Fundamental Factors In Incremental Cost Studies Of Pavements

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Incremental cost studies of highways have been in progress at Ohio State University for approximately two years. Certain factors related to pavement design prevent an "absolute" answer to incremental cost studies. These influences are discussed, and mention is made of the type of research needed to improve the accuracy of current incremental estimates.

The current report attempts to extend the work, previously developed for Ohio conditions, to more general application. A formula for general application is discussed, along with the assumptions and the qualifications required to apply it.

● RESEARCH STUDIES involving incremental costs of highways in Ohio have been under way for the past three years at the Engineering Experiment Station of the Ohio State University. The work has been made possible through research grants from individuals and groups active in the trucking industry. During the first two years of these investigations, special emphases were placed on the amount of taxes paid by various highway user groups and incremental costs of pavements. Two bulletins covering these studies were published by the Engineering Experiment Station (*1*, *2*).

At the conclusion of the two studies, additional funds were made available to study the incremental costs of the remaining items of the public costs of highways. The portion of the study covering incremental costs of structures has been prepared by Lindley (*3*). Completed analyses are scheduled for August, 1957.

The philosophy of the incremental studies at Ohio State is based on the assumption that obtaining absolute values is not practicable because of the many unknown relationships and intangible factors. This does not mean that engineers and economists charged with the responsibility of developing reliable estimates have been derelict for stating precise values. On the contrary, such men are paralleling all other engineering practice; that is, developing the best estimates possible under the given conditions and for the assumptions that are required. In line with the stated philosophy, all incremental analyses are on the basis of "bracketing" the true value, and maximum and minimum curves are used. These curves do not represent the maximum (or minimum) value that is possible for differential pavement costs; rather, the maximum and minimum relationships for the statistical "average" for the state.

In conducting the pavement studies, the inadequacy of current knowledge of pavement design became quite pronounced, and the influence of some of these factors on incremental costs was quite evident. The purpose of this paper is to delineate these areas of inadequacy, to indicate their importance on incremental costs of pavements in Ohio, and to suggest a general formula for use in pavement incremental cost analyses.

INTANGIBLE FACTORS

Several intangible factors create considerable difficulty in incremental studies of pavements. One of the more general implications comes from charts similar to that in Figure 1 which have been used to suggest the relationship between

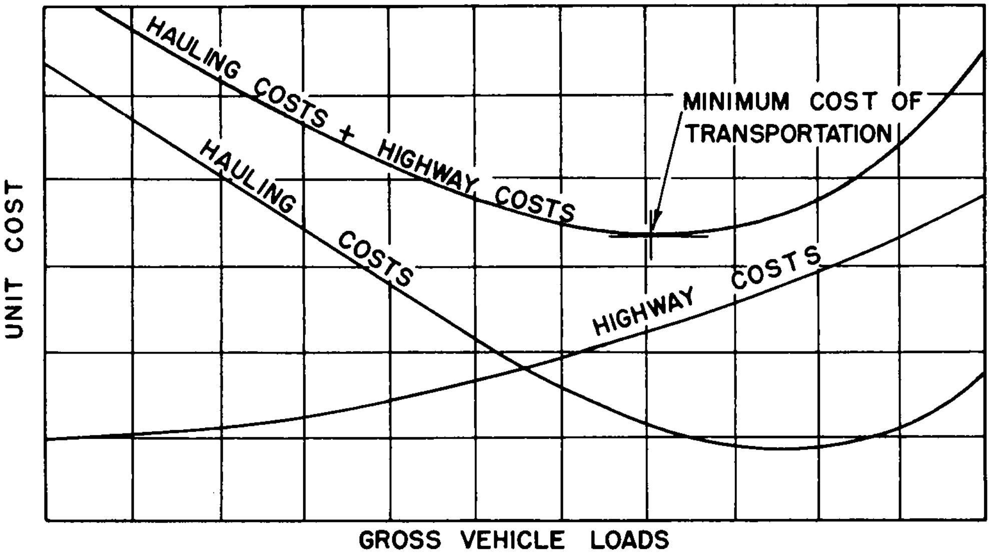

Figure 1. General relationships between unit cost and gross vehicle loads.

vehicle size and unit costs (public and private). Most frequently, the intersection of the two curves has been suggested as the "break-even" point. Presumably, this was done under the assumption that to increase highway costs beyond this intersection would not be beneficial to the operators of those vehicles producing the added cost. However, under the theory that the minimum total cost of transportation is the desired point of balance, the intersection of the two curves may not be the point of interest. If the latter theory were adopted, the question requiring ultimate resolution would be who is responsible for the added cost if the minimum point were to the right of the point of intersection.

There are two plausible methods for developing incremental costs. One technique consists of developing the best theoretical relationship between vehicle size and highway costs, and the other assumes that costs should be incremented on the basis of the approach used in design. Thus, for the latter procedure, if an error is made in design due to an overestimate (or underestimate) of the requirements for a larger vehicle, the cost responsibility is as much the responsibility of the larger vehicle as if the overestimate (or underestimate) were theoretically sound. The two methods are exactly the same if the design procedure parallels the best theoretical approach.

The interrelation between highway costs and the cost generators is involved with a complex, interwoven group of factors. A qualitative description of the interdependency has been suggested (*2*). However, each of the following general influences, which are not necessarily fixed, has a direct bearing on the development of precise incremental costs: (a) safety and convenience, (b) available funds, (c) future developments (construction and maintenance equipment, commercial vehicles, etc.), and (d) laws and their enforcement. It is quite obvious that assumptions must be made with regard to each of these types of factors, and that the assumptions made will have an appreciable influence on the incremental cost values obtained.

One of the most troublesome features of incremental cost analyses of pavements is the absence of a rational method of design. Without such techinques, any effort to relate vehicle load characteristics to pavement cost is destined to be an estimate with a questionable degree of accuracy.

For rigid pavements, the problem appears less complicated than for flexible types, because highway designers have generally accepted the methods based on Westergaard's theories (*4*). However, inability to evaluate the subgrade reaction on a theoretically sound basis has prevented a truly rational design for rigid slabs.

For flexible pavements, the technique utilized in design is much more varied. Most of the methods employ purely empirical relationships. The Highway Research Board's Committee on Flexible Pavement Design found by a questionaire (*5*) that very few states employed the same design criteria. In fact, there were 9 different methods used for evaluating traffic, 11 distinct ways of accounting for climate, 29 separate types of subgrade evaluation, and similar variations in determining strengths and quality of wearing courses, base courses, and sub-base courses. A recent report covered varying design solutions for the WASHO Test Road (*6*).

The complexities of pavement design are well understood, even though a completely rational approach has not been developed. Basic relationships between variables have been expressed qualitatively in many different fashions in recent years (*2*, *7*), and continued efforts have produced fundamental progress in pavement design technology (*8*, *9*, *10*).

In the absence of fundamentally sound relationships, engineers responsible for incremental analyses must resort to an examination of the influence of various basic factors. By so doing, one can judge whether a given factor is critical with regard to differential costs. For example, a given variable may create a difference in total cost requirements for a pavement designed to a certain standard, but may not cause the same degree of variation in incremental analyses.

MAJOR INFLUENCES ON PAVEMENT COSTS

The three major variables in pavement design are load, pavement thickness, and subgrade support. All design criteria are centered around these factors. The following discussion is included to show how variation in treatment of these major variables can influence pavement thickness (or cost).

Design Criteria

Many pavement design techniques employ families of curves based on load-subgrade support relationships. Rarely, however, does one find a plot of load versus pavement thickness for the same type of soil. One of the early reports covering this latter consideration was made by Benkleman (*11*). Figure 2 is adopted from a figure in Benkleman's report. One will note quickly that for various criteria, thickness requirements range from 15 to 20 in. for a 9000-lb wheel load; for a 4000-lb wheel, the range is from 7 to 13 in. These variations occur even though the subgrade support and the pavement strength characteristics are assumed to be the same.

On the other hand consider the incremental values. For the California method, the increase in thickness required to support a 9000-lb rather than a 4000-lb wheel is from 13 to 19 in. or an increase of 6 in. For the North Carolina method, the increment is from 9 to 15 in., or the same differential of 6 in. For the steeper sloped curves represented by the Canadian criteria, the differential is from 7 to 19 in. or an increase of 12 in. Thus, for the range of criteria used by Benkleman, the differential thickness requirement between 4000 and 9000-lb wheels is between 6 and 12 in.

For small load increments, however, the range of probable increase of pavement thickness is considerably less. For example, for the California method to increase the wheel load from 8000 to 9000 lb would require 1 to 2 in. of additional pavement thickness; whereas by the Canadian method a similar load increase would take only 2 to 3 in. more pavement. The small variation in this size increment gives a more encouraging picture.

The important consideration, however,

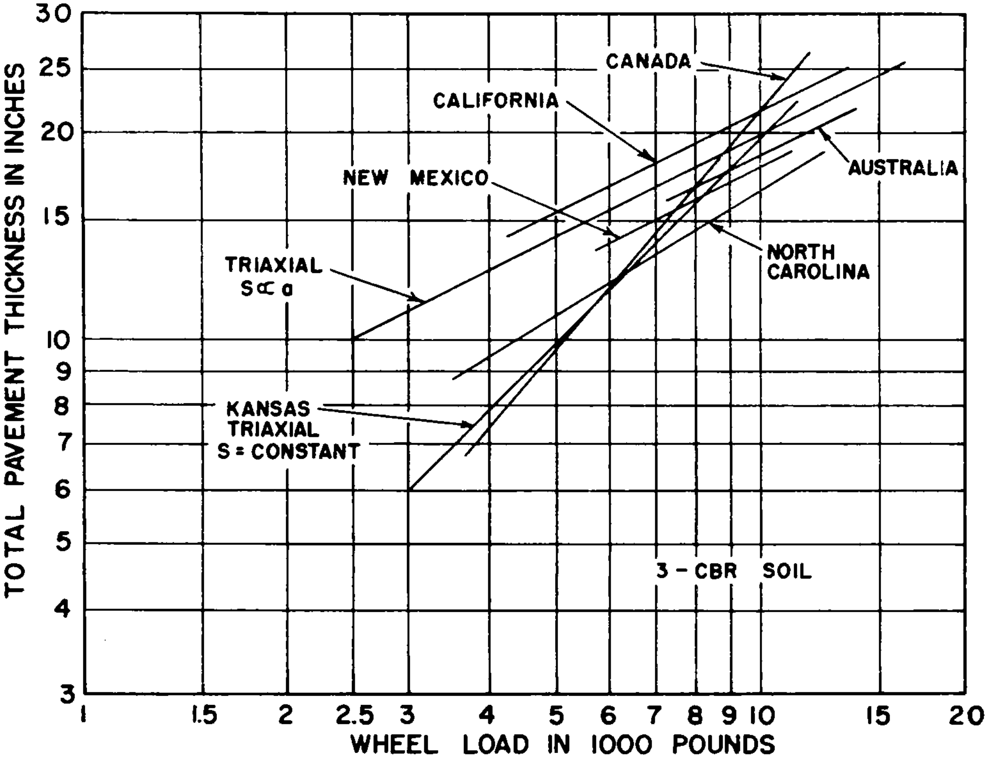

Figure 2. Load-thickness relations for highway loading (courtesy Engineering Experiment Station, University of Utah).

is that a 6-in. difference in pavement thickness can be produced by merely varying the design technique employed.

Soil Support

Relationships similar to that developed by Benkleman (Figure 2) were produced in the studies for design methods applicable to Ohio. A range of poor, medium, and good subgrade support was assumed. Typical of these data are the curves shown in Figure 3.

Using comparisons similar to those in the preceding section on design criteria, the pavement thickness requirement for a 9000-lb wheel load is 21, 15, and 9 in., respectively, for a poor, medium, and good soil. For the same soils and for a 4000-lb load, the variation is 15, 10, and 6 in., respectively. Thus, the total thickness required by a single design criterion can vary as much as 12 in. for a 9000-lb wheel depending upon the type of subgrade. For a 4000-lb wheel, the range in pavement thickness is 9 in.

It is apparent from the preceding comparisons that the degree of subgrade support can materially influence the total thickness requirements. As to incremental thicknesses, the increase in load from 4000 to 9000-lb wheels produces a change of 6 in. for a poor soil and only 3 in. for the good soil. Similar results can be obtained for the other design criteria.

Of special importance, then, is the fact that the type of subgrade support can produce a major variation in pavement thickness requirements. As to incremental costs for "average" conditions within a state or a larger region, the value developed for pavements will vary with the type of subgrade support assumed.

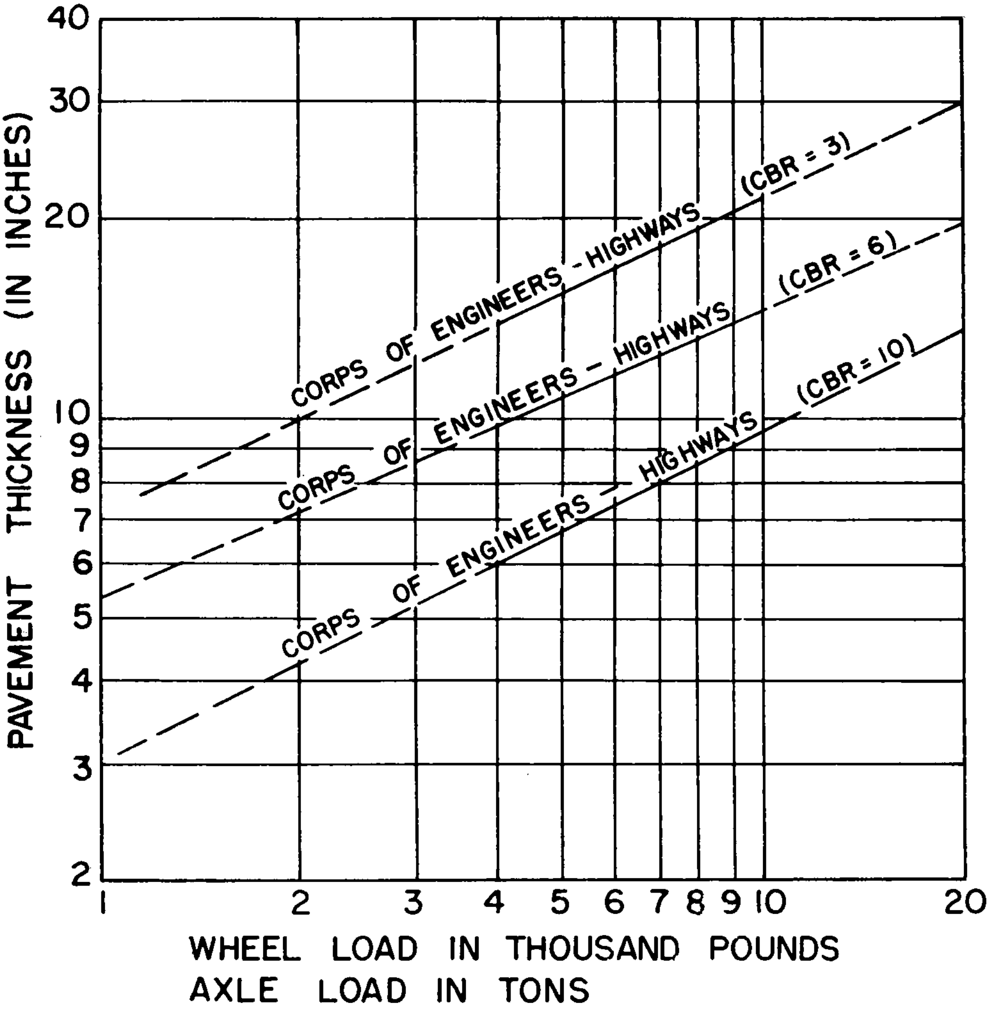

Figure 3.

Basic Vehicle

A common assumption among highway engineers is that a certain minimum pavement thickness is required on any road to withstand climatic conditions and to meet current economical construction standards. The basic vehicle normally refers to the largest vehicle for which the maximum wheel load does not require more than this minimum pavement thickness.

There is a difference of opinion, however, as to the size of the basic vehicle. In Pennsylvania (*12*), a 2000-lb axle was used, whereas Pancoast (*13*) in Ohio used the more frequently mentioned value of a 4000-lb axle. Fundamentally, the basic vehicle is a factor of (a) the minimum pavement thickness required to withstand soil and climatic conditions, (b) the minimum pavement thickness required for practical construction, and (c) accuracy limitations of pavement design theories. (That is, design theories are sufficiently accurate to permit evaluation of only the heavier axle loads.)

No effort was made at Ohio State to determine the proper value for the basic vehicle. It is obviously a complex variable, related to statistical averages of soil and climate factors. Considering the possibilities of 2000- and 4000-lb wheels for the basic vehicle, and using one design criterion and one type of soil (poor), Figure 3 shows that 10 and 15 in., respectively, would be required for the two loads. The difference of 5 in. obtained in the preceding paragraph indicates that incremental pavement cost can be affected materially by the size of the basic vehicle that is established.

Load Repetition

The influence of load repetition is important from the viewpoint of "fatigue" failures, as well as being necessary if incremental costs are to be reduced to a unit vehicle basis. Some pavement design criteria have empirically related the repetitional factor.

For the design of primary highway pavements, use has been made of the average daily traffic (ADT), of adjustments to the ADT depending upon the number of commercial vehicles, and of a system based upon the equivalent wheel load (EWL), (*14*).

With the exception of the EWL method, most criteria utilizing load repetition imply that unlimited repetitions of the legal load can occur without failure (assuming a normal distribution of heavy loads in the ADT). For the EWL technique, the following factors are normally assumed:

Axle Load (tons)	Factor	Axle Load (tons)	Factor
5	1	9	16
6	2	10	32
7	4	11	64
8	8	12	128

Thus, one 9-ton axle would require a design equivalent to that needed for sixteen 5-ton axles.

For incremental cost purposes, the EWL procedure will result in differentials of the order shown in the preceding list as adjusted by the number of axles of various magnitudes. With the other repetitional criteria, the increments will be quite variable, and more dependent upon the number of loads of various magnitudes. Thus, if one additional inch of pavement is required for 9-ton axles as compared to 8-ton axles, the unit vehicle cost responsibility can vary considerably, depending on whether 1000- or 100,000-lb axles are involved.

The repetitional effect is involved, too, with considerations of low-traffic highways. Thicknesses of this type of road are decided through a completely empirical approach. Much thinner pavements are used with thicknesses of 4 to 8 in. being common, as compared to 12 to 16 in. on the primary routes. The thinner pavements can and do carry a limited number of the heaviest legal axle loads, and for a much lighter load an unlimited number of applications can be sustained. The restriction on use by the heavy loads is normally not a legal one, rather one of road use. The question to be resolved is whether the occasional heavy load is responsible for part of the costs. Pancoast (*13*) assumed that it is not. Methods for estimating incremental costs under the assumption that all vehicles on low traffic roads share cost responsibility have been suggested by Baker and Karrer (*2*).

Thus, within the factor of load repetition, there are uncertainties that can lead to a range of estimates for incremental costs.

Quantities of Pavement Items

The quantity of pavement materials used on a given construction project is known to have an influence on unit costs; that is, with greater quantities, a reduction of unit costs is expected. Aside from the effect of thickness on these quantities, the pavement length and width are also of concern. In the Ohio State studies (*2*), it was shown that with increased width there is an increase in incremental cost per mile. This increase was one that resulted solely from the greater expenditures caused by thickness requirements, and did not involve any consideration of the argumentative problem dealing with pavement width versus vehicle size.

As to the pavement length, if the geometrics of the highway are improved so as to reduce the over-all length of the road, incremental pavement costs per mile will be reduced. Again, this will result because of a reduction in the amount of extra thickness required by the heavier axle loads.

In summation of the influences of pavement quantities, incremental pavement costs per mile will increase if higher pavement widths are used and decrease if better geometrics are employed. These comparisons exclude any consideration of the relationship between vehicle widths versus pavement width or vehicle performance (or length) versus geometrics.

INCREMENTAL PAVEMENT COST FORMULA

The discouraging picture presented in the preceding discussion has been prepared to emphasize the state of the knowledge of pavement design. Much more could be written on other phases of the same problem. Therefore, solutions to incremental pavement cost studies are necessarily based upon sweeping assumptions. The degree of accuracy achieved by such solutions will be an unknown factor, but confidence in the result can be materially improved by an understanding and proper interpretation of the fundamental variables.

The studies required the development of an estimate of incremental pavement costs for Ohio. Many of the factors were circumvented in recognition of the inherent weaknesses to various approaches. The system employed was a maximum and minimum relationship rather than a single curve. This latter requirement was not within the scope of the studies. A method was developed for estimating differential pavement costs (*2*) and in the following pages an expansion of the method to more general application is suggested.

One of the striking facts immediately apparent from Figures 2 and 3 is the slope of the straight-line relationship of total pavement thickness versus axle load on a log-log plot. Similar data were developed for rigid pavements using the Portland Cement Association design curves (*15*), and the entire set of data were converted to pavement costs per mile for Ohio conditions. The relationships for a "poor" type of soil are given in Figure 4. A rather surprising factor is that the slope relationships appear to remain fairly constant over a wide range of soil and pavement types.

No great concern was felt because the individual points of Figure 4 failed to describe a perfectly straight line. Contributing to any such discrepancy were the design of pavement components, the abrupt change of thickness caused by rounding to the nearest inch, and the ranges of unit costs that were used.

The straight-line relationship for any of the curves included on the log-log plot of Figure 4 is

$$P = CW^{s} \qquad (1)$$

in which

P = pavement cost required for a given axle load, in \$1,000-per-mile units;
C = pavement cost for the primary axle load, in \$1,000-per-mile units;
W = weight of a given axle load, in tons or as a ratio between the axle and the primary axle; and
s = slope of the line.

Eq. 1 can be used to estimate the cost of a pavement to carry any axle if C and s are known. Inasmuch as the cost requirement for any axle load is a questionable estimate, the equation will be most useful if the cost of providing a pavement for 10-ton axles is accepted as the definition of C, and W is expressed in terms of 10-ton axles. Thus, Eq. 1 would be

$$P = C_{10}W^{s} \qquad (2)$$

In Eq. 2, the value of W for 9-ton axles would be 0.9; for 8-ton axles, 0.8; etc., and C_{10} would be the cost per mile for a pavement to carry 10-ton axles. If 9-ton axles are preferred for the primary axle load, other axles must be expressed as a ratio of the 9-ton value.

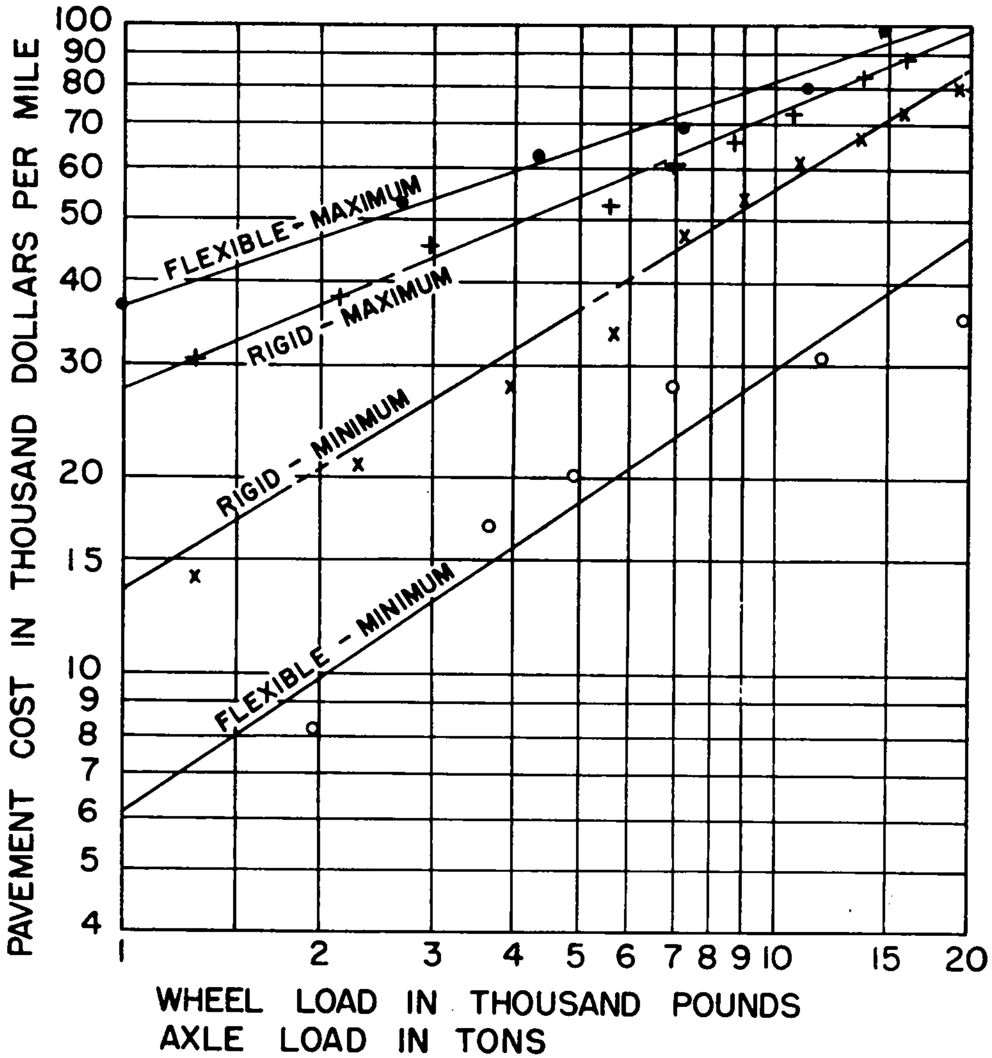

Figure 4.

With proper cognizance of the assumption made, and with evaluation of the design criteria applicable to an area, Eq. 2 should have general application. The accuracy of the results can be questioned since a rational method of design is not available. However, the results should be as good as the current design formulae.

The following represent important assumptions that must be made to apply to Eq. 1 or 2:

1. That the log-log plot of pavement thickness vs. axle load can be approximated by a straight line.
2. That thickness can be converted to cost without seriously disrupting the straight line relationship.
3. That a reasonable estimate can be made of the cost requirements for some magnitude of axle load.
4. That a reasonable estimate for s can be made.

The slope of the straight line varies

with the amount expended per mile for the pavement. The subgrade support is a major factor in such considerations. By preparing data for other soils, curves similar to those of Figure 4 were obtained, and the following direct relationship between C and s of Eq. 1 and 2 was indicated:

$$s = m^{C} + n \qquad (3)$$

The value of m and n are constants depending primarily upon the type of subgrade support.

For conditions in Ohio, m and n of Eq. 3 were estimated for three types of subgrade. It should be noted that the relationship between costs of pavement components as well as the types of materials included as components have an influence upon m and n. However, the effect of subgrade support is so predominant that within the range of accuracy of estimates obtained by Eq. 1 and 2, the influence of pavements components can be safely neglected. Values of m and n are given in Table 1, and general applicability is considered as feasible.

By the use of the data in Table 1, equations of the form of 1 and 2 can be solved if the pavement requirement cost of the primary axle load and the type of subgrade is known. For example, if fair subgrade support is to be expected, and if the cost of providing 2-lane pavement for a 10-ton axle load is $62,000 per mile, Eq. 3 can be used with data from Table 1 to solve for s:

For the values of $C = 62$, $m = -0.0112$, and $n = 1.04$, $s = -0.0112 \times 62 + 1.04 = 0.35$. By interpolation in Table 1, s can be obtained directly as 0.35. Substituting into Eq. 2:

$$P = 62W^{0.35} \qquad (4)$$

Eq. 4 can then be used to solve for the pavement cost required for any other axle load. For example, for a 12-ton axle load, $W = 1.2$ (ratio of 12:10), and substituting in Eq. 4 gives

$$P = 62\ (1.2)^{0.35} = 66$$

Therefore, the cost of providing a pavement for 12-ton axles is $66,000 per mile.

If the log-log plot of pavement thickness vs. axle load is as steep as that produced by such design criteria as indicated by the Kansas and Canadian method (Figure 2), the data in Table 1 will not apply. Similar data can be computed, however.

A general expression for incremental costs can be obtained by the use of Eq. 2 and 3. Assuming that D is equal to the differential in costs between P_1 and P_2 that is required by axle loads of W_1 and W_2, respectively, then:

$$D = P_2 - P_1 = C_{10}W_2^{s} - C_{10}W_1^{s} \qquad (5)$$

$$= C_{10}(W_2^{s} - W_1^{s}) \qquad (6)$$

Furthermore, if W_1 is assumed to be equal to unity (10 tons), then Eq. 6 becomes:

$$D = C_{10}(W_2^{s} - 1) \qquad (7)$$

From Eq. 3:

$$D = C(W_2^{mC + n} - 1) \qquad (8)$$

Therefore, Eq. 7 can be used to obtain the differential costs between pavement requirements for a 10-ton axle and those for any other axle load, provided the pavement costs for 10-ton axle loads are known and that the values of m and n are known (Table 1).

CONCLUSIONS

The following variables will have a marked influence on the values obtained in pavement cost studies:

1. The design criteria used in the analyses should be evaluated for the area under study, since different design techniques will not produce the same pavement thickness requirements. The variations can be as great as 12 inches for the same load and soil conditions. However, the design criteria may not be so critical insofar as incremental pavement costs are concerned.

TABLE 1
VALUES OF C_{10} AND S

C_{10}*	TYPE OF SUBGRADE		
	Poor (CBR = 3) $m = -0.0078$, $n = 0.78$	Fair (CBR = 6) $m = -0.0112$, $n = 1.04$	Good (CBR) = 10) $m = -0.0126$, $n = 1.12$
	s	s	s
110	0.12	—	—
100	0.19	—	—
90	0.27	0.04	—
80	0.35	0.15	0.12
70	0.43	0.26	0.25
60	0.51	0.37	0.37
50	0.58	0.48	0.49
40	0.66	0.59	0.62
30	0.74	0.70	0.74
20	0.82	0.81	0.86

* Cost in units of $1000 per mile for two-lane pavement; maximum of 24 ft in width.

2. The amount of subgrade support markedly affects both total and incremental pavement costs. The poorer the soil, the greater will be the pavement thickness required. Therefore, incremental cost studies for a given locale, will require statistical methods for developing the average subgrade type to be applied in the analyses.

3. The size of the basic vehicle will influence the magnitude of incremental pavement cost values. Statistical analyses should be used to provide a satisfactory interpretation of the influence of climate and construction practice on the selection of the basic vehicle.

4. The incremental cost relationships are greatly influenced by the number of loads applied and yet the effect of a given load or series of loads is not predictable with any degree of accuracy. Much research is needed in this field.

5. In addition to structural thickness, pavement quantities are a function of the roadway width and length. The quantity relationship to incremental costs is such that with added roadway width, the incremental values are increased, whereas for shorter lengths (better geometrics) the cost differentials are reduced. These influences are based upon the extra thickness requirements for the heavier loads, and exclude the controversial problem of pavement width versus vehicle width, and pavement geometrics versus vehicle performance.

For estimating incremental pavement costs if (a) pavement cost requirements per mile are known for one axle load and (b) the type of subgrade support can be predicted, the following is suggested:

$$D = C_1 \quad (W_2{}^{mC_1 + n} - W_1)$$

in which

D = incremental pavement costs per mile for axle loads W_1 and W_2 in $1,000 units;
C_1 = pavement cost per mile for axle load W_1 in $1,000 units;
W_2 = axle load to be compared, as a ratio of W_1;
W_1 = axle load for which pavement cost per mile is known, expressed as unity ($W_1 = 1.0$); and
m and n = constants depending on type of subgrade support (see Table 1).

The formula is based upon a number of standard design criteria and is considered valid within the limits of accuracy of the design methods. It can be applied to either rigid of flexible pavements. Use of the formula implies that certain assumptions are valid, and the effect of the assumptions should be evaluated for the area under consideration.

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