STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

THICKNESS OF FLEXIBLE PAVEMENTS BY THE CALIFORNIA FORMULA COMPARED TO AASHO ROAD TEST DATA

By

F. N. Hveem
Materials and Research Engineer

and

G. B. Sherman
Supervising Highway Engineer

63-05

Presented at the 42nd Annual Meeting
of the Highway Research Board
Washington, D.C.

January 7-11, 1963

ClibPDF - www.fastio.com

State of California
Department of Public Works
Division of Highways

THICKNESS OF FLEXIBLE PAVEMENTS BY THE CALIFORNIA FORMULA COMPARED TO AASHO ROAD TEST DATA

By

F. N. Hveem
Materials and Research Engineer

and

G. B. Sherman
Supervising Highway Engineer

Presented at the 42nd Annual Meeting
of the Highway Research Board
Washington, D.C.
January 7 - 11, 1963

ClibPDF - www.fastio.com

TABLE OF CONTENTS

	Page
List of Tables	ii
List of Figures	iii
Synopsis	
Introduction	1
The Pavement Problem	4
The Factors Which Must Be Taken Into Account In A Design Formula	12
Summary	32
Acknowledgements	35
References	36
Typical Example of Pavement Thickness Design	Appendix I
Definition of Statistical Terms	Appendix II
Tables	
Figures	

ClibPDF - www.fastio.com

LIST OF TABLES

1. Equivalencies of Treated Bases

2. Proposed Equivalencies for Bituminous Materials

3. Slope Values of Application vs. Gravel Equivalent Curves

4. Slope Values of Wheel Load vs. Gravel Equivalent Curves

5. Calculations to Determine Yearly ADT Constants for Truck Groups Based on 1959 Statewide Loadometer Survey

6. Average Daily Truck Constants for Various Classes of Trucks

ClibPDF - www.fastio.com

LIST OF FIGURES

1. Correlation of EWL_{57} With Gravel Equivalent

2. Analytical Chart to Show the Variables That Must Be Evaluated for the Structural Design of Asphalt Pavements

3. Schematic Representation of Plastic Flow Phenomena In Soils Supporting a Pavement

4. Alignment Chart to Indicate Thickness of Cohesive Layer Required Over Cohesionless Sand or Gravel

5. Thickness of Test Sections at AASHO Test Road vs. Calculated Design Thickness Using California Design Equation (1957)

6. Cohesiometer Values of Bituminous Pavement at Various Temperatures

7. Gravel Equivalent of Bituminous Pavement Based on AASHO Test Road Analysis

8. Log Gravel Equivalent of Pavement Section vs. Log Wheel Load

9. Thickness of Test Sections at AASHO Test Road vs. Calculated Design Thickness Using California Design Equation (1962)

10. Thickness of Test Sections at AASHO Test Road vs. Calculated Design Thickness Using California Design Equation (1962)(Equivalent Sections)

11. Nomograph for Solving $T = \frac{0.070(TI)(100 - R)}{C^{0.2}}$

ClibPDF - www.fastio.com

THICKNESS OF FLEXIBLE PAVEMENTS BY THE CALIFORNIA FORMULA COMPARED TO AASHO ROAD TEST DATA

By
F. N. Hveem
Materials and Research Engineer

and
G. B. Sherman
Supervising Highway Engineer
California Division of Highways
Sacramento, California

SYNOPSIS

For the past several years, the State of California has been using a pavement structural design method based upon test road data and on observed performance of pavement structures. The original formula, containing factors for traffic, supporting power of the soil, and slab strength of the pavement and base layers, has been modified at times as better information became available.

This paper describes not only the design formula but also modifications suggested from a study of the AASHO Test Road data. Correlation with test track data is shown.

(End of Synopsis)

ClibPDF - www.fastio.com

THICKNESS OF FLEXIBLE PAVEMENTS BY THE CALIFORNIA FORMULA COMPARED TO AASHO ROAD TEST DATA

By
F. N. Hveem
Materials and Research Engineer

and
G. B. Sherman
Supervising Highway Engineer
California Division of Highways
Sacramento, California

INTRODUCTION

Soils and granular materials have been used in building construction, for walls, floors, and pavements, for many thousands of years. Obviously the ancients must have had a great deal of practical knowledge about the use of such materials. When the designers and builders of ballistae, catapults and similar engines of war turned their attention to other forms of construction, precise methods for estimating the potential behavior of materials began to emerge. The need to design stable earthworks was probably most pressing on the military engineers and one of these, Charles Augustin Coulomb (1736-1806), was among the first to propose a formula by means of which the stability of earthwork embankments might be computed. Nevertheless, in spite of the long history of engineering works involving earthy materials, formulas for calculating the bearing capacity of soils have not been as reliable or perhaps not as well understood as are formulas for bridge members and other structures.

ClibPDF - www.fastio.com

Engineering is a profession which requires an understanding of several sciences and disciplines but which depends primarily upon a knowledge of materials and how the materials will perform or "stand up" under given conditions. The typical engineer has a working knowledge of physics, mechanics, mathematics, and is acquainted with a collection of somewhat inexact numbers and values optimistically referred to as "the strength of materials." The strength concept seems to be reasonable, sound and "common sense." However, it is deceptively simple and can be misleading. A layman knows that a 12- by 12-inch timber beam will sustain a greater load than will a 2- by 4-inch, and can also grasp the idea that a steel beam will support a greater load than a wooden beam of the same dimensions. Carpenters, millwrights, masons and even architects have designed and constructed some fairly elaborate structures without very much in the way of recognizable engineering training. However, while the strength properties of wood, stone or iron may be reasonably well appraised by experience or intuition, this approach has been less successful in estimating the ability of soils and foundations to sustain loads.

A great deal of the difficulty may be ascribed to the lack of means for identifying and measuring the important properties of the materials involved. While the "strength idea" is accepted almost spontaneously and instinctively and presents

ClibPDF - www.fastio.com

no serious difficulties when applied to such things as steel, timber, reinforced concrete, et cetera, it does become a little blurred and the image rather fuzzy when one tries to apply this term to the properties of soils. It becomes even more elusive when applied to cohesionless sand and fails completely to describe the properties of liquids such as water.

Webster's dictionary says that strength means:

> "Power to resist force; solidity or toughness; the quality of bodies by which they endure the application of force without breaking or yielding; a measure of the cohesion of material; firmness; coherence; as the strength of bone, beam, wall, rope, et cetera."

The word strength obviously has many meanings and shadings, and it does not mean the same thing when applied to different materials and circumstances. We may speak of a strong wind or a strong current of water but what we mean is that when either a gas or a liquid is in motion it can exert considerable force. A "strong man" may also be able to exert considerable force but he cannot necessarily withstand as much as a "weak woman." At least women have shown that they often have great powers of resistance! We speak of a strong steel cable or a nylon rope and such strands are strong in the sense of the dictionary definition meaning "cohesion." For most engineering materials, the word strength actually denotes only tensile strength, but materials such as soils can "endure the application of force" and yet possess little or no tensile strength. It, therefore,

ClibPDF - www.fastio.com

appears that a more precise general term for the properties in which we are interested is the term "resistance." This term is explicit and may be applied without confusion to a variety of materials. Thus, a strong steel wire or a cable requires a considerable force to overcome its resistance to breaking. A column of stone blocks or a dry rubble wall exerts considerable resistance to compressive forces. Even more pertinent to this discussion, the common materials of the earth's crust, rock, sand, gravel, soil or mud, all can be shown to offer measurable degrees of resistance to applied forces. But these materials have little cohesion and hence little or no "strength" unless combined with an artificial binder such as asphalt or portland cement, and even the tensile strength of concrete is not very great compared to steel, for example.

THE PAVEMENT PROBLEM

All pavements, regardless of type, rest upon the materials of the earth's surface, and while there are a few examples of relatively solid rock subgrades, the vast majority of highway pavements are supported by soils or related granular materials having low cohesive strength. Nevertheless, a wide variety of soils have "what it takes" to support pavements if the pavement structure is "properly designed." This means that soils possess some pertinent property other than cohesive strength and this

ClibPDF - www.fastio.com

property is easily identified as interparticle friction. The importance of both friction and cohesion were recognized by Coulomb and values for each appear in his formulas.

In order to apply the principles of engineering to the structural design of a pavement, the engineer must know what properties of materials are involved. Lack of reliable tests has been one of the greatest stumbling blocks. Many of the tests which have been applied to soils and paving materials do not provide measures of fundamental properties. For example, if one wishes to measure the tensile strength of steel, a carefully prepared specimen is attached to the jaws of a testing machine and the force required to pull the specimen apart is measured. This is a direct measurement of an important property. If the strength of concrete is involved, a carefully prepared test cylinder or cube is subjected to a direct compression loading. It is important to note that even though steel and concrete are often combined to produce reinforced concrete structures, one rarely attempts to measure the properties in combination. The individual strength properties are evaluated by separate tests. Unfortunately, in the case of soils and other granular materials, a number of test methods are affected by the two distinct properties acting simultaneously.

Many tests provide no means for differentiating between such radically different attributes as friction and the co-

ClibPDF - www.fastio.com

hesive resistance. While the resistance to deformation or displacement that is due to friction is fairly well defined (if not well measured), the cohesive "strength" or resistance is generally defined as "that portion of the resistance to sliding that is not affected by the pressure." This is a negative definition and differs from the dictionary definition of cohesive strength. In effect then, the soil mechanics definition of cohesion does not define what cohesion is, it merely says what it is not. The other element of confusion arises from the use of such devices as the Mohr circle analysis in which the intercept of the Mohr envelope on the vertical scale is defined as "cohesion." Tests on certain obviously cohesionless materials have shown a definite value for the intercept which would therefore be defined as "cohesion." Finally, a great many have been "thrown off the track" by the substitution of such terms as "shear strength" which by itself is not a property of materials; the total resistance to shear being again composed of variable portions of frictional and cohesive resistance. The resistance due to each of these dissimilar properties combines to produce the total resistance in an endless variety of combinations. The use of tests such as the CBR test, several varieties of direct shear tests, or unconfined compression tests, all tend to reflect or summarize some arbitrary combination of friction and cohesion. The relative proportions depend upon the geometry of the test specimen and speed of loading which usually

ClibPDF - www.fastio.com

differ considerably from the conditions on an actual roadway.

Both geologists and agronomists have studied fragmentary stone and the finer decomposition products called "soil" and each have developed classification schemes and names for the numerous varieties of rock, gravel, sand and soil types. These classifications have their uses and have proved helpful to the engineer but none are directly fitted to the engineer's problem. As stated by Dr. Jacob Feld, "an adequate soil classification scheme for engineers should be based upon engineering properties." All this leads up to the point that soil, sand, gravel and other naturally occurring mineral materials possess a number of properties and characteristics and can be variously described according to geologic origin, petrographic classification, grain size, soil texture, mineralogical composition or even in terms of the chemical compounds involved. These classifications may or may not indicate the suitability of the material or the best means of treatment for engineering purposes.

As in the case of all the other sciences concerned with soils, the engineer needs to know what properties are important to him and what determines the ability of the soil to support loads, and having identified these properties he must then know what test methods to use in order to measure them. This is a step which must be made first as no reliable or valid mathematical formula for structural design can be de-

ClibPDF - www.fastio.com

veloped unless it includes numerical values to express real and essential properties of the materials involved.

In 1948 a design formula for calculating the thickness of pavements[1] was reported which includes an expression for the measured resistance value of various soil or granular layers and for the tensile strength or cohesive resistance of all elements composing the pavement structure. The basic data for the relationships developed were derived from a small but full scale project known as the Brighton test track constructed by the California Division of Highways in 1940. For an expenditure of less than $100,000.00, it was possible to construct and operate a test track which included eight different types of base material varying in thickness from 3 inches to 18 inches resting on the same saturated silty clay soil having a CBR value of about 3 or an R-value of approximately 17. The track was subjected to a loaded truck and at the end of the operation it was obvious that the thickness required for the various types of base did not show any consistent relationship to the CBR value or the resistance value for the base material itself, but there was an orderly and consistent trend with the tensile strength of the materials as measured by the Cohesiometer. This test track made it possible to assign tentative values to some of the variables such as the effects of wheel load and repetition. While the underlying soil on the test track was uniform throughout and gave no range of value, some additional

ClibPDF - www.fastio.com

check points were obtainable from observations on the State highway system. A few scattered examples where the pavement thickness had been varied over different types of soils made it possible to establish a relationship. The establishment of a scale of values for soil support was greatly simplified by the fact that the thickness of pavement structure required bears a linear relationship to the Resistance Value of the soil as measured by the Stabilometer. There was no opportunity to introduce a variation in tire pressure so the effects of this variable were not established. The formula developed at the time was as follows:

$$T = \frac{(K\ P\sqrt{a}\ \ \log r)(P_h/P_v - 0.10)}{\sqrt[5]{C}}$$

where: T = Thickness of cover (base and pavement) in inches

K = .0175 for best correlation but without any factor of safety. For design purposes it is suggested that K = .02

P_h = Transmitted horizontal pressure in the Stabilometer test (#/sq.in.)

P_v = Applied vertical pressure in the Stabilometer test (typically 160#/sq.in.)

p = Effective tire pressure (#/sq.in.)

a = Effective tire area (sq.in.)

r = Number of load repetitions

c = Tensile strength of the cover material as measured by the Cohesiometer in gms. per sq.in. (approximately = Modulus of Rupture x 45.4)

The above formula was simplified by reducing the effects of

ClibPDF - www.fastio.com

load and repetition to an expression termed the Traffic Index and by reducing the Stabilometer data to a Resistance Value "R". The formula then becomes:

$$T = 0.095 \frac{(\text{Traffic Index})(90-R)}{\sqrt[5]{\text{cohesion value}}}$$

where: T = Required thickness of cover

R = Resistance value by Stabilometer

This formula was used for the design of pavements and any discrepancies that became apparent between prediction and performance were noted and modifications in the testing and design procedure were introduced as seemed to be warranted.

Upon the completion of the WASHO test road in Idaho, attempts were made to check the California formula by comparison with the performance on the WASHO test road. Unfortunately, the design of this project was such that only a very few definite points could be established. While the usable data from the WASHO road agreed with the predictions of the formula, they were insufficient to confirm its validity over any substantial range (See Figure 1).

The tremendously larger AASHO test road in Illinois furnishes a great deal more data and gives a much wider range of values for checking a previously established structural design formula. In order to make a comparison between calculated values and test road data, the various materials, basement soils, granular base, subbase and asphaltic pavement were

ClibPDF - www.fastio.com

tested and evaluated according to the California procedures. The wheel loads and number of trips were converted through the equivalent wheel load calculation to the traffic index number. With values derived by laboratory tests of the Illinois materials and calculations for the traffic, it is possible to arrive at a design thickness based on the California formula (1957 Model). The calculated thicknesses may then be compared with the actual thickness reported to be necessary on the test road. The correlation is shown in Figure 5. The statistical values showing a standard error of estimate of ± 2.7" and a coefficient of correlation of 0.87 (See Appendix II) seem to confirm the ability of the California design formula to predict the thickness of pavement required for a wide variety of traffic loads and materials. However, the test road data neither prove nor disprove the applicability of the California formula to other types of soil or granular base materials. The test road pavement structures were supported by only one type of basement soil. Because of this lack of variables on the AASHO project, it is not possible to develop a design formula by using the test road data alone. It will be noted that the statistical type formulas developed by the road test staff have no terms or identities which permit application to soils differing in properties and ability to support loads from those used on the test road. The test road formula does not identify or indicate means for measuring the properties or physical condi-

ClibPDF - www.fastio.com

tions which account for the performance of the subbases, bases and asphalt pavement types.

THE FACTORS WHICH MUST BE TAKEN INTO ACCOUNT IN A DESIGN FORMULA

A design formula for the structural elements of a pavement should embody all of the important factors which affect the ability of the pavement structure to sustain vehicle loads over a substantial period of years. There have been many formulas proposed. In an article entitled "Progress Report Subcommittee on Methods of Measuring Strength of Subgrade Soil - Review of Methods of Design of Flexible Pavements," Professor Kersten[2] listed 22 different formulas. Some of these were based on theoretical concepts, others were completely empirical, and some represented a mixture of the two approaches. The factors which influence the over-all performance of a pavement are so numerous and the desirable attributes of a pavement are so diverse that it seems impossible or highly improbable that all of these variables can ever be included in a single formula, or if such a formula were constructed only a highly sophisticated electronic calculator could hope to reach a solution. Even then, a certain allowance would be needed for the inability to do a perfect job.

Figure 2 is included to show the variables that can affect the performance of an asphalt pavement. It will be noted that at least 30 items have been identified. However, design formulas

ClibPDF - www.fastio.com

rarely need to cover every factor and many of the variables shown on the chart can be ignored or combined into a single element in the formula.

As an example of the simplification which is possible and quite practicable, an adequate structural design might be described as one which produces an economical or efficient pavement that will neither crack nor deform under the assumed traffic during the design life of the pavement. (Guarding against disintegration types of failure is primarily a question of mixture design and quality of materials rather than a structural design problem.) Column 3 of Figure 2 shows that there are three primary factors; namely, the effects of traffic, the strength of the pavement, and the ability of the foundation to support the load. The primary factors have the following relationship:

$$T = \frac{KD(90-R)}{S}$$

where: T = Thickness

K = Constant

D = Destructive Effect of Traffic

R = Resistance Value of Support

S = Strength of Pavement Structure

In order to derive a number to express the effect of traffic, it is necessary to consider Columns 4 and 5 which list some of the subdivisions which make up the traffic load effect or

ClibPDF - www.fastio.com

"the destructive effect of traffic." The principal variables are the total wheel load in contact with the pavement and the number of times this load passes over the pavement. The area of load influence is a factor but the problem has thus far been simplified for highway traffic as the maximum tire pressure on most motor trucks is in the order of 70 or 80 psi for the heavier vehicles. The axle spacing or "the proximity factor" is confined to only two typical configurations; namely, single axles some 15' apart or tandem axles (2 axles within 4'). While the comparative effects of tandem axles versus single axles differ markedly as between flexible pavements and rigid pavements, nevertheless, it is possible to convert these two types of axle spacings to a common denominator for each type of pavement. Examining all of the available data which include the Brighton test track, the Stockton track (constructed by the Corps of Engineers), the WASHO and the AASHO projects, it appears that the relative effects of traffic may be expressed as follows:

<u>For Flexible Pavement Design</u>

$$TI = 1.30\left(\frac{W}{5}\right)^{0.50}(r)^{0.119}$$

where: TI = Traffic Index

W = Wheel Load in kips for tandem axles; W = 1.10 individual wheel load

r = Number of load applications

This expression assumes a tire pressure in the range of 50 to

ClibPDF - www.fastio.com

100 psi but does not provide for effects of extreme variation in tire pressure as there are insufficient data available to indicate how variation in tire pressure may affect the performance of a road structure. Referring again to Figure 2, it will be observed that there are a number of factors which compose the overall properties of the pavement. Primarily, there is a question of stiffness* or the resistance to bending. Stiffness of a "flexible" pavement is influenced by the thickness, type and amount of asphalt and by the temperature. This means that an asphalt pavement has a high degree of stiffness

---

*The term "stiffness has been borrowed from a report by L. W. Nijboer and C. van der Poel[3]. Nijboer computes stiffness from the formula:

$$S = \frac{F_p(12)}{X_p}$$

F_p = Force acting on pavement in newtons. Limits of F_p between 10^4 newtons (1 ton) and 2 x 1 newtons (2 tons) respectively.

X_p = Deflection of the pavement in microns.

Therefore, the term "stiffness" bears a simple mathematical relationship to the deflection of the pavement and as used by Nijboer "stiffness" implies the resistance of all components including the pavement, bases, subbases and the underlying soil. For design purposes it seems preferable to us to associate the concept of stiffness with the pavement and base structures alone in which case there will not be a consistent relationship between "stiffness" and "deflection" as the character of the supporting soil will then represent a variable - "resilience."

ClibPDF - www.fastio.com

during cold weather and it also means that the lower courses provide greater stiffness in warm weather than the same mixture in the surface layer exposed directly to the sun. The stiffness of all materials can be expected to increase with the thickness of the layer but in the case of asphalt pavements the effect is enhanced by the lower temperatures in the bottom courses, especially where the pavement is of substantial depth. Flexibility is more or less the opposite number, or complement, of stiffness. This is a property not easily measured but it may enable a pavement to survive the flexing over resilient or springy foundations. It is a difficult value to include in a simple design formula. The word "stiffness" is also not entirely applicable or adequate to express the manner in which a pavement structure functions. The concept of "stiffness" is readily visualized in the case of a thick asphalt pavement. It is even more descriptive of a portland cement concrete slab, but a substantial layer of crushed stone or gravel will have the same effect, within the limits of its own resilience, in reducing deflections. Precisely speaking, the term stiffness hardly seems appropriate for a bed of cohesionless material. Nevertheless, in the absence of a better term, a thick layer of sand or gravel may be said to have "stiffness." The question of pavement stability and resistance to water action are properties which fall into the area of mix design and need not ordinarily be

ClibPDF - www.fastio.com

considered in a structural design formula.

The process of assigning strength or resistance values to foundation materials must resolve a great many variables due to the wide variety of materials which may be involved. The treated bases and subbases may possess properties similar to that of the pavement layer while granular bases and underlying soils are generally low or completely lacking in tensile strength or cohesive properties. As inferred above, a great deal of the so-called fundamental or theoretical approach to the design problem has focused attention upon the elastic properties but for the most part it is the plastic properties of soils, subbases and granular bases that have caused the most trouble. Again, one must recognize the very dissimilar response of friction and cohesion to most tests or loads.

The Stabilometer furnishes a means for measuring the internal friction of granular materials under load. When solid particles such as stone or sand grains are coated with asphalt or wet clay, a lubrication effect is introduced as soon as a sufficient quantity of the lubricant has been added. Obviously, the amount needed and the effects produced may vary considerably. Rough crushed stone particles are difficult to lubricate while smooth polished gravel and sands will tolerate only small amounts of asphalt or wet clay additions. The problem of stability of asphalt pavements or the

ClibPDF - www.fastio.com

ability of granular bases and subbases to support a pavement very largely depends upon the friction or the degree to which the friction has been reduced or lost by lubrication. Thus, the designer of bituminous mixtures or clay-bound stone bases is confronted with the fact that the very materials which are added to increase the cohesion (strength) will also reduce the friction through lubrication whenever sufficient amounts have been added.

When the cohesive effect is provided by a viscous liquid such as asphalt it becomes impossible to summarize the two unlike properties except under some specific condition of load area and speed of loading. Furthermore, it may be shown that the two properties are individually important and each is most effective in certain regions or zones of the pavement structure. A bed of cohesionless crushed stone, gravel or sand will support traffic provided the surface is covered with an adequate thickness of material which does possess some cohesion. A surface treatment or seal coat on a gravel road is an example but to be successful a certain depth of the gravel must have some coherence or cementing action furnished by a soil binder. In contrast, a thin seal coat would be completely ineffective on a bed of clean beach sand. There is ample evidence therefore to show that an adequate pavement structure must provide an upper layer of material having some coherence or tensile strength and the thickness of this layer

ClibPDF - www.fastio.com

must increase with increasing wheel loads. Beyond this critical depth, a completely cohesionless gravel or sand will serve quite well and will often prove to be less critical and give more lasting service than will base and subbase layers cemented with natural materials. Natural materials may consist of soil including clay or fines produced by degradation of the aggregate. Figure 3 is a sketch showing the regions in the pavement structure where cohesion and friction are respectively most influential or important. Figure 4 is an alignment chart suggesting the depths of pavement and/or cohesive base layer that is required over a completely cohesionless material.

For various magnitudes of wheel loading, the AASHO test road furnishes examples which supplement observations on the performance of actual highways. On Loop No. 2, it will be observed that the thin bituminous surface treatment resting directly on the soil gave a better performance and sustained a greater number of trips before failure than did the same thickness of surface resting on the gravel, yet the soil had a lower CBR, lower R-value and would be considered to be far less adequate by most methods of evaluation thus far developed. Referring to Loop No. 5, the wedge sections 457, 458, 467 and 468 also demonstrate that the failure of the pavement was due to the gravel base as it failed as readily with 15 inches of base depth as with 5 inches.

In the California formula, one of the factors which

ClibPDF - www.fastio.com

reflects the effect of pavement thickness is the (90 - R) factor which in effect states that a material of 90 R-value would be of sufficient strength to support any highway traffic load. This expression was developed from early data when the formula was devised and was based upon extrapolations from rather light traffic. Furthermore, the factor appeared to correlate with California experience.

Now the data from the AASHO Road Test would indicate that a more rational approach to determining thickness of pavement for heavy traffic would be to use a factor of (100 - R). This would provide adequate thickness over most of the sections which appeared to fail because of inadequate base cover. This adjustment in the (90 - R) factor is made possible through more accurate information on the effect of traffic and also by adjustment of the cohesion factor in the formula. If we again refer to the gravel base wedge sections in Loop No. 5 of the Road Test, we find that 4-1/2 inches of asphalt concrete, in lieu of the 3 inches provided, would have been required over the base material if any of the base thicknesses were to have survived the Test Road traffic. Likewise in Loop No. 4, for the same wedge of gravel base, it would appear that 3-3/4 inches, in lieu of 3 inches, would be required for the traffic of Loop No. 4 to have been satisfactorily carried over the wedge for the duration of the project. These increased thicknesses of surfacing over these cohesionless gravel materials

ClibPDF - www.fastio.com

would have allowed the effect of gravel thickness to have been measured in a uniform and consistent manner, with the principal variable being thickness of base. Figure 5 shows the correlation between the thickness computed by the California method (1957 revision)[4] and the actual minimum thickness found to be adequate on the AASHO test road. It appears that the greatest discrepancy between the predictions of the California formula and the actual performance is in the bituminous base sections and it is therefore evident that the assumed cohesive strength value which has been used for California asphalt pavements is not adequate to account for the performance of the thick asphalt section on the test road.

In order to properly evaluate the Test Road performance of thicker asphalt concrete sections, it was necessary to revise the scale of cohesion values used in the California formula. The original formula assumed a cohesion of 100 for gravel and that no materials would be less than 100. However, in trying to evaluate the AASHO test road, it became evident that the gravel base, for example, had far less than 100 cohesion. Actual tests performed on this material indicated a cohesion of only 20 grams per lineal inch. Cohesions on the crushed rock base material had a value of only 30. To obtain more accurate definition with the design formula, it appeared expedient to change the basic cohesion, for cohesionless materials such as the AASHO subbase, from 100 to 20 and to

ClibPDF - www.fastio.com

use a value of 30 for crushed rock bases. The use of a more cohesive material, such as asphalt, or a cementitious material, such as portland cement, has a greater effect in the reduction of thickness of section. An evaluation of the affect that bituminous bases have on performance of the wedge sections of the Test Road provides some information. Table 2.2-9 of AASHO Road Test Report 5 gives information showing the equivalencies in terms of inches of gravel for both the bituminous treated and the cement treated bases. From the AASHO information, the equivalencies in Table 1 were developed.

Table 1 would indicate that cement treated bases have an equivalency of 1.65 inches of gravel to 1 inch of base. This agrees quite favorably with California experience as we are currently using a factor of 1.75 to 1.

From the information on bituminous bases, on the other hand, it is apparent that the magnitude of load has a marked effect upon the equivalency of bituminous bases. We suspect that there is also an effect due to depth of layer and the number of repetitions. However, in these latter two cases, it was not possible to isolate the variables by means of the information available to us. It is possible that one effect offsets the other.

A study of air temperature data at the AASHO Test Road and corresponding pavement temperature data indicated

ClibPDF - www.fastio.com

that an approximate average pavement temperature of about 72° would represent the over-all condition of the test road pavement. Cohesion* (tensile strength) tests were made on AASHO pavement cores tested at various temperatures. The results are shown in Figure 6. At 72° the cohesion value of the AASHO mix is 5000 grams per lineal inch. The recovered penetration of the asphalt in these cores was 37.

To compare a normal California mix using a good crushed California aggregate and asphalt manufactured on the Pacific Coast the remaining series of tests indicated in Figure 6 were performed. For these California mixes it will be noted that the cohesion at 72° would be only 2000 grams per lineal inch.

Most observers would agree that the equivalency of a rigid layer of material, in terms of inches of gravel, should be directly related to its tensile strength and its depth of section. A somewhat different situation exists in the case of bituminous layers for in this case strength not only is related to composition but also to temperature, as is demonstrated in Figure 6. A bituminous mix varies in

*Cohesion test is performed by breaking a 2-1/2" x 4" diameter test specimen by bending. Cohesion value = grams per lineal inch to break specimen when the load is applied on a 30" lever arm.[6]

ClibPDF - www.fastio.com

temperature from top to bottom, and consequently there is a variation in that portion of its strength which is dependent upon the viscosity of the asphalt binder.

In order to evaluate the property of cohesion, an empirical formula was developed to fit AASHO conditions. This formula is:

Equivalent Cohesion,

$$C = \text{Cohesion at } 72^\circ \left(\frac{8}{W+2}\right)^{2.5}$$

where: W = Applied wheel load in kips (≥ 6)

Also,

Gravel Equivalency,

$$g.e. = \left(\frac{C}{\text{Cohesion of gravel}}\right)^{0.2}$$

Figure 6 indicated that mixes in themselves have widely divergent tensile strength characteristics, and in ordinary highway design problems an equivalency correction for wheel load would not be a simple matter since mixed traffic is involved and the weight of individual axles is rarely known, except on a statistical basis. However, assuming that lightly traveled roads will generally be designed for light loads, and heavy industrial roads will be subjected to heavy loads, a general relationship between equivalency and traffic index can be established.

Figure 7 is an empirical development from AASHO

ClibPDF - www.fastio.com

Test Road data which provides a means of adjusting equivalency for mixes which do not have the tensile strength characteristics of the AASHO asphalt concrete. We feel that these reductions in equivalency are necessary and need to be considered if flexible pavements are to be designed with the assurance of an adequate life. In California, therefore, we are proposing that a series of equivalencies be used that are based upon the predicted traffic.

The proposed equivalencies taken from Figure 7 are shown in Table 2. It covers a complete range of traffic currently using California streets and highways.

The coefficients listed in Table 2 would appear to challenge the validity of the coefficients D_1, D_2 and D_3 which were developed in the formula explaining the performance of the AASHO Test Road. These coefficients were obtained by statistical analysis of the factorial sections and most surely expressed what happened at the AASHO Test Road, yet there are the wedge sections and they, by our analysis at least, do not necessarily agree with the factorial sections. If we add to this the evidence reported by the British Road Test[8] that 6 inches of bituminous base is equivalent to 10 inches of gravel, and also consider Mr. Nichols' report from Virginia[9] concerning distress of a number of asphalt base projects in which the total base and surfacing equalled 9 inches, it would appear that there are other factors to consider before a single

ClibPDF - www.fastio.com

standardized ratio of equivalencies can be established for use under all conditions and all geographical areas. In Table 2 there is an attempt to indicate the ranges of equivalencies which might be encountered due to varying traffic conditions or varying quality of the asphalt concrete layer itself.

In 1957 the method for calculating traffic index in the California formula[4] was revised. The formula, based upon test road data and experience available at that time, was:

$$TI = 1.35 \left[\left(\frac{W}{5}\right)^5 \text{ repetitions}\right]^{0.113} \quad (1)$$

where: TI = Traffic Index, a number directly proportional to the required thickness of structural section.

The AASHO Road Test data were reviewed to determine the validity of the exponents in the formula. The number of applications at present serviceability index (psi) = 2.5 was plotted vs. the gravel equivalent of the individual sections. The plots on log log paper yielded the slopes shown in Table 3.

It will be noted in Table 3 that the use of different base materials results in different deterioration rates due to applications of a given load. However, the estimating of future traffic for purposes of design is, at best, only an approximation. Therefore, we do not feel that refinements in the exponent due to base type is justified until methods of traffic prediction are greatly improved. To encompass all reasonable possibilities, it appears that the exponent of 0.119

ClibPDF - www.fastio.com

would provide a reasonably satisfactory value.

Using the same procedure as above, a tabulation was made for the same test sections in which curves of wheel load vs. gravel equivalent were plotted for the indicated number of applications. The slopes are determined for the wheel load exponent. The tabulation is shown in Table 4 and typical curves are shown in Figure 8.

In Table 4 the factorial sections were omitted because we did not have sufficient data to interpolate exact thicknesses for given numbers of repetitions.

The average value of 0.48 is sufficiently close to a theoretical value of 0.50 to justify the use of the latter figure. Using the value of 0.50 our formula for thickness becomes:

$$T = \text{Constant } (W)^{0.50}(r)^{0.119} \quad \text{-----(2)}$$

where: T = Thickness
W = Wheel Load
r = Repetitions

From equation (2) Wheel Load Constants may be calculated which may be applied to mixed traffic.

$$\frac{T_1}{T_2} = \left(\frac{W_1}{W_2}\right)^{0.50}\left(\frac{r_1}{r_2}\right)^{0.119}$$

let: $T_1 = T_2$; $W_1 = 5000$ lb.; and

r_2 = one repetition of load W_2

then: $r_1 = \left(\frac{W_2}{5}\right)^{4.2}$ Equivalent 5 kip wheel loads (EWL)

ClibPDF - www.fastio.com

We will call the constants EWL_{62} to differentiate from previous EWL calculations made by the California Division of Highways.

In a paper entitled "Recent Changes in the California Design Method for Structural Sections of Flexible Pavements,"[4] the details of using this method to obtain constants applicable to mixed traffic are outlined.

Briefly, the method consists of a statistical sample of traffic as weighed at various loadometer stations throughout the State. The development of the method is shown in Table 5 where axle weights have been grouped together to show variations within classes of trucks, such as 2, 3, 4, 5 or 6 axle trucks. It will be noted in the table that wheel load factors for the 3, 4, 5 and 6 axle trucks show a variation within a given wheel load group. This is due to allowance for tandem effect. Based on test road data a 10% effect was allowed for each pair of tandems included. The number of tandem vehicles for each class of truck is estimated, using tables published in House Document #91, 1st Session of the 86th Congress. This document contains a large sample of truck combinations and loadings for various geographical areas of the United States. It contains sufficient information to establish the percentage of single and tandem axle combinations for each load group. These percentages were applied to the loadometer tables of the California Division of Highways to determine the average wheel load factor for each class of truck and for each loading.

ClibPDF - www.fastio.com

Table 6 shows the totals arrived at in Table 5 and develops the EWL_{62} constants for computing average daily traffic.

Since in California our traffic counts are reported as the total vehicles in two directions the truck constants developed in the last column of Table 6 are for these bi-directional counts. It should be pointed out that the constants in Table 6 are based on 1959 traffic and that any increase in allowable load limits will result in higher constants. These constants multiplied by the estimated number of trucks of each axle grouping will total to the design equivalent 5000 pound wheel loads (EWL). Constants could also be determined quite readily for equivalent 9000 pound wheel loads.

The EWL may be converted to traffic index by the formula:

$$TI = 1.30\ (EWL_{62})^{0.119}$$

A typical traffic index calculation is shown in Appendix I. Those who are familiar with and have used the California method previously will note a substantial reduction in the EWL constants. However, the relation between constants (i.e., the ratio of 2 axle to 5 axle or 3 axle to 6 axle vehicles) has not greatly changed. It should also be noted that for a given traffic situation the new EWL constants will result in virtually the same Traffic Index. For example, in Appendix I, the EWL_{57} would have a Traffic Index of 10.7 while the new 1962 constant will give a Traffic Index of 10.9.

ClibPDF - www.fastio.com

Having re-evaluated the various factors of the design formula in light of the AASHO data, it would appear the formula should be changed to read as follows:

$$\text{Thickness} = \frac{0.070\ (\text{Traffic Index})(100 - \text{Resistance Value})}{(\text{Cohesion})^{0.2}}$$

Also in Appendix I is a typical example showing the pavement thickness calculation using the nomograph (Figure 11) which solves the suggested new formula. This calculation illustrates how each layer may be evaluated, one on top of the other, to give the most economical thickness of cover material. Naturally, when applying this formula on a broad scale highway system, some additional factors of safety may be allowed, especially when the traffic factor cannot be accurately estimated. It is, of course, uneconomical to change structural sections too often on a single project so that some "rounding off" in sections is needed. For these reasons, many states provide design standards for minimum thicknesses of pavement and base for certain traffic conditions and allow only the subbase layer to be varied. In the example shown in Appendix I, however, the thickness determined by formula is shown.

By introducing an expression for an increased tensile strength allowance, coupled with a readjustment of the load and repetition exponents, a better correlation with the test road data is obtained as shown in Figure 9. The improved correlation is measured numerically by the reduction in the standard

ClibPDF - www.fastio.com

error of estimate from ± 2.7 inches shown in Figure 5 to ± 2.2 inches and the increase in coefficient of correlation from 0.87 to 0.93.

Figures 5 and 9 contain the statement that the sections which failed during the first spring thaw are omitted. The reason for doing this was lack of time to study all of the sections on the flexible pavement portions of the Test Road and since most of the highway mileage in California is in frost free areas, we made an analysis first on those sections which survived the first spring thaw. These two charts, Figures 5 and 9, report the results of this study.

It should be noted also in Figure 9 all the error is being placed in the subbase layer. This gives a maximum error of estimate and a minimum coefficient of correlation when such things are evaluated in terms of thickness of section. The reason for this is obvious in that the error between actual and calculated thickness must be determined first in terms of gravel equivalent thickness, then converted to inches of surface, base, and subbase. Subbase, having the lowest equivalency, gives the greatest error. Surface material, having the highest equivalency, will give the lowest error.

An example of how the correlation factors might be changed is illustrated by Figure 10. (Please note that Figure 10 shows the data for all section on the Test Road). This represents the same plot as Figure 9 except that the

ClibPDF - www.fastio.com

difference in gravel equivalent was prorated by thickness of layer to surface, base, and subbase. When this is done the error of estimate ± 2.2 inches in Figure 9 becomes ± 1.2 inches and the coefficient of correlation raises to 0.98.

SUMMARY

Figures 9 and 10 serve to illustrate the influence of the method used to judge the efficiency of a design formula. These figures also show that the thicknesses computed by means of the California formula (based on measured properties of the basement soil, the subbase, base, and surface, also the effects of traffic expressed by the Traffic Index) is in nearly all cases equal to or greater than the thickness indicated in the Serviceability Index of 2.5 on the test road. A similar relationship could be shown for 2.0 or 1.5 Serviceability Index. This is the only relationship which can be justified, as a design formula should provide a structure stronger than any section known to fail. In other words, no portions are expected to show failure within the design life of the project. It may be argued that this provides too great a factor of safety and that the theoretical thickness, in many cases, would be excessive compared to the depths reported as just adequate on the test road. In judging the validity of a pavement design formula by comparing the calculated thickness with

ClibPDF - www.fastio.com

test road data, the following facts must be considered:

1. Every effort was made to secure a high degree of uniformity on the test road, and no such uniformity of performance can be expected on a highway constructed by ordinary methods.

2. Traffic was continued on the test road for a period of only two years. This means that the test road did not undergo the large number of cycles ranging from high to low temperature and from wet to dry which affects the performance of a highway over a period of many years.

3. The asphaltic pavements and bases on the test road were only two years old at the end of the test. Virtually all asphalts harden to some degree and become brittle with age. One could not assume and equally good performance over a long period of time on the average highway.

Taking into account the above considerations, any design formula should be on the conservative side and provide some factor of safety over the thickness and strength of pavement which appeared to be barely adequate on the test road. The primary and important advantages of the California formula are:

ClibPDF - www.fastio.com

1. The California procedure utilizes numerical values derived from physical tests of the basement soil, the subbase, base and pavement.

2. The California method provides a logical means for converting miscellaneous traffic wheel loads to a single number - the Traffic Index. This number bears a direct linear relationship to the thickness of pavement structure required.

3. The California method has been in use for approximately 13 years and has demonstrated that it can accommodate wide variations in the type of soil, type of base, and type of pavement as well as variations in wheel loads and in the number of load repetitions.

ClibPDF - www.fastio.com

ACKNOWLEDGEMENTS

In addition to the many persons who have worked on the California pavement design formula for previous papers, the authors wish to acknowledge the help of several whose combined efforts made this paper possible. The review of the AASHO Road Test data was carried out by Mr. Parks M. Adams, Mr. David W. Eckhoff, Mr. Carl R. Sundquist, and Mr. Robert O. Watkins. Correlation tests were performed under the general direction of Mr. Ernest Zube. Mr. Clyde Gates, Mr. Daniel Howe, and Mr. Merle Nelson all contributed to the testing program and analysis of results.

We wish to thank Mr. William H. Yttrup, Mr. Robert Souza, Mrs. Agnes Lyon, Mrs. Mary Martin, and their staffs, for the exacting work of preparing the figures, reproductions and manuscript typing.

ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

REFERENCES

1. Hveem, F.N., and Carmany, R.M., "The Factors Underlying the Rational Design of Pavements." Proceedings, Highway Research Board (1948)

2. Kersten, Dr. M.S., Cosgrove, F.H., Goldbeck, A.T., Haines, R.M., and Olmstead, F.R., "Progress Report of Subcommittee on Methods of Measuring Strength of Subgrade Soil - Review of Methods of Design of Flexible Pavements." Proceedings, Highway Research Board (1945)

3. Nijboer, L.W., and van der Poel, C., "A Study of Vibration Phenomena in Asphaltic Road Constructions." Proceedings, The Association of Asphalt Paving Technologists, Vol. 22 (1953)

4. Sherman, G.B., "Recent Changes in the California Design Method for Structural Sections of Flexible Pavement." Proceedings, First Annual Highway Conference (1958)

5. Throughout the text references are made to data from the AASHO Road Test. These data are obtained primarily from Highway Research Board Special Report 61 E, "The AASHO Road Test, Report 5, Pavement Research." (1962)

6. California Division of Highways Materials Manual of Testing and Control Procedures, Vol. I

7. "Monroe Calculating Machine Methods - General Statistics" Published by Monroe Calculating Machine Company, Inc. (1960)

8. Lee, A.R., and Croney, D., "British Full-Scale Pavement Design Experiments." International Conference on the Structural Design of Asphalt Pavements (1962)

9. Nichols, F.P., Jr., "Effects of Compaction and Subgrade Stabilization on Deflection and Performance of Virginia Pavements." International Conference on the Structural Design of Asphalt Pavements (1962)

ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

APPENDIX I

TYPICAL EXAMPLE OF PAVEMENT THICKNESS DESIGN

Given the Resistance Value of a basement soil = 20, as measured by the Hveem Stabilometer, cohesion of gravel = 20, cohesion of crushed stone base = 30, cohesion of asphalt concrete = 2000, and the average daily truck traffic shown below.

The number of trucks counted in each class is multiplied by the yearly EWL constants listed in Table V to determine the annual Equivalent Wheel Load (EWL).

Truck Class by Axle	Average Daily *No. of Trucks	X	EWL (5000#) Yearly Constants	=	Yearly EWL
2	679		250		169,750
3	344		815		280,360
4	295		965		284,675
5	1539		2385		3,670,515
6	113		1475		166,675
			Total Annual EWL	=	4,571,975

Assuming that in 10 years the traffic will have increased 50%, the average annual design EWL is:

$$\frac{1.0 + 1.5}{2} (4,571,975) = 5,715,000 \text{ EWL}$$

The total design EWL for 10 years is:

$$10(5,715,000) = 57,150,000 \text{ EWL}$$

* 2 directional count

ClibPDF - www.fastio.com

Traffic Index (TI) is calculated from the EWL by the following equation:

$$TI = 1.30\ (EWL)^{0.119}$$

For the example above:

$$TI = 1.30\ (57,150,000)^{0.119}$$

$$= 1.30\ \left(10^{7.757}\right)^{0.119}$$

$$= 1.30\ \left(10^{0.923}\right) = 1.30(8.38) = 10.9$$

Use 11.0

PAVEMENT THICKNESS CALCULATION

The required Gravel Equivalent (G.E.) is determined by the equation:

$$G.\ E. = \frac{0.070\ (\text{Traffic Index})\ (100 - \text{Resistance Value})}{(\text{Cohesiometer value of gravel})^{0.2}}$$

For the example:

$$G.\ E. = \frac{0.070\ (11.0)\ (100 - 20)}{(20)^{0.2}} = 33.8''$$

SURFACE THICKNESS

To determine the thickness of asphalt concrete required, use the nomograph in Figure 11. The California specifications require a crushed aggregate base to have an 80 R-value minimum. With a straightedge, intersect Scale E at 80 R-value and Scale F at 11.0 traffic index. The intersection of this line with Scale G is the thickness of gravel equivalent required. Using

ClibPDF - www.fastio.com

this value of 8.5" gravel equivalent as a turning point, intersect Scale H at the appropriate value of cohesion for the AC. This cohesion value is found from the following equation:

$$C = C_T \left(\frac{5.14}{TI}\right)^{2.5} \leq C_T$$

where: C_T = 2000 and TI = 11.0

then: C = 300

The intersection of this line with Scale I gives 4.9" of asphalt concrete required. Use 5" in design.

BASE THICKNESS

Using California Standard Specifications of 60 R-value minimum for subbase materials (This value can be and is modified in the Special Provisions to fit local aggregate conditions.), Figure 11 indicates a gravel equivalent of 16.9" needed over the subbase materials. Since the 5" AC is equivalent to 8.6 gravel equivalent inches, 8.3" remains to be satisfied by the base material. A cohesion of 30 for a good crushed rock product would indicate 7.5" to be satisfactory. Use 8.0" of base material.

ClibPDF - www.fastio.com

SUBBASE THICKNESS DESIGN

Referring again to Figure 11, we find that a 20 R-value basement soil with TI = 11.0 requires a gravel equivalent of 33.8".

The G. E. of surface and base is:

5" surface = 8.6" G.E.
8" base = 8.8" G.E.
17.4"

Required thickness of subbase is, therefore:

33.8 - 17.4 = 16.4" Use 17.0" subbase

Thus the minimum allowable structural section over 20 R-value basement soil for very heavy truck traffic is:

5" AC
8" Class I Aggregate Base
17" 60 R-value Subbase
30" Total thickness

Various other structural sections which might also be found satisfactory for the above traffic and soil conditions would be:

5" Asphalt Concrete	5" Asphalt Concrete
8" Cement Treated Base	8" Bituminous Treated Base
11" Subbase	12" Subbase
24" Total	25" Total

ClibPDF - www.fastio.com

F. N. Hvem
G. B. Sherman

APPENDIX II

DEFINITION OF STATISTICAL TERMS

I. Coefficient of Correlation

Linear correlation is used to determine whether a relationship exists between two variates. There may be a direct, inverse, or no relationship between variates.

Pearson's coefficient of correlation for ungrouped data has theoretical limits of ± 1. A value of "r" approaching +1 indicates a direct relationship between the variates whereas a value approaching -1 indicates an inverse relationship. A value of "r" tending toward zero indicates that no relationship exists between the variates.

$$r = \frac{\frac{\Sigma xy}{N} - \frac{\Sigma x \Sigma y}{N^2}}{\sigma_x \sigma_y}$$

Where

$$\sigma_x = \sqrt{\frac{\Sigma x^2}{N} - \frac{(\Sigma x)^2}{N^2}}$$

$$\sigma_y = \sqrt{\frac{\Sigma y^2}{N} - \frac{(\Sigma y)^2}{N^2}}$$

ClibPDF - www.fastio.com

x = actual thickness - inches

y = computed thickness - inches

N = number of points

σ = standard deviation

r = coefficient of correlation

II. Line of Regression

If the plotted data indicate a linear relationship between the variates, then a straight line that best fits the data is called a line of regression. The general equation is expressed as y = mx + b and the values of m and b are found by using the method of m and b are found by using the method of least squares.

$$y = mx + b$$

Where

$$m = \frac{N\Sigma xy - \Sigma x\Sigma y}{N\Sigma x^2 - (\Sigma x)^2}$$

$$b = \frac{\Sigma y\Sigma x^2 - \Sigma x\Sigma xy}{N\Sigma x^2 - (\Sigma x)^2}$$

N = no. of points

y = computed thickness - inches

x = actual thickness - inches

m = slope

b = y-intercept

ClibPDF - www.fastio.com

III. Standard Error of Estimate

Standard error of estimate measures the concentration of the points clustered about the line of regression. A zone drawn parallel to the line of regression on either side at a vertical distance Sy will include approximately 67% of the points. A vertical distance 2 Sy will include approximately 95% of the points.

$$Sy = \sigma_y \sqrt{1-r^2}$$

Where:

σ = standard deviation

r = coefficient of correlation

Sy = standard error of estimate - inches

Note: Above information from: "Monroe Calculating Machine Methods - General Statistics" published by Monroe Calculating Machine Company, Inc.

ClibPDF - www.fastio.com

TABLE 1

EQUIVALENCIES OF TREATED BASES

App. (1000)	Base Type	Equivalency = in. of stone base per in of treated base							
		Loop 3		Loop 4		**Loop 5		*Loop 6	
		12K-S	24K-T	18K-S	32K-T	22.4K-S	40K-T	30K-S	48K-T
100	CTB			1.8	2.2			1.9	2.0
	BTB	2.9	3.2			2.4	2.3	3.0	2.9
300	CTB			1.7	1.8			1.6	1.6
	BTB	2.8	2.9			2.2	2.3	1.9	2.3
500	CTB			1.7	1.6			1.5	1.5
	BTB	2.7	3.0			2.3	2.4	1.7	2.1
700	CTB			1.6	1.6			1.5	1.5
	BTB	3.1	3.1			2.2	2.4	1.7	1.8
900	CTB			1.6	1.6			1.5	1.5
	BTB	3.3	3.1			2.2	2.4	1.7	1.7
1114	CTB			1.6	1.6			1.5	1.5
	BTB	3.4	3.1			2.2	2.4	1.7	1.7
Avg.	CTB			1.7	1.7	(1.65)	(1.65)	1.6	1.6
	BTB	3.0	3.1			2.3	2.4	2.0	2.1

CTB = Cement Treated Base BTB = Bituminous Treated Base

*For Loop 6, four inches of subbase was replaced by 3.5 inches of stone base for comparison purposes.

**Since there was no Stone Base Wedge Section in Loop 5, the average equivalency for CTB (1.65) from Loops 4 and 6 was assumed to be correct for Loop 5 also, and this value was used for comparison with the BTB Sections. The data for Loop 5 are, therefore, interpolations.

ClibPDF - www.fastio.com

TABLE 2

PROPOSED EQUIVALENCIES FOR BITUMINOUS MATERIALS

Showing Thickness of Gravel Layer That Would
Be Required to Equal 1" of Asphalt Concrete Pavement

Class of Road	Traffic Index Range	Gravel Equivalency - Inches	
		AASHO Mat'l	Calif. Mat'l
Heavy Industrial	12 11	2.0 2.1	1.6 1.7
Heavy Truck Traffic	10 9	2.2 2.3	1.8 1.9
Medium Truck Traffic	8 7	2.4 2.6	2.0 2.1
Light Truck Traffic	6	2.8	2.3
Residential Streets	5 4	3.0 3.0	2.5 2.5

ClibPDF - www.fastio.com

TABLE 3

SLOPE VALUES OF APPLICATION

VS GRAVEL EQUIVALENT CURVES

Loop	Lane	Slope of Application vs Gravel Equivalent Curve			
		All Factorial Sections	BTB Wedge	CTB Wedge	Stone Wedge
3	1	0.118	0.088		0.137
	2		0.099		0.111
4	1	0.146		0.100	0.067
	2	0.141		0.127	0.064
5	1	0.093	0.100	0.082	
	2	0.103	0.080	0.103	
6	1	0.097	0.162	0.086	0.046
	2	0.090	0.161	0.099	0.044
Average		0.112	0.115	0.099	0.078

ClibPDF - www.fastio.com

TABLE 4

SLOPE VALUES OF WHEEL LOAD

VS GRAVEL EQUIVALENT CURVES

Applications of Load	Slope of Wheel Load vs Gravel Equivalent Curve		
	BTB Wedge	CTB Wedge	Stone Wedge
100,000	0.504	0.411	0.563
300,000	0.535	0.476	0.488
500,000	0.595	0.431	0.455
700,000	0.636	0.394	0.380
900,000	0.653	0.349	0.349
1,114,000	0.668	0.359	0.347
Average	0.599	0.403	0.430
Total Average	0.48		

ClibPDF - www.fastio.com

TABLE 5

CALCULATIONS TO DETERMINE YEARLY ADT CONSTANTS FOR TRUCK GROUPS BASED ON 1959 STATEWIDE LOADOMETER SURVEY

Axle Group Kips	Wheel Load Kips	2 Axle Trucks			3 Axle Trucks			4 Axle Trucks			5 Axle Trucks			6 Axle Trucks		
		EWL Per Axle	No. Axles	EWL	EWL* Per Axle	No. Axles	EWL	EWL* Per Axle	No. Axles	EWL	EWL* Per Axle	No. Axles	EWL	EWL* Per Axle	No. Axles	EWL
2-8	2	0.02	1939	39	0.02	931	14	0.02	1104	21	0.02	3313	55	0.01	153	3
8-9	4-1/4	0.51	115	59	0.45	241	108	0.48	108	51	0.39	859	331	0.44	31	13
9-10	4-3/4	0.81	77	63	0.72	212	153	0.73	90	65	0.62	492	302	0.73	36	26
10-11	5-1/4	1.23	64	79	1.08	157	170	1.10	53	58	0.93	253	235	1.10	27	29
11-12	5-3/4	1.80	49	88	1.58	105	165	1.51	54	82	1.37	261	357	1.55	19	29
12-13	6-1/4	2.54	45	114	2.25	76	212	2.16	50	108	1.99	290	578	2.22	11	25
13-14	6-3/4	3.52	34	120	3.16	71	224	3.00	56	168	2.93	409	1198	3.07	23	70
14-15	7-1/4	4.75	28	134	4.24	105	444	4.05	64	259	3.97	515	2041	4.15	20	83
15-16	7-3/4	6.3	28	177	5.6	114	641	5.3	55	290	5.2	667	3494	5.5	12	66
16-17	8-1/4	8.2	15	123	7.3	66	483	6.9	53	365	6.8	675	4611	7.2	8	57
17-18	8-3/4	10.5	29	305	9.4	38	358	8.8	39	342	8.7	615	5362	9.1	6	55
18-19	9-1/4	13.2	15	198	11.9	16	190	11.2	26	290	11.0	276	3039	11.5	1	12
19-20	9-3/4	16.5	3	50	14.8	1	15	13.9	9	126	13.8	40	551	-	-	-
20-22	10-1/2	22.6	4	90	20.1	-	-	18.8	4	76	18.6	11	205	-	-	-
22-24	11-1/2	33	1	33	32	-	-	28	1	28	27	9	245	-	-	-
24-26	12-1/2	47	-	-	45	-	-	39	-	-	39	3	117	-	-	-
Total No. Axles			2446			2133			1763			8688			347	
Total EWL				1672			3177			2329			22721			468

*Based upon tandem effect (i.e., one tandem = one single 10% heavier than tandem wheel load)

Percentage of single and tandem axles extracted from House Document No. 91, 86th Congress, 1st Session, March 2, 1959

ClibPDF - www.fastio.com

TABLE 6

TABLE OF AVERAGE DAILY TRUCK CONSTANTS FOR VARIOUS CLASSES OF TRUCKS

No. of Axles Per Truck	Total No. Axles	Total EWL	EWL Per Axle	EWL Per Truck	*EWL for 365 Days	**EWL/year For One Truck in One Direction
2	2446	1672	0.684	1.368	499	250
3	2133	3177	1.489	4.467	1630	815
4	1763	2329	1.321	5.284	1929	965
5	8688	22721	2.615	13.075	4772	2385
6	347	468	1.349	8.094	2954	1475

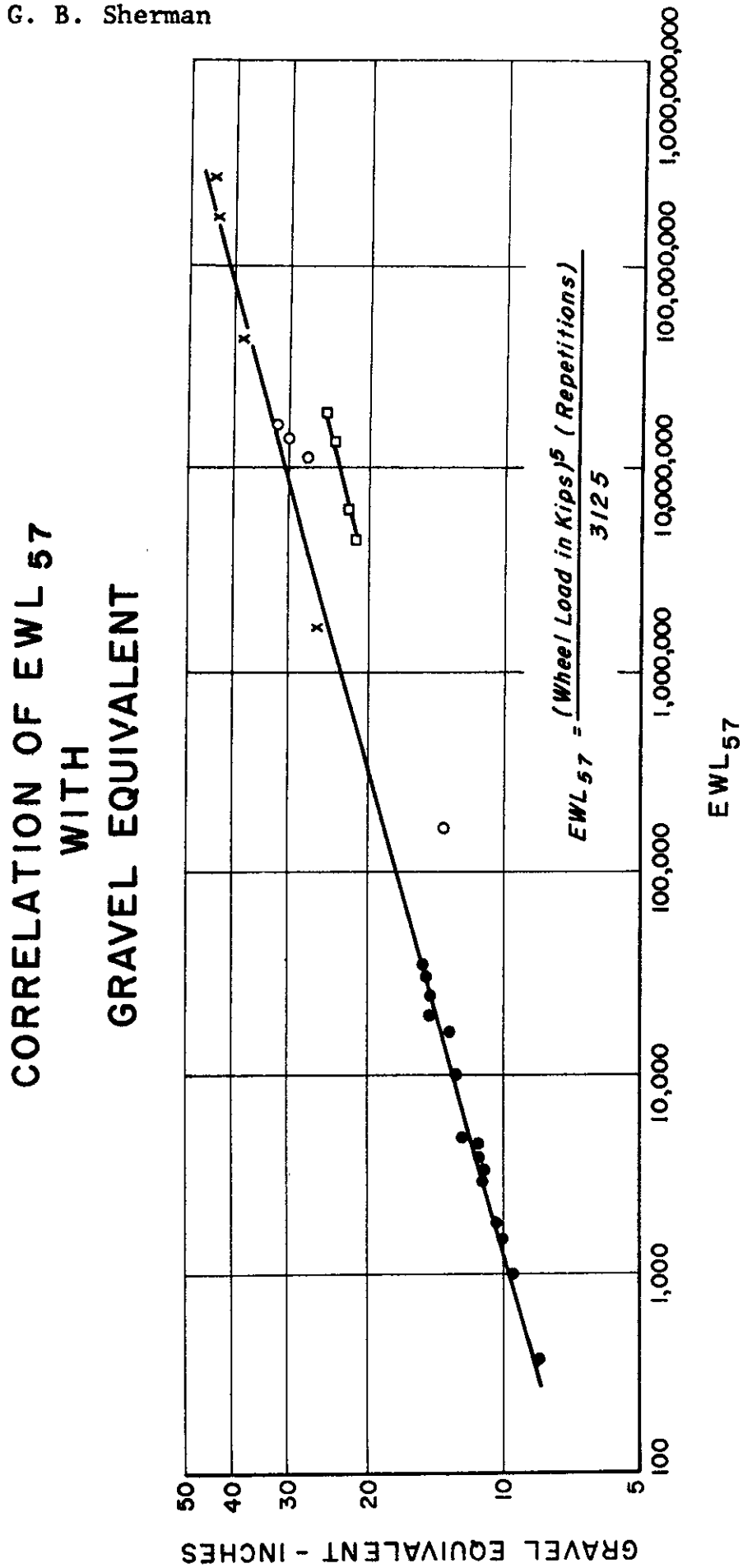
*Constants when traffic counts cover traffic in one direction only.

**Constants when traffic counts include bi-directional traffic.

ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 1

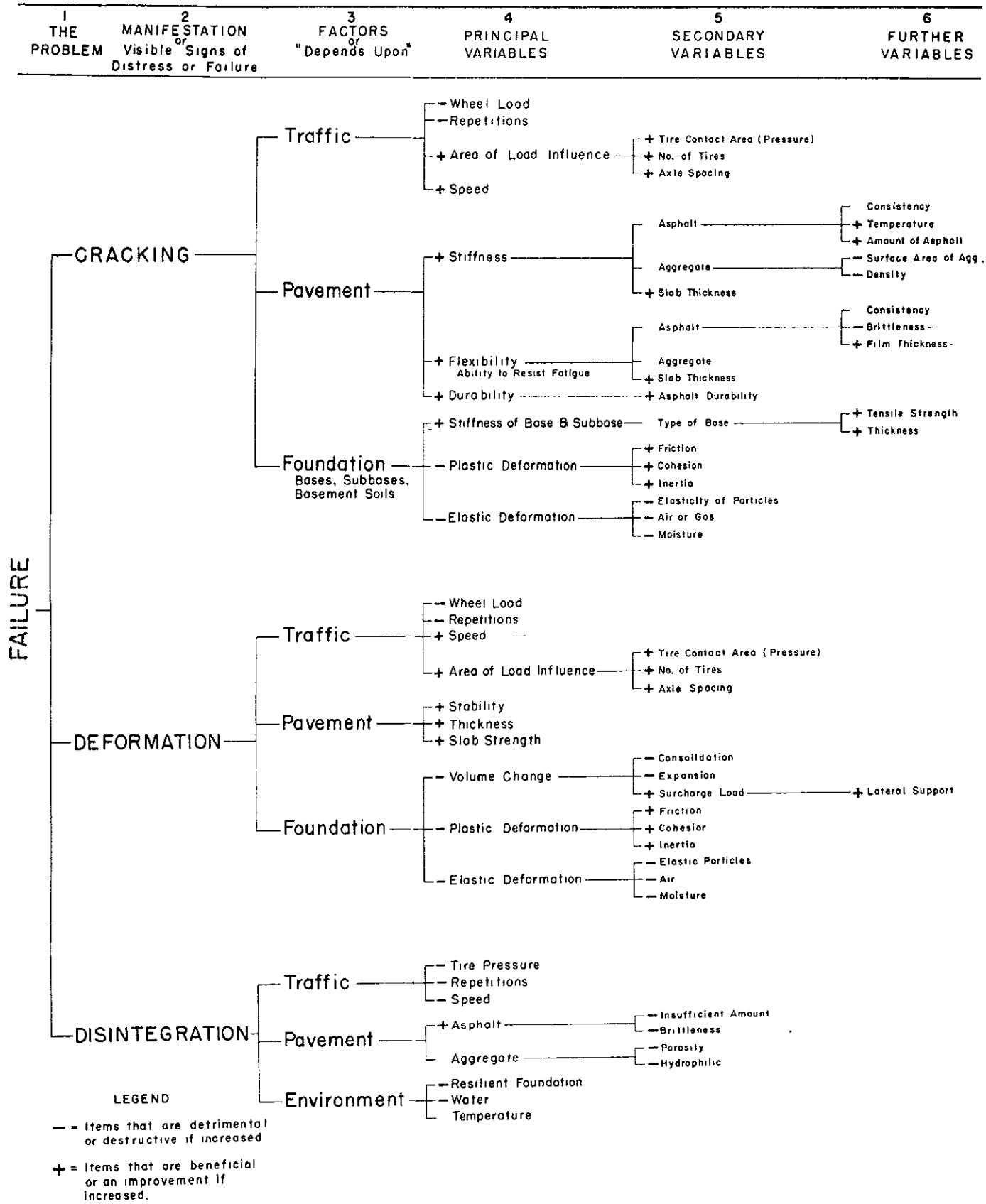


ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 2

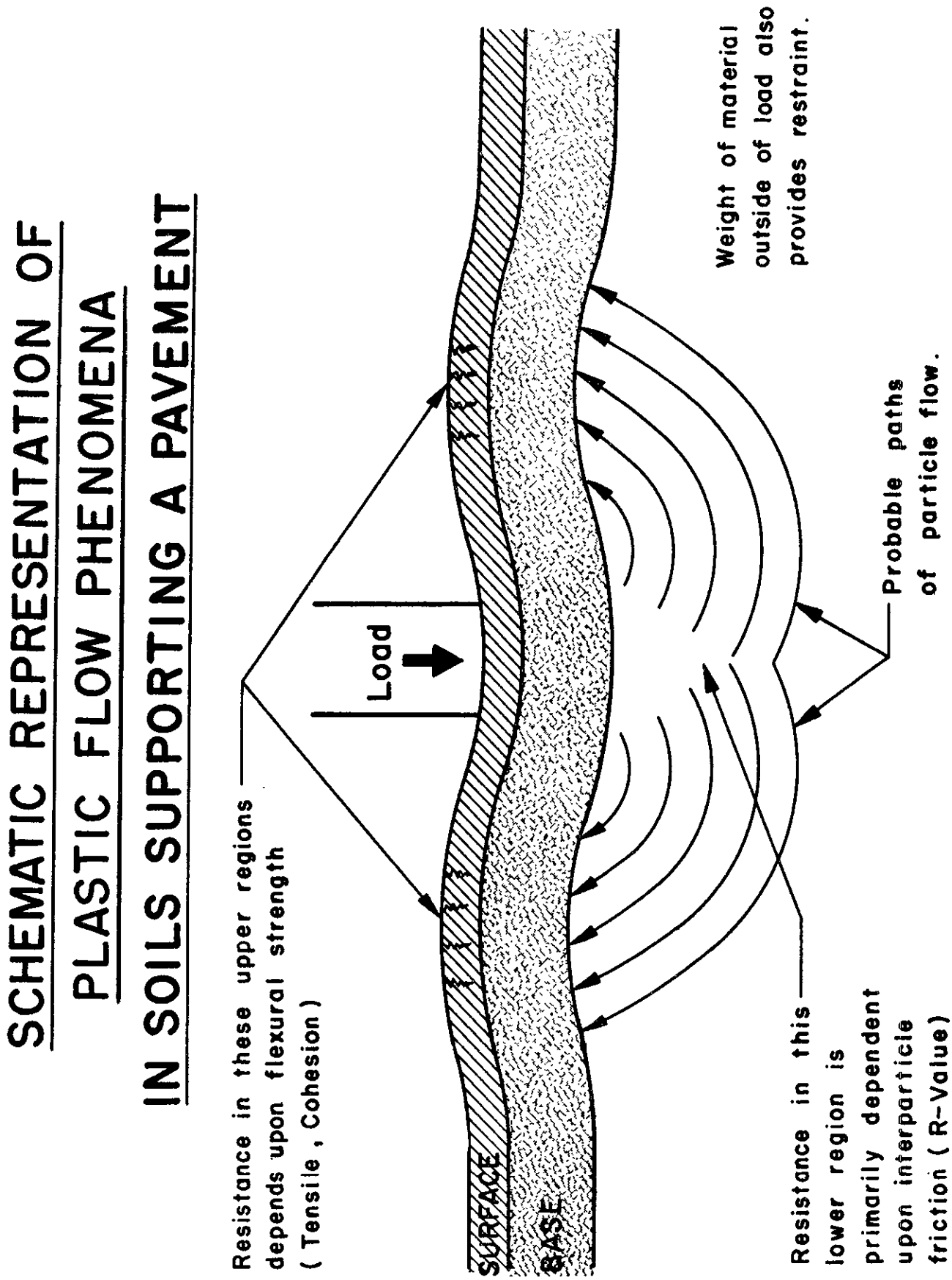
Analytical Chart To Show The Variables That Must Be Evaluated For The Structural Design of ASPHALT PAVEMENTS



ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 3

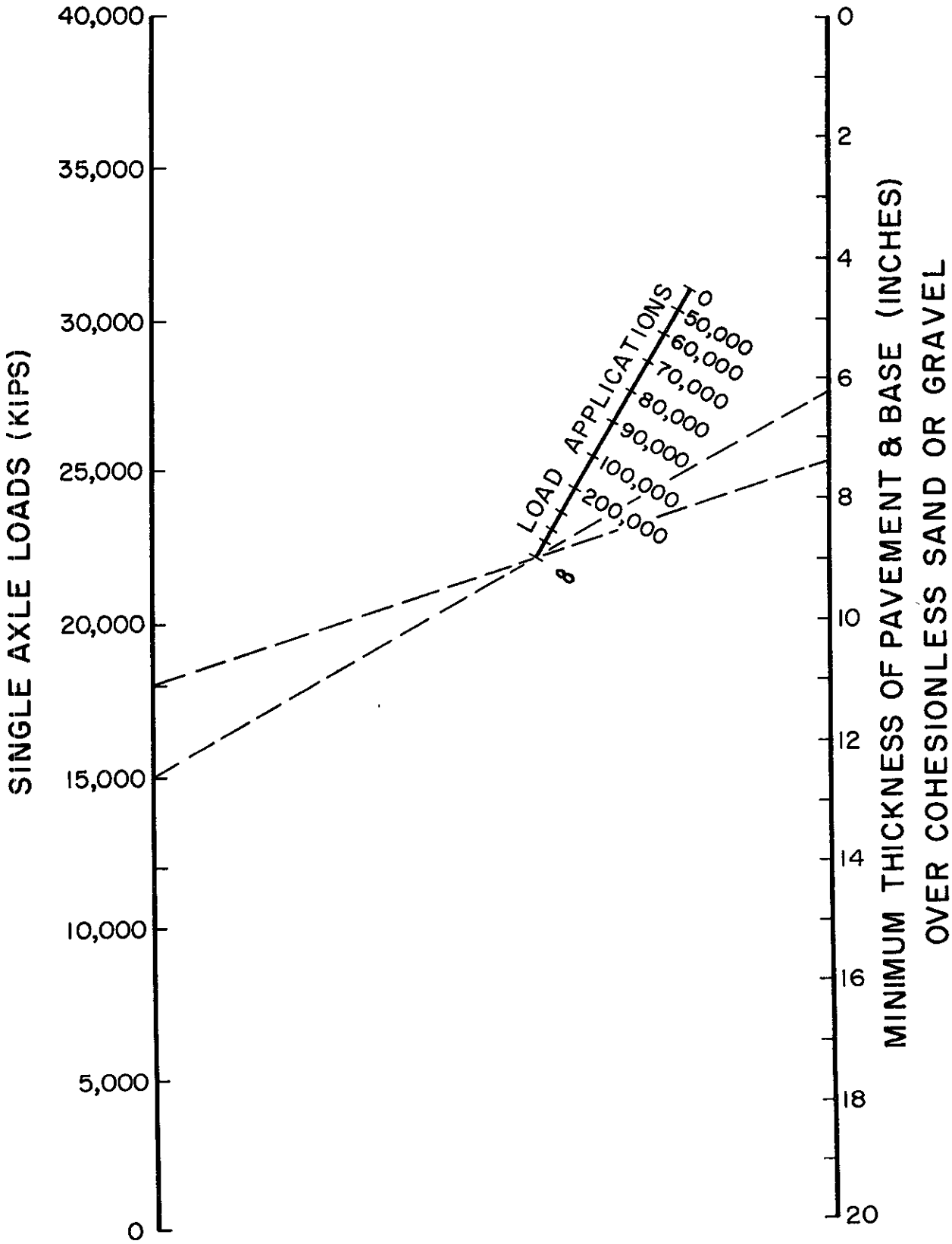


ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 4

ALIGNMENT CHART TO INDICATE THICKNESS OF COHESIVE LAYER REQUIRED OVER COHESIONLESS SAND OR GRAVEL



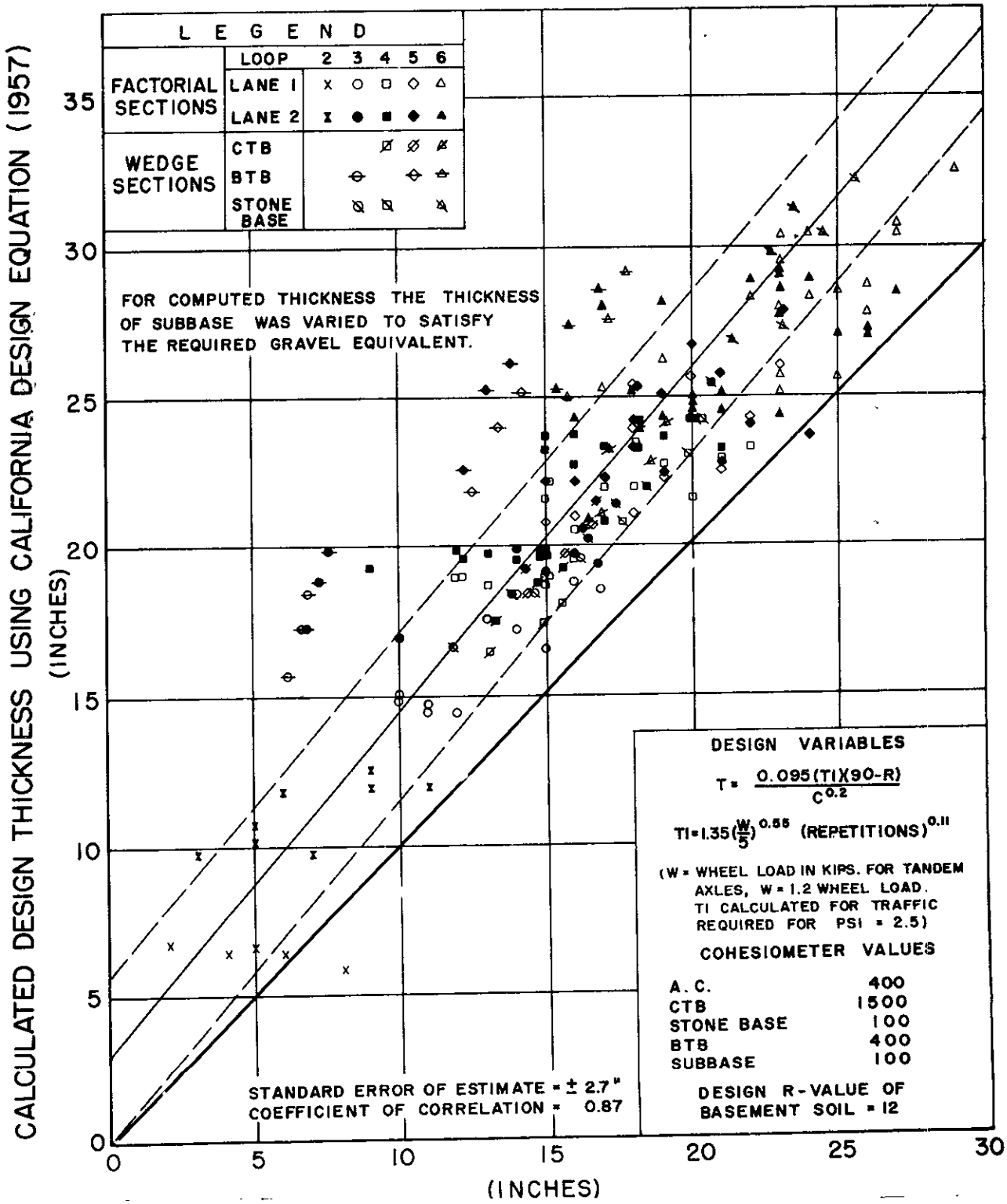
ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 5

THICKNESS OF TEST SECTIONS AT AASHO TEST ROAD VS. CALCULATED DESIGN THICKNESS USING CALIFORNIA DESIGN EQUATION (1957)

(SECTIONS WHICH FAILED DURING FIRST SPRING THAW ARE OMITTED)

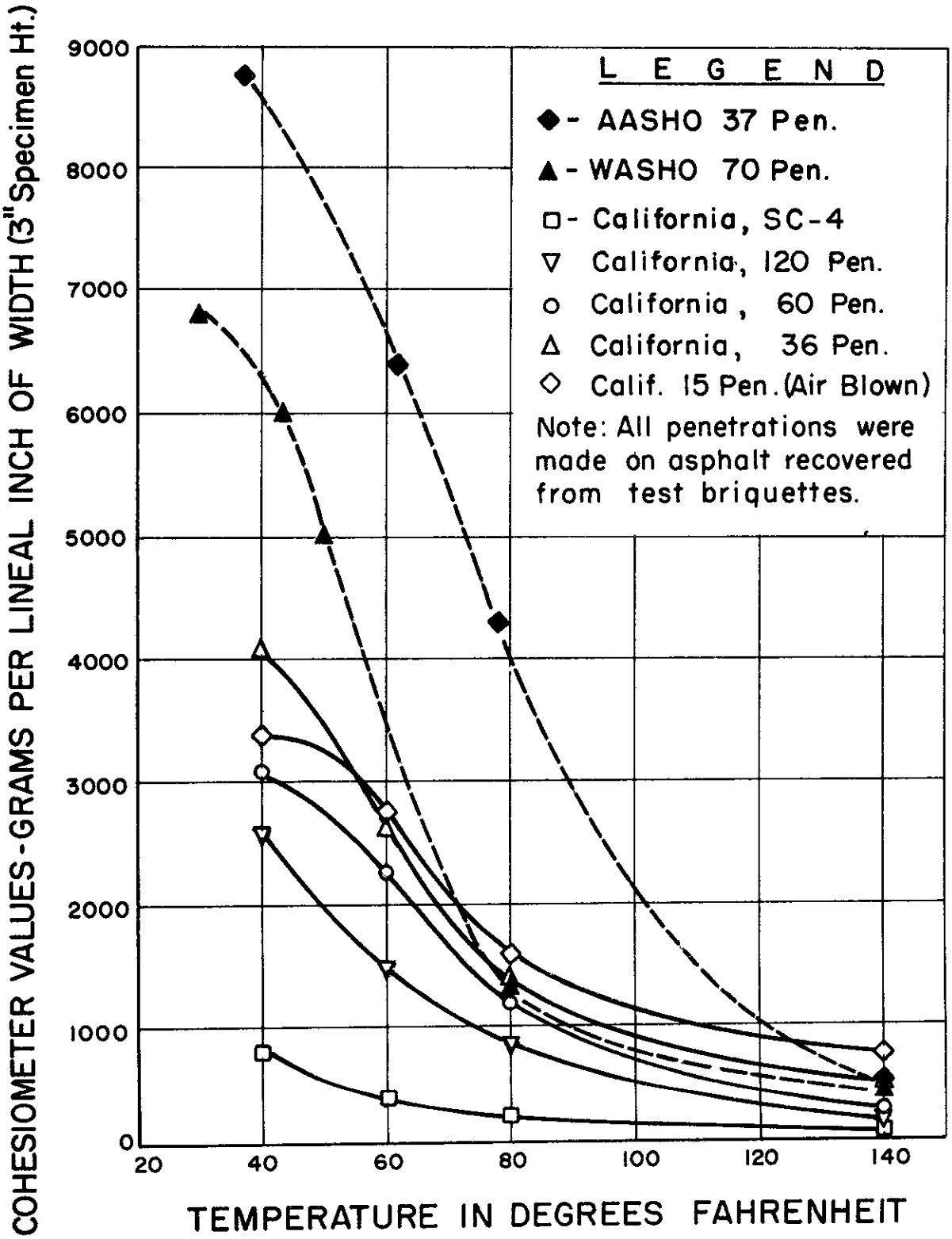


ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 6

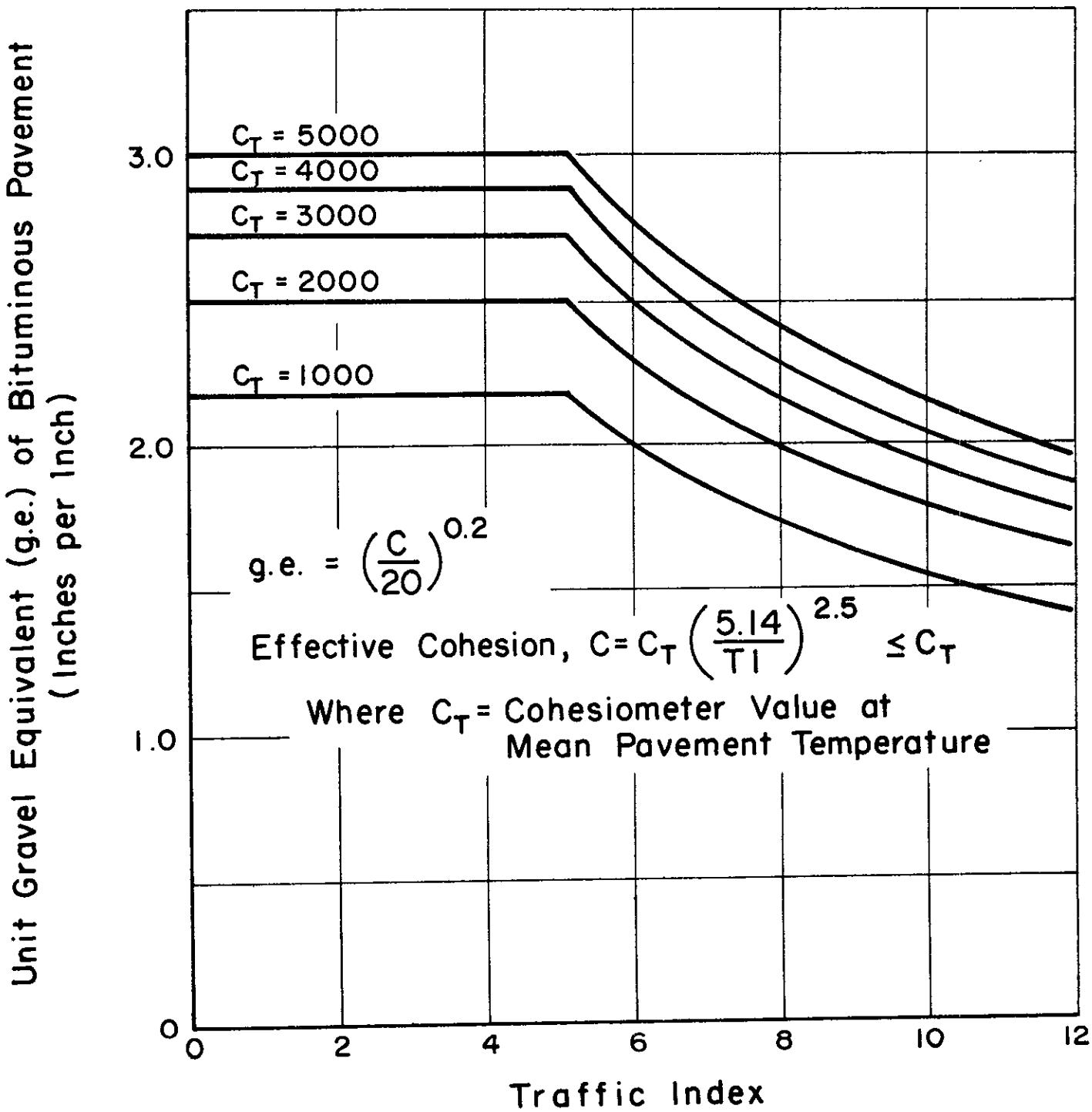
COHESIOMETER VALUES OF BITUMINOUS PAVEMENT AT VARIOUS TEMPERATURES



ClibPDF - www.fastio.com

Figure 7

GRAVEL EQUIVALENT OF BITUMINOUS PAVEMENT BASED ON AASHO TEST ROAD ANALYSIS

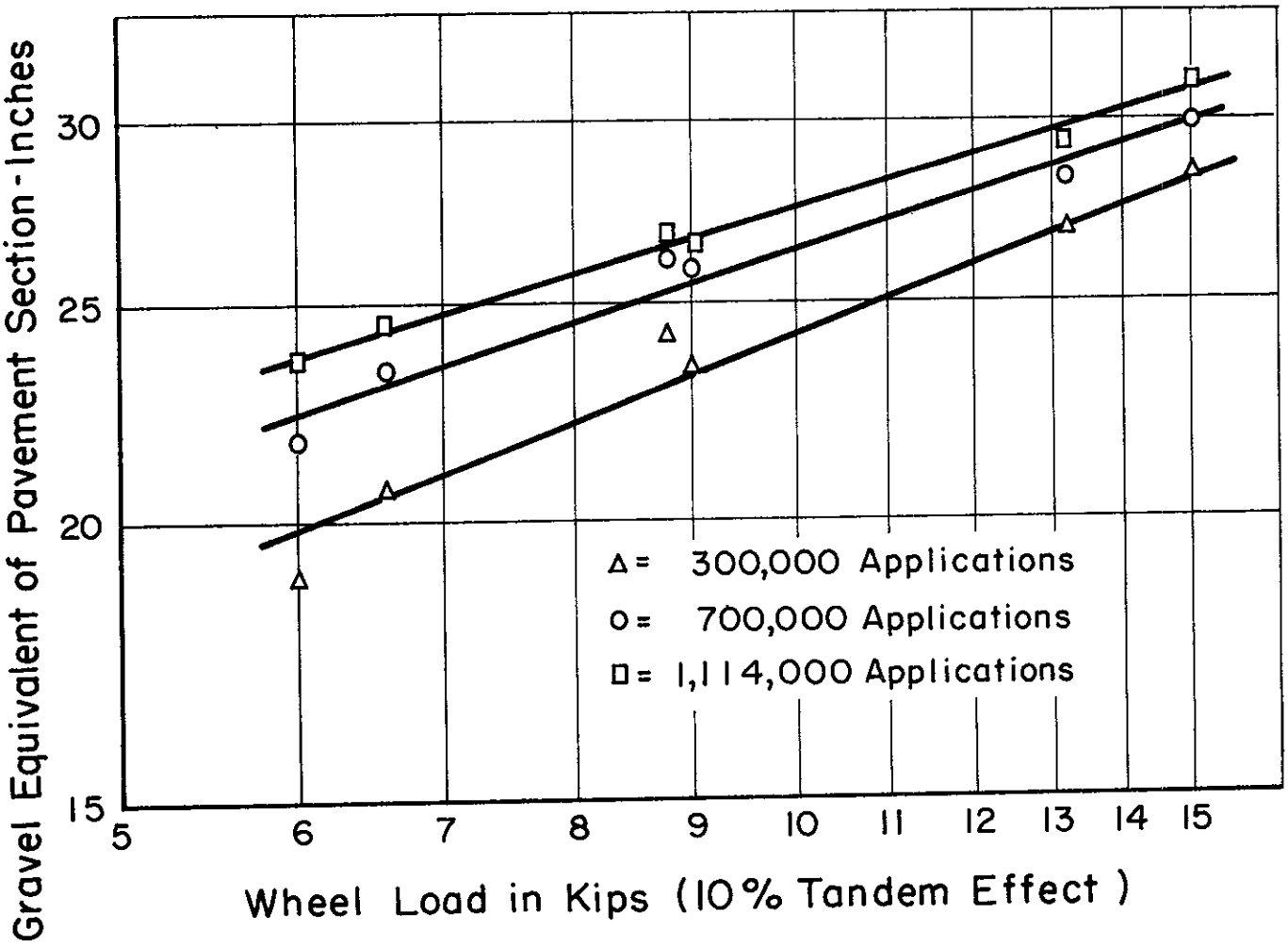


ClibPDF - www.fastio.com

Figure 8

LOG GRAVEL EQUIVALENT OF PAVEMENT SECTION VS. LOG WHEEL LOAD

DATA FROM STONE BASE WEDGE SECTIONS AASHO TEST ROAD



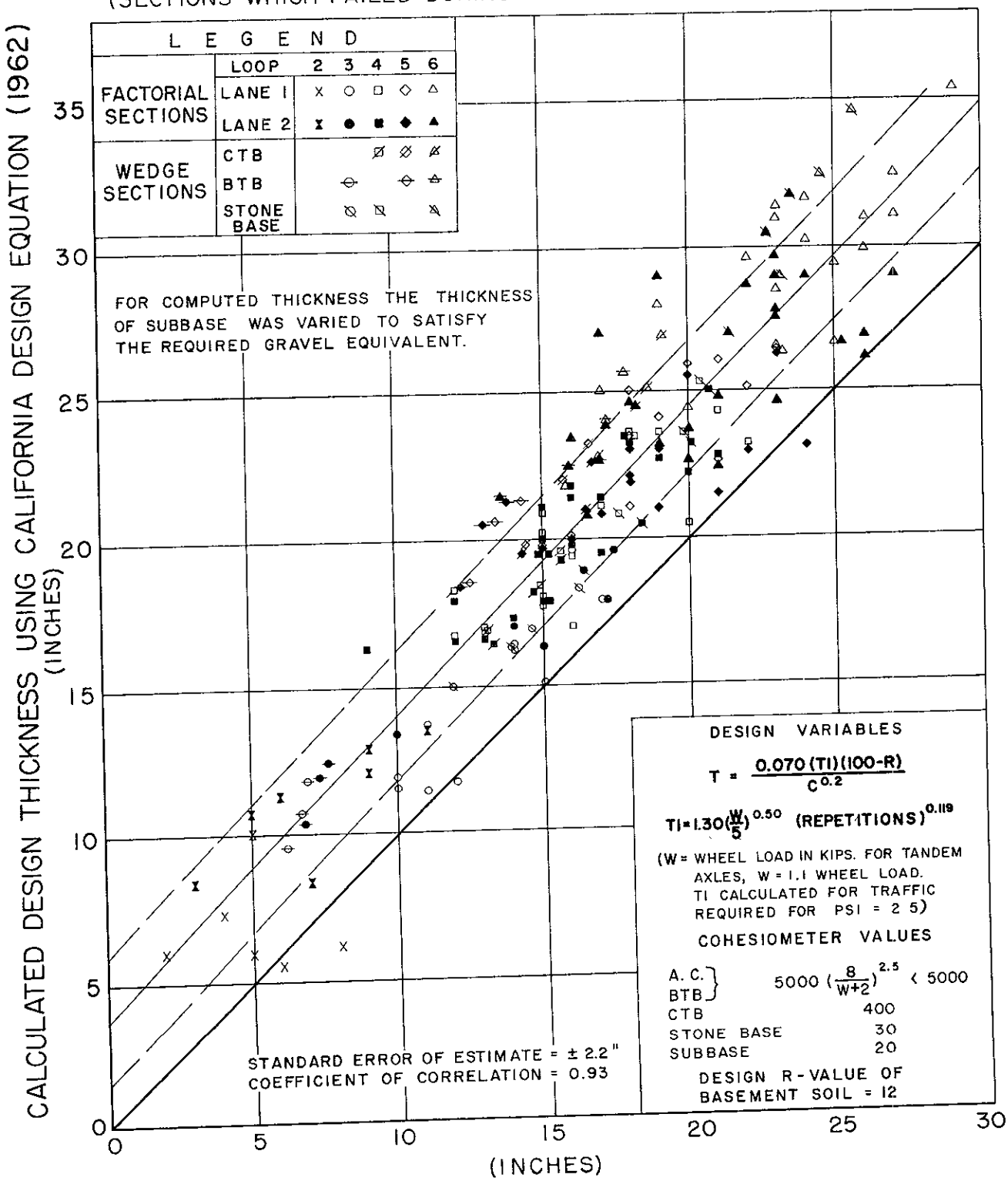
ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 9

THICKNESS OF TEST SECTIONS AT AASHO TEST ROAD VS. CALCULATED DESIGN THICKNESS USING CALIFORNIA DESIGN EQUATION (1962)

(SECTIONS WHICH FAILED DURING FIRST SPRING THAW ARE OMITTED)

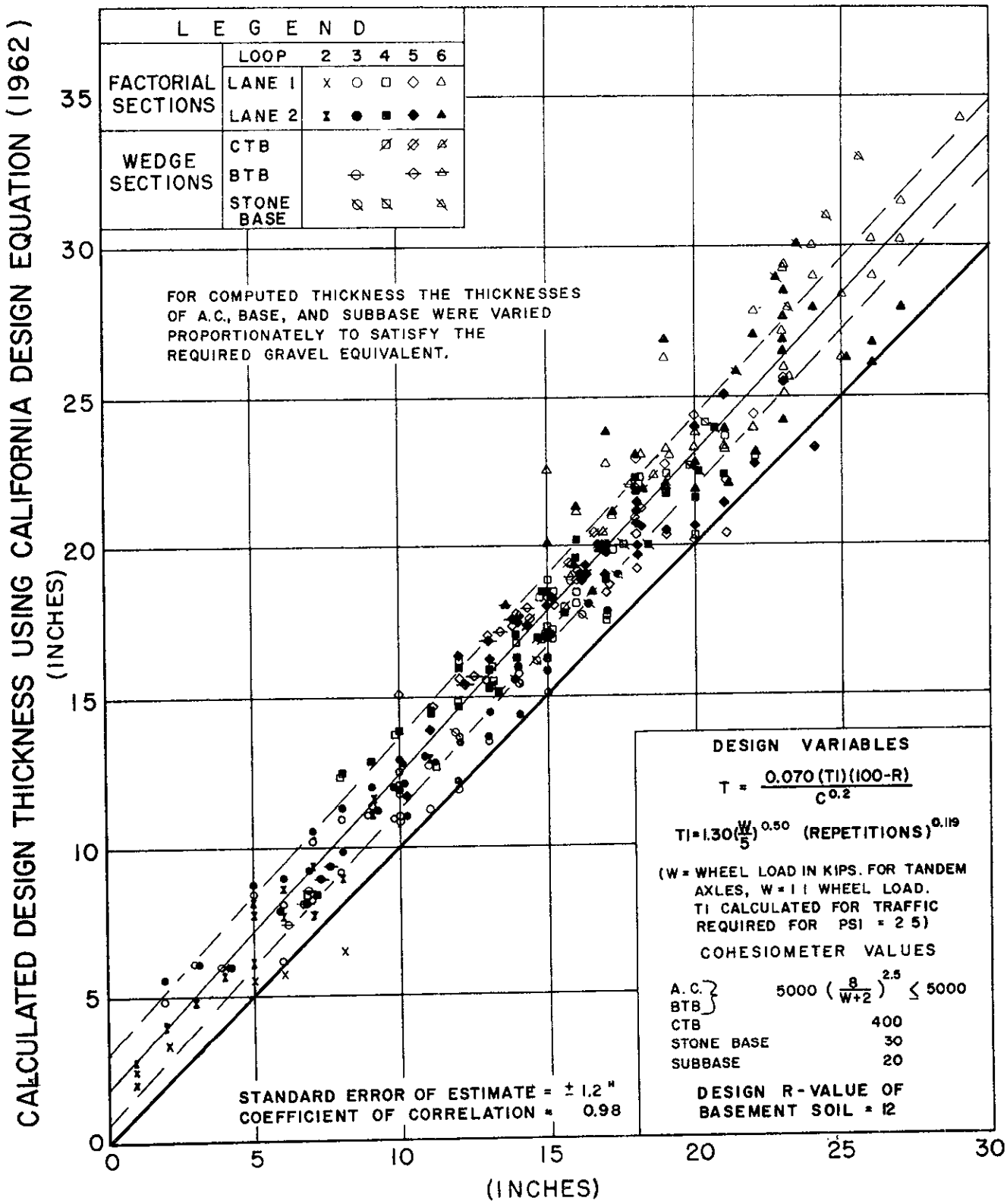


ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

Figure 10

THICKNESS OF TEST SECTIONS AT AASHO TEST ROAD VS. CALCULATED DESIGN THICKNESS USING CALIFORNIA DESIGN EQUATION (1962) (EQUIVALENT SECTIONS)

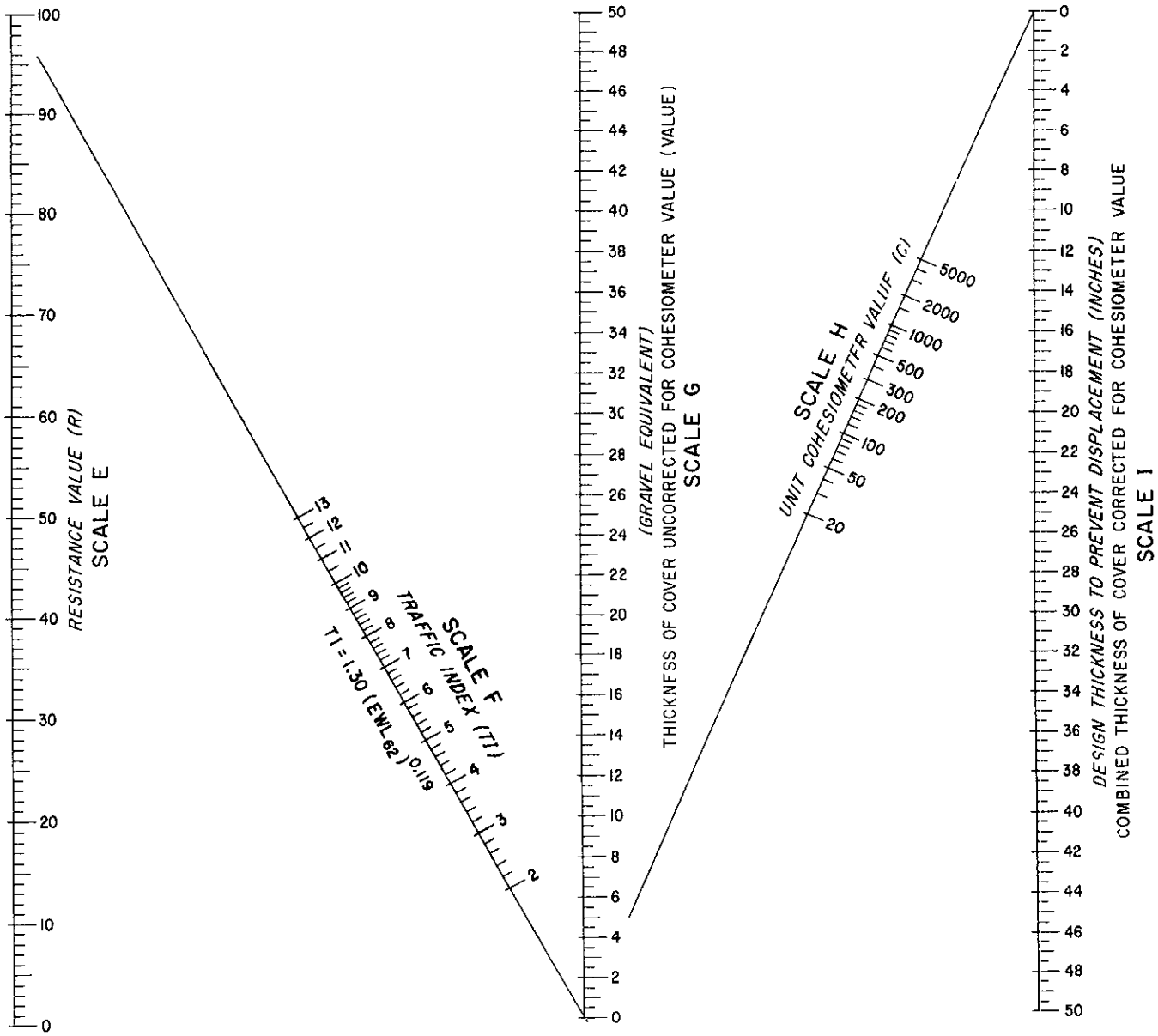


ClibPDF - www.fastio.com

F. N. Hveem
G. B. Sherman

FIGURE 11

$$T = \frac{0.070\,(TI)(100-R)}{C^{0.2}}$$



ClibPDF - www.fastio.com