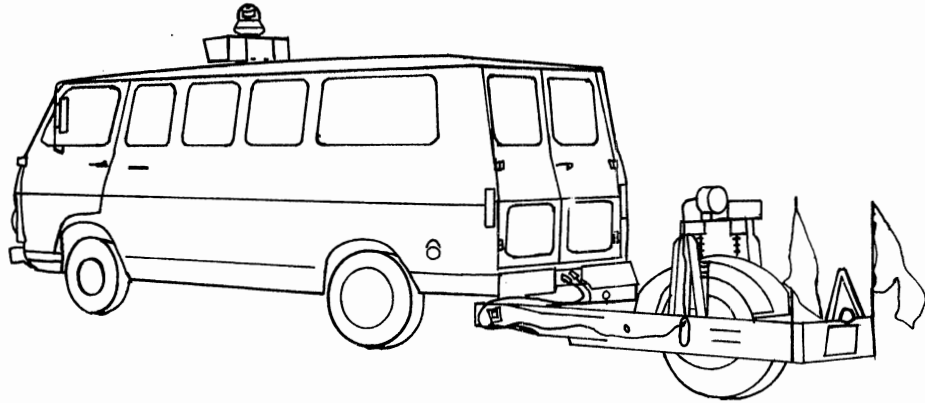
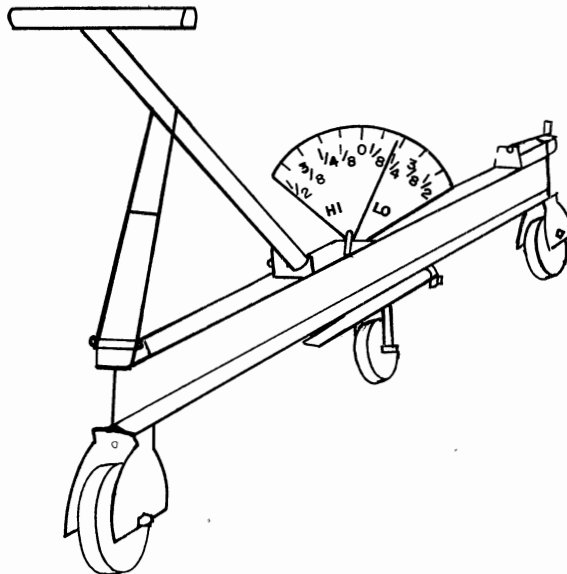


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"PAVEMENT RIDING QUALITY"



AN EXECUTIVE SUMMARY REPORT

April, 1974

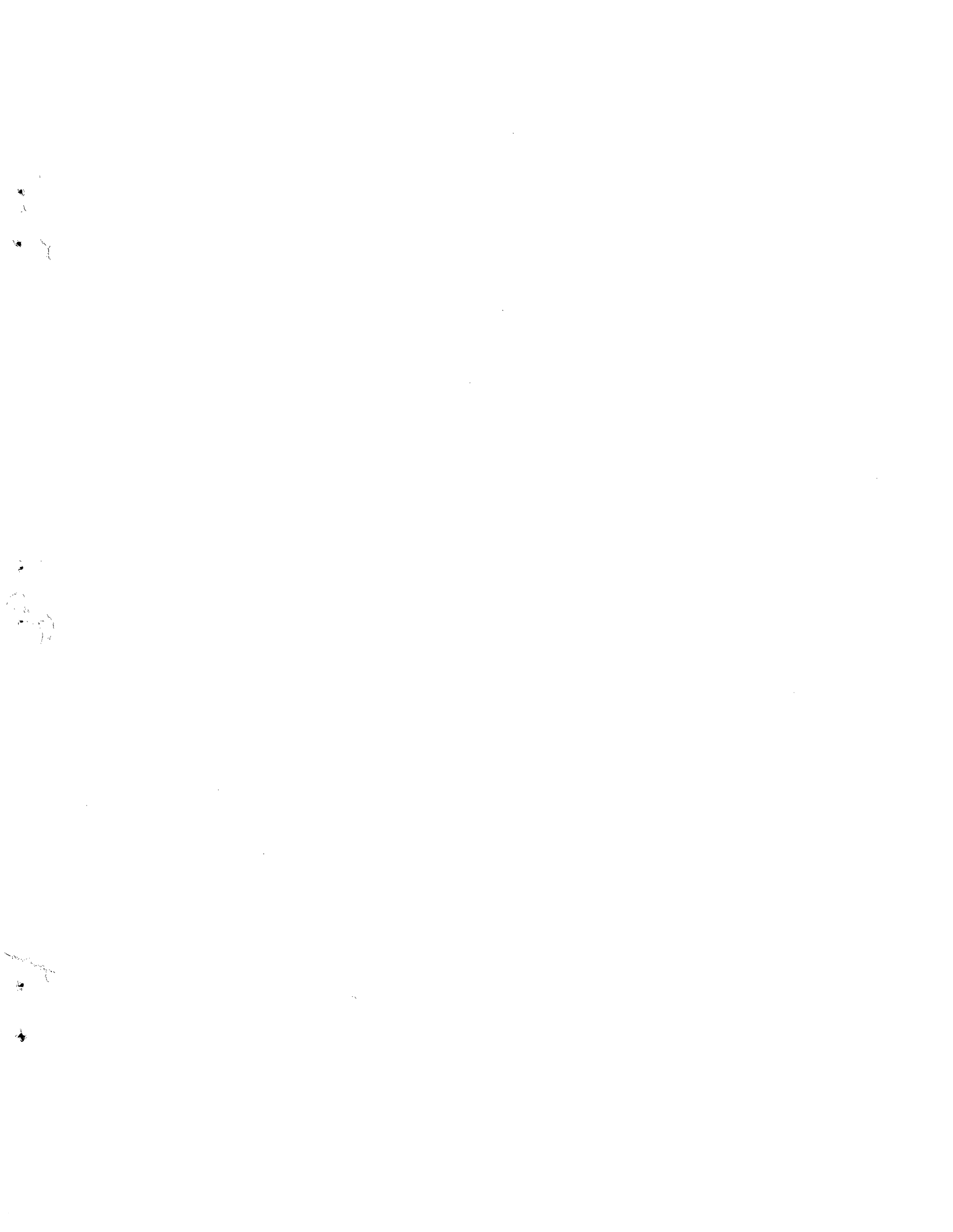


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PAVEMENT RIDING QUALITY

An Executive Summary Report

by:

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Research Report 74-001-7713

April, 1974



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 alignment.

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 AASHTO 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.

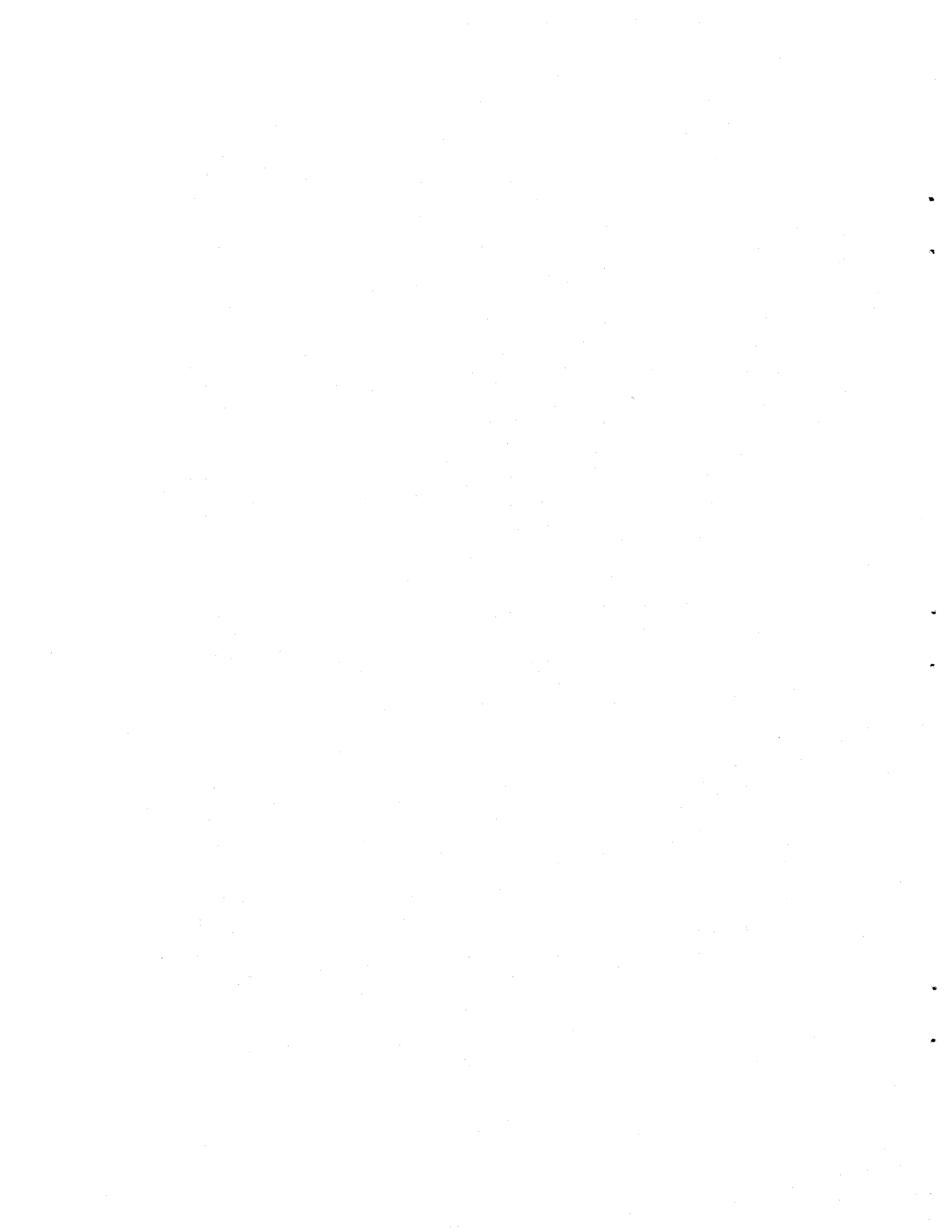


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1.0 RESEARCH OBJECTIVES

This summary report outlines the results of a five-year study undertaken to determine the riding qualities of recently constructed New Jersey pavements and bridges, to identify the sources of roughness on the measured surfaces, and to investigate the desirability of adopting riding quality acceptance specifications. The bituminous and concrete pavements studied all were of high-type (principally Interstate) construction on new alignment.

2.0 ROUGHNESS TESTING EQUIPMENT AND EVALUATION CRITERIA

2.1 General Information

The relative roughness determinations of this work were made with two measurement devices: a BPR-type roughometer and a 10-foot rolling straightedge. The output of the roughometer--the "Roughness Index" in inches per mile--represents the vertical excursions of a fifth-wheel towed along a roadway at a test speed of 20 miles per hour. The rolling straightedge indicates the length, magnitude, and high or low nature of individual surface variations exceeding 1/8 inch in ten feet. New Jersey specifications contain the requirement that no such defects are to be permitted in the finished surface of pavements or bridges.

2.2 The New Jersey Roughometer

The results of repeatability tests and comparison runs made with other roughometers have indicated the overall output of the New Jersey roughometer model to be both reasonably consistent and in general accord with that of similar equipment from other agencies. At various times during the study, however, considerable equipment downtime resulted from the

required repair or replacement of electrical and mechanical components of the roughometer. As a consequence, the roughness of certain of the later studied projects was gauged by straightedge measurements alone. To provide back-up for the roughometer in future riding quality studies, the Department is acquiring a similar, but reportedly more trouble-free, high-speed roughness measurement device known as the "Mays Ride Meter".

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 (FHWA). The adjective ratings applied to values of roughness index in the FHWA system (Table S-1) evolved from an analysis of riding quality achieved in practice, based on a multi-state sampling of new Interstate construction. As shown, different criteria are used for the two pavement types. Because of the generally greater roughness of concrete roads, the FHWA system is purposely less critical of the rideability of rigid type pavements.

TABLE S-1: FHWA ROUGHNESS EVALUATION CRITERIA

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

As an adjunct to descriptive ratings made using the FHWA guidelines, the studied pavements are to a limited extent also evaluated in terms of the "Present Serviceability Index" provided. Present Serviceability

Index (PSI) is a number between 0 and 5 that represents an estimate of the average opinion of highway users as to the ability of a particular pavement to serve traffic in its existing condition. This estimate is derived from equations combining various physical measurements of pavement characteristics, with the predominant weight being assigned to wheelpath roughness. The decrease in PSI with increased traffic loadings (or time) is the basis of an accepted definition of pavement performance.

The information as to the condition and estimated remaining 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. In the present research, the discussion offered principally centers on the fundamental lack of applicability of the serviceability concept to design and maintenance decisions in New Jersey.

2.3 The New Jersey Rolling Straightedge

A series of repeatability tests indicates that the rolling straightedge as used in New Jersey can, within a given day, provide a precise measure of the surface characteristics of a pavement. The accuracy of the readings and their subsequent repeatability are dependent upon factors which generally can be controlled by the user, the most important of which is the calibration of the device. If the high reliability required in a critical application such as smoothness acceptance testing is to be achieved, a (relatively quick and simple) straightedge calibration check must be performed each testing day.

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. Since the rolling straightedge is generally more useful for field control of project roughness than the roughometer, a major study effort was directed at determining evaluation criteria for straightedge data. This investigation consisted of determining the correlation between the output of the roughometer and rolling straightedge, and thus the extent to which the accepted riding quality standards for roughometer data can be transferred to a roughness equivalent in terms of straightedge data.

2.4 Interrelationship of Roughometer and Straightedge Measurements

In performing roughometer-rolling straightedge regression analyses, the Roughness Index for selected quarter-mile test sections was compared to rolling straightedge output expressed in terms of three summary statistics: the total number of deviations exceeding 1/8", the percent defective length, and deviation area. The latter two data presentations are employed to take into account the severity of the recorded deviations. Percent defective length is computed by adding the lengths of individual surface defects exceeding the 1/8" tolerance, dividing this sum by the length tested, and multiplying by 100 to convert to percent. The total deviation area in square inches is the sum of the areas of individual deviations calculated as rectangles having the deviation length and magnitude as sides.

Based on the comparison of roughness measurements on a total of 17 miles of concrete and 32 miles of bituminous pavement, a good relationship at a high level of significance was found to exist between the two New Jersey roughness measurements devices on both rigid and

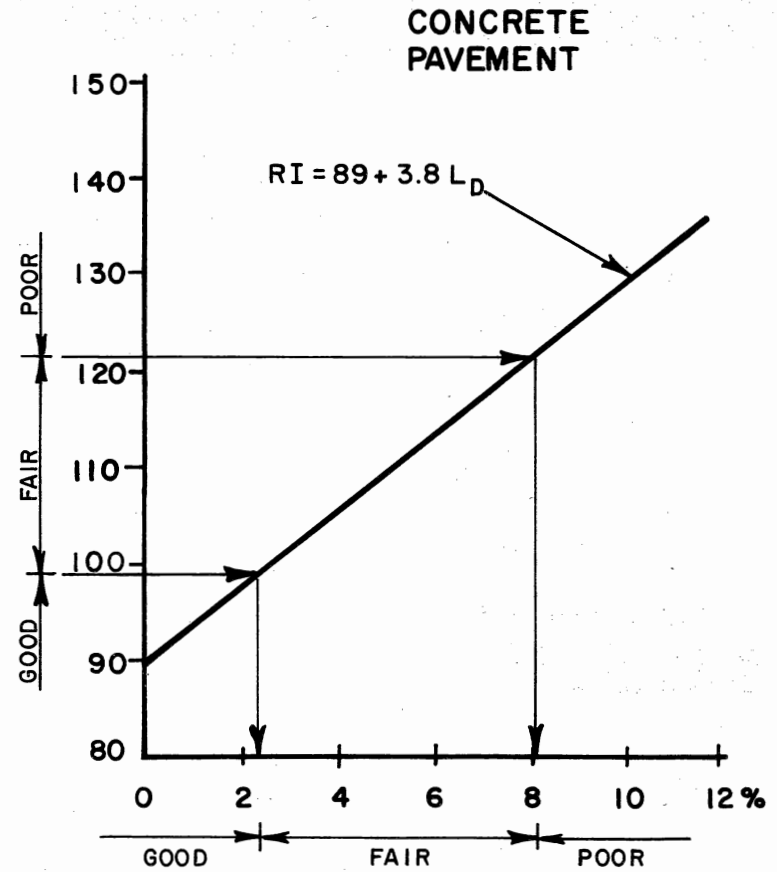
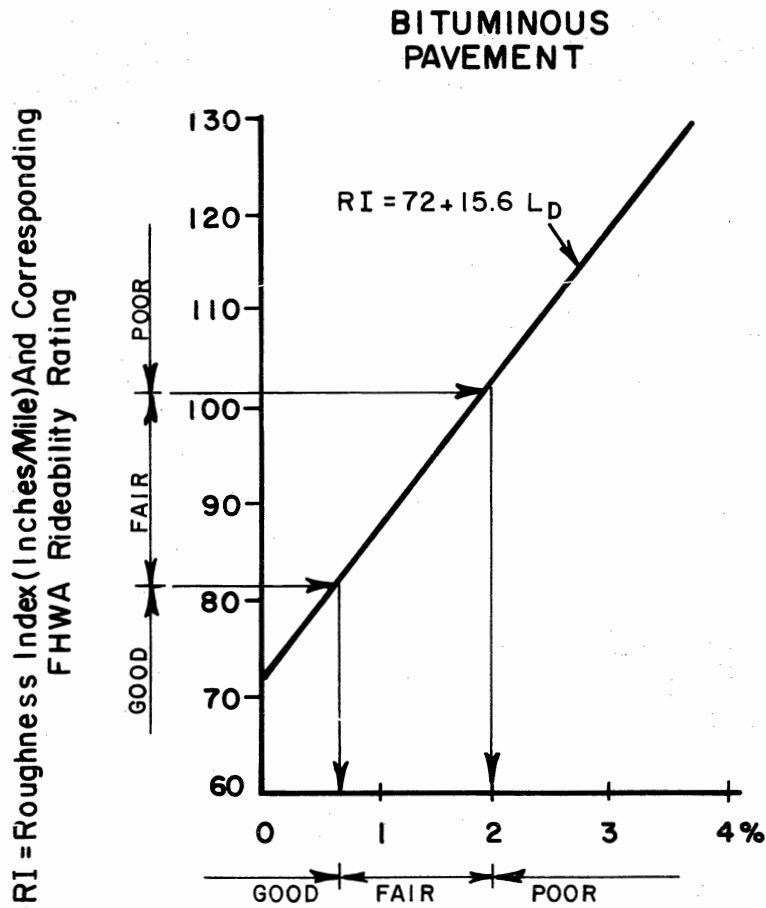
flexible pavement. In the roughness range of primary interest (i.e., up to 20 inches per mile into the "Poor" category), a simple linear relationship exists between roughness index and straightedge defects expressed in terms of each of the three measurement parameters (number, length, or area of defects). In view of this correlation, it is concluded that rolling straightedge data provides a valid alternate method of characterizing pavement rideability, and one which might reasonably be used as the basis for a smoothness acceptance specification in New Jersey.

A comparison of the roughness regression plots for New Jersey rigid and flexible pavements reveals a pronounced contrast with respect to the relative influence of measured surface irregularities on the two pavement types. This difference directly reflects on proposed future roughness control procedures. As illustrated in Figure S-1, if concrete and bituminous pavement contain equally extensive surface variations, the bituminous pavement will generally receive a markedly lower rideability rating. For example, a working range of 0 to 2 percent defective length almost completely defines "Good" thru "Poor" bituminous rideability. In contrast, any concrete pavement characterized by this range of data would be expected to receive a "Good" FHWA rating.

The indicated more severe relationship between the extent of straightedge defects and the rideability of bituminous pavements 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 is also expected if the roughness level is expressed in terms of straightedge data. The second influencing factor relates to differences in the absolute profile between formed and non-formed construction. That is, long- and/or short-wavelength surface defects that detract from rideability but which are not measured by the straightedge are apparently more prevalent on bituminous construction.

FIGURE S-1

Relationship Between New Jersey Roughometer Readings And The Percent Of The Pavement Length Exceeding A 1/8" In 10' Surface Tolerance.



L_D = Percent Defective Length

3.0 PAVEMENT RIDING QUALITY FINDINGS

3.1 Summary of Measurement Results

The riding quality of New Jersey's recent pavement construction was based on a roughometer sample consisting of a total of nearly 250 miles of data (998 quarter-mile sections) from 14 concrete projects and 270 miles of (top-course) data from 16 bituminous projects.

The mean Roughness Index of the individual concrete projects were found to range from 101 to 154 inches per mile and averaged 122 inches per mile. According to the FHWA criteria, the as-constructed average level of riding quality on one of the projects was "Good", six were "Fair", while the remaining half were "Poor". The overall average level of roughness for these projects coincides with a borderline "Fair-Poor" FHWA riding quality rating. Two recent projects not tested with the roughometer each exhibited straightedge data indicative of "Poor" rideability.

The average Roughness Index of the sampled bituminous projects ranged from 70 to 117 inches per mile and averaged 95 inches per mile. The "average" New Jersey bituminous pavement thus displayed about a 25 percent lower as-constructed roughness index than our average concrete pavement. According to the FHWA criteria, the average level of riding quality on one of the bituminous projects was a borderline "Excellent", five merited "Good", four "Fair", and six "Poor". The overall average corresponds to a "Fair" FHWA rating. One each of three recent bituminous projects whose roughness was gauged by straightedge measurements alone displayed surface variation that would be expected to yield "Excellent", "Good", and "Fair" roughometer readings respectively.

In addition to this rather extensive testing of finished pavement surfaces, a more limited sampling was also made of the roughness of successive bituminous courses on selected projects. The most significant point associated with the observed course-to-course reductions in Roughness Index is that the average total improvement on each of the tested projects was essentially the same: about 55 ± 15 inches per mile from base to top. This indication that there is a relatively fixed level of improvement that can be expected from the first to last courses placed emphasizes the necessity of minimizing surface irregularities in even the first course. The indicated course-to-course reductions in measured defects can be used to formulate rules-of-thumb as to the limiting values of straightedge defects on intermediate courses that will result in a final surface of the desired riding quality. Specifically, the collected data suggests that whenever the percent defective length exceeds about 1-1/2 to 2 percent on binder or 3 to 4 percent on base, one might generally expect a potential problem in finally achieving acceptable riding quality.

In Table S-2, a summary of New Jersey roughometer data for both rigid and flexible pavements is shown compared to the 580 mile, 17 state roughometer sample used to develop the FHWA rating criteria. The most striking difference between the two data distributions is the inordinate percentage of "Poor" riding quality sections of pavement in New Jersey: about 40 percent compared to 3 percent in the FHWA survey.

TABLE S-2: COMPARISON OF NEW JERSEY AND FHWA RELATIVE ROUGHNESS RESULTS

FHWA Riding Quality Rating	Percent of FHWA Survey in Category*	New Jersey Concrete		New Jersey Bituminous	
		Number of Projects	Percent of All Test Measurements	Number of Projects	Percent of All Test Measurements
Outstanding	7	0	0	0	0.3
Excellent	15	0	0.8	1(2)	3.4
Good	54	1	14.0	5(6)	23.5
Fair	21	6	40.9	4(5)	37.0
Poor	3	7(9)	44.3	6	35.7
Sample Size	580 miles, 17 states	14(16) Projects, 250 miles		16(19) Projects, 270 miles	

*bituminous and concrete pavement combined

()includes projects whose rideability was estimated from straightedge data

As previously alluded to, consideration of the described roughometer data in terms of the as-constructed serviceability level (i.e. the initial PSI values) indicates that the present serviceability concept apparently can have only marginal applicability in this state. In essence, the difference between the serviceability level of our pavements when they are new (average PSI's: concrete 3.5 and bituminous 3.0) and the serviceability level where rehabilitation is indicated (a PSI of 2.5) is commonly so small that little meaningful information as to the relationship between serviceability and applied loads might be expected from New Jersey's use of the serviceability concept.

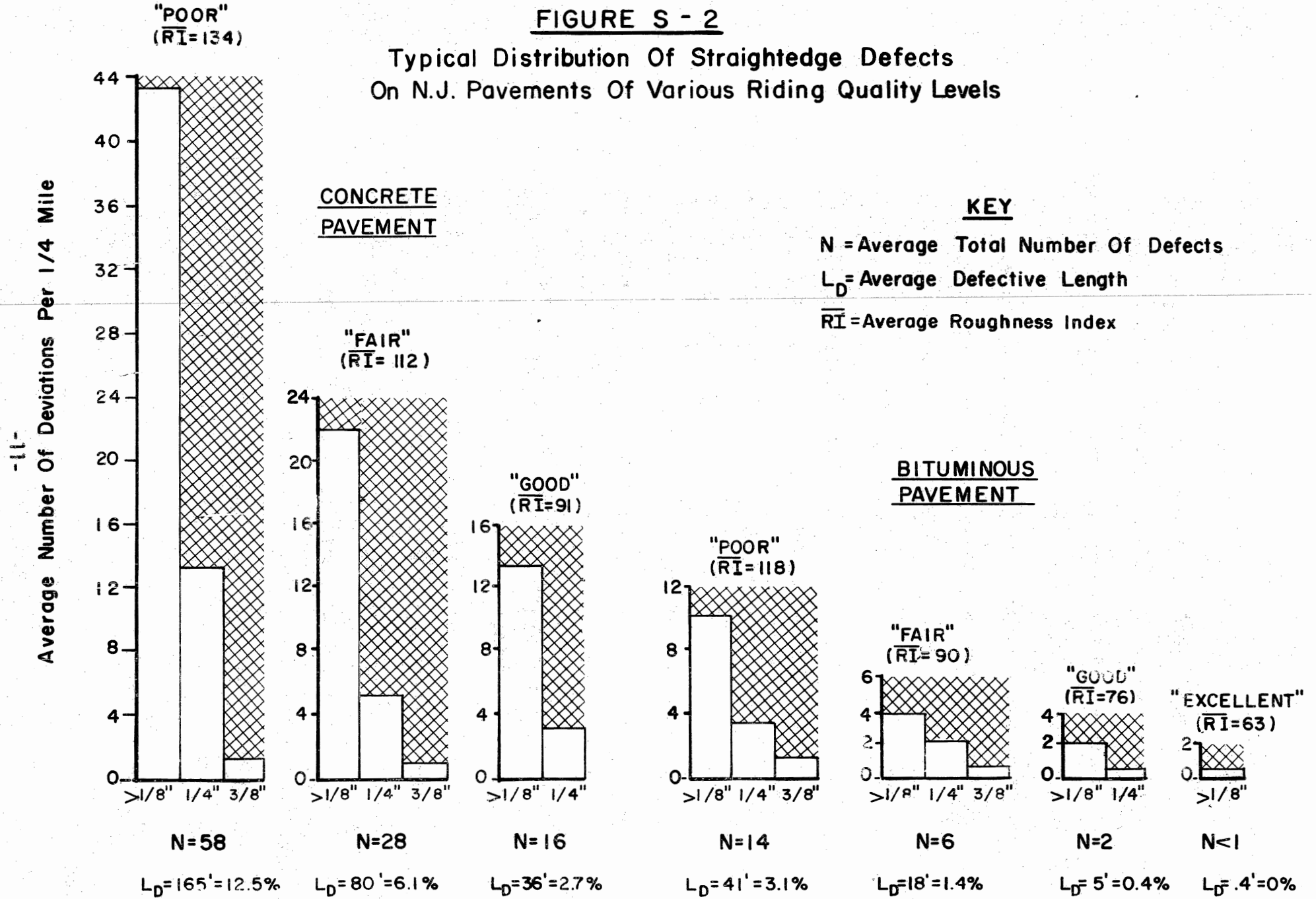
The histograms of Figure S-2 depict the average pattern of measured straightedge defects on pavements having New Jersey roughometer readings corresponding to "Good" thru "Poor" rideability respectively. This generalized illustration of how the number and severity of surface defects varies with Roughness Index thus provides an alternate view of the nature of pavements in our State. For example, a new bituminous pavement of the average roughness level measured in New Jersey generally might be expected to correspond to the histogram shown for "Fair" pavement, displaying about 6 defects totalling 18 feet exceeding our present specification surface tolerance in any quarter mile. The distribution of measured surface variations on the average new concrete pavement is intermediate to that shown for "Fair" and "Poor". Such a pavement would typically be characterized by about 40 defects totalling 110 feet per quarter mile in excess of our specification. On both pavement types, 1/8 inch defects are predominantly 1 to 3 feet long, while the higher magnitude defects are commonly 3 to 6 feet long.

3.2 Indicated Roughness Trends

In the present sample of New Jersey pavement rideability, there is a significant and encouraging trend for our more recent bituminous construction to be of improved smoothness. For example, with the exception of one contract, all projects surveyed which were constructed using (presently required) pavers equipped with automatic controls have received at least "Fair" ratings, with their average roughness (80 inches/mile) corresponding to an FHWA "Good". In contrast, the earlier sampled projects constructed using conventionally controlled pavers at best received "Fair" ratings and average "Poor" (105 inches/mile).

FIGURE S - 2

**Typical Distribution Of Straightedge Defects
On N.J. Pavements Of Various Riding Quality Levels**



Unfortunately, no such trend for improved riding quality with time or more modern (slip-form) methods and equipment is indicated for New Jersey concrete pavements. In fact, the reverse appears true. The generally "Fair to Poor" rideability data for the pavements of this study apparently represents a general reduction in quality level compared to work accomplished in earlier periods in New Jersey. A sampling with the FHWA prototype roughometer of New Jersey concrete pavements built during the late 1950's and early 1960's indicated that the then-current level of riding quality was generally "Good".

3.3 Influence of Joint Roughness on Concrete Pavement Rideability

New Jersey is almost unique in its use of a concrete pavement design which exclusively employs regularly spaced expansion joints (3/4" wide, spaced at 78'2"). These joints are normally of the formed type, with extensive handwork being involved in restoring a smooth finish to the surrounding plastic concrete. The data of this study indicates that surface defects introduced during such joint construction operations are the single most important factor contributing to the unfavorable concrete pavement rideability in this State.

While it has been long realized intuitively that joint-related defects detract from our pavement rideability, their actual frequency and severity is somewhat surprising. On the average, about 40 percent of all measured straightedge defects are associated with the portion of the pavement in the vicinity of the joints. Even more significantly, the longer and higher magnitude defects that detract most from rideability occur with even greater frequency in the joint area. For example, an average of one-half

of all 1/4" and two-thirds of all 3/8" surface irregularities occur at or near expansion joints. Apart from their number and generally greater severity, joint defects can also be expected to exert a further negative influence on user opinion because of the regularity of their occurrence.

While joint-related defects account for a substantial fraction of the overall roughness of concrete pavements of each smoothness category, there is a trend for such irregularities to account for a higher than average percentage of roughness on smoother pavements and a lesser percentage on rough pavements. In other words, on a well-controlled project containing relatively few defects between joints, the principal effect of joint roughness is to inhibit achievement of the best level of rideability. On the roughest pavements, joint roughness in essence represents but another contribution to an overall pattern of surface deficiencies.

Field forces have conducted considerable experimentation with construction methods and equipment in an attempt to reduce concrete pavement roughness in general and joint roughness in particular, occasionally with some success (e.g., by finishing joints with a mechanical tube float in slip-form work). The previously described roughness results indicate, however, that significantly improved rideability has yet to be consistently achieved on any recent project. Thus, while adoption of a realistic smoothness acceptance specification might be expected to stimulate contractor performance to some extent, there does not appear to be any substantial basis for optimism concerning a near-term improvement in the rideability of New Jersey's standard concrete pavement.

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, this Department recently constructed a concrete pavement of an alternate design. This experimental pavement employed sawed contraction joints rather than our conventional hand-formed expansion joints.

The "Fair" rideability indicated for the resulting work represents an improvement compared to the majority of studied projects and the involved contractor's previous efforts in particular. However, the magnitude of improvement unfortunately is far less than was expected.

3.4 Factors Influencing Bituminous Pavement Rideability

The specific rideability levels achieved on the bituminous pavements of this study were found to have been influenced by a number of diverse, sometimes interacting factors relating to workmanship, materials and equipment.

The most important factor in the trend for improved bituminous rideability in this state is the increasing (now required) use of pavers equipped with automatic controls. As previously indicated, bituminous projects constructed with automated pavers have displayed an average of about 25 inches per mile greater smoothness than those constructed using manually controlled pavers. Cited experience on certain of our projects, however, confirms well-known performance requirements: automatic controls must be used properly and must be accompanied by favorable workmanship and materials if the smoothness potential of the equipment is to be realized.

A second factor observed to influence bituminous rideability is the conduct of construction as a basically stop-and-go operation. That is, while paving manuals universally caution that the bituminous laydown operation should proceed at a speed which is both reasonably constant and

coordinated with the rate of material supply, erratic or stop-and-go operation has been observed on a number of New Jersey projects and for a variety of reasons (i.e., paver, material, and/or operator deficiencies). An extreme example of the extent to which defects introduced by stop-and-go operations detract from pavement rideability is provided in the full research report. The provision of an adequate supply of material and ensuring continuity of laydown will unfortunately become even more critical in the near future as New Jersey shifts toward echelon and thick-lift paving.

The high relative frequency of transverse construction joints in this State is a third factor influencing smoothness results. More specifically, as a result of a 500 foot limitation on the maximum length of bituminous mat pulls, most of the projects studied in this work could be expected to contain at least three construction joints per quarter mile. That this restriction had considerable bearing on the level of rideability achieved on particular projects is evidenced by the fact that in some cases studied, all of the surface defects observed in a test section were 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.

A fourth factor found to influence New Jersey bituminous rideability was the use of project specifications that 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 that an innate conflict exists between the attainment of a specified 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 specified minimum thickness without increasing the material quantity on which his bid is predicated. Since there is evidence that New Jersey contractors generally resolved this conflict between rideability and thickness in favor of thickness, the payment provisions of the Department's specifications have been changed from a square yard to a tonnage basis.

While the roughness equipment of this study did not permit making any determination of the relative roughness of courses underlying the bituminous structure, experience strongly suggests that the surface characteristics of these non-bituminous courses have also influenced New Jersey riding quality. Specifically, if the achievement of a quality final riding surface is the result of a concerted effort at each preceding level, then it follows 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. Similarly, observations suggest that the use of a difficult-to-construct macadam base course on about one-third of the 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.

Finally, and most elusively, the presence of a continuing concern for good riding quality in project planning and execution is certainly a significant factor. To use a phrase from the literature, good rideability requires the application of a spirit of "Smoothness Consciousness" on the part of State and Contractor personnel.

In spite of the subjective nature of such smoothness consciousness, comparison of the rideability results between consecutive, abutting projects built by one New Jersey bituminous contractor yields some evidence of this factor at work. That is, when confronted with documentation of the poor rideability results on the first of these two projects, the President of the contracting firm undertook measures on the next job that were designed to overcome previous equipment and materials supply shortcomings. 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 jobs in New Jersey.

4.0 PROPOSED PAVEMENT SMOOTHNESS SPECIFICATIONS

New Jersey's current surface smoothness specifications possess a number of important shortcomings. These include the lack of a specific sampling and data reporting requirement, an unrealistic choice of tolerances, and a slow, laborious method of test. The development of proposed alternate smoothness acceptance specifications for New Jersey pavements are described in considerable detail in the full report.

The proposed acceptance criteria require testing of the entire length of each day's production of concrete pavement and bituminous surface course with a rolling straightedge, computation of the pavement's percent defective length, and determination of the appropriate payment from Table S-3. The minimum number of full-length straightedge runs necessary to determine the percent defective length of a day's work varies in accordance with a given schedule, with the roughest pavements requiring the most extensive sampling.

TABLE S-3

**Proposed New Jersey Bid Price Adjustment
Schedules for Pavement Smoothness**

Schedule A: Bituminous

Measured Percent Defective Length	Percent Payment*
1.3 or less	100%
1.4 to 2.3	98
2.4 to 3.4	95
3.5 or more	Remove and replace or 80%

Schedule B: Concrete

Measured Percent Defective Length	Percent Payment
5.0 or less	100%
5.1 to 11.0	98
11.1 to 13.9	90
14.0 or more	Remove and replace or 80%

*pay item: total tonnage of surface and underlying courses (planned specification change)

An underlying philosophy of the specification is that whenever a contractor provides a pavement with a percent defective length that corresponds to a borderline "Fair/Good" or better FHWA rating, no penalty should be assessed. At the other extreme, the straightedge equivalent of "Poor to Very Poor" rideability is judged to be a totally rejectable quality level (i.e., a remove/replace condition). Based on the historical data of this study, a pavement receiving this most severe penalty would be expected to be at least 20 inches per mile into the "Poor" FHWA rideability category. 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. In this work, it is concluded that straightedge data corresponding to a borderline "Fair/Poor" should definitely be considered of marginal acceptability and should have at least some associated penalty.

Translating the described general limits of acceptability into specific acceptance plan provisions requires consideration of the measurement variation inherent in the straightedging process. A part of the work thus consisted of determining the specific extent to which variability is introduced by the precision of the straightedge and by sampling procedures (i.e., testing only a fraction of all wheelpaths) on pavements of various roughness levels. This observed measurement dispersion was in turn used to generate "operating characteristic curves". Use of these curves permitted the acceptance scheme to be so constructed as to minimize risks such as wrongly accepting pavements of poor rideability or rejecting those of good riding quality.

While leniency was employed at each stage of development of the proposed specifications--in determining the penalty ranges, the associated payment reductions, as well as the testing procedures--a "reasonableness check" was required to establish the probable impact of the proposal. On concrete pavement, this investigation consisted of a simulation of the proposed specifications to historical roughness data for New Jersey paving projects. On bituminous pavement, additional comparisons were made to the smoothness specifications and straightedge data of other agencies.

The trial application of the proposed smoothness specification to the collected data for bituminous projects suggests that a future project might be expected to receive less than a 3 percent average total payment reduction for smoothness. On concrete pavement, an average project penalty of 1 to 2 percent is indicated for "Fair" riding projects, and a 5 percent for the average "Poor" project. The indicated expected frequency and severity of penalties for future New Jersey projects is thought to be reasonable.

5.0 BRIDGE DECK RIDING QUALITY FINDINGS

5.1 Background

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

While it is obviously desirable that continuity of good riding quality be maintained on structures, roughness data from other agencies confirms that concrete deck construction is commonly considerably rougher than concrete pavement construction. As a consequence, some states are less critical of the rideability of bridge decks.

The historically greater roughness of bridge decks relative to pavements has generally been ascribed to significant construction differences/difficulties occasioned by the suspended nature of bridges. In particular, the literature indicates that the single most important factor entering into this trend is that deck construction has historically relied more on manual rather than mechanical means for concrete strike-off and finishing.

One mechanical deck screeding technique--the use of full span length, longitudinally* oscillating type equipment--has received uniformly favorable rideability reports. In several states, use of such equipment has been observed to consistently yield "Good" roughness data, the average magnitude of which was as little as half that for sampled manually finished construction. However, certain other types of mechanical deck finishing equipment have, at least in certain instances, received generally unfavorable reports. For example, the transversely oscillating type of screed has in some studies been found to yield equal or greater roughness than manual finishing.

*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.

In response to the improved rideability results apparently obtainable with various configurations of mechanical bridge deck screeding and finishing equipment, such mechanical methods currently enjoy very widespread use. It has recently been estimated, for example, that more than 90 percent of current nationwide bridge construction is accomplished with mechanical screeds.

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

Beginning in about 1967, a number of New Jersey bridge contractors, with Department encouragement, elected to employ 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.

5.2 Summary of Measurement Results

The bridge roughness determinations of this study were based on an 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.

· Manual finishing: As indicated in Table S-4, 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 versus 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 (one-third) greater roughness than our "average" (marginally acceptable) concrete pavement. Significantly, even if the more lenient bridge roughness guidelines used by some states were applied to this data, a "Poor" or "Rough" rideability rating would generally result.

The most important 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 approach conformity with our existing specification surface tolerance. As shown in Table S-4, 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). This substantial non-conformity also generally applies to the magnitude of the observed defects as well as their extent. For example, on some manually finished spans, as many as three-fourths of all defects were in excess of 1/4 inch.

TABLE S-4: Summary of Roughometer and Rolling Straightedge Data for New Jersey Bridge Decks

Finishing Method		Roughness Sample Size		Average Roughness Index of Individual Structures		Average Percent Defective Length, L _D	
		Projects	Spans	Range	Average	Range	Average
Manual		8	16	125-192 in/mi	161 in/mi	20.1-36.6%	29.4%
Transverse Roller Finisher		2	7	107-132 in/mi	120 in/mi	1.2-12.3%	4.4%
Longitudinal Oscillating Machine	Full Span Length Screed	3	6	107-139 in/mi	120 in/mi	3.9-13.2%	8.5%
	Partial* Span Length Screed	1	1	141 in/mi	141 in/mi	--	--

*This equipment is essentially a mechanized, 10-foot long bull float.

In essence then, the roughness measurements on the sampled New Jersey manually finished decks differ only in the degree of non-compliance with the required surface tolerance. This is a particularly significant and surprising finding in that certain of the studied decks resulted from well-executed manual finishing operations.

• Full span length, longitudinal screeds: Average roughometer readings of 107, 115, and 139 inches per mile were obtained on three projects constructed using full span length, longitudinally oscillating screeds. The highest of these readings was obtained on a deck which received only one rather than the manufacturer's recommended minimum of two finishing machine passes.

The benefits of full span length, longitudinal machine finishing relative to manual finishing can generally be appreciated from the roughness data shown in Table S-4 (i.e., from the 120 versus 161 inches per mile average roughness index and 8.5 versus 30 average percent defective length). However, the most meaningful comparison of roughness results between these two finishing methods is probably provided by the data obtained on one particular project. That is, on one contract, identical three-span structures were built by the same forces, in one case using manual methods and in the other, longitudinal machine finishing. Subsequent roughness measurements made on these companion bridges indicated the hand-finished structure to have twice the average percent defective length of the machine finished structure (27 versus 13 percent) and a 60 percent greater average roughness index (170 versus 107 inches/mile).

. Partial Span Length, Longitudinal Screeds: One of the studied New Jersey decks was constructed using a partial span length, longitudinal finishing machine. This equipment is the type most commonly employed nationally and essentially consists of a longitudinally oscillating 10-foot long float that is successively advanced across and along the deck.

The average roughness index of 141 inches/mile observed for this deck translates as a (very) "Poor" FHWA pavement rideability rating. Since the construction practices involved in placement and finishing were rated as "Good", it would appear that this sample can be considered as a reasonably representative trial of the subject type of 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 is similar to that reported by another state. That is, use of the partial span length equipment 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.

. Roller Finishing: As indicated in Table S-4, the average roughometer readings for the tested transverse roller-finished 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 New Jersey manual finishing average and merits a "Good" relative rideability rating according to the bridge deck roughness criteria of some other states.

The best straightedge data obtained on a project in this study resulted from transverse roller-finishing, two structures on one contract displaying near-perfect conformity to our existing surface tolerance ($L_D = 1.2\%$). Interestingly, the worst percent defective recorded for the roller-finished decks studied was only about half that for the best manually-finished deck sample.

5.3 Recently Adopted Changes in the Specified Construction Practices for New Jersey Bridge Decks

Based on the observed improved rideability achievable thru use of mechanized deck finishing equipment, as well as the associated potential for improved deck durability, New Jersey has recently adopted specifications which require use of such equipment on the majority of future projects. Manual deck finishing will be permitted only in the exceptional case where use of a mechanical finisher is impractical or impossible due to the limited number or size of structures in the contract or their geometric complexity.

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 discussion of these new requirements--which cover both the planning and execution phases of deck construction--and an extreme example demonstrating the need for such specifications are provided in the full report.

6.0 PROPOSED BRIDGE DECK SMOOTHNESS SPECIFICATIONS

6.1 General Information

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. Since none of the bridge decks evaluated in this study satisfied this absolute requirement, it seems apparent that a zero defect provision is an unrealistic means of dealing with the roughness variations expected on future New Jersey bridges.

Proposed alternate specifications for bridge deck smoothness are developed in the report. The criteria offered are patterned after the rolling straightedge-based provisions previously recommended for pavements.

The acceptance proposal for structures requires testing of the entire length of all wheelpaths in each day's production of deck concrete with a rolling straightedge, computation of the slab's percent defective length, and determination of the appropriate payment from Table S-5. As indicated, the percentage of the bid price paid for deck concrete displaying a given percent defective will generally vary, depending on the deck finishing method employed. That is, different requirements apply to decks machine finished by specification requirement, to machine finishing by contractor option, and to manual finishing.

6.2 Decks Required to be Machine Finished

The proposed riding quality requirements for decks where machine finishing is specifically required--thus, the provisions which would control in the majority of future cases--are shown in Schedule A of Table S-5.

TABLE S-5

Proposed New Jersey Bid Price Adjustment Schedules for Bridge Deck Smoothness

Schedule A: Machine Finishing <u>Required</u>			
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	Percent Payment	Measured Lot Percent Defective Length	Percent Payment
8.9% or less	100%	6.0% or less	100%
9.0-13.9	99%	6.1-8.9	99%
14.0-24.9	93%	9.0-13.9	97.5%
25% or more	Remove and Replace or 85%	14.0-24.9	93%
		25% or more	Remove and Replace or 85%

Schedule B: Machine Finishing <u>Optional*</u>			
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	Percent Payment	Measured Lot Percent Defective Length	Percent Payment
13.9% or less	100%	19.9% or less	100%
		20.0-27.0	97.5%
14.0-24.9	93%	27.1-34.9	93%
25% or more	Remove and Replace or 85%	35% or more	Remove and Replace or 85%

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

Outline of Proposed Cessation Requirements: If the percent defective length of a day's production exceeds the value corresponding to 100 percent payment in Schedule A or B, the Contractor may be required to discontinue the involved concreting operations and submit a written revised plan of operations. In no case will the contractor be permitted to immediately initiate further project deck pours if the percent defective exceeds 20 percent on any machine finished slab or 35 percent on any manually finished slab.

As indicated in Subschedule A1, it is suggested that the acceptance provisions for required machine finishing be implemented in two steps. An initial one-year period of very lenient provisions is proposed prior to the adoption of acceptance limits more accurately reflecting various degree of acceptability. Specifically, during the first year, a penalty of substance would be levied only if the straightedge equivalent of "Very Poor" rideability is exceeded. 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.

The acceptance schedule for such construction in following years (Subschedule A2) reflects the feasibility and desirability that acceptance limits for machine-finished decks be generally structured 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, depart from the acceptance plan for pavement at each end of the penalty spectrum. That is, the acceptable (no penalty) quality level for these machine-finished bridges is set at "Fair" rideability rather than "Good" as required for pavements. Further, the associated percentage payment reduction

is set such that the dollar value of any penalty can be expected to be relatively nominal unless "Poor" or worse rideability is provided. By employing these measures then, New Jersey would be following the previously noted practice of some other states of being less critical of deck rideability in comparison to pavements.

A more fundamental departure from the pavement acceptance plan is made at the other penalty extreme for bridges. That is, in the case of bridges, there is definitely a greater potential for extensive straightedge defects to occur. Further, the required removal of a "totally unacceptable" riding surface is of far greater monetary consequence on bridge decks than on pavements. It thus appears advisable that ranges of bridge deck percent defective length above the "Very Poor" rideability level be accepted but with increased percentage payment reductions. Consequently, during either specification period shown in Schedule A, decks displaying a percent defective up to nearly twice the point where "Very Poor" rideability is expected will be accepted with a penalty. 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. Suggested cessation requirements for deck smoothness are outlined at the bottom of Table S-5.

6.3 Manually Finished Decks

As previously noted, the roughness data obtained on our manual deck construction differs essentially only in the degree of non-compliance with required surface tolerances. In the writer's view, this effectively precludes formulating smoothness acceptance specifications for such construction based on a rational balancing of desired and achievable smoothness quality levels. 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, an essentially constant minimum level of penalties would be applied to hand-finished jobs. This circumstance would undoubtedly reflect in a proportionate increase in deck bid prices.

Consequently, as shown in Subschedule B2, the proposal for hand-finished decks contemplates accepting decks having the overall range of defects observed in the research sample. Penalties are levied exclusively on various categories of rideability which are well above a truly totally rejectable, "Very Poor" riding quality level. Due to their greater expected frequency on manual construction, these higher ranges of percent defective are accepted at a lesser relative payment reduction than on machine-finished decks of similar roughness.

6.4 Decks Machine Finished by Contractor Option

It is highly conceivable 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. Consequently, 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 Subschedule B1, 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--a penalty is appropriate. 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.

By adopting the latter criteria, New Jersey's position would be one of expecting generally good rideability (both absolutely and in relation to the hand-finishing option) but not requiring it. While this is not an ideal situation, consider the alternate: if a contractor elects to use hand finishing because he deems it his only practical option, good rideability will neither be required nor expected of the resulting work.

7.0 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 contraction 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 the Final 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 the Final 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 the Final 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.

8.0 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 the Final Report. The proposed smoothness specifications for decks are presented in Appendix F of that report.

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 trial use of the roller-finisher 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.



