

Construction Control of Rigid Pavement Roughness

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Results of a 2-year study of cause-effect relationships involved in roughness of concrete pavements are reported. Data were derived both from analog traces obtained in each wheelpath within hours after concrete placement on randomly selected pavements, and from qualitative observations of paving methods. Sampled construction consisted of 184 sections of 1- and 2-lane pavement built under 62 different contracts with 8 different form-type finishing machines and 3 different slipform pavers. Statistical analysis was held to a minimum by uncontrolled interactions, but 5 factors were found to be common and outstandingly significant in relation to roughness throughout the contracts studied: (a) backing up of the last finishing machine, (b) absence of a float, (c) use of less than 3 screeds, (d) use of a crown section as compared to a uniformly sloping section, and (e) lane-at-a-time paving. Nine other construction phenomena producing roughness, common to many projects but found less frequently than these five, are also covered in some detail.

●THE NEED TO MINIMIZE the roughness of concrete pavement during its placement derives from the established relationship of initial roughness to subsequent service life. Housel (1) demonstrated that most concrete pavements in Michigan increase in roughness at the same, fixed annual rate. The AASHO Road Test (2) produced procedures for computing the increase in roughness resulting from traffic and environment for many different pavement designs. Tallamy (3) applied Road Test concepts to the New York State Thruway, using an average of roughness measurements on unopened sections as an initial point, to predict the sequence of future pavement reconstruction. From these reports, it follows that the smoother that pavements are built, the longer they will serve traffic.

Over the years, construction control of concrete pavement roughness has been the subject of several studies. The development of the profilograph used in this investigation was reported by California (4). In 1968, Virginia (5) reported on bridge deck roughness measured with a 10-ft straightedge that had been correlated to the BPR roughometer. Virginia's results were particularly important, in that this was the first time that deviations measured with a straightedge were related to roughness measured with a device correlated to human response. The relationship of a profilograph (similar to the one used in this study) to the CHLOE profilometer used at the AASHO Road Test was explored by Texas (6). Together, these studies related initial roughness, as measured by various devices, to the roughness limit at which pavements should be rehabilitated.

Use of a 10-ft straightedge has been specified by New York since 1923 (7). It provided adequate control when paving production was measured in feet per hour of one 9- or 10-ft wide lane, because the inspector could take sufficient samples. However,

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as production increased to feet per minute, while the number of samples per day remained constant, undetected roughness occurred. This problem became aggravated both by further increases in production with the advent of central-mix concrete and by simultaneous placement of multilane pavement. Thus, the proportion of pavement that could be inspected dropped drastically.

Recognizing the increase in roughness resulting from this condition, New York tried a specification based on the BPR-type roughometer. However, this unit could not be operated until the pavement was 7 days old, and even then it could not pinpoint the location of roughness. Thus, it was found impractical as a quality control device. At this point (in 1967), the Engineering Research and Development Bureau was requested to investigate means of rapidly determining pavement roughness as soon as possible after concrete placement.

Because of the urgent need for an early solution to this problem, attention focused on existing equipment for evaluating roughness. The California profilograph (hereafter called the profilograph) was selected because it can be operated on the pavement within 4 to 6 hours after placing, is simple to operate, and provides a permanent record of roughness at a scale sufficient to permit identification of areas requiring remedial action. California's method for reducing the analog record to digital data, given in Appendix A, was also adopted without change. However, no information was available on profilograph reproducibility, operator influence, analog-to-digital conversion errors, machine dependability, or the ability of the manufacturer to produce identical machines with interchangeable parts. It was therefore necessary to evaluate the profilograph sufficiently to determine machine or operator variances. Once this was done, the magnitude and causes of roughness were evaluated.

Statewide paving schedules were obtained for the 1967 and 1968 construction seasons and an itinerary laid out for a 2-man crew to visit an average of 3 paving projects per week. No attempt was made to visit any specific project at a given time. The only 2 controls over contract selection were that paving be in progress on 2 or more projects within about 30 miles of one another, and that a general statewide distribution of sites be maintained. The analog traces for each sample, comprising 1 day's paving on a project, were digitized and the results entered on punched cards, together with observations on equipment and paving procedures.

The first field work began late in the 1967 construction season and thus produced only 71 samples, an inadequate number for detailed analysis in keeping with this study's experimental design. By the end of the second season, a total of 184 samples were available from 62 contracts. Again, full evaluation of the results was impossible because of the many interactions, widely different sample sizes, and the critical independent variables present in individual samples. However, the data were sufficient to permit testing of means and variances using standard statistical tests, when the assumption that each set contained equal percentages of all other independent variables could be verified. Various other analytical methods would have required a prejudgment of expected critical variables. Such prejudgments could not be made legitimately because of the scarcity of published information on cause-effect relationships. In this respect, the results of the present analysis are of immediate use in reducing roughness and in providing the knowledge required to make prejudgments in future work.

DATA COLLECTION AND ANALYSIS

The Profilograph

The profilograph (Fig. 1) is produced by Cox and Sons, Sacramento, California. Snap-lock clamps permit one man to assemble the 3 main frame sections and supporting components in about 10 minutes. The sections and components were found to be interchangeable with those of 2 other profilograph units produced in 2 other years. In 327 miles of operation with this Bureau's profilograph, less than \$50 was spent at local hardware stores for minor replacement parts.

The permanent record consists of a continuous trace of roughness along the tested path. The amplitude scale is one-to-one and the distance scale is 25 ft to the inch. Point roughness can be easily located to the nearest foot by scaling. A manually operated

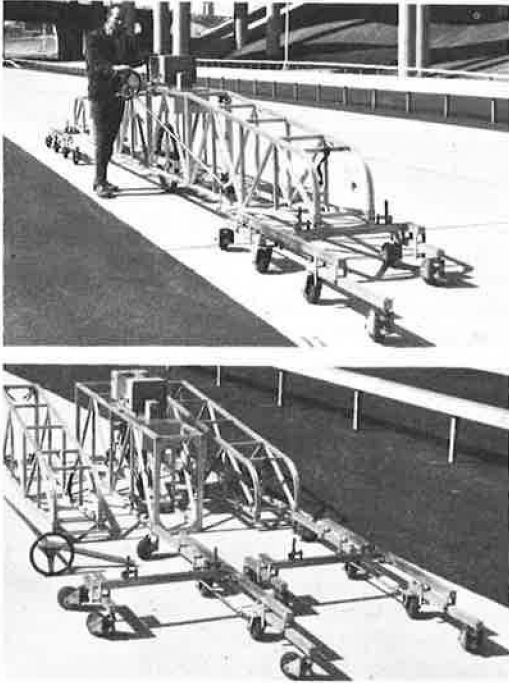


Figure 1. Profilograph assembled and disassembled.

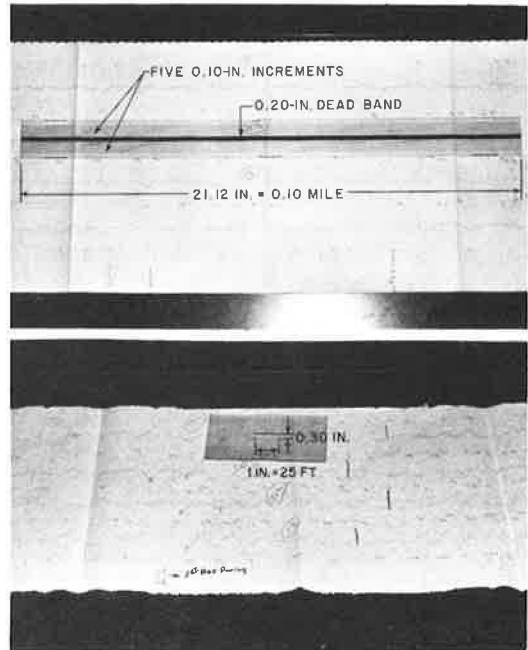


Figure 2. Profilograph traces and transparent templates used in data reduction.

event pen is available to denote stations, joints, or other references to facilitate relocation of points of interest. The analog trace is rapidly reduced to a digital value using a long plastic template, and a square template is used to detect isolated point roughness; both are shown in Figure 2. Digital data are expressed in inches per mile as detailed in the procedure given in Appendix A.

Site Selection and Field Procedures

Pavement sections were selected in a manner that attempted to minimize bias in estimating the variance contributed by specific equipment trains, contractors, projects, or other features that might prove to be significant influences on pavement roughness. The department's 10 regions readily furnished tentative paving dates for all projects. From this information, a map was prepared and projects selected to provide maximum statewide coverage.

The ideal experimental situation was selection of 5 projects within a 30-mile radius for inspection in a given week. The 2-man profilograph crew would then spend one afternoon watching and recording paving operations at one site. The following morning, they would measure roughness in every wheelpath, generating a permanent profilograph trace. The project site sample usually constituted about 0.2 mile of pavement, either 1 or 2 lanes wide. The operators would then continue to the nearest of the remaining 4 jobs. For the next 2 weeks, they would visit new areas with the intention of returning to each area and each job on an average of once every 3 weeks. No advance itinerary of the profilograph team was released. After each season ended, a few samples were taken from pavement placed between the dates when operations were recorded to be sure that no bias arose because of the profilograph's presence.

The original intention of obtaining from 5 to 10 samples from many projects was achieved. Many more projects, however, yielded only 1 to 4 samples. A few projects were also tested for their entire lengths to furnish specific information not available in smaller samples. Two of these were tested throughout their lengths with a 10-ft

straightedge, and the results were compared with similar data scaled from the profilograph tapes.

Paving Operations and Equipment Encountered

Five slipform projects were evaluated a total of 20 times, and 57 conventionally formed projects 164 times. Slipform pavers included those manufactured by Guntert-Zimmerman, CMI, and REX. Form pavers were Heltzel, Koehring, REX, Blaw-Knox, Jaeger, Lewis, Flexible Road Joint Machine, and Maxon. The last 4 machines were encountered on only 1 to 4 jobs. The Guntert-Zimmerman was observed placing concrete on processed gravel, soil-cement, and asphalt-stabilized bases; the REX slipform was observed only on asphalt-stabilized base; and all other data are from pavements on gravel base. Paving trains were evaluated that had both 1 and 2 finishing machines, with 2 to 5 screeds, and with and without a pan float. The CMI slipform was the only train to place single-course pavement with vibrated-in-place mesh; all others were 2-course. The most frequently used spreader was the Maxon. The Guntert-Zimmerman, however, dumped bottom course concrete directly on the grade from dump trucks. Central-mix concrete was most frequently used, transported in dump trucks without baffles in Maxon side dumps and in transit mix trucks operated as agitators. Ten contracts used paving mixers.

All slipformed pavement was placed full width, but formed pavement was placed lane-at-a-time, two-at-a-time, and two-plus-one. Both constant cross-slope and crowned tangents were observed. Geometric factors evaluated, in addition to the normal crowned section, were constant cross-slope tangents and curves, cross-slope transitions, and variable-width pavements. On specific projects, roughness-contributing factors evaluated included drainage structure inlets cast into the pavement and frequent interruptions introduced by bridges (but not bridge deck roughness). Contracts ranged from secondary highways on new locations to highly complex urban Interstate reconstruction.

Data Reliability and Limitations

General Data Characteristics and Limitations—The data were not suitable for rigorous analysis because of the numerous interacting variables and widely different sample sizes. However, it was possible to use some statistical tests on the various independent variables (taken one at a time). Thus, frequency distributions were prepared for the presence and absence of each independent variable, and the average, variance, and standard deviation were computed. When the variances were statistically similar, the means were tested at the 1 percent level of significance.

The data are presented as pairs of histograms (Fig. 5) and as both histograms and percentage probability plots (Fig. 7). The percentage probability plots eliminate the effect of different sample sizes, which obscure the trends depicted by the histograms.

An assumption that must be made and tested when analyzing paired data is that the difference being tested is truly due to the defined variable and not the effect of other interdependent variables distributed among the 2 groups being tested. This assumption was applied in screening and selecting samples for analysis. Sample sets of less than 30 generally failed to meet this constraint and are not included in the analysis, even though intuitively a difference should exist.

Trace Reproducibility—The profilograph was tested for trace reproducibility by making 25 forward and 25 reverse runs over the same 0.2-mile section of concrete (2 template lengths). Manual data reduction errors, discussed later, precluded the use of this method of reproducibility testing. Because no optical reduction instruments were available to provide exact trace conversion to digital form, the traces were overlaid in sequential sets of five on a light table, and no measurable differences were found in either the forward or reverse directions. No reproducibility errors could be introduced by changing operators or by interchanging major components, such as the recorder or truss sections from 2 other profilographs built in 2 different years. It was concluded, therefore, that the profilograph was a reproducible measuring device.

Motors profilometer (10) show that the latter unit is the only device with true response. These last 2 devices obtain their better frequency response from a reference generated by complex electronic circuits, rather than a fixed, finite-length structure.

The profilograph was also compared with a BPR-type roughometer. Both devices made test runs of identical length in the same wheelpaths on the same project. The profilograph traces were run the day after paving, and the roughometer runs as soon thereafter as possible, with the results shown in Figure 4. The indicated lack of correlation is contrary to implications in the literature. It can only be explained by noting the differences in response shown in Figure 3. Neither device has been correlated with driver acceptance of concrete pavement in this state. However, both devices have been so correlated independently elsewhere. Thus, both are assumed to produce an output related to driver response and therefore to each other.

Summary

In conclusion, it was found that the profilograph is suitable as a construction control device for monitoring concrete pavement roughness within hours after placement. The permanently recorded output is exactly reproducible and can be reduced from analog to digital form by trained personnel with an acceptable error. The absence of correlation between the profilograph and roughometer is accepted as predictable from their respective frequency response curves.

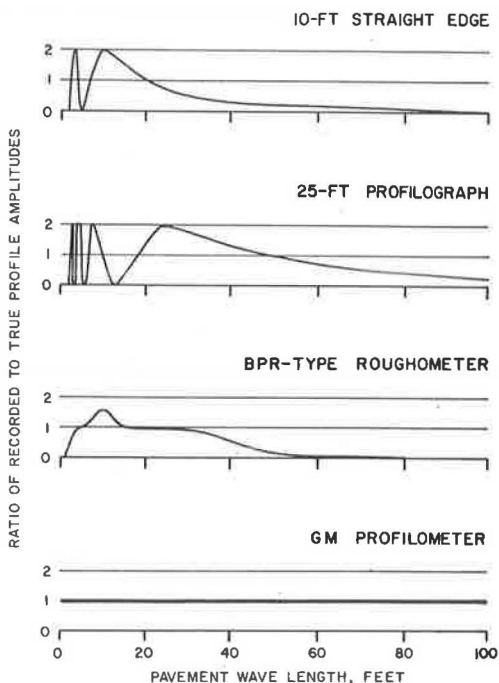


Figure 3. Theoretical differences between 4 roughness measuring devices.

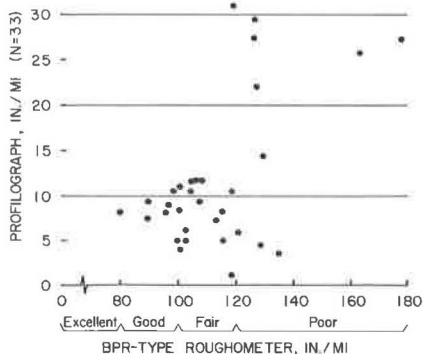


Figure 4. Relationship of profilograph and roughometer roughness (excellent, good, and fair are Bureau of Public Roads qualitative ratings).

DISCUSSIONS OF RESULTS

Sample and Contract Roughness: 1967-1968

A sampling of roughness built into newly constructed concrete pavements in New York State in 1967 and 1968 is shown in Figure 5. Two pairs of histograms are shown, the first averaging all daily test runs in each of the 2 survey years without reference to contract or project, and the second averaging by contract regardless of number of test runs per contract. Of particular interest in the case of average test roughness are the highly significant 25 percent reduction from 1967 to 1968 (from 23.8 to 17.9 in. per mile) and 33 percent reduction in standard deviation (from 13.7 to 9.2). These reductions were not accompanied by a similar change in overall average contract roughness (also shown in Figure 5), although the 34 percent reduction in standard deviation (from 12.8 to 8.5) is significant. The im-

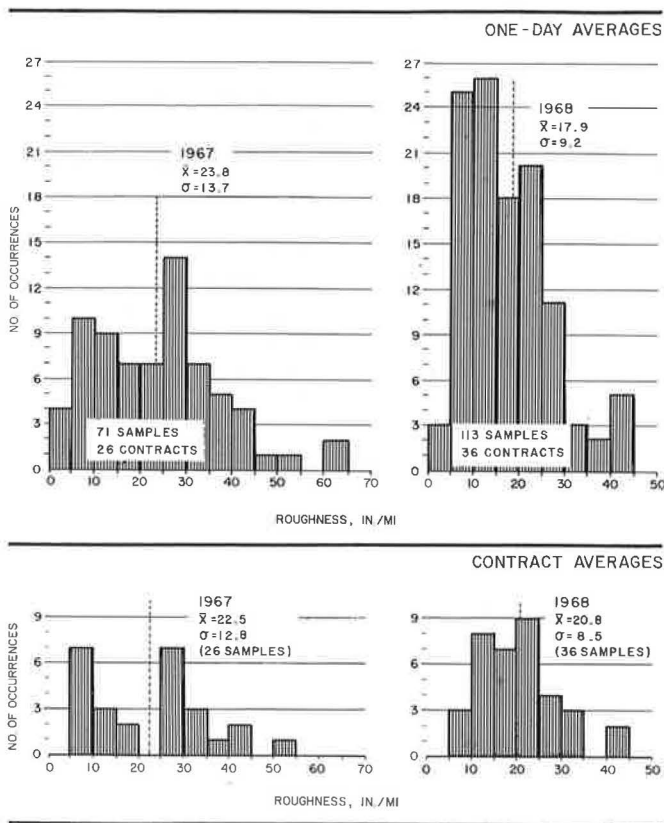


Figure 5. Two-year summary of roughness of newly constructed pavements by test days and by contracts.

plication is that individual projects decreased in number of rough pavement sections placed, but for various reasons (to be discussed later) no significant shift occurred in overall job performance. However, it should be noted that the causes of roughness were not yet defined in 1968, so no corrective action could yet be taken.

The influence of the contractor is shown in Figure 6, where annual averages are plotted for the contractors visited most frequently in this study's 2 seasons. Contractors F, G, H, and I demonstrated that smooth pavements can be placed consistently even in the absence of a roughness specification. Contractor D used a new paving train during 1968. Extensive equipment repairs and modifications are believed responsible for the reduced roughness found for contractor B in 1968. No reason is known for the increased roughness produced by E, the continued poor performance by C, or the extreme roughness produced by A using a late model slipform on an asphalt-stabilized base.

Factors Influencing Roughness Throughout the State

Five factors influencing roughness were readily identified when the combined 1967-1968 data were analyzed as discussed previously: (a) finishing machine backup, (b) presence or absence of float, (c) number of screeds, (d) crown versus constant cross slope, and (e) paving width.

Finishing Machine Backup—Backing up the finishing machine in conventional paving to produce the required multiple passes of the screeds has been standard practice.

However, as Figure 7A shows, obtaining a smooth pavement (one with little detectable roughness) is very difficult. The probability plot accompanying the histogram, showing the same data as percentages, quite vividly demonstrates the effect of backing up if any given set of roughness criteria are to be met. For example, if it is assumed that pavement must be ground smooth when the roughness exceeds 12 in. per mile and removed when it exceeds 30, continued backing up would result in removal of 20 percent of the pavement and grinding of 73 percent more. Corresponding values for not backing up would be 0 and 64 percent.

Presence or Absence of Float—
A simple pan float hung behind the finishing machine produced the reduction shown in Figure 7B.

Using the same limits just mentioned, 20 percent of the pavement would be removed and an additional 76 percent would require grinding, if the

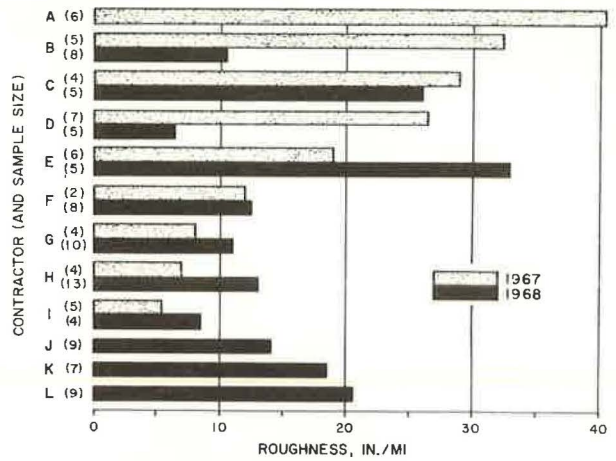


Figure 6. Annual average performance by contractors (numbers in parentheses are total samples measured).

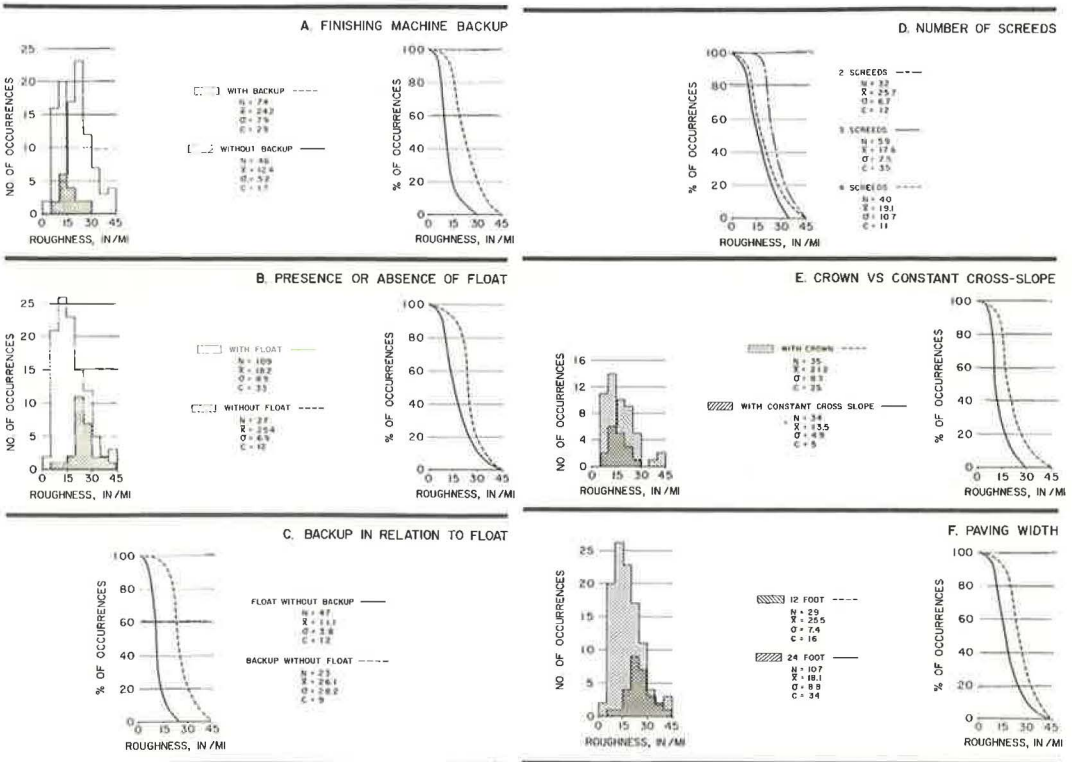


Figure 7. Roughness factors found statewide in 2 test years.

float is not used. Conversely, using the float would result in removing only 10 percent and grinding 70 percent. However, by separating data samples into the smoothest and roughest combinations (Fig. 7C), the former would result in no pavement removal and grinding less than 40 percent. On the other hand, the latter would require removal of 20 percent of the pavement and grinding the balance. Unfortunately, data are insufficient to continue this type of cumulative-effect analysis for the next 3 statewide phenomena discussed.

Number of Screeds—For many years, New York State paving specifications have required the use of 1 finishing machine with a minimum of 2 screeds. However, some regions have required a minimum of 3 screeds and others a minimum of 2 finishing machines with 2 screeds each. Further, some contractors have paving trains including as many as 6 screeds. It was therefore essential to determine the optimum combination. As Figure 7D shows, 3 screeds appear to be adequate, and 4 to produce rougher pavement; however, the difference is so small that it could well represent the previously discussed analog-to-digital conversion error and thus should be ignored. Insufficient data were collected on the other combinations, which thus are not included. One interesting fact that came up during review of multiple-finishing machine trains is that neither ability of the operator, mechanical condition, nor method of operation of the first machine had any significant effect on roughness. For example, one train observed several times producing smooth pavement had a very poorly maintained, badly worn-out old finishing machine, run by an inexperienced operator, followed by a new machine run by an experienced one. The first machine frequently had to back up and always moved at an erratic pace with frequent stops, while the second never backed up and always maintained a uniform pace. The first machine was subsequently rebuilt and assigned an experienced operator, without significant effect on pavement roughness.

Constant Cross Slope—Since the advent of multiple-lane paving, the contribution of the crowned cross section to roughness has been frequently discussed. Figure 7E shows the difference between the normal crown and a constant cross slope on tangent alignment. Here again, this one change would result in removing no pavement and grinding less than 40 percent to meet the previously discussed limits. Another significant point is that the roughest traces were obtained on projects where the contractor tried hardest to obtain a peaked crown. Transitions had an average roughness of 22.4 in. per mile—not significantly different from crowned tangents—but the variance was significantly higher. However, transitions were 66 percent rougher than tangents with constant cross slope and 25 percent rougher than superelevated curves. The implication, therefore, is that the methods used to adjust a finishing machine from 1 section to another require considerable improvement.

Paving Width—The earliest cause-effect relationship detected during this study was the cumulative roughness resulting from lane-at-a-time paving. Figure 7F shows the highly significant 41 percent average increase in roughness for the second lane of a 2-lane roadway, using single-lane rather than full-width placement. Similar increases are encountered for all successive lanes. Thus, the third lane of a pavement placed lane-at-a-time will be about 80 percent rougher than the first.

In summary, 5 factors were found responsible for pavement roughness throughout the state: backing the finishing machine, absence of a float, too few screeds, using a crowned cross section, and lane-at-a-time paving. Unfortunately, the data were insufficient for analysis of the total combined effects of these variables. However, avoidance of the first 2 factors showed that extremely smooth pavement could be produced even with the other three present. Thus, it is hypothesized that avoiding all 5 factors would ensure pavement of minimum roughness.

Factors Affecting Roughness on Single Contracts

Random occurrences of roughness should be expected on individual projects. The causes are legion. Some of the more significant encountered during this study are discussed next and were given special attention in the 1969 construction season.

Base Course—The type and roughness of the base material over which concrete pavement is placed have long been thought to influence final roughness of the riding

surface. In this regard, some question has remained as to the effect on roughness of the 12-in. beneficiated gravel base generally used in New York. Unfortunately, the absence of statewide use of treated bases precludes full-scale comparison. However, 2 contracts having such material were encountered and illustrate that presence of such material does not necessarily guarantee smoother pavement because other factors may exert more influence.

The first contract had several replicate sections of 8 in. of gravel, covered with (a) 4 in. of beneficiated gravel, (b) 4 in. of soil-cement, or (c) 3 in. of asphalt-stabilized base. The 8 gravel, 4 soil-cement, and 18 asphalt-stabilized sections had averages of 5.22, 6.88, and 2.59 in. per mile respectively and standard deviations of 3.74, 3.62, and 2.59. Although the asphalt-stabilized sections were numerically smoothest, the differences were not statistically significant. Further, the tendency of asphalt base to be associated with smoother pavement was not verified.

The second contract had 4 in. of bituminous-stabilized base over 8 in. of gravel throughout. Based on measurements made on pavement placed on 6 different days, average roughness was 40.22 in. per mile, with a range of 11.8 to 92.2 making it the roughest placed in the state during the study's 2 years.

Apparently, such extremes in roughness can be attributed to no one condition. Rather, the differences are believed to represent combinations of all parameters operating at their respective limits. However, from the first project, it does appear that special base courses might warrant further testing.

Supervision—Figure 8 shows one project on which the only change in operations was replacement of the paving train foreman between August 1 and 7. All other personnel and all equipment remained constant. The paving was 24-ft wide Interstate on new location. By July 3, the foreman was quite interested in reducing roughness. The following 4 tests show he was able to do so consistently. Unfortunately, his successor never was able to achieve the same control, although he did manage to equal the initial tests. An important point here is that, if the previously discussed roughness limits had been in effect, all pavement placed after August 1 would have required grinding.

Concrete Mix—The combined effects of a harsh mix and backing up the finishing machines are shown in Figure 9. This was formed, 2-lane pavement placed with 2 finishing machines. From data collected for this train on other contracts, a roughness

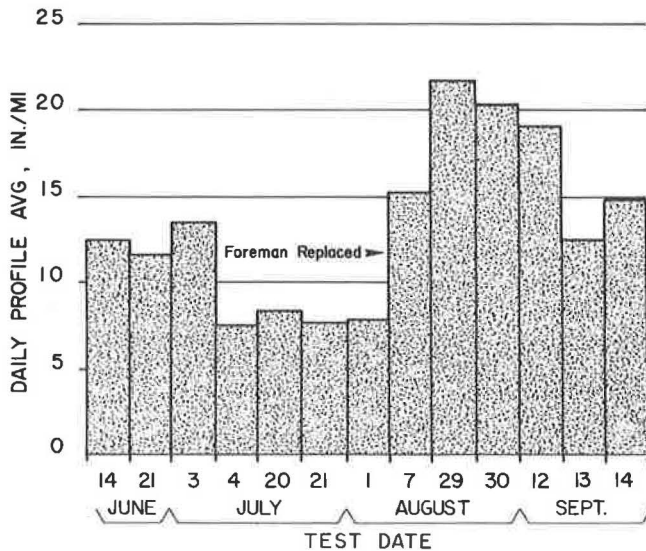


Figure 8. Effect of change of supervision.

average of about 11 in. per mile could be expected. However, the operator of the last finishing machine was backing up on October 22 at his own discretion. When the effect of backing up was pointed out, it was stopped. Then it became obvious that the finishing machines were having trouble because of the harshness of the mix. A 5 percent reduction in the quantity of 2- and 2½-in. stone brought roughness down to a respectable level.

Transverse Joints—The contractor has the option of either forming or sawing transverse contraction joints at the specified 60 ft 10 in. spacing. Figure 10A shows results of poor hand finishing; in this case, every joint is contributing 0.1 to 0.3 in. of roughness. Fortunately, not all joints were as bad as the three shown or average roughness per mile would have been increased 17.4 in. because of joint construction.

Forms—The care required in setting forms and the need for high-strength forms to produce smooth pavement have long been recognized.

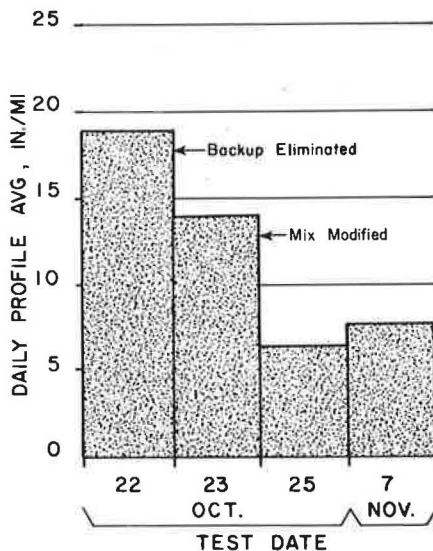


Figure 9. Effects of eliminating backup and modifying mix.

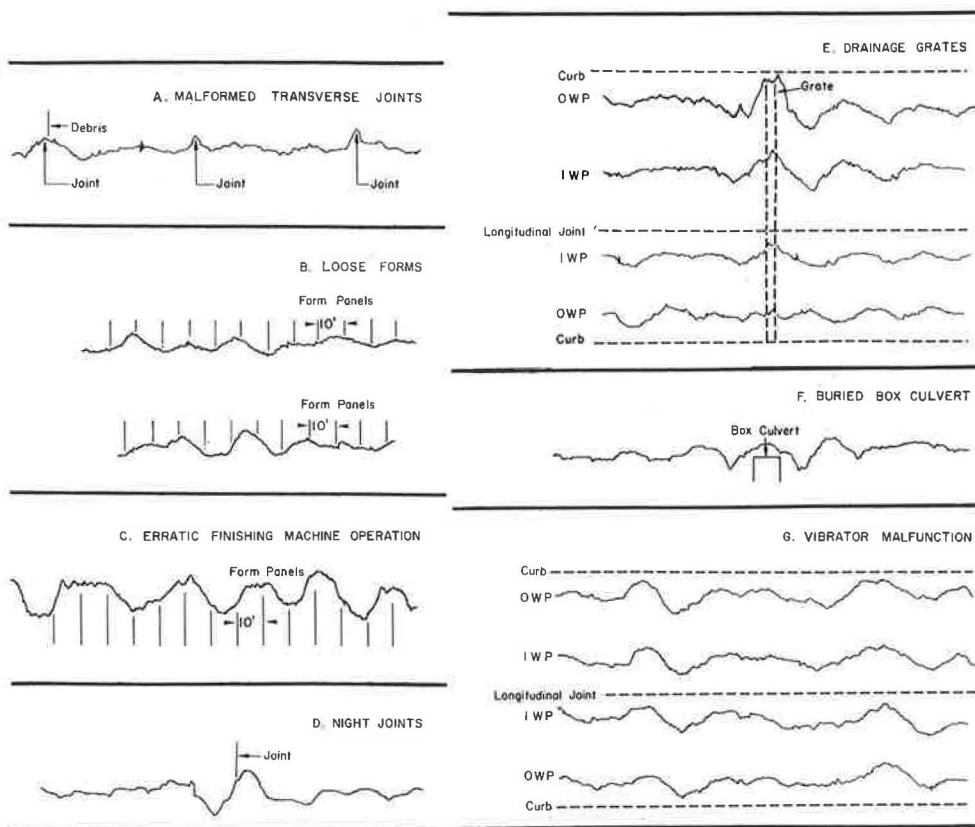


Figure 10. Typical profilograph traces showing roughness-generating conditions.

However, frequently overlooked is the treatment forms received during concrete placement. Figure 10B shows 2 cases of forms loosened by the operator of a Maxon spreader who frequently rammed his hopper against the stops as hard as possible. Loose or poorly set forms will produce even more pronounced roughness patterns. However, the pattern may be obscured by erratic finishing machine operation (shown in Fig. 10C). Here forms with as much as $\frac{1}{4}$ -in. sags between stake pockets and with damaged end plates were poorly set, pushed out of alignment by the grader operator doing fine grading, and further loosened by both the spreader and 2 or more passes of the finishing machine. In this case, it is almost impossible to delineate the forms although one possible relationship is indicated.

Night Joints—Joints formed at the end of the construction day are probably the most consistent source of roughness. Figure 10D shows a typical night joint in a very smooth slipform pavement. This joint would require grinding the full width of the pavement. This trace also delineates the multiple response of any finite-length, roughness-measuring device to large surface deviations. The swale to the right of the night joint results from the front support wheels of the profilograph climbing up to the night joint, allowing the sensor wheel to drop with respect to the frame. The high point of the night joint is emphasized by the sensor wheel resting on it while the front and rear support wheels are down. Additional distortion is probably caused by profilograph response to various wavelengths. For example, if the night joint had a wavelength of exactly 25.00, 8.33, or 5.00 ft, the trace would indicate twice the true amplitude. Fortunately, as discussed earlier, these wavelengths are usually canceled by those occurring at 12.50, 6.25, and 3.125 ft, which produce zero response. The trace to the left of the joint would then be a mirror image of the right.

Drainage Structures—Two types of drainage structures were found significantly to influence pavement roughness. The first is the standard flush-mounted inlet frame and grate cast into the pavement. This common parkway design will result in roughness patterns as shown in Figure 10E. The carryover from the edge of the grate through the third wheelpath, at least 16 ft in this case, is quite obvious. At the normally used spacing of 200 to 300 ft between inlets, these structures can constitute a significant source of roughness.

The second type of roughness-producing drainage structure is the buried unit. Figure 10F shows the effect of a large box culvert designed with the top of its roof very near the top of subgrade. In this case, the structure had been carefully backfilled several months prior to paving. The embankment also had served as a haul road for some time. However, the weight of the slipform paver supported by the extrusion plate presumably exceeded the capacity of the backfill material, because the tape implies depressions on either side of the structure.

Vibration—On most formed jobs, the primary means of vibration was a series of pan surface vibrators suspended across the rear of the top course spreader. These were occasionally found to be completely inoperative and were frequently suspected of faulty operation. Because no means of determining their absolute frequency and amplitude was available, only their presence and appearance were noted. Figure 10G shows a set of traces for a 2-lane pavement where the vibrators in the top lane were obviously not working and those in the bottom lane were. The roughness ranged from 18 in. per mile on top to 9 in. per mile on the lower trace. Similar cross-pavement variations were also encountered where surplus mortar was permitted to accumulate on the form rail or tracks of a slipform on the side of the paving operation checked infrequently by the foreman or the inspector.

Finishing Machines—The influence of various components of finishing machines (such as screeds, vibrators, and pan floats) on pavement roughness has been described. To prove that the differences were not due to equipment source, condition, or operation, most of these data were developed on projects where only one parameter was varied. However, data were collected on all equipment trains, and, although limited in regard to slipforms, no large disparities existed.

Eight different types of finishing machines were encountered on conventionally formed pavements. Three produced 95 percent of the data. Their average roughnesses

were 19.58, 19.10, and 19.85 in. per mile with corresponding standard deviations of 9.25, 9.10, and 8.00. The other 5 machines were not analyzed in detail because of their small sample sizes. All 8 manufacturers' machines varied in age and condition to the extent that any direct comparison with the new slipform machine would be misleading.

Three manufacturers' slipform pavers were evaluated. One wire-controlled machine paved 3 projects with averages of 6.2, 5.8, and 8.0 in. per mile, with corresponding standard deviations of 4.0, 1.7, and 3.5 in. per mile. A second wire-controlled machine paved one project with an average of 40.2 in. per mile and standard deviation of 13.0. The third machine was a grade-sensing unit, which paved one project with an average of 6.9 in. per mile and standard deviation of 3.4. The first machine was operated by the same personnel on all projects. The other two were run under factory supervision by local crews unfamiliar with this new paving method.

The outstanding feature of these data is the absence of any association between roughness and any one manufacturer or paving method. It is true that conventional equipment produced pavements with average roughnesses generally higher than slipform. However, many projects were equal in roughness to the best slipform contracts. Therefore, it is concluded that the higher averages are attributable to equipment age and condition, use of less than an optimum train, or poor operating methods.

CONCLUSIONS

This study's conclusions fall into 3 categories: suitability of the measuring method, roughness factors found most critical throughout the state, and influence of purely job-related occurrences on roughness:

1. The profilograph is suitable for rapidly obtaining a permanent, reproducible record of pavement roughness within hours after placement.
2. The factors most important in controlling roughness, in order of suggested ease of implementation, are as follows: (a) elimination of paving machine backup, (b) use of a pan float, (c) use of at least 3 screeds, (d) use of constant cross slope, and (e) use of full-width paving, or at least the elimination of lane-at-a-time paving.
3. Many purely job-related factors can override the best specifications. Those appearing most frequently were the following (not necessarily in order of importance): (a) changes in supervision, (b) mix design, (c) faulty equipment, and (d) design details in associated work such as drainage structures.

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6. A Study of Construction Equipment and Initial Pavement Roughness as Measured With a Profilograph. Texas Highway Dept., Research Rept. 49-2, 1968.
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Appendix A

EVALUATION OF PROFILES

Test Method No. Calif. 526-D, California Department of Public Works

EVALUATION OF PROFILES

Scope

This method describes the procedure used for determining the Profile Index from profilograms of pavements made with the California type Profilograph and also describes the procedure used to locate individual high areas when their reduction is required by the contract special provisions.

The profilogram is recorded on a scale of one-inch equal to 25 feet longitudinally and one-inch equal to one-inch, or full scale, vertically. The determination of the Profile Index involves measuring "scallop" that appear outside a "blanking" band. The determination of individual high areas involves the use of a special template.

PART I. DETERMINATION OF THE PROFILE INDEX

Procedure

A. Equipment

The only special equipment needed to determine the Profile Index is a plastic scale 1.70 inches wide and 21.12 inches long representing a pavement length of 528 feet or one-tenth of a mile at a scale of 1" = 25'. A plastic scale for the profilograph may be obtained by the Districts from the Service and Supply Department. Near the center of the scale is an opaque band 0.2 inch wide extending the entire length of 21.12 inches. On either side of this band are scribed lines 0.1 inch apart, parallel to the opaque band. These lines serve as a convenient scale to measure deviations or excursions of the graph above or below the blanking band. These are called "scallops".

B. Method of Counting

Place the plastic scale over the profile in such a way as to "blank out" as much of the profile as possible. When this is done, scallops above and below the blanking band usually will be approximately balanced. See Figure I.

The profile trace will move from a generally horizontal position when going around superelevated curves making it impossible to blank out the central portion of the trace without shifting the scale. When such conditions occur the profile should be broken into short sections and the blanking band repositioned on each section while counting as shown in the upper part of Figure II.

Starting at the right end of the scale, measure and total the height of all the scallops appearing both above and below the blanking band, measuring each scallop to the nearest 0.05 inch (half a tenth). Write this total on the profile sheet near the left end of the scale together with a small mark to align the scale when moving to the next section. Short portions of the profile line may be visible outside the blanking band but unless they project 0.03 inch or more and extend longitudinally for two feet (0.08" on the profilogram) or more, they are not included in the count. (See Figure I for illustration of these special conditions).

When scallops occurring in the first 0.1 mile are totaled, slide the scale to the left, aligning the right end of the scale with the small mark previously made, and proceed with the counting in the same manner. The last section counted may or may not be an even 0.1 mile. If not, its length should be scaled to determine its length in miles. An example follows:

Section length, miles	Counts, tenth of an inch
0.10	5.0
0.10	4.0
0.10	3.5
400' = 0.076	2.0
Total 0.370	14.5

The Profile Index is determined as "inches per mile in excess of the 0.2-inch blanking band" but is simply called the Profile Index. The procedure for converting counts of Profile Index is as follows:

Using the figures from the above example:

Length = 0.376 miles, total count = 14.5 tenths of an inch

$$\text{Profile Index} = \frac{1 \text{ mile}}{\text{length of profiles in miles}} \times \frac{\text{total count in inches}}{\text{inches}}$$

$$\text{PrI} = \frac{1}{0.376} \times 1.45 = 3.9$$

(Note that the formula uses the count in inches rather than tenths of an inch and is obtained by dividing the count by ten.)

The Profile Index is thus determined for the profile of any line called for in the specifications. Profile Indexes may be averaged for two or more profiles of the same section of road if the profiles are the same length.

Example:

	Section length, miles	Counts, tenths of an inch	
		Left wheel track	Right wheel track
	0.10	5.0	4.5
	0.10	4.0	5.0
	0.10	3.5	3.0
400' =	0.076	2.0	1.5
Total	0.376	14.5	14.0

PrI (by formula) 3.9 3.7

$$\text{Average} = \frac{3.9 + 3.7}{2} = 3.8$$

The specifications state which profiles to use when computing the average Profile Index for control of construction operations.

C. Limitations of Count in 0.1 Mile Sections

When the specifications limit the amount of roughness in "any one-tenth mile section," the scale is moved along the profile and counts made at various locations to find those sections if any, that do not conform to specifications. The limits are then noted on the profile and can be later located on the pavement preparatory to grinding.

D. Limits of Counts—Joints

When counting profiles, a day's paving is considered to include the last portion of the previous day's work, which includes the daily joint. The last 15 to 30 feet of a day's paving cannot usually be obtained until the following day. In general, the paving contractor is responsible for the smoothness of joints if he places the concrete pavement on both sides of the joint. On the other hand, the contractor is responsible

only for the pavement placed by him if the work abuts a bridge or a pavement placed under another contract. Profilograph readings when approaching such joints should be taken in conformance with current specifications.

E. Average Profile Index for the Whole Job

When averaging Profile Indexes to obtain an average for the job, the average for each day must be "weighted" according to its length. This is most easily done by totaling the counts for the 0.1 mile sections of a given line or lines and using the total length of the line in the computation for determining the Profile Index.

PART II. DETERMINATION OF HIGH POINTS IN EXCESS OF 0.3 INCH

Procedure

A. Equipment

The only special equipment needed is a plastic template having a line one-inch long scribed on one face with a small hole or scribed mark at either end, and a slot 0.3 inch from and parallel to the scribed line. See Figure II. (The one-inch line corresponds to a horizontal distance of 25 feet on the horizontal scale of the profilogram.) The plastic template may be obtained from Service and Supply Department.

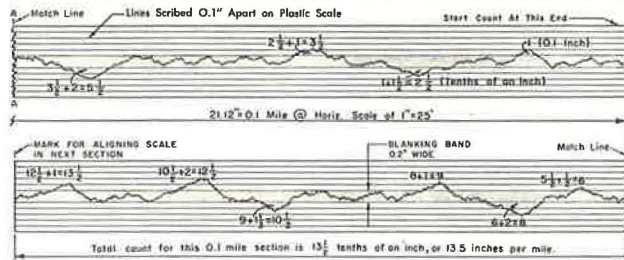
B. Locating High Points in Excess of 0.3 Inch

At each prominent peak or high point on the profile trace, place the template so that the small holes or scribe marks at each end of the scribed line intersect the profile trace to form a chord across the base of the peak or indicated bump. The line on the template need not be horizontal. With a sharp pencil draw a line using the narrow slot in the template as a guide. Any portion of the trace extending above this line will indicate the approximate length and height of the deviation in excess of 0.3 inch.

There may be instances where the distance between easily recognizable low points is less than one-inch (25 feet). In such cases a shorter chord length shall be used in making the scribed line on the template tangent to the trace at the low points. It is the intent however, of this requirement that the baseline for measuring the height of bumps will be as nearly 25 feet (1-inch) as possible, but in no case to exceed this value. When the distance between prominent low points is greater than 25 feet (1-inch) make the ends of the scribed line intersect the profile trace when the template is in a nearly horizontal position. A few examples of the procedure are shown in the lower portion of Figure II.

REFERENCE
 A California Method
 End of Text on Calif. 526-D

EXAMPLE SHOWING METHOD OF DERIVING PROFILE INDEX FROM PROFILOGRAMS



TYPICAL CONDITIONS

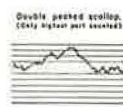
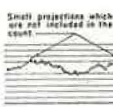
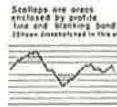
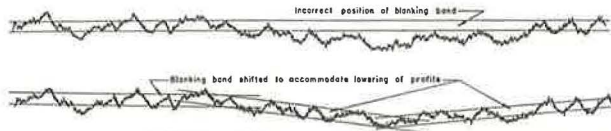


FIGURE I

SPECIAL CONDITIONS

METHOD OF COUNTING WHEN POSITION OF PROFILE SHIFTS AS IT MAY WHEN ROUNDING SHORT RADIUS CURVES WITH SUPERELEVATION



METHOD OF PLACING TEMPLATE WHEN LOCATING BUMPS TO BE REDUCED

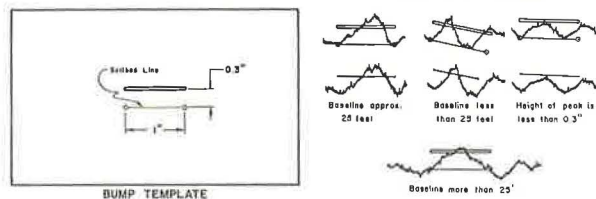


FIGURE II

Appendix B

DATA REDUCTION TESTING

To evaluate the error resulting from manual conversion of the analog trace to a digital value of inches per mile, concrete pavements representing the full range of measured roughness were selected for detailed analysis. Pavements selected had average roughness of 109.84, 14.32, and 3.70 in. per mile, and standard deviations of 7.34, 0.71, and 0.43 in. per mile respectively. Eleven persons, comprising 4 graduate engineers and 7 technicians without previous profilograph experience, reduced each set of 3 traces an average of 5 times in 1 continuous work period. The 2 regular operators had reduced the same traces, 1 set at a time, over a 2-year period. All tapes represented exactly 0.1 mile of pavement and were 21.12 in. long (25 ft per in.). Each person could select the portion of the trace to be covered by the 0.2-in. wide dead band on the template (Fig. 2). The magnitude of projections extending outside of the dead band was determined by counting the number of 0.1-in. increments inscribed on the template to the nearest quarter of an increment.

TABLE 3
REDUCTION OF IDENTICAL DATA BY TRAINED
AND UNTRAINED PERSONNEL

Trace	5-Run Avg.	Standard Deviation	Range	Coefficient of Variation, percent ^a
Trained				
1	5.19	0.28	4.75-5.75	5.5
2	1.81	0.30	1.25-2.25	17.0
3	5.38	0.45	4.75-6.00	8.4
4	2.38	0.42	1.75-3.25	17.6
Untrained				
1	5.46	0.30	5.25-6.00	5.5
2	1.96	0.34	1.50-2.50	17.3
3	6.04	1.04	4.75-7.50	17.2
4	2.82	0.34	2.25-3.25	12.1

TABLE 2
REDUCTION OF DATA BY UNTRAINED PERSONNEL

Trace	5-Run Avg.	Standard Deviation	Range	Coefficient of Variation, percent ^a
1	17.10	1.09	15.50-20.00	6.4
2	10.82	1.25	7.75-12.25	11.5
3	10.22	1.15	7.50-12.25	11.2
4	19.11	1.72	16.00-23.75	9.0

^a(S/X)100 = coefficient of variation.

TABLE 4
EFFECT OF TRAINING ON DATA REDUCERS

Operator	Trial ^a	Mean ^b	Standard Deviation	Range	Coefficient of Variation, percent ^c
1	Initial	121.44	2.25	119.50-124.25	1.85
	Replicate ^d	121.13	1.05	119.75-122.25	0.87
2	Initial	114.81	2.27	112.00-117.00	1.98
	Replicate	113.10	1.16	111.50-114.25	1.03
3	Initial	106.50	3.44	104.00-111.50	3.23
	Replicate	109.75	1.19	108.50-111.00	1.08
4	Initial	108.75	4.11	104.50-114.25	3.78
	Replicate	108.50	1.74	107.00-111.00	1.61
5	Initial	108.75	7.62	100.00-115.50	7.00
	Replicate	108.19	1.38	107.00-110.00	1.27
6	Initial	102.25	3.28	99.50-106.00	3.23
	Replicate	95.00	3.68	0.00- 98.75	3.87

^aA "trial" is examination of the same tape 4 times.

^bMean of the 4 examinations.

^cCoefficient of variation = (S/X)100.

^dSet of tapes examined after training period.

These 2 steps—covering the dead band and counting the increments—were determined to be the sources of error. Five untrained men produced the results given in Table 2 by replicating their reduction of 4 sets of traces 5 times each. The 2 regular operators with 2 years of experience were unable to produce better results for relatively smooth pavement than 2 untrained persons (Table 3). However, as roughness increased, experience provided the most reliable estimates. Tables 4 and 5 give the wide variability both within and between the work of reducers using the same set of traces throughout. Six persons were asked to evaluate the roughness of this set of traces over a 6-month period. The sixth man is one of the very few who did not reduce his standard deviation with time. His efforts are included here to show that such things occur. However, excluding him, these data indicate that a reduction in conversion variance can be achieved, while maintaining a constant mean.

TABLE 5
SUMMARY

Mean and Standard Deviation	Initial	Replicate
<u>Mean</u>		
Operators 1-5	112.05	112.13
Operator 6	102.25	95.00
Difference	-9.80	-17.13
<u>Standard Deviation</u>		
Operators 1-5	3.94	1.30
Operator 6	3.28	3.68
Difference	-0.66	+2.38