OBJECTIVE III

TO DETERMINE THE EFFECT OF VARIOUS SOURCES OF MATERIALS USED IN THE PROJECTS ON THE PERFORMANCE CHARACTERISTICS OF THE PAVEMENT

ANALYSIS OF CONSTRUCTION, MATERIALS, AND ENVIRONMENTAL VARIABLES

Once construction, materials, and environmental variables have been classified into levels or categories, one can examine the differences in performance (as measured by I, D, PRF, or PSI). In the present study, PRF and I were used in a statistical test (analysis of variance) designed to evaluate performance differences in terms of the random fluctuations of measurement always present in field examinations of this type. The variables listed below were examined as potential causes of pavement deterioration.

Average Yearly Rainfall

The geography of the State was divided into regions of high yearly rainfall (above the median) on the basis of all available weather station data. Projects were classified according to their geographic region to allow comparative examination of their performance.

Average Daily Temperature Differential

A method of classification similar to that for average yearly rainfall was applied to separate geographic regions of relatively high and low average daily temperature changes.

Contractor

In an attempt to determine if the contractor's workmanship had a significant effect on subsequent pavement performance, the Construction Division was requested to rate 34 paving contractors performing work on projects under study into three categories, "excellent," "good," and "fair." It was suggested that this rating should be based on workmanship during the period of 1947 through 1954 when these projects were under construction. The Construction Division rated 12 contractors in the "excellent," 10 in the "good," and 12 in the "fair" categories.

Subgrade

Each project was located on a state trunkline map over which was superimposed a map indicating regions of good, fair, or poor subgrade. Each project was assigned a value of 1, 2, or 3 according to the category shown on the map (Fig. 42). If a project did not lie exclusively within any one of the categories it was handled in either of two ways: 1) if 90 percent of the project was in one category location, it was given that category, or 2) if less than 90 percent was located in any one category, all pertinent grades were recorded.

Construction Period

Median construction dates (the date halfway between the earliest and latest concrete pour dates for each project) were divided into two categories--those falling in the summer months of June, July, and August, and those falling in the remaining months prior to, or subsequent to, the summer months.

Average Daily Commercial Traffic

The median of all commercial average daily traffic volumes was used to delineate "high" and "low" traffic categories. Traffic survey data were available only for 1947, 1955, 1957, and 1961, the years used to produce the overall average value for each period.

Coarse Aggregate

A convenient aggregate classification in the present study is made available through carbonate content tests. Carbonate content tests were not available from the aggregate incorporated in the construction projects. However, in subsequent years after construction, coarse aggregate from various pits was sampled and carbonate content tests were conducted. Even though these tests were pit samples taken some years after the pit aggregate was used in construction, it was felt that the carbonate content was reasonably representative of that used in the construction project. Aggregate categories based on estimated carbonate content provide the basis for classification and subsequent performance evaluation. These categories were 80-100 percent carbonate and 0-60 percent carbonate.

Figure 42. Distribution of subgrade types, Lower Michigan.

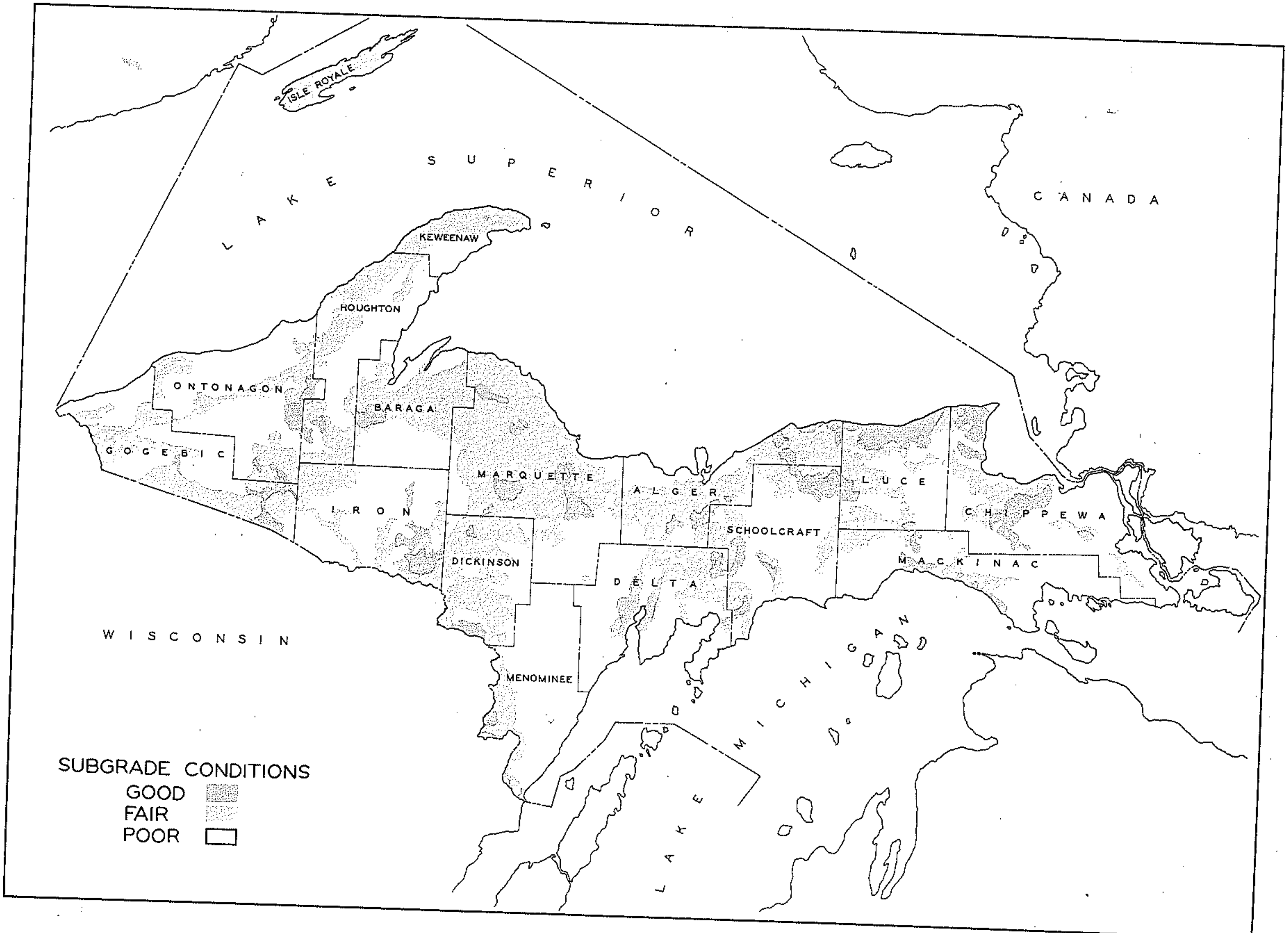

Figure 42 (cont.). Distribution of subgrade types, Upper Michigan.

DISCUSSION OF RESULTS WITH GENERAL PERFORMANCE INDICES

A general analysis of variance suggested the existence of relationships between average daily commercial traffic (ADCT), coarse aggregate, and deterioration, I. As shown in Figure 43, gravels containing high proportions of carbonates and aggregates composed of pure crushed limestone or dolomite perform best (generally lower I values) over the fifteen-year service period. At fifteen years of service, the average I is about 2-1/2 times greater for those projects built with gravels of relatively low carbonate content. More refined examination of these aggregate groups shows that further subdivision is possible: of the projects constructed with aggregates containing 80-100 percent carbonates, those using 100 percent pure crushed limestones and dolomites which were studied here had the smallest I values. Also, the pure gravels containing no carbonates performed a bit better than other aggregates in the 0-60 percent carbonate group. This suggests that aggregate heterogeneity and not merely carbonate contents more closely associates with pavement performance.

A rough attempt to quantify this possibility was made using the following formula:

$$H = \sin (P\pi)$$

Where H is defined as heterogeneity, and P is the proportion of carbonate in the coarse aggregate. Thus, 100-percent pure crushed limestone and 100-percent pure igneous rock gravel will have an H value of 0.0, while an aggregate composed of 50 percent carbonate and 50 percent other rock types will have the maximum H value of 1.0.

Figure 44 shows that, in general, performance tends to deteriorate as carbonate-gravel heterogeneity increases. This is especially the case after fifteen years of service where aggregate classes show wide performance variance. However, very general graphic comparisons, such as those just discussed, are rarely sufficient in themselves to pinpoint the causal mechanism involved. Clearly, many local conditions such as faulty joint construction, subgrade support, etc., relate to each particular case and type of deterioration and one cannot generally speak of one cause alone.

Moreover, even if a single factor is identified, it may not be causally important, but only statistically associated with the real cause of poor performance. Because the relationship is empirical, the possibility always exists that the statistical finding is misleading; the real mechanism being masked by the complex interrelationship between statistically associated variables. The relationship of aggregates to performance is a case in point: the poorer performance of the heterogeneous aggregates could be due to the differential thermal expansion rates of the several components in the aggregate, or to some other variable associated with aggregate heterogeneity. Past research indicates that the latter possibility is more likely (4). Cherts, soft, non-durable particles, hard absorbent particles, etc., have long been suspected as causes of various kinds of pavement deterioration. The absorption and expansion properties of the materials

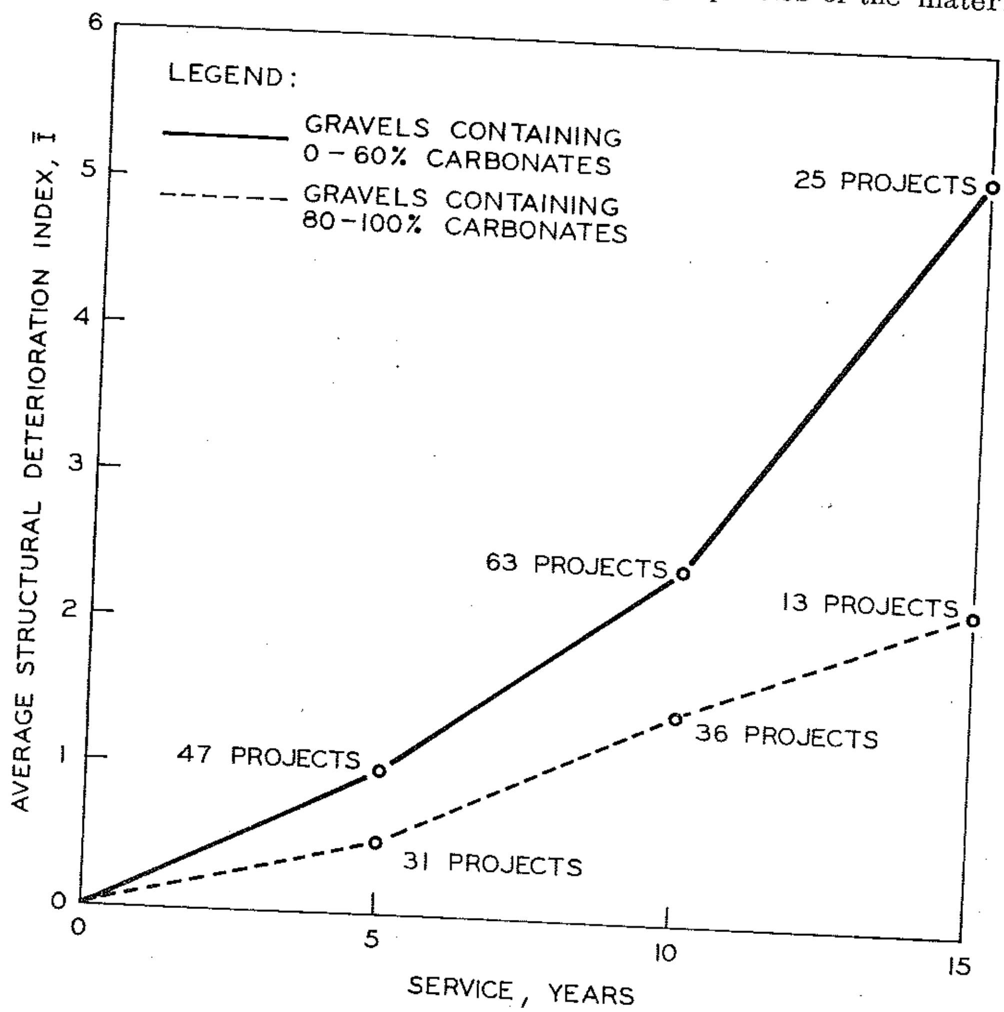

Figure 43. General performance as affected by two aggregate classes.

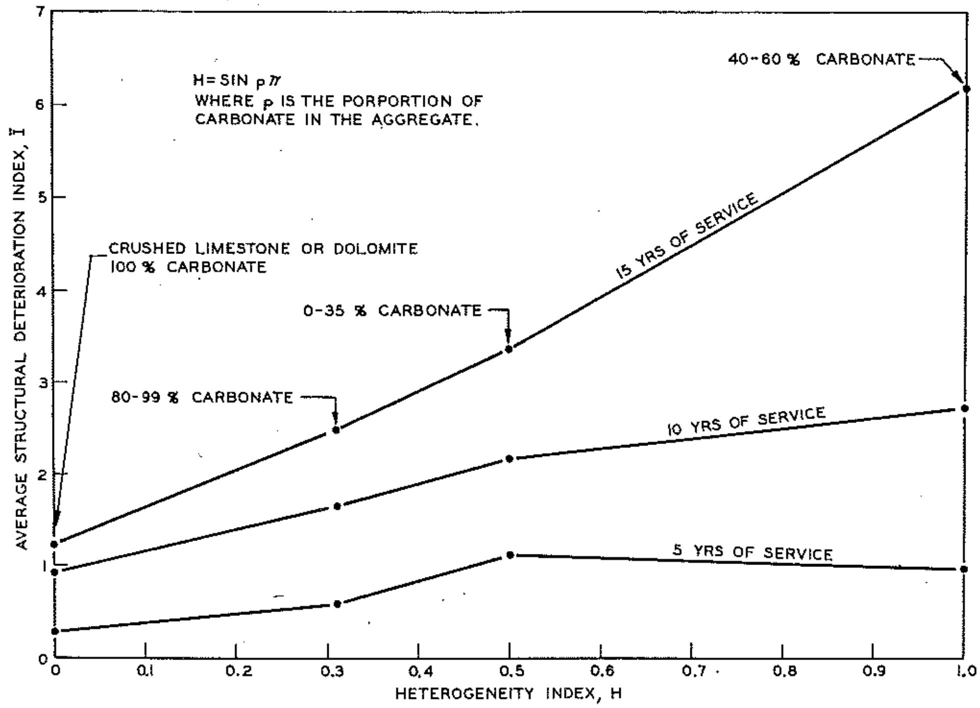

Figure 44. The effect of heterogeneity index on the structural deterioration index.

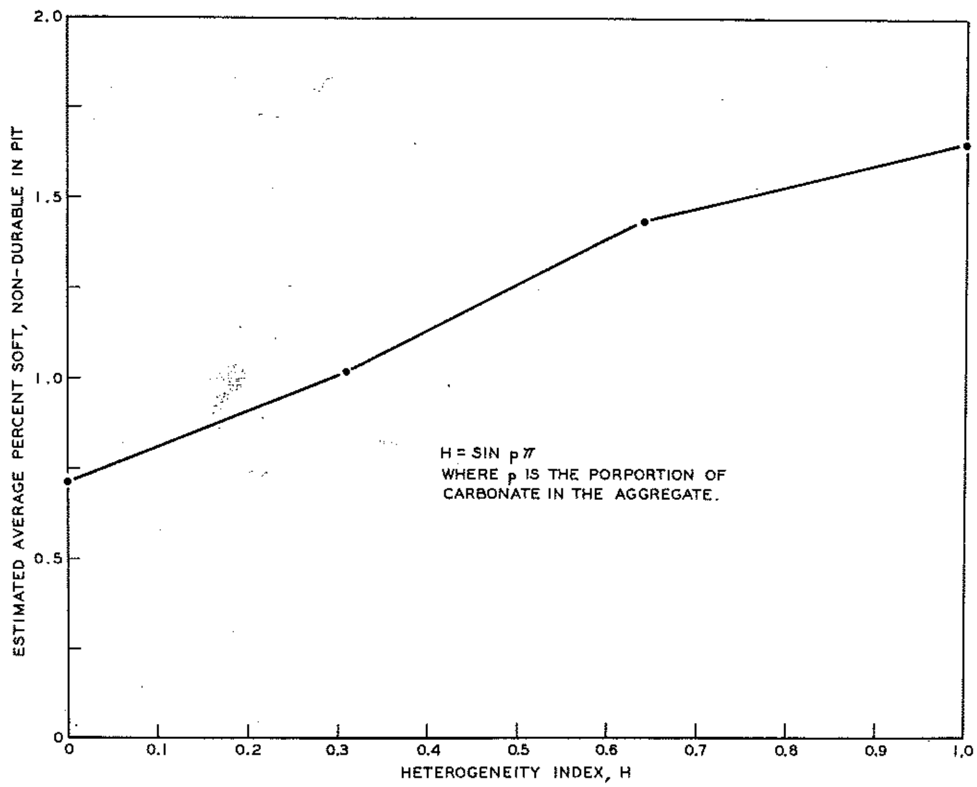

Figure 45. Relationship between coarse aggregate heterogeneity and soft, non-durable content.

have inspired attempts at performance forecasts through laboratory freeze-thaw tests. Soft, non-durables[4] seem to be present in Michigan's heterogeneous aggregates (Fig. 45) and may, as suggested by other research, be responsible for the structural performance differences encountered (5, 6, 7, 8).

These findings are similar to those of a blowup study to be discussed later which also shows a relationship between aggregate type and performance. Other investigators have also found associations between aggregates and various types of deterioration (9, 10, 11, 12). While the gravels and limestones could perform differently, past research indicates that the problem probably lies with the so-called deleterious particles found to various degrees in these aggregates.

Examination of Soft Particle and Chert Data

Because of past work in these areas, and the evidence shown in Figure 45, it was considered unlikely that the simple gravel-limestone aggregate classification used in the preceeding examinations would sufficiently define the performance-materials relationship. For this reason, PRF, I, and PSI values were examined in connection with available soft particle and chert information.

Projects for which field tests were available provided the basis for analysis. From these records, averages of test results for soft, non-durable and chert percentages were obtained and used as an estimate of the overall content of these materials in the coarse aggregate. Neither PRF, I, nor PSI showed significant dependence on the chert content; however, correlations appeared to exist between soft, non-durable content and PRF and I. Table 2 shows the results of a PRF analysis of variance on divided expressway for which soft, non-durable content and commercial traffic volume data were available. At the five-year service level, neither soft, non-durable content, traffic, roadway, or lane show PRF differences large enough to be considered significant.

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4 As defined by Michigan specifications, soft particles include shale, soft sandstone, ochre, iron-bearing clay, weathered schist, shells, floaters, partially disintegrated particles, cemented gravel and any other particles which are structurally weak or which fail to meet the soundness test. Michigan Specification for 4A and 10A aggregates used in concrete pavement: 3 percent maximum.

The ten- and fifteen-year PRF indices show noteworthy differences presumably due to traffic, lane, and soft content (see Table B-1, Appendix 2). Table 2 presents a summary of the percentage variance contributions attributable to the analysis variables and their interactions. Of special note is the sharp decrease in unexplained variance between contracts and lanes after the five-year survey period. The effects of soft, non-durables in the aggregate together with the overall and between-lane traffic patterns apparently become strong enough after five-years of service to account for much of the between roadway, contract, and lane variance. It must be remembered that because of classification restrictions, only four contracts (three service periods, divided roadways, and all four combinations of soft, non-durables and traffic values) have been herein examined. Consequently, these results are indications only; further analysis being necessary to establish confidence.

TABLE 2

COMPONENTS OF VARIANCE FOR PRF - (Divided Expressways)*

Years of Service	Percent Contribution to Total Performance Variance									
	Explained Variance							Unexplained Variance		
	Soft Non-durable	Traffic Volume	Soft-Traffic Interaction	Lane	Lane-Soft Interaction	Lane-Traffic Interaction	Lane-Soft-Traffic Interaction	Between Roadway	Between Contract	Between Lane
5	0	0	12	0	2	0	0	0	71	15
10	10	47	0	14	0	11	0	1	15	2
15	24	7	11	14	3	7	2	15	16	1

* Table B-1 (Appendix B) shows the full analysis of variance for the PRF. Table B-2 (Appendix B) shows the same analysis applied to 5-, 10-, and 15-year PSI data.

In general, (except for soft, non-durable at the fifteen-year level) the PSI index does not appear sensitive to the traffic or aggregate variables. There are slight differences, but again they are not large enough to be considered significant. It is known that the PSI depends largely on roughness (13), a performance measure only tenuously related to structural distress. This is because roughness is not particularly sensitive to such structural deterioration variables as transverse cracking because reinforcing has effectively prevented faulting. Also, other valuables such as corner and centerline spalling are generally not picked up by the roughometer wheel.

For graphical purposes, all projects were classified as to high or low soft, non-durable contents and high or low average daily commercial traffic (ADCT). The class divisions were based on the soft, non-durable and ADCT medians. Figures 46 through 51 show averages for five-, ten-, and fifteen-year periods of PRF, I, and PSI for the above classifications using

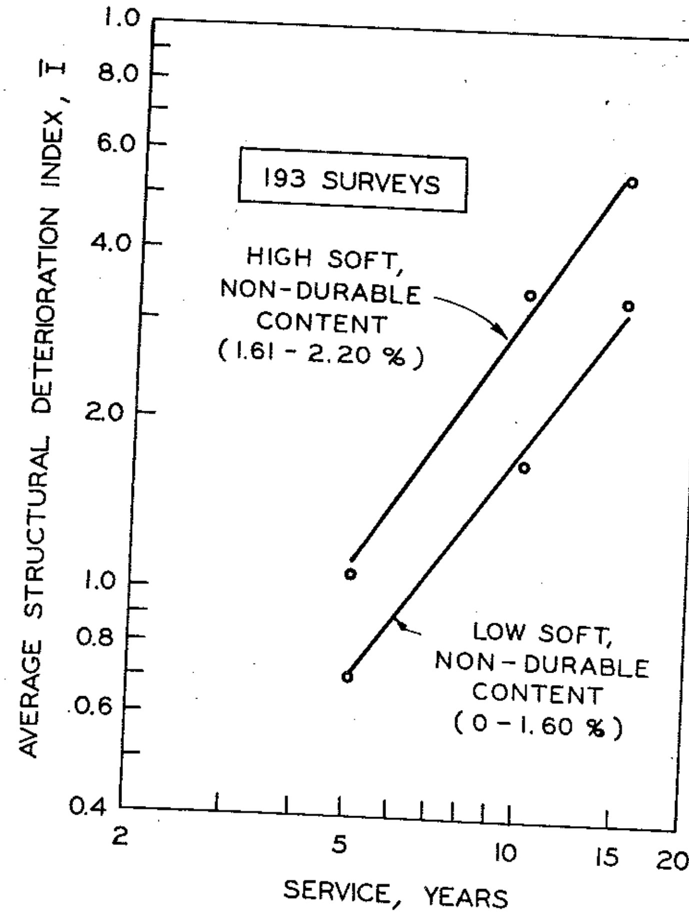


Figure 46. Average structural deterioration for projects with low and high soft, non-durable content.

data from all available non-divided roadway projects. Notice that low ADCT and low soft, non-durable values are associated with better performance for both indices. However, PRF and I are more affected than PSI. To show the effects in more detail, moving averages of I are plotted against both ADCT and soft, non-durable for the five-, ten-, and fifteen-year service periods in Figures 52 and 53. Log $\hat{I}$ appears to increase with both log soft, non-durables and log ADCT at about the same rate with each service period. These moving averages, while showing predominent trends, remove considerable scatter from the data--correlations are of the order of only 0.40 to 0.50. Correlations would be higher but for only five or six projects (out of nearly 100). These projects either had low traffic or low soft content (or both), and showed excessive deterioration early in service life. No reason could be found, and it is assumed that local soil conditions are responsible.

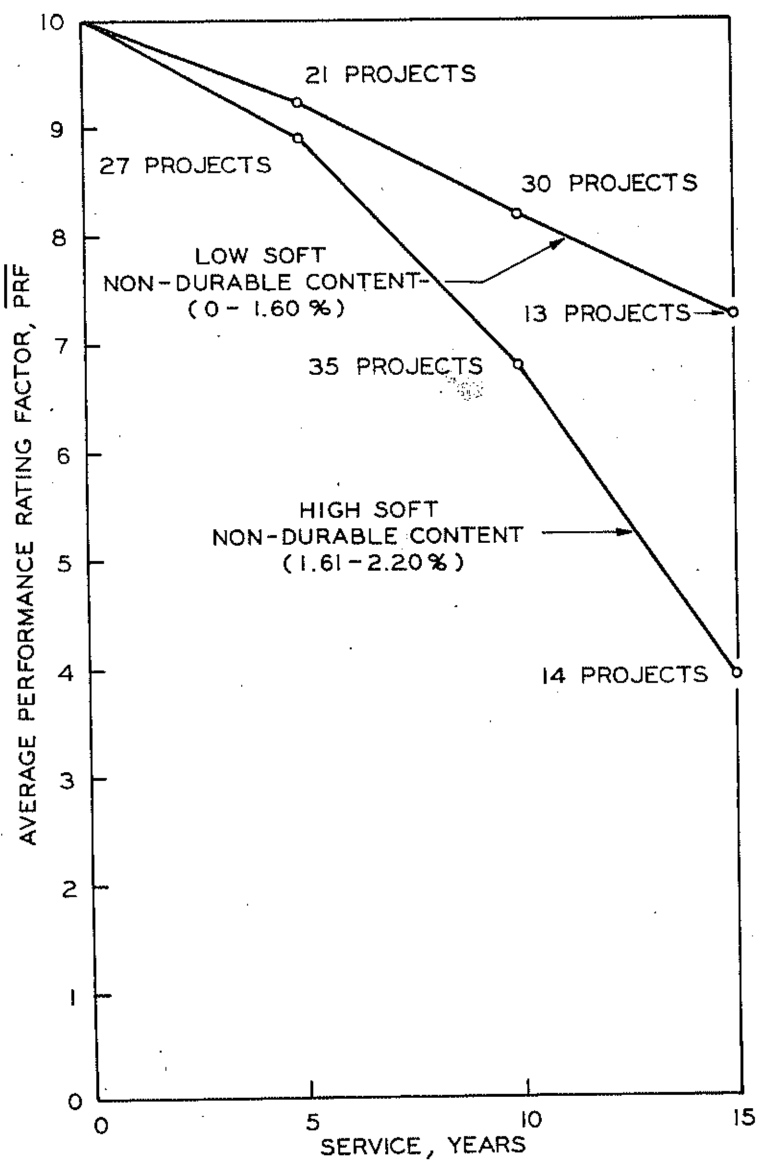


Figure 47. Performance rating factor for projects with low and high soft, non-durable content.

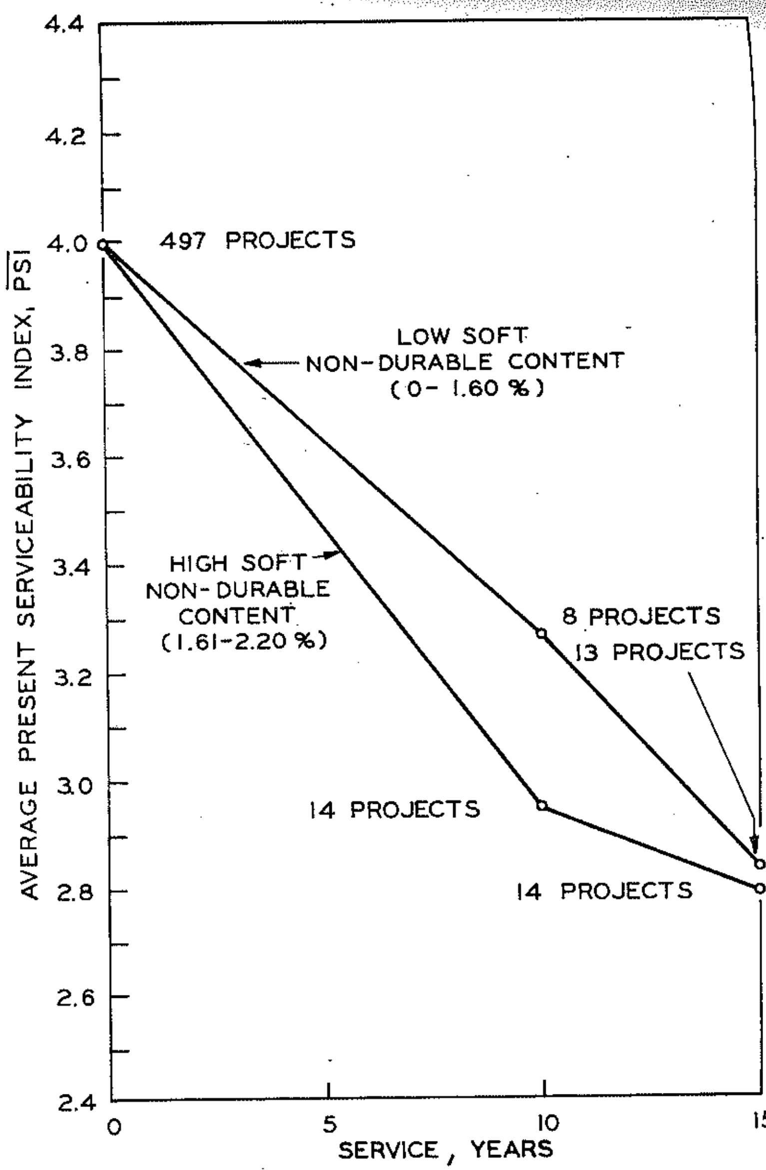


Figure 48. Present serviceability index for projects with low and high soft, non-durable content.

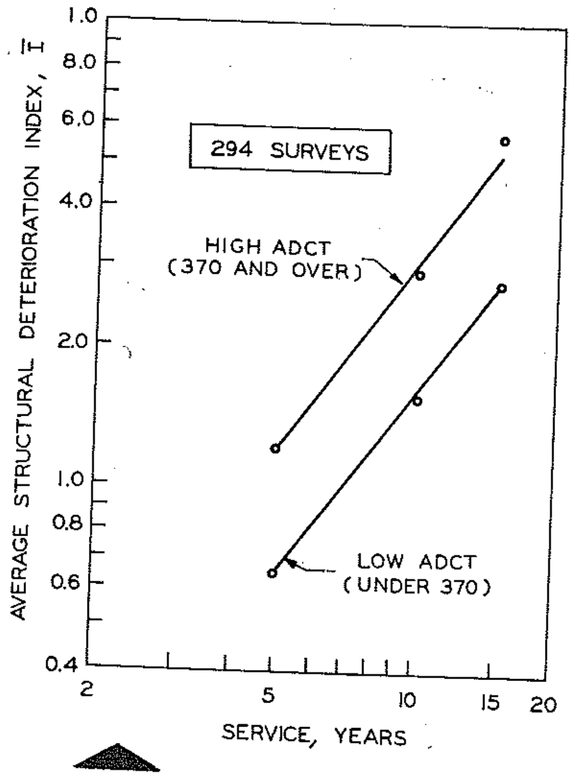


Figure 49. Relationship between average daily commercial traffic volume (ADCT) and average structural deterioration (I).

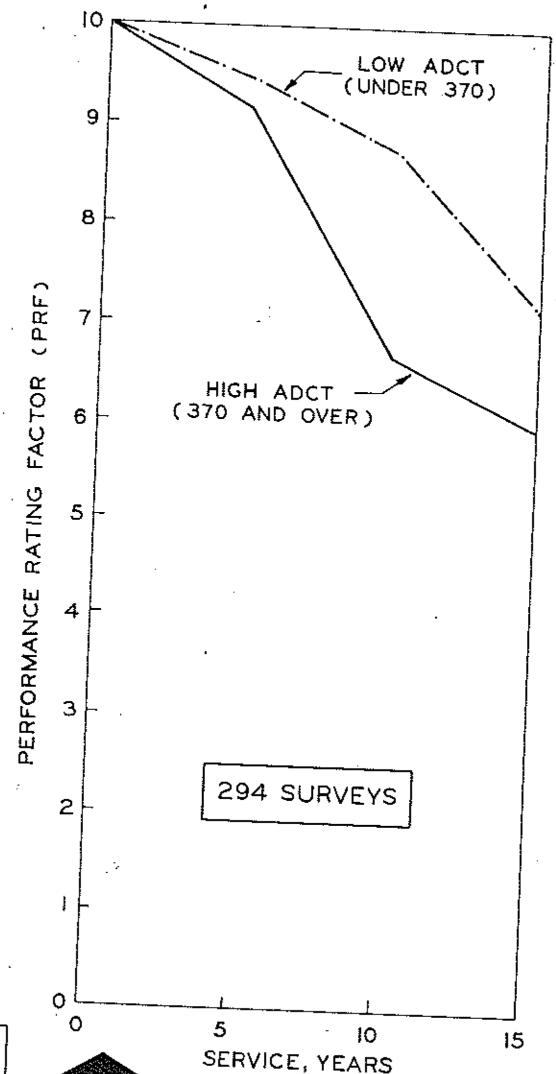


Figure 50. Relationship between average daily commercial traffic volume (ADCT) and average performance rating factor (PRF).

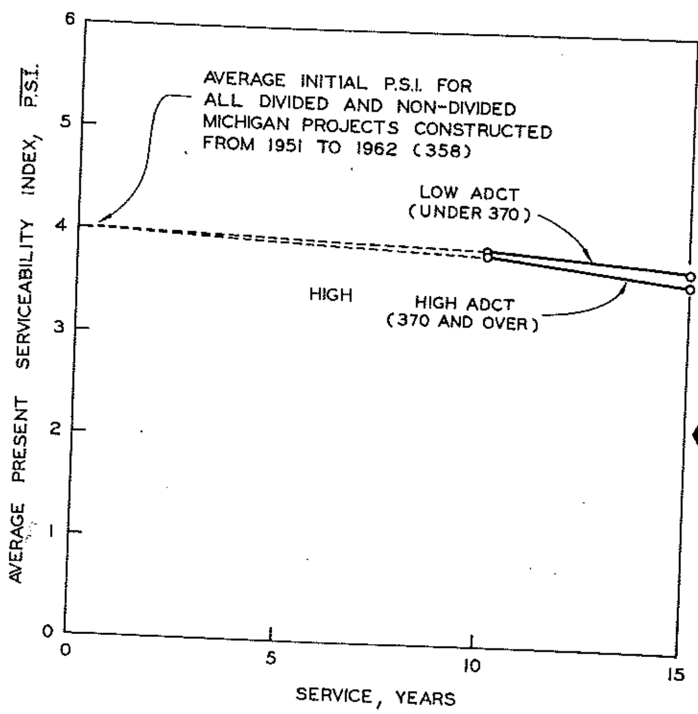


Figure 51. Relationship between average daily commercial traffic volume (ADCT) and average present serviceability index (PSI).

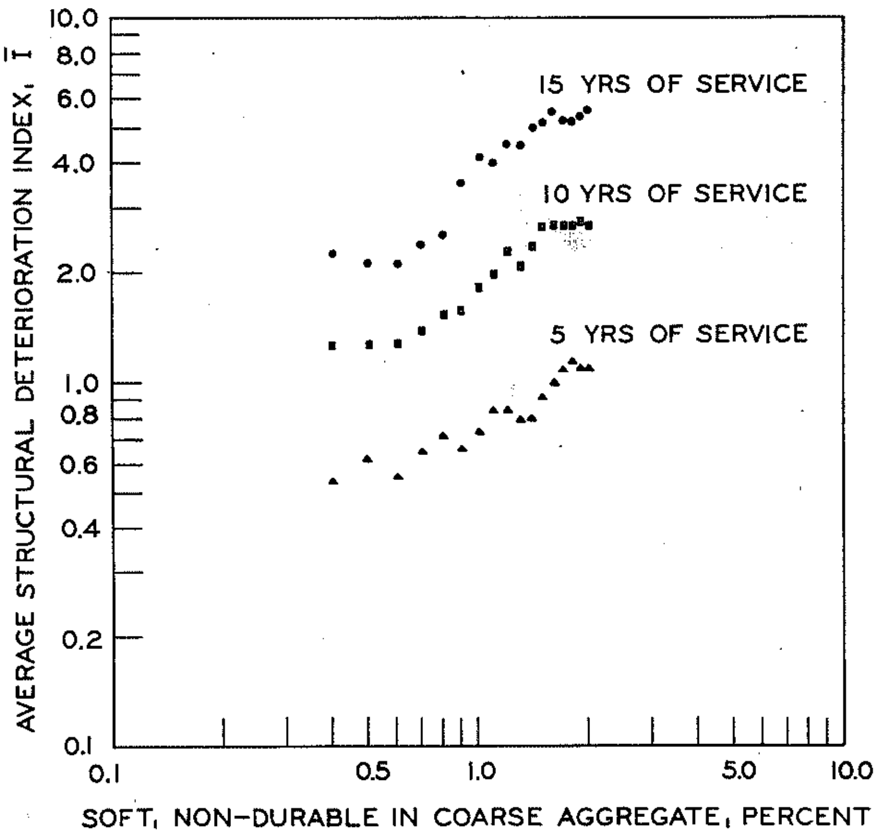


Figure 52. Relation between soft, non-durable and average structural deterioration.

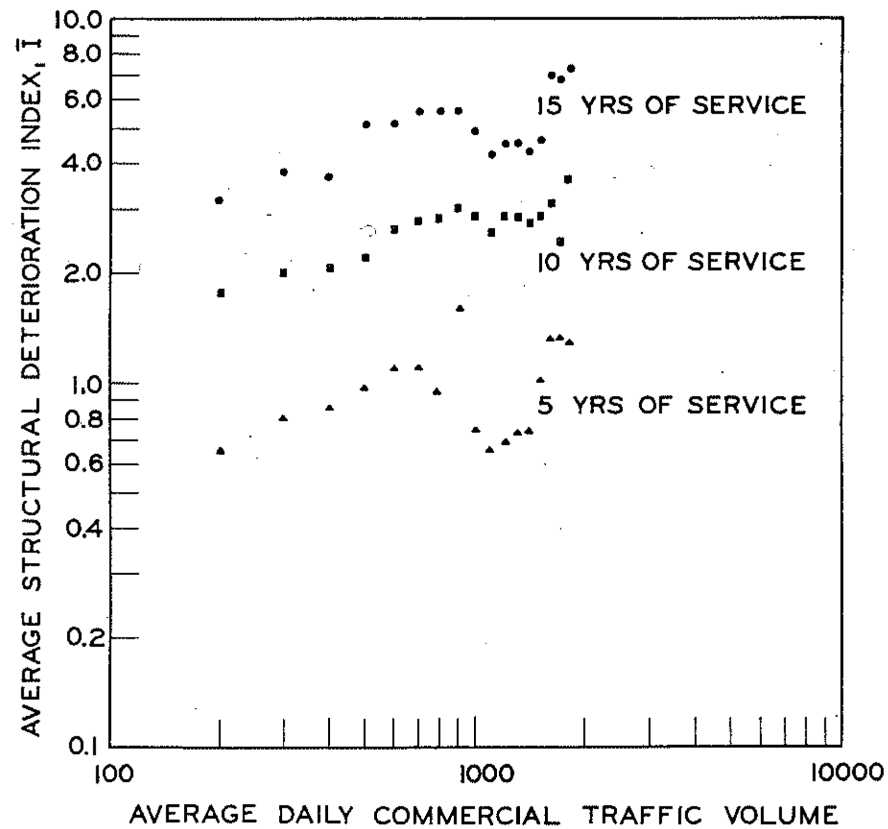


Figure 53. Relation between average daily commercial traffic volume and average structural deterioration (I).

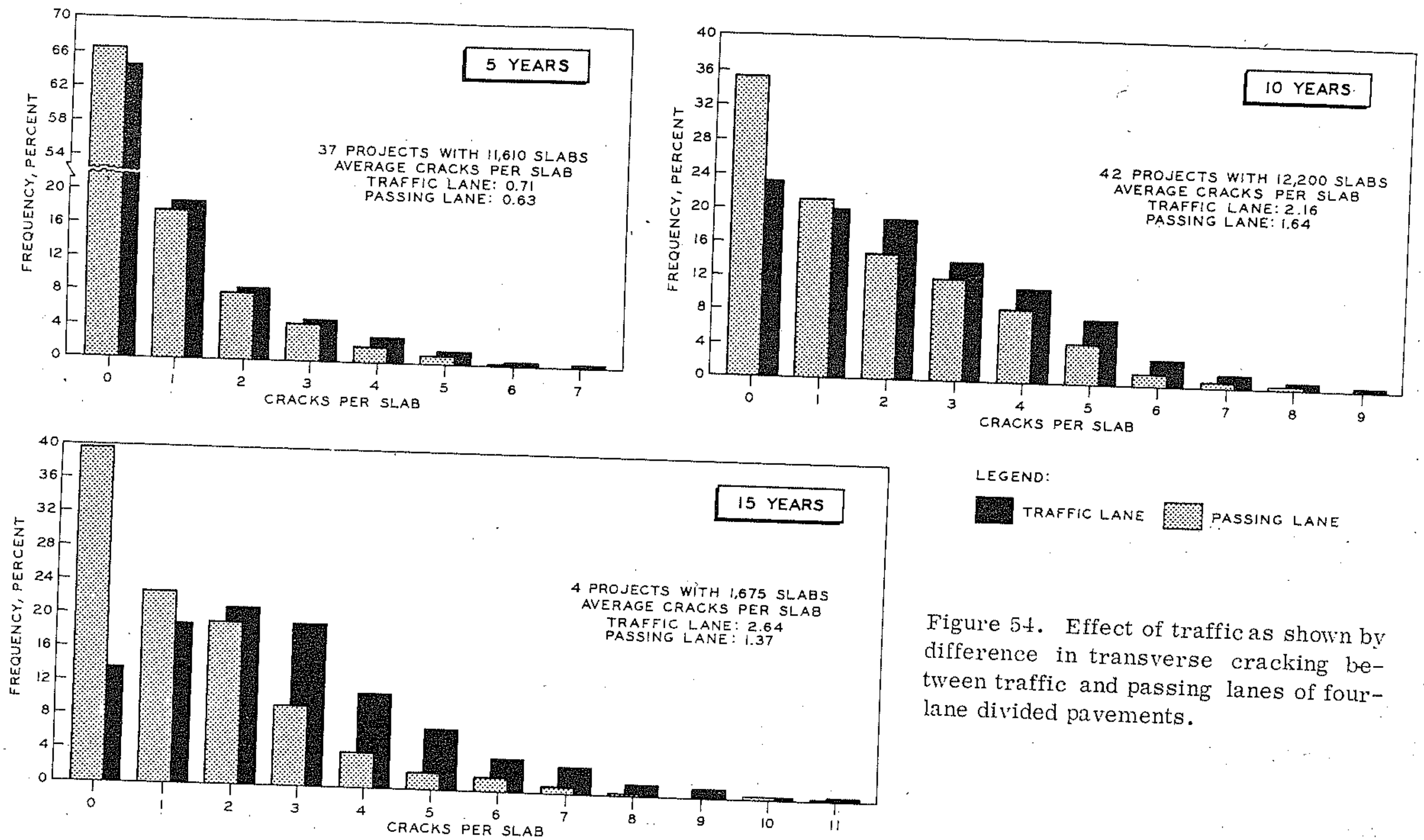


Figure 54. Effect of traffic as shown by difference in transverse cracking between traffic and passing lanes of four-lane divided pavements.

The data used for commercial traffic resulted from a single 24-hour sample taken during the service life of each project. Because these data are so weak, the influence of traffic on performance requires further examination. Four-lane divided expressways provide an excellent opportunity to evaluate lane performance differences attributable to differential usage. For these pavements, all construction, environment, design and materials variables are identical thus the difference in performance between traffic and passing lanes can be unequivocally assigned to differences in traffic load. A quantitative between-lane difference in traffic load was generally not available for the projects examined. However, it is well known that traffic lanes experience more loading than the corresponding passing lanes. In terms of equivalent 18 kip axle loads, the traffic lane can generally be assigned from 70 to 90 percent of the total in one direction.

The difference in transverse cracking between traffic and passing lanes of four-lane divided pavements is shown in Figure 54. It should be noted that the effect of traffic on performance of traffic lanes in comparison with passing lanes is small for five years of service; but with increased service, at ten and fifteen years, the difference is much more apparent. As a result of this study, all available construction projects on divided highways--including those which were surveyed after the initial cut-off data for this study--were examined to obtain a broader statistical basis for determining the effect of traffic.

In Figure 55 the average incidence of transverse cracking is shown to be higher for the traffic lane at five-, ten-, and fifteen-year service periods for all construction projects built as divided expressways. The traffic lane has, on the average, 62 percent more transverse cracking after fifteen years service than does the passing lane. The difference is even greater, as shown in Figure 56, for average longitudinal cracking; after fifteen years service the traffic lane has nearly twice as much cracking as the passing lane, 59 lin ft for 100 slabs as compared to 30 lin ft for the passing lane. This same difference in performance after fifteen years of service between traffic and passing lane can be noted for external corner spalls in Figure 57 (36 percent increase in traffic lane); internal corner spalls in Figure 58 (29 percent increase in traffic lane); amount of patching in Figure 59 (20 percent increase in traffic lane); and amount of pavement deterioration in Figure 60 (61 percent increase in traffic lane). It should be noted that in every case the traffic lane performed more poorly as a result of greater traffic than the passing lane.

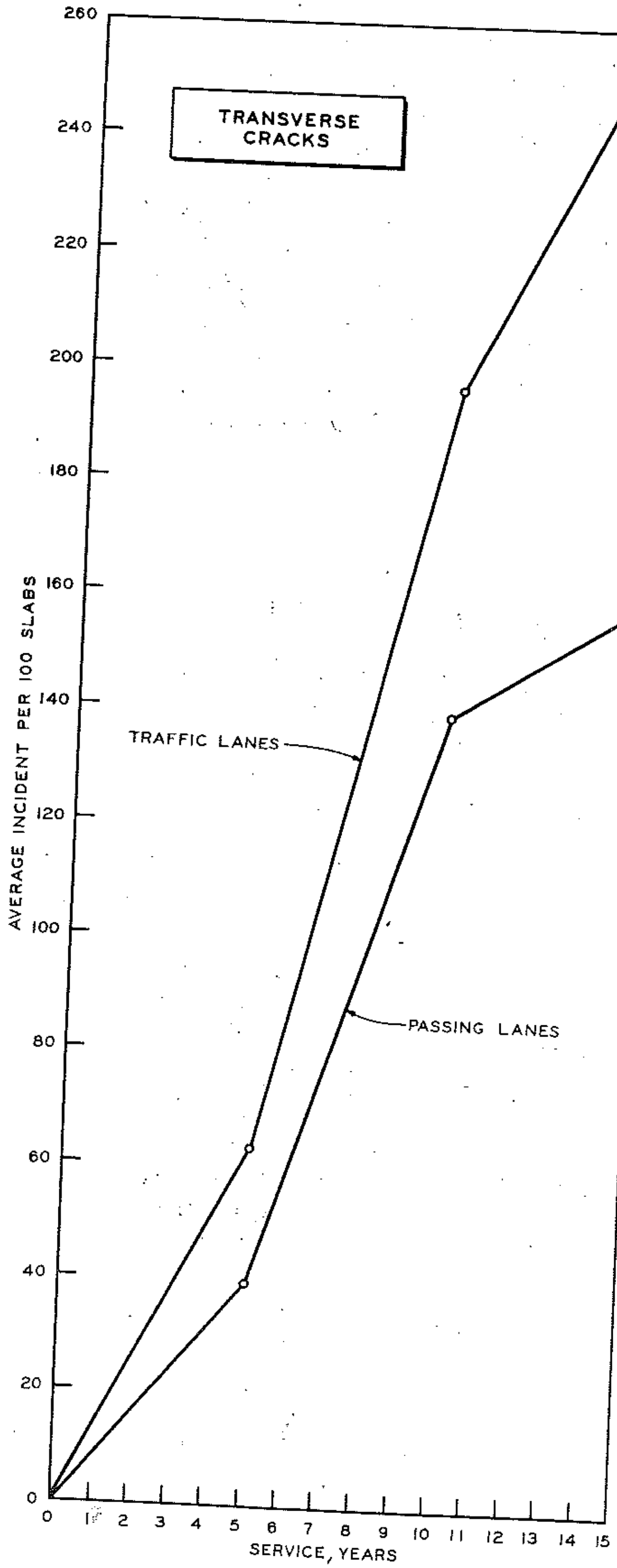


Figure 55. Effect of traffic on transverse cracking.

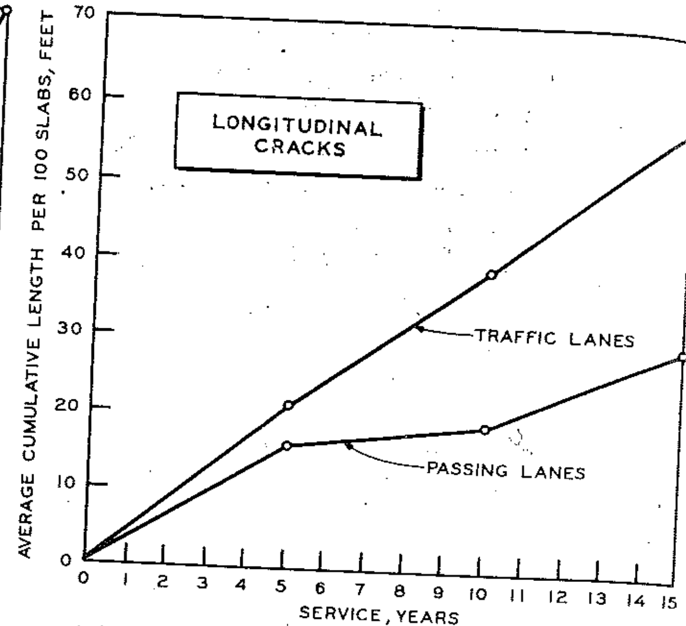


Figure 56. Effect of traffic on longitudinal cracking.

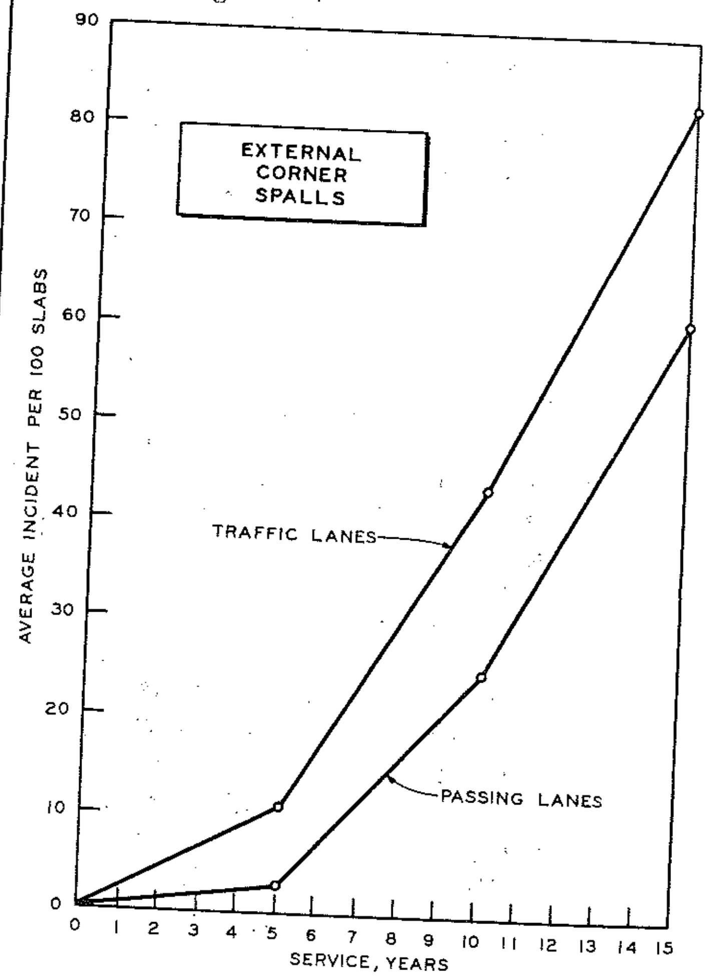


Figure 57. Effect of traffic on external corner spalls at transverse joints.

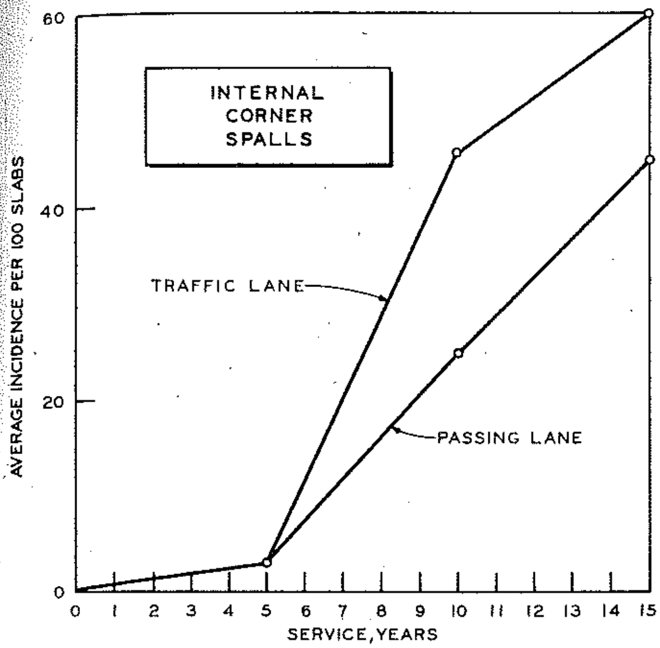
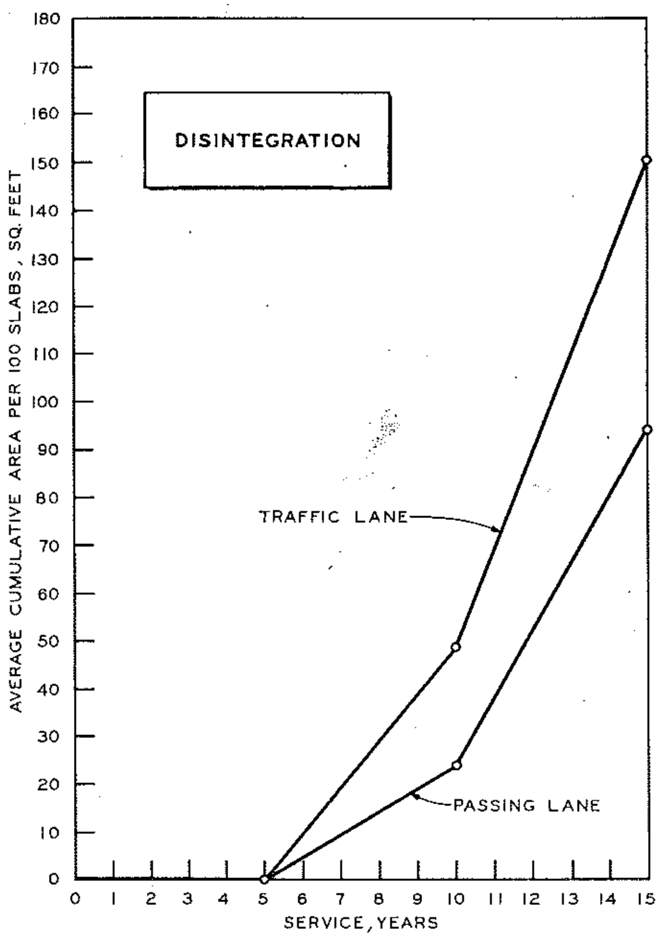


Figure 58. Effect of traffic on internal corner spalls at transverse joints.



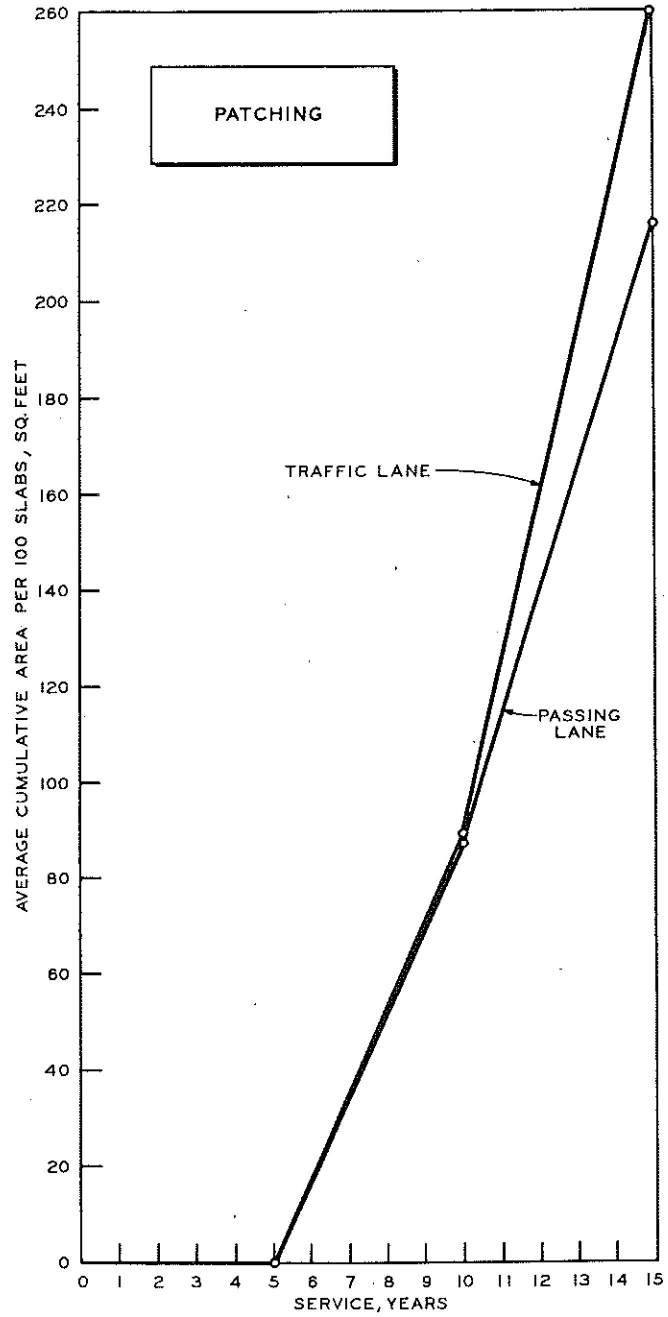


Figure 59. Effect of traffic and amount of patching.

Figure 60. Effect of traffic on amount of pavement deterioration.

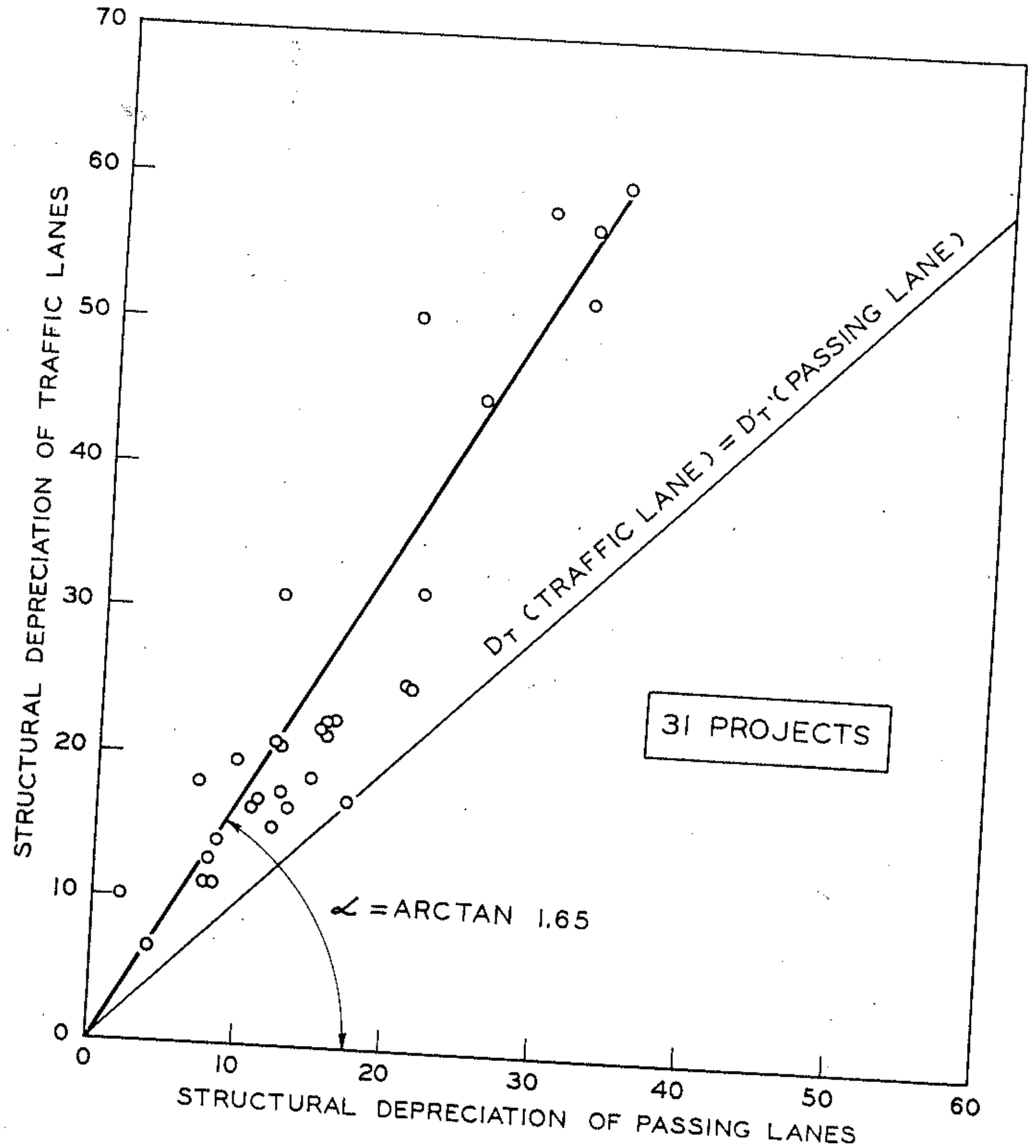


Figure 61. Average structural depreciation of passing lanes versus traffic lanes.

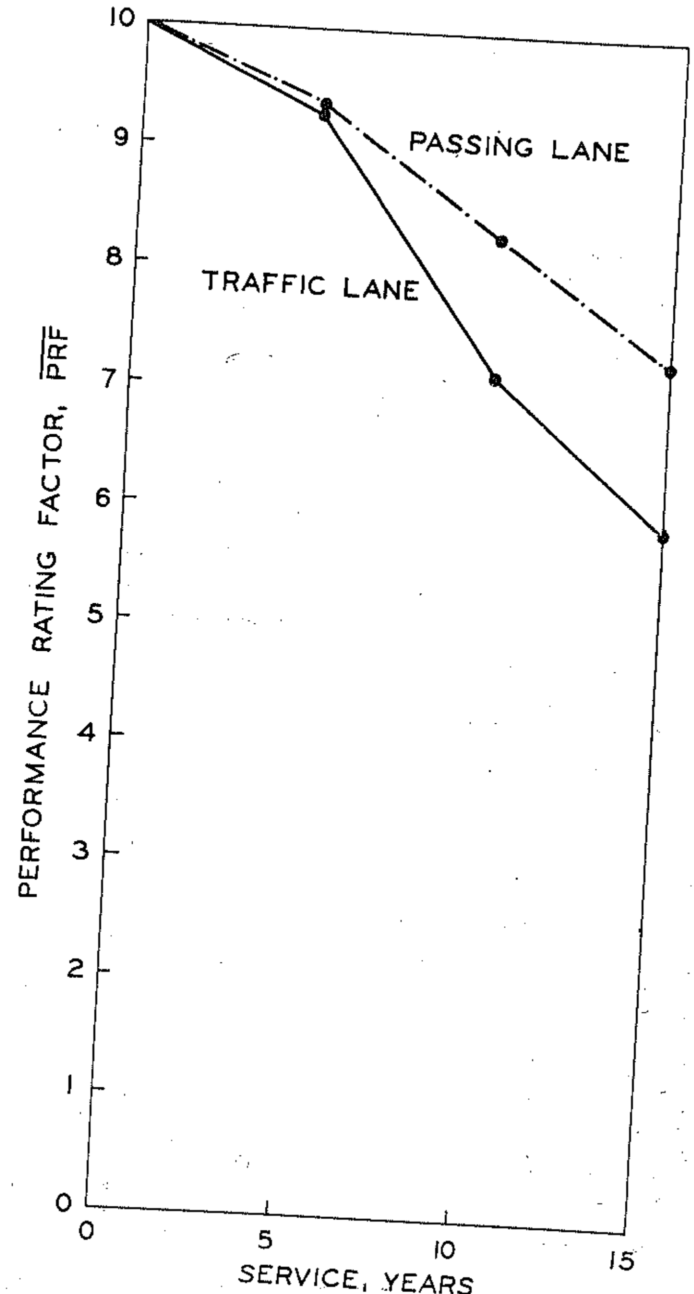


Figure 62. Performance of divided

Figure 61 shows the Depreciation Index (D) value for the traffic and corresponding passing lanes for each of 31 divided roadway projects (to be derived later). Also shown is a 45-degree line which, of course, indicates equal depreciation for each lane. The traffic-passing lane structural depreciation relationship, while linear, definitely does not have a slope of 1.0, necessary if both lanes performed equally. Overall, the traffic lanes show about 65 percent more structural deterioration (as measured by D) than the corresponding passing lanes. Figure 62 shows the same performance difference as measured by PRF.

As with overall traffic volumes, PSI's for matched traffic and passing lanes do not show appreciable differences even after fifteen years of service (Fig. 63). As could be expected, the survey variables which are heavily weighted in the structural performance index; i.e., corner cracking and spalling together with transverse and longitudinal cracking, do not noticeably influence PSI in the traffic wheel paths where roughometer measurements are made. Only after more extensive deterioration has taken place (much of which may stem from the initial failures measured by these variables) would roughness measurements be substantially affected. Because of the failure of the PSI to adequately reflect structural performance differences, further analysis with this measure was not undertaken. [5]

It should be pointed out that all projects herein examined were considered to have adequate subgrade support. Either they were constructed on natural sand and gravel subgrades with good natural drainage, or proper subbases with adequate thickness constructed to improve drainage. If performance is measured by the PSI, one would conclude from the traffic- passing lane study, that since commercial traffic does not perceptibly influence structural performance, subgrade support is adequate (Fig. 63). However, if performance is measured by structural condition variables collectively in indices such as D, one would conclude the opposite: because pavement performance, even with quality subgrade, is substantially affected by commercial traffic; grade support together with construction procedures could be improved. [6]

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5 All survey variables in equation 1 except blowups had larger average values in the traffic lane.

6 Since these projects were constructed, the Michigan subbase requirements have increased from 12 to 14 and thence to 15 in. of granular material. Also, contraction joint spacing has been decreased from 99 ft to 71 ft 2 in.

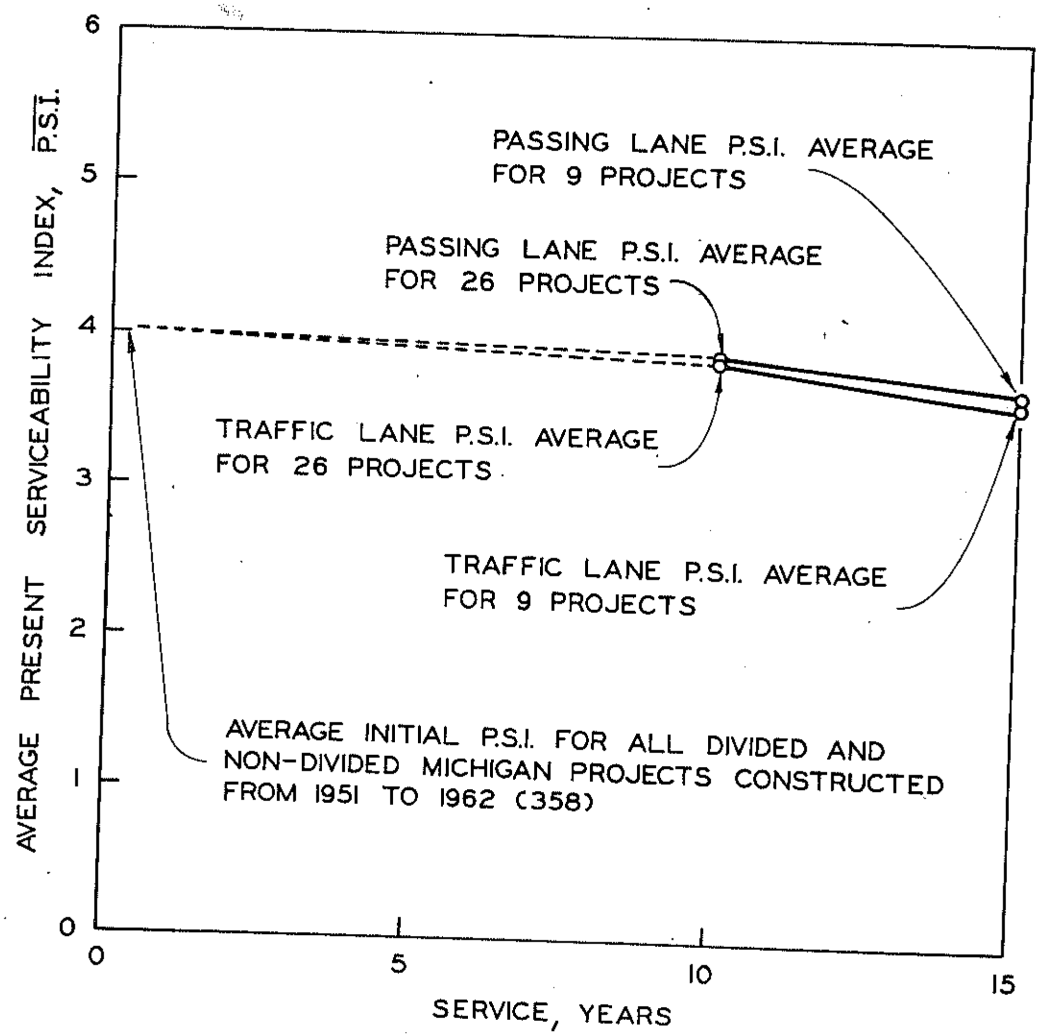

Figure 63. Present Serviceability Index by lanes.

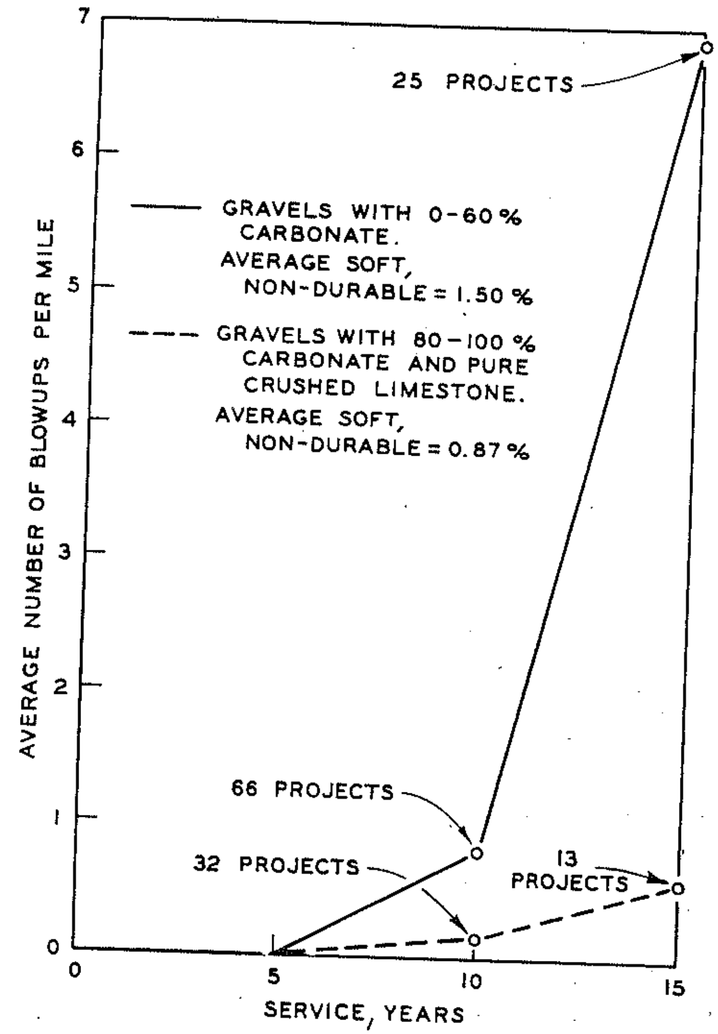

Figure 64. Blowup performance for two classifications of aggregate.

These examinations suggest three conclusions:

1. Of the deleterious materials examined, soft, non-durable content is the best predictor of ten- to fifteen-year structural performance as measured by either subjective or objective indices.

2. Average daily commercial traffic is definitely associated with structural deterioration as measured by the same indices. This is shown to be the case for both two-lane and four-lane divided roadway.

3. PSI does not appear significantly related to structural performance. Also, neither soft, non-durable content in coarse aggregates nor commercial traffic volume show any relationships to PSI. This may not be true for service periods beyond fifteen years when structural deterioration substantially affects roughness. However, up to 15 years of service, condition survey variables combined in indices appear to be the only effective early predictors of general structural deterioration.

Performance of Individual Variables - Blowups

One basic variable of special interest and concern is blowups. Because this form of pavement distress is more infrequent and occurs later in pavement life than most other kinds, it is more difficult to analyze. Blowups have been attributed to coarse aggregate types because of unusually high frequencies found in pavements constructed from aggregates coming from specific pits (14). Figure 64 shows substantial blowup incidence for gravels containing 0-60 percent carbonates. It should be noted that the difference in blowup performance itself for the two aggregate groups is a function of time--no difference at five years; some difference at ten years; and considerable difference at fifteen years.

More intensive examination of the aggregate data shows that blowup performance is probably related more to aggregate heterogeneity than carbonate content. For the present case, heterogeneity (H) was previously defined as:

$$H = \sin (P \pi)$$

where P is the estimated proportion of carbonate in the aggregate.

Figure 65 shows the relationship between blowups and aggregate heterogeneity (H) for four carbonate classes: 100 percent, 80-90 percent, 40-60 percent, and 0-35 percent. After fifteen years of service, homogeneous aggregates (100 percent crushed limestone or dolomite having an H value of zero) show very few blowups while highly heterogeneous aggregates (40-60 percent carbonates having an H value of 1.0) show substantially increased blowup frequency. As with general performance indices, blowups could be attributed to differential thermal expansion rates of soft, non-durables (15). Since Michigan specifications already control for soft, non-durables, it is expedient to develop models and make decisions on this basis (6, 16, 17).

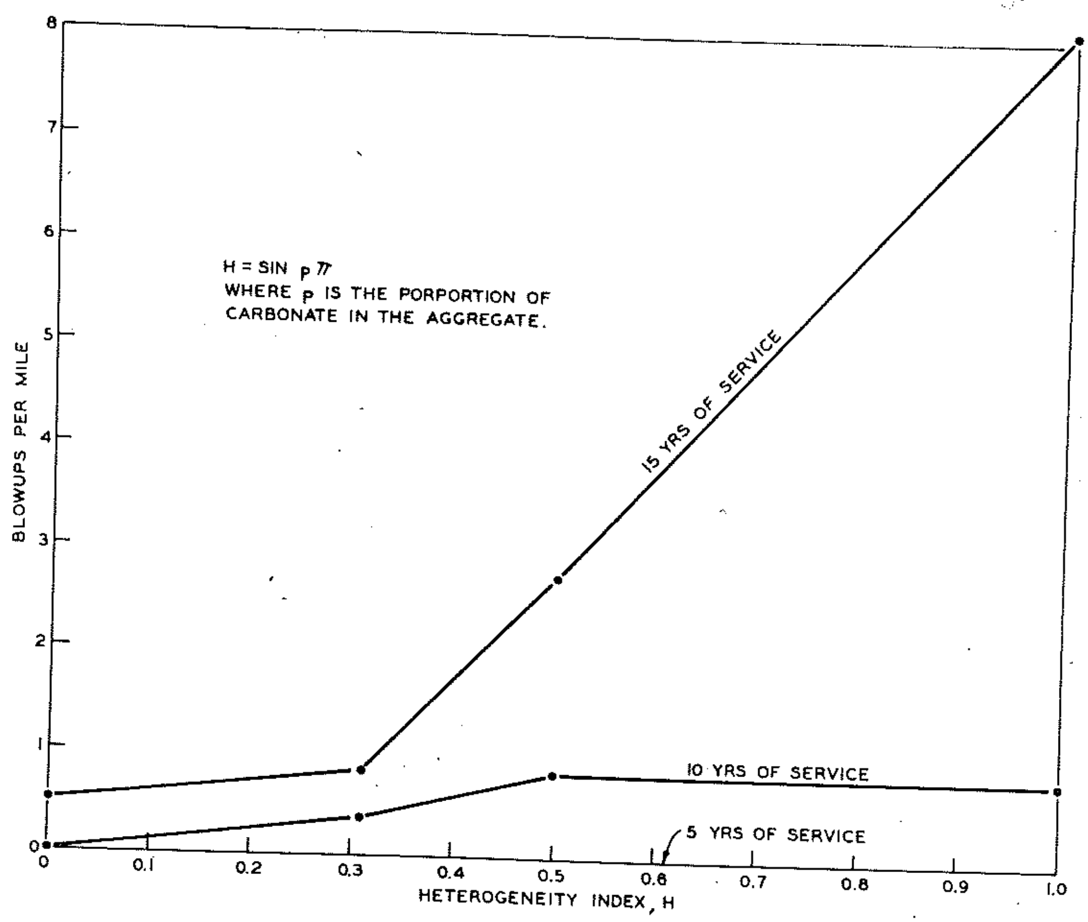

Figure 65. Effect of coarse aggregate heterogeneity on blowups.

Structural Performance Model

Assuming that the effects of soft, non-durable particles and average daily commercial traffic volume on performance are real, it seems reasonable to construct a performance prediction equation: Figures 46, 49, 52, and 53 suggest the following relationships:

$$\log \hat{I} = K_1 \log S + \log K_2 \quad (4)$$

$$\log \hat{I} = K_3 \log (ADCT) + \log K_4 \quad (5)$$

$$\log \hat{I} = K_5 \log t + \log K_6 \quad (6)$$

where:

$\hat{I}$ = estimate of structural deterioration index (I)

A = percentage of soft, non-durable in coarse aggregate

ADCT = average daily commercial traffic volume

t = Age of pavement in years

$K_1 \ldots K_6$ = Fitting constants with K_2 and K_4 dependent on the survey year. Ideally, these variables would be combined by multiple regression techniques. In the present case, however, a complete data matrix was not available since many projects did not have complete records for soft, non-durable content or condition surveys for all three service periods. Consequently, these variables were combined geometrically by first estimating the slopes for each variable by simple linear regression, and then summing the three equations (the geometric average results in a simpler model than the arithmetic average). Thus, we have in general:

$$\log \hat{I} = \frac{K_1}{3} \log S + \frac{K_3}{3} \log (ADCT) + \frac{K_5}{3} \log t + \log K_7$$

and in the present case, since $K_1 = K_3 = 0.54$ and $K_5 = 1.56$,

$$\hat{I} = K_7 S^{.18} (ADCT)^{.18} t^{.52}$$

Estimates of D_T can be obtained by integration:

$$d\hat{D}_T = \int_0^T I \, dt = K_7 S^{.18} (ADCT)^{.18} \int_0^T t^{.52} \, dt$$

and

$$\hat{D}_T = K_8 S^{.18} (ADCT)^{.18} T^{1.52} \quad (7)$$

In order that both traffic and passing lanes of divided expressway could be included with the two-lane pavements, ADCT given for the roadway only had to be distributed between the lanes. An approximate distribution formula was obtained as follows by equation(5)and the slopes in Figure 49:

$$\hat{I} = K_4 \text{ (ADCT) } K_3 \text{ and } \hat{D}_T = \int_0^T \hat{I}\, dt = K_4 \text{ (ADCT)}^{K_3} \; T$$

Dividing D_T for the traffic lane by D_T for the passing lane, and substituting the slope from Figure 49, we have:

$$\frac{\hat{D}_T \text{ (Traffic Lane)}}{\hat{D}_T \text{ (Passing Lane)}} = \left(\frac{\text{ADCT Traffic Lane}}{\text{ADCT Passing Lane}} \right)^{.54} \quad \alpha = \text{arc tan}\, \alpha = 1.65$$

from Figure 61. Therefore:

$$\frac{\text{ADCT traffic lane}}{\text{ADCT passing lane}} = (1.65)^{\frac{1}{0.54}} = 2.52$$

Because the percentages in the traffic and passing lanes must add to 100, we have:

$$\text{ADCT traffic lane} = .72 \text{ ADCT}$$

and

$$\text{ADCT passing lane} = .28 \text{ ADCT}$$

These formulas were used to divide the total roadway ADCT into volumes for each lane, thereby permitting the incorporation of both lanes of divided expressway into the final analysis.

K_8 of equation 7 can now be determined by regression of $\hat{D}_T$ on D_T, i.e.,

$$\hat{\hat{D}}_T = K_9 \ \hat{D}_T + K_{10} \qquad \text{which gives}$$

$$\hat{\hat{D}}_T = .33 \ S^{.18} \ (ADCT)^{.18} \ T^{1.62} - 28 \qquad (8)$$

The correlation coefficient for the regression is +0.77 which for the number of points (111) is highly significant.

Figure 66 is a plot of D_T and $\hat{D}_T$ for all projects for which five-, ten-, and fifteen-year data were available including divided expressways.

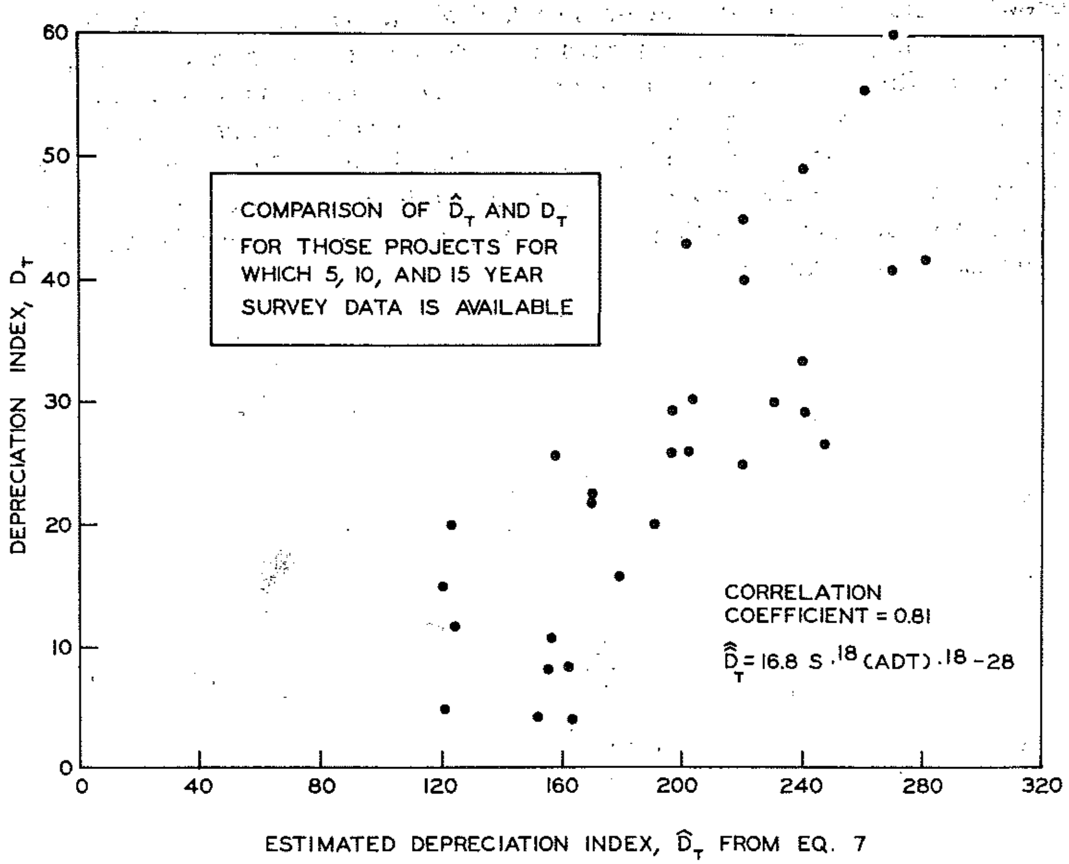

Figure 66. Comparison of $\hat{D}_T$ and D_T for those projects for which 5-, 10-, and 15-year survey data are available.

This is presented to show the structural depreciation predicting power of S and ADCT independently of time, when reasonably stable (three survey years available) D_T values can be calculated. Considering only these projects, equation (7) becomes:

$$\hat{\hat{D}}_T = .28\ \hat{D}_T - 28 = 16.8\ S^{.18}\ (ADCT)^{.18} - 28$$

and the correlation for the regression of D_T on $\hat{D}_T$ is a highly significant +0.81 for 31 projects. Thus, when only five-, ten-, and fifteen-year surveys are considered, 65 percent of the structural depreciation variance can be "explained" by the variables of soft, non-durable percentage and average daily commercial traffic volume. Presumably, if more surveys could be incorporated, thereby allowing more reliable time-deterioration curves, a somewhat better relationship could be established. The mainpoint is, however, that both percent soft, non-durable in the coarse aggregate and commercial traffic have been shown to have structural performance prediction power. This does not ipso facto "prove" causal relationship. However, background information on these variables (such as traffic-passing lane comparisons and the AASHO Road Test) suggests that the present correlations are meaningful, and that these variables are not merely "standing-in" for the "real" causes.

OBJECTIVE IV

RELATIONSHIP BETWEEN SOIL AND PERFORMANCE

Subbase Materials

In the early 1930's, sand subbase was found to be effective in reducing the spring thaw breakup of Michigan pavements. Subsequently, the use of sand subbase became more widespread throughout the State until, by 1940, a 12-in. sand subbase was required under all rigid pavements constructed over heavy natural soils. Incoherent subbase materials were stabilized through the top 3 in. with salvaged or pit run gravel, loamy soils or, as a last choice, clay soils.

In 1955, the subbase thickness was increased to 14 in., more to facilitate construction control than to improve pavement strength. The upper 3-in. layer of the subbase consisted of selected gravel. This 3-in. layer of gravel was to reduce losses in density due to drying and rutting, to provide a stable surface for pavement forms and paving equipment, and to prevent infiltration of fine uniform sands into the pavement joints. In 1963, the thickness of the layer of selected gravel subbase was increased to 4 in. making a total subbase thickness of 15 in.

From the history of Michigan subbase construction, it appears that subbases used under postwar rigid pavements were relatively uniform and that any relationship between subbase and pavement performance would be primarily caused by control of soil density during construction. However, subbase soil density data were not available on a project-by-project basis and thus could not be considered as a variable to study in relation to pavement performance.

Analysis of Influence of Subgrade Soil

Figure 42 is a map locating soils of varying suitability as subgrade materials. Figure 42 was developed from a Soil Map of Michigan by J. O. Veatch delineating soil areas for agricultural use. However, Veatch's map showed approximately 100 different soils which, for this study, were grouped by suitability for subgrade materials into three categories, "good," "fair," and "poor." Properties of the soils considered were drainage together with wet and dry strength.

In order to determine if these categories conveyed information on structural performance, the average transverse crack incidence for each of these categories over the fifteen-year service period was plotted in Figure 67. Notice that the order of performance follows soil quality for the 125 projects surveyed. It should also be remembered that the average for the fifteen-year service periods is less than would be expected. This is be-

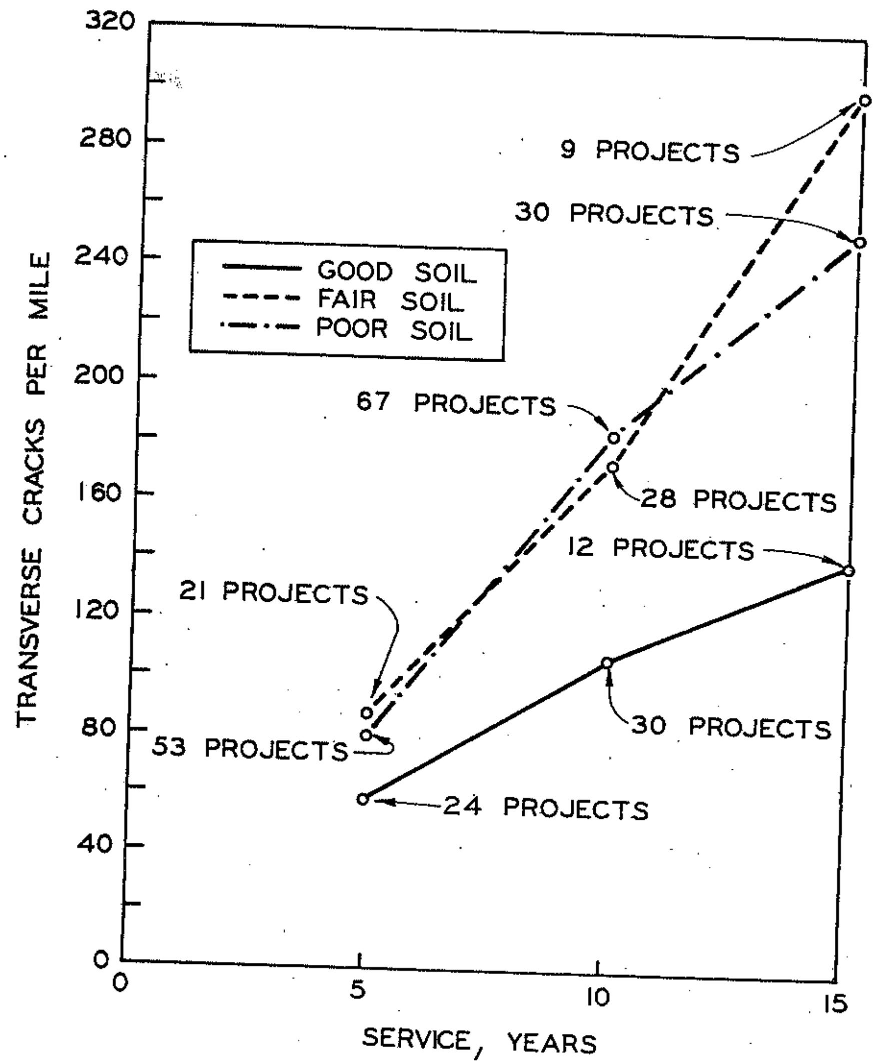

Figure 67. Soil versus transverse cracks.

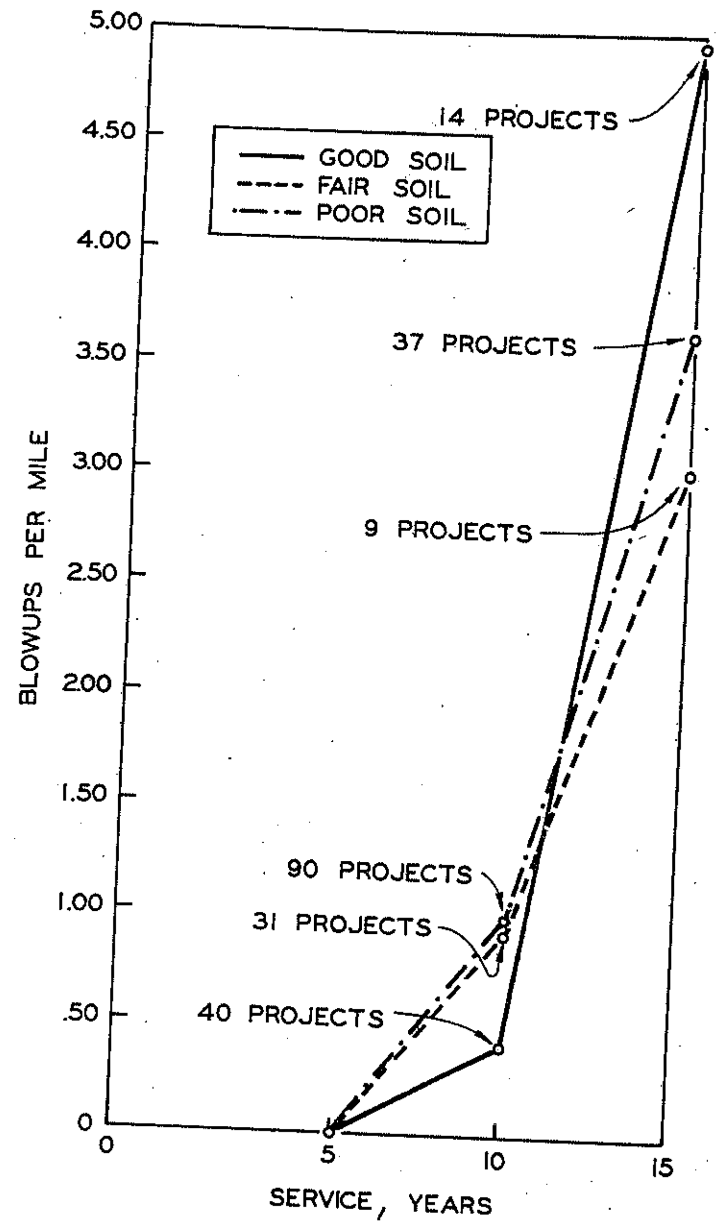

Figure 68. Soil versus blowups per mile.

cause highly cracked portions of ten-year projects are generally resurfaced before fifteen years and this results in substantial underestimation of fifteen-year cracking. Even though resurfaced portions are not considered in the analysis, the biasing effect is still present.

Because soil quality regions are somewhat geographically correlated with aggregate quality, it was decided to compare soils groups using variables known not to be affected by subgrade support. To this end, blowup frequencies for each soils group were compared both graphically and statistically (Fig. 68). As expected, no association of blowups and soil quality was found. Therefore it was assumed that coarse aggregates were not responsible for the pavement performance differences in question.

The only other variable found to be related to general performance was average daily commercial traffic volume. Figure 69 shows that transverse cracks are associated with commercial traffic. Moreover, the association is stronger with age: r = 0.14, 0.33, and 0.52 for the five-, ten-, and fifteen-year surveys, respectively. The latter two correlations are significant and highly significant. It was thought that the cracking-traffic correlation might be responsible for the findings concerning the soils (Fig. 67) since it was known that many generally poor soil regions in Michigan are found in high population density areas; just as good soils are often found in remote regions with low traffic volumes. To show the statewide relationship between soils and traffic, the average commercial volume for each soil type was plotted in Figure 70. Despite considerable scatter in the raw data, a trend is apparent: pavements built in regions with poor soils generally have higher commercial volumes than those built in regions of good soils. Because of this fortuitous correlation, the original findings; namely that a geographic soils map indicated performance differences attributable to soil quality, is probably erroneous. The evidence, which includes the traffic - passing lane comparisons of divided expressway, suggests that structural performance in general, and transverse cracks in particular, are causally related to commercial traffic volume. Soil quality is undoubtedly an additional factor, but information based on general classifications for large geographic areas is not sufficiently precise to improve performance prediction. For example, the fifteen-year multiple correlation of transverse cracks on soil and traffic is 0.54, while the partial correlation with traffic is 0.51. Thus, we see that the addition of this type of soils information adds little to our performance forecasting ability.

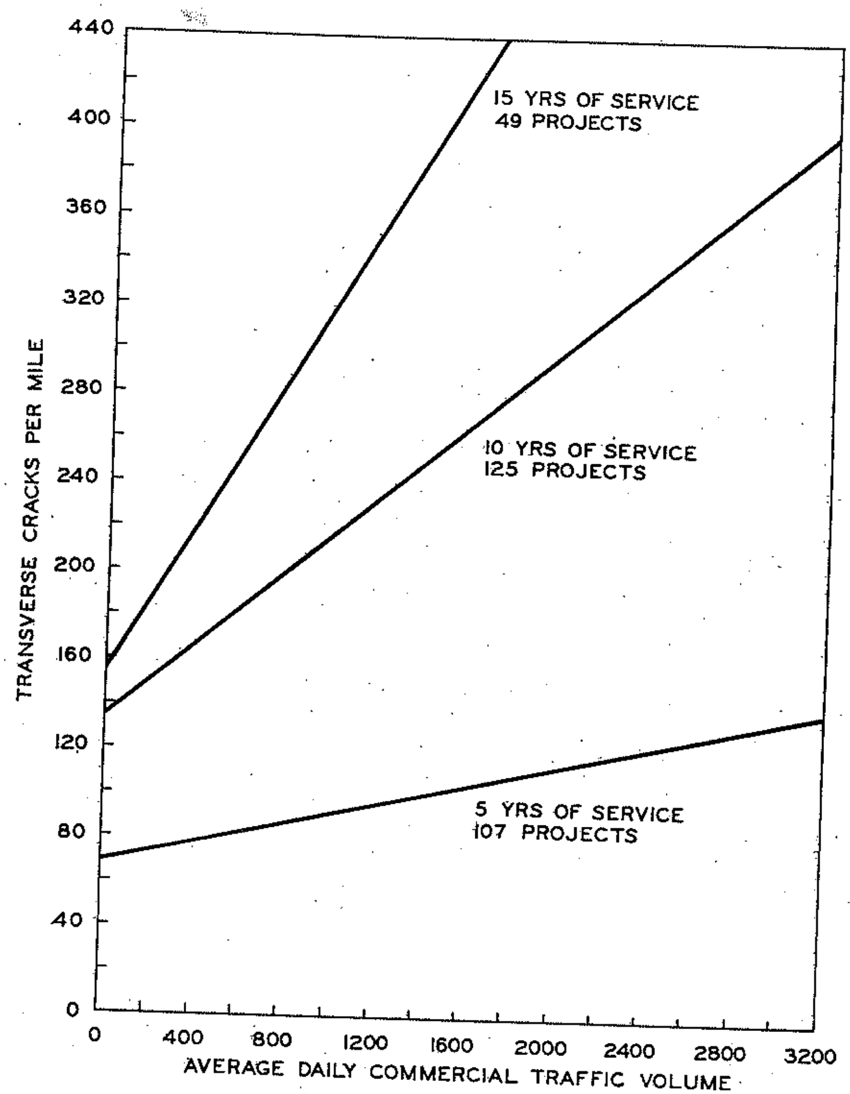

Figure 69. Traffic versus transverse cracks.

Figure 70. Soil versus commercial traffic volume.