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PAVEMENT RIDING QUALITY

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ABSTRACT

The results of a five-year study of the riding qualities of recently constructed New Jersey pavements and bridges are reported. The principal sources of roughness on these surfaces and the development of proposed smoothness acceptance specifications are described. The bituminous and concrete pavements studied were all of high-type (principally Interstate) construction on new alinement.

Determinations of relative roughness were made with a BPR-type roughometer and a 10-foot rolling straightedge. The output of the roughometer is evaluated using the FHWA adjective rating system and, to a limited extent, in terms of the AASHO Road Test "Present Serviceability Concept". The latter (PSI) criteria appears to have little applicability to New Jersey conditions. Rolling straightedge data is evaluated by means of criteria developed from observed correlations between the rideability indicated by the roughometer and the severity and extent of surface irregularities.

According to the FHWA criteria, the average new bituminous pavement surveyed during this study possessed only a "Fair" level of riding quality. However, there is a significant and encouraging trend for more recent bituminous construction to be of improved smoothness. Described improvements in the specified equipment, methods of construction, and payment method appear to be the major causal factors.

The average new concrete pavement was found to possess an even lower level of rideability. An FHWA adjective rating of "Fair to Poor" is indicated for typical New Jersey concrete construction. This result represents a general reduction in quality level compared to work accomplished in earlier periods in New Jersey. In spite of considerable experimentation with construction methods and equipment (including slip-forming), significant rideability improvements in pavements of New Jersey's present standard design appear unachievable without a return to long-past standards of workmanship.

The roughness data obtained on New Jersey bridge decks confirms the beneficial effect of using mechanical rather than manual methods for concrete strike-off and finishing. Recent specification changes--including provisions which require use of mechanized deck finishing equipment on the majority of future projects--can be expected to effect an overall improvement in New Jersey bridge rideability.

New Jersey's current "zero" straightedge defect smoothness specification is unrealistic and unenforceable. New surface smoothness specifications have been developed for New Jersey. These require acceptance testing of pavements and bridges with a rolling straightedge to determine the percentage of the surface length exceeding a tolerance of 1/8 inch in 10 feet. A graduated schedule of payment reductions is proposed when a non-compliant level of riding quality is indicated.

IMPLEMENTATION STATEMENT

The roughness information developed during the course of this research has provided the New Jersey Department of Transportation with documentation of the need for and guidance as to methods of achieving improved rideability. A number of improvements effected in the areas of New Jersey bridge deck finishing and bituminous pavement equipment and construction methods are described in the report. Much of the impetus for these improvements was provided by the initial findings of this study.

The implementation of the research findings can be completed by adopting the bridge deck and pavement smoothness acceptance specifications recommended in the report.

ACKNOWLEDGEMENTS

The writer gratefully acknowledges the cooperation provided by the resident engineers on the various construction projects studied in this work.

Jerry Budwig of Federal Highway Administration Region 15 furnished a multi-state straightedge data sample that provides an interesting basis of comparison for New Jersey results.

William Bancroft, Construction Engineer, provided valuable assistance in bridge deck field studies. Construction Engineer John Walz was similarly helpful in a field study of bituminous paver controls on the I-287, 7D project. Highway Inspector John Licko took many of the report photographs.

The Research Division's technicians and Carey Younger in particular, are commended for their diligence in roughness data collection.

Research Engineers Karl Brodtman and John Senyk performed the repairs periodically required on the roughometer.

Research Engineer Robert Santoro and Construction Engineer Ted Stine were co-investigators in the I-80, 1M pavement study. Mr. Santoro additionally provided a number of worthy suggestions concerning the Draft report. Research Engineer Richard Weed generated certain of the statistical curves used in pavement smoothness specification development. Research Engineer Donna Troiano assisted in compiling and computerizing the roughness data.

Research Bureau Chief Kenneth Afferton made a particularly significant contribution thru advice provided during the conduct of the work and on reviewing the draft report.

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PART I: INTRODUCTION

1.1 RESEARCH OBJECTIVES

The principal objectives in undertaking the present research were

. to develop an index of riding quality for recently constructed New Jersey pavement and bridges using a BPR-type roughometer,

. to identify the sources of roughness on the measured surfaces and

. to investigate the desirability and feasibility of adopting riding quality acceptance specifications.

1.2 BACKGROUND

The major stimulus for initiating a statewide study of riding quality was the findings of New Jersey pavement roughness surveys made in 1962 and 1963 using the Federal Highway Administration (FHWA) prototype roughometer. This sampling indicated that a general improvement over the then current level of rideability of new construction projects was needed, particularly with regard to bituminous pavements and bridge decks.

More specifically, according to roughness evaluation criteria developed by the FHWA, the surveyed bituminous pavements were generally considered to be of "Fair" riding quality. In the case of the 1962 testing, the sampled New Jersey bituminous pavements were characterized by an average of from 10 to 60 percent greater relative roughness than flexible pavements surveyed in three* other northeastern states during the same period. While the tested concrete pavements of the early 1960's generally merited a "Good" roughness rating, improvement was felt to be possible since old concrete pavements tested at the same time in certain cases exhibited equivalent or significantly lower roughness levels after 15 or more years service. The limited sample of bridge decks tested in 1963 indicated theat these surfaces were of "Very Poor" riding quality.

In the fall of 1967, the Department's Division of Research purchased a BPR-type roughometer. After acquiring the roughometer, approximately six months were spent in making familiarization runs, in comparing the output of the New Jersey device to that of other roughometers, and in collecting data on bituminous overlays. In mid-1968, data collection began on the projects described in this report: new construction on new alignment.

As a complement to determinations of relative smoothness made with the roughometer, a 10-foot rolling straightedge was used concurrently to survey selected bridges and sections of pavement. One objective of this straightedging was to provide a smaller scale, more readily interpretable indication of the surface characteristics and sources of roughness on the measured surfaces than that provided by the roughometer. A second equally important objective was to determine the potential of the straightedge as a construction control/acceptance device in this State.

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*Massachusetts, New Hampshire and Vermont

PART II: ROUGHNESS MEASUREMENT EQUIPMENT AND TEST METHODOLOGY

2.1 ROUGHOMETER

2.1.1 Nature of the Device: As shown in Figure 1, the roughometer consists of a test wheel mounted on a rectangular towing frame thru two single-leaf springs and cylindrical damping devices. As the roughometer is towed along the roadway at a standard speed of 20 mph, the test wheel deflects with respect to the towing frame in proportion to the roughness of the road. The amount of differential movement between the test wheel and the high mass frame is automatically measured by electronic equipment and reported as the "Roughness Index" (RI) in inches per mile.

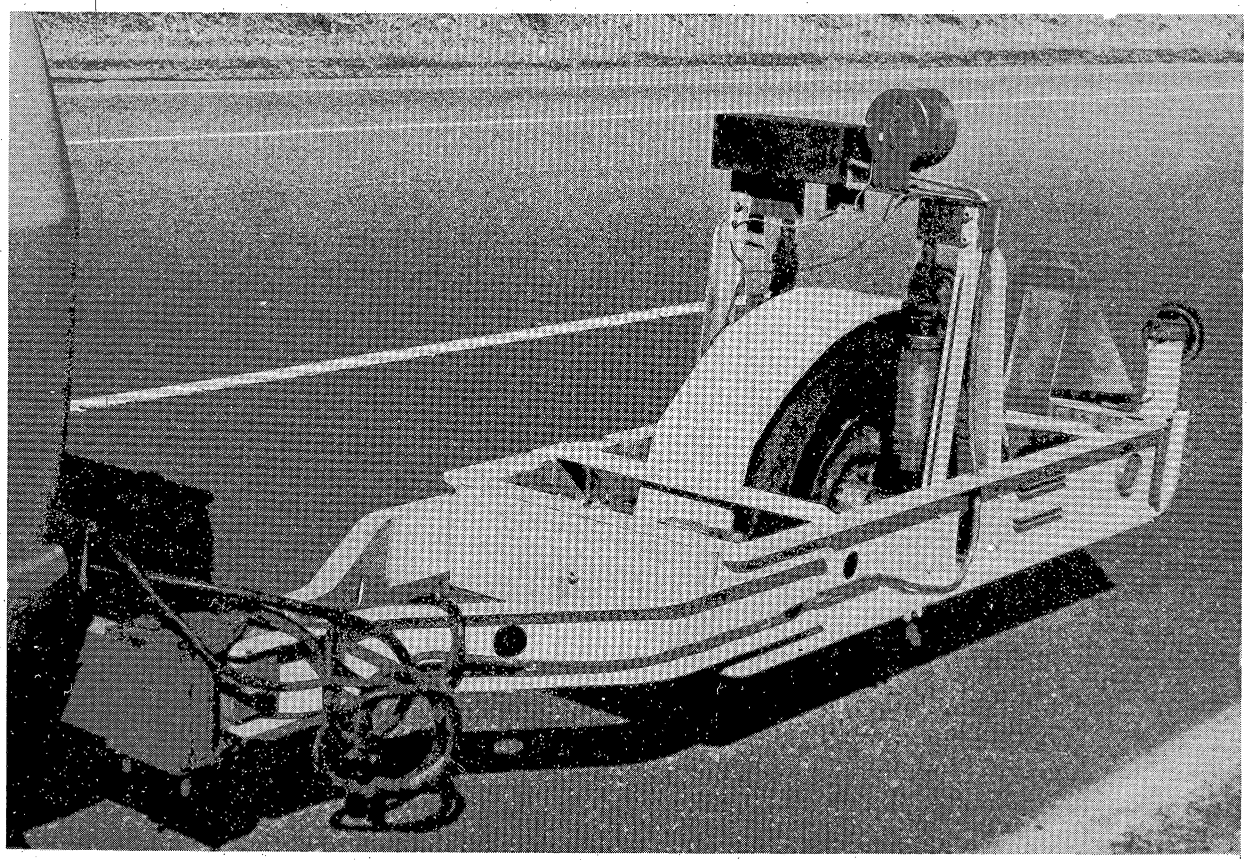

FIGURE 1. The New Jersey Roughometer

2.1.2 General Testing Procedures: As project conditions permitted, roughness determinations were made on all lanes and wheelpaths for the entire length of the paving projects selected for study. A large sample size is particularly desirable in collecting roughometer data since a wide range of roughness levels is usually encountered on individual projects*.

The Roughness Index reported for each project is the average of the RI's obtained for each one-fourth mile increment of pavement, with an individual roughness value being the average of at least two consecutive measurements.

When "pavement" roughness is described, the roughness of any included bridges has either been (proportionally) corrected for or eliminated from the averaging process.

2.1.3 Evaluation Criteria:

FHWA Adjective Rating System: Perhaps the most widely applied criteria for evaluating roughometer output, and that given emphasis in the present report, was developed by the Federal Highway Administration. The FHWA qualitative rating system evolved from an analysis of the level of riding quality actually achieved in practice, based on a sampling of 580 miles of new rural Interstate construction in 17 states.

The adjective ratings corresponding to particular roughness levels for new pavements designed for the above service are presented in Table 1.

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*The mean range of roughness observed on individual New Jersey paving projects is 62 inches/mile on concrete and 46 inches/mile on bituminous projects.

Table 1. FHWA Roughness Evaluation Criteria

Roughness Index (Inches Per Mile)		Adjective Rating
Bituminous Pavement	Concrete Pavement	
below 54	below 67	Outstanding
54-66	67-81	Excellent
66-82	81-99	Good
82-102	99-121	Fair
Above 102	Above 121	Poor

At least 20 states have conducted pavement evaluations using a roughometer and, in a number of cases, have employed different rating criteria than that promulgated by the FHWA. This use of individualized roughness evaluation guidelines is a reflection of the fact that differences in the output of various roughometer models exist, as well as differences in the prevailing level of riding quality. However, while the use of the FHWA guidelines is not completely standardized, responses to a questionnaire indicate that when alternate criteria are employed, they are generally patterned after that of the FHWA. As an example, Table 2 shows the FHWA criteria compared to guidelines which have been used in evaluating concrete pavement in several states. The principal modifications made by the states shown in this sample are the combination of the FHWA's "Outstanding" and "Excellent" ratings into a single "very smooth" category (less than 80 inches/mile) and the occasional addition of a "very rough" category. Each of these states uses essentially the same cutpoff point between a "Fair" and "Poor" riding quality pavement: 120 to 125 inches/mile.

TABLE 2

Comparison of Roughness Evaluation Guidelines from Various Agencies (Concrete Pavement)

FHWA		States A and B		State C		State D*		State E**	
RI	Rating	RI	Rating	RI	Rating	RI	Rating	RI	Rating
< 67	Outstanding	--	--	--	--	--	--	--	--
67-81	Excellent	< 75	V. Smooth	< 80	V. Good	< 80	Excellent	< 80	V. Smooth
81-99	Good	75-90	Smooth	80-100	Good	80-95	V. Good	80-100	Smooth
99-121	Fair	90-125	Sl. Rough	100-120	Fair	95-110	Good	100-125	Acceptable
> 121	Poor	125-170	Rough	> 120	Rough	110-120	Fair	125-160	Rough
--	--	170-220	V. Rough	--	--	> 120	Poor	> 160	V. Rough

*Used for both bituminous and concrete; state D is thus less critical in rating bituminous pavement than the FHWA.

**System used in the 1960's; state E presently employs FHWA criteria.

Pavement Serviceability - Performance Concept: While the FHWA adjective rating system is the principal yardstick employed to gauge the quality level of pavements described in this work, it is important to note that the relevance of roughometer data fundamentally accrues from the proven ability of such data to measure user opinion. In this regard, the estimate of user opinion provided by roughness measurements is the major factor in determining pavement performance thru application of the "Pavement Serviceability - Performance" concept[1] developed at the AASHO Road Test.

The pavement serviceability concept is in essence a statement of the proposition that the degree of acceptability of a given pavement should be based on the opinion of the road user. The finding which permitted application of the serviceability concept was the discovery that the subjective judgement of a representative cross-section of road users could be closely estimated through the use of equations statistically developed from physical measurements of pavement characteristics, including wheelpath roughness.

In the practice of developing serviceability equations at the Illinois test and in a subsequent large-scale satellite study at Purdue University[2], panels of judges consisting of highway professionals and laymen rode the selected roads and rated them on a scale of 0 to 5, in order of increasing acceptability. The panel rating was then correlated with significant physical pavement characteristics in a regression

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[1]Carey, W. N. Jr. and Irick, P. E. "The Pavement Serviceability - Performance Concept", HRB Bulletin 250, pp. 40-58 (1960)

[2]Yoder, E. J. and Milhous, R. T. "Comparison of Different Methods of Measuring Pavement Condition", NCHRP Report 7 (1964)

equation of the general form

$$PSI = C_0 - C_1 F_1 - C_2 F_2 - C_3 F_3 \qquad \text{(Equation 1)}$$

Where PSI = Present Serviceability Index = estimate of mean user opinion on a scale of 0 to 5 as to the ability of a specific section of pavement to serve high-speed, high-volume, mixed traffic at the time of the evaluation.
C = coefficients
F = measured factors of pavement roughness, cracking and patching, and rutting

Once an initial serviceability index is determined for a given pavement,the performance of that pavement is then defined in terms of the decrease in PSI with increasing load applications. Simply stated then, the PSI measure of pavement performance is based on a history of the estimated opinion of highway users as to the level of service provided.

The objective information as to the condition and estimated remaining service life of pavements obtainable thru application of the present serviceability concept has been used by numerous states to compare alternate pavement designs and to assist in programming rehabilitation work. As an adjunct to descriptive ratings of New Jersey pavement roughness data made using the FHWA guidelines, this data is also discussed to a limited extent in terms of Present Serviceability equivalents. Such discussion principally centers on the fundamental applicability (or lack of applicability) of the serviceability concept to design and maintenance decisions in New Jersey.

Unlike the FHWA criteria for new Interstate construction, a user rating resulting from application of the PSI concept will not specifically reflect on the age or class of service provided. It thus might be expected that, given a particular level of roughness, a pavement will be rated less severely according to the PSI system rather than the FHWA system. To insure that New Jersey data is given the appropriate interpretation in terms of PSI, it would be necessary to conduct a statistical study to determine a unique equation reflecting our particular equipment and local conditions or to conduct an in-depth correlation with equipment for which a PSI equivalency has been developed. As an alternate to these measures, equations 2 and 3 have been adopted for this work. These equations -- subsequently referred to as the "Guidelines" equations -- are generalized[3] formulas resulting from experience with eight BPR-type roughometers over a considerable number of test sections at the AASHO and Purdue test sites.

Concrete Pavement

$$PSI = 11.10 - 3.67 \log RI - .09 \sqrt{C + P} \quad \text{(Equation 2)}$$

Bituminous Pavement

$$PSI = 11.29 - 4.11 \log RI - .01 \sqrt{C + P} - 1.23RD^2 \quad \text{(Equation 3)}$$

Where:

PSI = Present Serviceability Index (dimensionless)
RI = Roughness Index, inches per mile
C = Linear feet of cracking per 1000 square feet
P = Square feet of patching per 1000 square feet
RD = Average rut depth, inches

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[3] Irick, P. E. and Hudson, W. R. "Guidelines for Satellite Studies of Pavement Performance", NCHRP Report 2A, Appendix D (1964)

The new pavements considered in this study had negligible cracking, patching and rutting at the time of the roughometer surveys. Thus, initial PSI values are calculated solely on the basis of the observed roughness index. In this connection, it should be noted that in using the described PSI equations to estimate user opinion at <u>any</u> particular time, the predominant weight is given to the surface roughness factor. For example, on a rigid pavement the indicated maximum influence of cracking and patching is only 0.13 units on the 5 unit PSI scale. Similarly, the maximum reduction in PSI for a bituminous pavement having an average rut depth of as much as 1/2 inch is only 0.32 units.

The <u>terminal</u> serviceability level -- that is, the lowest serviceability level that will be tolerated before resurfacing or reconstruction becomes necessary -- is generally accepted to be a value of 2.5 for major highways[4]. This criterion for resurfacing corresponds to a (mid-range) "Fair" user rating according to the evaluation system used at the AASHO Road Test. A minimum acceptable value for the <u>initial</u> serviceability of new construction is not, however, as well established. The FHWA has suggested that a borderline "Fair/Good" according to their rating system constitutes an "Acceptable" as-constructed serviceability level. This would appear reasonable inasmuch as three-fourths of the new pavement included in the FHWA's multi-state roughometer survey equalled or exceeded this rating level. Using equations 2 and 3, the PSI equivalents of this "Fair/Good" suggested minimum rating are 3.7 and 3.3, respectively, on concrete and bituminous pavement.

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[4]"AASHO Interim Guide for Design of Pavement Structures", pp. 5-6 (1972)

2.1.4 Output Variation of the New Jersey Roughometer: A discussion of the output variation of the New Jersey roughometer and attendant implications on the reliability of the roughness data obtained is presented in some detail in Appendix A. The appended discussion is summarized here for the reader interested only in a general understanding of output variability.

To determine the extent to which the overall output of the New Jersey roughometer agrees with that of BPR type devices from other agencies, actual comparison runs have been made with other roughometers. At various times, New Jersey roughometer readings for specific sections of pavement have been compared to readings obtained at the same time by the BPR, Maryland, North Carolina, and New York roughometer models. These comparison tests indicated that the output of the various devices was in reasonable accord. When differences in roughometer output were observed in these comparisons, they generally were in the direction of an underestimate (i.e. low readings) by the New Jersey device.

To determine whether consistent readings were obtained during the course of the work, periodic test runs were made on control sections established on three pavements located near Trenton. As a result of hourly, daily and seasonal trends observed on these sites, it is believed that duplicate readings made with the New Jersey roughometer at a particular time during this study might generally be expected to vary from a representative central value resulting from numerous runs on the pavement under study by a maximum of about $\pm$ 6% on bituminous pavements and by about $\pm$ 8% on concrete.

As will be described, a significant correlation was observed to exist between the roughometer and rolling straightedge data collected in this work. Thus, comparison of the data output from the two devices provided a reciprocal "reasonableness" check.

2.1.5 Problems Associated with the New Jersey Roughometer: While the New Jersey roughometer has provided useful, reasonably reliable roughness information, considerable difficulty was encountered in keeping the device operable at certain stages of the work. For various reasons, the equipment was unavailable for a portion of 1969, for most of 1971 and the entire year 1972. The earliest problems encountered were of a relatively routine, but nonetheless time-consuming nature (i.e. replacement of faulty gears, springs, electrical and mechanical cables, minor electrical components, etc). The later, more lengthy periods of downtime were associated with either the replacement of major mechanical or electrical components (e.g. inverter, damping assembly) or involved considerable troubleshooting.

As a consequence, the roughness of certain of the later studied projects was gauged by measurements made with the BPR prototype roughometer -- loaned to the Department for several weeks in 1972 -- or by straightedge measurements alone.

To provide back-up for the roughometer in any future riding quality studies, the Department has made arrangements to purchase a "Mays Ride Meter". While the basic operation of this device is similar to the roughometer, it differs from the latter principally in that the roughness detection apparatus is contained in a passenger vehicle rather than in a towed trailer, with the indicated roughness being based on relative motion between the car axle and chassis. Also, test speeds more closely resembling actual highway speeds can be employed (40 or 50 mph versus 20 mph). In the Mays Meter, roughness index is determined by measuring the length of a paper record depicting individual axle excursions rather than from an electronic display of roughness count.

2.2 ROLLING STRAIGHTEDGE

2.2.1 Nature of the Device: The rolling straightedge used in New Jersey consists of a 10-foot aluminum beam that rolls on hard-rubber wheels and suspends an indicator wheel at its midpoint (Figures 2 and 3). As the straightedge is pushed along the roadway, surface irregularities are transmitted from the indicator wheel to an enlarged scale which indicates the magnitude of the deviation (0 to 1/2" in 1/8" increments) and its nature (i.e., bump or depression). The length of the deviation exceeding 1/8 inch in 10 feet is automatically marked on the pavement in red dye by a cam-activated dye release mechanism*.

2.2.2. Objectives and General Testing Procedures: Straightedge data was collected with two basic objectives in mind. The first was to obtain data of a more usable type and scale than that provided by the roughometer on which to judge both the nature of New Jersey pavement roughness and the extent to which certain design features and construction practices add incremental roughness to the finished product. The second objective was to determine the suitability of the rolling straightedge as a construction control and acceptance device in this state.

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*The cam-activated dye release is a Research modification replacing a manual release furnished by the straightedge vendor. An automatic marking system of this type -- standard on certain straightedge brands -- should be specified if additional straightedges are purchased by New Jersey.

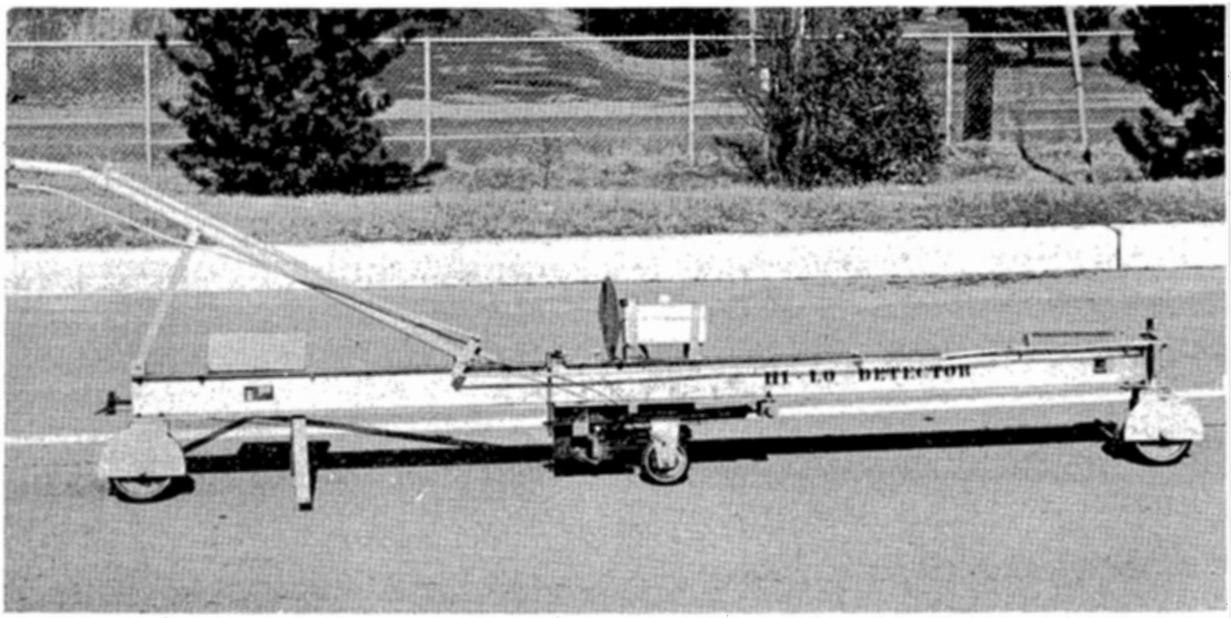

FIGURE 2. 10-foot Rolling Straightedge, side view

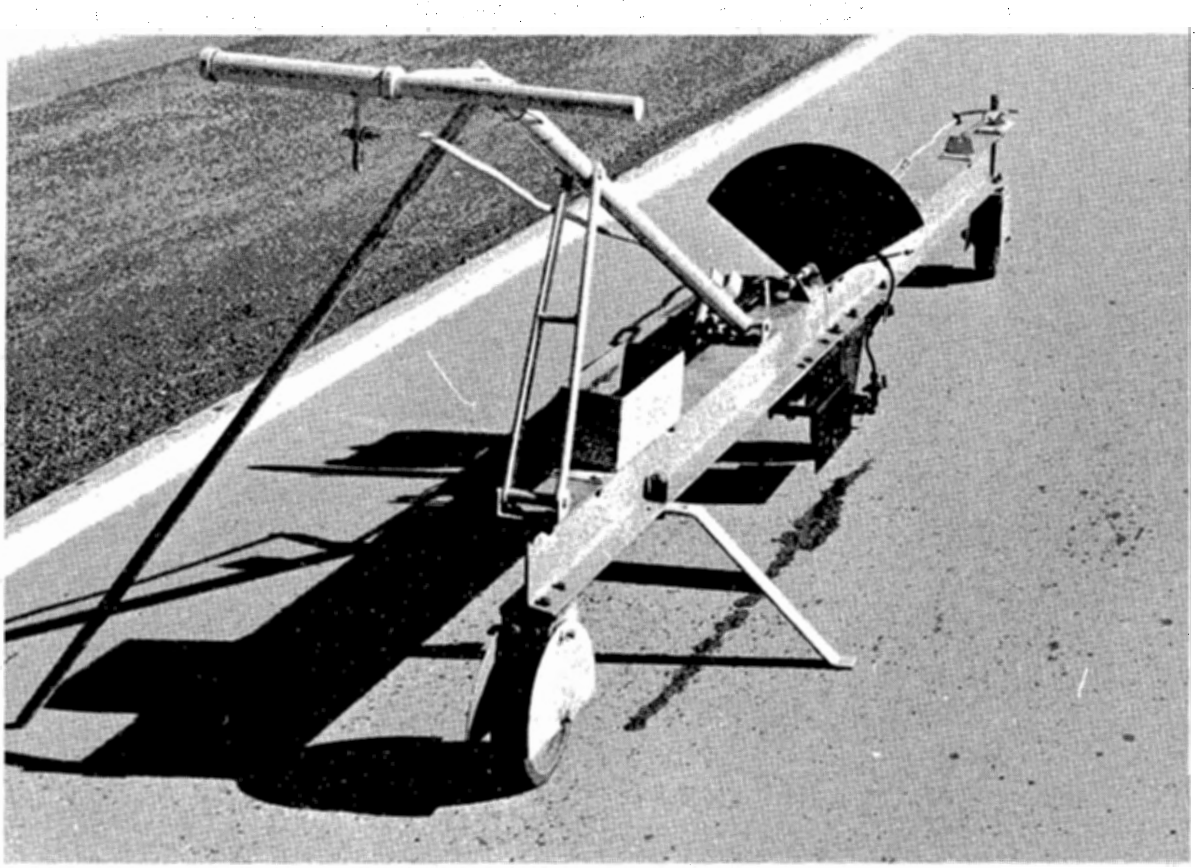

FIGURE 3. 10-foot Rolling Straightedge, operator's view

To some extent, these objectives overlap and thus lend themselves to the same investigative technique: a roughometer-rolling straightedge regression analysis. For example, a correlation between the output of the two devices would not only provide an alternate method of characterizing surface roughness, but would also yield a rational basis for developing a rolling straightedge-based acceptance specification.

To provide a common basis for comparing data, the one-fourth mile data reporting unit employed in roughometer surveys was adopted for use in collecting straightedge data.

In selecting roughometer sections from particular projects for straightedging, a random sampling process was not generally employed. That is, sections displaying extremes in roughness were sought rather than sections having roughness representative of the project as a whole. Thus, care must be exercised in analyzing this straightedge data on an individual project basis (e.g. in simulating straightedge-based specifications).

The data recorded for a straightedge section generally resulted from a single test run and includes the following information for individual surface defects: the deviation length measured to the nearest foot, the <u>maximum</u> vertical excursion of the indicator wheel in eighths of an inch, high or low nature, and location.

An acceptable limit for straightedge deviations measured on a project -- in fact, the format in which such data should be evaluated -- is an unsettled question. For purposes of analysis, data for individual surface defects occurring within a quarter-mile are here expressed in terms of three summary statistics: the total number of deviations exceeding 1/8", the percent defective length and the total area of deviations. Since the simple number of straightedge deviations does not reflect their severity, the latter two data presentations are employed to take into account deviation span length and span length and magnitude, respectively. Equations 4 and 5 define percent defective length and deviation area as used in this work.

$$L_D = \frac{\sum L_i}{L_T} \times 100 \qquad \text{(Equation 4)}$$

$$A_D = \sum(12L_i \times M_i) \qquad \text{(Equation 5)}$$

Where: L_D = Defective length, %

L_i = Length of an individual deviation >1/8" in 10', feet

L_T = Total length tested, feet

A_D = Defective Area, in^2

M_i = Magnitude of an individual deviation, inches

Application of the percent defective length parameter has the advantage that test sections of variable lengths (e.g. bridge decks) can be compared on a common basis. Since defective area is calculated as a rectangle having the <u>maximum</u> deviation magnitude as one side, this indicator statistic might generally be expected to yield an overestimate of actual deviation area.

2.2.3 Influence of Straightedge Characteristics on Data Output: As with many of the various instruments which have been satisfactorily used to measure pavement roughness, the rolling straightedge has inherent limitations or disadvantages which accrue from the design and operating characteristics of the device. The more important observed or reported limitations of the rolling straightedge are as follows:

Non-existent Deviations: While the rolling straightedge may indicate that a specific number of deviations exist on a pavement, it is to be realized that certain of the indicated deviations may not be present in reality[10]. That is, as the straightedge passes over a bump (or depression), it may indicate the adjacent pavement to be low (or high) relative to the bump (Figure 4).

Since these apparent deviations are of lesser magnitude than the actual deviation which they reflect, they have generally been found to be prevalent only on rough surfaces (e.g. bituminous bases, bridge decks).

Given that the rolling straightedge might be expected to give an overestimate* of actual surface distortion on a rough surface, it is apparent that supplementary measurements would be required to some extent if corrective action is contemplated. In particular, if grinding of a bridge deck was being considered, additional measurements with a stringline or ordinary straightedge would be necessary. In this connection, deviations which should be checked in particular are those which immediately precede or follow a longer, higher magnitude deviation of opposite (high or low) nature.

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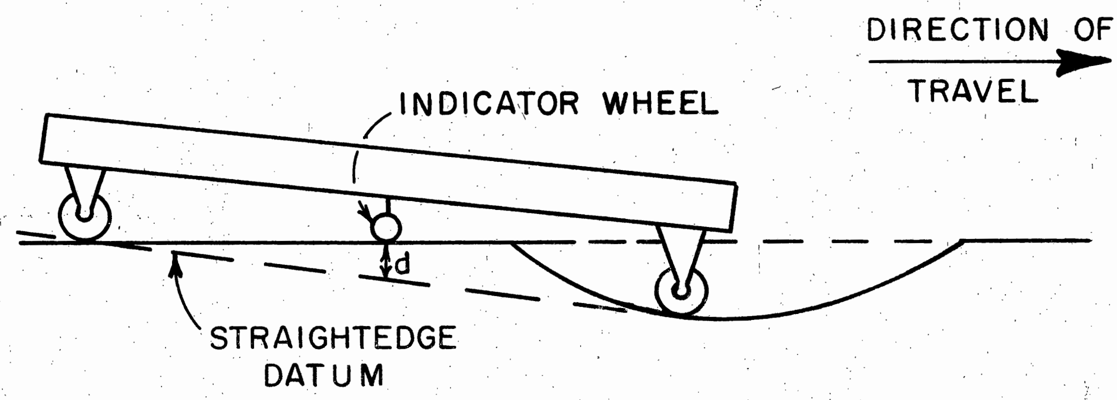
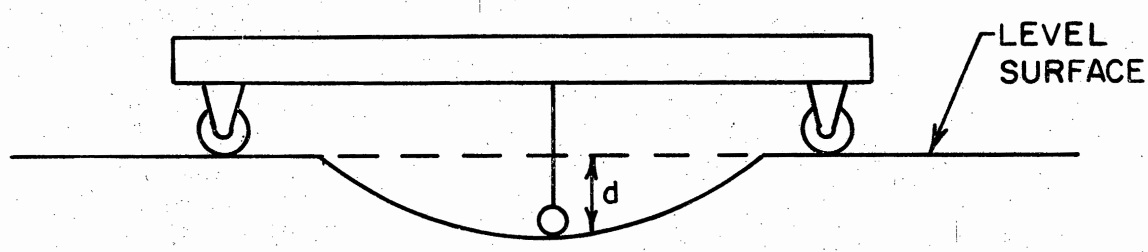
[10]Hveem, F. N. "Devices for Recording and Evaluating Pavement Roughness", HRB Bulletin 264, p. 7 (1960)

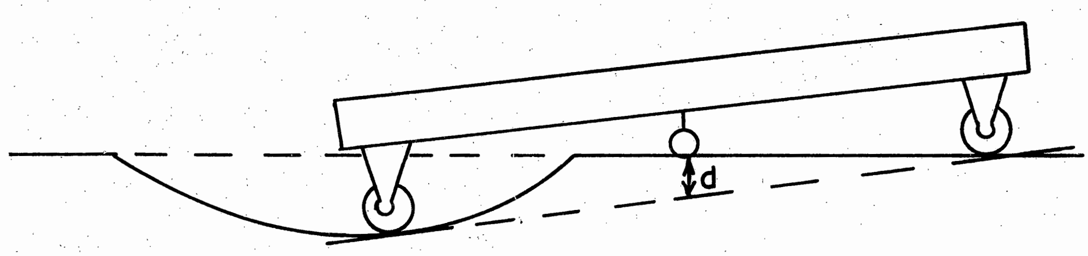
*It is to be realized that an ordinary ten-foot straightedge, if used alone, may not only give a similar overestimate but an erroneous indication of deviation magnitude and high or low nature as well.



POSITION NO 1: RELATIVE HIGH INDICATED



POSITION NO. 2: ACTUAL DEVIATION INDICATED



POSITION NO. 3: RELATIVE HIGH INDICATED

FIGURE 4: SKETCH SHOWING POSSIBILITY OF MEASURING NONEXISTENT DEVIATIONS USING ROLLING STRAIGHTEDGE

Influence of Low Magnitude Deviations: The smallest deviation magnitude measured and marked on the pavement by the New Jersey rolling straightedge is 1/8 inch. There are indications that smaller, unmarked surface defects are sometimes prevalent on and detract from our pavement riding quality[11]. This is evidenced by the fact that on certain sections of pavement having a relatively high roughometer reading, few deviations of 1/8 inch or more were observed, but the straightedge indicator constantly bounced back and forth between the 1/8 inch high or low graduations.

While such straightedge "chatter" has been observed on both concrete and bituminous pavements, in New Jersey, this effect is more prevalent on the various (base thru top course) surfaces of flexible pavements.

This small-scale unevenness indicated by the straightedge may to some extent be a function of the materials used (i.e. texture) in the case of bituminous binder. However, it is believed that on finished bituminous and concrete surfaces, "chatter" is predominantly a reflection of undulations introduced by construction methods or equipment. Texture does not explain, for example, within-project chatter variations observed where no apparent changes in material occurred.

One state using a rolling straightedge for acceptance testing employs procedures to minimize the effect of the small asperities reflected as "chatter". In that state, all rolling straightedge measurements are supplemented by normal straightedging, including places where plus to minus swings of the deviation indicator are observed. If the differential movement exceeds 1/8" on a concrete pavement, correction by grinding is made.

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[11] For a discussion of a similar situation observed in another state, see Hankins, K.D. and Orellana, H. "Development of a Construction Control Profilograph", Texas Highway Department Research Report 49-3F, pp. 1-3 (August 1968).

Influence of Deviation Wave Length: Hveem[10] has noted that it is in the nature of any 3-wheeled roughness measuring device that certain combinations of short wavelength deviations might not be indicated. For this to occur with the New Jersey device, a situation would have to occur in which the pavement was shaped somewhat like a sine wave of 5 foot wavelength.

While it is possible that some such cyclic pattern of defects may be present in New Jersey pavements, it is the writer's opinion that long wavelength deviations represent a more probable class of defects which would be detected by the motorist but not by the straightedge. An upper boundary for measured wavelength is, of course, not unique to the rolling straightedge.

2.2.4 Repeatability of the New Jersey Rolling Straightedge: At various times during the course of this study, informal checks were made on the accuracy and precision of the New Jersey rolling straightedge. Apart from frequent checks on the calibration* of the device itself, accuracy checks consisted of comparisons of rolling straightedge output to stringline and (normal) straightedge measurements. Expectedly, these comparisons indicated that a calibrated straightedge yields a valid representation of the actual nature of surface defects.

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*The first step in the calibration procedure is to mount the straightedge in a wooden instrument stand and check for looseness or wear of any part. A spring-loaded string line is then passed from the front to back of the reference beam and across the travel wheels. The actual movement of the test wheel relative to the string line zero and the dye release off/on is checked against the indicated movement for each division of the "High" side. After slipping 1/2" shims between the travel wheels and stringline, the process is repeated for the "Low" side. Any necessary adjustments can usually be made with small hand tools.

In late 1972, a series of short and long-term repeatability tests were undertaken to quantify previous informal observations as to the precision of the New Jersey rolling straightedge. In the present work "short-term" refers to measurements made within a particular day or one day apart, while "long-term" applies to repeat measurements made weeks or months apart.

Since short-term data minimizes the major sources of variability in the straightedging process (i.e. errors in calibrating the device and in following the same line of travel), the principal significance of this type data is in determining the <u>capability</u> of the rolling straightedge to pinpoint roughness on <u>future</u> projects, particularly in an acceptance testing situation. The long-term repeatability tests were undertaken to provide some insight as to the possible magnitude of variability associated with data obtained over an extended period, such as that described in the <u>present</u> report.

Based on this repeatability testing -- the details of which are presented in Appendix B -- several conclusions appear warranted. The collected short-term data indicates that the rolling straightedge as used in New Jersey can, within a given day, provide a precise measure of the surface characteristics of pavements ranging from smooth to rough. More specifically, the observed standard deviations suggest that measurements resulting from a single, quarter mile pass with the rolling straightedge will vary from the mean value of numerous repeat runs on the subject section during the same day within a maximum of about $\pm$ 2-3 defects, $\pm$ 0.5 percent defective length (equivalent to $\pm$ 6-7 feet of measured length), and $\pm$ 9 square inches of defective area (equivalent to $\pm$ 6 feet of 1/8" deviation). On a relative basis, the short-term repeatability of each of the three straightedge parameters is approximately the same ($\pm$ 6-10% of the mean).

The accuracy of the readings within a particular day and their subsequent repeatability at a later date are dependent upon factors which can generally be controlled by the user. The most important in this regard is the calibration of the device: If the rolling straighteedge is used in a critical application such as acceptance testing, calibration must be checked each testing day. If readings on a particular test profile line are to be repeated at a later date, it would appear worthwhile to lay out guide marks on the pavement so as to minimize variability associated with the straightedge line of travel, particularly for interior lanes and wheelpaths.

While it is difficult to proportionally assign total variation to specific sources, the long-term data collected in this repeatability study does indicate the presence of calibration errors. When such calibration differences occurred, they entailed a relatively small decrease in the precision with which the straightedge could detect the number and length of deviations. In contrast, calibration errors significantly diminished the precision of the more sensitive defective area parameter. Since deviation area is based on the maximum magnitude encountered in a particular span, a difference in calibration sufficient to cause a relatively small number of missed or foreshortened defects may cause 100% error in deviation area. This greater precision for the number and length statistics and their simplicity of calculation relative to defective area indicate them to be more useful parameters.

Variation in the magnitude of detected deviations between measurements made at long-term intervals will generally be limited to the smallest division on the deviation dial (1/8"), with the actual error being on the order of $\pm$ 1/16".

PART III: CONCRETE PAVEMENT RIDING QUALITY RESULTS

3.1 ROUGHOMETER DATA

3.1.1 Average Project Roughness: Table 3 presents a summary of roughness data obtained on 14 recently constructed concrete paving projects. This sample comprises nearly 250 miles of roughometer data (998 quarter-mile sections).

The mean Roughness Index of these individual projects ranges from 101 to 154 inches per mile and averages 122 inches per mile. According to the FHWA Criteria, the average level of riding quality provided on eight of the projects is "Poor" while the remaining six would be rated as "Fair". The average level of roughness of the project means (122 inches/mile) corresponds to a borderline "Fair-Poor" FHWA riding quality rating.

In comparing individual projects, it should be noted that these pavements were surveyed at varying intervals after opening to traffic. Specifically, eleven projects were surveyed within four months of opening, two within two years, and one (I-287, 6F and 7B) after 45 months. It might be reasonably assumed that roughometer measurements obtained for 11 of the projects are representative of the "as-constructed" state. Two of the projects would be considered "new" pavement, but should have some tolerance applied to the indicated readings to place them on a common as-constructed basis. The I-287 project should probably not be considered on the same basis as the other projects.

TABLE 3: Summary of Roughometer Data for Concrete Paving Projects

Project		Date Opened t_1	Date Surveyed t_2	$t_2 - t_1$ (Months)	Length of Project	Length Surveyed	Roughness Index (inches/mile)			Initial PSI
No.	Route and Section						Range	Mean	FHWA Rating	
1	I-80,1N	--	8/72	0	4.1 mi.	3.0 mi.	100-220	154	POOR	3.07
2	I-295,3B&4A	10/72	7/72	0	4.2	2.0	92-174	114	FAIR	3.55
3	I-295,2L&3A	10/72	7/72	0	3.4	1.5	90-165	124	POOR	3.42
4	I-280,6G	6/72	8/72	2	1.0	.75	112-152	124	POOR	3.42
5	I-280,6L&7E	6/72	8/72	2	1.0	.75	112-132	122	POOR	3.44
6	NJ 21(FWY),4A	12/68	12/68	0	1.3	1.0	96-161	139	POOR	3.24
7	I-295,1R	12/68	10/68	0	5.9	3.0	90-139	113	FAIR	3.56
8	I-78,2G	10/68	11/68	1	11.3*	2.0	103-158	128	POOR	3.37
9	I-287,7C	10/68	11/68	1	3.8	2.0	92-156	124	POOR	3.42
10	I-78,2M&3E	7/68	11/68	4	3.1	2.0	93-144	112	FAIR	3.58
11	I-78,3F	12/67	4/68	4	4.1	4.0	74-150	101	FAIR	3.74
12	I-78,3G	7/66	5/68	22	5.4*	3.5	76-140	107	FAIR	3.65
13	I-287,6E	7/66	10/68	27	2.4	1.0	108-158	127	POOR	3.38
14	I-287,6F&7B	7/66	4/70	45	2.0	1.5	101-147	119	FAIR	3.48
						AVERAGES	62	122	POOR	3.45

*includes bituminous portion of project

Unfortunately, there is no relationship known to the writer which might be applied specifically to New Jersey data to extrapolate in-service roughness readings to an as-constructed condition. However, yearly increases in roughness for concrete pavements have been reported for other states. For example, Alabama[12] reports an average increase of 3 inches per mile per year, while 4-5 inches per mile is considered "normal" for Michigan[13] conditions. In view of the high traffic volumes and truck percentages prevailing in this state, yearly increases at least as high as those reported for other states might be expected in New Jersey.

To provide some information in this regard, Figure 5 shows the absolute roughness differences observed from resurveys of 78 test sections selected from three projects subjected to 1-1/2 to 3 years of traffic. As indicated, mixed results were obtained in this small resurvey sample. The I-287 project showed essentially no change in average roughness (actually a slight indicated decrease), while the I-78, 3F and 2G* projects displayed consistent increases averaging 6 and 16 inches per mile per year, respectively.

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[12]Holman, F. L. "Pavement Roughness and Deflection Studies of Alabama Highways", Alabama Highway Department Research Report 41, p. 56 (1969)

[13]Housel, W. S. "Cumulative Changes in Rigid Pavements with Age in Service", HRB Bulletin 328, p. 22 (1962)

*While such was not investigated in this work, the large roughness increase observed for the I-78, 2G project may be atypical in that the influence of pumping is strongly suggested. This type distress was observed even before the project was opened to traffic.

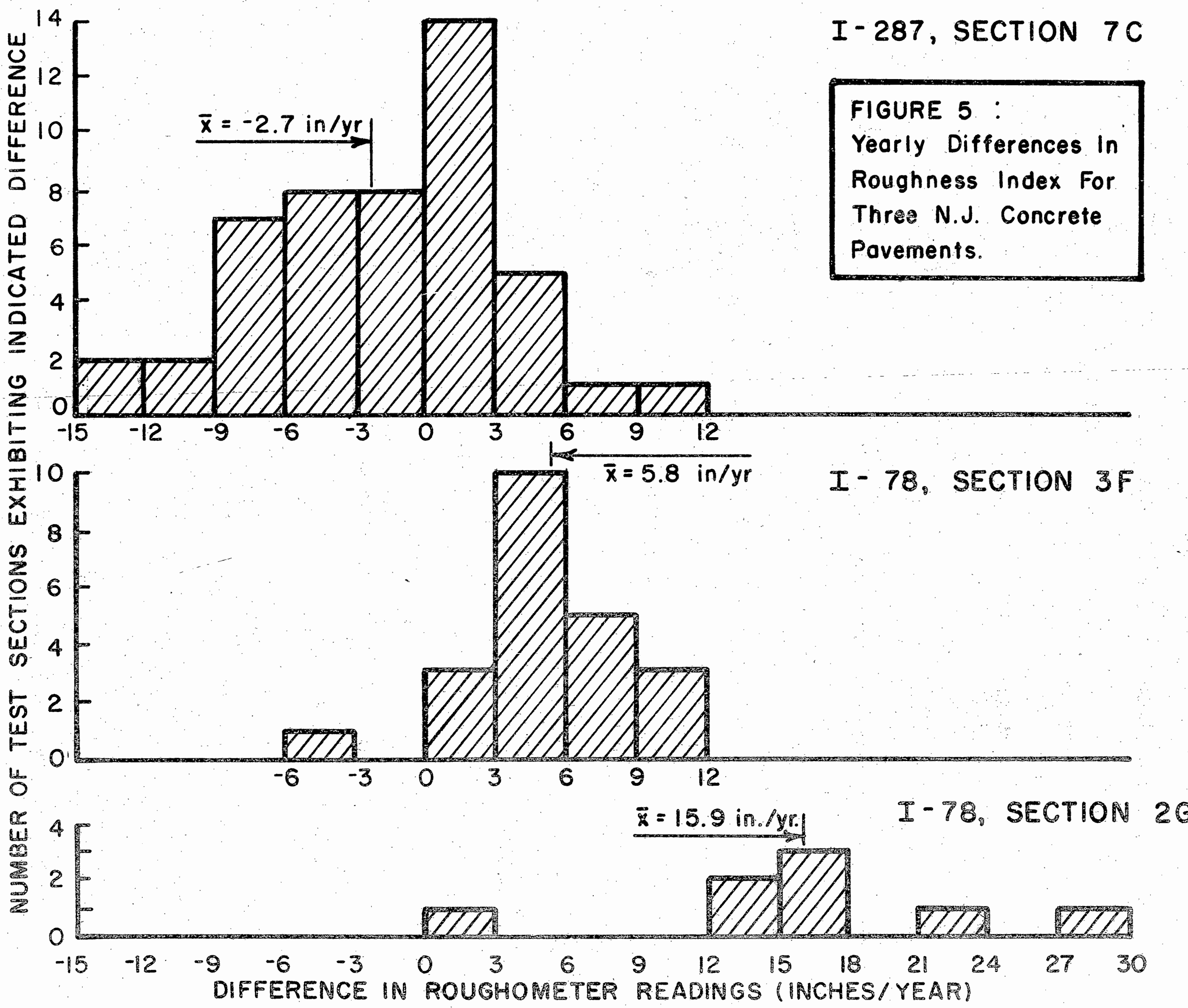


FIGURE 5 : Yearly Differences In Roughness Index For Three N.J. Concrete Pavements.

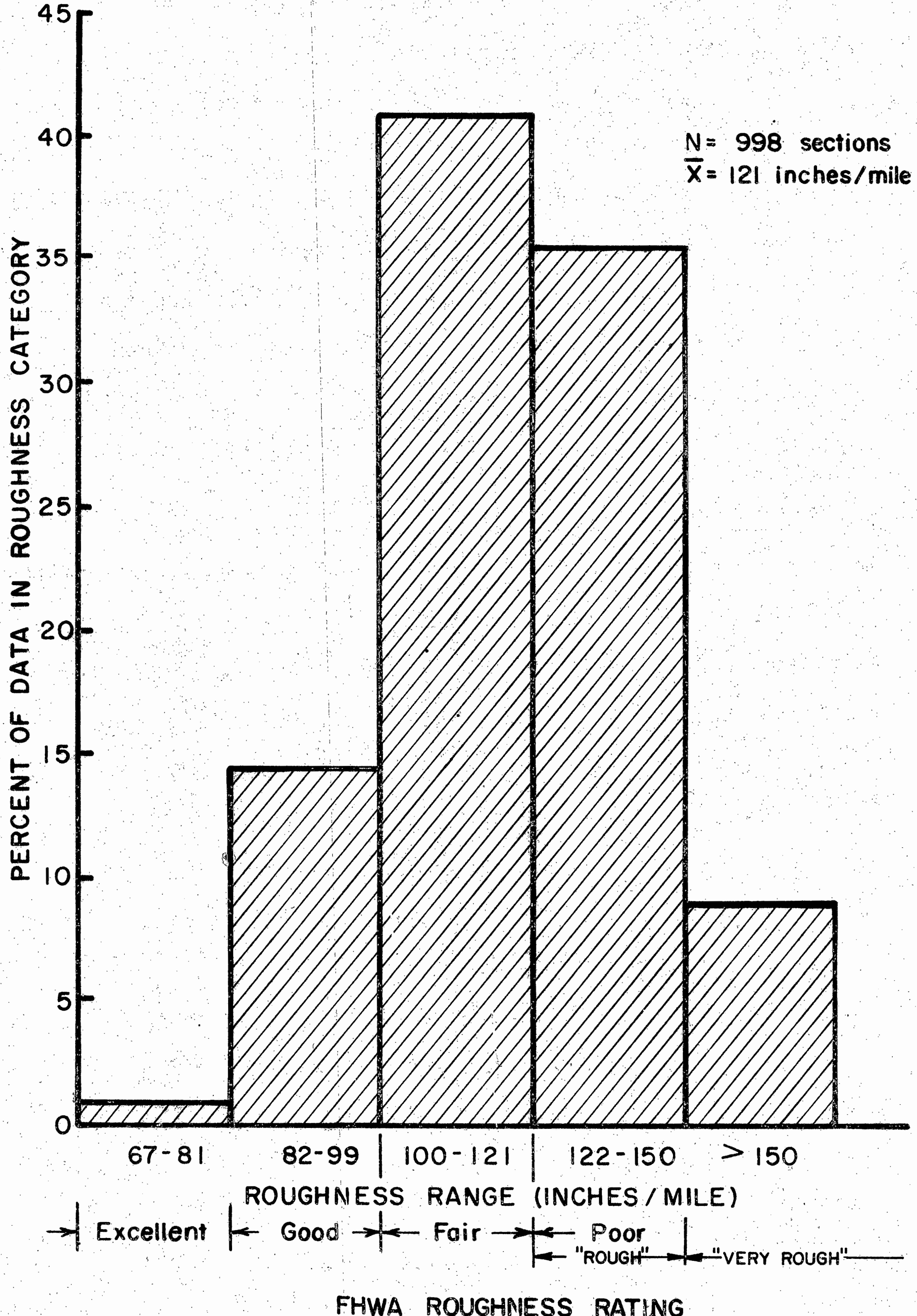
If increases of 6 inches per year or more are typical of New Jersey rigid pavements, the roughness data shown in Table 3 for the I-78, 3G and I-287, 6E projects could respectively be extrapolated to "Good" and "Fair" ratings on an as-constructed basis.

If, as suggested by the FHWA, a borderline "Fair/Good" riding quality rating (RI $\leq$ 99 inches/mile) constitutes a minimum acceptable value for new construction, then only two older projects--I-78 Sections 3F and 3G--would be considered as providing an "acceptable" initial level of service.

3.1.2 Roughness of Individual Test Sections: While the average riding quality rating of each of the studied projects is relatively uniform at "Fair" or "Poor", Table 3 indicates that within a given project, considerable variation was generally observed between the riding quality of individual quarter-mile test sections. Thus, most of the projects have some sections which would merit a "Good" or better rating (99 or fewer inches/mile) and all projects have some sections of "Poor" riding quality. On an average basis, the roughness difference between the highest and lowest rated sections on particular projects amounts to 62 inches per mile.

The riding quality distribution of the 998 individual test sections sampled in this work is shown in Figure 6. When the data is considered on this basis, a somewhat more optimistic view of New Jersey concrete pavement riding quality prevails, with the "Fair" and "Good" riding quality categories predominating. However, less than one-fourth of the sampled sections satisfy the FHWA criteria for "acceptable"

FIGURE 6
Roughness Distribution Of Individual Roughometer Sections
(CONCRETE PAVEMENT)



initial serviceability. The additional category (greater than 150 inches/mile) shown in the poor riding quality zone is arbitrary and represents the writer's opinion of "Very Rough" concrete pavement.

While all of the indicated data represents "pavement" roughness, 122 of the sections (12%) contained one or more bridges. Although the roughness of the included bridges were proportionally eliminated, these sections contained bridge approach and transition slabs (Detail 1, Appendix C*). The roughness of these more difficultly constructed sections, containing multiple short slabs, averages 135 inches per mile ("Poor"). The remaining sections--consisting exclusively of our normal mainline design--average 119 inches per mile (marginal "Fair").

3.1.3 <u>Present Serviceability Equivalents of Roughometer Data</u>: The present serviceability index (PSI) equivalents of the project roughness shown in Table 3 are relatively uniform, ranging from 3.07 to 3.74 and averaging 3.45. When the PSI level of these pavements is considered on the basis of individual test sections (Figure 7), several important points become apparent.

First, the net effect of converting roughness data to PSI equivalents is to reduce the spread of the data, with more than 90 percent of the test sections falling within a single (3.0-4.0) PSI range. If the basis for evaluating the data were the AASHO Road Test criteria (i.e., neglecting the fact that the pavements are new, predominantly Interstate type construction), a "Good" rating would be indicated for this PSI range. This of course is in contrast to the

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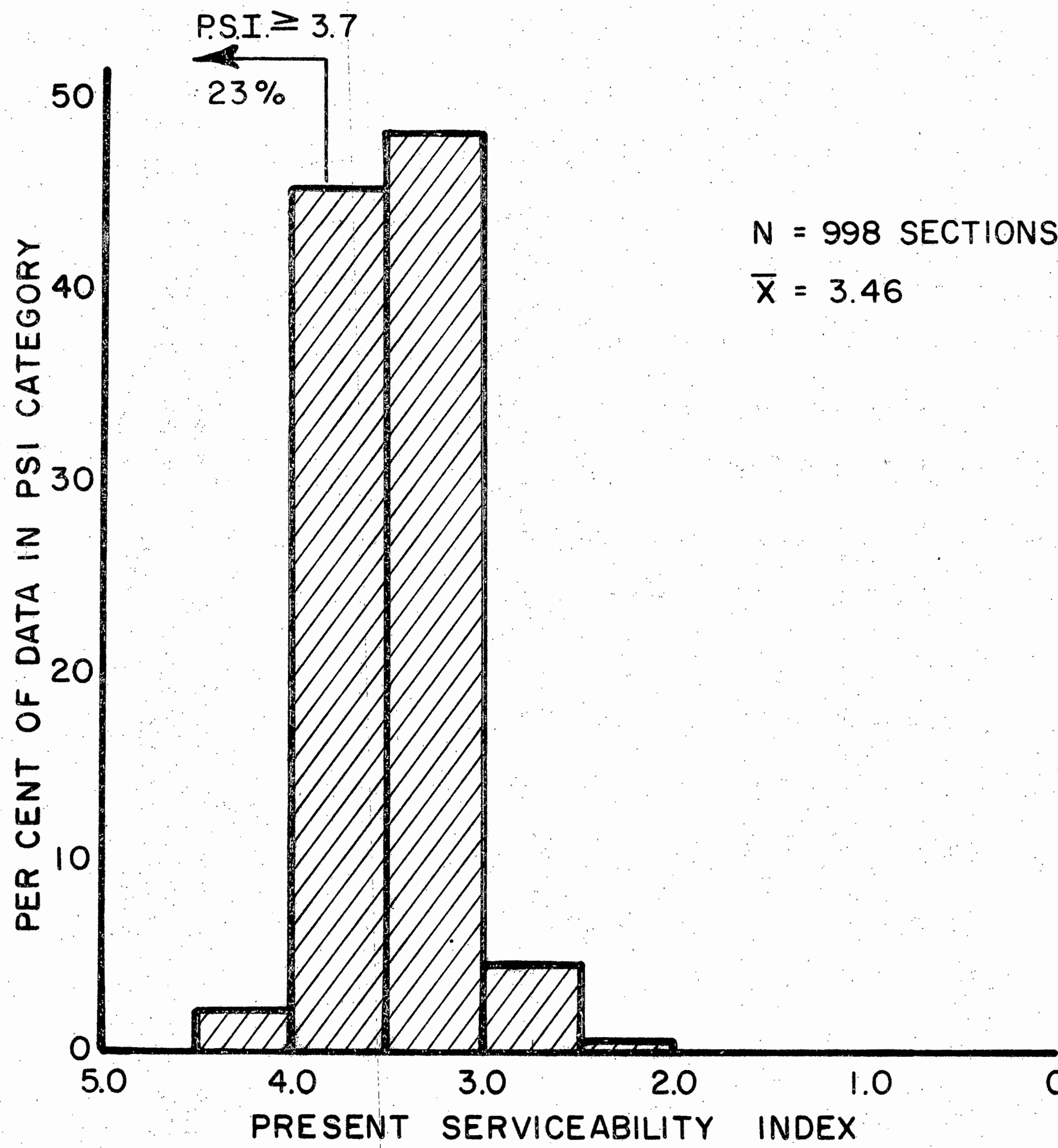
*page 225

FIGURE 7
Histogram Of Roughometer Data Converted To Present Serviceability Equivalents
(Concrete Pavement)



assessment via the FHWA criteria that most of the pavement sections evaluated did not provide acceptable initial serviceability. However, the important and surprising point here is not the higher quality rating indicated by the PSI system, but rather that any single rating in the PSI approach could apply uniformly to the wide range of concrete pavement roughness data collected in this study.

Secondly, and most significantly--given the current as-constructed serviceability level of our concrete pavements and the use of 2.5 as a terminal serviceability index--it appears that the present serviceability concept can have only marginal applicability in New Jersey. That is, in determining the performance record of a pavement--defined as the trend in present serviceability with accumulated axle loads (or time)--it has been indicated[3] as important that a serviceability drop of at least 1.0 from the initial to terminal PSI be available. Slightly less than half of the New Jersey concrete pavement serviceability data would meet this criteria of a one PSI unit differential if AASHO's recommended 2.5 terminal PSI were applied. Thus, due to the probable slight slope of the PSI curve and attendant limited information as to the relationship between serviceability and applied loads, application of the present serviceability concept to many sections of New Jersey concrete would provide little guidance in determining meaningful performance trends.

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[3] Op. Cit., p. 14

3.2 ROLLING STRAIGHTEDGE DATA

3.2.1 Nature and Size of the Sample: A total of 68 quarter-mile test sections of known roughness index have been surveyed with the rolling straightedge. The tested sections were selected from 12 of the 14 previously listed concrete paving projects. An additional straightedge sample from two (slip-form) projects not tested with the roughometer was also obtained and will be described separately.

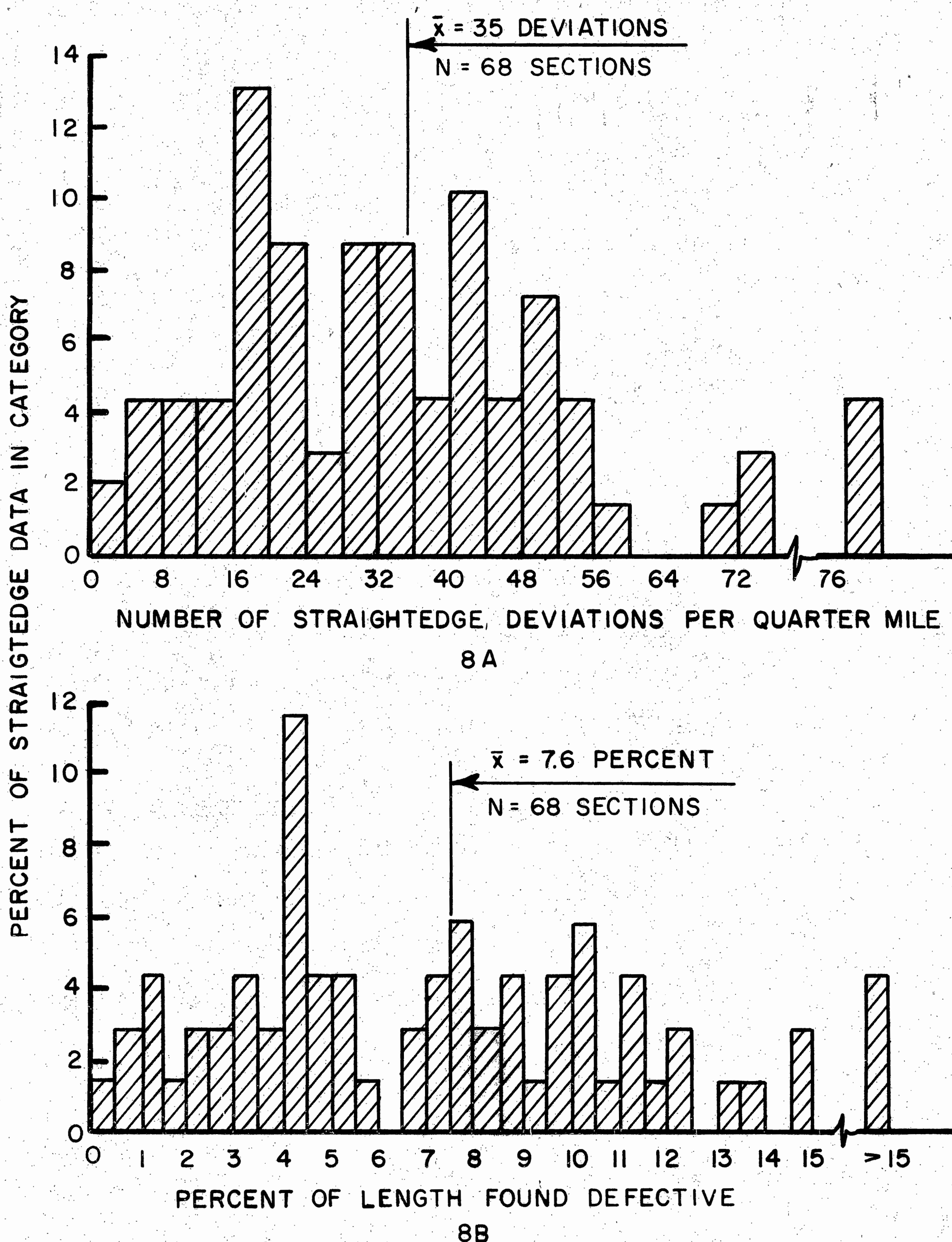
All of the data subsequently referred to is "raw" data in that no attempt has been made to eliminate any reflected (non-existent) deviations. To simplify the analysis, no distinction between high and low deviations is made. (On the average project, highs constitute about three-fourths of the measured defects.)

The number of defects observed in the concrete pavement straightedge sample ranged from 4 to 122 and averaged 35 per quarter mile (Figure 8A). The calculated defective length ranged from less than 0.5% to more than 28% and averaged 7.6 percent of the tested length (Figure 8B). This average percent defective corresponds to 100 feet per quarter mile of deviation exceeding 1/8 inch in 10 feet.

3.2.2 Patterns of Defects and Influence of Joint Roughness: Later sections of this report present conventional regression plots illustrating specific relationships between the various straightedge parameters and the level of riding quality (Roughness Index) provided.

As a first, generalized indication of the surface characteristics of New Jersey concrete, histograms have been prepared illustrating how the number and severity of surface defects changes with roughness levels. Figures 9 and 10 show the average pattern of measured straightedge defects observed on pavements having roughometer readings corresponding

FIGURE 8
Frequency Distribution of Rolling Straightedge Data Sample
(Concrete Pavement)



to "Good", "Fair" and "Poor" rideability respectively. The histogram for "Good" riding quality is a composite of data collected on 12 sections from 5 projects; "Fair" represents 34 sections from 10 projects, and "Poor" is composed of 22 sections from 10 projects.

Before proceeding with a discussion of the subject histograms, a definition of the "joint" roughness indicated on these figures is in order.

The extent of defects occurring in the vicinity of transverse pavement joints was separately recorded so as to determine the relative influence of this design feature on overall roughness. New Jersey and Mississippi are the only states known to employ a pavement design which exclusively uses regularly spaced expansion joints* (3/4" wide, spaced at 78 feet 2 inches). These joints are normally of the formed type, with extensive hand-work being involved in restoring a smooth finish to the surrounding plastic concrete. In deciding which straightedge deviations should be considered as occurring at the joint, it was conservatively assumed that pavement 1.5 feet on either side of the joint proper might be influenced by joint construction practices. Since the rolling straightedge can indicate a deviation to be offset as much as 5 feet from its actual location, deviations measured 6-1/2 feet on either side of the joint are herein defined as occurring at the "joint". A schematic representation of this joint definition is provided in Figure 11.

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*A detail of the New Jersey expansion joint and photographs illustrating the method of construction are contained in Appendix C, Details 2 thru 4 (pages 226-230).

FIGURE 9

TYPICAL DISTRIBUTION OF STRAIGHTEDGE DEFECT MAGNITUDES ON CONCRETE PAVEMENTS OF VARIOUS RIDING QUALITY LEVELS

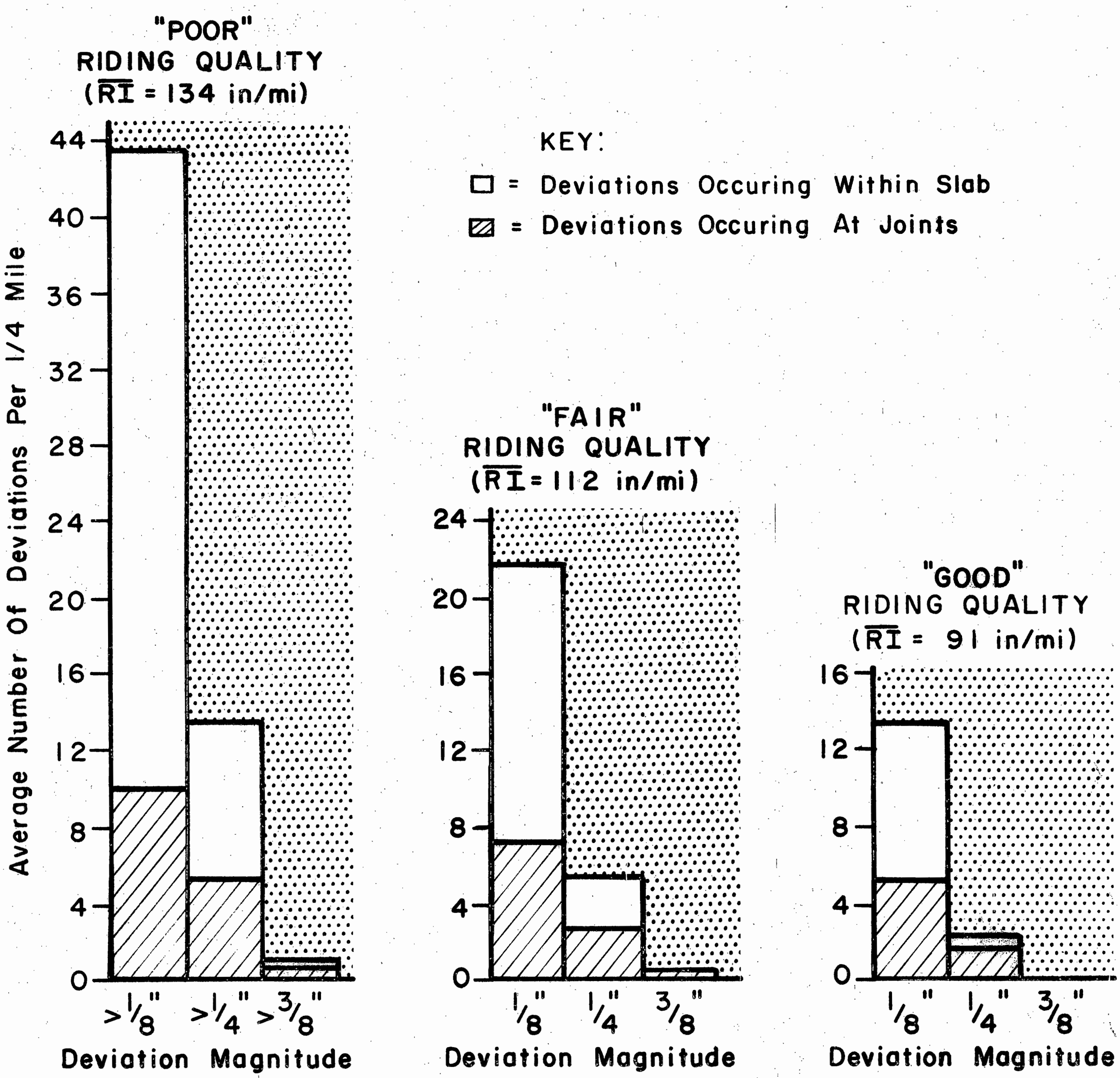


FIGURE 10
TYPICAL DISTRIBUTION OF SURFACE DEFECT LENGTHS ON CONCRETE PAVEMENTS OF VARIOUS RIDING QUALITY LEVELS

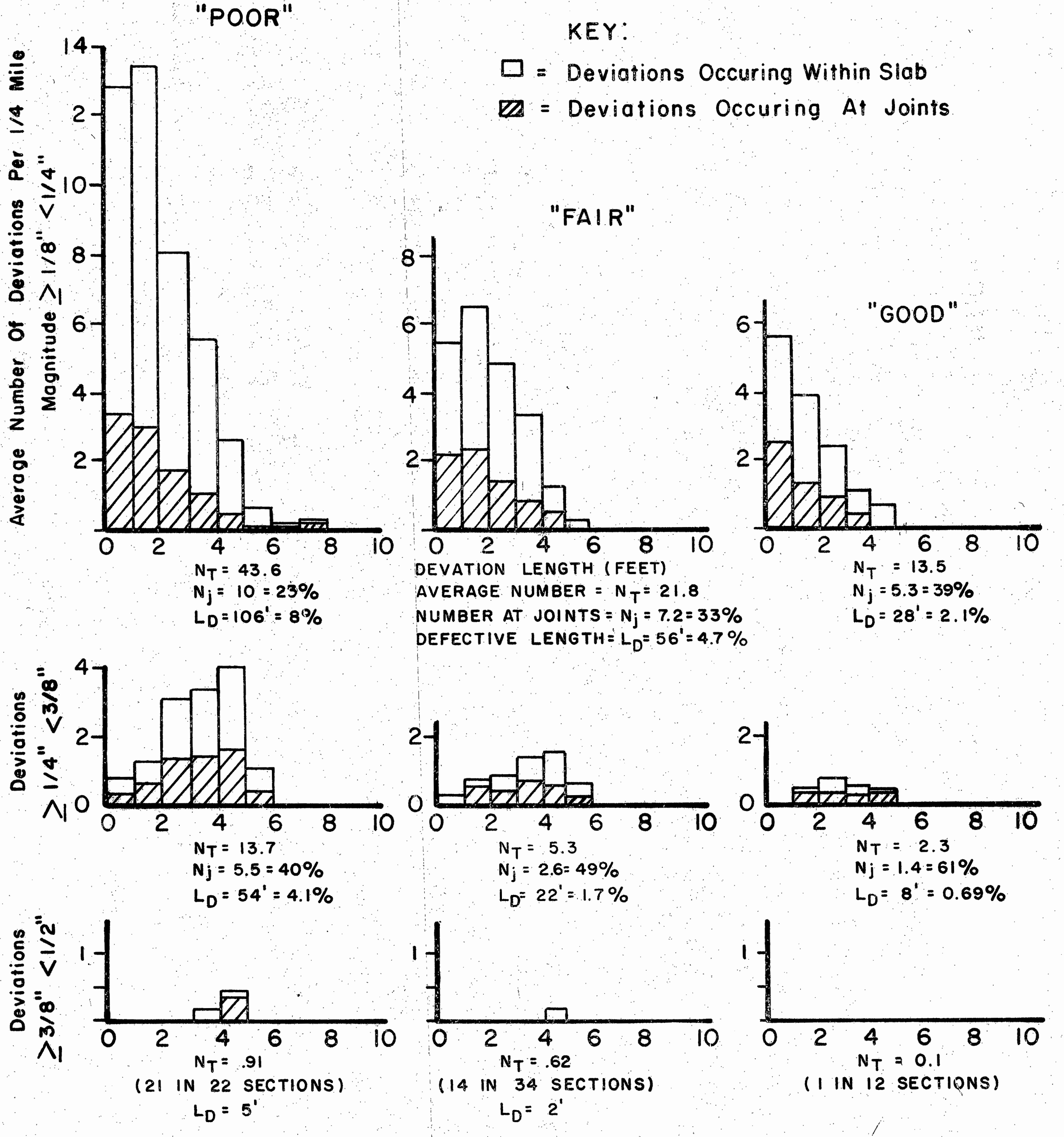
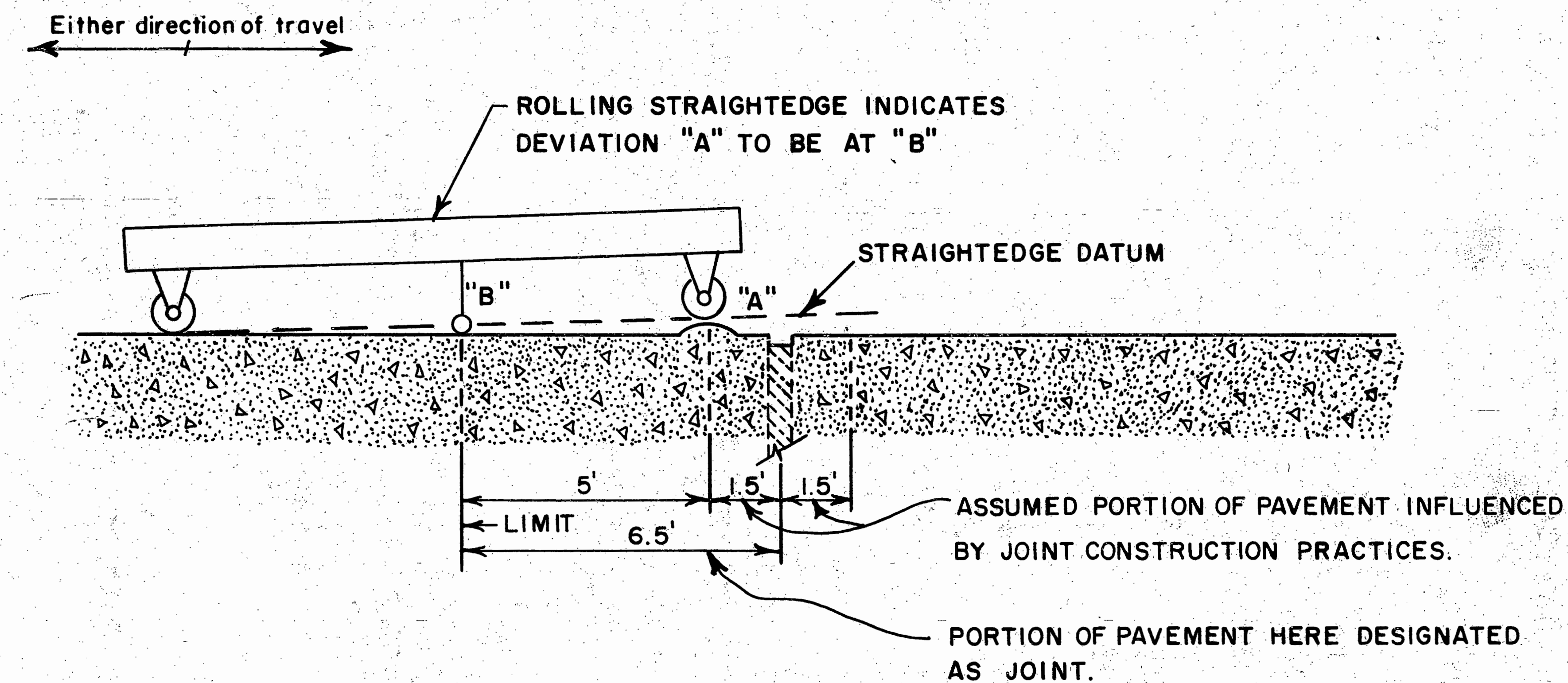


FIGURE II. SKETCH ILLUSTRATING PORTION OF PORTLAND CEMENT CONCRETE PAVEMENT CONSIDERED TO BE INFLUENCED BY "JOINT ROUGHNESS."



Observations as to the indicated average patterns of straightedge deviations for New Jersey concrete pavements shown in Figures 9 and 10 are as follows:

Predominant magnitude and length of deviations: The most common measured surface defect is a short (1 to 3 foot), 1/8 inch deviation. This class of deviation accounts for about two-thirds of the total number on "Fair" and "Poor" rated pavements and three-fourths of the total on "Good" riding surfaces.

Expectedly, when the larger magnitude deviations occur, they are accompanied by an increase in length.

Defect ratios: As might be anticipated, lower-rated pavements show an increasing number of deviations of all magnitudes. For 1/8 inch deviations, the ratio of the average number of defects on Good: Fair: Poor riding quality pavements is about 1:1.5:3. In terms of the average total length of deviations, this ratio becomes 1:2:4.

While an acceptable ride is compatible with some limited number of 1/8 inch deviations, 1/4 inch or greater magnitudes apparently have an inordinate effect on riding quality and should be severely restricted.

Relative influence of joint roughness: Based on the severity and extent of straightedge deviations, several trends are apparent with regard to the overall contribution of joint roughness.

First, on the smoother pavements, a substantial portion of the surface roughness is due to the joint construction practices, joint deviations accounting for about 35 and 45 percent of the total number of defects on "Fair" and "Good" riding quality pavements respectively. On a rough pavement, joint deviations contribute relatively less (25-30%), most of the surface defects thus being associated with the construction of the slab proper. There thus is a general trend for joint roughness to represent a higher proportionate share of overall roughness with increased pavement smoothness.

It is important to note, however, that while the percentage of roughness occurring at joints does vary and illustrate a trend, it is also somewhat centralized about a constant value. Specifically, the joint roughness contribution for about two-thirds of the straightedge test sections falls in the 30 to 50 percent range. On an average basis, about 40 percent of all defects are associated with the portion of the pavement in the vicinity of joints.

A second even more significant trend concerns the <u>severity</u> of joint related defects. For pavements of <u>each</u> roughness category, an increase in the length or magnitude of defects is generally associated with an increase in the relative contribution of the joints. Thus, for example, an average of half of all 1/4 inch and two-thirds of the 3/8 inch deviations occur at the joints. Since these more severe deviations make a larger relative contribution to roughness index, it can in turn be expected that roughness in the vicinity of joints detracts even <u>more</u> from riding quality than the simple proportion of total defects which they represent.

Alternate statements concerning the influence of joint roughness can be formulated by considering the relative length of pavement over which joint defects are distributed. As previously defined, the total length of joint influence for New Jersey's 78 foot slab is 13 feet. Thus, if the smoothness quality in the vicinity of the joints and within the slab itself were equal, only 16.7 percent of the measured defects would occur at the joints. However, since joints contribute an average of about 40 percent of total deviations, deviations of <u>all</u> magnitudes are more than twice as common (i.e. 40/16.7) in the 13 feet surrounding the expansion joint as compared to any equal length within the slab. On this same basis, 1/4 and 3/8 inch deviations occur 3 and 4 times more frequently at the joint.

Apart from their number and generally greater severity, surface irregularities in the vicinity of joints can be expected to exert a further negative influence on user opinion because of the <u>regularity</u> of their occurence. The Road Research Laboratory[17], for example, has noted that rhythmic roughness of a relatively small amount (1/16 to 1/4 inch) is the most objectionable type of roughness on high speed roads.

While roughness introduced during the construction of expansion joints is of course not the only problem in providing more rideable concrete pavements in this State, joint roughness does account for a significant portion of the roughness of the present data sample and thus provides possibly the <u>single</u> most promising area for improvement.

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[17] Kirkham R. H. H. "The Riding Quality of Concrete Roads", Road Research Technical Paper 60 (1963)

3.3 ROUGHOMETER - ROLLING STRAIGHTEDGE CORRELATION

3.3.1 Objectives and a Note on Statistics: The preceding section of the report indicated that there is a definite trend for decreased pavement rideability to be associated with an increasing number and severity of measured straightedge defects. The following comparisons of roughometer and rolling straightedge data for individual test sections are principally designed to better delineate these trends and in particular, to determine what constitutes an "acceptable" level of straightedge deviations measured on a project.

Statistical correlation or regression techniques were used to formulate mathematical expressions relating the output of the rolling straightedge and the roughometer. In assessing the strength of these relationships, various statistical yardsticks have been employed. The following is a very brief description of the general and particular[14] statistical standards applied to the present data:

Calculation of the linear correlation coefficient (r) and comparison to conventionally used standards gives a qualitative measure of the degree of relationship between two variables. The standards applied herein are:

Correlation Coefficient	Relationship Demonstrated
1.0	Perfect
0.9	Very Good
0.8	Good
0.7	Fair
0.6	Poor
0.5 or less	Very Poor

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[14]Hughes, C. S. et al, "Application of Some Statistical Techniques to Experiments in Highway Engineering," Virginia Council of Highway Investigation and Research (Rough Draft; February 1964)

In contrast to the correlation coefficient, the standard error of estimate (Syx) gives a quantitative measure of the degree of relationship between two variables. In the present work, the standard error of estimate is used to provide a statement of the accuracy with which one variable (Roughness Index) can be predicted from the other (the extent of straightedge defects). In this application, use is made of the fact that actual future values of roughness index will be the predicted value (i.e. the value from the best-fit line) within a tolerance of ± Syx in about 68% of all cases and within ± 2 Syx in about 95% of all cases.

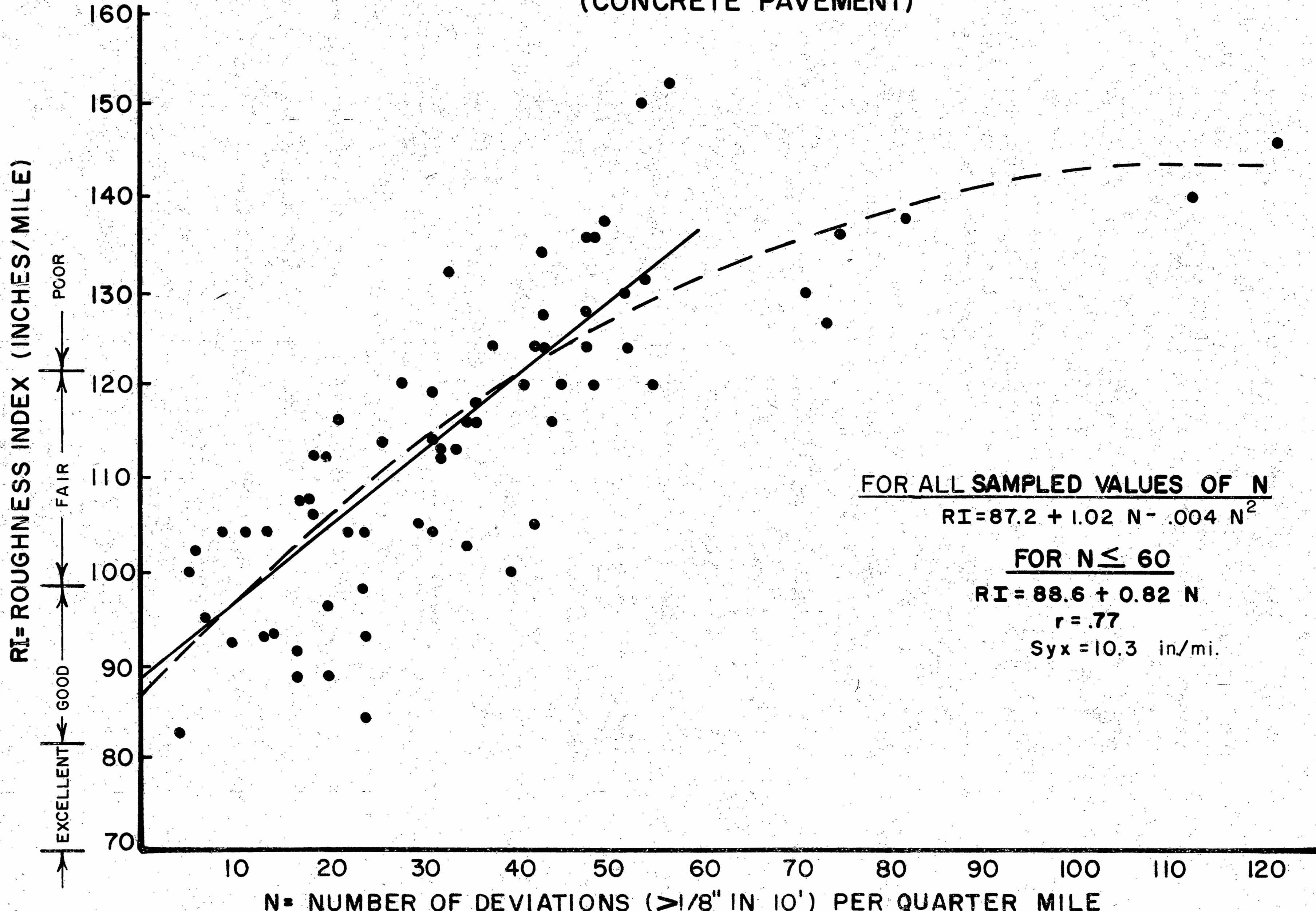
Significance tests are applied to the experimental data of this study essentially to answer the question, "Do I have enough data to say that the observed relationship between variables is not due to chance?" For example, one might obtain a correlation coefficient of 1.0 for 2 data points (perfect relationship), but not expect subsequent data to "perfectly" fit the equation described by the two points. The relative terms used in describing significance range from "high" to "insignificant" for 1% to greater than 10% respective risks that a relationship may be due to chance.

3.3.2 General Characteristics of Regression Plots: The plots relating each of the straightedge parameters (number, length, and area of defects) possess several features in common. A discussion of the general characteristics of these regression plots, using as a particular case the easiest of the straightedge parameters to relate to--the simple number of defects--is as follows:

Overall shape of the curves: Each of the curves displays the characteristic shape shown for the roughness index versus number of defects curve of Figure 12. That is, for pavements of relatively moderate roughness (up to about 15 inches/mile into the "Poor" category), the best-fit curve is a straight line. Thus, in the roughness range of primary interest, a simple linear relationship exists between the output of the two devices. At high roughness levels, the curve departs significantly from linearity.

FIGURE 12

RELATIONSHIP BETWEEN ROUGHNESS INDEX
AND NUMBER OF STRAIGHTEDGE DEVIATIONS
(CONCRETE PAVEMENT)



This observed non-linearity for portions of the curve is at variance with a roughometer-rolling straightedge correlation observed in a Virginia[15] study of (bridge deck) concrete smoothness. In the cited work, a direct relationship was found to exist between the output of the two devices even for very rough concrete surfaces (i.e., up to 50 percent defective and a Roughness Index of 300).

While the purpose here is not to overemphasize the non-linear portion of the regression curve, it is worthwhile to discuss the possible reasons for the difference in curve fit in the region where many defects are present.

It is believed that the indicated non-linearity arises from two sources: the operating characteristics of the New Jersey roughometer in particular and from the nature of the rolling straightedge in general. That is, in the first place, there appears to be an upper limit on the roughness output of our roughometer. This is evidenced by the fact that in the "before" portion of before/after roughometer surveys of deteriorated pavements scheduled to be resurfaced, the <u>maximum</u> readings obtained have been on the order of 225 inches per mile. This suggests that the New Jersey roughometer does not proportionately reflect the roughness of an extremely rough surface. Secondly, when a great many defects are indicated to exist on a pavement, some (possibly substantial) fraction of those defects are apparent or reflected deviations not measured by the roughometer. In such cases, the relationship to roughness index

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[15] Hilton, M. H. "Construction Techniques as Related to Bridge Deck Roughness," HRB Record 248, p. 38 (1968)

would be expected to be different than that prevailing when indicated deviations are predominantly actual deviations. Both of these effects would likely cause the curve to level off in the region where a gross number of defects are indicated.

Fit of the Data: The nature of the best-fit lines relating the number, length and area of straightedge deviations to roughness index and the scatter of data about these regression lines are each similarly influenced by two factors peculiar to the present study: the use of two roughometers and a long interval between testing of individual projects.

The principal influence of the data obtained with the FHWA prototype roughometer--representing 5 of the 12 tested projects--is to cause the best-fit line to indicate slightly higher roughness indexes for the smoothest pavement class. That is, while the FHWA and New Jersey roughometers yielded comparable readings on moderately rough to rough pavements, the FHWA device read about 7 inches per mile higher than New Jersey's at the smooth end of the roughness spectrum. Thus, the regression lines indicated roughness index for pavements containing no defects (i.e., the Y-intercept of Figure 12) would be reduced to 81 inches per mile (FHWA "Excellent") if the basis of the analysis were the New Jersey roughometer readings alone.

As might generally be expected, the use of an extended data collection period is a contributing factor to the scatter about the subject regression lines. Figure 12 and subsequent similar plots should thus be thought of as "generalized" relationships which reflect long-term variation in both the roughometer and rolling straightedge. The relationship between the output of these devices observed on any single future project might be expected to show closer agreement. Certain individual projects in the present data set have, for example, shown correlation coefficients as high as 0.99 (near-perfect) and a prediction tolerance (Syx) as low as $\pm$ 1.6 inches per mile.

3.3.3 <u>Roughness Index Correlated to Number of Deviations:</u> The 0.77 correlation coefficient obtained for the curve of Figure 12 indicates that a "Fair" to "Good" relationship at a "high" significance level exists between the measured number of straightedge deviations and roughness index.

The Y-intercept of the best-fit line reveals that if a concrete pavement were constructed with no deviations, we might expect it to be rated as "Good" based on roughometer readings. The slope of the line (0.8) indicates that two deviations built into a concrete pavement translates about an additional 1-1/2 inches per mile of roughness.

A new concrete pavement of the average roughness level measured in New Jersey (RI = 122 inches/mile) might typically be expected to have about 40 associated defects exceeding our present specification surface tolerance in any quarter mile.

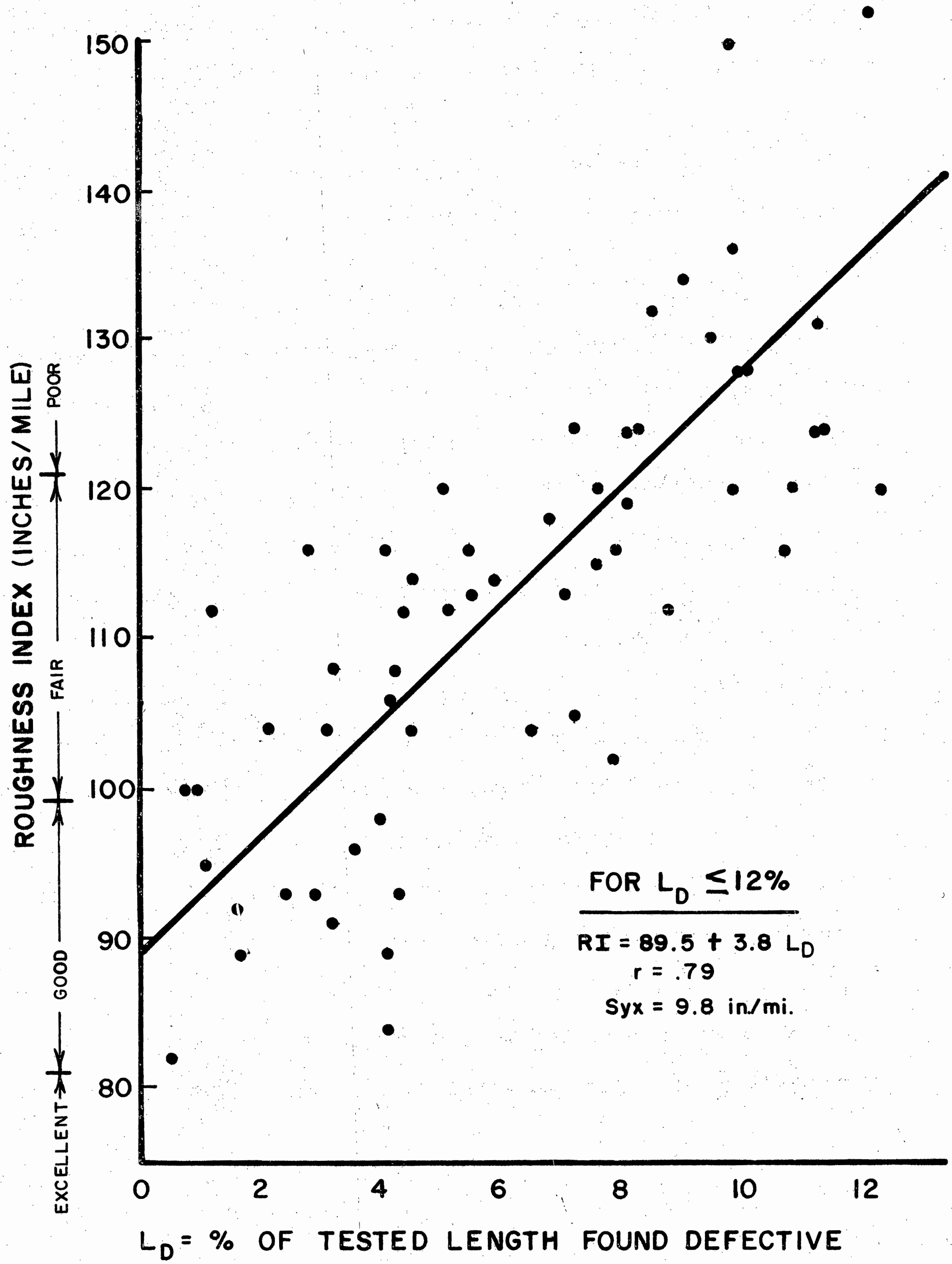
The regression plot further shows that it is possible to obtain pavements of acceptable riding quality containing some limited number of straightedge deviations. For example, to achieve an <u>average</u> level of riding quality corresponding to a borderline "Fair/Good" FHWA rating (99 inches/mile), as many as 15 deviations per quarter mile could be tolerated. However, while the most probable roughness index equivalent of 15 deviations is 99 inches per mile, roughness readings as high as 119 inches/mile (99 + 2 Syx) and as low as 79 inches/mile (99 - 2 Syx) might occasionally be expected on pavements containing 15 defects per quarter mile. Thus, due to the variability (Syx) in the predictor equation, a specification provision of some lesser allowable number of deviations would apparently need to be applied to insure that "Good" riding quality is consistently achieved.

3.3.4 <u>Roughness Index Correlated to Length of Deviations:</u> Figure 13 indicates that a "Good" relationship generally exists between the roughometer reading obtained on a section of concrete pavement and the percentage of the pavement length exceeding a surface tolerance of 1/8 inch in 10 feet.

Based on the indicated equivalency between New Jersey roughometer and rolling straightedge measurements, the average new concrete pavement in this state (RI = 122 inches/mile) would be expected to have about 110 feet of deviation per quarter mile exceeding the present specification smoothness tolerance (i.e., 8.5 percent defective). In order to achieve the FHWA's suggested minimum level of acceptability (a Fair/Good rating), the maximum total length of defects per quarter mile would have to be reduced by about two-thirds to 40 feet (3 percent defective).

FIGURE 13

RELATIONSHIP BETWEEN ROUGHNESS INDEX AND LENGTH OF STRAIGHTEDGE DEVIATIONS (CONCRETE PAVEMENT)



3.3.5 Roughness Index Correlated to Area of Deviations: Figure 14 presents a plot of roughness index versus the total area of deviations per quarter mile. Since the area of deviations reflects their severity, it was thought that presenting the data in this form might offer a better fit with roughometer data. However, this is not the case, with the correlation parameters being essentially the same as in the other methods of analysis (r = 0.8 = Good; Syx = 9.7 inches/mile).

3.4 SLIP-FORM PAVING IN NEW JERSEY

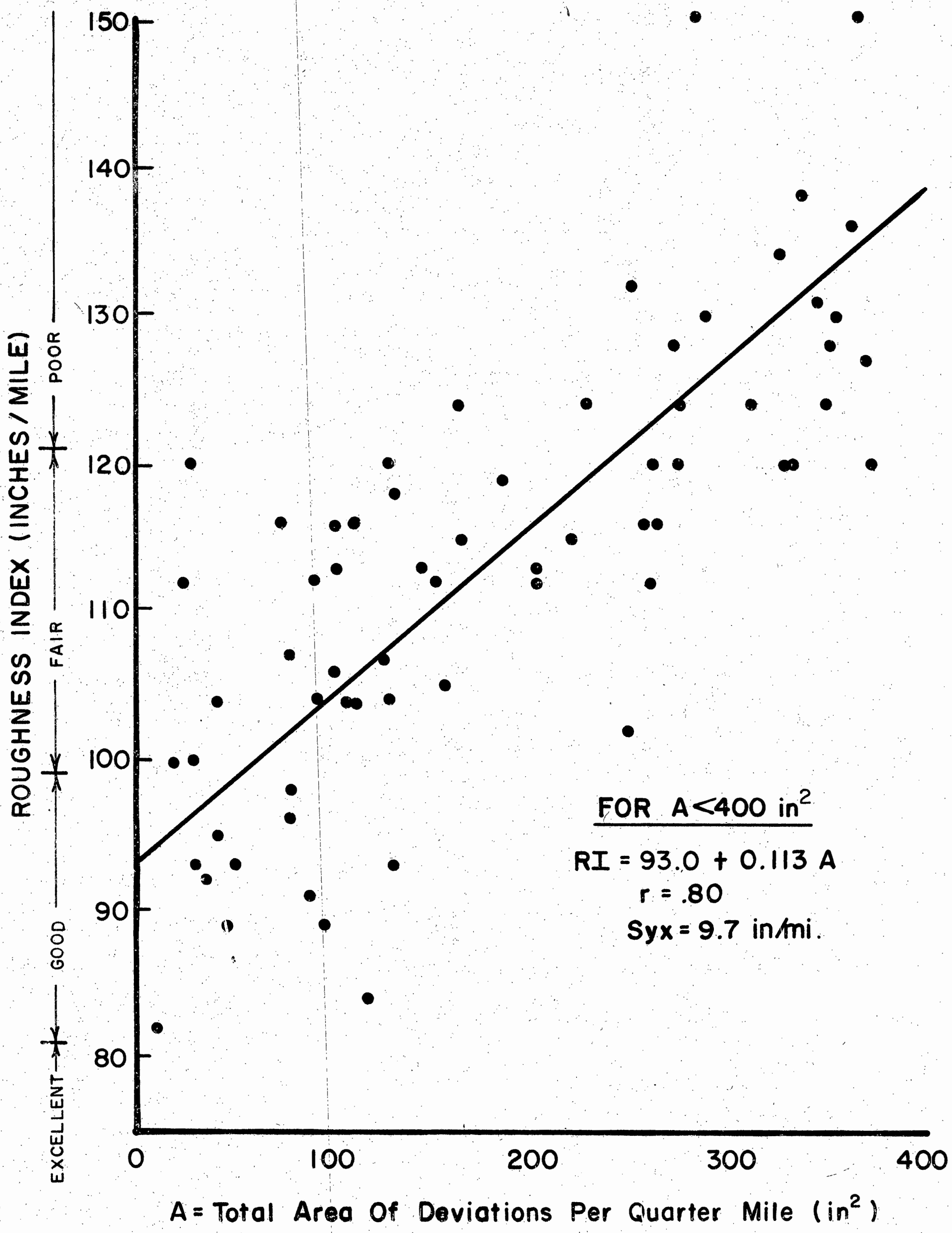
3.4.1 Current Methods of Construction and Quality Level Obtained: The use of the slip-form paving technique has been only a recent development in this state. To date, only three New Jersey expansion joint projects have been slip-formed: I-295, Section 2L and 3A; I-295, Section 4C and 5A; and I-280, Section 1B-5P. A paving train of the same manufacture (CMI) was used on each of these projects, and the latter two projects were built by the same Contractor.

In applying the slip-form technique, field forces performed considerable experimentation with joint construction methods in order to determine the method most compatible with our relatively unique joint design. While various construction techniques were thus employed both within and between projects, a brief summarization of the principal construction modifications used on the three projects can be provided.

On each project, it was necessary to cut off the outer six inches of the 3/4 inch expansion joint filler so as to avoid interference with the spreading and extruding equipment. These sections

FIGURE 14

RELATIONSHIP BETWEEN ROUGHNESS INDEX AND AREA OF STRAIGHTEDGE DEVIATIONS (CONCRETE PAVEMENT)



were subsequently replaced to complete the joint after passage of the paver. To prevent localized edge slump-off, a short section of wooden form was placed against the edge of pavement at the time of the filler paper replacement.

On the I-295, 2L and 3A project, after removal of the joint alignment pins and protection cap, a chamfer strip was nailed to the top of the expansion paper to serve as a crack control device. The surface was then given a preliminary hand finish, followed by final finishing with a mechanized longitudinal tube float and burlap drag. The joint sealant reservoir was subsequently formed by sawing. The same general procedure was employed on the I-295, 4C and 5A project except that the tube float was not used in the immediate vicinity of the joint. On the I-280 project, except for a short section at the beginning of the project, joints were constructed using essentially the same methods as in formed construction (i.e. hand floating and edging around a temporary filler strip). Like the 295, 4C and 5A project then, the concrete surrounding these joints did not receive benefit of the longitudinal float. Additionally, the final finish texture on the I-280 project was accomplished with a mechanical broom rather than a burlap drag.

A summary of straightedge data obtained on these slip-form projects is presented in Table 4. As indicated, based on the extent of measured straightedge defects, the projects would be expected to merit only "Fair" or "Poor" riding quality ratings. While the I-295, 2L and 3A project had some sections which displayed a low number of defects, the data for the other two projects are quite uniform at the "Fair" or "Poor" level. The sample of hand-finished joints constructed in the later

TABLE 4: SUMMARY OF STRAIGHTEDGE DATA FROM NEW JERSEY SLIP-FORM PROJECTS

	I-295, 2L&3A	I-295, 4C&5A	I-280, 1B-5P		
General Method of Forming Joints	Sawing	Sawing	Sawing	Hand (early work)	Hand (later work)
Number of Sections Sampled	6	8	4	4	4
Number of Deviations, N					
Range	4-50	30-69	38-42	48-58	31-39
Average	22	45	41	51	36
Percent Defective Length, L_D					
Range	0.8-13	6.6-15.7	8.5-9.8	10.7-11.6	6.4-9.3
Average	5.5	9.5	9.0	11.1	7.8
Average Riding Quality Rating of Straightedge Sample (Estimated from L_D)	Fair*	Poor	Poor	Very Poor	Fair

*Actual roughness index of sample: 116 = Fair stages of the I-280 work show an improvement with respect to both the sawed and hand-formed construction at the beginning of the project.

The apparent beneficial effect of the longitudinal tube float can be appreciated by considering the differences in the relative influence of joint roughness between projects. Specifically, when the mechanized longitudinal tube float was used over the entire pavement surface, the relative smoothness quality of the pavement both at and between joints was the same (i.e. the 16.7 percent of the pavement represented by joints accounted for an average of 15 percent of all defects); when the float was not used at the joint, the surrounding concrete was more than about 2-1/2 times rougher (i.e. joints accounted for an average of about 45% of all defects).

In addition to these generally disappointing riding quality results, other factors have caused the slip-form paving technique to be less than a success in this state. That is, on certain portions of the I-295, 4C and 5A project, the lack of timely sawing and/or replacement of the short sections of filler paper at the edges of the slab led to surface and corner spalling requiring repair with epoxies. In other, more isolated instances, edge slump-off between adjacent lanes led to an undesirable drainage situation.

Further, apart from these quality considerations, no substantial cost savings have accrued to the state from the use of slip-forming. On the two projects on which a credit was given the State for permitting slip-form rather than conventional construction, the credit amounted to only 1-1/2 to 2 percent of the unit price of the pavement.

3.4.2 Use of Contraction Joint Design: New Jersey's expansion joint design, constructed by conventional (formed) methods, has demonstrated a long-term ability to maintain structural integrity when subjected to our high prevailing truck volumes. However, in order to determine the desirability and feasibility of New Jersey's converting to a design system offering a potential for both improved smoothness and greater compatibility with slip-forming, the Department in 1973 undertook the construction of an experimental contraction joint pavement. This project was constructed on 4-1/2 miles of Route I-80 (Section 1P). The Contractor on this work was the builder of the previous I-295, 4C and 5A and I-280 slip-form projects.

The essential features of the experimental pavement are the predominant use of unreinforced slabs, a 15 foot spacing of contraction joints containing essentially the present load transfer device, and unsealed sawed joints (1/8 to 3/16" wide). Conventional bridge approach and transition slabs continued in use.

Evaluations of the construction work and pavement riding quality were conducted under a separate study for which a formal report is now in preparation*. The average level of smoothness achieved on the project would merit a mid-range "Fair" FHWA rating. While this result represents an improvement over the contractor's previous slip-form efforts, the improvement is far less than was expected. The key factors influencing the observed roughness were the unconfined nature of the pavement edge, night joints, and matching techniques used in placing adjacent lanes.

Since the performance of the experimental design remains to be determined, and in view of certain new and substantial construction difficulties posed[33], further applications of the contraction joint design will not be undertaken in the near future.

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*interim reports issued:
[33]Santoro, R. R. "Preliminary Comments on Construction of the I-80 Experimental Contraction Joint Pavement" N.J. Dept. of Transportation Research Report (1973)
[34]Croteau, J. R. "Initial Rideability Results for the I-80 Experimental Contraction Joint Pavement" N.J. Dept. of Transportation Research Report (1973)

PART IV: BITUMINOUS PAVEMENT RIDING QUALITY RESULTS

4.1 ROUGHOMETER DATA

4.1.1 Average Project Roughness: Table 5 presents a summary of roughometer measurements made on the surface course of the 16 new bituminous paving projects surveyed during this study. The tabulated roughness information represents nearly 270 miles of roughometer data (1,070 quarter-mile sections).

The average Roughness Index of the sampled bituminous projects range from 70 to 117 inches per mile and average 95 inches per mile. According to the FHWA criteria, the average level of riding quality provided on one of the projects would be a borderline "Excellent", four would merit "Good", five "Fair"*,and six would be rated "Poor". The average of the project means corresponds to a "Fair" FHWA rating.

In contrast to the previously described results for concrete pavements, not only do the sampled bituminous projects generally exhibit a lower Roughness Index (average: 25%), there is a trend for our more recent projects and those constructed with more modern equipment (i.e. automatic paver controls) to be the smoothest.

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*If a yearly roughness increase as low as 3 inches per mile can be assumed for New Jersey conditions, the riding quality rating of the bituminous portion of the I-78, 3-G project could be extrapolated to "Good" on an as-constructed basis. [In the previously cited Alabama study[12], an average yearly increase of 4 inches per mile is reported for bituminous pavements.]

TABLE 5: Summary of Roughometer Data for Bituminous Paving Projects

Project		Date Opened t_1	Date Surveyed t_2	$t_2 - t_1$ (Months)	Length of Project	Length Surveyed	Roughness Index (inches/mile)			Initial PSI
No.	Route and Section						Range	Average	FHWA Rating	
1	I-280, 1B-5P	--	8/72	0	9.7[a] mi.	3.0 mi.	68-120	89	Fair*	3.28
2	N.J. 55 (Fwy), 6F & 7E	10/72	8/72	0	5.3	1.75	68-92	78	Good*	3.51
3	I-195, 3B & 4A	7/72	8/72	1	5.0	4.0	64-120	82	Good*	3.42
4	I-195, 4B	7/72	7/72	0	4.0	3.0	70-120	88	Fair*	3.30
5	I-195, 2A & 3A	7/72	11/70	0	3.7	2.5	96-140	112	Poor	2.87
6	I-78, 4F & 4G	7/71	7/70	0	5.6	1.5	67-102	83	Fair to Good	3.40
7	I-80, 1M	4/71	3/71	0	2.0	1.5	80-144	113	Poor*	2.85
8	I-78, 4J	12/70	5/70	0	4.5	1.0	86-132	110	Poor	2.90
9	N.J. 55 (Fwy), 5B-7B	10/69	5/69	0	8.1	2.0	53-107	76	Good*	3.56
10	N.J. 35 (Fwy), 2B & 3A	7/69	12/68	0	2.8	1.0	93-123	104	Poor	3.00
11	I-80, 3K	7/69	10/68	0	5.6	2.0	80-149	117	Poor	2.79
12	I-295, 1S	12/68	3/69	3	6.1	2.0	57-86	70	Good to Excellent *	3.71
13	N.J. 35 (Fwy), 1A & 2A	11/68	12/68	1	4.0	2.0	80-124	100	Fair	3.07
14	N.J. 72, 6A & 7A	11/68	12/68	1	5.2	2.0	85-120	99	Fair	3.09
15	I-78, 3G	7/66	5/68	22	5.4[a]	1.25	76-122	89	Fair	3.28
16	I-78, 4K	7/66	10/68	27	2.7	2.0	84-147	112	Poor	2.87
						Averages	46	95	Fair	2.97

[a]including concrete portion of project

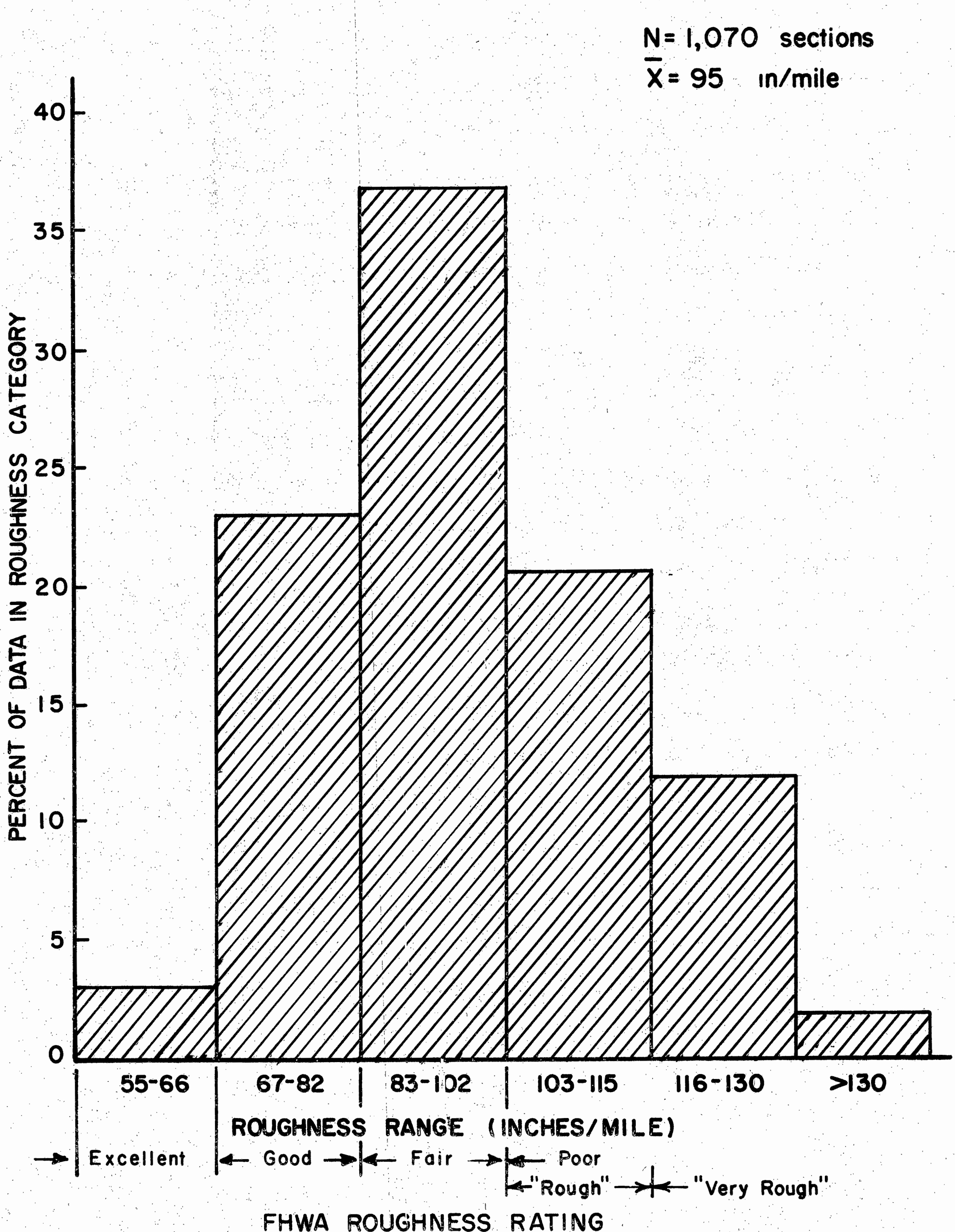
*denotes projects on which automatic paver controls were employed at least to some extent

4.1.2 Roughness of Individual Test Sections: As in the case of the sampled concrete pavements, Table 5 indicates that considerable variation generally exists between the highest and lowest roughometer reading within a particular bituminous project. On both pavement types, the mean range of roughness amounts to about half the average level of roughness. Unlike the roughness situation prevailing on New Jersey concrete pavements, however, certain of the sampled bituminous pavements--notably, the I-295,1S and N.J. 55, 6F and 7E projects--do show a low range of roughness as well as a low average, thus indicating consistent achievement of a quality product.

The riding quality distribution of the individual bituminous pavement test measurements is shown in Figure 15. The "Poor" riding quality category has again been arbitrarily divided into what might be considered "Rough" and "Very Rough" sub-categories.

As indicated, two-thirds of the roughometer measurements made on the bituminous pavements samples over the past five years would merit a "Fair" or better FHWA riding quality rating. About 15 percent of the sample has a roughness index falling in the "Very Rough" category (i.e., is more than 10 percent above the "Fair/Poor" cutoff). Nearly all (92%) of the roughometer measurements made on bituminous pavement are less than the average of the measurements made on concrete. However, as previously noted, a different (more severe) equivalency between

FIGURE 15
Roughness Distribution Of Individual Roughometer Test Sections
(BITUMINOUS PAVEMENT)



measured roughness and rideability rating is used for bituminous pavements under the FHWA rating system. When this factor is considered, essentially the only difference between the test measurements on our bituminous and concrete pavements is that about 12 percent more of the bituminous pavement measurements fall in the "Good or Excellent" rather than the "Fair or Poor" categories (cf. Table 6 following).

4.1.3 Inter- and Intra-State Riding Quality Comparisions:

Inter-State: In Table 6, a summary of New Jersey roughometer data for both rigid and flexible pavements is shown compared to the results of the 580 mile, 17 state roughometer sample used to develop the FHWA rating criteria.

The five-year sample of measurements on New Jersey concrete and bituminous pavements each show an inordinate percentage of "Poor" riding quality sections compared to the FHWA's multi-state sample: about 40 percent compared to 3 percent "Poor".

Intra-State: When faced with the particularly disappointing riding quality ratings in the earliest stages of this work, the writer undertook to determine the extent to which roughometer readings agreed with a judgment of very good riding quality for bituminous portions of the Garden State Parkway. Thru the courtesy of the involved agencies, this sampling was expanded at the time of testing (mid-1969) to include

TABLE 6: COMPARISON OF NEW JERSEY AND FHWA RELATIVE ROUGHNESS RESULTS

FHWA Riding Quality Rating	Percent of FHWA Survey in Category [a]	New Jersey Concrete		New Jersey Bituminous	
		Number of Projects [b]	Percent of All Test Measurements	Number of Projects [b]	Percent of All Test Measurements
Outstanding	7	0	0	0	0.3
Excellent	15	0	0.8	1	3.4
Good	54	1	14.0	5	23.5
Fair	21	6	40.9	4	37.0
Poor	3	7	44.3	6	35.7

[a] bituminous and concrete pavements combined

[b] two concrete and one bituminous project extrapolated to as-constructed state

TABLE 7: COMPARATIVE BITUMINOUS PAVEMENT ROUGHNESS DATA FOR NEW JERSEY TOLL ROADS

Pavement Tested	Test Location	Age At Time	Tested Length and (No. of Sections)	Roughness Index		Rating
				Range	Average	
Parkway	Milepost 70-72	15 yrs	2 miles (32)	53-89	71	Good to Excellent
Expressway	Milepost 29-31	5 yrs	2 miles (64)	46-93	65	Excellent
	Milepost 14-17	5 yrs	2.75 miles (88)	53-105	75	Good
Turnpike	Contract W1104	Not Open	1 mile (16)	83-139	110	Poor

bituminous pavement on the other toll roads in this state: The New Jersey Turnpike and Atlantic City Expressway. The results of this toll road testing are presented here simply since most New Jersey readers will be familiar with the roads in question and thus may be able to relate to the roughness data.

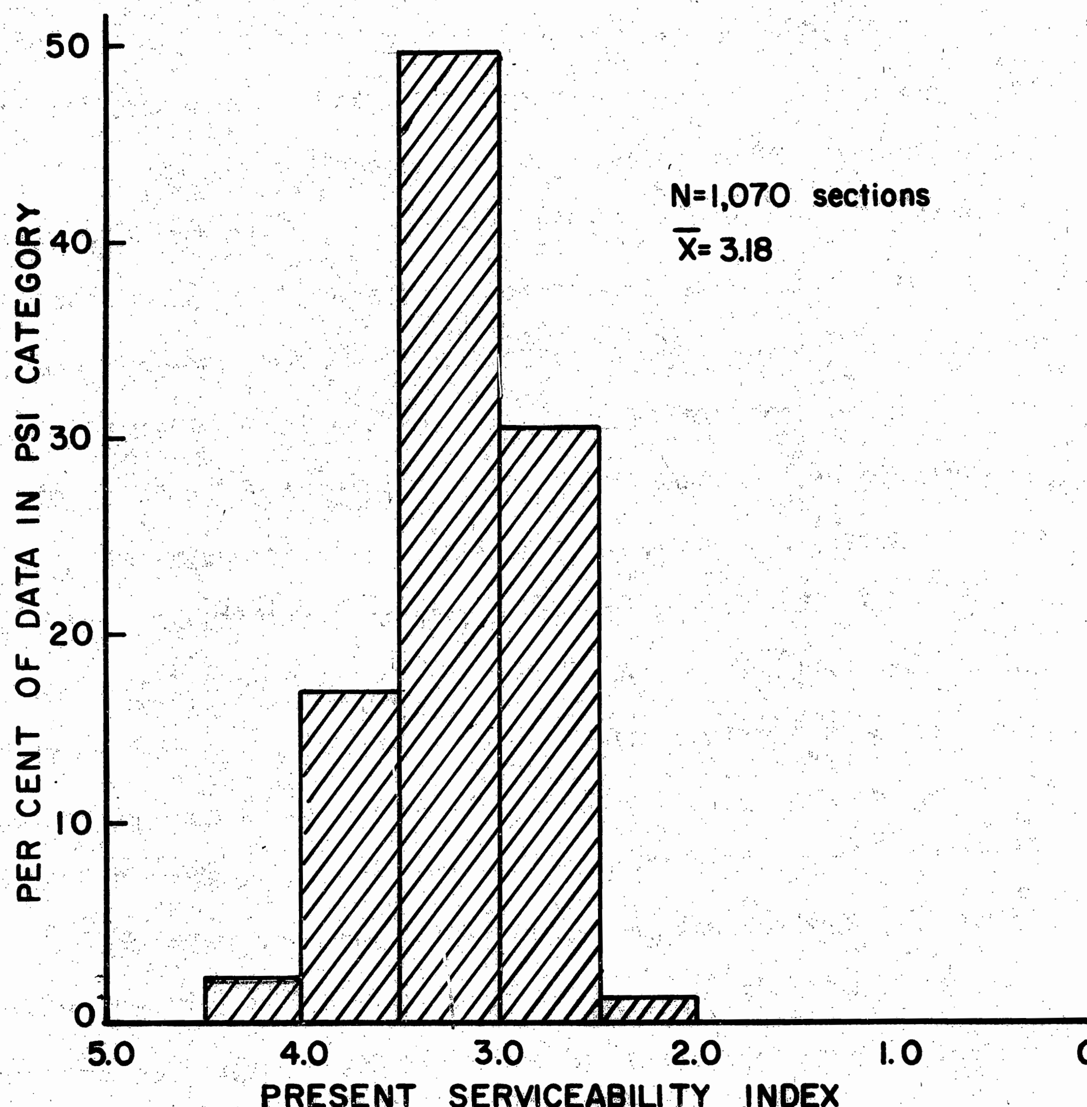
As shown in Table 7, the riding qualities of the tested portions of the Expressway and Parkway -- in service for 5 and 15 years respectively -- were rated as "Good" to "Excellent". The readings for these roads are thus on the same order as the best of the new construction studied in this work. A "Poor" rating was indicated for the smaller sample of new construction on the Turnpike.

4.1.4 Present Serviceability Equivalents of Roughometer Data: The present serviceability index equivalents for the bituminous projects listed in Table 5 range from 2.85 to 3.71 and average 2.97 (0.5 units above the recommended terminal index). Five of the 16 projects have an initial serviceability index above the suggested minimum acceptable value of 3.4. In comparison to the sampled concrete, the bituminous projects thus show a higher fraction of acceptable individual projects but a lower overall serviceability level (2.97 versus 3.46 average project PSI).

If a substantial fraction of initial serviceability indices should be at least one PSI unit above the terminal value (2.5) in order to obtain a meaningful index of performance, then the serviceability concept would appear even less applicable to our bituminous pavements than our concrete: As shown in Figure 16, less than 20 percent of the bituminous serviceability indices are 3.5 or above, compared to about 50 percent for concrete.

While the potential for future application of the serviceability concept is enhanced by the improved riding quality obtained in our more recent work, a more fundamental factor in the question of applicability would appear to be the validity of the PSI equation itself. There are indications that, due to the weight given to the roughness factor in the Guidelines PSI equation, the above described results for bituminous pavement may be overly pessimistic. That is, given the past history of readings from our particular roughometer, the values at the upper end of the PSI scale appear unattainable even for pavements whose riding quality compares favorably to the <u>best</u> new construction obtained in other states. For example, the single lowest value obtained on a state project (52 inches/mile = "Outstanding") is equivalent to a PSI of only 4.23. Similarly, certain pavements receiving an "Excellent" FHWA rating correspond to a PSI of less than 4.0 according to the Guidelines equation (e.g. 66 inches/mile = 3.8). The working range of PSI values in this state would thus appear to be only about 1.5 units (i.e. from 2.5 to about 4.0). Significantly, this is in spite of the fact that several entire projects, and many individual roughometer sections tested, have been built to the closest surface tolerance which our present and projected future specifications require (i.e. essentially or completely free of 1/8 inch straightedge deviations).

FIGURE 16
Histogram Of Roughometer Data Converted To Present Serviceability Equivalents
(Bituminous Pavement)



It is important to note that New York -- one of the states whose roughometer was used in developing the Guidelines equation -- has since developed a modified equation[16] to more accurately reflect their particular pavement conditions and roughness equipment. The coefficients in the modified New York equation yield a higher serviceability equivalent than the Guidelines equation for a given Roughness Index and assign substantially greater weight to rutting.

From the preceding, it appears reasonable that -- should design engineers in the future wish to compare the relative adequacy of bituminous pavement designs by means of the serviceability concept -- the serviceability equation or its application would have to be modified for use in this State. In this connection, work has recently been initiated to develop a modified format for serviceability information that will enable New Jersey Maintenance forces to better judge priorities in extensive resurfacing programs.

4.2 ROLLING STRAIGHTEDGE DATA

4.2.1 Nature and Size of the Sample: A total of 129 quarter-mile sections of bituminous top course having a known roughness index have been surveyed with the rolling straightedge, the tested sections being selected from 12 of the 16 projects listed in Table 5. An additional

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[16] Vyce, J.A. "Development of a Flexible Pavement Performance Equation", New York Department of Transportation Research Report 68-4 (1968)

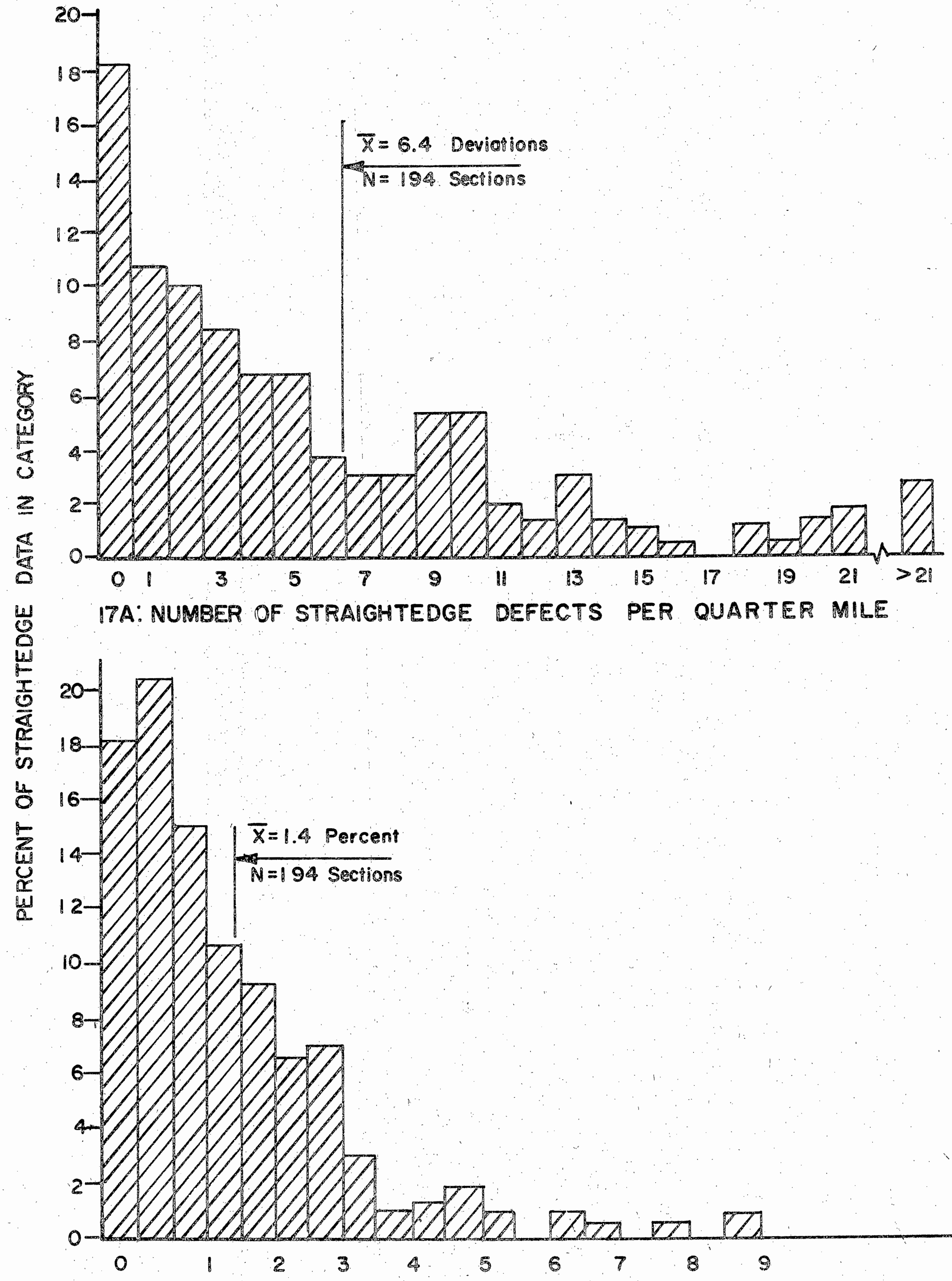
sample of 65 sections was obtained from three recently constructed projects not tested with the roughometer. The entire bituminous (surface course) sample obtained in this work thus amounts to nearly 50 miles of data (194 sections).

The number of defects observed in the total bituminous pavement sample range from none to 49 and average 6 per quarter mile (Figure 17A). As shown, nearly 40 percent of the tested sections contained two or fewer defects. The calculated percent defective length ranges from zero to 8.5 percent and averages 1.4 percent of the tested length (Figure 17B). This average percent defective corresponds to about 18 feet of deviation exceeding 1/8 inch in 10 feet per quarter mile.

While a difference in the surface characteristics of rigid and flexible pavements might be expected intuitively as well from the previously noted (25 percent) lower average roughometer readings for bituminous pavement, the described straightedge data indicates that a marked contrast exists with respect to the measured surface irregularities on the two pavement types. For example, the concrete straightedge data on the average displays about 5-1/2 times more defects and defective length than the bituminous pavement sample (i.e., 35 versus 6 defects and 100 versus 18 total feet of defect per quarter mile).

FIGURE 17

FREQUENCY DISTRIBUTION OF ROLLING STRAIGHTEDGE DATA
(BITUMINOUS PAVEMENT)



17A: NUMBER OF STRAIGHTEDGE DEFECTS PER QUARTER MILE

17B: PERCENT OF LENGTH FOUND DEFECTIVE

4.2.2 Patterns of Defects Common to Pavements of Various Riding Quality Levels:

The average patterns of straightedge defects corresponding to particular roughness ratings for concrete pavement have previously been shown in Figure 9. The 12 project sample of straightedge data for bituminous projects is shown in a similar format in Figure 18.

The most striking difference between the general patterns of defects on the two pavement types is the significantly greater reduction in riding quality accompanying 1/8 inch or greater straightedge defects on flexible pavements. To achieve a "Good" flexible pavement riding quality, for example, substantial if not complete compliance with a zero straightedge defect provision is generally required. At the other extreme, a bituminous pavement containing the same total number of defects as the average "Good" concrete pavement (14 per quarter mile) can be expected to receive a "Poor" rating.

The span length distribution of bituminous straightedge defects (not shown) is essentially the same as on concrete. That is, about 90 percent of all 1/8 inch deviations are 3 feet or less, with two-foot defects predominating. Also, when deviations of 1/4 inch or greater magnitude occur, they are commonly 3 to 6 feet in length.

The generally more severe relationship between the extent of straightedge defects and riding quality rating for bituminous pavement relative to concrete is believed to result from two sources. First, since a bituminous pavement generally must display a lower Roughness Index than a concrete pavement for the same FHWA rating to be applied, a more critical rating also is expected if the roughness level is expressed in terms of straightedge rather than roughometer data. The second influencing factor relates to differences in the <u>absolute</u> profile between formed and unformed construction. That is, as previously noted, there is evidence that surface defects not measured by the straightedge (i.e., multiple short deviations reflected as straightedge "chatter") are sometimes prevalent on and detract from the ride of bituminous pavement, thereby increasing the roughometer reading for a particular <u>measured</u> level of straightedge defects. Additionally, long wave length defects unique to or more prevalent on non-formed construction might possibly exert a similar influence.

To the reader charged with responsibility for achieving good riding bituminous pavements in practice, an important ramification of the described severe influence of measureable surface defects should be apparent. Our data strongly suggests that even an <u>occasional</u> lapse in the application of proper construction practices can be expected to assume critical proportions with respect to the pavements' resultant level of rideability.

4.3 ROUGHOMETER - ROLLING STRAIGHTEDGE CORRELATION

4.3.1 <u>Roughness Index Correlated to Number of Deviations</u>: Figure 19 presents a plot of Roughness Index versus the number of bituminous pavement straightedge defects per quarter mile.

FIGURE 18
TYPICAL DISTRIBUTION OF SURFACE DEFECTS
ON BITUMINOUS PAVEMENTS OF VARIOUS RIDING QUALITY LEVELS

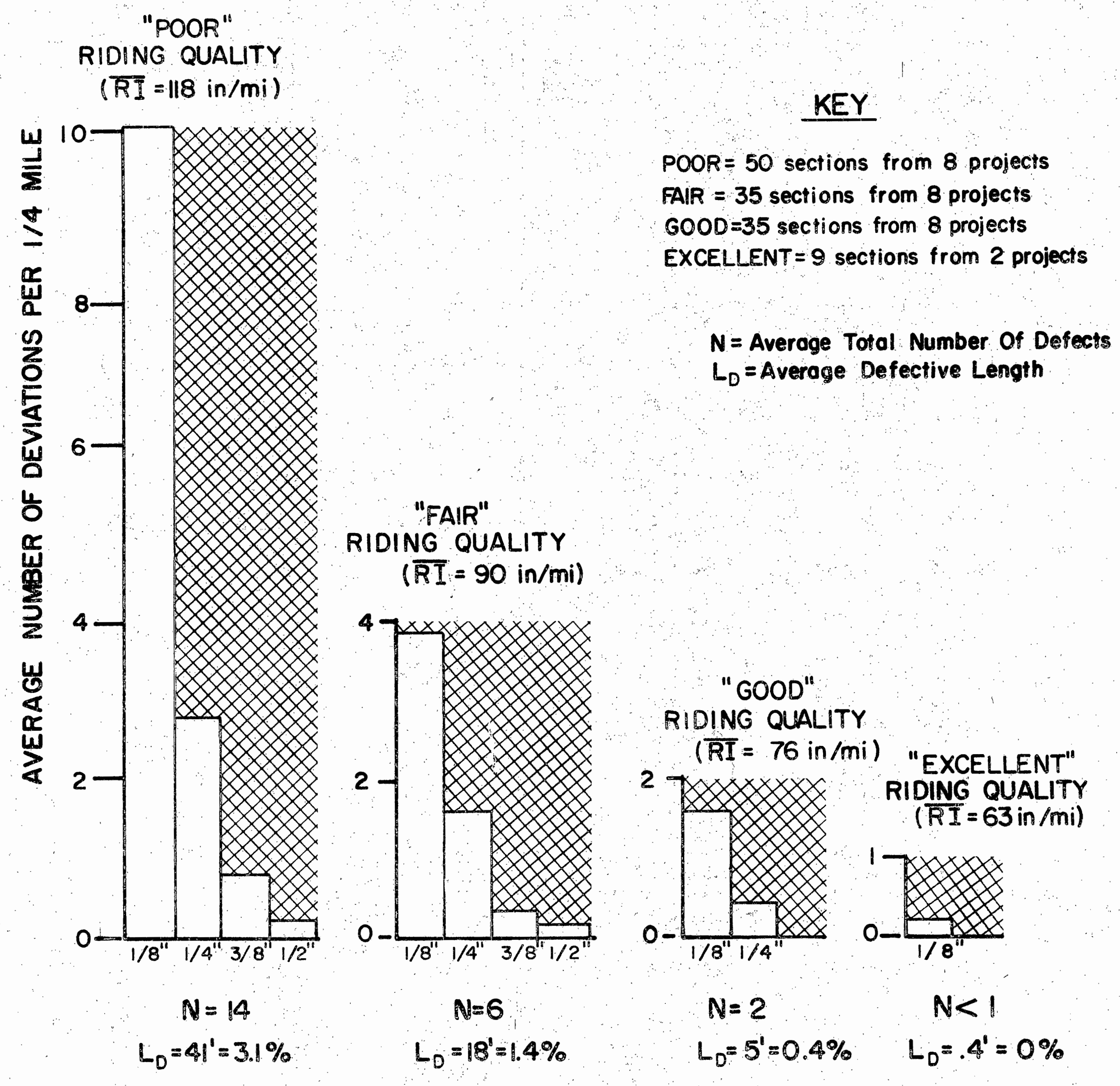
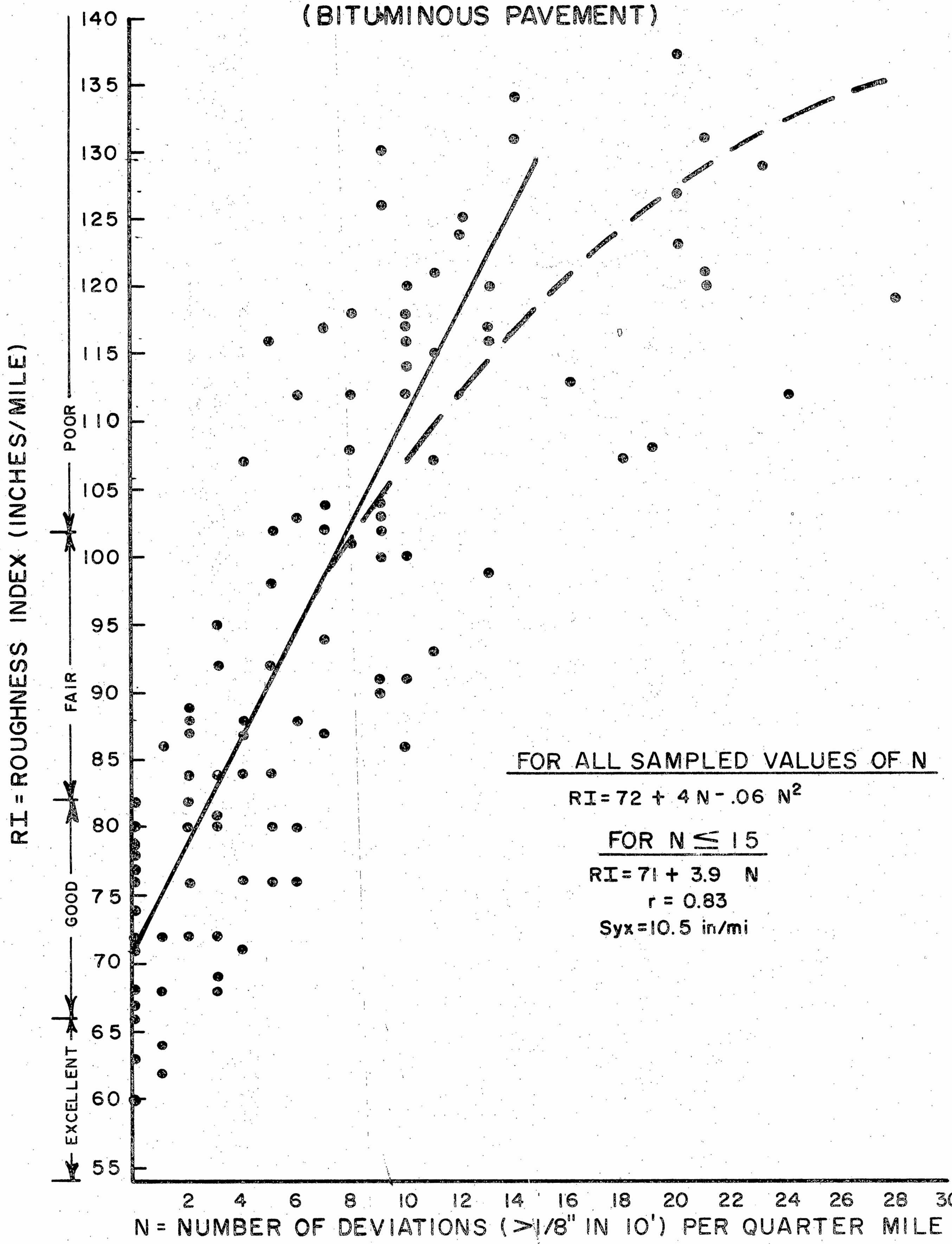


FIGURE 19
RELATIONSHIP BETWEEN ROUGHNESS INDEX AND NUMBER OF STRAIGHTEDGE DEVIATIONS (BITUMINOUS PAVEMENT)



As in the case of concrete pavement, the best-fit line departs from linearity in the "Poor" to "Very Poor" riding quality zone. Again, however, in the straightedge data range of interest, the relationship is linear. The 0.83 correlation coefficient obtained for this regression line indicates that a "Good" relationship at a "High" significance level exists between the two measures of roughness.

The Y-intercept of the best-fit line shows that a bituminous pavement containing no straightedge defects in excess of 1/8 inch will generally merit a "Good to Excellent" FHWA riding quality rating. The slope of the line (3.9) indicates that each deviation built into a bituminous pavement will increase the roughness index by about four inches per mile. In comparison to concrete, the incremental roughness index contribution of a single straightedge defect is nearly <u>five</u> times greater on bituminous pavement.

According to Figure 19, in order to achieve an average level of riding quality equal to the FHWA's suggested minimum level of acceptability (a "Fair/Good" rating), the number of defects per quarter mile would have to be held to three or less. As the number of defects increases above nine (a borderline "Fair/Poor"), roughness index increases until--at about 13 defects--there is less than a 3% chance (based on Syx = 10.5 inches per mile) that anything other than "Poor" or "Very Poor" riding quality will be obtained.

4.3.2 <u>Roughness Index Correlated to Length of Deviations:</u> Figure 20 indicates that a good relationship also exists between New Jersey roughometer readings for bituminous pavement and straightedge data expressed in terms of the percent defective length parameter.

Based on the subject relationship, a 50 percent reduction in the percentage of pavement length exceeding a surface tolerance of 1/8 inch in 10 feet is required if the average new bituminous pavement in this State is to consistently merit a "Fair" or better riding quality rating (i.e. from an average of 1.5 to .75 percent defective).

In comparing the number and defective length parameters with regard to their relative merits for use in controlling roughness during construction, it appears that the defective length parameter would be less restrictive and more practical. That is, implicit in the previous discussion of the equivalency between the number of defects and rideability is the fact that these defects are of some typical magnitude and length in New Jersey. Figure 20 suggests that if the defects incorporated during construction are short, some greater than average number could be tolerated providing their total length is held to about 10 feet. Conversely, of course, a pavement containing an "acceptable" number of defects would not be expected to receive an "acceptable" riding quality rating if the defects were atypically long.

4.3.3 Roughness Index Correlated to Area of Deviations: While a good relationship exists between the total area of straightedge deviations and roughness index (Figure 21), the greater calculation effort required for this parameter -- coupled with the fact that it is not a statistic which one can easily relate to -- indicate that defective area would be

FIGURE 20
RELATIONSHIP BETWEEN ROUGHNESS INDEX AND LENGTH OF STRAIGHTEDGE DEVIATIONS (BITUMINOUS PAVEMENT)

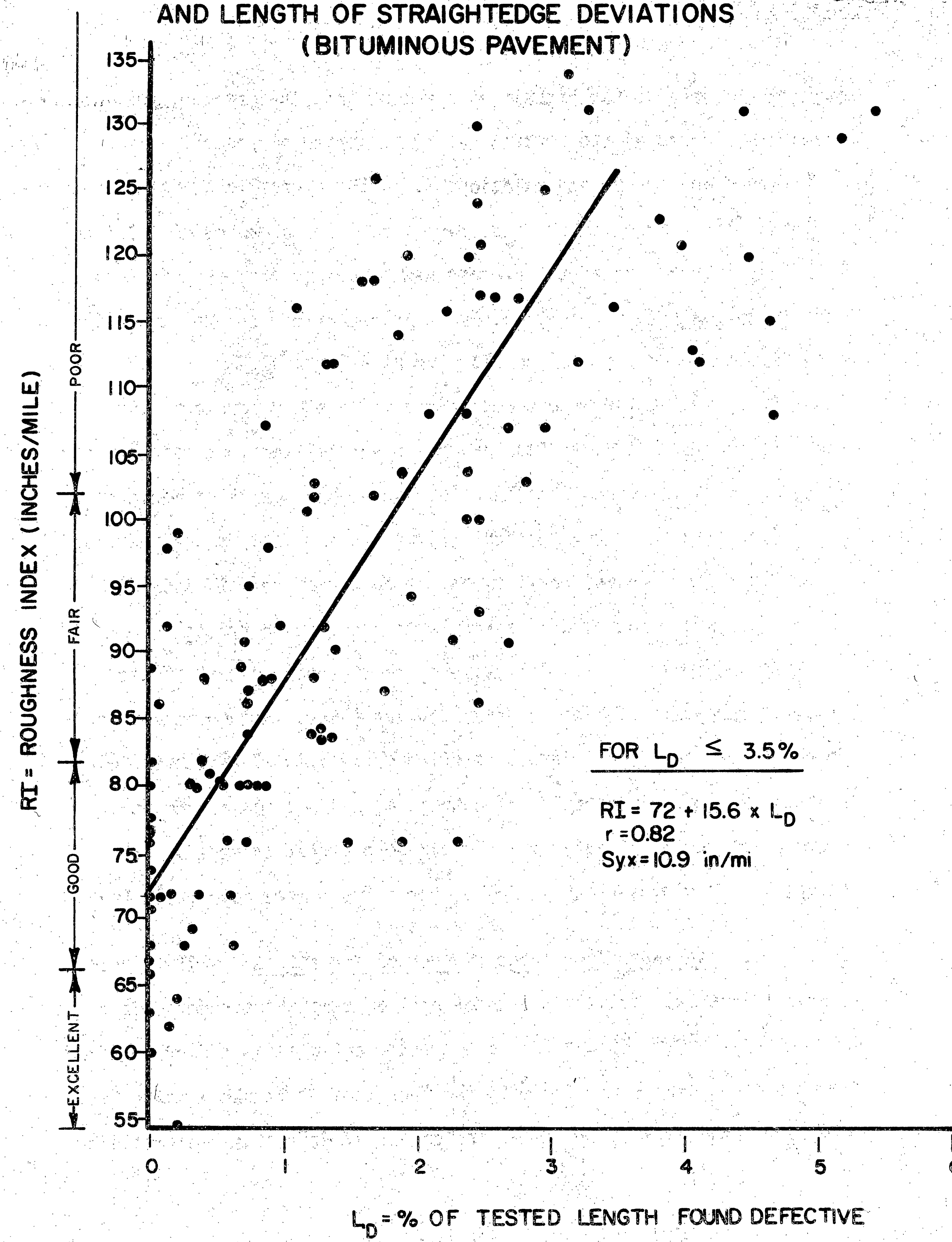
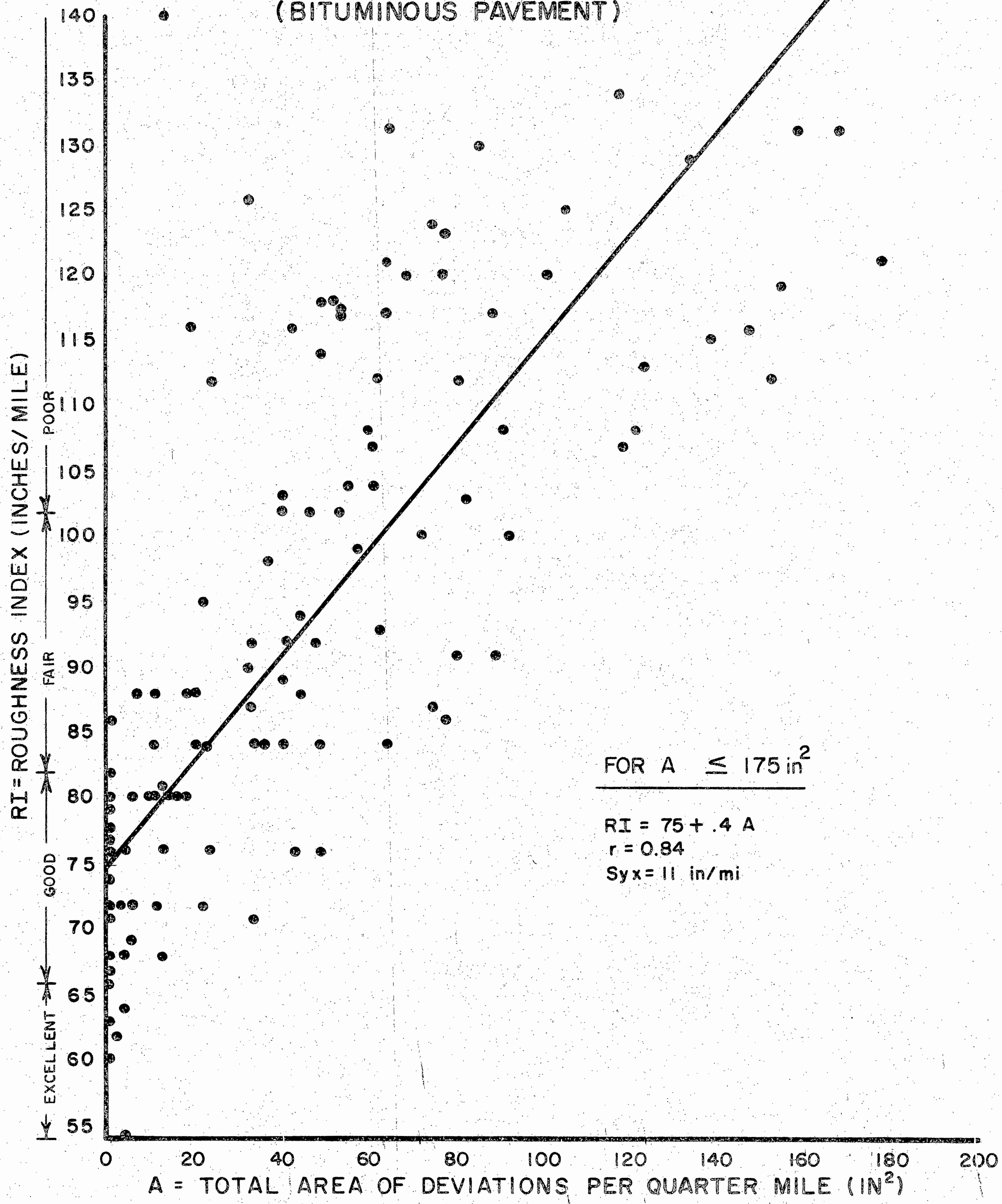


FIGURE 21

RELATIONSHIP BETWEEN ROUGHNESS INDEX AND AREA OF STRAIGHTEDGE DEVIATIONS (BITUMINOUS PAVEMENT)



less useful than the number or length parameters in a field application. For research purposes, however, defective area is a useful parameter in that it provides a measure of the difference in straightedge defect severity in a single statistic.

4.3.4 Estimated Riding Quality Rating of Recently Constructed Projects:

Based on the described correlations between New Jersey roughometer and straightedge measurements, an estimate can be made of the riding qualities of three recent projects whose roughness was sampled only with the rolling straightedge: Route I-80, Section 1L; New Jersey 55, Section 7F and 8A; and I-287*, Section 7D-9G.

The estimated rideability ratings for these projects, shown in Table 8, represent a continuation of the previously noted trend for New Jersey's more recent bituminous construction to be of a higher level of acceptability.

It is interesting to note that the differences in ratings of the three projects are not the result of some difference in the best quality level achieved (i.e. each project contains some excellent work), but rather are apparently a function of the uniformity or control of the quality level. This is exemplified by the fact that the Route 55

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*The pavement section and method of construction on this project were different than usual in that thick-lift base construction was employed (2, 4-inch lifts) and the standard (1-1/2") lift of binder was eliminated between the base and top.

Table 8:

Estimated Riding Quality Rating of Three Recently Constructed Projects not Tested with the Roughometer

	PROJECT		
	Route I-80 Section 1L	N.J. 55(Fwy) Sect. 7F&8A	Route I-287 Sect. 7D-9G
Length of Project	7.5 mi	2.3 mi	5.4 mi
Date Opened to Traffic	1/73	6/73	2/73
Number of Sections Sampled	33	8	24
Number of Deviations, N			
Range	0-18*	0-2	0-15
Average	5.4	0.5	2.5
Percent Defective Length, L_D			
Range	0-3.18*	0-.38	0-1.67
Average	1.14%	0.1%	0.36%
Estimated Average Riding Quality Rating of Straightedge Sample	Fair to Good	Good to Excellent	Good

*One very rough section (N=37, L_D = 8.71%) eliminated sample contains none of the marginally acceptable sections observed on I-287, while the tested portions of the I-287 project have none of the very poor sections of the I-80 work.

4.4 COMPARISON OF NEW JERSEY STRAIGHTEDGE DATA TO RESULTS IN OTHER STATES:

The majority of states have the same specification smoothness requirement as New Jersey: No straightedge defect exceeding 1/8 inch in 10 feet.

In the case of concrete pavement, comparative straightedge data is not available to specifically determine the extent to which construction in other states actually conforms to this zero defect provision. However, as a result of an ongoing FHWA Demonstration Project*, that agency has accumulated a large sampling of rolling straightedge data on new bituminous concrete in numerous states. This data sample -- presented in terms of the defective length parameter -- thus provides an alternate basis for judging relative roughness results in our state.

Based on information provided by the FHWA, the histogram of defective length shown in Figure 22 represents <u>at least</u> 92 miles of straightedge data from 16 states. As shown, more than half of the pavements in this multi-state sample were completely free of measured

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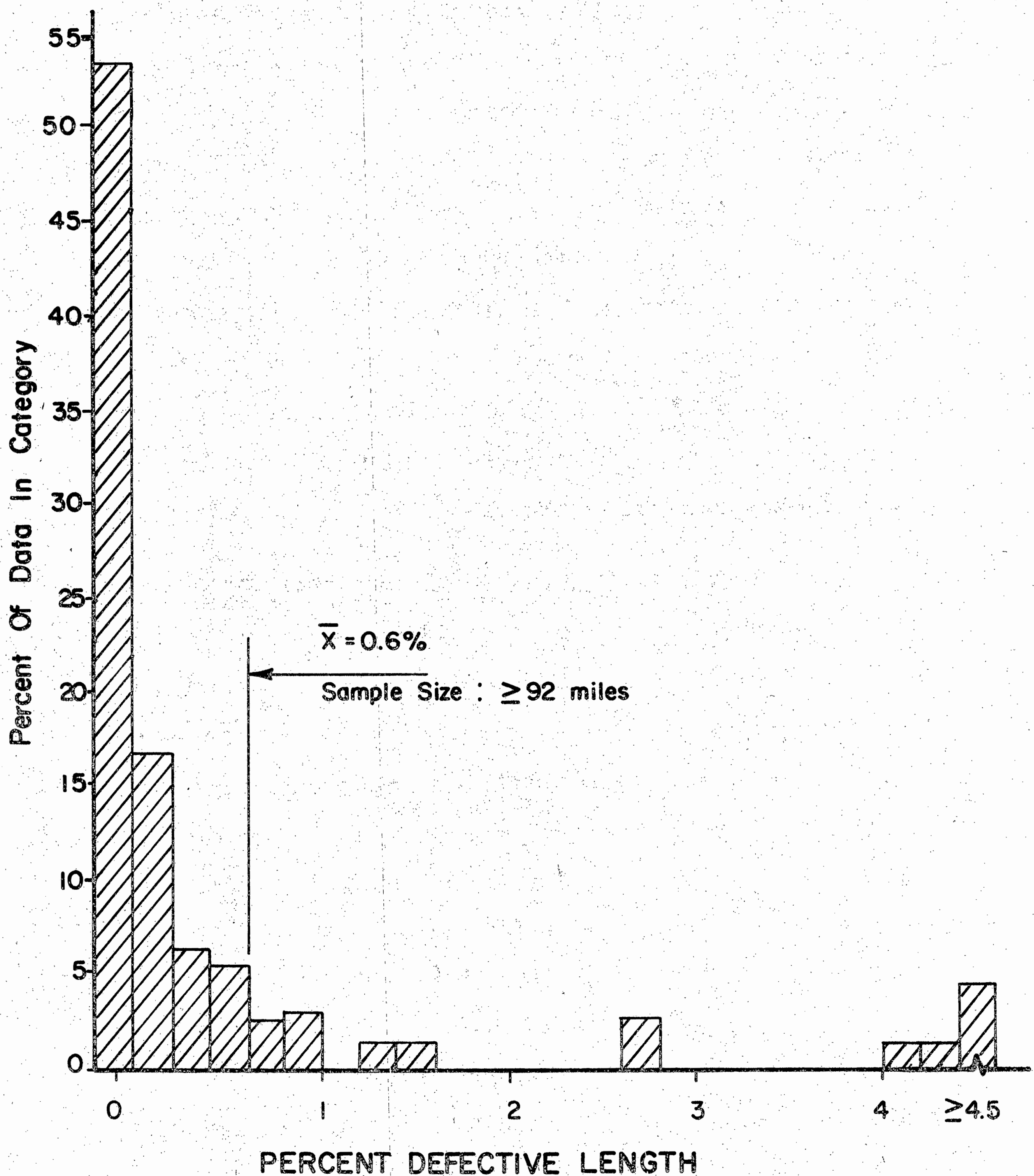
*FHWA Region 15 Demonstration Project 2: "Improved Quality Assurance of Bituminous Concrete"

Figure 22

Distribution of Straightedge Surface Defects Observed by the FHWA in a Multi-State Survey (Bituminous Pavement)



defects and nearly all of the data (90 percent) displayed one percent defective or less. In the five-year New Jersey data sample (Figure 17B), 18 percent of the pavements were free of straightedge deviations and the 90th percentile corresponds to 3 percent defective.

Based on the straightedge-roughometer correlation observed in the present work, more than half of the pavements surveyed by the FHWA would be expected to receive "Good to Excellent" ratings if tested with the New Jersey roughometer. Significantly, about 85 percent of these bituminous pavements would be expected to meet the criteria for "acceptable" initial serviceability (i.e., above the "Fair/Good" demarcation which corresponds to about 0.75 percent defective length).

The preceding straightedge data is thus in agreement with the previous roughometer - based indication that the New Jersey pavements studied over the past five years have not generally been constructed to the surface smoothness standards achieved in other states.

4.5 COURSE-TO-COURSE DIFFERENCES IN BITUMINOUS PAVEMENT ROUGHNESS

4.5.1 Purpose of Testing: In discussions of riding quality, many experienced resident engineers have probably had a contractor remark, "Don't worry about the roughness, we'll take it out in the next course." Depending on the conditions existing on a particular project, the spirit of optimism voiced in this comment obviously may or may not have a basis in fact.

Later in this report, rolling straightedge based surface smoothness specifications are described and recommended for use in New Jersey. If such specifications are adopted, resident engineers will be provided with a means of rapidly obtaining data on which to judge the potential for achieving an acceptable final level of riding quality at each stage of construction. Implicit in such a determination by the engineer is the resolution of two related questions: "Where do I stand with regard to roughness at the present course level?" and "What improvement can I expect?" While a short period of experience with the straightedge should yield specific answers to these questions appropriate to a given set of project conditions, at least initially, some historical perspective is required.

In order to determine the extent to which roughness is removed from the various New Jersey flexible pavement layers and to develop some possible guidelines for future control of intermediate course roughness, successive roughometer and straightedge measurements were made on the base thru top course surfaces of selected projects. Unfortunately, the number of such consecutive measurements obtained was somewhat limited due to roughometer breakdowns and difficulties in coordinating data collection with construction operations.

4.5.2 Average Levels of Roughness and Roughness Improvement for Intermediate Courses: A summary of the average values of straightedge and roughometer data obtained on the base, binder and top course of the individual projects sampled in this work is presented in Table 9. Since the roughness variation between projects (i.e., the range) is about half the average value in the case of roughometer data and as much as twice the average in the case of straightedge data, it is apparent that the tabulated averages present a very generalized view of the roughness of the various courses.

The historical data of Table 9 indicates that construction of the top course on the average will remove about half the straightedge defects in the binder. It follows then that a limiting or target value of about 6 to 8 defects or 1.5 to 2 percent defective length or less should be sought for the binder in order to achieve surface course values for these parameters that correspond to "acceptable" riding quality. Since the expected average base to binder improvement is also about 50-60%, when the number or length of base course defects exceed about 12 to 16 or 3 to 4 percent respectively, one might similarly expect a potential problem in finally achieving acceptable riding quality.

As indicated in Table 9, the average improvement in Roughness Index from first to last paving course amounts to about 80 inches/mile, and the improvement from final base to riding surface averages 50 inches/mile.

In comparing the roughness improvements indicated by the straightedge and roughometer, there is an apparent disparity between the two devices: The largest average decrease in defects (base to binder) corresponds to the smallest roughness index decrease, while the smallest straightedge decrease (binder to top) yields the largest roughness index improvement.

TABLE 9:

Average Level of Roughness on Intermediate and Final Courses of Bituminous Projects

Paving Course	STRAIGHTEDGE DATA			ROUGHOMETER DATA	
	Number of Projects Tested	Average Number	Average Defective Length	Number of Projects Tested	Average Roughness Index
Top	15	6 (0-21)*	1.4% (0-3.5)	16	95 in/mi (70-117)
Binder	4	14 (4-22)	3.1% (0.8-5.7)	5	125 in/mi (97-153)
Final Base	4	32 (10-54)	6.8% (2.0-11.0)	6	142 in/mi (118-158)
First Base	3	45 (11-96)	9.8% (1.3-22.0)	2	178 in/mi (157 & 200)

*range of data for projects tested

Such differences between the reduction in measured surface irregularities and the improvement in roughness index for intermediate paving courses are not unique to either the paving in this state or the rolling straightedge. For example, in a Colorado paving study[18] in which surface irregularities were expressed in terms of profilometer output (units: slope variance), a 12 unit reduction in profile irregularities accomplished in the laydown of a second base course corresponded to a roughness index reduction of 35 inches per mile. In contrast, a reduction of only 2 units between binder and top course on this same project was equivalent to a 45 inches per mile decrease in roughness index.

The indication that a large decrease in straightedge defects on a base course may not result in a proportionate decrease in roughness index is believed to result simply from the fact that a lower course generally contains extensive surface irregularities of relatively high magnitude. As was previously observed in the (surface course) correlation plots, a relatively small difference in roughness index can be expected between pavements having "many" and "very many" irregularities (i.e. straightedge data falling in the non-linear portion of the best-fit curve).

A contributing factor to the larger average decrease in roughness index relative to the reduction in straightedge defects accomplished from binder to top course is that binder course apparently contains

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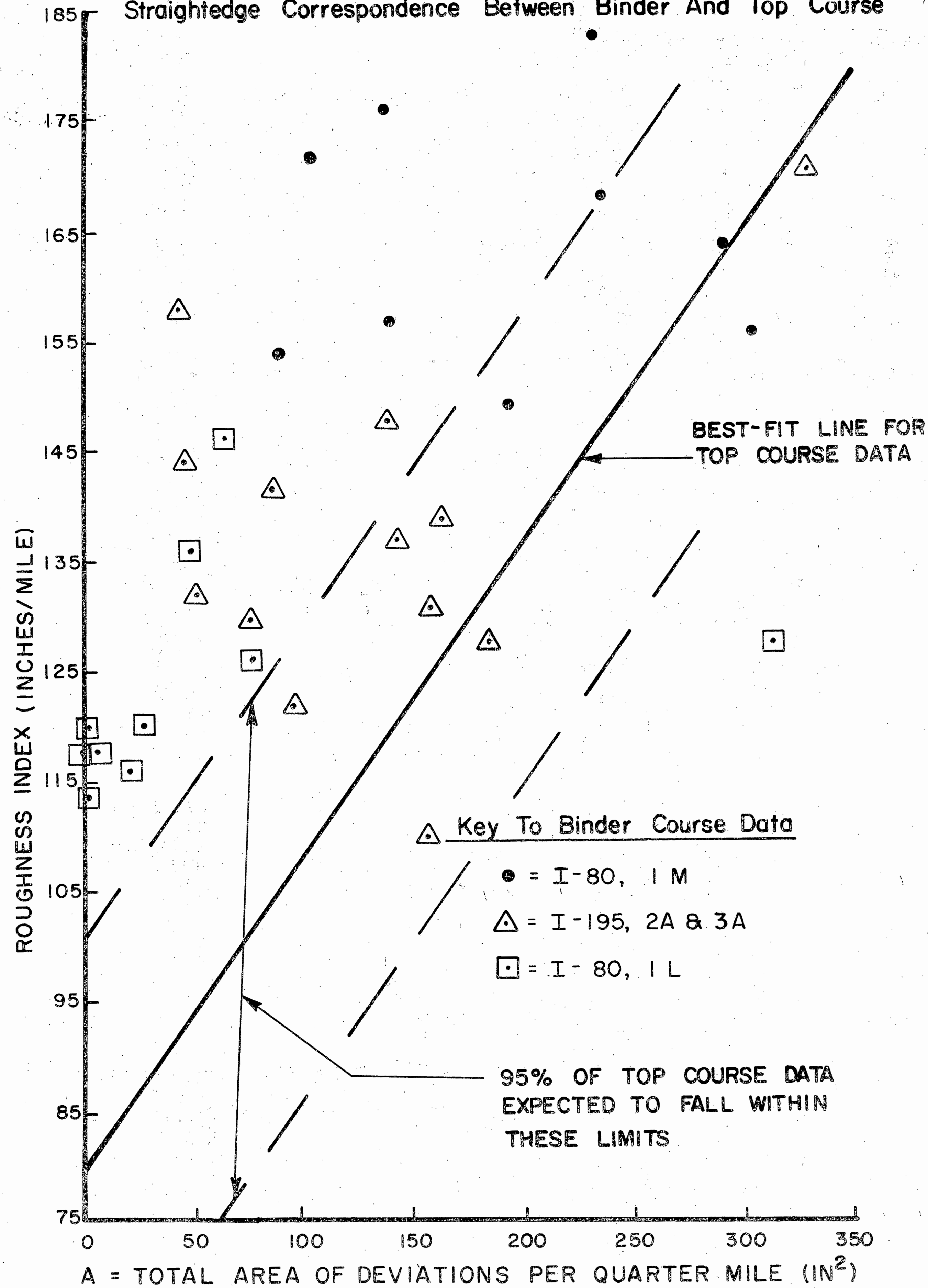
[18] Bower, L. C. and Gerhardt, B. R. "Automatic Controls on Construction Equipment: State of the Art," HRB Record 316, pp. 9-10 (1970)

defects not measured by the straightedge. Textural and long wavelength are the most probable non-measured defects. Elimination of these defects in the top course will lower the roughness index even if the measured level of defects remains the same.

The presence of these binder course irregularities detected by the roughometer but not by the straightedge is evidenced in Figure 23. In this Figure, about 2/3 of the sampled sections of binder course display a higher roughometer reading than would be expected for a section of top course having the same severity of straightedge defects. This difference in Roughness for binder is generally at least 20 inches per mile above the expected average value for top course.

Since the distribution of these unmeasured defects between "textural" and long wavelength irregularities is not known, their influence on the riding quality ultimately achieved cannot be precisely determined. In general, however, it seems reasonable to assume that if the higher roughometer readings for binder are principally a question of texture, an increase in rideability beyond the relative decrease in measured defects would almost automatically result. In such cases, the resultant improvement might be expected to be of some relatively fixed magnitude, the actual value of which would be dependent on the materials and construction techniques of the particular project. On the other hand, if long wavelength or other non-textural roughness is a source of the higher binder course roughometer readings, their elimination is equally as dependent as that of measurable defects on

FIGURE 23 Plot Illustrating Differences In The Roughometer-Straightedge Correspondence Between Binder And Top Course



the application of proper construction practices. Perhaps the most important point in this connection is that since there is at least a possibility that unmeasured surface irregularities may reflect into and detract from the riding quality of the finished surface, it is even more imperative that measurable defects be held in check thruout the construction.

4.5.3 Roughness Improvements for Individual Projects: A summary of straightedge and roughometer data for consecutive sections of final base thru top course from selected projects is presented in Tables 10 and 11.

Examination of the course-to course differences in straightedge data (Table 10) indicates that there is a general trend for the reduction achieved in a course to be proportional to the extent of defects in the previous course.

While it might be expected that removal of the last increments of straightedge roughness would be increasingly more difficult as the potential for removal decreases (i.e. as the general quality level improves), there is an indication that at least on some projects, it in fact apparently becomes more difficult to avoid an increase in defects. That is, as shown in Table 10A, the projects displaying the lowest average number of binder defects have the highest percentage of sections showing either no change or an increase in defects. This effect is most pronounced on the sampled project showing the lowest average level of binder course defects: I-80, Section 1L. On this

Table 10: Course-to-Course Differences in Bituminous Pavement Roughness Based on Straightedge Data

10A: Binder to Top Course

PROJECT No.	PROJECT Section	Final Rating	No. of Sections Tested	Number Showing Improvement	No. of Defects Binder	No. of Defects Top	Defective Length Binder	Defective Length Top	Average Difference in Straightedge Defects Number	Average Difference in Straightedge Defects Defective Length
1	I-80,1L	Fair	33	12 of 33	4 (0-30)*	6 (0-37)	0.8 (0-9.4)	1.4 (0-8.7)	+2	+0.6% (8' per 1/4 mi.)
2	I-280,1B-5P	Fair	20	12 of 20	9 (1-32)	7 (2-24)	1.72 (0.2-6.1)	1.45 (0.2-4.2)	-2	-0.3% (4')
3	I-195,2A&3A	Poor	10	6 of 10	20 (12-47)	14 (3-25)	3.75 (1.8-8.9)	3.18 (0.8-5.2)	-6	-0.6% (8')
4	I-80,1M	Poor	9	7 of 9	21 (13-36)	15 (7-28)	5.7 ---	4.4 ---	-6	-1.3 (17')
5	I-287,7D-9G	Good	24	22 of 24	35[a] (5-106)	3 (0-15)	7.5[a] (0.7-24)	0.4 (0-1.67)	-32	-7.1% (93')

[a]Stabilized base; binder not used on project *range of data for projects tested

10B: Base to Binder Course

No.	Section	Final Rating	No. of Sections Tested	Number Showing Improvement	Base	Binder	Base	Binder	Number	Defective Length
1	I-80,1L	Fair	27	25 of 27	11 (2-47)	3 (0-9)	1.9 (2-8.9)	0.5 (0-1.74)	-8	-1.5% (20')
2	I-280,1B-5P	Fair	10	All	27 (13-49)	13 (3-32)	6.8 (1.89-19.2)	2.5 (0.5-6.1)	-14	-4.3% (57')
3	I-195,2A&3A	Poor	3	All	73 (51-103)	21 (16-24)	10.1 (6.8-14.3)	4.2 (2.7-5.5)	-51	-5.9 (78')
4	I-80,1M	Poor	9	All	66 (20-117)	21 (13-36)	15.6 --	5.7 ---	-45	-9.9% (130')

TABLE 11: Course-to-Course Differences in Bituminous Pavement Roughness Based on Roughometer Data

11A: Binder to Top

Project		Final Riding Quality Rating	Number of Sections Tested	Number Showing Improvement	Roughness Index		Average Reduction
No.	Section				Binder	Top	
1	I-80, 1M	Poor	12	All	156 (131-192)	122 (100-140)	34 in/mi
2	I-195, 2A&3A	Poor	10	All	143 (122-171)	117 (104-131)	26 in/mi
3	I-295, 1S	Good to Excellent	14	All	97 (90-108)	63 (56-68)	34 in/mi

11B: Base to Binder

					Base	Binder	Average Reduction
1	I-80, 1M	Poor	12	9 of 12	177 (136-219)	156 (131-182)	23 in/mi
2	I-195, 2A&3A	Poor	11	All	153 (138-170)	129 (115-142)	24 in/mi
3	I-295, 1S	Good to Excellent	14	All	124 (108-140)	97 (90-108)	27 in/mi

project, 21 of the 33 tested sections displayed an increase in defective length from binder to top, on 12 of which the addition was greater than the acceptable limit for straightedge defects (i.e., $L_D > 0.75\%$). Again, when large decreases in top course defects on the individual sections of this project were observed, they were accomplished on those sections having the most defects in the binder (8-30), while increases were generally observed on the sections having a low number of binder defects (0-6).

The course-to-course improvements in straightedge defects on the individual projects of Table 10 thus show considerable variation compared to the average reductions on which the rules-of-thumb for limitations on deviations on successive courses were postulated (Table 9). Since this variation is generally in the direction of a lower achievable reduction on pavements of the desired better riding quality, the suggested guidelines should at least initially be viewed as the upper boundary for allowable defects on future projects, particularly in the case of binder course.

The course-to-course Roughness Index improvement for several projects is shown in Table 11. The most significant point in connection with this data is that the average improvements observed on our best riding project and on two of the poorest are almost identical: about 25 inches/mile from base to binder and 30 inches/mile binder to top, or a total of about 55 inches from base to top.

These similar average improvements noted do not appear to be unique to the three samples shown inasmuch as the average base to top improvement noted on sections from three other projects is on the same order of magnitude (Specifically: 40, 42, and 69 inches per mile). The average total course-to-course improvement for the six sampled projects is thus about 55 ± 15 inches per mile. This indication that there apparently is a relatively fixed roughness index improvement that can be expected further emphasises the fact that care must be exercised in holding surface irregularities to the minimum even in the first course placed.

4.6 FACTORS INFLUENCING THE LEVEL OF BITUMINOUS PAVEMENT RIDEABILITY ACHIEVED IN NEW JERSEY

4.6.1 General: It is axiomatic that the achievement of quality highway construction of any type depends on the adequacy of three construction inputs: men, materials and equipment. A relative deficiency in any of these inputs -- even in the face of a superiority in each of the others -- can result in unacceptable quality.

In the case of pavement rideability in particular, the number of such possible deficiencies are substantial. One publication[19] alone indicates some twenty potential causes of a rough, uneven bituminous riding surface. The specific rideability levels achieved on particular projects in this state are thus unquestionably a function of the control of many different, sometimes interacting factors.

The following is a discussion of what are felt to be the most significant influences on the riding quality of bituminous pavements in New Jersey.

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[19] "Asphalt Paving Manual", The Asphalt Institute, Table A-11, p. 161 (1965).

4.6.2 Use of Automated Pavers: As previously indicated, there is a trend for New Jersey's more recent bituminous construction to be the smoothest. The most important factor in this improvement in rideability is the increasing (now required) use of pavers equipped with automatic grade* controls.

With the exception of one contract, all projects surveyed to date which were constructed using automatic controls have received at least "Fair" ratings, with their average roughness (80 inches/mile) corresponding to an FHWA "Good". In contrast, the sampled projects constructed with conventionally controlled pavers have at best received "Fair" ratings and average "Poor" (105 inches/mile).

While generally improved riding quality results have been obtained in this State with grade references ranging from a simple ski to high-type erected stringlines, experience on certain of our projects has confirmed performance requirements long-known by the paving industry. That is, automatic controls must be used properly and must be accompanied by favorable conditions of workmanship and materials if the smoothness potential of the equipment is to be realized, indeed, if the work is to be acceptable.

An example of the extent to which less than complete observance of overall good construction procedures can outweigh the contribution of automatic paver controls has been described in a report[20] on the Route I-80, Section 1M paving experiment. Here

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*Certain of these pavers were additionally equipped with automatic feed controls that minimize variable materials pressure against the screed and associated detrimental effects on the finished mat. In such cases, the relative smoothness contribution between grade and feed controls cannot be determined.

[20] "A Comparative Study of Thick-Lift and Standard Bituminous Stabilized Base Construction", N.J. Department of Transportation Research Report 72-003 (December 1971)

the conduct of construction basically as a stop-and-go operation was a fundamental factor in negating the beneficial effects of the paver's automated controls.

In the cited work, the eastbound roadway of a 2-mile, six lane facility was constructed exclusively with a paver equipped with electronic grade controls while the westbound roadway was placed with the same paver and conventional controls. The two roadways were found to have almost identical roughness at the levels of both binder and top course, with each receiving a "Poor" final rating. The sampled sections of top course from this project in fact showed the most extensive straightedge surface defects of any project studied in this research. The particularly disappointing nature of this finding can be appreciated for the fact that the work was in part specifically undertaken to showcase the results obtainable with automatic paver controls preparatory to the adoption of specification requirements for their use. ("Good" to "Excellent" rideability had been obtained on two projects built with automatic controls in the preceding construction season.)

An example of the extent to which different methods of deploying grade controls for a given paver can affect rideability was provided on the Route I-287, Section 7D-9G project. As previously noted, the pavement section of this 5-1/2 mile, four-lane divided facility consisted of two, 4-inch lifts of bituminous stabilized base topped with a 2-inch riding surface.

Just prior to the beginning of paving on the southbound roadway of the subject project, straightedge measurements were made on the completed stabilized base on the northbound roadway. This straightedge sampling revealed not only a high number of defects, but a general pattern in which the number and length of deviations increased from the inner to outermost wheelpaths (average difference: 15 defects per quarter mile).

This pattern of defects strongly suggested that the method of grade control then being used--sensing from an erected stringline at the inside edge of the pavement followed thru with automatic slope control--was inappropriate for the lift thickness and (particularly) the 27 foot width of paving. Consequently, it was suggested to the contractor that an available 20 foot long, footed ski be used as an additional reference on the outer edge of the paver in lieu of the slope control.

The contractor resisted such a change, but did agree to a field comparison of the two methods of control. In this comparison testing, rolling straightedge measurements made on a randomly selected 1,000 foot section of base constructed using the stringline/slope control method were compared to a section of equal length constructed the same day using the suggested stingline/footed ski referencing system.

As shown in Table 12, the base course built using the slope control continued the trend observed in the adjacent roadway, with the total length of defects near the outer pavement edge in this case being twice that of those on the inside. The use of the alternate method of grade referencing not only reduced the transverse variation in defects,

TABLE 12: COMPARATIVE STRAIGHTEDGE DATA FOR THICK-LIFT, DOUBLE LANE PAVING USING TWO METHODS OF GRADE CONTROL

(Route I-287, Section 7D-9G)

	First Method: erected stringline plus slope control				Second Method: erected stringline plus footed ski			
	Inner Lane		Outer Lane		Inner Lane		Outer Lane	
	Inner Wheelpath	Outer Wheelpath	Inner Wheelpath	Outer Wheelpath	Inner Wheelpath	Outer Wheelpath	Inner Wheelpath	Outer Wheelpath
Number of Defects > 1/8" in 10'	29	31	33	44	18	14	9	15
Average	34 defects per 1000 feet				14 defects per 1000 feet			
Percent Defective Length	6.6	6.5	9.8	13.8	5.7	5.3	2.2	5.0
Average	9.2 percent				4.6 percent			

but halved their overall average number and length. As a consequence, a double reference system was used for constructing the remainder of the project. (Interestingly, a sample of follow-up measurements made on the next day's work confirmed the relative efficiency of the alternate system, an average defective length of 3 percent being observed.)

4.6.3 Maintaining Uniform Forward Motion of the Paver: Paving manuals and handbooks universally caution that the laydown operation should proceed at a speed which is both reasonably constant and coordinated with the rate of material supply. Erratic paver speed can lead to an overall pattern of waviness due to induced variations in density and thickness, while an overly fast speed results in unnecessary stops and starts and allied surface defects.

Erratic or stop-and-go operation has been informally observed on a number of New Jersey projects and for disparate reasons. In one instance, for example, intermittency resulted from the use of a paver equipped with a screed extension but not an auger extension. On some other projects, the condition appeared to be the consequence of the workmanship of operators who seemingly are motivated by a desire to provide frequent work breaks.

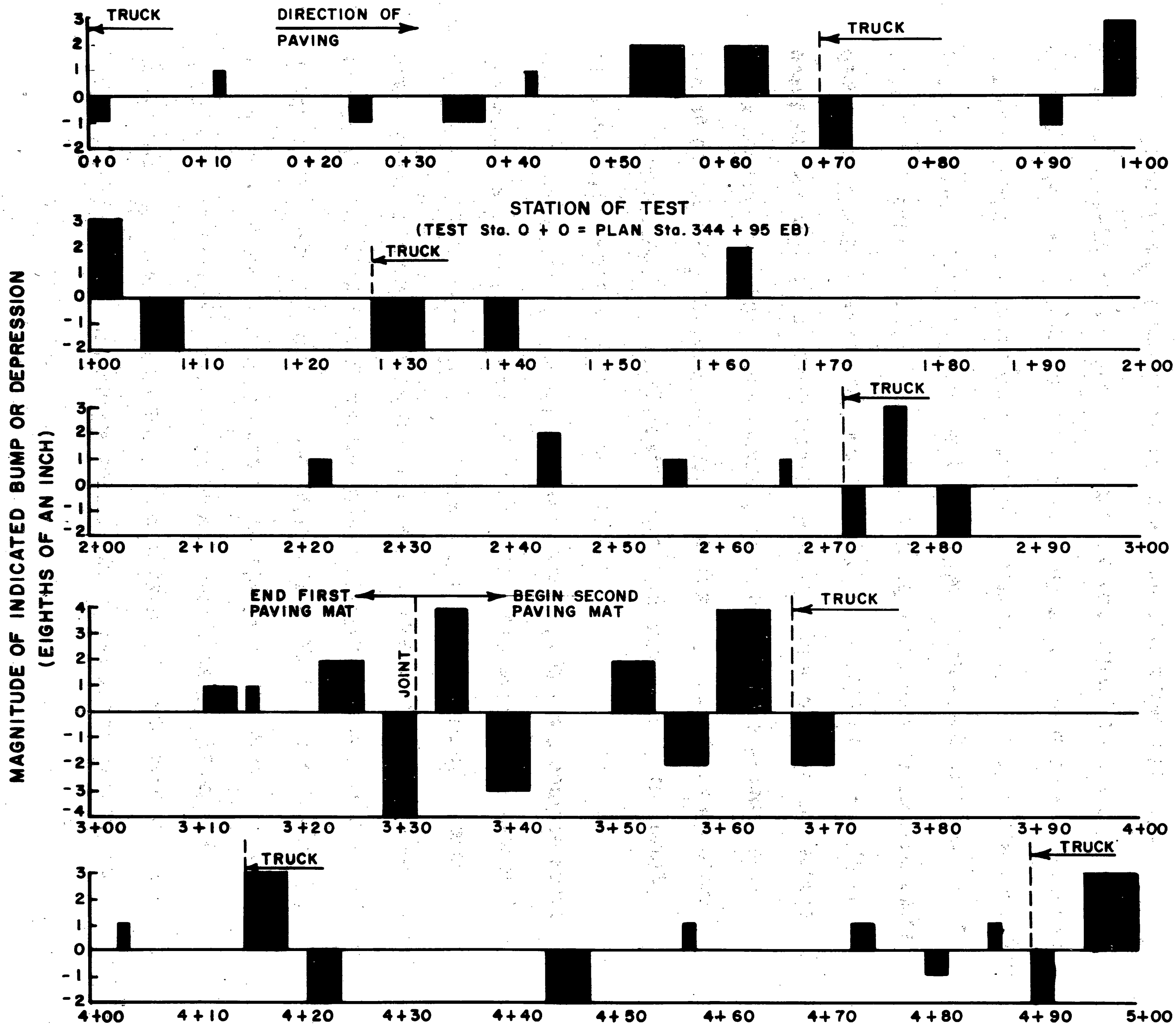
As previously alluded to, the poor rideability obtained on the I-80, 1M project was in part due to the stop-and-go nature of the operation. At one point in this construction, for example, a paver speed of 56 feet per minute was being used in the laydown of a 4 inch base being supplied to the job at an average rate of 100 tons per hour. That this speed was excessive can be appreciated from the fact that constant operation at 56 feet per minute for the given mat width and thickness would require an average material supply 10 to 11 times greater than that actually provided. In other words, only a small fraction (1/10) of the working hour could be used productively at the given rates of laydown and supply. Further, even with a full hopper, the (originally supplied) slat conveyor system could not furnish material to the spreader fast enough to maintain a constant speed. Consequently, the paver was forced to stop at about 10 foot intervals to feed material. These frequent stops to feed material as well as those waiting for resupply resulted in 1/8 to 1/2 inch deep screed marks in the mat surface which were not eliminated on subsequent rolling.

The pattern of straightedge defects on 500 feet of the early paving on the I-80 project, annotated to identify truck pick-up points and a construction joint, is presented in Figure 24. As shown, each point of resupply in this particular length of pavement had an associated depression due to screed settlement, occasionally closely preceded or followed by other defects. The magnitude of these defects in some cases reflect a truck backing into the paver. The interesting point in connection with the start-up operation (Station 3+30) is that the indicated considerable length required to obtain a relatively defect-free operation (i.e., the length of the paver or more) is not unique to the I-80 work.

Several points are of significance in connection with the possibilities for stop-and-go operation on future New Jersey projects:

FIGURE 24: BLOCK DIAGRAM INDICATING SURFACE DEFECTS INTRODUCED DURING PAVER START-UP AND RESUPPLY

(ROUTE I-80, IM BITUMINOUS BASE)



First, while some field experimentation certainly may be required to match paver speed to material supply, simple (yield-supply) calculations obviously should be made or specially prepared tables consulted to give a reasonable approximation of the appropriate speed to be used. At a minimum, such would preclude gross mismatches in laydown and supply rates. Figure 25 is an example of the available[21] charts that can be used for guidance in coordinating paver speed and material supply.

Secondly, a recently added provision to the New Jersey Standard Specifications--a requirement for echelon paving on all courses--can be expected to aggravate or create the potential for a stop-and-go operation. This results since a relatively large increase in material supply or a decrease in paver speed will be required for the echelon mode of paving. Additionally, a relative change in either material supply or laydown rate will also be required on those projects employing thick-lift base construction, a technique which this Department is increasingly willing to permit. In combination, echelon and thick-lift paving could pose a monumental problem in providing adequate material supply.

While this Department has considered requiring a minimum rate of supply on at least some projects (e.g., thick-lift work) as a measure to minimize intermittency of paving, problems were foreseen in the enforcement of such provisions. Also, the provision of an adequate supply of material and maintaining continuity of laydown fundamentally appeared best to be the province of the Contractor. Adoption of a penalty schedule for deficient pavement riding quality would, however, provide an indirect control over the contractor's operation inasmuch as stop-and-go work would have a high probability of receiving penalties.

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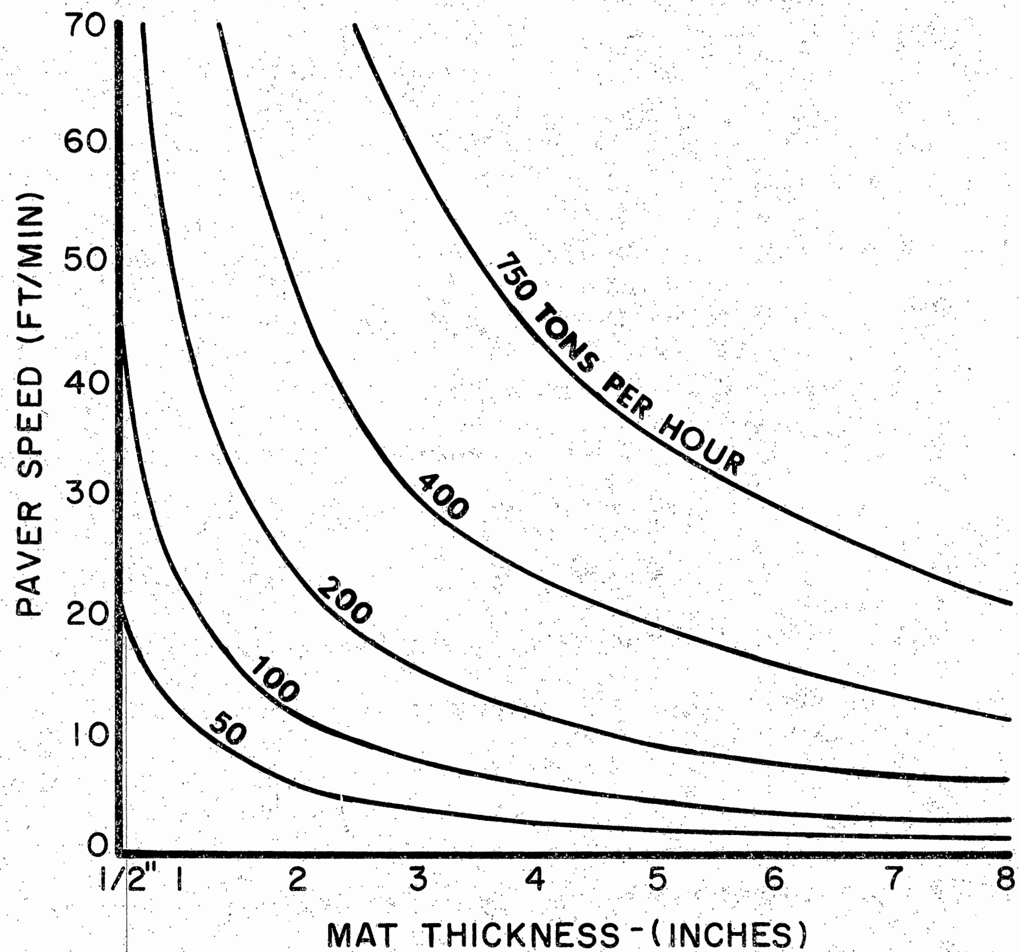
[21]Foster, C. R. "Smooth Pavements", National Asphalt Paving Association (1973).

FIGURE 25

TONS PER HOUR REQUIRED TO KEEP PAVER MOVING[a]

(Basis: 12 foot Lane, 144 pcf)

[a] Excerpted from the National Asphalt Paving Association Booklet, "Smooth Pavements"



4.6.4 Frequency of Transverse Joints: The majority of bituminous projects studied in this research were built under specifications which required that when less than full-width paving was employed (the typical case), the spreading and finishing operation could not be advanced for more than 500 feet or one hour. When that mat length or time was reached, the paver was required to move back and resume paving in the adjacent lane. As result of this provision then, a quarter mile of paving could be expected to contain very nearly three construction joints.

As previously noted in Figure 18, a bituminous surface course containing six defects per quarter mile typically receives only a "Fair" rideability rating. Thus, if surface course defects introduced during the start-up at joints were held to a maximum of only two per joint, this aspect of the paving operation alone would cause the pavement to have less than "Good" riding quality. Importantly, limiting the number of defects to two at a construction joint or even to the same magnitude and length as those elsewhere in the mat would, in a number of cases, be a very significant improvement. In a few extreme cases studied, all of the defects occurring in a quarter-mile section have been associated with the resumption of paving at a joint.

Realizing the difficulties in achieving a smooth ride in a pavement containing numerous transverse joints, the Department in mid-1970 changed the Standard Specifications to allow laydown to extend to a maximum of 1500 feet or such distance that the material at the longitudinal joint could be maintained at not less than 150°F. Whether the reduction in joints permitted by the 1500 foot allowance is actually achieved on future work obviously will depend on the quantity and quality (i.e., temperature) of materials supplied to the job.

4.6.5 Other (Non-Quantifiable) Factors: Apart from the preceding, experience strongly suggests that a number of additional factors have influenced New Jersey pavement riding quality and in particular, the indicated trend for improved rideability results. These factors relate to the smoothness quality of the non-bituminous courses of the pavement structure, the method of payment for bituminous paving, and a spirit of "Quality Consciousness" on the part of State and Contractor personnel. Unfortunately, while the effect of these factors has been noted by other investigators, their specific influence on rideability in our state cannot be quantified due to either the absence of research controls or their essentially subjective nature.

Quality level of non-bituminous courses: The roughness equipment of this study did not permit making any determination of the relative roughness of courses underlying the bituminous structure. However, if one accepts the premise that the achievement of a quality final riding surface is the result of a concerted effort at each preceding level, then it seems reasonable to assume that the historical trend for better New Jersey bituminous rideability must at least to some extent be a reflection of the increasing use of automated fine-grading machines for base and subbase courses. The use of this automated equipment has in part been stimulated by the fact that the necessary (erected stringline) grading reference is now required for subsequent paving.

Similarly, informal observations suggest that the use of a difficult-to-construct macadam base course* on about one-third of the

*Consisted of nominal 1-1/2 or 2-1/2 inch aggregate with surface and inverted chokes of screenings. Specifications permitted a maximum surface variation of ± 1/2" in 16'.

projects studied in this research in some cases was a factor in the ultimate level of riding quality obtained. In point of fact, the difficulty in achieving a relatively smooth paving platform using macadam base was a consideration in the Department's decision to eliminate this item from pavement designs subsequent to 1970.

Conflict between square yard payment and thickness penalties for bituminous pavement: Until recently, New Jersey project specifications provided for the payment of bituminous paving courses on a square yard basis and the assessment of penalties for deficient thickness.

It is well-known[22] that an innate conflict exists between the attainment of a minimum thickness and smooth ride when payment is on a square yard basis. That is, it is a practical impossibility for the contractor to provide the variable thicknesses necessary to correct for surface irregularities in the preceding course and also maintain a minimum thickness without increasing the material quantity on which his bid is predicated.

In New Jersey, this conflict between rideability and thickness was generally resolved in favor of thickness. That is, the formalized sampling plan for thickness determinations and attendant computational requirements for penalties automatically invited close adherence to the requirements. In contrast, the data of this study indicates that surface tolerance requirements--for which no formal sampling plan is provided or data reporting required--were only sporadically enforced. Additionally,

[22] "Symposium--Thickness Variations of Asphalt Concrete", AAPT Proceedings, Vol. 33 (February 1964)

on at least two projects where automatic grade controls were used on intermediate courses, such controls were suspended on the top course and the paver set and operated to achieve a uniform thickness. This appears to be further evidence of which option a contractor would elect when faced with a smoothness/thickness conflict.

Since payment on a square yard basis can inhibit achievement of good riding quality in general, and the achievement of the full potential of electronically controlled pavers in particular, provisions for tonnage payment were incorporated in Department specifications at the time automated pavers were required.

"Smoothness Consciousness": In achieving a quality improvement in any item of construction, the necessity for an awareness and acceptance of the problem followed by planning to execute the improvement is self-evident. The presence of a continuing awareness and concern for quality in project planning and execution is, in turn, a reflection of the successful application of the essentially subjective processes of management and training and the even more elusive qualities of professionalism and pride of workmanship.

In applying these concepts to bituminous riding quality in particular, Charles Foster[21] of the National Asphalt Paving Association has indicated the necessity for re-establishing a spirit of "Smoothness Consciousness" extending from top management to project labor. Foster notes, for example, that contractor management must be willing to allow smoothness considerations to take precedence over production in some cases. The development of such a sense of smoothness consciousness is obviously equally applicable to State personnel.

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[21] Op. Cit.

In recent years, there have been renewed efforts on the part of this Department and the New Jersey Asphalt Paving Association directed at stimulating such smoothness consciousness. Within the Department, these efforts have taken the form of training seminars on paving equipment and techniques as well as presentations to operating personnel on trends in New Jersey pavement rideability. Additionally, an annual series of lectures at Rutgers University which have been increasingly or exclusively devoted to bituminous pavement rideability have doubtless stimulated a keener awareness of the need for and methods of achieving improved riding quality.

In spite of the subjective nature of smoothness consciousness, comparison of the rideability results between the I-80, 1M and 1L projects--each built by the same contractor--yields some evidence of this factor at work. That is, when confronted with documentation of the poor results on the 1M project, the President of the contracting firm indicated that his first reaction was to determine "who to sue or who to fire." On the company's next (1L) project--located in the same physical surroundings and supervised by the same State Resident--a number of measures were undertaken to overcome shortcomings noted on the previous project. These measures included purchase of a new paver equipped with high-type grade controls and furnishing a high production, on-site asphalt plant. Comparison of straightedge data made on the two projects indicated that the contractor's work had advanced from possibly the worst to one of the better riding New Jersey jobs. The firm thus deserves a measure of congratulations for the spirit of professionalism evidenced in the marked improvement between jobs. While it should be apparent, it is worth emphasizing that certain of the measures undertaken on the 1L project were equally beneficial to Contractor and State: The provision of an increased supply of material (about 300 versus 100 tons per hour) not only served to minimize the potential for stop-and-go operation and allied defects, but also maximized the contractor's profit potential.

As a means of emphasizing this Department's interest in achieving good rideability to State and Contractor personnel and to the motoring public, the furnishing of an annual pavement smoothness award (or awards) has been considered. Such a proposal has not been implemented since, at least at certain periods, a New Jersey pavement smoothness award would have been something less than meaningful. However, since roughness data for some of our recent flexible pavements compares favorably with that achieved in other states, it is believed that a "Smooth Pavement" (based on rideability alone) or "Good Pavement" (all aspects of construction quality considered) award might now be feasible. In deliberating the merits of an award proposal, it is the writer's opinion that some thought should be given to providing a monetary prize to the State personnel producing the best rideability ($400 is awarded in one state).

PART V: PROPOSED PENALTY SCHEDULES FOR DEFICIENT PAVEMENT RIDING QUALITY

5.1 INADEQUACIES OF THE PRESENT SPECIFICATION

New Jersey's current surface smoothness specifications possess a number of shortcomings:

Lack of specific sampling plan: New Jersey specifications indicate only that bituminous and (plastic) concrete pavements "shall be tested", while the "entire" (hardened) concrete surface is to be checked for conformity. No report of the straightedge data obtained is required for either type of finished pavement. In the absence of a sampling plan which is both reasonable and firm and without an associated reporting requirement, testing may or may not be performed.

Choice of tolerances: The present specification requires zero straightedge defects: "all" projections and depressions exceeding 1/8 inch in 10 feet are to be corrected by removal and replacement in the case of bituminous pavement, or "as directed or approved" in the case of concrete. However, as has been described, research data confirms what might be expected intuitively: It is not necessary for a surface to be completely free of 1/8 inch defects to obtain acceptable riding quality. Further, for projects having some manageable number of defects, it is more reasonable to assess monetary penalties to some proportion to their influence on riding quality than to always require removal and replacement.

Type of testing device: The surface is to be tested with a "10-foot straightedge". Using an ordinary (non-rolling) straightedge, data collection is slow and laborious, and the measured defects may or may not reflect the actual nature of pavement defects.

5.2 DEVELOPMENT OF ALTERNATE SURFACE SMOOTHNESS PROVISIONS

The development of a proposed alternate specification--one which would bring to bear the greater speed of data collection and demonstrated relationship to riding quality of the rolling straightedge--is presented in step-wise fashion in the following subsections.

5.2.1 Choice of the Riding Quality Parameter to be used in Determining Acceptability: As previously noted, rolling straightedge data in either of three forms--the number, length or area of defects--yields an equally valid representation of pavement rideability. However, the percent defective length parameter possesses the distinct advantage that its application is independent of the quantity of pavement measured. Thus, the basic test unit for acceptance purposes (i.e., the "lot" size) can be the total length of a day's paving, an obviously variable quantity. The use of this particular measure of surface irregularities is additionally desirable in that application of the concept of "lot percent defective" is firmly established in the quality assurance literature. It is probably for these same reasons that percent defective length has been used in the pavement acceptance schemes of other agencies.

5.2.2 Limits of Acceptability for the Quality Parameter: Given that the specification will be based on a measure of the percent defective length of each day's paving, it is next necessary to place engineering limits on the defective length parameter setting forth what constitutes an acceptable quality level and a rejectable quality level.

In the writer's judgment, a reasonable value for the acceptable quality level is the guideline suggested by the FHWA: An average "Fair to Good" rideability rating. Based on the correlation between the New Jersey roughometer and rolling straightedge, this "no penalty" point corresponds to a maximum percent defective of about 0.75 and 3.0 percent, respectively, on bituminous and concrete pavement.

At the other extreme, a totally rejectable quality level (i.e., a remove/replace criterion) of "Poor to Very Poor" rideability is thought appropriate. In terms of straightedge data, this means that removal and replacement should be required or a very severe payment reduction should be assessed whenever the percentage of the surface exceeding 1/8 inch in 10 feet is 3.5 percent or more on a bituminous pavement or 14.0 percent or more on a concrete pavement. Based on the historical data of this study, when the percent of the pavement length out of specification reaches these values, there is less than a 3 percent chance that the pavement will at <u>best</u> be of "Fair" rideability, with the <u>expected</u> average riding quality rating being about 20 inches/mile into the "Poor" zone.

As the extent of surface irregularities increases from the acceptable quality level to the totally rejectable quality level, it is apparent that at some intermediate point, marginal acceptability is reached. While numerous possible values of defective length could be considered as marginally acceptable, it is concluded that borderline "Fair/Poor" riding quality should definitely be considered of marginal acceptability and should have at least some associated penalty. The percent defective length corresponding to this marginal rating is 2.0 percent on flexible pavement and 8.0 on rigid pavement.

A summary of the specific rideability ratings to be given consideration in the development of the proposed surface smoothness specification and the general philosophy underlying the provisions is presented in Table 13.

Table 13

Percent Defective Length Values to be Considered in the New Jersey Surface Smoothness Specification

Specification Quality Level	Rideability Equivalent	General Type of Penalty to be Assessed	Corresponding* Percent Defective Length	
			Bituminous Pavement	Concrete Pavement
Acceptable	Fair to Good	None or Very Slight	0.75% or less	3.0% or less
Marginally Acceptable	Fair to Poor	Some	2.0	8.0
Totally Unacceptable	Poor to Very Poor	Severe or Remove/Replace	3.5 or more	14.0 or more

*In each case, values of defective length are rounded off in the direction of leniency.

5.2.3. <u>Development of Procedures to Determine Compliance with the Acceptability Standards</u>: Having decided on the limits of acceptability, the first step in devising a plan to measure the extent to which future projects conform to these standards is to determine the amount of testing which might reasonably be performed. The test sample size in turn is a function of who will perform the tests and when, as well as the quantity of pavement to be evaluated.

In New Jersey, a "typical" day's production of bituminous surface course might be expected to consist of paving three-fourths of a mile, two lanes wide (1,000 tons). Concrete paving commonly consists of at least one-fourth mile, two lanes wide. Since there are two possible test locations (wheelpaths) per lane, complete testing of a day's production would involve collection of straightedge data on 3 wheelpath miles of bituminous and one wheelpath-mile of concrete. While the time involved in such smoothness testing varies considerably depending on the level of roughness, simply pushing the device along 3 miles of perfectly smooth pavement would, for example, involve <u>at least</u> an hour. Given that smoothness acceptance testing should be performed daily and by State project personnel, it is believed that manpower limitations would permit the testing of only a fraction of the involved wheelpath miles. Consequently, the basic sampling plan recommended for use in New Jersey is one devised by the FHWA and consists of the following: A single longitudinal run extending for the full length of the day's paving is made with the rolling straightedge, with the transverse location of the test (i.e., lane and wheelpath) being determined randomly and varied every 300 feet. This sampling plan would thus involve 50% and 25% testing of the total wheelpath-miles of single and double lane paving, respectively.

As in the case of any testing process, the introduction of variability is implicit in the decision to perform less than 100 percent straightedge sampling. The percent defective length obtained in the proposed sampling plan thus clearly will be only an <u>estimate</u> of the pavement's <u>true</u> percent defective. The strength of this estimate will be a function not only of sampling variability, but the previously described variability of the instrument itself (Appendix B).

To determine the extent of measurement variability resulting from fractional sampling, a simulation process[23] was employed in which the described testing plan was applied to actual straightedge data records for New Jersey concrete and bituminous pavements of various roughness levels. Numerous applications (at least 60 and up to 256 tests per section) confirmed the validity of the proposed fractional testing plan, with the defective lengths resulting from individual simulations being normally distributed and displaying a mean value in very close agreement with the actual defective length measured in the field. While it was expected that the variability introduced by the sampling procedure (expressed in terms of the standard deviation statistic) would increase with a reduction in the level of testing and with an increase in pavement roughness, the relative magnitude

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[23]Weed, R. M. "Rolling Straightedge Sampling Plan Simulation and Specification Derivation" (A paper submitted for presentation at the 1974 HRB meeting)

of this variability was somewhat surprising, particularly in comparison to instrument variation. A plot of the respective standard deviations associated with sampling and instrument precision (Figure 26) indicates that for fractional sampling on pavements of the general roughness levels observed in our State, sampling error* will be the more important component of variation to be considered in the acceptance plan. The total measurement variation expected in the straightedge process is determined from the following relationship:

$$\sigma_T = \sqrt{\sigma_s^2 + \sigma_p^2} \qquad \text{(Equation 6)}$$

Where σ_T = Total standard deviation of a straightedge test result.

σ_s = Standard deviation associated with a given fractional sample size and roughness level.

σ_p = Standard deviation associated with instrument precision at a given roughness level.

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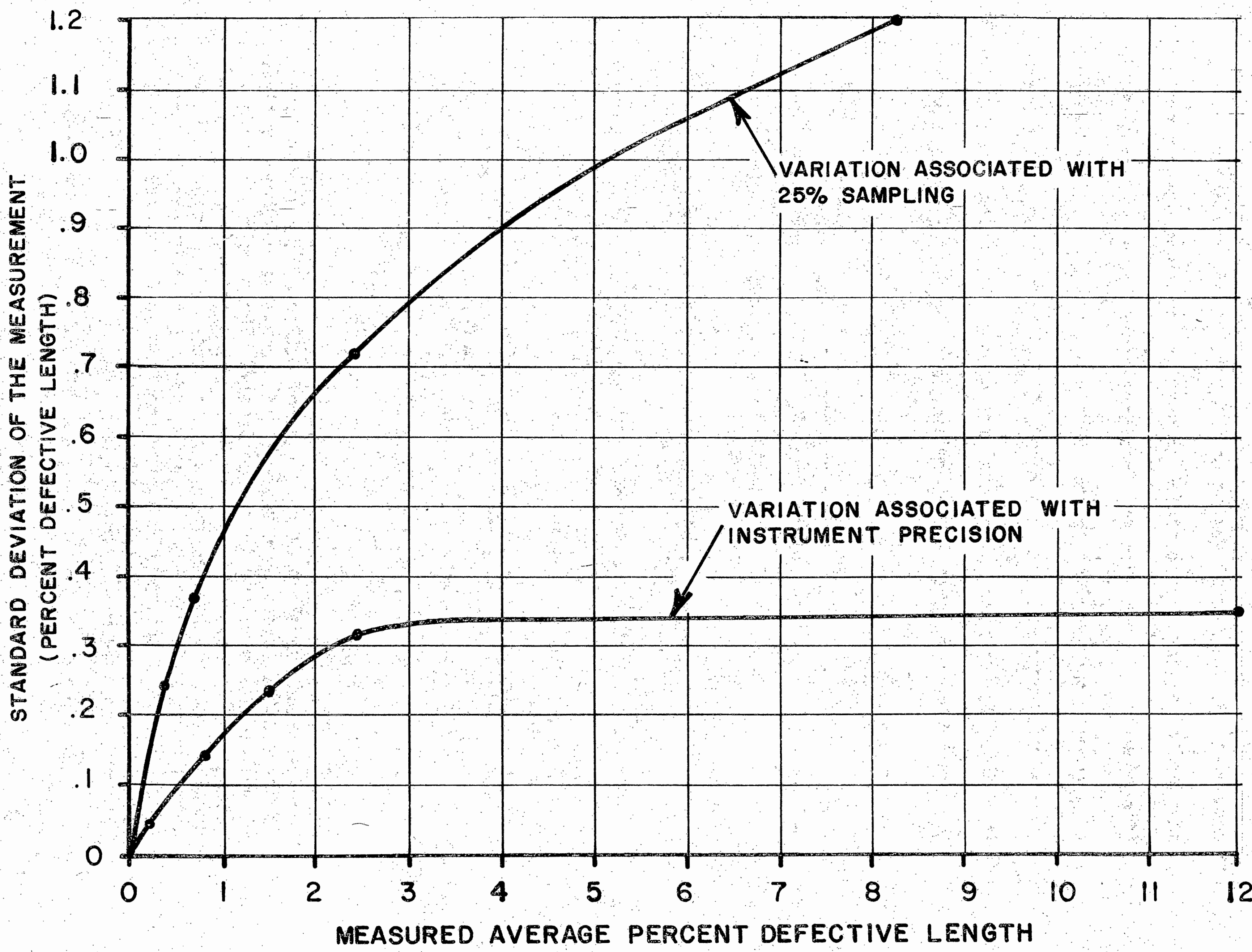
*The described "sampling" error is a reflection of the variability of the product (i.e., longitudinal and transverse roughness variation) as well as the sampling technique itself. The particular variation illustrated in Figure 26 is for 25 percent testing (i.e., a single straightedge pass over two lanes). Based on more limited data, the variation introduced by 50% sampling appears to be about half that of 25 percent sampling. Thus, the sampling error expected from a single pass over a pavement laid in a single lane will be about half that for the <u>same</u> production placed in two lanes.

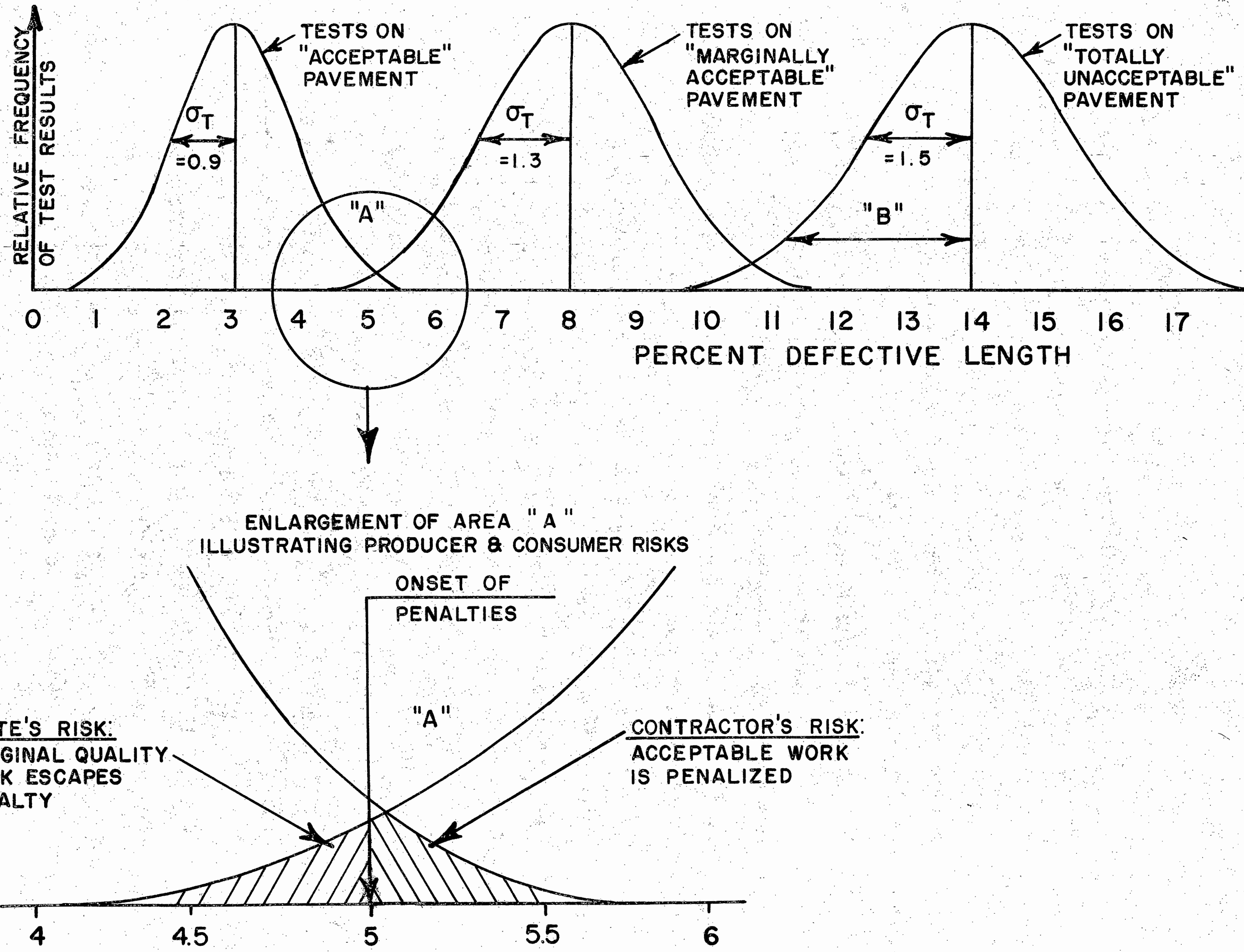
FIGURE 26: EXPECTED VARIABILITY IN THE STRAIGHTEDGE PROCESS: SAMPLING ERROR COMPARED TO INSTRUMENT PRECISION



In the present application, the preceding total straightedge process variation will reflect on the acceptance plan as an uncertainty in differentiating between any given quality levels. This uncertainty in turn requires that the acceptance scheme be so constructed as to minimize risks such as wrongly accepting pavements of poor rideability or rejecting those of good riding quality.

Figure 27 illustrates the expected (normal) distribution of defective length measurements resulting from a single pass over concrete pavements respectively having riding quality corresponding exactly to the three standards of acceptability: acceptable, marginally acceptable, and totally unacceptable. As shown in this figure, a number of possibilities exist as to the exact value of defective length to be used as the onset of penalties. For example, if it were decided to never penalize acceptable work, a defective length of 6 percent could be adopted as the no penalty demarcation. If this were done, however, a large proportion of test results from marginally acceptable pavement would escape penalties. Similarly, adopting 4 percent defective as the onset of penalties would always penalize a pavement of marginal quality, but would also penalize too great a fraction of test results from acceptable pavement. Since the distribution of test results from acceptable and marginally acceptable work overlap, and are thus indistinguishable, there is no way of eliminating at least some risk to the State (i.e., accepting marginal quality) or Contractor (i.e., penalizing acceptable work) using a 25 percent sampling fraction. As a consequence, a commonly used policy for

FIGURE 27: EXPECTED DISTRIBUTION OF STRAIGHTEDGE TEST RESULTS ON CONCRETE PAVEMENTS OF VARIOUS RIDING QUALITY LEVELS (BASIS: 25% TESTING)



proportioning such risks -- setting the consumer and producer risks at an equal (low) level -- is adopted here. Applying this philosophy to the initial acceptance level leads to the choice of 5 percent defective as the onset of penalties for concrete pavements. At this level, the producer's and consumer's risks will both be at 1 percent -- that is, acceptable pavement will have only a negligible (1 percent) risk of having a penalty assessed, while there is an overwhelming probability (99%) that a marginally acceptable pavement will be subjected to a payment reduction.

Measurement uncertainty obviously should also be taken into account in providing for penalty graduations in the acceptance plan. For example, a pavement whose rideability coincides exactly with the "totally unacceptable" quality level has an equal chance of any single test value being above or below the true value. To insure that an unacceptable pavement will receive at least a moderately severe penalty, it is necessary to add a penalty range that will include the portion of the test distribution to the left of the remove/replace limit (Distance "B" in Figure 27). If this distance is chosen as 3 percent defective ($2\sigma_T$) then concrete pavement with an actual percent defective of 14% will have about a 98 percent chance of receiving at least a moderately severe penalty. The suggested moderate penalty range thus extends from the 14 percent defective level down to the 11 percent level.

Since percent defective length is a continuous function, there are innumerable test distributions such as Figure 27 that could be prepared, and thus innumerable penalty risks that could be calculated. A more convenient way of showing the risks associated with a sampling plan is to plot a curve known as the "operating characteristic" of that test procedure and sampling plan. This curve shows for any particular level of percent defective in test samples what percent of the samples will be accepted (or rejected) by this inspection plan. In this work, this percentage is expressed as the "probability of the specified penalty being applied." Thus a value of 70 percent means that,on the average, in 70 out of 100 cases, a pavement of the given defective length will be expected to receive a penalty. Conversely, in 30 out of 100 cases, no penalty (or a lesser penalty) is expected.

Figure 28 shows the operating characteristic curves for 25 percent sampling on concrete. The existence of a family of curves is a reflection of the fact that when a graduated penalty scale is employed, it is necessary to determine the relative risks of <u>various</u> levels of penalties being applied. For example, when 5 percent defective is used as the onset of penalties, there is about an 80* percent probability that a pavement which is actually 6 percent defective will receive a slight penalty, and a 20 percent probability that it will receive no penalty. A pavement of borderline "Poor"

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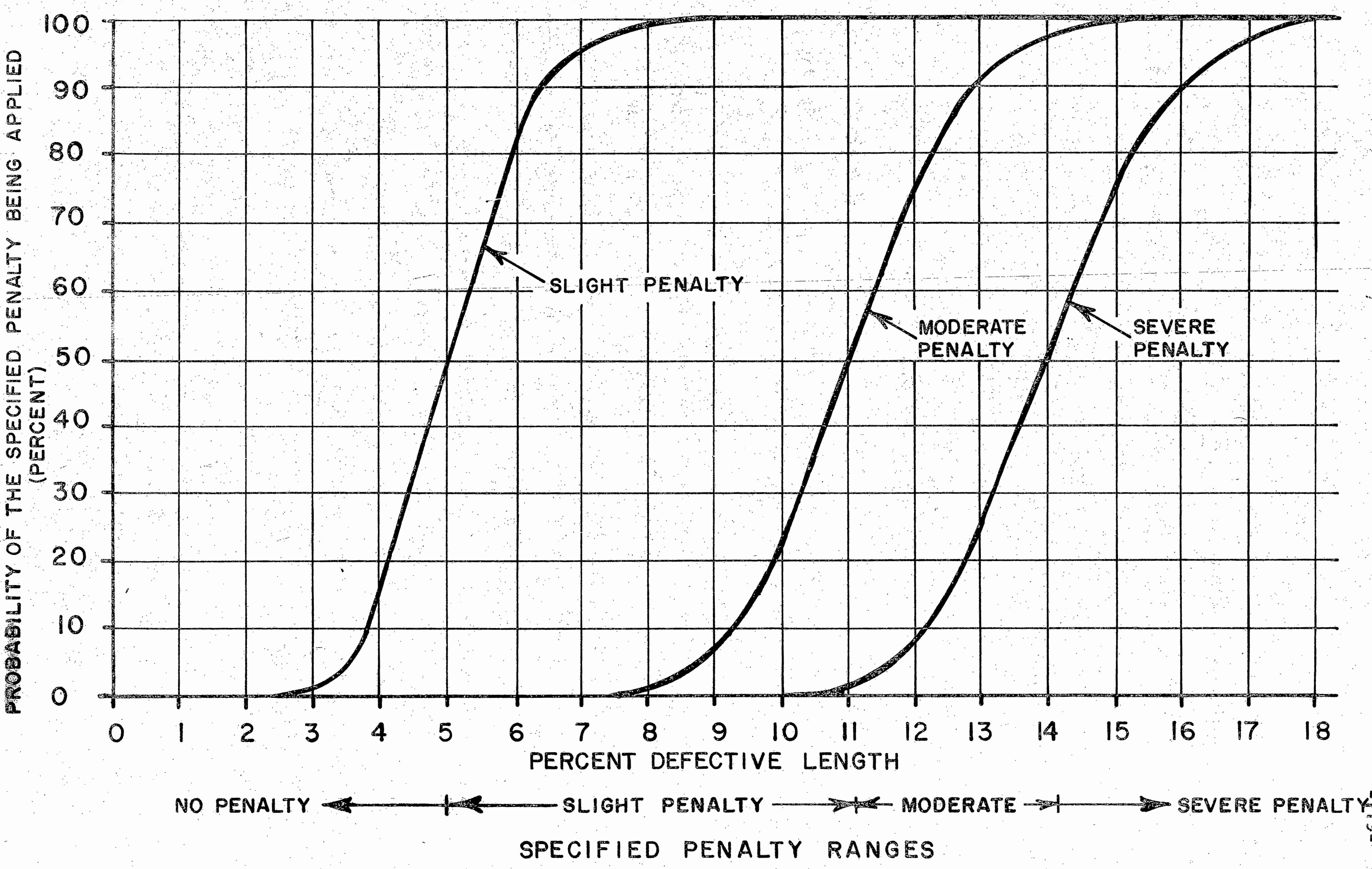
*Again, it is to be noted that these risks are for 25 percent sampling. If single lane construction is tested, measurement dispersion will decrease and the risks to <u>both</u> state and contractor will decrease.

FIGURE 28: OPERATING CHARACTERISTIC CURVES FOR 25 PERCENT STRAIGHTEDGE SAMPLING OF CONCRETE PAVEMENT



riding quality or worse (8.0 percent defective or more) can always be expected to receive some penalty, but there is a very small chance that such a marginally acceptable pavement will receive a moderate penalty. The chances of receiving a moderate penalty are not 50-50 until 11 percent defective is reached (corresponding average riding quality: 10 inches/mile into "Poor").

The allocation of risks necessary to set acceptance limits on bituminous pavement is more difficult than in the case of concrete, due to the greater relative roughness contribution of straightedge defects on bituminous pavement. That is, only 1.25 percent defective separates acceptable and marginally acceptable bituminous pavement (0.75 and 2.0 percent defective), while the difference between these same quality limits is four times larger on concrete (3.0 to 8.0 percent defective). As a consequence, measurements between different quality levels on bituminous pavement are less distinguishable than on concrete (i.e., the distribution of test results overlap more than at point "A" in Figure 27) and the allied consumer and producer risks increase. While these risks could be set equal, they would be quite high. Reduction of measurement dispersion and associated risks requires that in some cases, additional tests must be conducted on bituminous pavement. This reduction accrues from the fact that the standard deviation of the average of two test measurements will be about 70 percent of that for a single test*. A sequential testing

*In general,

$$\sigma_{\overline{X}} = \frac{\sigma_T}{\sqrt{N}}$$

Where: $\sigma_{\overline{X}}$ = standard error = standard deviation of the average of a sample of N tests

σ_T = standard deviation

N = number of tests

procedure, involving the use of a retest when the first test fails to indicate acceptable pavement, is considered the most efficient means of increasing the testing workload.

Figure 29 presents operating characteristic curves for the testing of bituminous pavement. As shown, if an acceptance limit of one percent defective is employed for a single test, there would be about an 8 percent chance that a marginally acceptable bituminous pavement (2 percent defective) could escape detection and thus penalties. While this is judged to be a reasonable risk for the state, it would be unfair to <u>penalize</u> based on a single test since there is about a 30 percent probability that a single measurement from a truly acceptable pavement (0.75 percent defective) would be penalized. If, however, a second test is made and averaged with the first, use of 1.3 percent defective as the onset of penalties would provide balanced (8%) State and Contractor risks. The basic acceptance plan for bituminous pavement can thus be formulated into two rules:

> <u>Rule one</u>: Routinely perform a single straightedge test. If the indicated percent defective is one percent or less, accept the pavement; if more than one percent, perform a second test*.
>
> <u>Rule two</u>: If the average of the two tests is 1.3 percent defective or less, accept; if more than 1.3 percent defective, apply a slight penalty.

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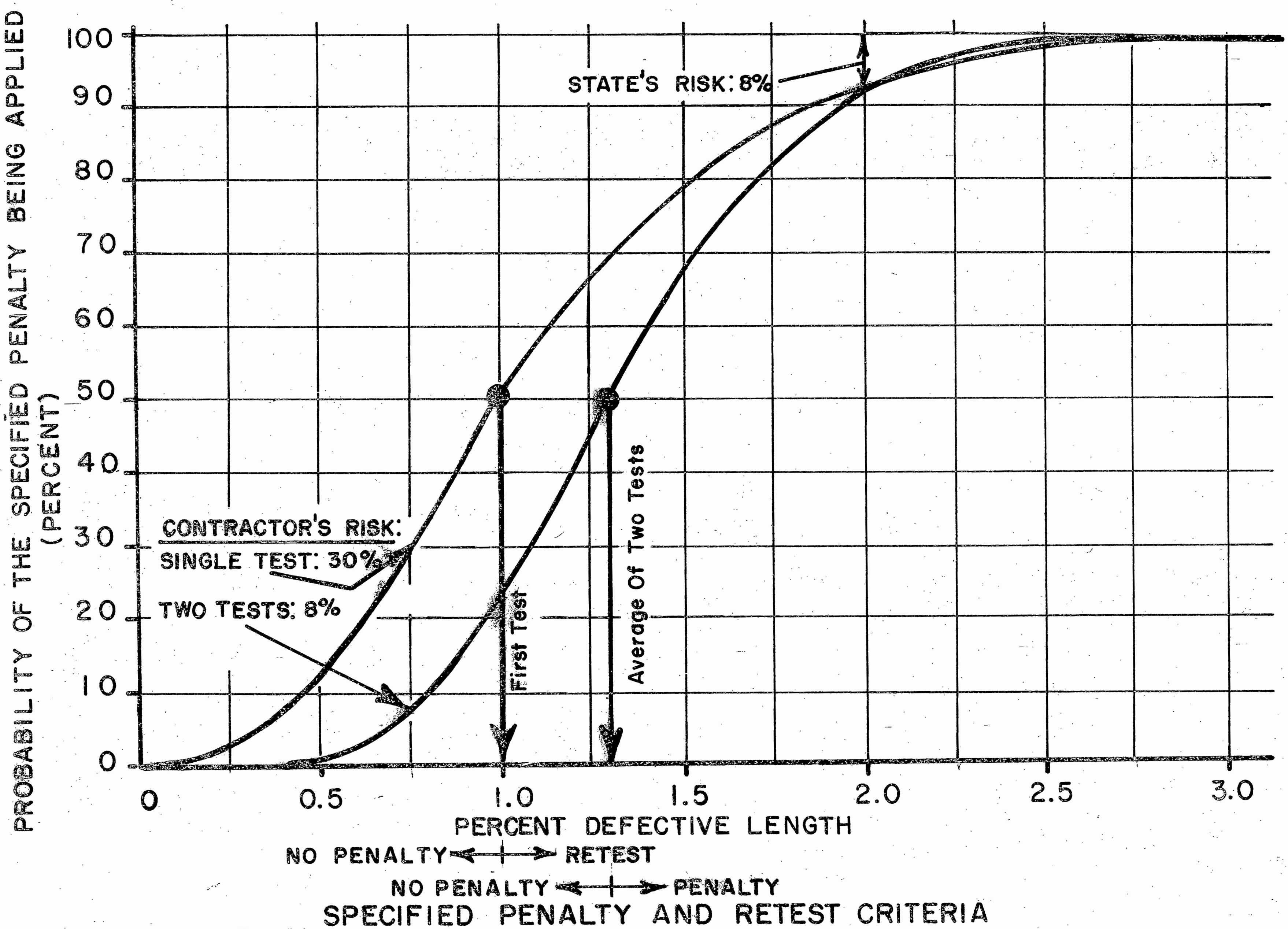
*This retest should be a <u>replicate</u> in the statistical sense, not a <u>duplicate</u>. That is, the initial and intermediate transverse location of the test run should again be determined randomly before the testing is repeated.

FIGURE 29: OPERATING CHARACTERISTIC CURVES ILLUSTRATING CRITERIA FOR THE ONSET OF PENALTIES ON BITUMINOUS PAVEMENT



As in the case of concrete pavement, an additional (moderately severe) penalty range is proposed for bituminous pavement as insurance against totally unacceptable work receiving only a slight penalty. The use of 2.3 percent defective as the onset of this moderate penalty will limit the State's risk of accepting poor rideability without at least a moderate penalty to about a 3 percent chance.

Operating characteristic curves for 50* percent sampling of bituminous pavement are shown in Figure 30. The principal difference in risks between concrete and bituminous pavements is that a bituminous pavement having a borderline "Fair/Poor" riding quality has about a 25 percent chance of receiving a moderate penalty, whereas a concrete pavement of this same quality level has a negligible chance of receiving a moderate penalty. These differences in contractor risks are, once again, the result of differences between the surface characteristics of the two pavement types (i.e., the "spread" of defective length between any given quality levels). This relatively greater contractor risk will be mitigated by making the consequences of a moderate penalty (i.e., the indicated payment reduction) less for bituminous pavement than for concrete.

At least certain of the described acceptance limits appear to be quite lenient. For example, a concrete pavement having a defective length of 11 percent has only a 50 percent chance of receiving a moderate penalty. Translated into terms of the actual

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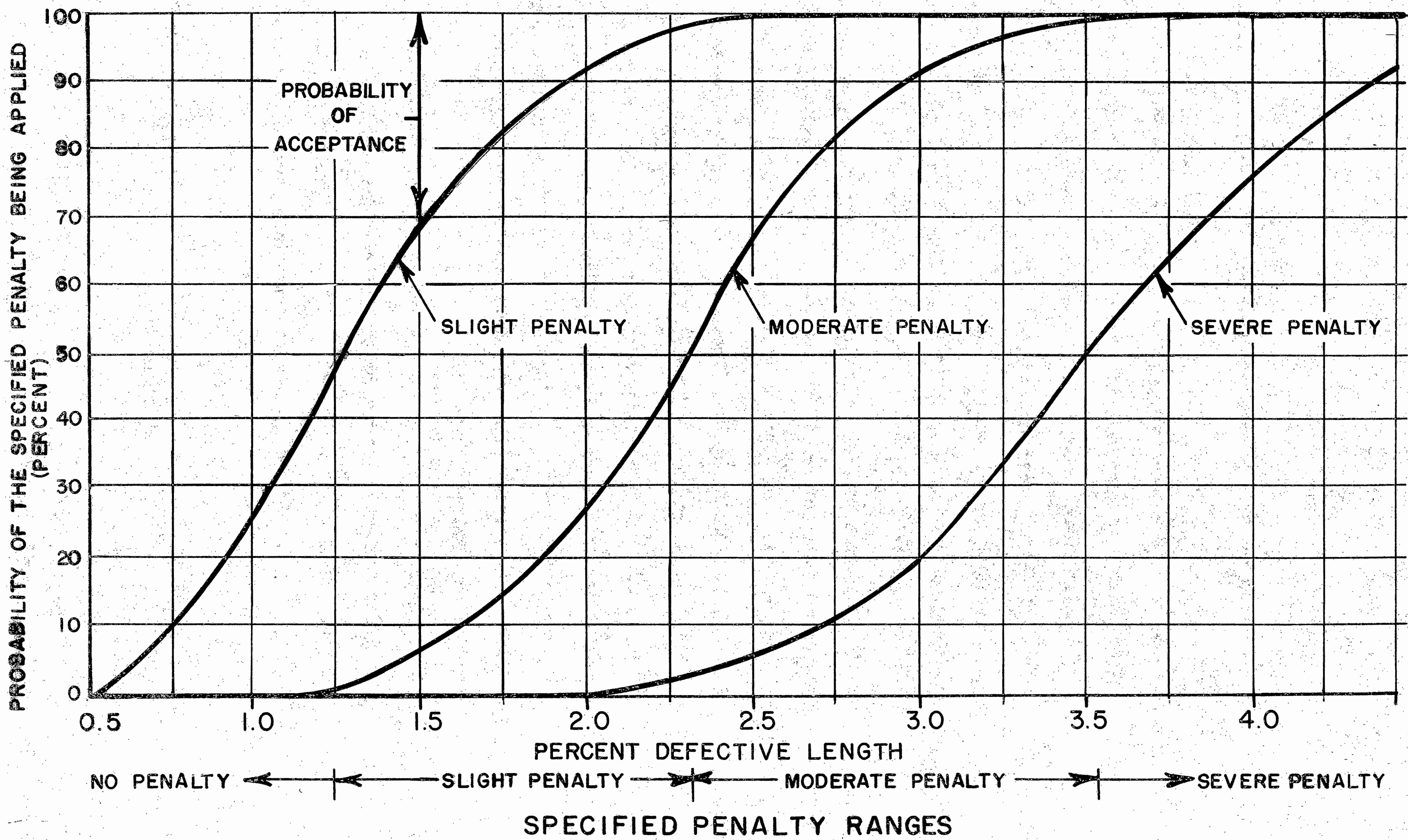
*In this instance, 50 percent sampling means replication of the 25 percent sampling and averaging of the results.

FIGURE 30: OPERATING CHARACTERISTIC CURVES FOR 50 PERCENT STRAIGHTEDGE SAMPLING OF BITUMINOUS PAVEMENT



physical condition of the pavement, this means that the State is willing to accept that in half of all cases, only a slight penalty will be applied to a concrete pavement which on the average has one foot in each ten feet exceeding our specification. As a matter of practical necessity, however, it appears likely that the acceptance plan will have to be modified in a manner which will serve to further increase the leniency of the plan. That is, it appears reasonable that at least initially, all pavements whose defective length equals or exceeds the remove/replace limit will have to be subjected to 100* percent testing (i.e., the full length of each lane and wheelpath). By performing only fractional testing below the remove/replace limit and complete testing above the limit, acceptance risks will be shifted in favor of the Contractor. That is, certain pavements which are actually totally unacceptable will have test results that fall below the remove/replace limit when fractional testing is employed and will at most be subjected to a moderate penalty. On the other hand, 100 percent testing above the limit will reduce measurement dispersion and thus will insure that the severe penalty is applied to pavements which are, indeed, grossly rough.

Figure 31 presents operating characteristic curves showing

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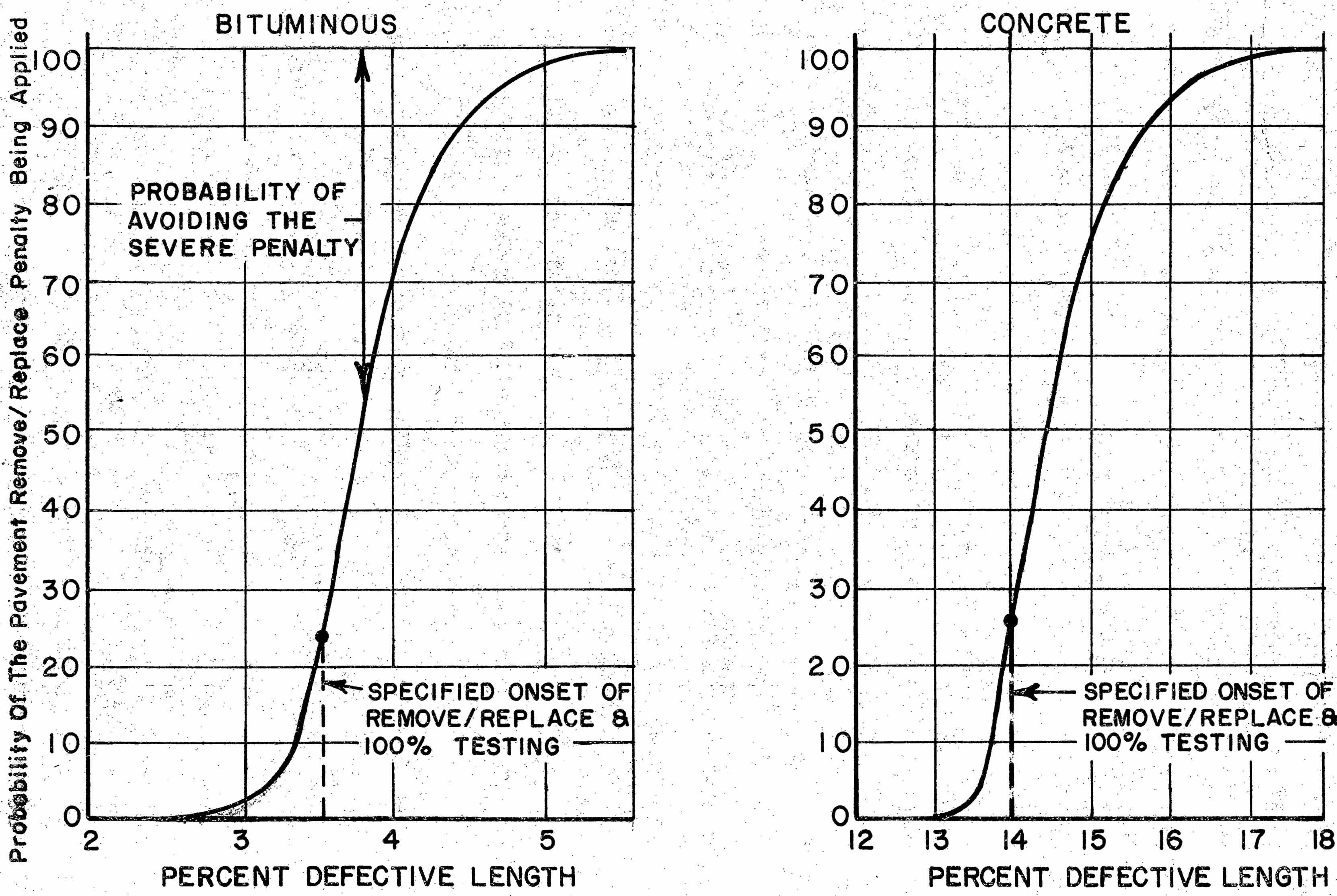
*In the case of this 100 percent testing, the first test result is not averaged with subsequent tests. The first test is used only as an indication of the need for complete testing. The procedure for 100 percent testing is to simply make a full length run along each wheelpath.

FIGURE 31: OPERATING CHARACTERISTIC CURVES FOR 100% TESTING OF TOTALLY REJECTABLE CONCRETE AND BITUMINOUS PAVEMENTS.



the specific extent to which a difference in sample fraction between values above and below the severe penalty limit will shift State and Contractor risks. Note, for example, that a pavement of either type which falls exactly on the remove/replace limit will have only a 25 percent chance of being severely penalized rather than the usual (and more equitable) 50 percent chance. This arises from the fact that since the Contractor's risk of being penalized at each of the first and subsequent tests is 50 percent, his combined risk is the product of the two risks (i.e., 0.5x0.5 = 0.25). [An analogy to this situation would be to allow the loser of a coin toss to call the first toss"practice".] Further, observe that while a concrete pavement having roughness one defective length unit below the severe penalty limit has essentially no chance of being severely penalized, a pavement an equal amount above the limit does not have the equivalent (full) risk of being penalized (actually, 70 percent). A similar situation exists on bituminous pavement.

5.2.4. <u>Assigning Monetary Penalties to the Specification Acceptance Plan</u>: It is obviously a delicate task to assign a dollar value to a quality as subjective as rideability in general, and thus to assign specific monetary penalties for deficiencies in particular.

In making these value judgements, the writer is principally guided by a philosophy that New Jersey smoothness provisions should at least initially be <u>lenient</u>. That is, while the adoption of an enforced riding quality specification might be expected to stimulate contractor performance to some extent, the needed rideability improvement of our pavements (particularly concrete) can reasonably be expected to occur only gradually. Thus, it is felt that the first step in a planned improvement is the adoption of a specification with realistic acceptance limits but with lenient penalties. At some reasonable, fixed future date, the associated monetary penalties would be stiffened to be more consistent with the quality of workmanship desired.

As a further point of philosophy, however, it is the writer's opinion that the principle of leniency should apply only to those pavements of moderate roughness, not to totally rejectable pavements (i.e., values beyond the remove/replace point). At a minimum, any penalty provisions should preclude acceptance of grossly rough surfaces. As has been described, the acceptance procedure will ensure that these severely penalized pavements are truly of unacceptable quality and in fact, will allow certain of them to escape with only a moderate penalty.

The basis of payment for future New Jersey concrete pavements and thus the basis for the indicated penalties will continue to be the pavement area in square yards. It is important to note, however, that in the near future, the basis of payment for our bituminous pavements will be markedly changed. That is, the Department's specifications group has elected to substitute a single (tonnage) payment item -- "Hot-mix bituminous pavement ______ inches thick*" -- for the present individual

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*For new construction, a total thickness of 9 or 11 inches is commonly employed.

(base, binder and top) course payment items. This specification change thus precludes assessing penalties on the surface course and instead requires that rigid and flexible pavement penalties be levied on the same basis: the total quantity of paving material furnished.

The proposed adjusted payment schedules for surface smoothness are shown in Table 14. Table 15 is a schedule of tests showing whether the indicated payment is to be made or if the pavement is to be subjected to further tests. If the proposed specifications are adopted, the desirability of performing more tests than the minimum listed in Table 15 and the consequences of performing additional tests only on Contractor request should be emphasized to State field personnel.

While there will be not distinct pay item for surface course on future New Jersey projects, the payment reduction alternate to pavement removal and replacement indicated in Table 14 is predicated on completely rejecting surface course having very poor rideability. That is, the amount of the reduced payment is approximately in the ratio of the usual surface course thickness to the common total pavement thickness (i.e., 1-1/2":9"). Thus, the most severe payment reduction might be expected to at least generally correspond to the dollar value of the surface course removal/replacement alternate. An identical 20 percent payment reduction is applied to concrete pavement which similarly has totally rejectable riding quality.

TABLE 14:

Proposed Bid Price Adjustment Schedules
for Pavement Smoothness

Schedule A: Bituminous		Schedule B: Concrete	
Lot Percent Defective Length	Percent Payment	Lot Percent Defective Length	Percent Payment
0 - 1.3	100%	0 - 5.0	100%
1.4 - 2.3	98	5.1 - 11.0	98
2.4 - 3.4	95	11.1 - 13.9	90
3.5 or more	Remove and replace or 80%	14.0 or more	Remove and replace or 80%

TABLE 15:

Proposed Smoothness Acceptance
Testing Schedules

Bituminous

Test Basis	Lot Percent Defective Length	Payment or Retest Require-ment
Single Straightedge Test	0 to 1.0	Pay 100%
	1.1 to 3.4	Perform 2nd Test
	3.5 or more	Test Each Wheelpath
Average of Two Tests	0 to 3.4	Pay as Per Schedule A
	3.5 or more	Test Each Wheelpath
Average of Straightedge Tests on Each Wheelpath	All Values	Pay as Per Schedule A

Concrete

Test Basis	Lot Percent Defective Length	Payment or Retest Require-ment
Single Straightedge Test	0 to 13.9	Pay as Per Schedule B
	14 or more	Test Each Wheelpath
Average of Straightedge Test on Each Wheelpath	All Values	Pay as Per Schedule B

5.2.5. Simulation of the Proposed Smoothness Provisions: While leniency has been employed at each stage of development of the proposed specifications, it is apparent that the probable impact of these provisions -- the relative frequency and severity of expected penalties -- must be specifically investigated. This investigation will essentially be a "reasonableness check" to determine whether the proposed smoothness specification can be adopted immediately and intact or whether modifications in the specified acceptance limits and/or associated penalties are required.

On concrete pavement, this reasonableness check will consist of a simulation of the proposed specification to historical data for New Jersey paving projects. On bituminous pavement, additional comparisons will be made to the smoothness specifications and straightedge data of other agencies.

Table 16 shows the proposed schedule of bid price adjustments for New Jersey bituminous pavements compared to that of specifications endorsed and recommended for use by the FHWA.[24]

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[24] Bolling, D. Y. and Weingarten, H. "Improved Quality Assurance of Bituminous Pavement: New Jersey Report", FHWA Region 15, Appendix 1: FHWA Bituminous Pavement Guide Specification (January 1973)

TABLE 16:

Comparison of FHWA and New Jersey Bituminous Pavement Smoothness Acceptance Plans

FHWA		NEW JERSEY	
Percent Defective Length	Percent Payment	Percent Defective Length	Percent Payment
0 - 1.0[a]	100%	0 - 1.3[b]	100%
1.1 - 3.5	95	1.4 - 2.3	98
		2.4 - 3.4	95
over 3.5	replace or 40%	3.5 or more	replace or 80%

[a]Test basis: a single full-length straightedge run

[b]Accept 1.0 percent defective on single test; penalize on basis of at least two full-length tests.

As shown, there is essentially no difference in the acceptable and totally rejectable quality levels between these two acceptance plans. Two relatively minor differences arise from the fact that the New Jersey proposal provides for multiple tests to minimize penalty risks and a penalty graduation (in part) designed to reflect differences in the degree of unacceptability of the pavement. A more fundamental difference is that the FHWA payment reductions are based on the tonnage of surface course, whereas the proposed New Jersey payment reductions are levied on the tonnage of the total thickness.

In summary, the net effect of differences in the percentage payment reduction and pay item between the two specifications is that the New Jersey specification will result in a more severe dollar reduction for a given degree of unacceptability. However, as will be shown by example, the greater payment reductions of the specification proposed for our State are believed warranted since the maximum dollar value of FHWA penalties for any smoothness quality level other than totally rejectable are very nominal.More specifically, let us assume that three "typical" 4 mile long, 4 lane bituminous projects are so constructed that each day's production of surface course on these projects respectively correspond to "Fair to Poor", "Poor", and "Very Poor" rideability. As might be expected, the occurrence of such a uniform project rideability, particularly "Poor" or worse, is an extreme case that might be expected to occur infrequently (actual frequency of such straightedge data in New Jersey: none). Table 17 shows the respective penalties that would apply if each of these projects were governed by the FHWA and New Jersey Smoothness Specifications.

TABLE 17

Comparative Simulation of FHWA and New Jersey
Bituminous Pavement Smoothness Penalties to Projects
of Various Riding Quality Levels

(Basis: $12 per ton bid for 9,300 tons of surface course
and 56,000 total mainline tons)

Project	Riding Quality	Typical Defective Length	Total Project Penalty	
			FHWA Penalty	New Jersey Penalty
"A"	Fair to Poor	2%	$5,700	$13,400
"B"	Poor	3%	$5,700	$33,400
"C"	Very Poor	more than 3.5%	Replace at cost X or $67,000 Reduction	Replace at same cost X or $140,000 Reduction

As shown, a Contractor working under either set of smoothness provisions would suffer a very drastic penalty if his process were so out of control that the extreme case occurred: every day's work is grossly rough. On the other hand, the penalty associated with providing pavement of any quality level better than "Very Poor" would be very modest according to the FHWA proposal. The consequences of giving us <u>all</u> poor rideability ($5,700) or <u>half</u> poor ($2,850) would, for example, be of substantially less impact on the contractor than providing the yearly wages of one laborer on the job. While leniency is sought in the New Jersey specification, it is the writer's opinion that the specification should not only motivate the contractor to avoid providing the state with totally rejectable pavement, but should also yield a penalty to some extent commersuate with the degree of success in eliminating <u>marginally</u> acceptable work. Thus, it is concluded that a modification of the percent payment reduction of the New Jersey specification to be more in line with the FHWA specification would not be desirable.

While the end product is essentially the same, the engineering judgements necessary to develop the acceptance ranges of the described New Jersey and FHWA smoothness specification were apparently based on different considerations: the roughometer-rolling straightedge correlation in the case of New Jersey, and the actual level of riding quality achieved in practice in the case of the FHWA.[25] In turn, the FHWA'a indication of results achievable in practice was based on a multi-state straightedge sampling, (partial) results of which have been previously shown in Figure 22 (p. 79). A general indication of the relative severity of the proposed New Jersey specification can thus be obtained by simulating the provisions to the FHWA data sample.

TABLE 18

Simulation of the Proposed New Jersey Bituminous Pavement Smoothness Specification to the Results of an FHWA Multi-State Data Sample

New Jersey Specification		Approximate Percentage of FHWA Data in Category
Percent Defective Length	Percent Payment	
0 - 1.3	100%	88%
1.4 - 2.3	98	3
2.4 - 3.4	95	2
3.5 or more	replace or 80%	7

[25] Since some of the features of the FHWA Guide Specification were patterned after work conducted by the State of Louisiana, that State's bituminous smoothness specification is of some interest. In a 1972 issue of "Paving Forum", Verdi Adam indicates use of the following provisions in Louisiana:

Percent Defective Length	0 - 1.0	1.1 - 1.5	1.6 - 2.5	2.6 or more
Percent Payment (Surface Course)	100%	95%	80%	replace or 50%

As shown in Table 18, a low incidence and severity of penalties results from application of the proposed specification to the FHWA's sixteen-state data sample. No penalty is indicated for nearly 90 percent of the data for other states, with the penalized sections being about equally divided between slight/moderate and severe.

Table 19 presents a simulation of the proposed smoothness provisions to 15 bituminous projects constructed in this State. As indicated, about 60 percent of the New Jersey straightedge data would have no associated penalty, while the slight and moderate penalties occur with equal frequency (14%). A severe penalty would be applied to about 10 percent of this data sample, with half of the severe penalties occuring on one job (the I-80, 1M thick-lift project). The mean project payment is 97.3 percent.

It is important to note that there are a number of reasons why the indicated expected frequency and severity of penalties indicated in Table 19 may be overly pessimistic.

First, it is to be realized that the simulation was performed on an historical sample. Thus, since changes in the specified methods of construction have occurred during the period of study, certain of the listed projects are undoubtedly not typical of our present work. For example, if we consider only those projects constructed using the (presently required) automated paver controls, essentially complete payment (99.6 percent or more) is indicated for 7 of 10 projects, one each would receive a 2% and 3.5% payment reduction, while only the I-80, 1M project would receive a substantial (10%) overall payment reduction.

TABLE 19

Simulation of the Proposed Penalty

Schedule to New Jersey Bituminous Projects

Route and Section	Year Open To Traffic	FHWA Roughness Rating	Number of Sections Sampled	Number of Sections Receiving the Indicated Penalty				Percent Payment for the Project
				No Penalty	2% Penalty	5% Penalty	20% Penalty	
N.J. 55, 7F&8A	1973	Good*	8	8	0	0	0	100.0
I-287, 7D-9G	1973	Good*	24	22	2	0	0	99.8
I-280, 1B-5P	1973	Fair*	20	13	3	1	3	96.5
I-80, 1L	1972	Fair*	33	19	7	6	1	98.1
N.J. 55, 6F&7E	1972	Good*	8	7	1	0	0	99.8
I-195, 2A&3A	1972	Poor	10	1	1	4	4	89.8
I-195, 3B&4A	1972	Good*	9	7	2	0	0	99.6
I-195, 4B	1972	Fair*	8	7	1	0	0	99.8
I-78, 4F&4G	1971	Fair	11	8	1	2	0	98.9
I-80, 1M	1971	Poor*	27	2	4	11	10	90.3
I-78, 4J	1970	Poor	12	7	4	1	0	98.9
N.J. 55, 5B-7B	1969	Good*	12	12	0	0	0	100.0
I-295, 1S	1968	Good*	8	8	0	0	0	100.0
N.J. 72, 6A&7A	1968	Fair	7	4	1	1	1	96.2
I-78, 4K	1966	Poor	8	0	3	3	2	92.4
Average Penalty Frequency				61.0%	14.6%	14.1%	10.2%	MEAN = 97.3

*Denotes projects on which automatic paver controls were employed to at least some extent.

Secondly, if the suggested _enforced_ riding quality acceptance provisions are adopted for use, it might reasonably be expected that a Contractor would take action that would mitigate his chances of receiving a penalty. That is, if rolling straightedges are provided on New Jersey bituminous projects, it obviously would be appropriate for the Contractor to perform _control_ testing, so timed that _remedial_ measures can be undertaken prior to _acceptance_ testing. Thus, certainly in the case of a severe penalty, the Contractor would have to be deficient on two counts: The work would have to be totally unacceptable and control testing would have to be almost non-existent.

Based on the preceding, it is here concluded that the adoption of the proposed bituminous pavement smoothness specification on an immediate basis and in its entirety is both desirable and feasible.

The entire penalty situation for concrete pavement is colored by the fact that New Jersey's rigid pavement rideability results do not compare favorably to the results of other states. Given that our concrete pavements are at best "Fair" and often of "Poor" rideability, it is apparent that _any_ specification which at a _minimum_ attempts to eliminate the "Poor" smoothness category will result in a substantial fraction of our projects being penalized. Further, unlike our bituminous pavements, there unfortunately is no trend toward improved results for our more recent work. In fact, the reverse appears true. Thus, while adoption of enforced smoothness provisions might again be expected to stimulate contractor performance, there does not appear to be any substantial basis for optimism concerning a near-term improvement in rideability.

The sampling of straightedge data obtained on the concrete pavements of this study is smaller than that obtained on bituminous pavements. To strengthen the estimate of probable concrete pavement penalties, the straightedge sample will be compared to the (10 times) larger sample of roughometer data from these pavements. Such a comparison (shown in Table 20) is possible since the roughometer-straightedge correlation permits roughometer data to be converted to a roughness equivalent in terms of straightedge defects.

TABLE 20

Simulation of the Proposed Concrete
Pavement Smoothness Specification
to the Overall Distribution of New Jersey Roughness Data

Proposed Penalty Schedule		Percent of Tested Quarter Miles in Category	
Percent Defective	Percent Payment	Straightedge Data	Roughometer Data Equivalent
0 - 5.0	100%	31.3%	31.0%
5.1 - 11.0	98	47.9	41.4
11.1 - 13.9	90	12.5	13.3
14 or more	Replace or 80%	8.3	14.3
Average Percent Payment for Indicated Data		96%	95%

As indicated in Table 20, the overall distribution of test data from both roughness measurement devices are in close agreement. Both types of data indicate that if the distribution of roughness results on future concrete pavements conformed to the historical average for New Jersey, about three-fourths of the tested sections of pavement would receive no penalty or a slight penalty, while the remaining one-fourth would receive a moderate or severe penalty. A corresponding average payment reduction of 4 to 5 percent is indicated.

A simulation of the proposed concrete smoothness specification to historical data for 15 individual projects is shown in Table 21. Based on this data, the maximum penalty for the individual sections of about 40 percent of the projects is 2 percent, while a maximum 10 percent penalty is indicated for another 40 percent. About 20 percent of the projects have at least some sections on which a severe penalty would be levied. In terms of rideability, this sample indicates that a future pavement of "Fair" rideability might at most be expected to receive a 2 percent average penalty, with essentially complete payment (98.9%) being indicated for the average "Fair" work. Except for one project*, the payment reductions for those pavements of "Poor" rideability ranges from 1.5 to 10 percent, with the average "Poor" riding project receiving 95 percent payment.

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*The small data sample on New Jersey 21 Freeway

TABLE 21

Simulation of the Proposed Penalty Schedule to New Jersey Concrete Projects

Route and Section	Year Open To Traffic	FHWA Roughness Rating	Number of Sections Sampled	Number of Sections Receiving the Indicated Penalty				Percent Payment for the Project
				No Penalty	2% Penalty	10% Penalty	20% Penalty	
I-280, 1B-5P	1973	Poor	12	0	9	3	0	96.0
I-80, 1N	1973	Poor	6	0	5	1	0	96.7
I-295, 4C&5A	1973	Poor	8	0	5	1	2	92.5
I-295, 3B&4A	1972	Fair	8	5	3	0	0	99.3
I-295, 2L&3A	1972	Poor	8	6	1	1	0	98.5
I-280, 6G	1972	Poor	6	0	5	1	0	96.7
I-280, 6L&7E	1972	Poor	4	0	1	3	0	92.0
N.J. 21, 4A	1968	Poor	3	0	0	0	3	80.0
I-295, 1R	1968	Fair	6	3	3	0	0	99.0
I-78, 2G	1968	Poor	3	1	2	0	0	98.7
I-287, 7C	1968	Poor	8	1	3	1	3	90.5
I-78, 2M&3E	1968	Fair	6	1	5	0	0	98.3
I-78, 3F	1967	Fair	6	6	0	0	0	100.0
I-297, 6F&7B	1966	Fair	4	1	3	0	0	98.5
I-78, 3G	1966	Fair	8	6	1	1	0	98.5
Average Penalty Frequency				31.3%	47.9%	12.5%	8.3%	MEAN = 95.7

While the dollar value of even a small percentage payment reduction for concrete paving is substantial*, it is the writer's opinion that the 1 and 5 percent average penalties respectively indicated for "Fair" and "Poor" riding projects are reasonable. The adoption of the concrete pavement smoothness specification as proposed is therefore recommended.

A description of the proposed smoothness provisions in an actual specification format is presented in Appendix D of this report.

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*If a 3 mile long, 6 lane concrete project is considered of "typical" size, an average total payment reduction of about $13,000 is expected if the pavement is "Fair", while a total reduction of $65,000 is expected if "Poor" rideability is provided. [Basis: 127,000 square yards bid at $10 per square yard or $1.27 million.]

PART VI: BRIDGE DECK RIDING QUALITY RESULTS

6.1 BACKGROUND

6.1.1 Bridge Deck Roughness Results and Evaluation Criteria from Other States:

There is no widely accepted "standard" for evaluating bridge deck rideability, the previously described FHWA roughometer criteria having been developed strictly from considerations of pavement riding quality.

While it is obviously desirable that good riding quality be continued in approaching, traveling on, and exiting from structures, roughness data from other agencies indicates that concrete bridge deck construction is commonly considerably rougher than concrete pavement construction. The surprising point here is the actual magnitude of roughness difference sometimes reported between the riding surfaces of concrete pavements and bridge decks. In the three-state sample of roughometer results shown in Table 22, for example, the "average" bridge deck is approximately 2/3 to 3/4 rougher than the "average" concrete pavement built during the same period. If the FHWA pavement roughness criteria were applicable to the data of Table 22, the bridge decks would receive "Fair" to "Poor" ratings, while the abutting pavements would generally be considered of "Good" to "Excellent" rideability.

TABLE 22: COMPARATIVE ROUGHOMETER DATA FOR NEW CONCRETE PAVEMENTS AND BRIDGE DECKS IN OTHER STATES

State	Period of Study	Concrete Pavement Roughness	Concrete Bridge Deck Roughness	Average Roughness Difference
Tennessee[26]	1961-1965	The most common Interstate roughness measurement was less than 75 in/mi	9 bridges ranged from 123 to 168 and averaged 144 in/mi	50 in/mi* (60%)
"A"	1964	31 test sections ranged from 64 to 126 in/mi and averaged 84 in/mi	21 decks ranged from 118 to 177 in/mi and averaged 150 in/mi	66 in/mi (79%)
"B"	1966	80% of new mileage was 77 in/mi or less	5 bridges ranged from 97 to 147 in/mi and averaged 116 in/mi	45 in/mi* (63%)

*estimated; specific mean pavement roughness not indicated

TABLE 23: COMPARISON OF FHWA PAVEMENT CRITERIA AND SUGGESTED BRIDGE DECK ROUGHNESS EVALUATION GUIDELINES FROM OTHER STATES

FHWA Concrete Pavement Criteria		Virginia[15] Bridge Deck Roughness Guidelines		State "C" Bridge Deck Roughness Guidelines	
Roughness Index	Rideability Rating	Roughness Index	Rideability Rating	Roughness Index	Rideability Rating
<67 in/mi	Outstanding	---	---	---	---
67-81	Excellent	<80	Excellent	<75	Excellent
81-99	Good	80-99	V. Good	75-100	V. Good
99-121	Fair	99-121	Good	100-125	Good
>121	Poor	121-140	Fair	125-150	Fair
		>140	Poor	150-175	Poor
				>175	Rough

The historically greater roughness of bridge decks relative to pavements has resulted in some states being less critical of the rideability of such construction, either informally or thru specific bridge deck roughness evaluation guidelines. For example, Table 23 shows suggested roughometer-based bridge deck rating guidelines from two states compared to the FHWA concrete pavement roughness criteria. As indicated, the criteria proposed by both states are almost identical, except that State "C" employs two categories of "Poor" bridge deck rideability. In essence, both generally represent a modification of the FHWA concrete pavement criteria wherein the adjective rating that would be assigned to a pavement of a particular roughness index range is increased by one rating category in the case of a bridge deck (i.e., an FHWA "Fair" pavement rating equates as a "Good" bridge rideability rating, etc.). In comparison to the FHWA pavement criteria then, these states are as much as 20 to 30 inches/mile more lenient in rating bridge decks.

6.1.2 <u>Major Factors Reported as Influencing the Greater Roughness of Bridge Decks</u>: While the general requirements for achieving a good riding concrete surface are basically the same for both bridge and pavement construction (e.g., an adequate supply of quality materials, competent workmen and supervision, etc.), a number of investigators[27-29]

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[27] McKnight, J. W. "Specifications and Construction Controls to Obtain Smooth-Riding Bridge Decks", HRB Bulletin 295, pp. 6-18 (1961)

[28] Gray, N. "Smooth-Riding Bridge Decks", HRB Bulletin 243, pp. 18-27 (1960)

[29] Wickham, W. W. "Control of Construction to Secure Surface Smoothness of Bridge Decks", Proc. AASHO, pp. 268-82

have pointed out differences between the two types of construction that influence relative roughness results. The noted differences include

. rigidity of supports: In comparison to pavement subgrade, bridge beams are relatively flexible. The problem of setting and maintaining the correct strike-off elevation is thus relatively more difficult on a bridge. Failure to adequately compensate for actual beam camber and dead load deflection is known to result in long wavelength profile irregularities.

. space limitations: The restricted working space native to bridges often necessitates different, especially well-planned methods for supplying and finishing structural concrete.

. labor situation: The relatively short duration of a bridge pour does not generally permit on-the-job development of proper techniques.

. use of mechanized equipment: In contrast to paving on grade, bridge construction has historically relied more on manual rather than mechanical means for concrete strike-off and finishing. The experience and skills of the involved workmen is thus an especially important variable in the case of bridge rideability results.

The previously cited[15] comprehensive study by Virginia of bridge deck roughness indicated this latter (screeding technique) factor to have the most significant influence on deck rideability. In that state, the use of full span length, longitudinally* oscillating mechanical screeds consistently produced simple span bridges with

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*The "longitudinal" and "transverse" finishing machine nomenclature used in this work relates to the orientation of the working face of the screed with respect to traffic. Thus, in longitudinal finishing, any ridges introduced into the concrete are predominantly parallel with traffic.

Roughness Indices less than 100 inches per mile (i.e., meriting at least an FHWA "Good" pavement rideability rating). The next smoothest class of bridges sampled (manually screeded) displayed more than 50 inches per mile greater roughness.

The beneficial effect of keeping any corrugations in the finished surface parallel to traffic was evidenced by the fact that the mechanical screeds that provided the smoothest Virginia bridges when operated longitudinally, yielded the roughest decks when operated transversely. Further, Virginia observed that the roughness of decks struck transversely could be substantially improved(up to 25 percent) by follow-up longitudinal floating.

Similar rideability results have been reported in Michigan[30,31] studies. In that state's research, bridges built using various screeding methods were tested with a profilograph* and the resultant data compared to the following standards:

"Good" bridge rideability = less than 100 profilograph units
"Average" = 100 to 160 units
"Poor" = over 160 units

According to this criteria, each of the tested bridges constructed with full span length longitudinal screeds provided what Michigan considered to be "Good" rideability (average roughness: 64 units). No significant benefit for transverse machine over hand finishing was observed, with both

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[30]Church, C. D. "Profilometer Measurement of Bridge Roughness", Seventh [Final] Progress Report, Michigan State Highway Department (November 1965)

[31]Williams, G. M. "Special Report on Methods of Improving the Riding Quality of Bridge Decks", FHWA Circular Memorandum (September 17, 1963)

*This device is essentially a 20 foot long, recording rolling straightedge.

of these types of construction displaying average roughness levels about twice as great as that for longitudinal finishing (124-128 units). Use of another type of mechanized screeding equipment which strikes the concrete longitudinally in partial span length increments yielded intermediate smoothness results in the Michigan sample (average: 96 units = "Good").

In response to the improved rideability results apparently obtainable with <u>various</u> configurations of mechanical bridge deck screeding and finishing equipment, such mechanical methods currently enjoy very widespread use. A recent Highway Research Board questionnaire[32] indicates that about half the states and Canadian provinces presently require mechanical screeding equipment for construction of bridge floors. Further, the combination of specification requirements and contractor preference has resulted in more than 90 percent of current bridge construction being accomplished with mechanical screeds.

6.2 NATURE OF THE NEW JERSEY STUDY

6.2.1 Character and Size of the Roughness Sample: At the inception of the present research, the use of mechanical screeding was not required for New Jersey bridge construction and manual strike-off methods--most commonly, hand-propelled vibratory screeds--predominated.

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[32] "Bridge Deck Finishing", HRB Questionnaire 133 (May 1972)

Beginning in about 1967, a number of New Jersey bridge contractors, with Department encouragement, elected to employ various types of mechanical finishing equipment. The particular devices selected for use and studied in this research included various of the longitudinally oscillating screeds so favorably reported on in the literature, as well as a newer type of equipment that finishes the concrete by means of a rotating cylinder working transversely across the deck.

As shown in Table 24, the relative roughness determinations of this bridge study phase were based on the evaluation of roughometer and/or rolling straightedge data from 30 bridge spans. This represents a sampling of 14 individual projects, with the test sample being about equally divided between mechanically and manually finished decks. Each of the studied bridges were of the simple span design that predominates in this State.

TABLE 24: DISTRIBUTION OF THE NEW JERSEY BRIDGE ROUGHNESS SAMPLE BETWEEN MECHANICAL AND MANUAL FINISHING METHODS

FINISHING METHOD		ROUGHNESS TEST SAMPLE		
		Projects	Bridges	Spans
Manual		8	11	16
Transverse Roller Finisher		2	4	7
Longitudinal Oscillating Machine	Full Length Screed	3	3	6
	Partial Length Screed	1	1	1
	TOTALS	14	19	30

In addition to rideability evaluations based on objective roughness measurements, most of the projects selected for study were given a subjective evaluation by experienced bridge engineers from the Department's Bureau of Construction Practices. These latter on-site evaluations considered the general level of planning, organization, and control evidenced in the work. A judgment was also made as to the relative adequacy of the specific placement and finishing operations used.

Figures 32 thru 35 present selected photographs illustrating the particular equipment studied and the major steps of the various deck finishing sequences.

Specifically, Figure 32 depicts a "typical" finishing operation relying exclusively on manual methods. The transverse orientation of the strike-off and floating shown in this figure is the most common* finishing arrangement used in New Jersey. In view of subsequent roughness data, it is worth noting that the particular project shown in the photographs (the New Jersey 72 - U.S. 9 crossing) was excellently organized and very well executed and represents perhaps the best hand finishing operation tested.

Figure 33 shows the type of full-span length screed used on each of the three longitudinally machine finished structures studied. On two of these projects, the minimum of two screeding passes suggested by the equipment manufacturer were employed. The use of a single

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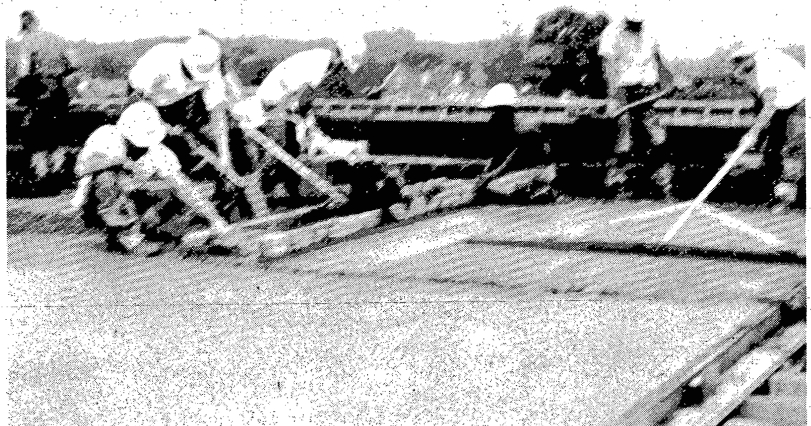
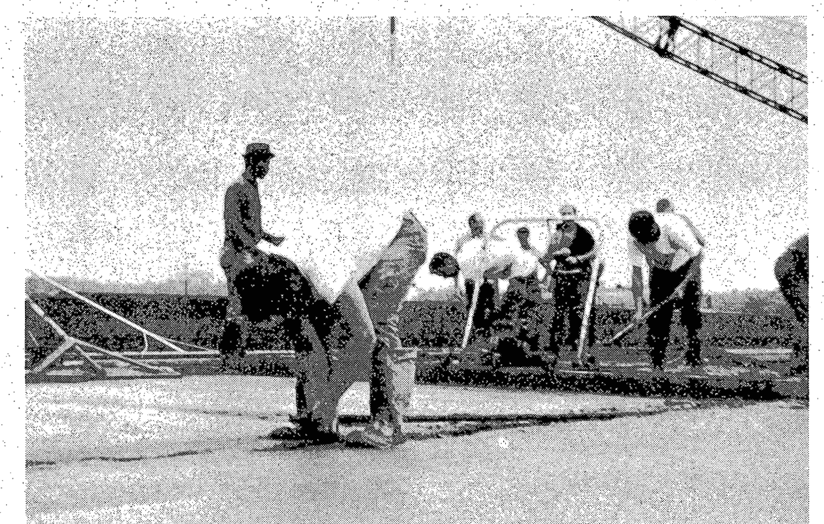
*Only one of the manually finished projects--the I-76 Viaduct (Project 6 of Table 25)--is known to have been finished predominantly in the longitudinal direction.

FIGURE 32: Selected Photographs of Manual Deck Finishing Operation (N.J. 72 over U.S. 9)

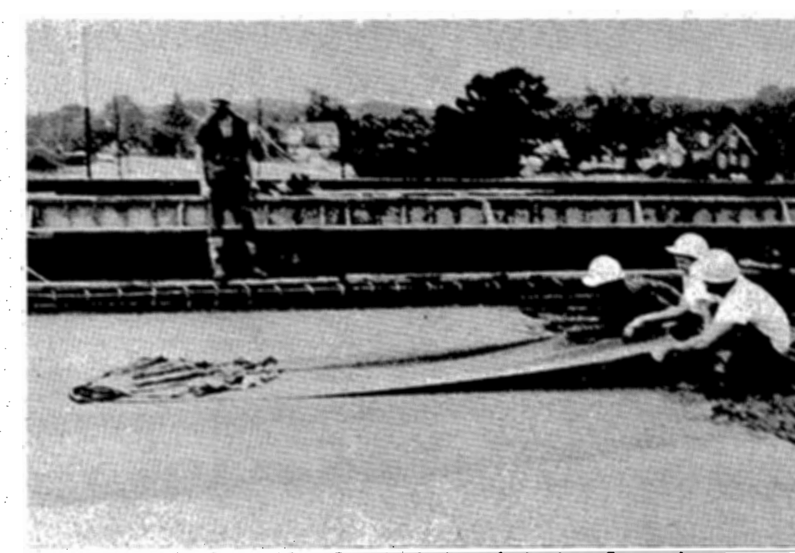


32A. Initial strike-off with vibratory screed.

32B. Intermediate finishing with scraping straightedge and lute.

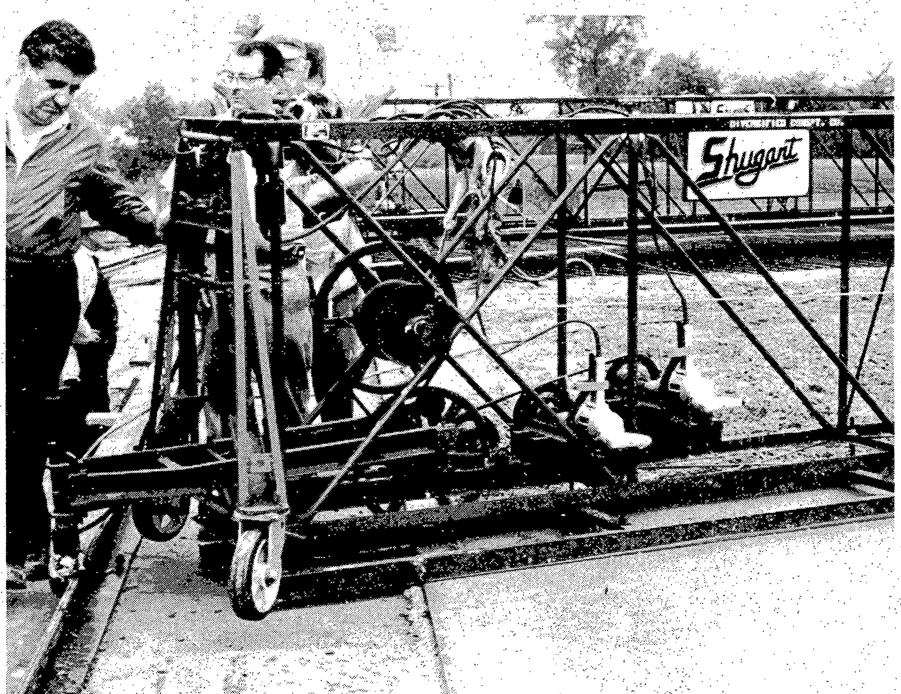


32C. Disturbing finished concrete to remove pipe screed guides.

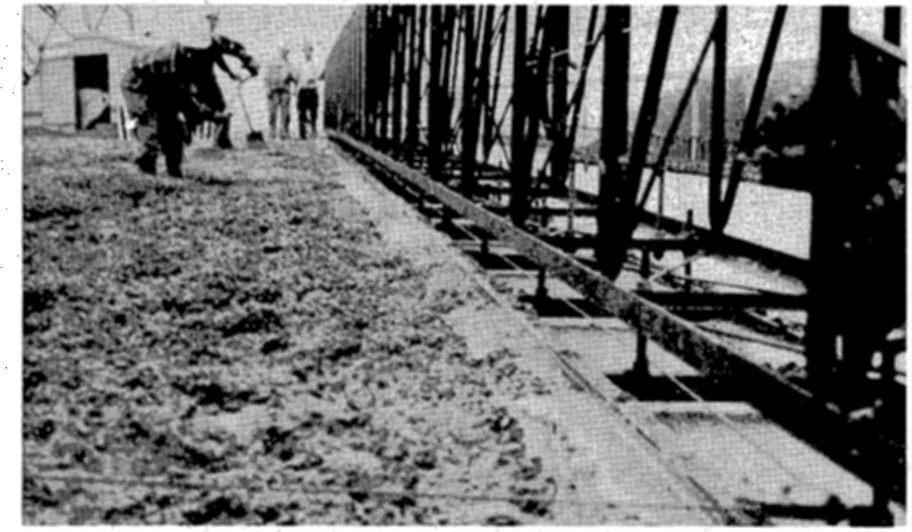


32D. Applying final finish with burlap drag.

FIGURE 33: Selected Photographs of Deck Finishing Operation Employing Full Span Length, Longitudinal Screeding.
(I-95 over W. Pierson Avenue)



33A. Drive section of screed resting on a thin metal wear plate and extending out to temporary plywood work platform. Oscillating action is achieved by the drill motor powered eccentric stroking against the push rail.



33B. First screed pass. Lateral movement across the deck is accomplished by taking up on the cable shown in the foreground. (The cable reel is the upper wheel in Figure 33A)

33C. Applying final finish using automated belt. This combined work bridge-belt finisher is a separate item of equipment.

screed pass on the other tested deck was considered insufficient at the time of construction and apparently contributed significantly to the (25 to 30 inches/mile) greater roughness for that deck relative to the double-pass construction. On each of these projects, longitudinal screeding was followed directly by belt finishing (i.e., with a minimum, if any, of hand operations). However, on only the I-95 project shown was the belting operation automated.

Figure 34 shows deck construction using a finishing machine in which the direction of both equipment travel and screeding are longitudinal. As shown, this equipment is essentially a mechanized, ten-foot long float. Although only one such deck was studied in this research, it is interesting to note that this type of equipment is the most commonly employed nationally[32]. While it is correct to refer to the operation shown in Figure 34 as "machine" finishing, it is apparent that some (reduced) level of hand work is still required.

Figure 35 shows the transverse deck finishing operations on two New Jersey projects constructed using a roller finisher. As indicated, mechanical finishing is achieved by means of a three-component tool: auger(s) for striking the concrete to approximate grade, a rotating cylinder for intermediate finishing, and a pan float for sealing the surface. Notice that again in this case, the use of a mechanical finisher did not completely eliminate the need for supplemental hand floating.

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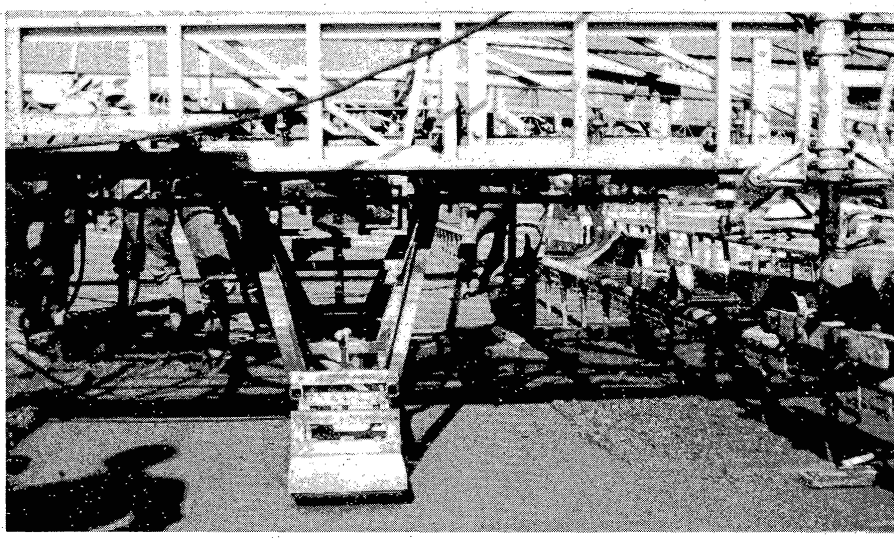
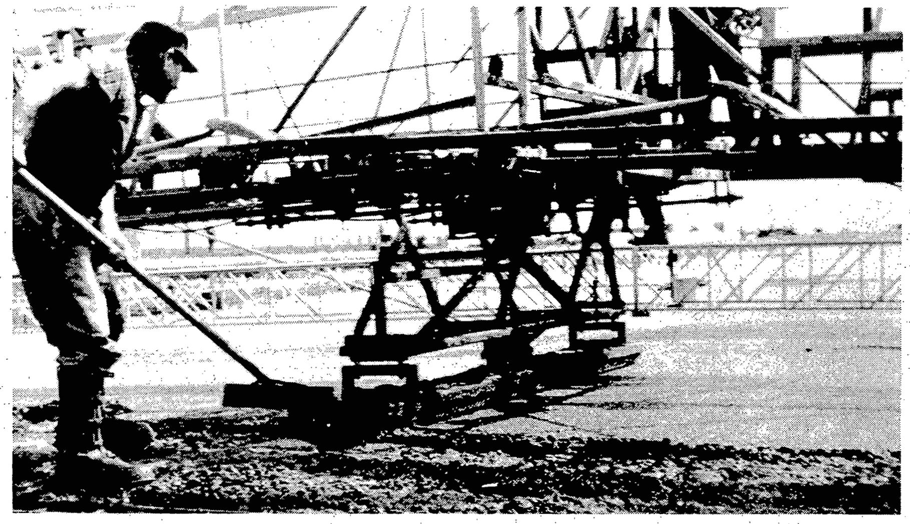
[32] Op. Cit.

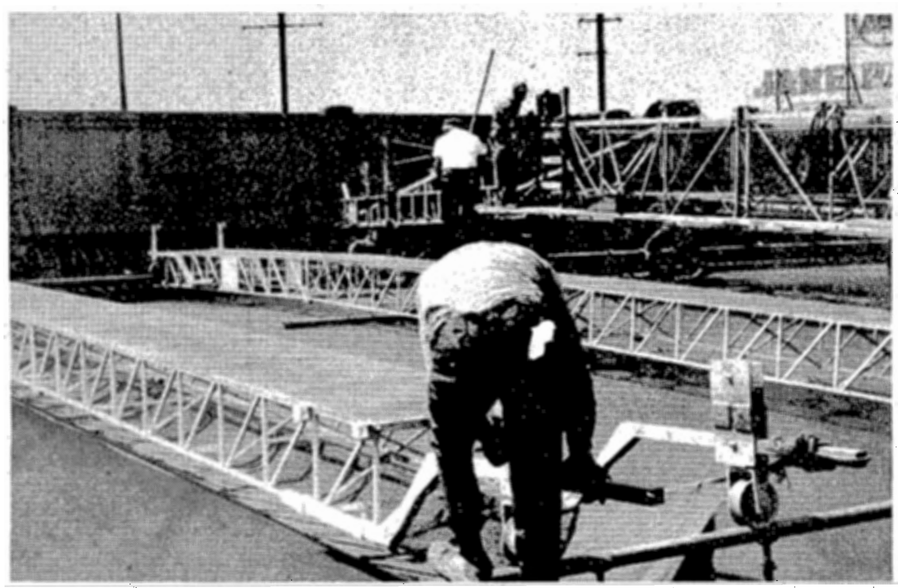
FIGURE 34: Selected Photographs of Deck Finishing Operation Employing Partial Span Length, Longitudinal Screeding
(I-78 over Waverly R.R. Yard)



34A. End view showing main finisher truss, the suspended finishing tool (bull float), and electrically powered screed rollers that propel the machine longitudinally along erected screed pipes.



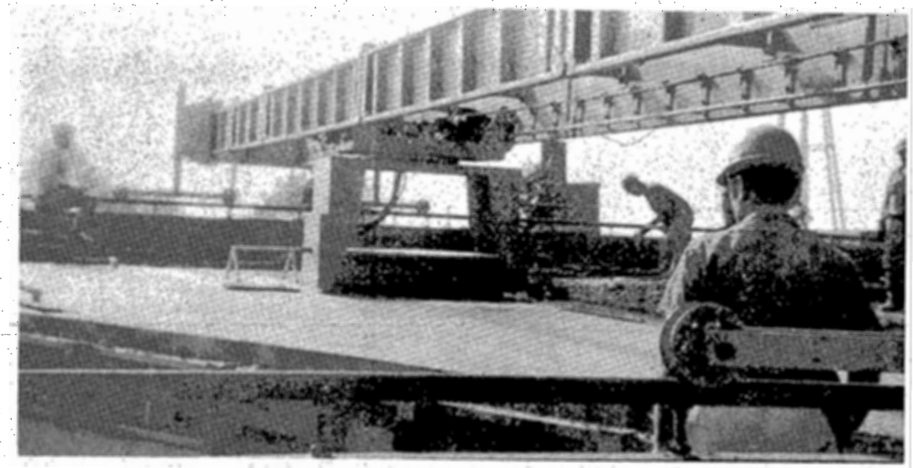
34B. Concrete is struck and finished by advancing the longitudinally oscillating screed (one foot stroke) across the deck.



34C. Intermediate transverse finishing with a tube float and application of final finish with a burlap drag.

FIGURE 35: Selected Photographs of a Deck Finishing Operation Employing a Transverse Roller Finisher

35A. Finishing and sealing of concrete by a revolving cylinder and pan float following initial strike with an auger(I-295, 3B&4A). Cylinder rotation is reversed on second (final) equipment pass. Notice that some small transverse ridges remain to be removed after machine finishing.



35B. Another machine configuration (N.J. 174,1A). This particular finisher uses two forward augers and a larger finishing cylinder. The suspended finishing head travels across the deck in the truss-enclosed carriageway and is advanced longitudinally using chain-driven rollers.

35C. Intermediate hand finishing using a metal float

35D. Applying final finish with a burlap drag.

6.2.2 Data Collection Procedures: The methods of collecting and reporting roughometer and straightedge data for the studied bridge decks differ in some respects from those employed for pavements.

The first of these procedural differences reflects as a generally reduced relative precision for bridge deck roughometer results. That is, it is apparent that bridge deck roughometer test data must be multiplied by various large conversion factors to place the data on the common basis of inches per mile (e.g., by 52.8 in the case of a 100 foot deck). Thus, any error in following the same line of travel with the roughometer test wheel or in repeating the start/stop points will be considerably magnified in the computed roughness index. Further, apart from magnification in the computational process, the consequence of any inadvertent offset from the intended line of travel is inherently more important on a bridge because of the large transverse variation in roughness common to structures. In order to reduce this additional aspect of short-term measurement variability, as many as four repeat readings per wheelpath (rather than the usual duplicates) were made on some structures.

A second difference in roughness test procedures between pavements and bridges is the occasional use of a different (larger) sample size for straightedge data than for roughometer data. This reflects as a difference in the degree of association of the two types of roughness measurements. That is, on about half of the bridges tested with both types of equipment, closely spaced profile lines were tested with the straightedge in order to develop "contours" of surface defects, while only a selected few of these profiles (and in some instances, different profiles) were tested with the roughometer. Since the fractional sample size and test profile location are thus not consistently the same, strict comparisons between the output of the two roughness measurement devices on a particular bridge are not always appropriate.

6.3 COMPARATIVE ROUGHOMETER AND STRAIGHTEDGE DATA FOR MANUALLY AND MACHINE FINISHED DECKS

Summaries of the average roughometer and rolling straightedge measurements for the various New Jersey bridge decks studied in this research are presented in Tables 25 and 26.

6.3.1 Manual Finishing: As shown in Table 25, the concrete surfaces of the tested manually finished decks displayed average roughometer readings ranging from about the same to substantially greater than our "average" concrete pavement (i.e., 125 to 192 vs. 122 inches/mile). These roughness values are in each case indicative of a "Poor" FHWA pavement rideability rating. On an overall basis, the "average" manually finished deck is characterized by about 40 inches per mile or one-third greater roughness than our "average" (marginally acceptable) concrete pavement. Significantly, even if the previously described, more lenient bridge roughness guidelines used by some states are applied to this data, a "Poor" or "Rough" rideability rating would result for 8 of the 10 tested structures, while only two would be rated as "Fair/Good".

TABLE 25: SUMMARY OF ROUGHOMETER DATA FOR BRIDGE DECKS

Project No.	Project Route & Section	Project Date Opened	Structure Tested	Average Roughness Index	Finishing Method
1	I-78, 3G	7/66	I-78 over No. Branch Raritan River, 2 WB Spans	159	Hand
			I-78 over Cowperthwaite Road, 1 WB Span	167	
			I-78 over Lamington River, 2 WB Spans	177	
			I-78 over Matheson Road, 1 WB Span	192	
2	I-78, 3F	12/67	I-78 over Route 523, 1 WB Span	152	
3	I-78, 2M&3E	7/68	Ramp "A" over I-78	167	
4	N.J.72, 6A&7A	11/68	N.J. 72 over U.S.9, 1 WB Span	125	
5	N.J.36, 3D	11/69	Ramp "L" over N.J. 36	126	
6	I-76, 1F&2C	4/73	8th Street Viaduct, 2 WB Spans	174	
7A	I-295, 1S	12/68	U.S. 322 EB over I-295, 3 Spans	170	
HAND FINISHED: RANGE 125-192 IN/MI, AVERAGE 161 IN/MI					
7B	I-295, 1S	12/68	U.S. 322 WB over I-295, 3 Spans	107	Longitudinal Machine
8	U.S. 1, 6D	11/69	U.S. 1 over Raritan River, 2 SB Spans	139[a]	
9	I-95, 19A	1/70	I-95 over West Pierson Avenue	115	
10	I-78, 5Y	5/69	I-78 over Waverly RR Yards 1 EB Span	141[b]	
LONGITUDINAL MACHINE FINISHED: RANGE 107-141 IN/MI, AVERAGE 125 IN/MI					
11	I-295, 3B&4A	10/72	Elbow Lane over I-295, Both Spans	107	Transverse Roller Finisher
			Woodlane Road over I-295, Both Spans	120	
			Beverly Road over I-295, 2 EB Spans	132	
TRANSVERSE MACHINE FINISHED: RANGE 107-132 IN/MI, AVERAGE 120 IN/MI					

[a] Single screeding pass used
[b] Partial span length, longitudinally propelled equipment; others full span length, transversely propelled

TABLE 26: SUMMARY OF STRAIGHTEDGE DATA FOR BRIDGE DECKS

PROJECT			Structure Tested	Average Percent Defective Length	Finishing Method
No.	Route & Section	Date Opened			
1	N.J. 72, 6A & 7A	11/68	N.J. 72 Over U.S. 9, 1 WB Span	20.1%	Hand
2	N.J. 36, 3D	11/69	Ramp "L" Over N.J. 36	36.6	
3	I-76, 1F & 2C	4/73	8th Street Viaduct, 2 WB Spans	32.2	
4	I-80, 1K	7/73	I-80 WB Over Waterloo Road	31.1	
5A	I-295, 1S	12/68	U.S. 322 EB Over I-295, 3 Spans	27.0	
HAND FINISHED: RANGE 20.1-36.6%, AVERAGE 29.4%					
5B	I-295, 1S	12/68	U.S. 322 WB Over I-295, 3 Spans	13.2	Longitudinal Machine[a]
6	I-95, 19A	1/70	I-95 Over West Pierson Avenue	3.9	
LONGITUDINAL MACHINE FINISHED: RANGE 3.9-13.2, AVERAGE 8.5%					
7	I-295, 3B & 4A	10/72	Elbow Lane Over I-295, Both Spans	1.2	Transverse Roller Finisher
			Woodlane Road Over I-295, Both Spans	3.1	
			Beverly Road Over I-295, 2 EB Spans	1.2	
8	N.J. 174, 1A	10/73	U.S. 1 SB over Whitehead Road	12.3	
TRANSVERSE MACHINE FINISHED: RANGE 1.2-12.3, AVERAGE 4.4%					

[a]full span length equipment

This level of roughness readings is, however, in some instances quite similar to that reported for decks in other states (e.g., by two of the three states in Table 22).

The most significant point in connection with the straightedge data for manually finished structures is that in no case did the tested portions of any of these decks even <u>approach</u> conformity with our existing specification surface tolerance. The average level of conformity with our present stipulation of "no" defects in excess of 1/8 inch was found to be only 70 percent (i.e., L_D = 30 percent). One mitigating factor in this regard, however, is that the measured percent defective length of bridges includes a higher proportion of apparent (non-existent) deviations* than pavements. To some extent then, the reported percent defective length is an overestimate of the actual non-conformity of the surface. Since the opportunity for these reflected deviations increases with deviation magnitude (i.e., for 1/4" or greater defects), this effect is confined predominantly to this manually-finished class of decks which commonly display severe as well as extensive defects.

The manually finished deck showing the lowest roughness is the N.J. 72-U.S. 9 crossing which, as previously noted, was considered at the time of construction to be a very well-executed manual operation. A plot of rolling straightedge data for this smoothest manually finished deck is shown in Figure 36.

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*Previously discussed in section 2.2.3 of this report (pp.17-18).

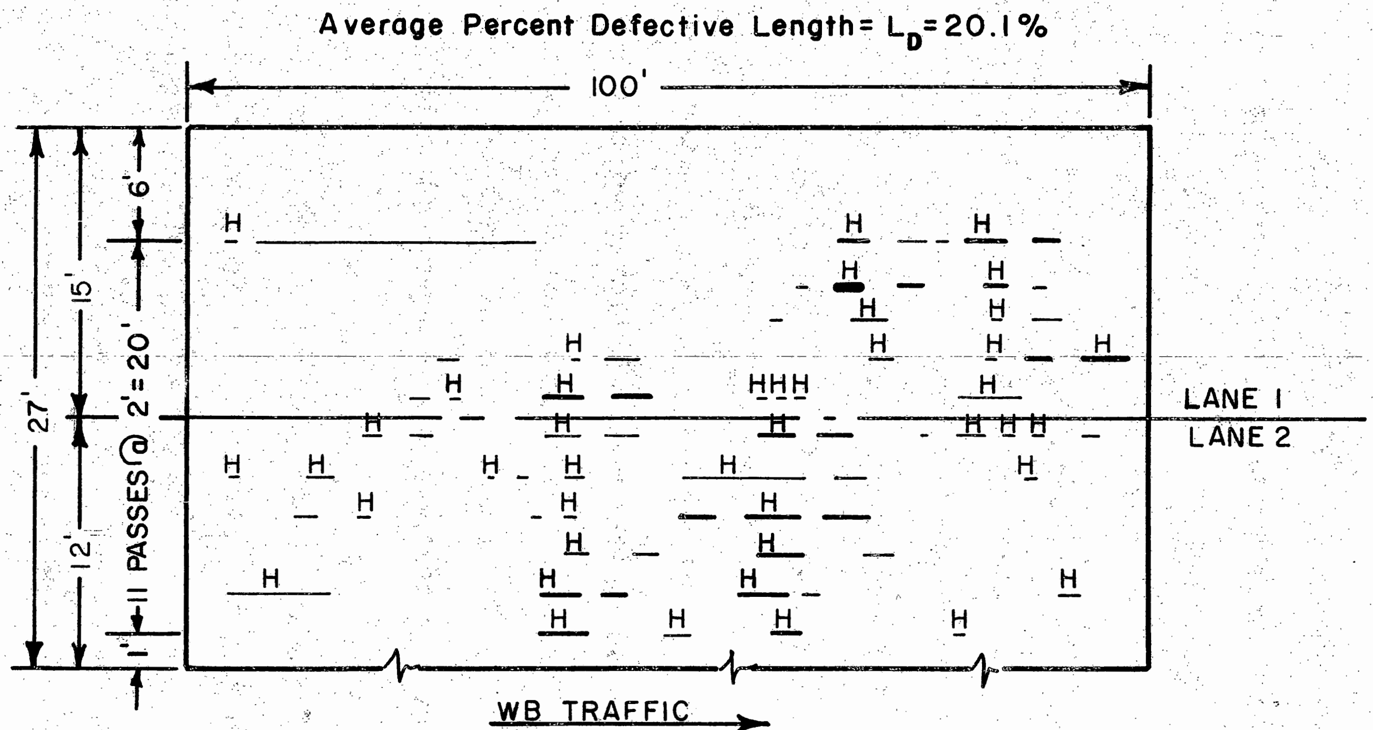

FIGURE 36:

PLOT OF ROLLING STRAIGHTEDGE DATA

N.J. 72 OVER U.S. 9

(WESTBOUND LANES 1 & 2)

HAND FINISHED

(SCALE 1" = 20' H 1" = 10' V)

LEGEND

1/8" = —

1/4" = —

3/8" = —

H = HIGH

_ = LOW

6.3.2 Full Span Length, Longitudinal Machine Finishing: Average roughometer readings of 107, 115, and 139 inches per mile were obtained on the three projects using full span length, longitudinally oscillating screeds. As noted, the highest of these readings was obtained on a deck on the U.S. 1, 6D project which received only one rather than the recommended minimum of two passes with the finishing machine.

While the benefits of full span length, longitudinal finishing relative to manual finishing can be appreciated from the data in general (i.e.- from the 120 vs. 161 inches per mile average roughness index and 8.5 versus 30 average percent defective length), perhaps the most meaningful evaluation of the roughness results between these two finishing methods is provided by the particular data from the I-295, 1S project. On that project, identical three-span structures were built by the same forces, in one case using manual finishing and in the other, machine finishing. As indicated in Tables 25 and 26, subsequent roughness measurements indicated the hand finished structure to have twice the percent defective length of the machine finished structure (27 vs. 13 percent) and a 60 percent greater average roughness index (170 vs. 107 inches/mile).

Examination of the detailed straightedge data for these two structures (Figure 37) is also of interest. Notice that in addition to their greater number, surface defects on the hand-finished structure are also of generally greater magnitude. Specifically, an average of only about 10 percent of the defects on the westbound structure exceed 1/4 inch,

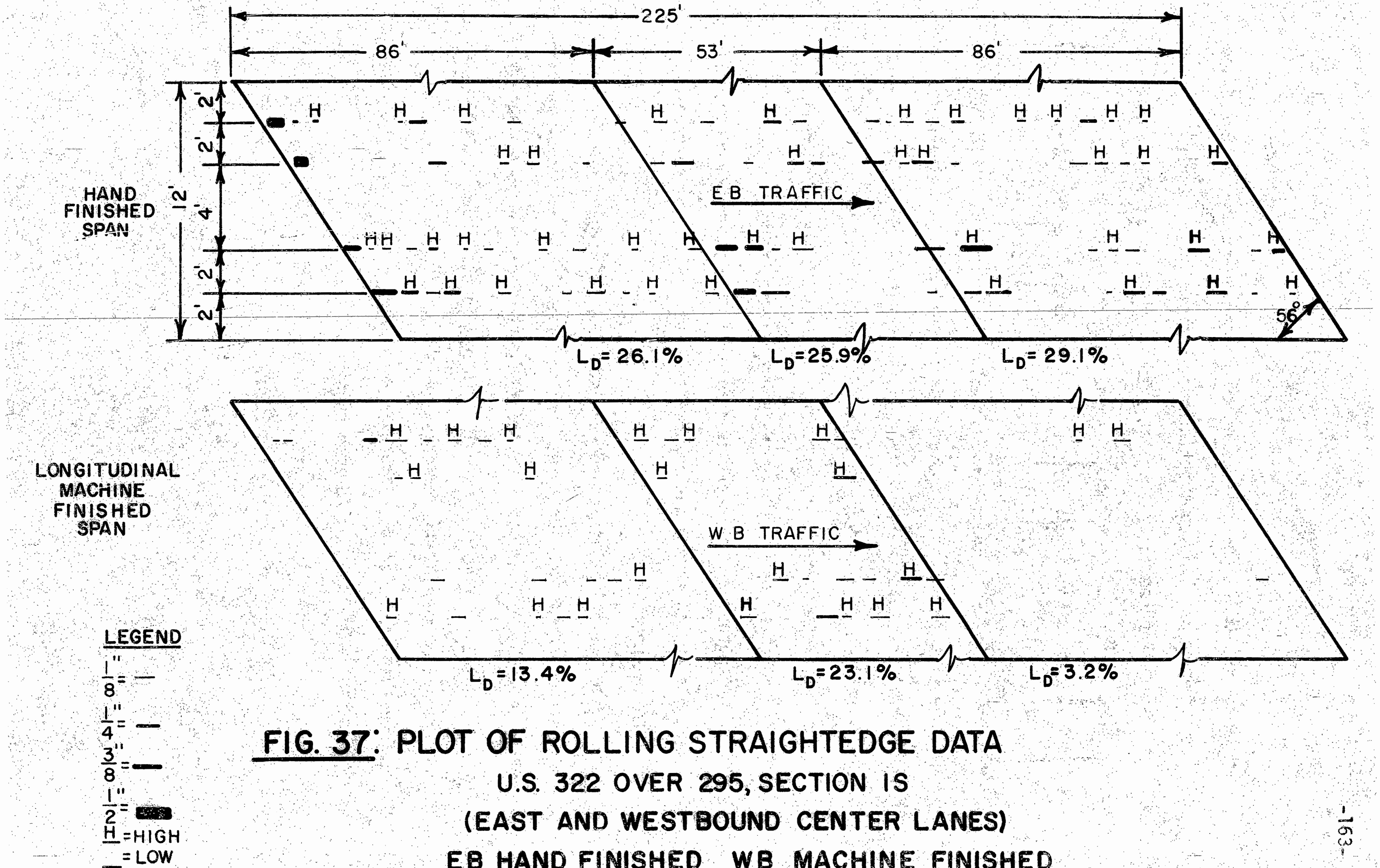

FIG. 37: PLOT OF ROLLING STRAIGHTEDGE DATA

U.S. 322 OVER 295, SECTION 1S

(EAST AND WESTBOUND CENTER LANES)

EB HAND FINISHED WB MACHINE FINISHED

(SCALE 1" = 30'H 1" = 6' V)

while 40 percent of the defects on the companion structure exceed 1/4 inch. Figure 37 also shows that the percentage of the manually finished deck exceeding a 1/8 inch tolerance was relatively constant at about 26 percent from span-to-span. On the other hand, the machine finished deck displays marked span-to-span differences in percent defective. This variation in the extent of surface defects in turn lead to individual roughometer test values ranging from 70 to 125 inches per mile (i.e., running the gamut from "Excellent" to "Fair/Poor" FHWA rideability ratings). One apparently important factor entering into this variation is extent to which the contractor was guided in his use of the equipment by the manufacturer. That is, the smoothest deck resulted from an operation supervised and participated in by the designer/manufacturer of the finishing machine; on the two rougher spans, the screed manufacturer was either not present or not actively engaged in the work.

The on-site assistance of the screed manufacturer similarly represented a construction "plus" in the case of the deck construction on Route I-95, Section 19A. The distribution of straightedge defects on this deck is shown in Figure 38. As previously noted, this deck also benefited from an automated rather than manual final belt finishing. Observe that the relatively few measured straightedge defects are again predominantly limited to 1/8 inch magnitude.

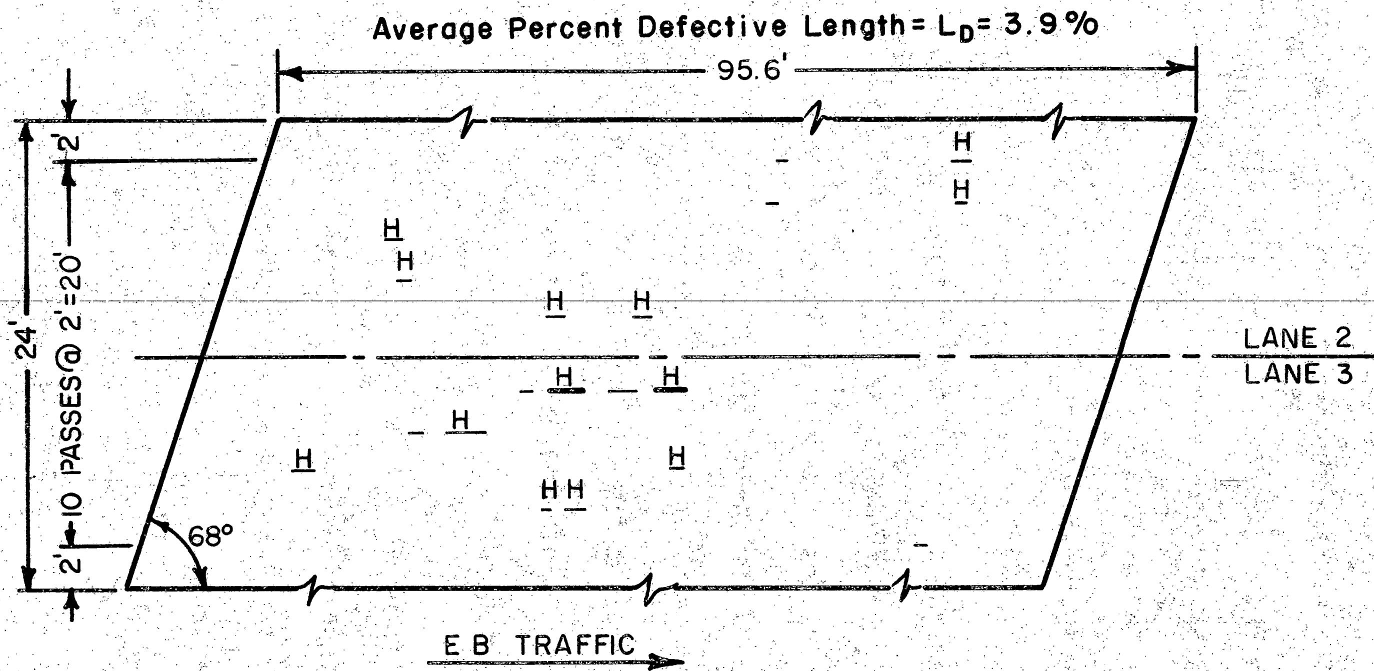

FIGURE 38:

PLOT OF ROLLING STRAIGHTEDGE DATA

I-95 OVER WEST PIERSON AVE.

(EASTBOUND LANES 2 & 3)

LONGITUDINAL MACHINE FINISHED

(SCALE: 1" = 20' H 1" = 10' V)

LEGEND

$\frac{1}{8}$" = —

$\frac{1}{4}$" = —

H = HIGH

_ = LOW

6.3.3 Partial Span Length, Longitudinal Machine Finishing: The roughness of the one studied deck (I-78, Section 5Y) constructed using a partial span length, longitudinal finishing machine was gauged by roughometer measurements alone. The average roughness index of 141 inches per mile observed for this deck translates as a (very) "Poor" FHWA pavement rideability rating and as a "Fair/Poor" bridge rating using the smoothness criteria of Table 23.

Since the construction practices involved in placing and finishing this deck were rated as "Good", it would appear that this sample can be considered as a reasonably representative trial of the partial span length type of longitudinal finishing equipment. While it is of course difficult to draw conclusions of any great moment from a single test such as this, our limited experience does appear to be similar to that reported by Michigan[30]. That is, equipment of this partial span length configuration yielded a rideability improvement compared to the general run of manually finished decks, but did not provide the smoothness achieved on the best of the decks finished with full span length screeds.

6.3.4 Transverse Roller Finished: While two transverse roller-finished bridge projects were investigated--the New Jersey 174, 1A and I-295, 3B and 4A contracts--only the latter work was tested with the roughometer as well as the straightedge.

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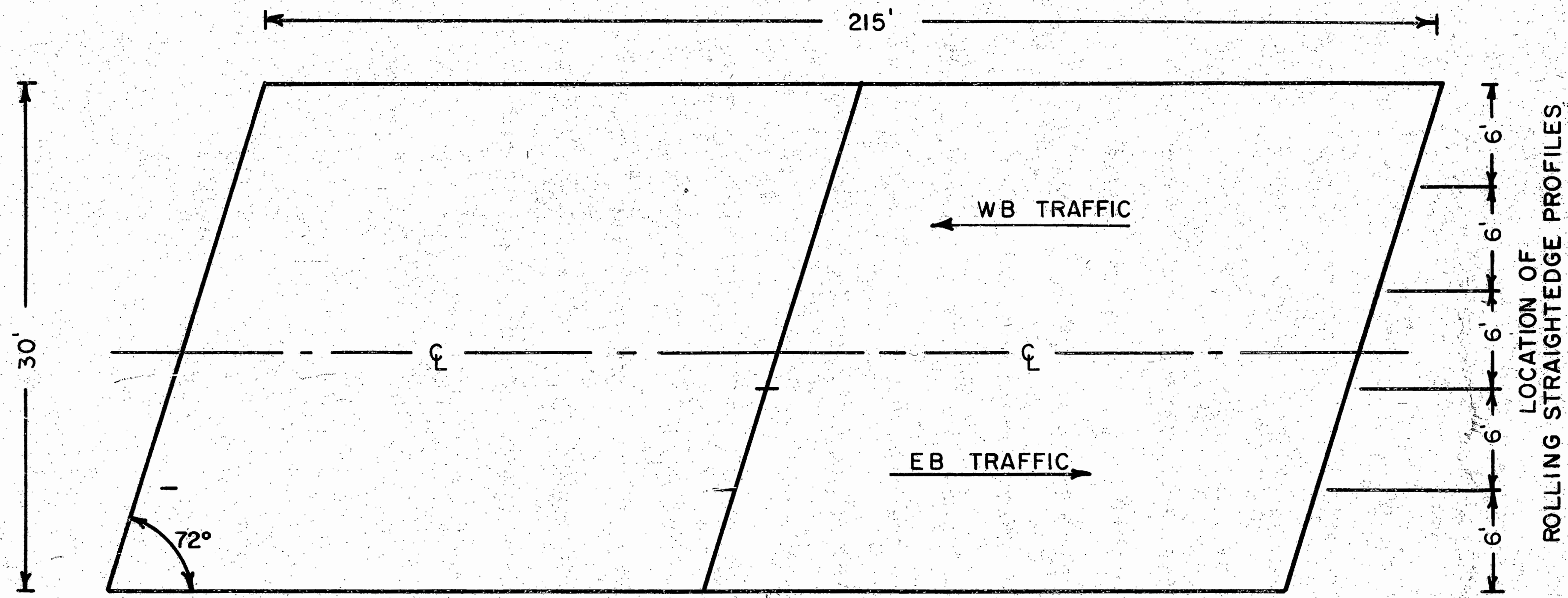
[30] Op. Cit.

As indicated in Table 25, the average roughometer readings for the three tested I-295 bridges were about the same as those for the full-length longitudinally screeded decks, with respect to both range and mean. The overall average of 120 inches per mile for these structures is again about 40 inches per mile less than the manual finishing average and merits a "Good" relative rideability rating according to the bridge deck roughness criteria of other states.

The magnitude of these particular readings--although generally "Good"--are, however, surprisingly high in view of the straightedge data for the structures. As indicated in Table 26, the tested portions of the I-295 decks show the greatest conformity to our existing surface tolerance of any the decks studied. The low measured percent defective length (1.2-3.1 percent) for these decks was in fact seldom observed on the sampled concrete pavements of this study. The extent of straightedge defects on the other roller-finished job (Route 174), while higher than that of the I-295 work, is only about half that for the best manually finished deck sample (i.e., about 12 vs. 20 percent defective).

A plot of the smoothest of the tested decks--the I-295 Elbow Lane structure--is presented in Figure 39. As shown, each of the three measured defects occurred near a joint, the portion of the slab receiving the most supplemental hand work.



(THE THREE DEVIATIONS NOTED ARE 1/8" HIGHS)

Average Percent Defective Length = L_D = 1.16%

FIGURE 39:

PLOT OF ROLLING STRAIGHTEDGE DATA

ELBOW LANE OVER ROUTE I-295, SECTION 3B & 4A

TRANSVERSE MACHINE FINISHED

(SCALE: 1" = 10' V 1" = 30' H)

6.4 RECENTLY ADOPTED CHANGES IN THE SPECIFIED CONSTRUCTION PRACTICES FOR NEW JERSEY BRIDGE DECKS

6.4.1 Nature of the Changes: Based on the observed improved rideability achievable thru use of mechanized deck finishing equipment, as well as the associated potential for improved durability*, New Jersey has recently adopted specifications requiring their use.

Realizing that a quality improvement (rideability in particular) will not accrue automatically from the mere provision of mechanized finishing equipment, our new specifications also contain provisions designed to yield an overall construction climate conducive to quality work. A copy of the new bridge deck construction specification is provided as Report Appendix E. A brief summary of the major points in these new provisions is as follows:

• required pre-planning: At least a month before the proposed start of deck concreting, the contractor must submit a written plan of operations for review by the engineer. In this plan, the contractor is required to provide details as to his proposed methods, equipment, and personnel utilization. Concrete placement will not be permitted until the engineer is satisfied that, first, the operation

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*The potential for improved durability accrues from the possibilities for minimizing such detrimental hand-finishing practices as overfinishing and sprinkling, from more timely finishing, and from more consistent achievement of desired reinforcement cover. With regard to the latter point, while surface irregularities (lows) are of course not a necessary condition for deficient cover, such may be sufficient cause for at least isolated cover reductions.

will be completed within the scheduled time, secondly, the necessary on-site preparations have been made and, finally, unless there is a reasonable expectation that the contractor's proposal will result in work of the required quality.

• minimum rate of placement: Concrete delivery, distribution and consolidation is to proceed at a uniform rate to insure a continuous operation. A minimum placement rate of 30 cubic yards per hour is to be maintained for decks of 180 cubic yards or less, while 40 cubic yards per hour is specified for decks of greater volume.

• permitted finishing equipment: Unless otherwise indicated on the plans*, an approved self-propelled finishing machine of either the rotating cylinder or oscillating type is required for deck strike-off and finishing. Longitudinal or transverse type machines are permitted for spans up to 75 feet, while machines for spans in excess of 75 feet are required to be of the transverse type. Longitudinal finishing equipment must be of the full span length variety. Transverse machines must generally be of sufficient size to finish a width at least equal to that of the approach pavement. Prior to the placement operation, the adjustment of the finishing system (both the machine and guide rails) and the cover over rebars and forms are to be checked by means of a dry-run.

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*According to criteria developed jointly by Department design and construction forces, specific conditions which preclude machine finishing are a limited number or size of structures (a one bridge, two span contract; slabs less than 60 feet long and/or 24 feet wide; deck volumes less than 75 cubic yards) and difficult/complex geometry (decks on a radius of 250 feet or less; acute skew angles less than 40°; variable cross-slope; certain combinations of variable width).

• <u>concrete placement</u>: The delivery and distribution of concrete shall be such that the working face of fresh material is at all times approximately parallel to the finishing machine or other strike-off. The operation of a transverse finishing machine shall be coordinated such that the initial strike is never more than 10 feet behind the placement. Strike-off by a longitudinal machine is to be delayed until concrete has been placed a minimum of two bays wide over its entire length. This delay will permit that portion of the deck to assume most of its final deflection and thus will minimize the potential for deficient cover/slab thickness. Subsequent strike-off by the longitudinal machine is to uniformly lag placement by the minimum two bay width. After the initial strike, any operation requiring access to the surface shall be made by means of a work bridge.

While many readers may be familiar with the general need for specification requirements such as those described, the following extreme example illustrating this particular need is believed worthwhile:

On one of the studied bridge projects, the resident engineer felt that the contractor's proposed methods of placement and finishing (hand) would be inappropriate for the approximately 145 cubic yard pour. The resident was not, however, able to force modification in the proposal under the existing specification framework. The anticipated problems were realized on commencing the operation. The placement method proved inadequate and a hand-pushed buggy delivery system had to be improvised. This in turn necessitated on-the-spot recruitment of additional labor from elsewhere on the project (e.g., steel painters, asphalt laborers, a foreman from another contractor). Placement proceeded at a rate of about 12 cubic yards per hour until dark. However, the available finishing force--in part hampered by delivery of concrete of widely varying workability--was not able to keep up with even this relatively modest rate of placement. Final finishing continued until about midnight under the (inadequate) illumination provided by vehicle headlights and several propane lamps. Subsequent rolling straightedge measurements indicated that about one-third of the deck exceeded the specified surface tolerance, with individual defects ranging up to 1/2 inch plus.

While a number of observations can be made concerning this example, possibly the most important is the obvious need for a well thought-out plan of construction.

6.4.2 Implementation of the Changes: The described changes in New Jersey bridge deck specifications were implemented in a two-step process. That is, prior to actual adoption of the specification, the contractor groups affected were notified of the impending change and strongly encouraged to use machine finishing, with the revisions actually being incorporated six months later (July 1, 1973).

An encouraging development in this regard has been the cooperation and feedback by New Jersey contractor groups, notably thru the New Jersey Heavy and Highway Construction Industry Advancement Fund (NJCIAF). A series of deck finishing seminars jointly sponsored by the Department and NJCIAF have stimulated a better understanding of the advantages and the limitations of machine finishing (e.g., the need for designs <u>compatible</u> with machine methods) on the part of the contractor, consultant and Transportation Department employees attending.

6.5 PROPOSED BRIDGE DECK SMOOTHNESS ACCEPTANCE SPECIFICATIONS

6.5.1 <u>General</u>: A close analogy exists between the use of mechanical bridge deck finishers and automated paver controls with respect to the equipment's potential impact on rideability and the actual rideability achieved. That is, while required machine finishing can be expected to effect an <u>overall</u> improvement in New Jersey bridge deck rideability, the degree of acceptability of <u>individual</u> future projects will continue to depend on the extent to which the variability inherent in every construction input -- men, materials and equipment -- is controlled. There is a reasonable expectation that even on well-planned projects, an occasional shortfall will occur with respect to the specified rate of supply, the proper use of equipment, or the quality of workmanship.

The class of deck construction most likely to provide exceptions to any trend for improved rideability are those where hand finishing is permitted by specification exception. Since none of the hand-finished decks tested in this work approached conformity with required surface tolerances, it seems reasonable to expect substantial nonconformity on future projects, especially since one basis for permitting hand-finishing in the future will be the relative complexity of the deck geometry.

New Jersey's deck construction provisions continue to specify that the deck shall be completely free of straightedge deviations in excess of 1/8 inch in 10 feet. In the event of a non-conformity, the contractor is "allowed" to remove high spots up to 1/2 inch by grinding. This zero defect provision is equally, if not more, unrealistic for bridges than for pavements.

The underlying philosophy and details of proposed alternate specifications for bridge deck smoothness are developed in the following two report subsections. The criteria offered are patterned after the rolling straightedge-based provisions previously recommended for pavements.

6.5.2. Underlying Philosophy: Developing the overall framework for a riding quality specification is fundamentally an exercise in engineering judgement. This is particularly true in the case of bridge deck smoothness provisions since, while adequate, the present deck rideability sample is certainly not exhaustive as to roughness results obtainable with machine finishing.

A discussion presenting the writer's opinion as to an appropriate basis for smoothness acceptance of New Jersey bridge decks is as follows:

. Specification orientation: Future New Jersey bridge decks will fall in one of three general finishing categories--machine finished by specification requirement, machine finished by contractor option, or manually finished.

Obviously then, the first decision which must be made is the type of deck finishing results (i.e., hand, machine, or both) to which the specification is to be oriented.

The significantly different level of surface defects between hand and machine-finished structures immediately suggests that the use of a single, "umbrella" provision for both types of construction is not desirable. This would be especially true if the specification was oriented to hand finishing. The problem here is that while it would not be fair to penalize a well-executed hand-finished job, available data indicates that even our best manual construction dsplays considerable defective length. Thus, the required leniency in a specification including manual methods would preclude the use of acceptance limits that accurately reflect the desired level of rideability. Further, such leniency would not stimulate contractors who use machine finishing to obtain the best results achievable with the equipment. In view of these difficulties and the relatively low estimated percentage of future deck construction that will be excepted from machine finishing requirements (about 20-25%), it seems apparent that manual and machine-finished bridge decks should be governed by separate acceptance schedules.

An additional important consideration in developing smoothness specifications for bridges is the desire to encourage use of mechanical deck finishers even where such equipment is not specifically required. This factor suggests that the smoothness provisions for machine finished decks be divided into subcategories reflecting whether use of mechanized methods was required or elected. It is highly conceivable, for example, that if given a choice between finishing methods and faced with a single (relatively stringent) set of provisions applicable to machine finishing, a contractor would be extremely hesitant to use other than manual methods.

Based on the preceding then, it is proposed that separate acceptance policies be adopted for each of the three classes of deck finishing, the provisions of which generally proceed in order of increasing leniency from required machine to optional machine to manual finishing.

• Limits of acceptability: Since the optional machine and manual finishing categories will be the exception of future deck construction projects, a discussion of proposed acceptance limits for these cases will be delayed to a later report subsection (6.5.3).

In the case of decks specified to be machine finished, it is believed both feasible and desirable that acceptance limits be generally structured so as to achieve a goal of comparable rideability with concrete pavements. Like pavements then, a graduated penalty scale is proposed for decks which exhibit surface irregularities intermediate to an acceptable quality level and a totally rejectable quality level.

The proposal for decks does, however, envision departures from the acceptance plan for pavements at each end of the penalty spectrum. The first of these involves the penalty/no penalty demarcation for machine-finished decks and is best described as a "feature" of the deck acceptance plan, rather than a "difference" between deck/pavement plans. The onset of penalties for these machine-finished decks is proposed at 6 percent defective length rather than the 5 percent previously established for concrete pavement. Use of this slightly higher acceptance limit, combined with a (later described) higher straightedge sampling rate, will significantly reduce a contractor's risk of having adequate deck rideability rejected and penalized. Further, this combination of a higher acceptance limit and sampling rate will effectively <u>redefine</u> the acceptable (no penalty) quality level for machine-finished bridges as "Fair" rideability rather than "Good" as required for pavements. In effect then, New Jersey would actually be following the previously noted practice of some other states of being less critical of deck rideability.

Additionally, due to the greater expected frequency of extensive straightedge defects and their associated greater (monetary) consequence on a bridge deck compared to a pavement, a more fundamental departure from the pavement acceptance plan is necessary at the other penalty extreme. That is, available data* suggests only an infrequent occurrence of pavement lots so consistently rough as to call for the most severe penalty. In contrast, even some of the machine-finished spans in the

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*cf. Table 21, page 141

present data sample display a percent defective in excess of the remove/replace criteria for concrete pavement (i.e., $L_D > 14\%$). If removal and replacement is a drastic and seldom exercised measure for a pavement, it is even more so in the case of a deck. Consequently, while "Very Poor" rideability could reasonably be used as a totally rejectable quality level on both pavements and bridges, it is suggested that some ranges of bridge deck percent defective length above this truly "totally rejectable" level be accepted but with increased percentage payment reductions. This is not to say, however, that the state should consistently accept decks which are actually of totally rejectable riding quality from a given contractor. If a contractor provides a span with a gross percent defective length, this is evidence that his methods and/or equipment are inadequate and he should not be permitted to initiate any further project pours until a revised plan of operations is approved. It is here suggested that if a machine-finished deck displays 20 percent defective length, this constitutes a "grossly non-compliant" level of surface defects, indicative of a need for revised construction practices.

• Penalty dollar value: It seems reasonable that the dollar value of any bid price adjustments for rideability deficiencies should be essentially the same for concrete pavement and bridge deck construction. That is, the concrete pavement and deck smoothness provisions should be structured such that a straightedge percent defective length corresponding to a given degree of unacceptability will result in about the same "X" dollar payment reduction per unit of surface area on either type of construction.

While the underlying basis of smoothness penalties is the amount of riding surface area provided, bridge deck bid price adjustments should for convenience be levied on the cubic yard pay item for structural concrete. Current bid prices indicate that to achieve comparable penalties, each one percent payment reduction per square yard of concrete pavement should correspond to about a 1/4 of one percent payment reduction per cubic yard of deck concrete furnished*.

Any attempt to achieve comparable penalties for concrete deck and pavement construction must, however, reflect the fact that application of a small percentage payment reduction to the relatively small area of a bridge deck can result in a very nominal absolute penalty. To illustrate, Table 27 shows the expected dollar value of a slight (2%) penalty applied to a "typical" day's production of bridge and on-grade paving. From these calculations, it appears reasonable that a contractor placing a pavement would, thru appropriate control procedures, actively attempt to minimize his chances of receiving even this lowest penalty. In contrast, the consequence of the slight penalty on a bridge deck is so modest as to be of dubious value in motivating the contractor. Based on these considerations, the lowest smoothness penalty for bridge decks will be set at a level which hopefully will stimulate the contractor to avoid providing the state with marginally acceptable as well as totally rejectable riding quality.

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*Example: A one percent penalty assessed on 9 inch thick New Jersey pavement typically bid at $10 to $12 per square yard amounts to a payment reduction of 40 to 50 cents per cubic yard supplied. Approximately the same reduction would accrue from an 0.25 percent penalty on our typical deck concrete bid at $150 to $170 per cubic yard.

TABLE 27

Estimated Dollar Value of a "Slight" Percentage Payment Reduction Applied to Concrete Pavement and Bridge Deck Construction

	"Typical" Concrete Pavement	"Typical" Concrete Bridge Deck
Daily Production = Acceptance Lot Size	3,500 $yard^2$ per day	a 125 $yard^3$ deck pour
Bid Price	\$10 per $yard^2$	\$160 per $yard^3$
Unit Bid Price Adjustment Associated with a "Slight" Penalty	2 percent per $yard^2$ = 20¢ per $yard^2$ or 80¢ per $yard^3$	1/2 percent per $yard^3$ = same 80¢ per $yard^3$
Total Penalty Applied to the Day's Work	\$700	\$100

• Timing of specification implementation: It is proposed that New Jersey's smoothness acceptance provisions for machine-finished decks be implemented in a schedule which provides a one year period of very lenient provisions (i.e., penalties suspended except for "Poor" or "Very Poor" rideability) prior to adoption of acceptance limits accurately reflecting various degrees of unacceptability. This transition period would provide contractors with the opportunity to gain further experience with mechanical finishing equipment, our new deck specifications in general, and enforced surface tolerance requirements in particular.

• Amount of testing performed: Unlike pavements, it is entirely practical to routinely test the full length of each wheelpath of a bridge span with the rolling straightedge. Consequently, such a 100 percent sampling plan is incorporated in the recommended smoothness acceptance scheme for bridges.

An important benefit of testing all wheelpaths is that in comparison to pavements, contractor and state penalty risks (rejection of good and acceptance of poor rideability, respectively) can both be reduced. This accrues from the fact that elimination of variability introduced by fractional sampling--generally by far the larger component of total straightedge measurement process variability*--will cause bridge deck straightedge measurement dispersion to be principally a function of the precision of the instrument itself. This fact can, for example, be expected to result in the measurement standard deviation being reduced by at least a factor of three compared to various factional sampling plans employed for acceptance of concrete pavement.

As prevously alluded to, this relative reduction in measurement uncertainty in turn has an implication on the comparative leniency between the smoothness acceptance plans for concrete pavement and bridge decks. That is, recall that the percent defective length corresponding to the onset of concrete pavement smoothness penalties was not set solely on the basis of the acceptable quality level (L_D = 3% = "Good"), but rather at a higher level (L_D = 5% = "Fair") that allowed for measurement uncertainty. Since less measurement

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*cf. Figure 26, page 114

variation is expected for bridge data, the onset of penalties could be set at a level closer to the desired quality level with no increase in risks*. Consequently, use of the same "no penalty" demarcation for decks as for pavement (5%) actually would be more lenient in the case of a deck since it would in itself effect a redefinition of the acceptable quality level from "Good" to "mid-range Fair" rideability. The current proposal to increase this no-penalty demarcation from 5 percent to 6 percent results in an even more lenient acceptance criterion.

• Retaining the engineer's discretion: While application of the proposed penalties for deficient riding quality is not optional with the project resident, it is felt that any decision as to remedial measures for surface irregularities should retain engineering discretion. The proposed specification consequently contains a conditional statement that the engineer may order any or all surface defects in excess of 1/8 inch in 10 feet to be corrected. The important fact here is that even isolated surface deficiencies may require correction because of their pronounced detrimental effect on rideability or the overall proper functioning of the deck due to their magnitude, location or interference with drainage.

In this connection, it is to be noted that this matter of engineering judgment also applied to cessation of deck concreting. Our new deck specifications will permit the engineer to reject equipment

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*Consider the extreme case: If there were no measurement variation in straightedge data, the onset of penalties could be set any slight increment above the acceptable quality level with no risk of making an inappropriate acceptance/rejection decision.

or methods which result in work that does not meet the 1/8th inch surface tolerance. Thus, the previously suggested (20% defective) limit for a revised plan of operations is not intended as _the_ limit for discontinuing operations, but rather--in the writer's view--as a boundary above which there is no reasonable alternate. On either the mechanized or manual type of deck construction then, the engineer may (and should) in some cases exercise his option to discontinue operations on decks where some lesser percent defective results.

• _Diminished value of a corrected surface_: Thus far, the discussion of a deck smoothness acceptance scheme has by implication dealt with only one of the two possible general cases of deck acceptance: That is, with the case where surface irregularities in excess of the specification tolerance are allowed to remain in place on the deck. An appropriate level of penalties for the second possible case--that where the Engineer requires or permits surface deficiencies to be corrected by either filling or grinding--remains to be determined.

It seems reasonable that if surface restorations are required, factors quite apart from rideability--including the diminished appearance, durability, or skid resistance of a ground or patched surface--call for at least some minimum payment reduction.

In the subject deck specification, it is proposed that if surface corrective measures are required, a second straightedge sampling is to be made of the corrected surface. The contractor is then assessed a penalty corresponding to the revised percent defective length indicated in the retest or _at least_ 2.5 percent of the bid price of the concrete incorporated in the affected slab. Thus, if surface defects are so extensive or severe as to require selected surface restorations, a minimum penalty of about $500 can be expected for a "typical" day's production.

6.5.3 Proposed Smoothness Acceptance Schedules: A discussion of the specific acceptance schedules proposed for each of the three general classes of New Jersey deck finishing is as follows:

- Machine finishing by specification requirement: The proposed riding quality requirements for decks where machine finishing is specifically required--thus, the provisions which will control in the majority of future cases--are shown compared to the concrete pavement acceptance plan in Table 28.

As indicated, during the one-year transition period following adoption of the specification, any percent defective length that would be expected to yield an average rideability rating better than borderline "Fair/Poor" will be accepted without penalty. Note, however, that during this first year, a penalty of substance will not be levied until the straightedge equivalent of "Very Poor" rideability is exceeded (i.e., L_D = 14% = totally rejectable pavement rideability). A similar situation is indicated for decks in following years. That is, the expected dollar value of any percent payment reduction can be expected to be relatively nominal unless "Poor" or worse rideability is provided.

During either specification period, decks displaying a percent defective up to nearly twice the truly totally rejectable level (i.e., L_D up to 25%) will be accepted with a penalty. The indicated acceptance

Table 28: Comparison of Proposed Smoothness Acceptance Schedules for Concrete Pavements and for Those Bridges Required to be Machine Finished

<table>
<tr><th colspan="3">CONCRETE PAVEMENTS</th><th colspan="8">CONCRETE BRIDGE DECKS
(Machine Finishing Required by Specification)</th></tr>
<tr><th colspan="3"></th><th colspan="4">Decks Bid in the One Year Period, X to Y</th><th colspan="4">Decks Bid Subsequent to Date Y</th></tr>
<tr><th>Lot Percent Defective Length, L_D</th><th>Expected Riding Quality</th><th>Percent Payment Reduction Per yd^2 (Note A)</th><th>L_D (Note B)</th><th>Expected Riding Quality</th><th>Percent Payment Reduction Per yd^3</th><th>"Typical" Penalty Dollar Value (Note C)</th><th>L_D</th><th>Expected Riding Quality</th><th>Percent Payment Reduction Per yd^3</th><th>"Typical" Penalty Dollar Value</th></tr>
<tr><td>5% or less</td><td>Fair or Better</td><td>none</td><td rowspan="2">8.9% or less</td><td rowspan="2">Fair/Poor or Better</td><td rowspan="2">none</td><td rowspan="2">0</td><td>6% or less</td><td>Fair or Better</td><td>none</td><td>0</td></tr>
<tr><td>5.1-11.0</td><td>Fair to Poor</td><td>2%</td><td>6.1-8.9</td><td>Fair to Fair/Poor</td><td>1%</td><td>$ 200</td></tr>
<tr><td>11.1-13.9</td><td>Poor to Very Poor</td><td>10%</td><td>9.0-13.9</td><td>Fair/Poor to Very Poor</td><td>1%</td><td>$ 200</td><td>9.0-13.9</td><td>Fair/Poor to Very Poor</td><td>2.5%</td><td>$ 500</td></tr>
<tr><td rowspan="2">14% or more</td><td rowspan="2">Very Poor</td><td rowspan="2">20% or remove</td><td>14.0-24.9</td><td>Very Poor</td><td>7%</td><td>$1,400</td><td>14.0-24.9</td><td>Very Poor</td><td>7%</td><td>$1,400</td></tr>
<tr><td>25% or more</td><td>Very Poor</td><td>15%</td><td>$3,000</td><td>25% or more</td><td>Very Poor</td><td>15%</td><td>$3,000</td></tr>
</table>

Notes: A. Percentage Payment Reductions: An "X" percent penalty per square yard is also equal to an "X" percent penalty per cubic yard. Thus, the unit dollar value of smoothness penalties for pavement and bridges will by about equal where the percentage reductions are in the same ratio as the usual bid prices (i.e., bridge/pavement : 1/4).

B. Lot Size: Deck concrete is to be accepted in lots equal to the number of cubic yards placed in each production day.

C. Typical Penalty Dollar Value: Assumes a "typical" pour 125 cubic yards bid at $160 per yard or $20,000 schedule thus will essentially encompass the entire range of machine finishing results observed in this work. The penalty dollar value associated with the roughest decks is in about the (2:1) proportion that they exceed the totally rejectable, "Very Poor" level.

· Manual finishing by specification exception: As previously noted, the roughness data obtained on our manual construction differs essentially only in the degree of "Poor" rideability indicated. In the writer's view, this effectively precludes formulating smoothness acceptance specifications for such construction based on a rational balancing of desired quality levels with the quality achieved. The available data instead dictates that acceptance be based almost exclusively on the prevailing quality level. If, for example, the acceptance schedule penalized some justifiable but as yet unattained level of defects (say L_D = 14% versus the observed minimum of 20%) an essentially constant minimum level of penalties would generally be applied to hand-finished jobs. This circumstance would undoubtedly in turn reflect in a proportionate increase in deck bid prices.

Consequently, as shown in Table 29, the proposal for hand-finished decks contemplates accepting decks having the overall range of defects observed in the research sample, with penalties being levied exclusively on various categories of rideability which are above a truly totally rejectable quality level.

Due to their greater expected frequency on manual construction, the higher ranges of percent defective are accepted at a lesser relative payment reduction than on similarly rough machine-finished decks. The

Table 29: Comparison of Proposed Smoothness Acceptance Schedules for Manually Finished and Machine Finished Bridge Decks

MACHINE FINISHING SPECIFIED*			MACHINE FINISHING OPTIONAL							
			Machine Finishing Chosen				Manual Finishing Chosen			
Percent Defective Length, L_D	Expected Riding Quality	Percent Payment Reduction Per yd^3	L_D	Expected Riding Quality	Percent Payment Reduction Per yd^3	"Typcial" Penalty Dollar Value	L_D	Expected Riding Quality	Percent Payment Reduction Per yd^3	"Typical" Penalty Dollar Value
6% or less	Fair or Better	none	13.9% or less	Better than Very Poor	none	0	19.9% or less	Any Quality Level, Including Very Poor	none	0
6.1-8.9	Fair to Fair/Poor	1%								
9.0-13.9	Fair/Poor to Very Poor	2.5%								
14.0-24.9	Very Poor	7%	14.0-24.9	Very Poor	7%	$1,400	20.0-27.0	Very Poor	2.5%	$ 500
25% or more	Very Poor	15%	25% or more	Very Poor	15%	$3,000	27.1-34.9	Very Poor	7%	$1,400
							35% or more	Very Poor	15%	$3,000

*Applicable to decks bid subsequent to the one-year transition period.

most severe payment reduction is applied to a percent defective of 35 not only because of the high absolute magnitude of that value, but also because 35 percent appears to be the upper limit expected for even poorly executed work. That is, recall that in the previously described example of hand-finishing where numerous construction factors did not favor quality work (page 171), "only" one-third of the deck exceeded the specified surface tolerance.

While obvious, it is worthwhile to emphasize an important point with regard to permitting hand finishing methods. In view of the historical roughness results obtained with manual finishing and considering that this Department patently is interested more in obtaining quality work than payment reductions, it is imperative that from the conceptual design stage onward, an attempt be made to minimize the number of structures which are not amenable to machine finishing. Additionally, particular thought should be given to the situation where a hand-finishing option is contemplated because of the limited size or number of structures rather than from the standpoint of a physical incompatibility with mechanical finishing.

. Machine finishing by contractor option: To encourage use of mechanized deck finishing equipment where such is not specifically required, it is proposed that an acceptance schedule intermediate to the two previously presented be adopted. Specifically, as shown in Table 29, it is proposed that if a contractor elects to use mechanical finishing methods, smoothness penalties be suspended up to the point where

"Very Poor" rideability is expected. However, if mechanical finishing results in "Very Poor" rideability--regardless of whether such methods were required or chosen--the contractor should be penalized. Since a reasonably conscientious contractor can be expected to meet these requirements, their adoption hopefully will cause the contractor to base his choice of finishing method on factors other than smoothness penalties.

Essentially, by adopting this specification, New Jersey's position would be one of <u>expecting</u> generally good rideability (both absolutely and in relation to the hand-finishing option) but not <u>requiring</u> it. While this is not an ideal situation, consider the (hand-finishing) alternate: good rideability is neither required <u>nor</u> expected.

A description of the proposed deck smoothness provisions in an actual specification format is presented in Appendix F of this report.

PART VII: CONCLUSIONS

The principal conclusions derived from this five-year study of New Jersey pavement riding quality are as follows:

1. The FHWA roughness evaluation criteria is judged to be an appropriate means for appraising the rideability of New Jersey pavements. Use of this criteria is predicated on obtaining a reliable assessment of a pavement's "Roughness Index". The roughness index as measured directly by a BPR type roughometer, or as calculated from rolling straightedge output, was found to be readily determinable and with an acceptable degree of precision.

2. The "Present Serviceability Index" concept developed from work at the AASHO Road Test has little applicability to design and maintenance decisions in New Jersey. The difference between initial and terminal serviceability index values for New Jersey pavements is typically too small to permit valid judgments regarding pavement performance. (average difference: 1.0 for concrete, 0.5 for bituminous)

3. According to the FHWA criteria, and thus in comparison to the work of other states, the average new bituminous pavement surveyed during this study possessed only a "Fair" level of riding quality. However, there is a significant and encouraging trend for more recent bituminous construction to be of improved smoothness. Improvements in the specified equipment, methods of construction, and payment method appear to be the major causal factors. The impetus for certain of these changes was provided by the initial findings of this study.

4. The average new concrete pavement was found to possess an even lower level of rideability than bituminous roadways. An FHWA adjective rating of "Fair to Poor" is indicated for typical New Jersey concrete construction. In spite of considerable experimentation with construction methods and equipment, significant rideability improvements in pavements of New Jersey's present standard design appear unachievable without a return to long-past standards of workmanship. Recent use of a different design, requiring sawed construction joints rather than formed expansion joints, did not provide an overall improvement of the desired magnitude.

5. The major factors contributing to the roughness of bituminous construction monitored during this study were:

a. Manual rather than automatic paver controls; improper use of the automated controls.

b. Stop-and-go paver operation; failure to match laydown speeds with rates of material supply.

c. Overly frequent transverse construction joints.

d. Use of a method of payment (square yards) that in practice required that a choice be made between avoiding thickness penalties or achieving good rideability.

e. Use of non-bituminous base courses that were difficult to construct to proper grade.

f. Lack of sufficient awareness or concern for achieving smooth pavements on the part of some Department and Contractor personnel.

Responsive action by the Department and the contracting industry in the form of specification improvements, changes in construction practices, and educational programs appear to be making significant progress in overcoming these deficiencies.

6. Transverse joint construction is the most significant item affecting the rideability of New Jersey's concrete pavements. On a typical project, about 40 percent of the pavement's surface defects are associated with the construction of transverse expansion joints.

7. The ten-foot rolling straightedge provides an acceptable means for measuring the surface defects of a New Jersey pavement and determining the associated level of rideability. Within the roughness ranges experienced in this study, the output of the straightedge expressed in terms of the percent defective length correlated well with the Roughness Index indicated by the roughometer. The specific correlations established are provided on Pages 48 and 72 of this report.

8. The Department's current surface smoothness specifications are overly restrictive and difficult to apply. The requirement that there be no surface deviations from a 10 foot straightedge in excess of 1/8 inch is unrealistic and, thus, unenforceable. Additionally, the required method of measurement is too slow and its description in the specifications is incomplete, lacking necessary guidance regarding sampling technique and data recordation.

9. New surface smoothness specifications have been developed for New Jersey pavements. These require acceptance testing of a pavement with a rolling straightedge and subsequent comparisons of the measured percent defective length to certain standards of acceptance. A graduated schedule of payment reductions is to be applied when a non-compliant level of riding quality is indicated.

The standards of acceptance, payment reduction schedule, and sampling requirements have all been formulated by statistical means to assure that an FHWA indicated "Good" or better riding pavement will yield full payment to a contractor. Progressively poorer rideability is accompanied by increasingly larger payment reductions. The detailed specification provisions formulated as part of this research are given in Appendix D (pp. 231-35) of this report.

10. The roughness data obtained on New Jersey bridge decks confirms the beneficial effect of using mechanical rather than manual methods for concrete strike-off and finishing. Each of the sampled manually-finished decks displayed extensive surface irregularities and, as a consequence, none merited other than a "Poor" FHWA rideability rating. Expectedly, the relative improvement in riding quality observed for mechanized deck finishing varied for particular types of equipment and project conditions. On an overall basis, surface defects on the "average" machine-finished deck were only about 1/3 to 1/7 as extensive as on the "average" hand-finished deck. This resulted in approximately a one-third lower average roughness index.

11. Recent New Jersey specification changes--including provisions which will require use of mechanized deck finishing equipment on the majority of future projects--can be expected to effect an overall improvement in our bridge rideability. It is further expected however, that two general exceptions to any such trend for improved rideability will occur.

First, since none of the hand-finished decks tested in this work even approached conformity with required surface tolerances--including some well-executed manual operations--it seems reasonable to expect substantial non-conformity for this entire class of construction in the future. It is thus imperative that from the conceptual design stage onward, every attempt be made to minimize the number of structures which are not amenable to machine finishing.

Secondly, required machine finishing notwithstanding, the actual degree of smoothness attained on all future deck projects will continue to depend on the extent to which the variability in every construction input--men, materials, and equipment--is controlled. In order to stimulate contractors to exercise the requisite control over their operations, a realistic and enforceable New Jersey smoothness specification is in order. Importantly, our existing "zero" straightedge defect provision satisfies neither of these criteria.

12. New surface smoothness provisions have been developed for New Jersey bridge decks. Like the proposal for pavements, the deck acceptance plan requires testing of a deck slab with the rolling straightedge and application of a graduated scale of payment reductions to non-compliant levels of measured percent defective length.

For a given level of roughness, the percentage of the bid price paid for deck concrete will generally be different than that applied to a concrete pavement, and will vary depending on the deck finishing method employed. This penalty variation reflects the fact that generally different roughness levels are achieved on pavements and bridges and among deck finishing techniques.

The detailed deck smoothness specification provisions formulated as part of this research are given in Appendix F (pp. 241-46) of this report.

It is to be noted that the writer's basic philosophy in developing both the deck and pavement smoothness provisions is that they should initially be somewhat lenient. Implicit in this course of action is that these provisions should not be static, but rather should be reviewed and updated in the future to reflect then-prevailing (improved) quality levels.

PART VIII: RECOMMENDATIONS

1. It is recommended that the New Jersey Department of Transportation adopt pavement and bridge deck smoothness acceptance specifications based on the output of a 10-foot rolling straightedge. A description of the proposed pavement smoothness acceptance provisions in a suggested specification format is presented in Appendix D of this report. The proposed smoothness specifications for decks are presented in Appendix F.

2. There are two possibilities for performing the necessary straightedge testing of future construction projects: the use of project inspection forces or the organization of specialized, regional crews. The use of project inspection forces would have the single important advantage of a greater immediacy of the roughness readings and consequent greater potential for roughness control. The use of specialty straightedge crews would offer a number of important advantages, including ease of operator training, greater operator proficiency and standardization of equipment usage and maintenance.

It is recommended that straightedge testing be performed by regional testing forces, staffed and organized so as to provide timely riding quality information.

3. In the near future, the basis of payment for New Jersey bituminous pavements will be markedly changed. That is, the Department has elected to substitute a single (tonnage) payment item--"Hot-mix bituminous pavement, _____inches thick" for the present individual bituminous payment items. The proposed smoothness acceptance plan was constructed accordingly, with the basis of penalties being the total, full-depth tonnage of material supplied rather than surface course alone. In the case of riding quality penalties, the determination of the quantity of material in an acceptance lot will be clumsy, requiring considerable calculations on the part of field forces to

determine the tonnage of bituminous materials underlying a day's production of surface course. In contrast, a determination of the daily tonnage of surface course is quite straightforward, requiring simply a totalling of daily material delivery slips. It is therefore recommended that the Department make provisions in the overall framework of bituminous specifications so as to permit the assessment of smoothness penalties on surface course tonnage alone. The required (proportional) changes in payment reductions for smoothness non-compliance would be furnished by Research.

4. On some of the bridge decks studied in this research, the use of a transverse roller-finisher resulted in concrete surfaces which were almost completely free of measured straightedge defects. Since these roller-finishers have been employed by others for paving on-grade, it seems possible that including such equipment in the paving train might effect a needed rideability improvement for New Jersey concrete pavement. In particular, use of this equipment to apply a machine finish in the immediate vicinity of expansion joints potentially would eliminate a major source of defects.

The manufacturer of the subject equipment has indicated willingness to provide a (no-charge) demonstration on a New Jersey concrete pavement construction project. It is thus recommended that this Department make arrangements on a future project for a <u>trial</u> use of the roller-finishing equipment to determine its actual fitness for use on New Jersey concrete paving. Apart from the magnitude of any rideability improvement and overall compatibility with New Jersey conditions, a key factor to be determined in this regard is the achievable production rate for on-grade paving.

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A P P E N D I C E S

APPENDIX A: DISCUSSION OF THE OUTPUT VARIATION OF THE NEW JERSEY ROUGHOMETER

1. Inter-Agency Roughometer Comparisons: To determine the extent to which the overall output of the New Jersey roughometer agrees with that of devices from other agencies, two series of equipment comparisons were made during the course of the work.

In the first such series, conducted in April 1968, the New Jersey roughometer was compared to the New York model on ten pavements located in the vicinity of Trenton. While a variety of pavement types and ages were selected for testing, the sites chosen were generally all of "Fair" to "Poor" riding quality. As shown in Table A-1, the New Jersey readings were higher than New York's on six of the first eight sites by from 2 to 16%. Prior to testing on site nine, it was noticed that a gear was loose in the New Jersey integrator unit. After this was corrected, the New Jersey readings were 5 and 8% lower than New York's on the following runs. Based on short- and long-term data subsequently obtained on test sites one thru three*, the New Jersey roughometer apparently maintained this tendency towards lower readings than the New York equipment.

In June 1970, the New Jersey, North Carolina, Maryland and BPR roughometers were compared on five pavements located near the FHWA's Virginia research facility. The selected test sites were each one mile long and displayed roughness ranging from "Very Good" to "Fair". As shown in Table A-2, the output of the North Carolina and New Jersey roughometers were very similar, as was that of the Maryland and BPR equipment. The readings obtained with the latter two devices were, however, an average of

*cf. Table A-3, page 206

Table A-1: 1968 Roughness Equipment Comparison
(New York and New Jersey Roughometers)

Test Site*	Route	Pavement Type	Roughness Index		Ratio N.J./N.Y.
			N.Y.	N.J.	
1	N.J. 129	Bit.	118,118,119 118	126,127,126 126	1.07
2	N.J. 129	Bit.	121,120,120 120	125,123,123 123	1.02
3	N.J. 29	PCC	140,141,139 140	138,137,137 137	.98
4	U.S. 130	CRC	109,109,110 110	111,112 112	1.02
5	U.S. 130	CRC	109,106,109 108	122,118,122 120	1.11
6	N.J. 32	Bit.	104,104,104 104	120,122,120 121	1.16
7	U.S. 1	PCC	117,118,116 117	126,126,126 126	1.08
8	U.S. 1	Bit.	142,139 140	126 126	.90
9	**I-287	Bit.	99,105 102	98,95 97	.95
10	**I-287	PCC	105,102 103	99,93,93 95	.92

*All sites one mile long except site 6 (.45 mi.)
**Run after gear correction on New Jersey roughometer

Table A-2: 1970 Roughness Equipment Comparisons
(North Carolina, Maryland, BPR, and New Jersey Roughometers)

Site	Pavement Type	Roughness Index in inches per mile			
		N.J.	N.C.	Md.	BPR
1 (Va. 123)	Bit.	60,61,61 61 66,66,66* 66	72,69,70 70 70,71,71* 71	66,66,65 66 65,65,66* 65	69,75,72 72 71,71,73* 72
2 (G.W. Pky.)	Bit.	92,94,96 94	93,92,92 92	104,104,105 104	103,104,102 103
2A (Access Rd.)	Bit.	80,79,82 80	82,78,79 80	88,90,87 88	93,85,88 88
3 (I-495)	PCC	96,96,94 95	94,95,94 94	105,105,110 107	111,111,111 111
5 (G.W. Pky.)	Bit.	89,93,93 92	94,92,92 93	105,108,105 106	106,105,105 105

*Repeat run made on Site 1 on June 3, all other data obtained June 2 about 10% greater than those obtained with the New Jersey and North Carolina equipment for the four higher roughness sites. The best-fit lines relating the data obtained in this testing are shown in Figure A1.

Based on the relationships observed to exist at the time of the described comparison runs, it is concluded that the general level of roughness readings obtained with the New Jersey roughometer were in reasonable accord with data from other BPR-type roughometers. When differences in roughometer output have been observed, they generally have been in the direction of an underestimate of actual roughness by the New Jersey device.

2. Roughness Variation on Control Sections: To gain some insight as to the output variation of the New Jersey roughometer, historical data was gathered on three relatively low traffic volume sites located on New Jersey Routes 129 and 29. The two Route 129 sites are "Rough" bituminous pavement and the Route 29 pavement is "Rough" concrete. While it obviously would be desirable to have comparable data for smooth pavements, appropriate control sites were not available within a reasonable distance of the research facility.

Table A-3 is a tabulation of the average reading obtained on the control sections on the dates indicated, with the data being collected at various times of the day and a variable number of duplicate readings being employed. While control section data was obtained subsequent to the last date shown in Table A-3, such data is not presented since it does not truly represent the inherent variation of the device (i.e., the device was recalibrated after numerous equipment repairs).

Tables A-4 thru A-6 present hourly readings for runs made from 8 a.m. to 5 p.m. on cool and warm days nine months apart.

FIGURE A1: PLOT OF COMPARATIVE ROUGHNESS DATA FROM FOUR AGENCIES

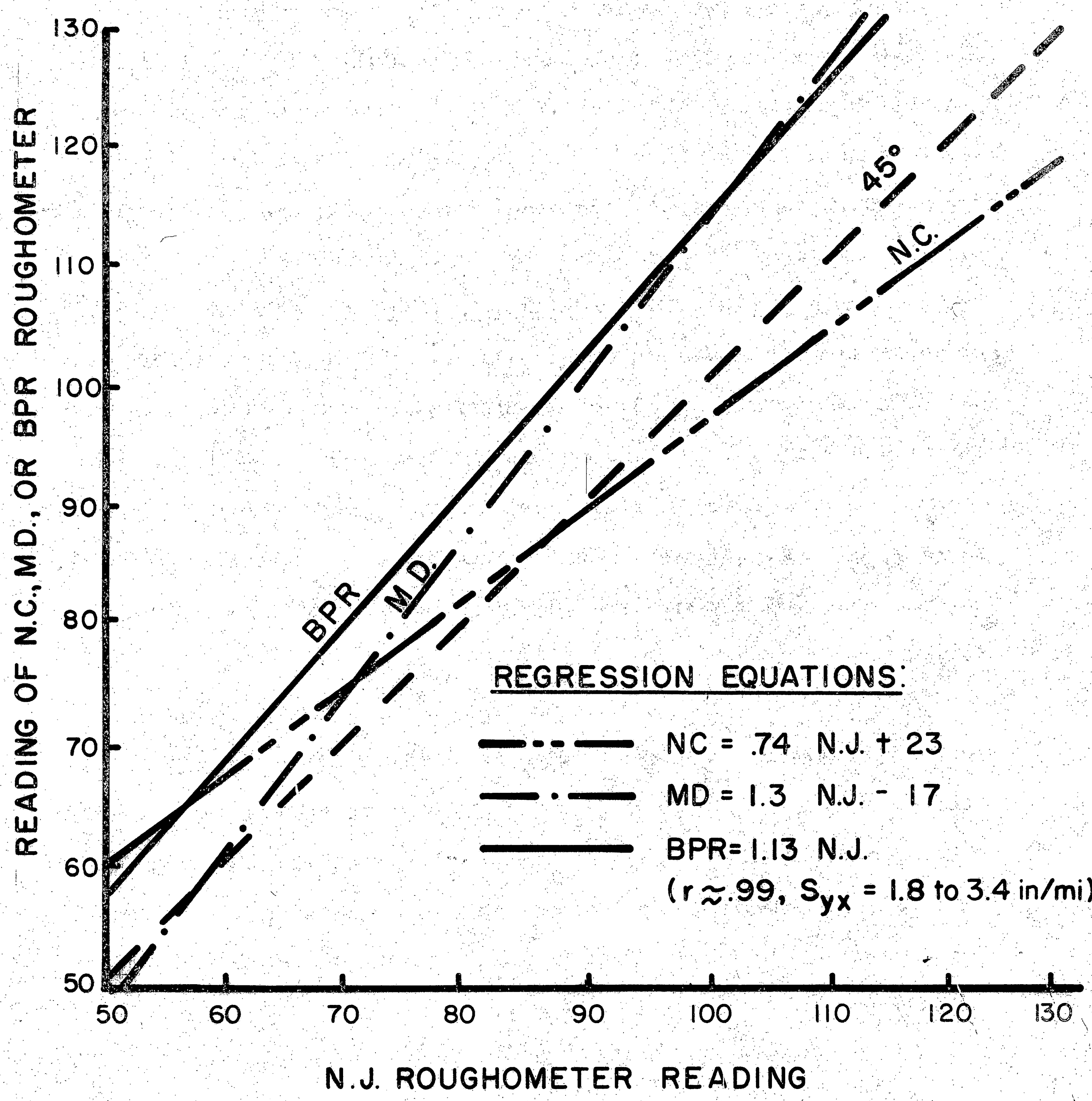

Table A-3
SUMMARY OF ROUGHNESS VARIATION ON CONTROL SECTIONS

Survey Date	Air Temperature	N.J. 129 (EB) (bituminous)	N.J. 129 (WB) (bituminous)	N.J. 29 (concrete)
1968				
Jan. 15	36°F	122 in/mi	116 in/mi	132 in/mi
Jan. 17	33	125	117	130
Jan. 29	34	116	114	---
Apr. 17	--	(118)[a]	(120)	(140)
Apr. 19	59	110	---	117
July 17	83	114	107	123
Aug. 23	74	114	109	125
Sept. 10	71	123	116	131
Sept. 18	68	118	113	129
Oct. 9	65	119	118	126
Nov. 4	31	117	114	127
Dec. 19	29	119	112	131
Yearly average =		118	114	127
Yearly range =		110 - 125	107 - 118	117 - 132
Percent variation of daily mean[c] =		±7.4%	±6.1%	±7.2%
1969				
Jan. 28	23	122	120	126
Feb. 11	36	117	113	132
Feb. 17	37	122	119	133
Mar. 12	37	115	111	120
Mar. 28	29	118	112	---
Apr. 4	40	122	113	116
May 12	69	120	115	119
June 2	82	125	121	128
July 11[b]	70-86	124	118	134
Aug. 4	76	120	110	132
(Roughometer inoperative last part of 1969)				
Yearly average		120	115	127
Yearly range =		115 - 125	110 - 121	116 - 134
% variation of daily mean[c] =		±5.2%	±7.0%	±10.7%
1970				
Jan. 30	39	121	110	138
Feb. 17	31	125	120	136
Mar. 4	35	123	117	139
Mar. 19[b]	41-51	118	117	136
April 21	47	120	116	135
July 14	73	119	119	138
Sept. 10	61	118	115	138
Yearly average =		121	116	137
Yearly range =		118 - 125	110 - 120	135 - 139
% variation of daily mean[c] =		±4.3%	±5.6%	±2.2%

[a] Reading obtained with New York Roughometer

[b] Data obtained 8 a.m. - 5 p.m.

[c] 95% confidence level ($2\sigma/\bar{X}$)

Table A-4: HOURLY CONCRETE PAVEMENT ROUGHNESS DATA (JULY 11, 1969 AND MARCH 19, 1970)

TIME	AIR TEMPERATURE		ROUGHNESS INDEX ON ROUTE N.J. 29					
			RUN 1	RUN 2	RUN 1	RUN 2	HOURLY AVERAGE	
	7/69	3/70	7/69		3/70		7/69	3/70
			in/mi	in/mi	in/mi	in/mi		
8:00 a.m.	70°F	--	130.2	129.4	---	---	130	---
9:00 a.m.	74	41°F	135.1	136.9	129.7	130.9	136	130
10:00 a.m.	74	43	127.6	129.2	138.7	138.2	128	138
11:00 a.m.	79	43	134.3	135.1	143.7	141.6	135	142
12:00 noon	80	47	139.0	135.4	140.6	139.8	137	140
1:00 p.m.	82	51	134.8	135.3	137.2	139.0	135	138
2:00 p.m.	82	51	138.5	138.7	140.6	137.1	139	139
3:00 p.m.	84	49	139.2	139.3	128.1	129.0	139	129
4:00 p.m.	85	48	131.6	132.7	136.9	135.4	132	136
5:00 p.m.	86	48	131.2	132.9	135.9	136.7	132	136
Mean, $\overline{X}$							134 in/mi	136 in/mi
Range							11 in/mi	13 in/mi
Standard deviation of successive readings, σ_R							1.10 in/mi	1.20 in/mi
Coefficient of Variation, $V_R = \sigma_R/\overline{X}$							0.82%	0.88%
Standard deviation of daily readings, σ_d							3.65 in/mi	4.53 in/mi
Coefficient of Variation, $V_D = \sigma_d/\overline{X}$							2.72%	3.33%

Table A-5: HOURLY BITUMINOUS PAVEMENT ROUGHNESS DATA (JULY 11, 1969 and MARCH 19, 1970)

TIME	AIR TEMPERATURE		ROUGHNESS INDEX ON ROUTE N.J. 129 (EB)					
			RUN 1	RUN 2	RUN 1	RUN 2	HOURLY AVERAGE	
	7/69	3/70	7/69		3/70		7/69	3/70
			in/mi	in/mi	in/mi	in/mi		
8:15 a.m.	75°F	--	123.1	125.2	---	---	124	---
9:15 a.m.	76	41°F	122.5	123.9	112.0	115.1	123	114
10:15 a.m.	76	43	120.5	120.9	118.6	119.9	121	119
11:15 a.m.	78	45	127.5	127.9	122.1	119.9	128	121
12:15 p.m.	80	47	123.7	127.6	121.5	118.5	125	120
1:15 p.m.	80	51	129.2	126.9	123.4	118.1	128	121
2:15 p.m.	82	51	126.3	127.6	120.5	119.3	127	120
3:15 p.m.	84	49	120.6	120.5	113.0	111.4	121	112
4:15 p.m.	86	48	119.3	120.2	117.9	119.7	120	118
5:15 p.m.	86	48	121.2	123.4	118.6	116.8	122	117
Mean, $\overline{X}$							124 in/mi	118 in/mi
Range							8 in/mi	9 in/mi
Standard deviation of successive readings, σ_R							1.31 in/mi	1.88 in/mi
Coefficient of Variation, $V_R = \sigma_R/\overline{X}$							1.06%	1.59%
Standard deviation of daily readings, σ_d							3.48 in/mi	3.17 in/mi
Coefficient of Variation, $V_D = \sigma_d/\overline{X}$							2.80%	2.68%

Table A-6: HOURLY BITUMINOUS PAVEMENT ROUGHNESS DATA (JULY 11, 1969 AND MARCH 19, 1970)

TIME	AIR TEMPERATURE		ROUGHNESS INDEX ON ROUTE N.J. 129 (WB)					
			RUN 1	RUN 2	RUN 1	RUN 2	HOURLY AVERAGE	
	7/69	3/70	7/69		3/70		7/69	3/70
			in/mi	in/mi	in/mi	in/mi		
8:20 a.m.	75°F	--	112.0	114.3	---	---	113	---
9:20 a.m.	76	41°F	116.6	118.9	117.2	117.1	118	117
10:20 a.m.	76	43	120.1	120.9	118.2	119.1	120	119
11:20 a.m.	78	45	122.2	122.3	120.7	119.0	122	120
12:20 p.m.	80	47	121.6	121.6	119.8	116.7	122	119
1:20 p.m.	80	51	118.6	116.6	118.5	114.3	118	116
2:20 p.m.	82	51	119.7	119.8	117.2	116.0	120	117
3:20 p.m.	85	49	---	116.6	115.3	116.0	117	116
4:20 p.m.	86	49	109.9	110.6	114.3	111.8	110	113
5:20 p.m.	86	49	111.3	112.7	116.2	117.8	112	117
Mean, $\overline{X}$							118 in/mi	117 in/mi
Range							12 in/mi	7 in/mi
Standard deviation of successive readings, σ_R							0.99 in/mi	1.52 in/mi
Coefficient of Variation, $V_R = \sigma_R/\overline{X}$							0.84%	1.30%
Standard deviation of daily readings, σ_d							4.14 in/mi	1.94 in/mi
Coefficient of Variation, $V_D = \sigma_d/\overline{X}$							3.51%	1.66%

Comments concerning the observed roughness variation are as follows:

Variation of Repeat Measurements Made Within a Given Hour: The FHWA reports[5] that in general, a dispersion of about 2% from the mean may be expected for duplicate roughometer readings. If this tolerance is interpreted as meaning that the standard deviation of successive readings should be a maximum of 1%, then the maximum difference between readings should be 2.83% at the 95% confidence level[6].

The standard deviation* of .82% and .88% obtained for the concrete pavement on the two dates indicates that the great majority of duplicate readings repeated within 2.5% (3.4 inches/mile), less than the FHWA suggested tolerance**. The maximum short-term differences observed on the bituminous pavement are also considered generally satisfactory (3 - 5 inches/mile or 2.4 - 4.5%).

Variation of Hourly Readings: Table A-4 indicates that on a "Rough" concrete pavement, roughness differences of up to 13 units (8-10%) might be expected for runs conducted over a nine hour span. On the bituminous control sites, this difference between the highest and lowest daily reading -- while generally slightly less -- was also observed to be as much as 10%. Based on

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[5]"Tentative Manual of Information Regarding the Operation and Maintenance of the BPR Relative Road Roughness Indicator", FHWA, p. 15 (May 1968).

[6]"Use of Terms Precision and Accuracy", ASTM E177

*The variation of duplicate readings is here calculated as

$$\sigma_R^2 = 1/2N \sum_{1}^{n} (X_1 - X_2)^2$$

Where: σ_R = standard deviation of successive readings
N = number of duplicate readings
X_1, X_2 = successive readings

**The operators manual furnished by the roughometer vendor suggests a similar tolerance: $\pm$ 5 for RI = 150 $\pm$ and $\pm$ 2 for RI = 60 $\pm$

the variability observed in this sampling, the mean of a particular set of duplicate readings made with the New Jersey roughometer might be expected to be within about $\pm$ 6% (2 σ_d) of the mean value that would result if readings were taken at each hour of that testing day.

On a concrete pavement, all of the within-day variation in roughometer readings may not be assignable to instrument error: joint warping may change the nature of the surface being measured[7].

The fact that roughometer output varies within a given day is not a unique characteristic of the New Jersey roughometer. Data from other studies[8,9] indicate that the hourly differences observed for the New Jersey sites might reasonable be expected of BPR-type roughometers in general.

Long-term Variation and Overall Confidence Limits for New Jersey Roughometer Data: Table A-3 indicates that the roughness of the bituminous control sections remained essentially unchanged over a three year span, while the concrete pavement appears to have increased in roughness between 1969 and 1970. If this is the case, then -- with the possible exception of the 1969 concrete data -- the yearly mean roughness might be considered as a reliable estimate of the "true" roughness of the sites.

Based on this short- and long-term variation observed on the control sections, it is the writer's opinion that New Jersey roughometer data obtained at a particular time might generally be expected to vary from a representative central value resulting from numerous runs on the pavement

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[7]Ohlborn, G. and Moyer, R. A. "New Developments in the BPR Roughness Indicator and Tests on California Pavements", HRB Bulletin 139, pp. 21-22 (1956)

[8]Law, S. M. "Rolling Straightedge Correlation Study", Louisiana Department of Highways (1967)

[9]Crawford, R. A. et al. "South Dakota Roughometer Comparison Tests - 1962", HRR #28 (1963)

under study by a maximum of about ± 6% and ± 8%, respectively, for bituminous and concrete pavements. Since the line of travel of the roughometer tire is less important for smooth pavements, thus enhancing repeatability, these tolerances might to some extent be overly conservative for the smooth pavement class.

<u>Effect of Temperature</u>: No definable relationship between roughometer output and air temperature is apparent for the range of temperatures encountered in the control site testing (23 - 86°F.).

APPENDIX B:

DISCUSSION OF THE REPEATABILITY OF THE NEW JERSEY ROLLING STRAIGHTEDGE

1. Short-term data: Table B-1 presents a summary of repeat straightedge measurements obtained within a particular day or spaced one day apart. Based on the observed number of straightedge deviations, the pavements selected for test are representative of riding quality ratings ranging from good to poor.

Since this short-term data does include sections having low, intermediate, and high values for the various straightedge parameters, it is believed that the measures of variability observed for this sample might reasonably be used to formulate a generalized precision statement for short-term straightedge data. To provide summary statistics that would yield such a rule-of-thumb, the weighted* mean of the straightedge parameters -- number,

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*

$$\overline{X} = \frac{\sum (n-1)X}{\sum (n-1)}; \quad \overline{\sigma} = \sqrt{\frac{\sum (n-1)\sigma^2}{\sum (n-1)}}; \quad \overline{V} = \frac{\overline{\sigma}}{\overline{X}} \cdot 100$$

where: $\overline{X}$ = weighted mean number (N), Length (L), or Area (A)
X = N, L, or A from individual test sections
$\overline{\sigma}$ = weighted standard deviation
σ = standard deviation from individual test sections
n = number of individual test measurements
$\overline{V}$ = weighted coefficient of variation, %

length, and area -- and the associated measures of variability are given at the bottom of Table B-1*.

The indicated weighted means of this group of data, if present in an individual quarter mile section, would be indicative of a "Poor" riding quality bituminous pavement or a "Fair" concrete pavement.

The weighted standard deviations suggest that measurements resulting from a single, quarter mile pass with the rolling straightedge will generally vary from the mean value of numerous repeat runs on the subject section during the same day within a maximum of about ± 2-3 defects ± 0.5 percent defective (equivalent to ± 6-7 feet of measured length), and ± 9 inches of defective area (equivalent to ± 6 feet of 1/8" deviation). The weighted coefficients of variation indicate that, on a relative basis, the repeatability of each of the three straightedge parameters is essentially the same (± 6-10% of the mean).

While the above precision statement is useful in gauging the short-term variability of the device in general, it is of obvious interest to have some information as to the precision of the device at specific roughness levels such as those where marginal riding quality and associated penalties might be expected.

To provide information in this regard, in the upper portion of Tables B-3 thru B-5, the standard deviations of the short-term data sample are summarized by the ranges of straightedge data corresponding to "Good", "Fair", and "Poor" FHWA riding quality ratings. The indicated relationship between straightedge deviations and riding quality rating is based on the roughometer-straightedge correlation described in the body of this report.

*In these calculations data for eight smooth riding sections showing high measurement precision are eliminated so as to provide a <u>conservative</u> estimate of variability. If these smoother sections were included for example the standard deviation for defective length would be reduced by about 25%. A similar deletion is made for 3 sections in the long-term data (Table B-2).

Table B-1

Summary of Rolling Straightedge Repeatability Tests

(short-term variation)

Project	Pavement Type	Number of Repeats	Test Section	STRAIGHTEDGE PARAMETERS* NUMBER $\bar{N}$	σ_N	V_N	DEFECTIVE LENGTH,% $\bar{L}$	σ_L	V_L	DEFECTIVE AREA,in^2 $\bar{A}$	σ_A	V_A
N.J. 29	PCC	3	1	40.7	.58	1.42	10.8	.31	2.87	371	6.93	1.86
		3	2	48	0	0	12.2	0	0	415.5	0	0
N.J. 129	Bit. Top	3	3	47.7	3.21	6.74	11.6	.57	4.91	268	11.3	4.21
		3	4	55.3	1.15	2.08	14.5	.24	1.65	428	3.06	.72
		3	5	48	0	0	8.94	0	0	207	0	0
I-287 SECTION 7D-9G	Bit. Base	2	6	12.5	2.12	16.9	2.42	.318	13.1	60.7	5.3	8.73
		2	7	6.5	2.12	32.7	.95	.269	28.3	18.8	5.3	28.2
		2	8	26	1.41	5.42	6.18	.05	.80	180	2.12	1.17
		2	9	6.5	.706	10.9	1.14	.318	27.9	22.5	6.36	28.3
	Bituminous Top Course	4	10	10.2	.96	9.41	1.73	.186	10.75	36.0	2.12	5.88
		3	11	5.7	.41	71.9	.86	.191	22.2	16.7	3.25	19.5
		3	12	2.7	.57	21.1	.56	.087	15.5	11	1.73	15.7
		3	13	1.3	.57	43.8	.43	.044	10.23	8.5	0.9	10.6
		3	14	1	0	0	.278	.088	31.6	5.5	1.73	31.5
		3	15	2.3	1.15	50.0	.28	.118	42.1	5.5	3.46	62.9
		3	16	3	0	0	.30	0	0	6.0	0	0
		3	17	1	0	0	.08	0	0	1.5	0	0
		3	18	1	0	0	.08	0	0	1.5	0	0
		3	19	2	0	0	.15	0	0	3.0	0	0
		3	20	0	0	0	0	0	0	0	0	0
		3	21	0	0	0	0	0	0	0	0	0
WEIGHTED MEAN (Test Sections 1-13)				25.25	1.293	5.12	5.90	0.249	4.22	167.0	4.72	2.83

* $\bar{N}$, $\bar{L}$, $\bar{A}$ = Mean Test Value σ = Standard Deviation V = Coefficient Of Variation (%)

TABLE B-2

Summary of Rolling Straightedge Repeatability Tests

(Long-Term Variation)

Project	Pavement Type	Number of Measurements	Test Interval in Days	Test Section	STRAIGHTEDGE PARAMETER								
					Number of Defects			Defective Length, %			Defective Area, in^2		
					$\bar{N}$	σ_N	V_N	$\bar{L}$	σ_L	V_L	$\bar{A}$	σ_A	V_A
I-287, 7D	Bit.Base	2	6	1	17	2.83	16.6	2.56	.43	16.7	54.8	9.55	17.4
		2	6	2	14.5	3.53	24.3	2.24	.262	11.7	60.8	4.24	7.1
		2	14	3	18	1.41	7.83	2.61	.268	10.26	66.0	4.24	6.4
I-280 Section 1B-5P	Concrete	2	57	4	40	0	0	9.13	.375	3.93	251.2	56.2	22.36
		2	57	5	42	8.48	20.2	7.46	1.01	13.53	201	44.6	22.18
		2	57	6	38	1.41	3.71	8.60	.0566	.65	258	36.1	13.99
		2	57	7	44	4.24	9.63	9.78	1.067	10.91	306	74.3	29.02
		2	53	8	43	7.08	16.46	10.35	0.502	5.00	393	25.45	6.47
		2	53	9	50	5.65	11.30	10.91	1.91	17.50	378	67.9	17.96
I-280 Sec. 6L		2	81	10	34.5	2.12	6.14	7.35	0.75	10.20	197.3	73.1	36.96
		2	81	11	57	2.83	4.96	11.17	1.017	9.10	283.5	61.5	21.69
		2	81	12	48	0	0	10.72	1.017	9.48	286.5	87.0	30.36
NJ 29		6	32	13	44.3	4.03	9.08	11.5	0.789	6.86	393	24.7	6.28
NJ 129	Bituminous	6	32	14	51.5	4.72	9.16	13.05	1.66	12.72	348	87.7	25.20
I-195 Sec. 3B, 4A		2	315	15	5	0	0	1.44	0.007	.48	24.4	6.36	13.25
		2	315	16	1.5	.71	47.33	0.26	.155	59.61	7.5	6.36	84.80
		2	315	17	0.5	.71	1.42	0.75	.106	1.41	1.5	2.12	141
		2	315	18	1	1.41	1.41	0.22	.318	1.41	4.5	6.36	141
WEIGHTED MEAN (Test Sections 1-15)					40.7	4.18	10.25	10.0	1.06	10.6	285.4	56.9	19.9

TABLE B-3

Rolling Straightedge Data Standard Deviations

Summarized by Expected Level of Riding Quality

(Parameter: Number of Defects)

		Number of Defects per 1/4 mile				
		0-5	5-10	10-20	20-40	40+
Expected Riding Quality Rating	Concrete	← Good		→	← Fair →	← Poor →
	Bituminous	← Good →	← Fair →	← Poor		→
Short-Term Data	Number of Test Sections in Category	10	3	2	1	5
Short-Term Data	Average Number of Defects in Category	1.3	6.1	10.8	26	47.9
Short-Term Data	Weighted Standard Deviation	.44	.58	1.35	1.41	1.63
Long-Term Data	Number of Test Sections in Category	3	1	3	3	8
Long-Term Data	Average Number of Defects in Category	1	5	16.5	37.5	47.7
Long-Term Data	Weighted Standard Deviation	.99	0	2.74	1.47	3.05

TABLE B-4

Rolling Straightedge Data Standard Deviations

Summarized by Expected Level of Riding Quality

(Parameter: Percent Defective Length)

	Expected Riding Quality Rating	Concrete Bituminous	Percent Defective Length (Range) 0-.5	.5-1.0	1.0-2.0	2.0-4.0	4.0-9.0	9.0+
		Concrete	GOOD	GOOD	GOOD	GOOD	FAIR	POOR
		Bituminous	GOOD	GOOD	FAIR	POOR	POOR	POOR
Short-Term Data	Number of Test Sections in Category		9	3	2	1	2	4
Short-Term Data	Average % Defective in Category		.18	.738	1.58	2.42	8.02	12.27
Short-Term Data	Weighted Standard Deviations		.051	.147	.226	.318	.04	.346
Long-Term Data	Number of Test Sections in Category		3	0	0	3	3	9
Long-Term Data	Average % Defective in Category		.187	-	-	2.47	7.8	11.46
Long-Term Data	Weighted Standard Deviations		.213	-	-	.33	.727	1.20

TABLE B-5

Rolling Straightedge Data Standard Deviations

Summarized by Expected Level of Riding Quality

(Parameter: Area of Defects)

		Area of Defects per 1/4 mile(in^2)			
		0-25	25-75	75-250	250+
	Expected Riding Quality Rating — Concrete	GOOD		FAIR	POOR
	Expected Riding Quality Rating — Bituminous	GOOD	FAIR	POOR	
Short-Term Data	Number of Test Sections in Category	13	2	2	4
	Average Defective Area in Category	6.65	42.2	198	370
	Weighted Standard Deviation	2.30	3.22	1.22	6.80
Long-Term Data	Number of Test Sections in Category	4	3	3	8
	Average Defective Area in Category	9.5	60.3	216.5	350.6
	Weighted Standard Deviation	5.6	6.5	59.13	63.7

As indicated in these calculations, the absolute variation of straightedge data (i.e., the weighted standard deviations) can be expected to increase with an increase in the measured number, length, or area of deviations. However, while the standard deviation does change and illustrate a trend, the difference in variation between straightedge measurements on "Good" or "Poor" riding quality sections is generally quite small. For example, while a short-term measurement tolerance of one defect is associated with sections having a 5 or fewer defects, the expected variability for a mean of 50 defects is only $\pm$ 3 defects. Similarly, the difference in straightedge data variation on "Good" and "Poor" riding quality pavements for the Percent Defective parameter amounts to only about 5 feet of measured length per quarter mile (.75 $\pm$ 0.3 versus 12 $\pm$ 0.7 Percent Defective). In view of these small differences in precision, it is believed that the previous rule-of-thumb precision statement can in fact be considered generally applicable.

Experience has shown that for a given number, length, or area of deviations, a bituminous pavement generally would receive a lower riding quality rating than a concrete pavement. Thus, one implication of the above discussion of variability is that if a particular riding quality level is selected as the onset of a penalty criteria, the precision with which the straightedge is capable of differentiating between penalty/no penalty bituminous pavement will be slightly better than that indicated in the previous generalized precision statement.

2. Long-term Data:

A. Observed Variation: Table B-2 presents a summary of repeat straightedge measurements obtained in which the time difference between duplicate measurements varied from one week to 10 months.

Unlike the short-term data sample, the pavements selected for long-term repeatability tests are predominantly "Rough" riding pavements. The weighted mean of each of the straightedge parameters for the data set of Table B-2 are 2/3 greater than those of Table B-1.

While the mean relative variation or precision observed for the short-term data was approximately the same for each of the three straightedge parameters, in the case of the long-term data, this is true only of the number and defective length statistics. A mean coefficient of variation of 10% was recorded for both these parameters. The defective area parameter, in contrast, had a coefficient of 20%. For all three parameters the relative precision for long-term measurements was significantly larger than that for short-term data - twice as large for number and defective length and seven times as large for defective area. A comparison of long and short term precisions by roughness levels (Tables B-3 to B-5) further reveals the greatest loss of precision to occur with rough pavements. Specifically, in examining the percent defective length tabulation, it appears that while the precision representative of intermediate roughness remain the same (i.e. $\pm$ 0.3 percent defective), the effect of a long interval between measurements was to increase the variability associated with the "Poor" roughness category four fold (1.3% vs. 0.3%). A similar pattern of reduced precision occurs with the defective area parameter. The indicated long-term repeatability for deviation area of pavements in the roughest riding category amounts to the equivalent of 40 feet of 1/4 inch deviation per quarter mile. Roughness level seems to have little effect on the on the long-term precision associated with the number of defects parameter.

B. Sources of Variability: While a number of factors may enter into the reduction of precision for long-term data in particular cases (e.g., actual changes in the surface being measured, operator differences), it is believed that generally the most significant variation can be attributed to two sources: differences in the line of travel between measurements and errors in the calibration of the straightedge.

Line of travel variation: It is in the nature of the New Jersey rolling straightedge that, in the practice of testing, a departure of one foot or more from the intended line of travel might commonly be expected at intervals throughout the length of being tested. This problem of following a desired line is aggravated when testing projects under construction, due to the absence of painted lane markings.

Sample straightedge "contours" made on a number of projects have indicated that on rough pavements such as those considered in the present long-term data set, measurements as close as six inches transversely can exhibit significant differences in deviation magnitude or length.

Examination of the data for test sections 3 and 5 of Table B-1 gives a specific indication of the relative magnitude of roughness variation within a given length of a particular lane. These two sections -- profile lines 1-1/2 feet apart in the same lane -- exhibit the same number of defects, but a 30% difference in defective length and deviation area.

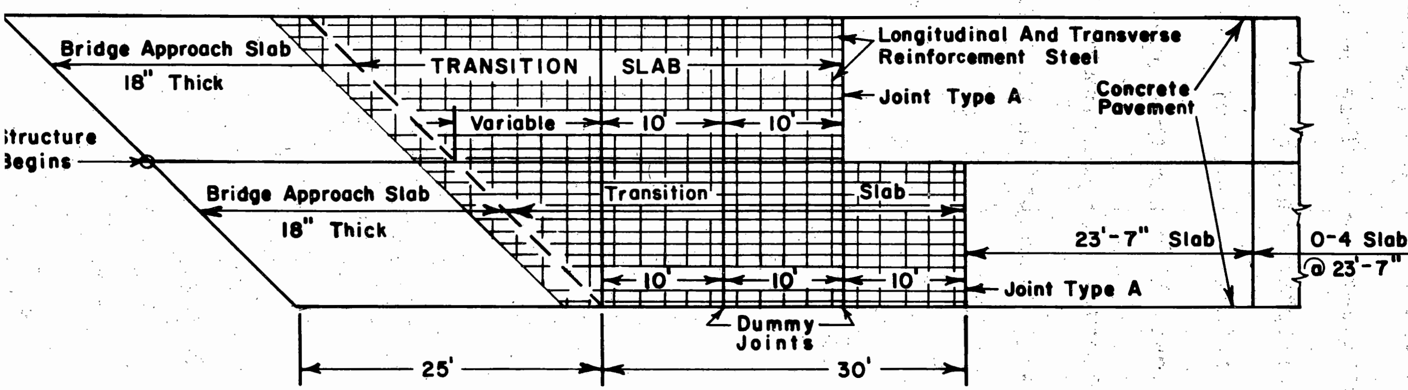
It would thus appear reasonable to assume that normal "weaving" about a test profile line or the inadvertant choice of an offset from the intended profile line could account for a significant portion of the variability in this or any similarly obtained set of long-term straightedge measurements. Any such effect obviously would be a reflection of process variability rather than straightedge error.

Calibration Variation: If, as in the present case, the calculated deviation area for long-term straightedge data shows a disproportionate precision loss compared to the deviation number and length parameters, it is apparent that differences in the deviation magnitude must have existed between repeat measurements.

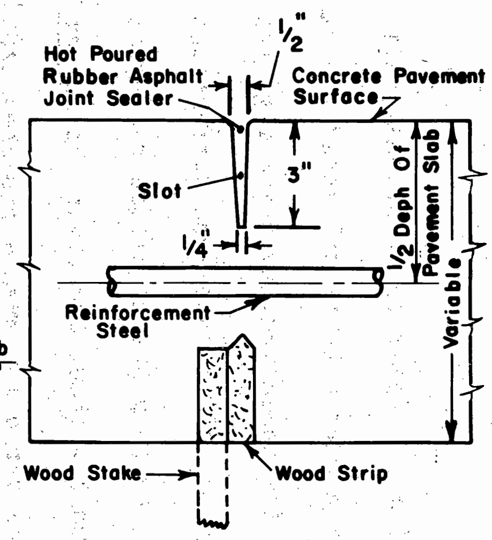
This is in fact true of the data of Table B-2, with the readings for both I-280 projects (constituting the majority of the data) showing a general decrease rather than random variation in the indicated deviation magnitude. Approximately one-fourth of the indicated number of deviations were reduced from 1/4" to 1/8" between the first (early fall) and second (late fall) measurements on these projects.

The consistent pattern of variability observed on these two projects indicates that a substantial portion of the observed difference in readings is due to differences in calibration of the straightedge. The greater influence of calibration on the calculated defective are in comparison to the number and length parameters arises from the sensitivity of the device and the method of calculation. That is, since the smallest increment on the straightedge dial is 1/8",a difference in calibration sufficient to cause a relatively small number of missed or foreshortened defects may cause a 100% error in deviation area (recall that deviation area is based on the maximum magnitude encountered in a particular span).

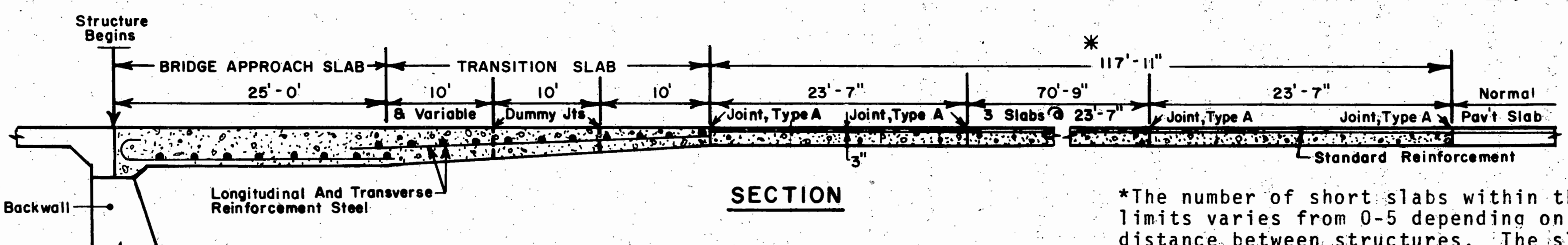
Since this testing indicates that at least an occasional calibration difference can be expected when straightedge data is collected over an extended period of time, a tolerance for indicated deviation magnitude is obviously in order. In New Jersey practice, when such differences have occurred, the maximum difference between the magnitude of repeat readings of individual defects is almost without exception the lowest value recordable (1/8"). However, if actual variation even approached 1/8" throughout a section, it is apparent that a very considerable difference in the indicated number of deviations would exist between repeat readings (i.e. the consistent appearance or disappearance of 1/8" deviations). As previously mentioned, this situation is not indicated by the data. It would thus appear that an intermediate magnitude precision--on the order of a maximum of 1/16"--might more reasonably be associated with the data collected in this work.



PLAN VIEW



DETAIL OF DUMMY JOINT

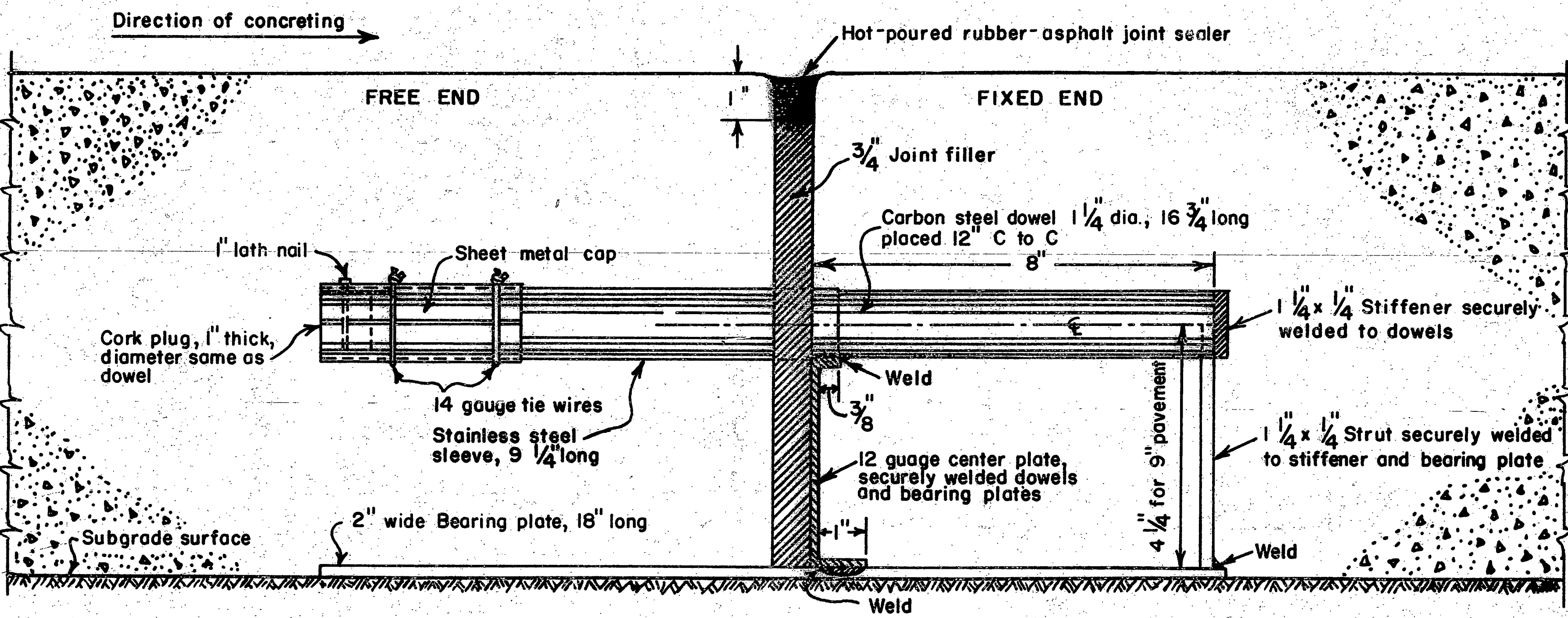


SECTION

*The number of short slabs within these limits varies from 0-5 depending on the distance between structures. The slabs are 23'-7" long with the same joint devices between slabs as installed elsewhere on the project, except that the joint filler is 1" thick, rather than 3/4".

DETAIL I

Bridge Approach, Transition And Short Slabs Between Normal Concrete Pavement And Structures (Simplified)

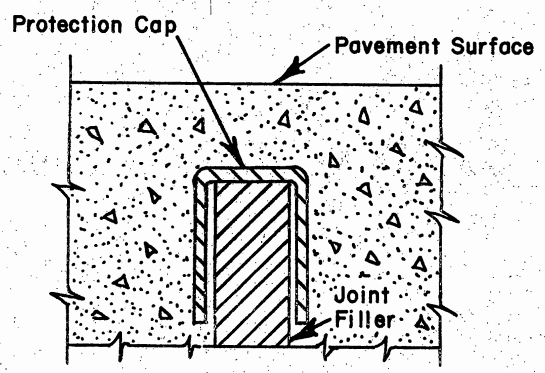


Note: The dowels shall be parallel with each other, parallel with the bearing plates, and perpendicular to the center plate.

DETAIL 2

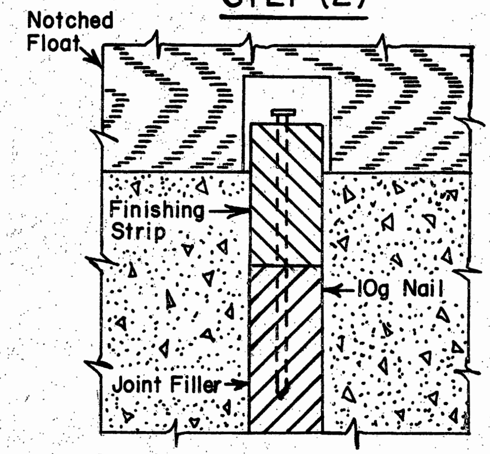
NEW JERSEY TYPE A EXPANSION JOINT
TYPICAL CROSS SECTION

STEP (1)



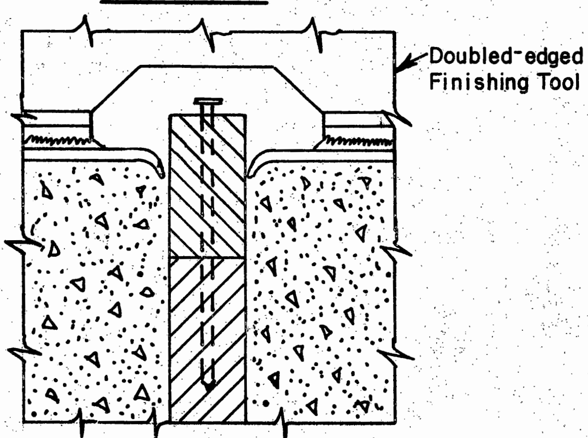
Top of joint filler is protected by a sheet metal protection cap during concrete placement and machine finishing operations. The protection cap is removed after final passage of the finishing machines.

STEP (2)



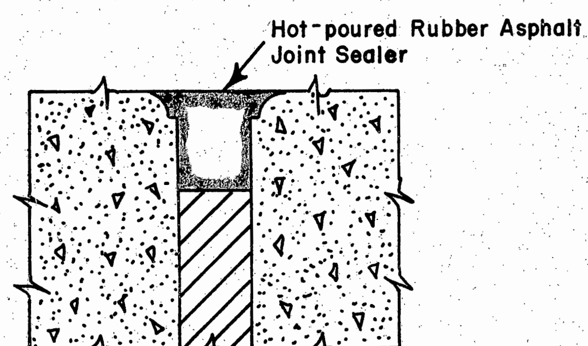
Upon removal of the protection cap, a finishing strip is placed. After replacement of disturbed concrete, the pavement surface is finished to the proper grade by means of a notched float

STEP (3)



When the concrete has set sufficiently, and after brooming, the concrete at the joint is lightly edged and finished with a double-edged tool.

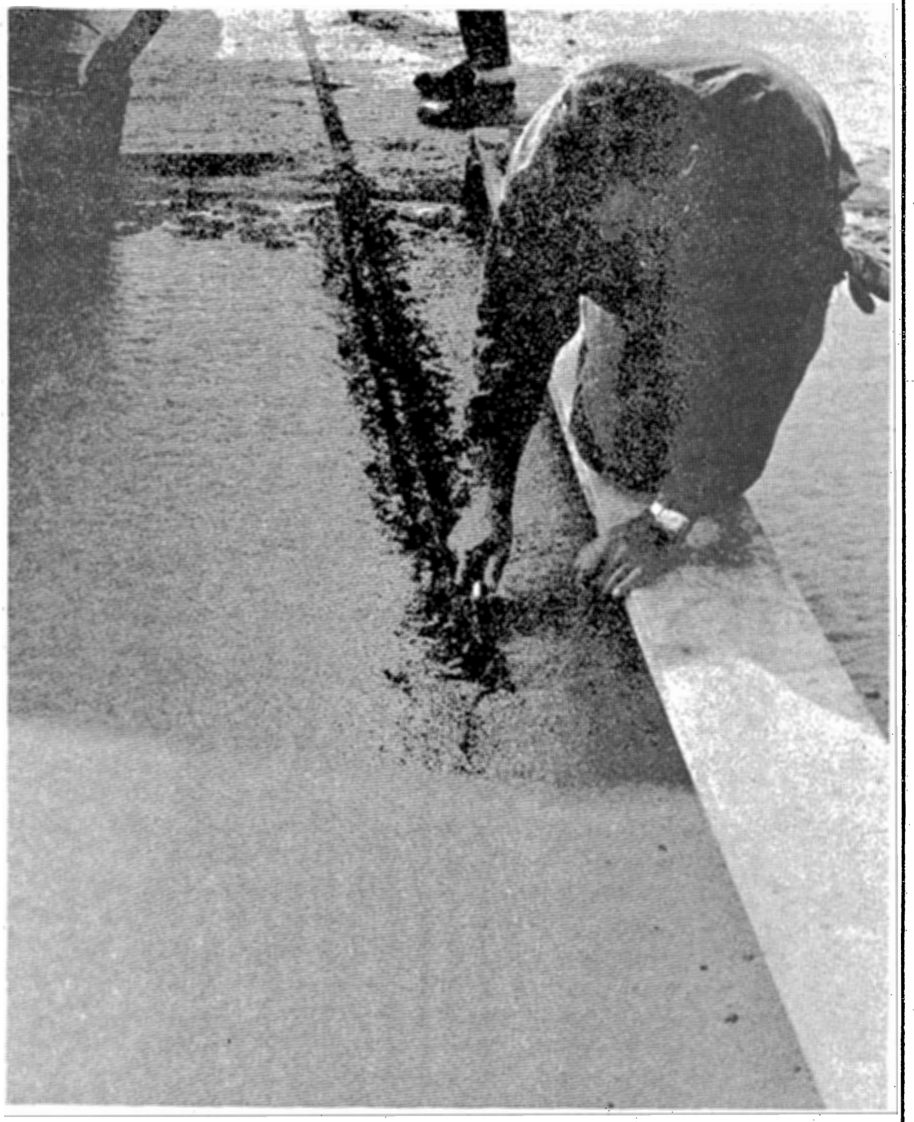
STEP (4)



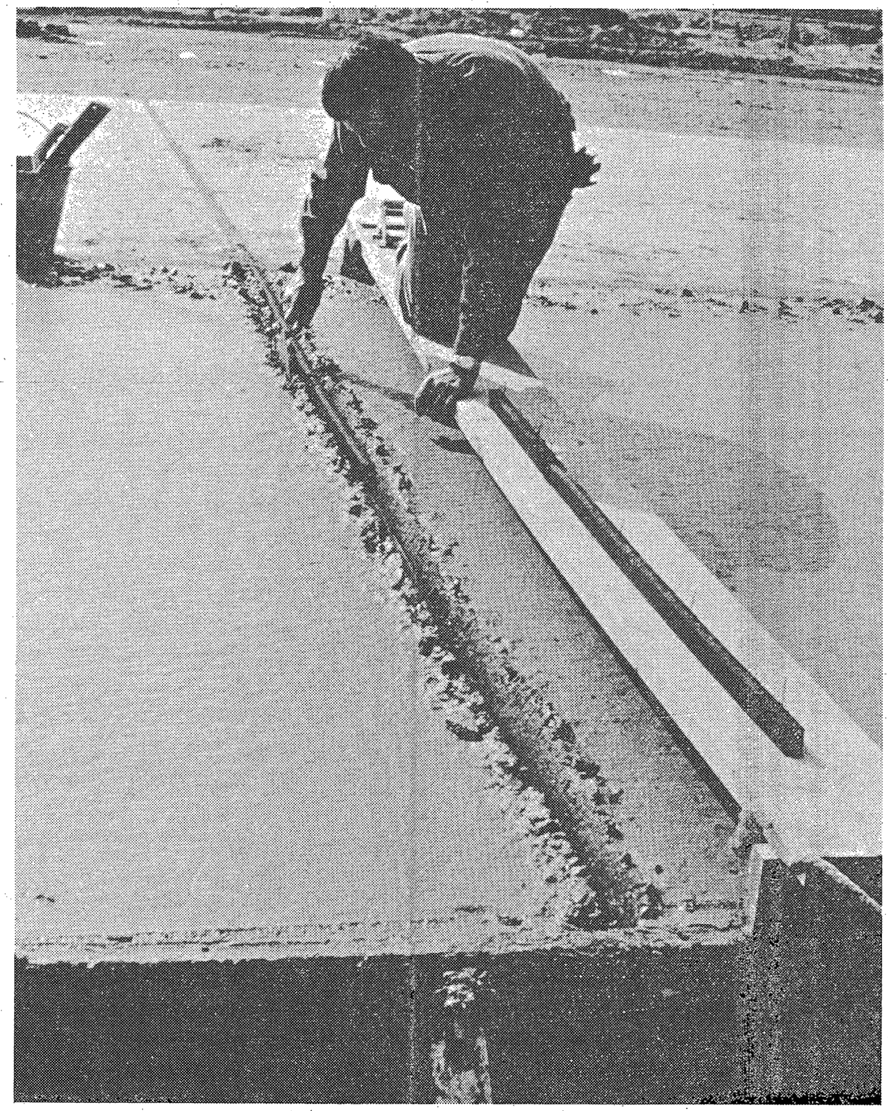
Completed joint

Procedure For The Edging And Finishing Of Transverse Joints

DETAIL 3



Displacing concrete to remove sheet metal protection cap.



Installing finishing strip over joint filler.

DETAIL 4

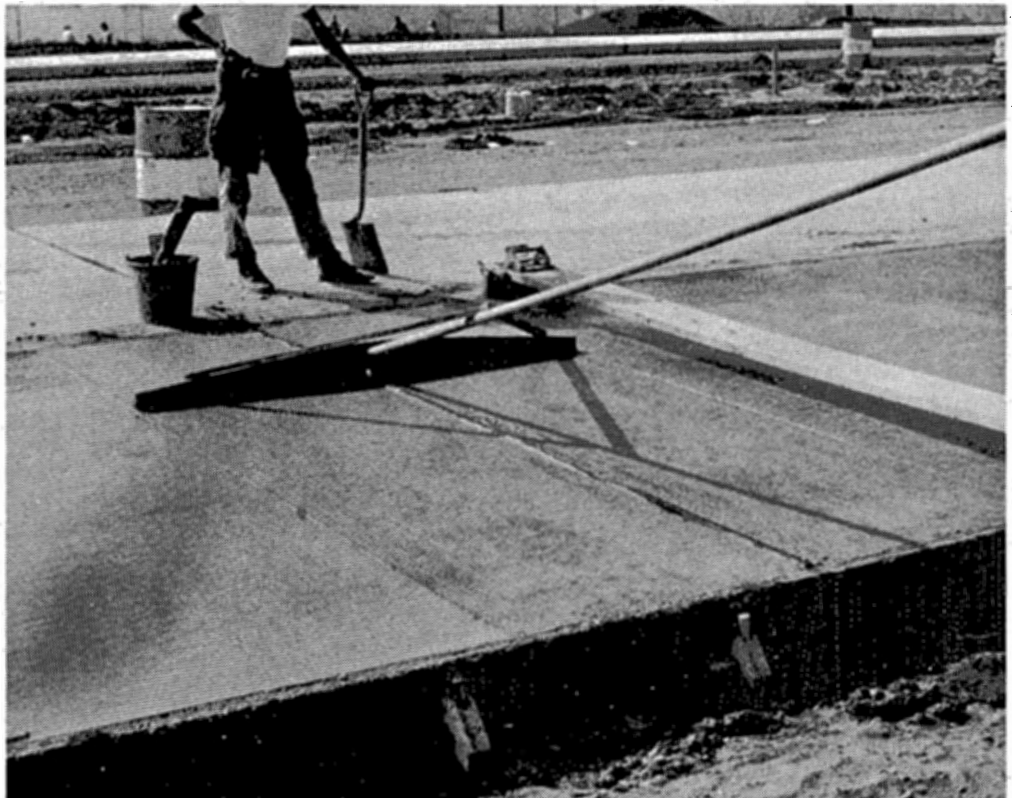
SEQUENCE OF EXPANSION JOINT FINISHING OPERATIONS

Replacement of disturbed concrete.

Initial surface at joint.

DETAIL 4A

SEQUENCE OF EXPANSION JOINT FINISHING OPERATIONS (Con't)



Restoring pavement surface to proper grade by means of a 6 ft. long notched float.

After brooming, joint finishing is completed by light application of double-edged tool.

DETAIL 4 B

SEQUENCE OF EXPANSION JOINT FINISHING OPERATIONS (Con't)

APPENDIX D

PROPOSED SMOOTHNESS SPECIFICATIONS
FOR
BITUMINOUS AND CONCRETE PAVEMENTS

1.0 Smoothness Testing of Hot-Mix Bituminous Concrete and Concrete Surface Pavements

1.1 Control Testing: The Contractor shall be responsible for checking his work during placement to enable him to make corrections while the material is in a workable condition.

1.2 Acceptance Testing: Acceptance testing will be performed on the wearing course of Hot-Mix Bituminous Concrete and on finished Concrete Surface Pavement. Such testing will be performed by the Engineer with an approved 10-foot rolling straightedge that automatically marks in colored dye the length of pavement surface variations exceeding 1/8 inch in 10 feet. The timing of smoothness acceptance tests shall be completely at the option of the Engineer. Generally, acceptance testing of a lot of Hot-Mix Bituminous Concrete will be performed the same working day the lot is placed. Smoothness acceptance testing of Concrete Surface Pavement will generally be performed the working day following placement of that lot.

Any required sweeping of the surfaces of bituminous and concrete pavement prior to acceptance testing and notching of expansion joint filler paper necessary to permit passage of the straightedge on Concrete Surface Pavement shall be performed by the Contractor as part of the work of pavement construction and shall be included in the unit price bid therefor.

Concrete Surface Pavement shall be accepted in lots equal to the number of square yards of Concrete Surface Pavement placed in each production day. Hot-Mix Bituminous Concrete shall be accepted in lots equal to the total number of tons represented by the sum of the number of tons of wearing course placed in each production day and the number of tons of all bituminous courses underlying the day's production of wearing course.

The acceptance of a lot will be based on the percentage of the total length of the lot having surface variation exceeding 1/8 inch in 10 feet, this percent non-compliance being defined as the Lot Percent Defective Length. Lot Percent Defective Length is computed by adding the lengths of individual surface defects exceeding the specified tolerance, dividing this sum by the length of pavement tested, and multiplying by 100 to convert to percent.

The full extent of the lot will be tested in the longitudinal direction. The transverse location of the test will generally be in the wheel-paths of vehicle travel, here defined as the two imaginary lines located approximately 3 feet on each side of the centerline of the lane and extending for the full length of the lane. The wheelpath of the test shall be determined randomly and varied every 300 to 400 feet.

The <u>minimum</u> number of full-length tests required to determine the Lot Percent Defective Length is given in Test Schedules 1 and 2. The 25% sample plan, wherein the number of tests is at least equal to

SCHEDULE 1: ACCEPTANCE TESTING SCHEDULE FOR HOT-MIX BITUMINOUS PAVEMENT

Sampling Plan	Corresponding Number Of Tests				Lot Percent Defective Length Measured	Payment Or Retest Requirement
	One Lane	Two Lanes	Three Lanes	Four Lanes		
25% Plan	-	1	2	2	0 to 1.0	Pay 100%
					1.1 to 3.4	Perform 50% Testing
					3.5 or more	Test Each Wheelpath
50% Plan	1	2	3	4	0 to 3.4	Pay as Per Schedule A
					3.5 or more	Test Each Wheelpath
100% Plan	2	4	6	8	All Values	Pay as Per Schedule A

SCHEDULE A: BID PRICE ADJUSTMENT SCHEDULE FOR HOT-MIX BITUMINOUS CONCRETE

Lot Percent Defective Length	Pay Factor
0 - 1.3	1.0
1.4 - 2.3	0.98
2.4 - 3.4	0.95

SCHEDULE 2: ACCEPTANCE TESTING SCHEDULE FOR CONCRETE SURFACE PAVEMENT

Sampling Plan	Corresponding Number of Tests				Lot Percent Defective Length Measured	Payment Or Retest Requirement
	One Lane	Two Lanes	Three Lanes	Four Lanes		
25% Plan	1	1	2	2	0 to 13.9	Pay as Per Schedule B
					14 or more	Test Each Wheelpath
100% Plan	2	4	6	8	All Values	Pay as Per Schedule B

SCHEDULE B: BID PRICE ADJUSTMENT SCHEDULE FOR CONCRETE SURFACE PAVEMENT

Lot Percent Defective Length	Pay Factor
0 - 5.0	1.0
5.1 - 11.0	0.98
11.1 - 13.9	0.90

one-fourth of the number of wheelpaths in a day's production, is to be used initially with both pavement types. Final compliance of Concrete Surface Pavement may be based on the results of the 25% sampling except that if the Lot Percent Defective Length exceeds the maximum value in Schedule B, each wheelpath shall be tested. Hot-Mix Bituminous Concrete Pavement will be accepted at a 1.0 pay factor based on the 25% sample plan. If a pay factor other than 1.0 is indicated by the tests of the 25% sample plan, additional tests shall be performed such that the total number of tests performed equals that shown for the 50% sample plan. If the Lot Percent Defective Length exceeds the maximum value in Schedule A, each wheelpath shall be tested.

When more than one test is specified in Schedules 1 or 2, the initial and intermediate transverse locations of each test is to be determined randomly. In no case will exact duplicate tests be performed. When testing of all wheelpaths is specified, no intermediate transverse variation of the individual tests will be made. The results of preceding tests shall not be included in the computation of Lot Percent Defective Length when application of the 100% sample plan is indicated.

The number of tests performed beyond the minimums specified in Schedules 1 and 2, if any, shall be completely at the option of the Engineer. Generally, the number of tests performed will be the maximum number feasible with available State manpower. In addition to the tests run on randomly selected sites, the Engineer reserves the right to test any area which appears defective, including a previous day's production which subsequently becomes damaged.

If the Lot Percent Defective Length for Hot-Mix Bituminous Concrete or Concrete Surface Pavement exceeds the amount shown for the 1.0 pay factor shown in Schedules A and B respectively, and if the Contractor elects not to remove and replace the pavement, the lot may be accepted upon written request of the Contractor at an adjusted unit price.

The adjusted unit price for a lot of Hot-Mix Bituminous Concrete shall be the product of the Contract unit bid price for the item and the appropriate pay factor of Schedule A. The adjusted unit price for Concrete Surface Pavement shall be the product of the Contract unit bid price for the item and the appropriate pay factor of Schedule B.

If the Lot Percent Defective Length for Hot-Mix Bituminous Concrete or Concrete Surface Pavement exceeds the maximum value shown in Schedules A and B respectively, the Engineer may order removal of any or all of the pavement in the lot or if the material is allowed to remain in place, computation of the adjusted unit price will be based upon a pay factor of 0.80.

APPENDIX E

RECENTLY ADOPTED SPECIFICATION

FOR

CONCRETE DECK SLAB

PLACEMENT AND FINISHING

Article 4.1.3 Concrete Structures

All reference to concrete deck slabs in the last paragraph on page 225 and in the 2nd and 3rd full paragraphs on page 226 of the standard specification are deleted and the following two subsections are substituted therefor:

Concrete Deck Slabs. At least 30 calendar days prior to the proposed start of placing bridge deck concrete, the contractor shall submit a written plan of operation for review by the engineer. This plan shall include a screed and rail erection plan, deck grades, the sequence and proposed rate of placing concrete, the number and type of personnel who will be engaged in the work, and a complete description of the equipment to be used in handling, placing, and finishing the concrete. Approval of this plan will not relieve the contractor of the responsibility for the satisfactory performance of his methods and equipment.

Computations for setting forms and screed supports shall be based on an accurate set of elevations run by the contractor at points no further than 10 feet apart on each beam.

The placing of concrete will not be permitted until the engineer is satisfied that the proposed placement and finishing operation will be completed within the scheduled time, that experienced concrete finishers are available to finish the deck, that any required weather protective materials are in place, and that all necessary finishing tools and equipment are on hand at the site of the work and are in satisfactory condition for use.

Methods, procedures, and equipment shall be used which will insure a smooth riding surface complying with the surface tolerances specified herein below without overvibration or segregation of the components of the concrete.

Any change in the number, location or configuration of construction joints from that shown on the design drawings must be approved by the engineer.

The contractor shall maintain a minimum rate of placement of 30 cubic yards per hour for all deck slabs of 180 cubic yards or less. When the deck slab is in excess of 180 cubic yards of concrete, the minimum rate of placement shall be 40 cubic yards per hour. The placement of concrete shall be scheduled such that finishing operations can be completed during daylight hours unless adequate lighting facilities are present on the site and the engineer's approval is given.

The concrete shall be delivered, distributed and consolidated at a uniform rate to insure a continuous operation. The working face of fresh concrete shall at all times be maintained approximately parallel to the finishing machine or other strikeoff.

Unless otherwise indicated on the plans, an approved self-propelled finishing machine will be required for striking off and finishing the surface of all structures. The finishing machine shall be the rotating cylinder type or the oscillating type. Longitudinal or transverse type finishing machines may be employed for spans up to 75 feet, while finishing machines for spans exceeding 75 feet shall be of the transverse type. The finishing machine shall be capable of being propelled both forward and backward to enable repeat passes to be made in order to correct surface irregularities and to produce a surface which conforms to the required profile grade, cross-section and surface smoothness. Longitudinal finishing machines shall be the full length of the span. Transverse finishing machines shall preferably be of sufficient size to finish the full width of deck between curbs, but not less than the width of the approach pavement or the distance between longitudinal construction joints. In areas outside the width of traffic lanes or in areas inaccessible by machine, vibratory screeds or other manually operated strikeoff approved by the engineer may be used.

The weight of the finishing machine shall not cause undue deflection of the bridge members or falsework. The machine shall travel on steel rails, pipe or other approved grade control, which shall be adequately supported by vertical supports securely fastened in place at spacing sufficiently close to prevent any appreciable deflection between rail supports. The supports for the rails, when located in the deck concrete, shall be of the type which can be removed without disturbing the concrete or partially removable so that no part remains above 2-1/2 inches below the finished concrete surface. If such supports are removed before initial set has taken place, the resulting holes shall be filled with deck concrete: if the concrete has hardened holes shall be satisfactorily filled with non-shrink, non-staining grout.

Prior to placing the concrete, rails or other guides for the finishing machine shall be completely in place, accurately set to achieve the deck elevations shown on the plans, and secured for the full length of the concrete placement plus such additional distance that the machine will clear all finishing operations.

The finishing machine shall be operated over the full length of the bridge segment to be finished prior to beginning concreting operations. This test run shall be made with the screed adjusted to its finishing position. During the test run checks shall be made of the deflection and adjustment of guide rails and of the cover over slab reinforcement and forms. All necessary corrections shall be made before concreting is begun. If the finishing machine is of the longitudinal type, the test run may be omitted when reinforcement clearances preclude movement of the machine across the deck.

Concrete placement and initial strikeoff by a transverse finishing machine shall be coordinated so that initial strikeoff is never more than 10 feet behind the concrete placement.

Strikeoff by a longitudinal finishing machine shall not be initiated until concrete has been placed a minimum of two bays wide for the entire slab length. In this context, a bay is defined as the horizontal distance between adjacent girders. The final pass by the longitudinal finishing machine shall subsequently uniformly lag the placement by the minimum two bay width. Sufficient depth checks shall be made behind the machine and along the full length of the span to insure achievement of the required section and reinforcement cover.

The concrete shall be given as few passes of the machine as are necessary to obtain a smooth, dense surface of the required contour. A small uniform quantity of mortar shall be maintained ahead of the screed on each pass. At no time shall the quantity of concrete carried ahead of the screed be so great as to cause slipping or lifting of the finishing machine on the rails.

Improper adjustment or operation of the finishing machine which results in unsatisfactory consolidation, reinforcement cover, or smoothness shall be corrected immediately. Unsatisfactory performance, particularly with respect to the surface smoothness attained, may be cause for rejection of the equipment.

A work bridge or other positive means of permitting access to the surface of the deck shall be provided by the contractor for the purpose of finishing, straight-edging, making corrections, and the other operations requiring access to the surface of the deck after the passing of the screed. Before concrete placing operations begin, substantial bulkheads or headers shall be set and shaped to the required deck surface cross-section. Unless otherwise specified, the concrete shall be placed as a monolithic unit in a continuous operation between joints.

When the concrete placing is within any complete unit (i.e. for trusses, arches, continuous or cantilevered unit) is to be divided as shown on plans, the placing shall be made and finished in the numbered sequence shown, beginning with the lowest number. All sections having the same number shall be placed before sections of higher number. However, the sequence of placing sections having the same number shall be at the discretion of the contractor. No deck section shall be placed until all previously placed concrete within the complete unit has cured for 48 hours. This requirement may be waived, under certain conditons if the succeeding section can be completed, with 4 hours of the initial placement of the day. Written approval of the engineer will be required to waive this requirement.

Unless otherwise shown, the sidewalks, parapets and curbs within any one complete unit shall not be placed until all the deck slabs within that complete unit have been placed. The numbered sequence shown shall also apply to pedestrian sidewalks (over 2'-6" wide) sections, but it need not apply to safety curbs (2'-6" wide or less), curbs, and parapets.

For simple spans the placing of concrete shall preferably progress upgrade. However, deck slabs may be placed with a finishing machine in a continuous operation from either end of a bridge regardless of grade.

<u>Finishing deck slab surfaces.</u> Bridge deck or top slabs of structures serving as finished pavements or bases shall be finished as specified above.

Finishing shall continue until such time as there remains no deviation greater than 1/8-inch when tested for trueness with a 10 foot metal straight edge furnished by the contractor. When a bituminous concrete surface is to be placed on a bridge deck, then said deviation may be relaxed to 1/4-inch, when tested for trueness with a 10 foot metal straightedge.

After finishing has been completed and as soon as all excess moisture has disappeared and while it is still possible to produce a uniform surface of gritty texture, the roadway surface shall be broomed as specified under article 3.12.3. Sidewalks and top of safety curbs shall receive their final finish with a fine bristled broom.

If the bridge deck concrete does not meet the above smoothness specifications, the contractor will be allowed to remove high spots up to 1/2-inch by means of grinding. The use of bush hammers will not be allowed. The contractor shall restore the broomed surface texture finish character of the area so ground in a manner satisfactory to the engineer. No concrete shall be removed that will result in a concrete slab thickness less than that called for on the plans. Any other corrections shall be made only with the written approval of the engineer.

APPENDIX F

Proposed Smoothness Specifications

for

Concrete Deck Slabs

1.0 Smoothness Evaluation of Concrete Deck Slabs

1.1 Control Testing: The Contractor shall be responsible for systematically checking the smoothness of deck slab surfaces during placement to enable him to make corrections while the material is in a workable condition.

Such systematic control testing shall generally be performed as follows: After the intended final pass with the finishing machine or other strikeoff, the deck surface shall be checked by the Contractor with a 10-foot metal straightedge operated parallel to the centerline of the bridge. Surface variations from the testing face of the straightedge shall be corrected before the concrete sets. Major deviations shall be corrected by the finishing machine or other strikeoff, while minor deviations may be corrected by the straightedge or an approved float.

The specific conduct of the straightedging, including the number and location of straightedge checks, shall be entirely the province of the Contractor. However, it is suggested that the checking operation progress in five-foot longitudinal increments, with at least one full-slab length straightedge check being made within the transverse limits of each of the designated lanes of traffic.

1.2 <u>Acceptance Testing</u>: Concrete deck slabs will be tested for smoothness acceptance in lots equal to the number of cubic yards of deck concrete placed each production day.

Acceptance testing will be performed by the Engineer with an approved 10-foot rolling straightedge that automatically marks in colored dye the length of pavement surface variations exceeding 1/8 inch in 10 feet. Such testing will not be initiated until after a slab's final set is achieved. The specific timing of smoothness acceptance tests shall be completely at the option of the Engineer. Generally, smoothness acceptance testing of a concrete deck slab will be performed the working day following placement of that slab.

The smoothness acceptance of a lot will be based on the percentage of the total length of the lot having surface variation exceeding 1/8 inch in 10 feet, this percent non-compliance being defined as the Lot Percent Defective Length. Lot Percent Defective Length is computed by adding the lengths of individual surface defects exceeding the specified tolerance, dividing this sum by the total length tested, and multiplying by 100 to convert to percent.

The full extent of the lot will be tested in the longitudinal direction. The transverse location of the test will generally be in the wheelpaths of vehicle travel, here defined as the two imaginary lines located approximately 3 feet on each side of the centerline of the lane and extending for the full length of the lane.

The minimum number of full-length tests required to determine the Lot Percent Defective Length shall be equal to the total number of wheelpaths in the lot. The number of tests performed beyond this minimum, if any, and their location, shall be completely at the option of the Engineer.

The Lot Percent Defective Length of concrete deck slabs which are required to be struck and finished with a self-propelled finishing machine shall be evaluated using Schedule A, the appropriate subschedule being dependent on the bid date of the project. If manual strikeoff and finishing is permitted by plan exception, Lot Percent Defective Length shall be evaluated using Schedule B, the appropriate subschedule being dependent on the finishing method (machine or manual) actually selected for use by the Contractor.

If the Lot Percent Defective Length for a concrete deck slab exceeds the amount shown for the 1.0 pay factor in the appropriate subschedule, and if the Contractor elects not to remove and replace the slab, the lot may be accepted upon written request of the Contractor at an adjusted unit price.

The adjusted unit price for a lot of Class B Concrete incorporated in a bridge deck shall be the product of the Contract unit bid price for the item and the appropriate pay factor of Schedule A or B.

If the Lot Percent Defective Length of a machine finished deck slab is 25.0 percent or more, irrespective of whether such machine finishing was required or optional, the Engineer may order removal of any or all of the concrete in the lot or if the material is allowed to remain

Schedules A and B: BID PRICE ADJUSTMENT SCHEDULES FOR CLASS B CONCRETE IN DECK SLABS

Schedule A: Machine Finishing Required			
Subschedule A1: Decks Bid in the One Year Period, X to Y		Subschedule A2: Decks Bid Subsequent to Date Y	
Measured Lot Percent Defective Length	Pay Factor	Measured Lot Percent Defective Length	Pay Factor
8.9% or less	1.0	6.0% or less	1.0
		6.1-8.9	0.99
9.0-13.9	0.99	9.0-13.9	0.975
14.0-24.9	0.93	14.0-24.9	0.93

Schedule B: Machine Finishing Optional*			
Subschedule B1: Machine Finishing Selected for Use by the Contractor		Subschedule B2: Manual Finishing Selected for Use by the Contractor	
Measured Lot Percent Defective Length	Pay Factor	Measured Lot Percent Defective Length	Pay Factor
13.9% or less	1.0	19.9% or less	1.0
		20.0-27.0	0.975
14.0-24.9	0.93	27.1-34.9	0.93

*The provisions of this schedule are independent of project bid date.

in place, computation of the adjusted unit price will be based upon a pay factor of 0.85. If the Lot Percent Defective Length of a manually struck and finished deck slab is 35.0 percent or more, the Engineer may order removal of any or all of the concrete in the lot or if the material is allowed to remain in place, computation of the adjusted unit price will be based upon a pay factor of 0.85.

1.3 Cessation of Deck Concreting: The Engineer reserves the right to reject methods or equipment which do not result in substantial conformity with a 1/8 inch in 10 feet surface tolerance. In this context, a deck will be considered in substantial conformity with the required surface tolerance only if the Lot Percent Defective Length does not exceed the value corresponding to a 1.0 pay factor in the appropriate Schedule A or B.

In no case shall the Contractor be permitted to immediately initiate further project deck pours if the Lot Percent Defective Length equals or exceeds 20.0 percent on any machine finished deck slab or 35.0 percent on any manually struck and finished deck. If these limitations be exceeded, the particular placement and finishing operations involved shall be discontinued until other methods or equipment are proposed for trial by the Contractor, submitted in writing to the Engineer, and approved. Approval of this revised plan of operations will not relieve the Contractor of the responsibility for the satisfactory performance of his revised methods or equipment.

The Contractor will not be granted additional compensation, extension of time, or other concession because of the required execution and approval of a revised plan of operations.

1.4 <u>Surface Remedial Measures</u>: Regardless of the overall smoothness conformity of a lot of bridge deck concrete, if surface deviations have a detrimental effect on deck drainage or reinforcement steel cover, the Engineer may require the Contractor to undertake appropriate remedial measures to restore any or all of the deck slab surface to the required grades and surface tolerance. When such remedial procedures are ordered by the Engineer, the Contractor shall submit in writing, for approval by the Engineer and the Bureau of Structural Design, a proposal setting forth the intended limits of the surface restoration and a complete description of the methods, equipment, and materials proposed for use.

Following satisfactory completion of the approved surface restoration measures to the bridge slab, the entire lot containing the affected area shall be retested for smoothness acceptance. The resulting measurement of Lot Percent Defective Length is to be used to determine a revised pay factor from the appropriate Schedule A or B. The revised pay factor indicated from this retesting or a pay factor of 0.975, whichever is smaller, shall be used to determine the adjusted unit price for the affected lot.

The entire work of planning and executing surface restorations, including all materials, labor, equipment, and all else necessary therefor and incidental thereto, shall be considered part of the work of concrete deck slab construction. The Contractor will not be granted additional compensation, extension of time, or other concession for any surface restorations ordered by the Engineer.