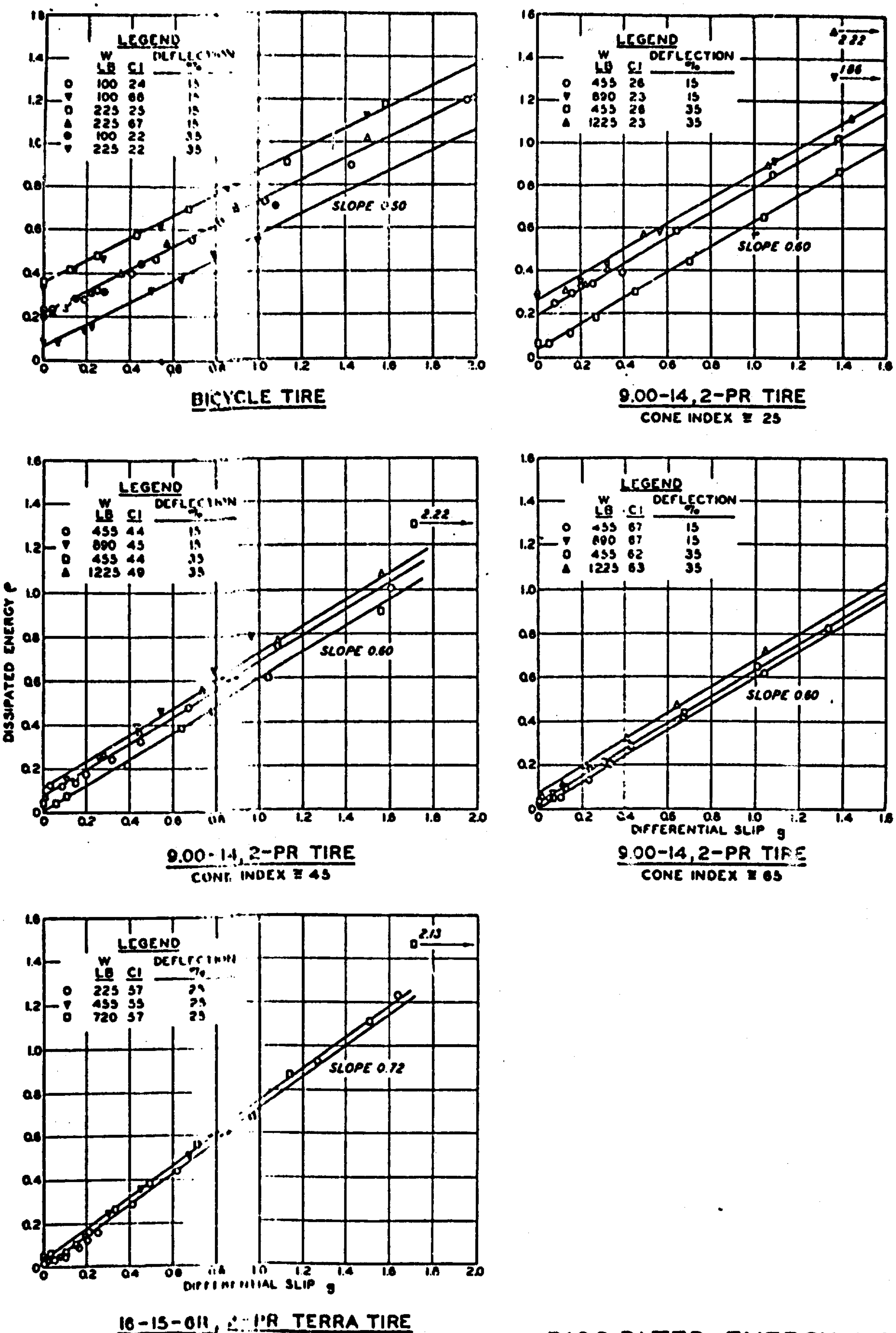

16-15-6R, 2-PR TERRA TIRE
25% DEFLECTION
W=225 LB
CI=57
TORQUE ENERGY COEFFICIENT η
DISSIPATED ENERGY COEFFICIENT ρ
PULL ENERGY COEFFICIENT λ = P/W
η, ρ, λ
η=0
s=-1
DIFFERENTIAL SLIP s
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
ENERGY COEFFICIENTS
η, ρ, λ VS
DIFFERENTIAL SLIP

Fig. 1



TORQUE ENERGY VS
DIFFERENTIAL SLIP

Fig. 2



DISSIPATED ENERGY VS DIFFERENTIAL SLIP

Fig. 3

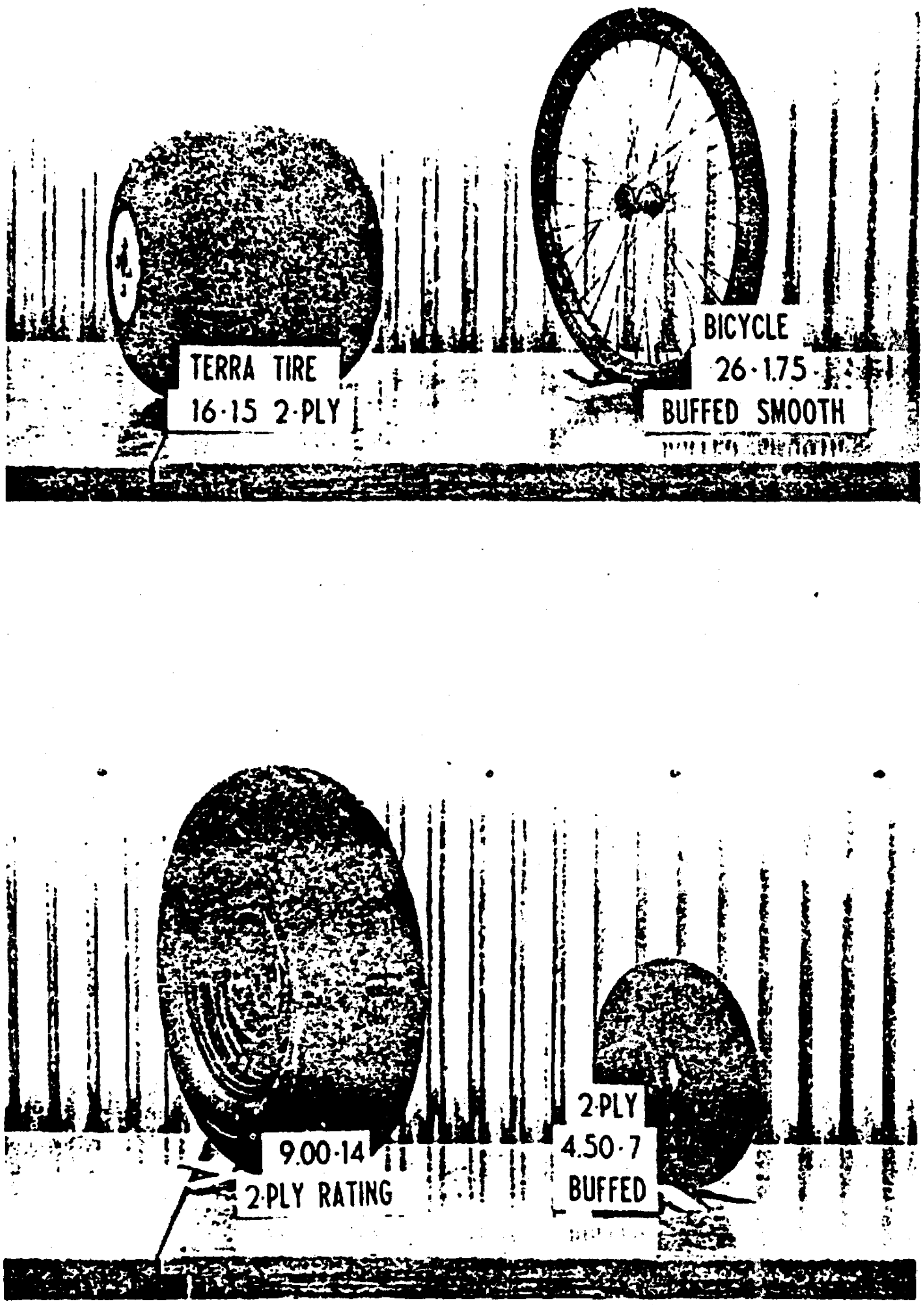


Fig. 4. Test Tires