NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **275**

PAVEMENT ROUGHNESS AND RIDEABILITY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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PAVEMENT ROUGHNESS AND RIDEABILITY

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AREAS OF INTEREST:

PLANNING
PAVEMENT DESIGN AND PERFORMANCE
MAINTENANCE
(HIGHWAY TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. SEPTEMBER 1985

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation Research Board

This report describes the development of a new method for assessing pavement roughness. The method is based on a statistical transform between the physical measure of a pavement profile and the subjective rating of the pavement rideability. It is expressed as the pavement sections rideability number (RN). The report also contains a model for determining a pavement section's need for repair based on the RN computed from the pavement profile. The findings of this study will be of particular interest to highway personnel responsible for pavement rehabilitation and management programs, for collection and analysis of data on pavement surface characteristics, and for testing and research activities.

During the AASHTO Road Test completed in 1961, pavement serviceability was defined as the ability of the pavement to serve the traveling public, as determined by the subjective evaluation by a panel of motorists. The most commonly used objective measure of serviceability, the Present Serviceability Index (PSI), is generally derived from measurements made with response-type road roughness systems. However, this PSI only approximates the original panel rating concept and sometimes considers pavement defects as well as rideability. For pavement management, both at the network and project levels, it is desirable to have separate measures for rideability and for surface detects. Therefore, there is a need to develop a method of assessing pavement roughness that correlates well with the subjective panel rating or public's perception of rideability

The research approach used by the KETRON, Inc., project staff for development of a method for assessing pavement roughness or rideability involved (1) formulation of subjective rating procedures, (2) selection of pilot and full-scale test sites including pavements with varying degrees of roughness, (3) conduct of pilot and full-scale tests including collection of subjective ratings and objective profile data for the selected pavement sections, and (4) analysis of the subjective and objective data to determine the transforms or models that can be used to convert pavement profile data to subjective panel ratings or the public's perception of the pavement rideability.

The pilot studies, conducted on pavements in Pennsylvania and Florida, indicated that it appeared possible to identify specific frequency bands of longitudinal pavement roughness that are highly correlated with subjective ratings of pavement rideability. It was also found that, within the limited ranges used in the studies, vehicle size, vehicle speed, rating panel driving experience, and location of residence had little effect on subjective rating of pavement rideability. A major finding of the full-scale study conducted in Ohio was that longitudinal roughness as measured with a profilometer in the band of frequencies between 0.125 and 0.630 cycles per foot is highly correlated with the mean panel rating for portland cement concrete, asphalt concrete, and composite pavements.

The research described in this report has produced a tentative method for converting objective measures of pavement roughness (longitudinal profiles) to subjective measures of the public's perception of rideability (mean panel ratings) expressed as the rideability number (RN). The report also describes the requirements for equipment to measure pavement profiles in the specific band of frequencies needed to compute RN values. A field evaluation phase of the research has been initiated to provide regional verification of the method and determine its suitability for adoption by AASHTO as a universal method for determining pavement rideability.

The field evaluation phase is expected to be completed by mid-1987.

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Michael S. Janoff, Manager, Transportation Research Group, was the principal investigator. Dr. James B. Nick designed the ride quality experiments and the pilot analyses. Messrs. Paul S. Davit and Larry E. Decina, and Dr. Lorin K. Staplin were responsible for performing the ride quality experiment. Dr. Gordon F. Hayhoe, D&S Consulting, directed the profilometry work by Penn State and performed many of the analyses on the main experimental data.

Grateful acknowledgment and appreciation is made to the Pennsylvania, Florida, and Ohio Transportation Departments for their cooperation and assistance in supplying data, performing many physical measurements, and providing extensive staff assistance.

PAVEMENT ROUGHNESS AND RIDEABILITY

SUMMARY

During the AASHO Road Test, serviceability was defined as the ability of a pavement to serve the traveling public. The most commonly used objective measure of serviceability, the Present Serviceability Index (PSI), is derived from measurements made with response-type road roughness measuring systems (RTRRMS). This index, however, only approximates the original panel rating concept and is recognized as having shortcomings. Whether the public's perception of serviceability is the same today as it was 20 years ago is questionable; vehicles, highway characteristics, and travel speeds have changed, and serviceability is not exclusively a measurement of pavement rideability, but is confounded by the inclusion of factors for surface defects.

For management of pavement inventory, it would be better to have separate measures of ride quality and surface defects. Therefore, there is a need to develop a new pavement rating scale to ensure that objective pavement evaluations are directly and reasonably related to the public's perception of ride quality.

The research conducted under NCHRP Project 1-23 is directed toward answering that need. The general goals of the research were to (1) develop a scale that accurately reflects the public's perception of pavement roughness, (2) develop transforms that relate pavement profiles to this scale, and (3) show how roughness statistics produced by various RTRRMS relate to this scale.

The research addresses three items related to pavement roughness and ride quality: subjective measures, objective or physical measures, and statistical comparisons. It is far too complicated, time consuming, and expensive to rely on subjective ratings alone. The physical measurements, in combination with appropriate statistical transformations, are clearly preferred. However, the accuracy and validity of the physical correlates must be determined before they can be used as a replacement or surrogate for the subjective but more realistic human responses.

The tasks necessary to accomplish the goals of the study included, first, a review and critical evaluation of the literature, on-going research, and state experiences and practices to establish guidelines that could be used to aid the proposed research.

The second task was to formulate an experimental design to subjectively evaluate ride quality by means of a rating panel and physically measure longitudinal pavement roughness using a profilometer. Two experiments were designed: (1) a pilot experiment to evaluate the effects of such variables as vehicle size, vehicle speed, regionality of rating panel, and training of rating panel, and to develop the proposed methods of analysis for the subjective panel rating data, the profile data, and the statistical analyses used to relate these two types of data; and (2) a main experiment to evaluate ride quality and longitudinal roughness for three surface types—bituminous concrete (BC), portland cement concrete (PCC), and composite—and develop transforms between them.

The third task consisted of the actual performance of the experiments designed in Task 2.

The fourth task consisted of (1) the analysis of the pilot study data to determine the effects of regionality, training, vehicle size, and vehicle speed on subjective ratings and to develop analysis methods; and (2) the analysis of the main study data to develop transforms between the subjective ratings and longitudinal roughness measures for all three surface types (bituminous concrete, portland cement concrete, and composite).

The final task used these statistical relationships to develop transforms between the data types and develop procedures for implementing these transforms by the highway agencies to assess the ride quality of pavement surfaces.

The review of the literature and on-going research provided a number of inputs into the design and conduct of the panel rating experiments, including the selection of a subjective rating scale, the instructions for panel ratings of ride quality, and the effects of such factors as driver sex, driver age, and driving experience on the subjective appraisal of ride quality.

The pilot study, performed on 34 BC test sections in Pennsylvania and 31 BC sections in Florida and employing five panels of 21 drivers, revealed the effects of vehicle speed, vehicle size (two evaluated), panel regionality (i.e., the area or state in which a panelist resides), and panel training (i.e., untrained, average driver versus professionals who had expertise in the area of pavement evaluation and measurement) on the subjective appraisal of ride quality. Only panel regionality caused a small, but significant, effect on the subjective appraisal of ride quality. The second major finding of the pilot study was that it was possible to identify specific frequency bands of longitudinal pavement roughness where the amplitude of the longitudinal roughness was highly correlated with mean panel ratings (MPRs) of ride quality and linear regression methods provided highly significant statistical relationships ($r = -0.92$).

The main panel experiment was conducted in Ohio on 81 test sections including all three surface types, with 36 panel members, and employed two different profilometers—a noncontact type and one with following wheels, and a Mays ride meter (MRM) for physical measures.

A major finding of the main experiment was that longitudinal roughness as measured with a profilometer in the band of frequencies between 0.125 and 0.630 c/ft (10–50 Hz at 55 mph) is highly correlated with MPRs for all three surface types ($r = -0.94$). The resulting regression equation that transforms longitudinal roughness in this frequency band into MPR is:

$$\text{MPR} = -1.74 - 3.03 \log (\text{PI})$$

where PI, or profile index, is defined as the square root of the mean square of the profile height in the specified frequency band. (See Appendix D for a complete definition.) This equation accounts for over 88 percent of the variance. PI, the physical measure of longitudinal roughness in this frequency band, was also found to be an excellent predictor of MPRs for Florida data.

The foregoing transform results in a predictive equation:

$$\text{RN} = -1.74 - 3.03 \log (\text{PI}) \tag{1}$$

where RN is defined as the rideability number of a given pavement section. RN would thus be a value which is derived from PI by using Eq. 1 and which is an approximation for the true MPR of a given pavement section. It is not equivalent to PSI because it excludes measures of surface defects.

For BC surfaces, MPR was also found to be highly correlated with simple roughness indexes (MRM index or ¼ car index; $r = -0.91$), but for PCC and composite surfaces the correlation between simple roughness and MPR is poor to fair only. The MPR of a given test section is also an accurate predictor of the public's subjective perception of whether a specific test section needs repair. The percentage of the driving public that feels that a given pavement section requires repair is defined by:

$$NR = 132.6 - 33.5\ MPR \quad \text{or} \qquad (2)$$
$$NR = 132.6 - 33.5\ RN$$

Therefore, based only on longitudinal roughness measures (i.e., PI), one can compute both the rideability number (RN from Eq. 1) and the exact percentage of the driving population that thinks the road should be repaired (NR from Eq. 2).

The final result of this study was the development of general performance specifications for a simple roughness meter whose measurements would accurately predict RN, and, hence, the public's perception of the ride quality of roadways. Such a meter should respond accurately to longitudinal roughness in the frequency band from 0.125 to 0.630 c/ft (10–50 Hz at 55 mph) but not respond to longitudinal roughness outside this range; measure such roughness in both wheelpaths or, alternatively, first correlate single wheelpath measures with measures in both wheelpaths if only one wheelpath is measured; and be calibrated by a profilometer to ensure that it is responding accurately to the longitudinal roughness in the specified frequency band.

The major applications of these findings include (1) the proposed use of the transform that relates profile index to rideability number and needs repair rating, which is valid for all three surface types, (2) proposed performance specifications for an instrument to measure profile index in a specific band of frequencies, and (3) proposed interim methods for predicting RN from RTRRMS measures.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

During the AASHO Road Test, serviceability was defined as the ability of a pavement to serve the traveling public. The most commonly used objective measure of serviceability, the Present Serviceability Index (PSI), is derived from measurements made with response-type road roughness measuring systems (RTRRMS). This PSI, however, only approximates the original panel rating concept and is recognized as having shortcomings. Whether the public's perception of serviceability is the same today as it was 20 years ago is questionable; vehicles, highway characteristics, and travel speeds have changed, and serviceability is not exclusively a measurement of pavement rideability, but is confounded by the inclusion of factors for surface defects.

For management of pavement inventory, it would be better to have separate measures of rideability and surface defects. Therefore, there is a need to develop a new pavement rating scale to ensure that objective pavement evaluations are directly and reasonably related to the public's perception of rideability. *Rideability* is defined as the subjective evaluation of pavement roughness. *Roughness,* or more specifically longitudinal roughness, is defined as the longitudinal deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, and dynamic pavement loads (*1*). In the remainder of this report, *roughness* will mean *longitudinal pavement* roughness, unless otherwise stated.

RESEARCH OBJECTIVES

The general goals of this research were to (1) develop a scale that accurately reflects the public's perception of pavement roughness, (2) develop transforms that relate pavement profiles to this scale, and (3) show how roughness statistics produced by various RTRRMS relate to this scale. The specific objectives of this research were as follows:

1. Select an array of pavement sections representing a wide range of pavement roughness.
2. Make a subjective rideability evaluation of the pavement sections.

3. Measure and record the profiles of both wheel tracks of the pavement sections concurrent with subjective evaluations.
4. Correlate the subjective scale values with the measured profiles.
5. Recommend procedures for implementation of the findings by highway agencies to determine rideability for RTRRMS measurements.

Pavement roughness and ride quality involve three related items: subjective measures, objective or physical measures, and statistical comparisons. It is far too complicated, time consuming, and expensive to rely on subjective ratings alone. The physical measurements, in combination with appropriate statistical transformations, are clearly preferred. However, the accuracy and validity of the physical correlates must be determined before they can be used as a replacement or surrogate for the subjective but more realistic human responses.

RESEARCH APPROACH

To meet the specific objectives of the study, a research plan was adopted which consisted of five tasks. The first task included a review and critical evaluation of the literature, on-going research, and state experiences and practices to determine which definitions, variables, methodologies, techniques, and procedures could be employed and which results of past work could be used to guide or aid the proposed research.

The second task was to formulate an experimental design to subjectively evaluate ride quality by means of a rating panel and physically measure road roughness using a profilometer. Two experiments were designed: (1) a pilot experiment to evaluate the effects of such variables as vehicle size, vehicle speed, regionality of rating panel, and training of rating panel (i.e., trained versus layman) and to develop the proposed methods of analysis for the subjective panel rating data, the profile data, and the statistical analyses used to relate the previous two types of data; and (2) a main experiment to evaluate ride quality and roughness and their relationships.

The third task consisted of the actual performance of the experiments designed in Task 2. The pilot study was conducted first using a selection of 34 bituminous concrete (BC) road sections in Pennsylvania and 31 BC sections in Florida. The sections were selected to represent a wide range of roughness conditions. Five rating panels of 21 persons each and two different size vehicles were also employed. The main panel study was performed employing 36 persons and four identical vehicles in Ohio on 81 sections of road, including 25 BC, 22 portland cement concrete (PCC), and 34 composite. Profile data and Mays ride meter (MRM) indices were collected in all three states.

The fourth task consisted of (1) the analysis of the pilot study data to determine the effect of regionality, training, vehicle size, and vehicle speed on subjective ratings and to develop analysis methods; and (2) the analysis of the main study data to develop transforms between the subjective ratings and roughness measures for all three surface types (BC, PCC, and composite).

The final task used these statistical relationships to (1) develop transforms between the objective measurements obtained with the profilometer and subjective rideability measures, (2) develop transforms between the objective measurements obtained with the profilometer and those that can be obtained by the use of RTRRMS, (3) develop transforms that relate RTRRMS to the subjective measures, (4) develop transforms between subjective need for repair ratings and subjective panel ratings, and (5) develop procedures for implementing these transforms by highway agencies to assess rideability of pavement surfaces.

The following sections describe the pilot study and main experiment in detail.

Pilot Study

Objectives

The objectives of this experiment were to (1) evaluate the effect of vehicle size, vehicle speed, panel regionality, and panel training on the subjective evaluation of pavement ride quality, and (2) develop and test analysis methods for relating subjective measures of pavement ride quality to physical profile measures.

Panel regionality differences affect the generalizations of the results to other areas; panel training addresses the use of trained (in pavement evaluation) state employees instead of laymen for subjective evaluations; and vehicle size and speed are two of the main variables that define the actual protocol of the panel experiment.

Experimental Design

The panel rating experiment was designed to provide a subjective evaluation of ride quality. The material in this section is organized into four parts: (1) rating method, (2) panel, (3) sites, and (4) experimental plan.

1. *Rating Method*—Based on the results of previous work (*2*), the Weaver/AASHO scale illustrated in Figure 1 was selected. This scale was chosen because it preserved continuity with past work by Weaver and others and because there was virtually no difference in performance (i.e., correlation of subjective ratings with MRM-derived roughness and inter-rater agreement) between it and either of the other scales employed in the previous research.

2. *Panel*—Five panels were used, as given in Table 1. The total panel consisted of 63 Pennsylvania licensed drivers, 21 Florida licensed drivers, and 21 trained Pennsylvania raters (i.e., individuals who by training and experience had expertise in the area of pavement evaluation). The 63 Pennsylvania drivers were drawn from the Pennsylvania Department of Transportation (PennDOT) employees, Ketron employees, and members of the driving public; the 21 Florida drivers were drawn from University of Florida (UFLA) employees and members of the driving public; and the trained raters included professionals from PennDOT.

All nontrained panels were composed of licensed drivers, included both sexes, spanned a wide range of ages/driving experience, and excluded any individual who evaluated roads as part of his or her normal working duties. Other factors were shown to be unimportant in previous research (*2*).

The size of the panels (21 each) was determined from the statistical theory related to the experimental design. The use of hypothesis tests in these experiments required a sample size of 21 to detect a minimum difference of 0.5 scale units between two treatment groups (e.g., panel regionality or vehicle size)

Table 1. Panels for pilot study.

Individual Study	Number	Composition
Regionality	42	21 Pennsylvania drivers 21 Florida drivers
Vehicle speed	21	Pennsylvania drivers
Vehicle size	21	Pennsylvania drivers
Expert/Laymen	21	Pennsylvania drivers

with a probability of 90 percent that the effect will be found if it exists with a 5 percent error (type 1) (*3*).

3. *Sites*—The major site classification variable for the experiments was roughness. That is, a wide range of roughness was spanned by the sites selected for use. Surface type was restricted to flexible (BC), all sites were in rural areas, and the topography of the sites was generally straight and level. All of the sites were similar in appearance (except perhaps for cues related to roughness such as cracks), so that the subjective ratings were not influenced by other variables.

Thirty-four BC sites were used for the Pennsylvania route. Thirty-one sites were then selected in Florida to provide a route similar to that in Pennsylvania. The site characteristics are described under the "Experimental Protocol" section.

4. *Experimental Plan*—Table 2 summarizes the experimental plan for the study, including an overview of the key variables and the hypotheses that were tested. Profilometry and MRM measurements were obtained concurrent with panel ratings.

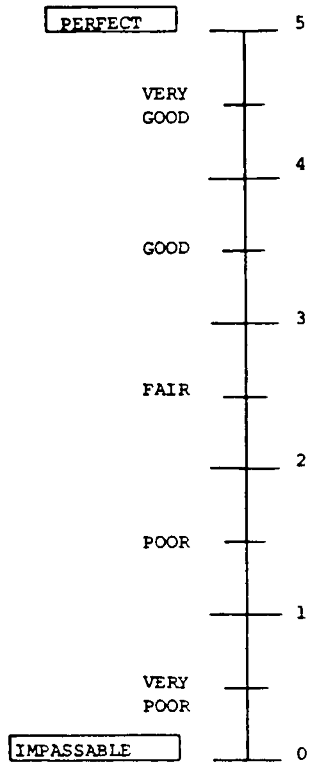

Figure 1. The Weaver/AASHO scale.

Experimental Protocol

This section describes the procedures that were followed to conduct the four experiments. These procedures included panel selection, site selection and marking, and data collection.

1. *Panel Selection*—The Pennsylvania panels were obtained from PennDOT, the driving public (via a newspaper advertisement), and the Ketron administrative staff. The Florida panel was selected from UFLA staff and the driving public (via an advertisement in the Gainesville, Florida, area). The trained panel was drawn from PennDOT.

On the basis of the results of previous work (*2*), a primary consideration during panel selection was to ensure a wide range of "years of driving experience," because this factor was the only panel-related variable previously evaluated which seemed to influence subjective ratings of ride quality.

2. *Site Selection and Marking*—Three tasks were involved in

Table 2. Summary of experimental plan.

Experiment	Panel	(#)	Sites	Vehicle[1]	Speeds	Null Hypothesis
Panel Regionality	21 PA 21 FL	1-a 1-b	FL FL	K-Car K-Car	1 per site 1 per site	No difference between the mean ratings for regionally different panels.
Vehicle Size	21 PA 21 PA	1-a 2	PA PA	K-Car Subcompact	1 per site 1 per site	No difference between the mean ratings obtained from either vehicle.
Vehicle Speed	21 PA 21 PA	1-a 3	PA PA	K-Car K-Car	1 per site 1 per site but 6-8 site speeds changed	Different speeds have no effect on subjective appraisals of ride quality.
Trained/ Laymen	21 PA 21 PA Experts	1-a 4	PA PA	K-Car K-Car	1 per site 1 per site	No difference between the mean ratings made by trained and laymen panels.

1 All K-Cars were as identical as possible (age, mileage, tires, tire pressure). The subcompact had front-wheel drive.

selecting the final test sections used for this study: (1) planning and surveying potential routes and sites, (2) measuring and marking the selected route and sites, and (3) obtaining physical measures of road roughness. These tasks were performed in both Pennsylvania and Florida.

To select the Pennsylvania route the following procedures were followed:

a. Obtain MRM data for all legislative routes in the Chester County area.
b. Select a range of sites (roughness and functional class) and link together a possible route.
c. Visit sites; delete sites not meeting criteria (e.g., resurfaced, including anomalous sections, not uniform roughness).
d. Link remaining sites together and visually pick additional sites on link roads.
e. Pick additional sites on the route to equalize travel time between sites.
f. Measure and mark all sites to obtain uniform time exposures (25 sec) on each site, e.g., a 55-mph test site would be (25 × 81 =) 2,025 ft long. In addition, about 1,200 ft preceding and 1,200 ft following each test section would have the same roughness. Only the 2,025-ft section is employed for ratings and physical measurements.
g. Measure roughness on each test section (e.g., center 2,025 ft) with an MRM.

Figure 2 shows the Pennsylvania route. The individual sites are described in Appendix B. They have a range of MRM values of 85 to 639 in./mi.

The Florida route was selected to be as similar as possible to the Pennsylvania route—including number of sites, route length, topography, area type, and roughness. The procedure followed was quite similar to that employed in Pennsylvania except that, since MRM data were only available for the State roads (not county or local roads), a candidate route was not selected until after almost all of the State and county roads in the Gainesville area were visited. The final Florida route is illustrated in Figure 3. Appendix B summarizes the individual

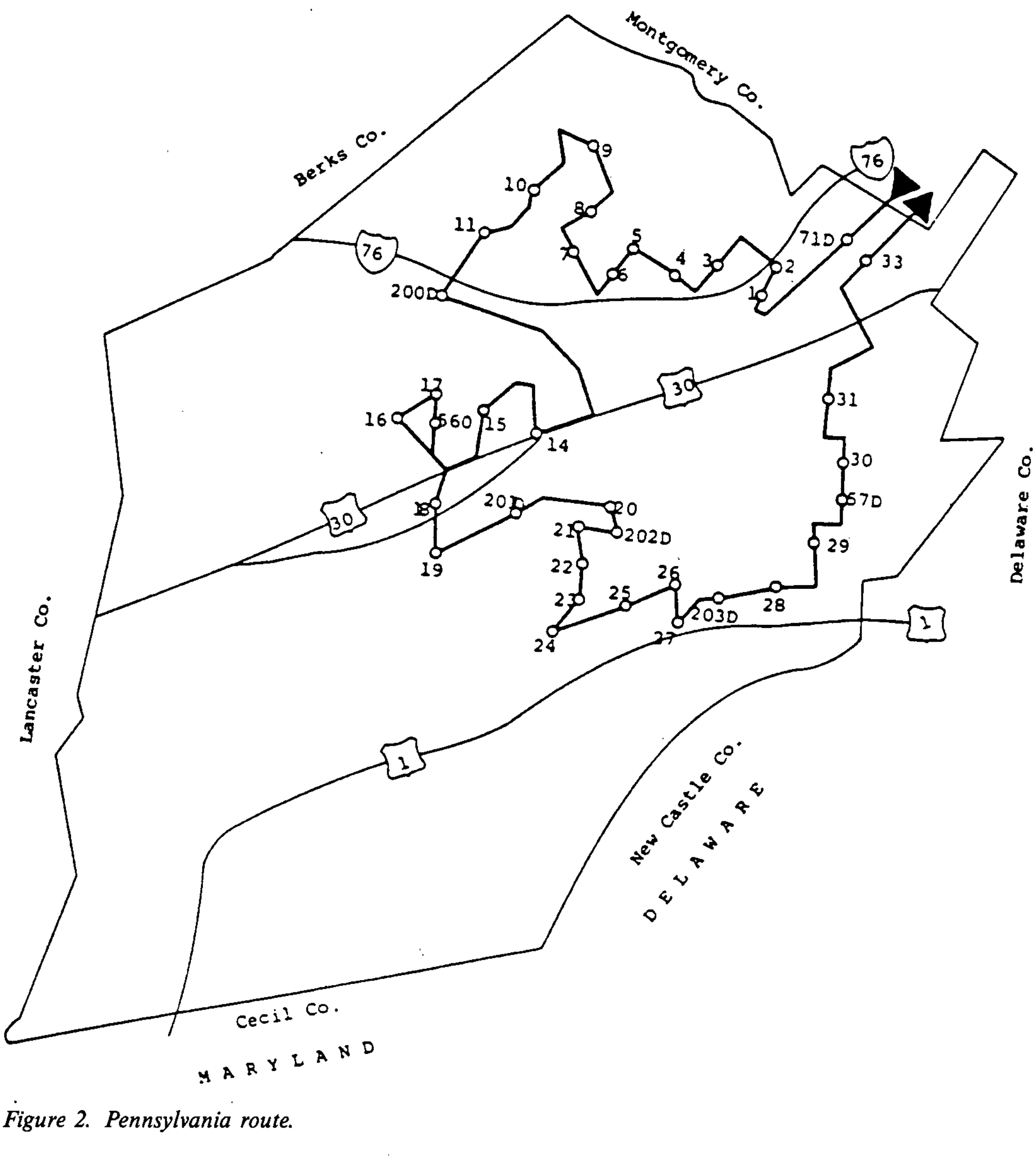

Figure 2. Pennsylvania route.

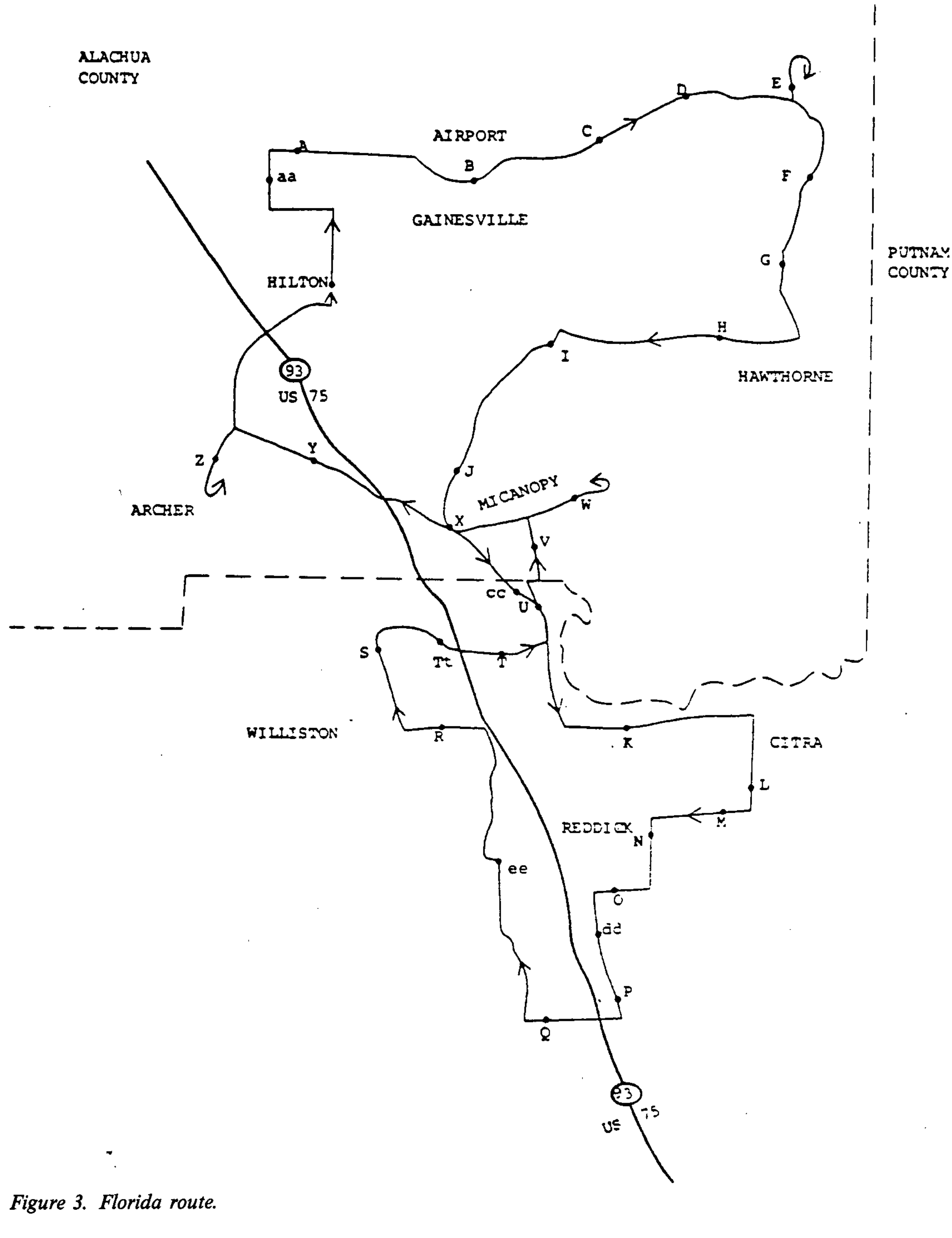

Figure 3. Florida route.

sites, which have a range of MRM values of 28–355 in./mi on the PA MRM (4–225 in./mi on the FL MRM).

3. *Data Collection*—Data collection included the following steps: (1) instrumentation, (2) instructions for raters, (3) data collection, (4) data reduction, and (5) physical measurements.

Instrumentation consisted of rating forms, instructions, and vehicles. The choice of K-Cars as the main test vehicles and a subcompact as the alternate was based on the recent trends toward front-wheel drive and the general downsizing of the U.S. auto fleet.

The rating form included identification number, section number (which identified roughness, etc.), and the Weaver/AASHO scale. (All site/panel identification was provided from the identification and the section numbers.) One form was provided for each panel member for each site. A sample form is illustrated in Appendix B.

The rating form also included a secondary two-alternative forced choice (i.e., one of two boxes must be checked for each site by each panel member) to subjectively evaluate whether each pavement section requires repair or maintenance or does not require repair or maintenance. This rating was used to obtain the public's perception of whether specific roughness levels require maintenance and how this may correlate with the physical and subjective measures. If, for example, a specific roughness level was perceived by 85 percent of the panel members as requiring maintenance, highway administrators would have more useful insight into selecting projects for maintenance or rehabilitation based on the opinions of the driving public.

The instructions for the raters are probably the most important aspect of the subjective ratings. These instructions include explanation of the attribute of ride quality being assessed; the scale to be employed; the process of rating, including response to panelists' questions concerning this process; schedule, including meals, breaks, and return time; confidentiality of ratings and use of nonidentified grouped data; definitions that the raters should understand concerning the points on the rating scale; and answers to any questions the raters may have concerning the task desired of them, the procedures, definitions, etc. The instructions were given to the panel members at the beginning of each experimental period in a standardized format to remove the effect of personal interpretation of the experimenters. Questions arising during the study were answered in a similar uniform manner. Panel instructions are presented in Appendix B.

The data collection procedures can be illustrated by the steps employed during one typical day.

a. Raters meet with experimenters at central site.
b. Teams are formed (three raters plus one experimenter).
c. Seat positions are assigned.
d. Rater forms are distributed—ordered by route (i.e., site information precoded on forms).
e. Instructions are read and questions answered.
f. Raters are driven to beginning of route and additional questions are answered.
g. Speed for next site is selected by experimenter.
h. Site is rated.
i. Forms are collected after each site. (Repeat steps g, h, and i to end of route.)
j. Breaks are taken as necessary.
k. When route is finished, raters are returned to central site and forms are collected from all experimenters for data reduction.

The forms were compiled on a daily basis, immediately checked for completeness, and duplicated (the copy for a safe file, the original for data reduction and analysis). The data on each individual form were then coded and keypunched for statistical analysis.

The data were reduced by measuring the distance, to the nearest $\frac{1}{10}$ in., of the rating mark from the bottom of the scale.

Physical measurements of roughness were accomplished with the PSU profilometer and the MRM concurrent with the panel ratings. The Florida MRM was then calibrated against the Pennsylvania MRM on all 31 Florida test sections.

Data Analysis

Five analyses were planned for the pilot study:

1. An analysis of the effect of panel regionality (i.e., residence of rating panel) on the subjective evaluation of ride quality.
2. An analysis of the effect of vehicle size on the subjective evaluation of ride quality.
3. An analysis of the effect of vehicle speed on the subjective evaluation of ride quality.
4. An analysis of the effect of using trained raters (i.e., experts) on the subjective evaluation of ride quality.
5. A comparative analysis of the subjective rating data and the physical profile and response-type roughness data to develop preferred methods for developing transforms between the data types.

Main Experiment

Objectives

One of the objectives of this experiment was to select an array of pavement sections of all three surface types. The sections were also to represent a wide range of roughness conditions. Other objectives were to make a ride quality evaluation of the pavement sections; measure and record the profiles and response-type roughness concurrent with the subjective ride quality ratings; and analyze the subjective, profile, and response-type roughness data to develop transforms between the data types.

Experimental Design

The experimental design was very similar to that used in the pilot study and is summarized as follows:

1. *Rating Method*—Weaver/AASHO scale including modified secondary rating (deleting reference to money), as illustrated in Appendix C.
2. *Panel*—Thirty-six employees of the Ohio Department of Transportation (ODOT), all laymen, spanning a range of driving experience of 1–50 years.
3. *Sites*—Eighty-one test sections in the Columbus, Ohio, area, including 25 BC, 22 PCC, and 34 composite. Appendix C describes the test sections and the route.
4. *Test Vehicles*—Four K-Cars of similar age and mileage used for all ratings.
5. *Instructions*—As in pilot study, with editorial changes (e.g., "Pennsylvania" changed to "Ohio").
6. *Site Selection and Marking*—Similar to method used in Florida for pilot study.

Experimental Protocol

Same as pilot study except two days were required to rate all 81 test sections for each group of panelists.

Data Reduction

Same as in pilot study.

Profilometry

All 81 test sections were profiled by ODOT using their new K. J. Law noncontact profilometer as well as the ODOT MRM. Eleven test sections were also profiled using the PSU profilometer.

Data Analysis

The following analyses were planned using 20 BC, 20 PCC, and 20 composite test sections spanning the widest possible range of roughness:

1. Mean panel ratings (MPRs) correlated with ¼ car, MRM, and "needs repair" for all three surface types individually and for all 60 sections combined. Apply transforms of physical data as necessary (e.g., log).
2. Correlation of "needs repair" with ¼ car and MRM for all three surfaces individually and combined.
3. Correlation of MRM and ¼ car for all three surfaces individually and combined.
4. Effect of road class (or other road variables) on analyses 1 and 2.
5. Graphical analyses of profiles of right wheelpaths.
6. One-third octave analysis of profiles of right wheelpaths (correlate Profile Index (PI) in one-third octave bands with MPRs). (An octave is a band of frequencies extending from X c/ft to $2X$ c/ft (or from X Hz to $2X$ Hz) for any value X. Each octave contains 3⅓ octave bands.)
7. Selection of cutoff points: identification of upper, lower, center bands, etc., and correlation of PI in these bands with MPRs for all three surface types individually and combined.
8. Application of transforms to physical data. Analyses 6 and 7 repeated as necessary.
9. Comparison of results of analyses 1 to 9 for ODOT and Florida Department of Transportation (FLDOT) data.
10. Comparison of ¼ car, PI, graphical outputs, etc., of 11 sections for two different profilometers (ODOT noncontact versus PSU with contact wheels).
11. Development of transforms between profiles and MPRs, between RTRRMS and MPRs, between profiles and RTRRMS, and between MPRs and need for repair (NR).

CHAPTER TWO

FINDINGS

LITERATURE REVIEW

A search of the TRIS data base, U.S. Department of Transportation library, and other sources revealed 34 references that were related in some way to the objectives of the study. These items were obtained, reviewed, and classified into five major categories of information: (1) definitions and concepts, (2) subjective rating methods, (3) objective (physical) measurements, (4) statistical methods, and (5) uses of roughness and rideability data. The major results of this review are summarized in this chapter and discussed in detail in Appendix A.

Definitions and Concepts

Rideability or ride quality is the subjective evaluation of pavement roughness; *roughness* is the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, and dynamic pavement loads (*1*). This latter definition excludes the (visual) effects of surface defects such as cracking, potholing, spalling, and patching, which were included in the original concept of pavement serviceability defined by Carey and Irick (*4*). Their definition of pavement serviceability, based on how well pavements serve traffic, forms the basis for the preceding definition of ride quality. Carey and Irick found that serviceability is quantifiable and is a psychological quality or experience, not a physical measure of surface roughness.

Subjective Rating Methods

The system developed by Carey and Irick (*4*) employs an adjective comparison scale of 0 to 5 with word cues ranging from "very poor" to "very good" to describe the serviceability of each test section. Hutchinson (*5*) analyzed this rating system with respect to the basic principles of subjective rating scale construction and found that the original AASHO scale included some of the more common distortions and biases to which rating scales are vulnerable (e.g., error of leniency, halo effect, central tendency, and anchoring).

Weaver (*6*) continued the analysis of Hutchinson for the New York Department of Transportation and developed a refined rating procedure that included a larger number of test sections (90), a larger number of raters (60), exact test section lengths, homogeneity of test sections, rapid transition between test sections, exact rater instructions and procedures, and new rater forms and analysis procedures. Weaver found that highway user-perceived serviceability can be precisely measured at any time or place to permit calibration of vehicle-mounted roughness measuring systems whose output is highly correlated with serviceability.

Janoff and Nick (*2*) continued the preceding analyses to determine the preferred psychophysical scaling method for pavement ride quality evaluations. Three different psychophysical scales were evaluated: (1) the Weaver/AASHO scale, (2) Holbrook's graphic scale (more accurate definition and placement of intermediate cue words than for AASHO scale), and (3) a nonsegmented scale with cue words only at the endpoints. Figure 4 shows these scales.

Using three panels of 18 raters each, 30 BC test sections spanning a wide range of roughness, exact instructions, and both analysis of concordance and regression analysis, it was found that each of the scales, when properly employed, can provide high correlations between response-type roughness measures and subjective ratings.

Objective (Physical) Measurements

Road roughness is evaluated by two types of equipment, one measuring the responses to roughness (response-type equipment) and the other measuring actual profiles (profilometers).

Response-Type Equipment

Response-type equipment records the dynamic response of a mechanical system traveling over a pavement surface at a constant speed; therefore, the characteristics of the mechanical system and the speed of travel affect this measurement. Response-type equipment includes meters such as the BPR roughometer, the PCA (Portland Cement Association) meter, and the Mays meter.

Response-type equipment is widely used because of its simplicity, low cost, and high-speed operation. However, it is known to be unstable, and suitable calibration procedures must be employed to provide useful data.

Road meters measure a dynamic effect of the roughness, but do not define the profile of the roughness. The selection of the mechanical system is critical, because some wavelengths will be amplified while others will be attenuated.

Profiling Equipment

Profilometers are designed to provide accurate, scaled reproductions of the pavement profile along a straight line. The advantage of a profilometer is that it provides complete information about the pavement profile, which can be evaluated according to specific needs. However, the initial cost and/or operation of this equipment is high, and additional data processing is often required to meet specific informational needs.

The simplest profilometer is a straightedge which is operated either statically or at very low speed, and is not readily suitable for wide-scale profiling.

General Motors Research (GMR) Laboratories developed the first modern roadway profiling equipment, the GMR profilometer, in the 1960s. It used two spring-loaded, road-following wheels, instrumented with a linear potentiometer to measure relative displacements between the road surface and a computed inertial reference. Improvements to the original profilometer include (1) on-board computers to digitally compute profiles as they are measured (instead of the original analog computation) and (2) noncontact sensors to replace the two spring-loaded following wheels.

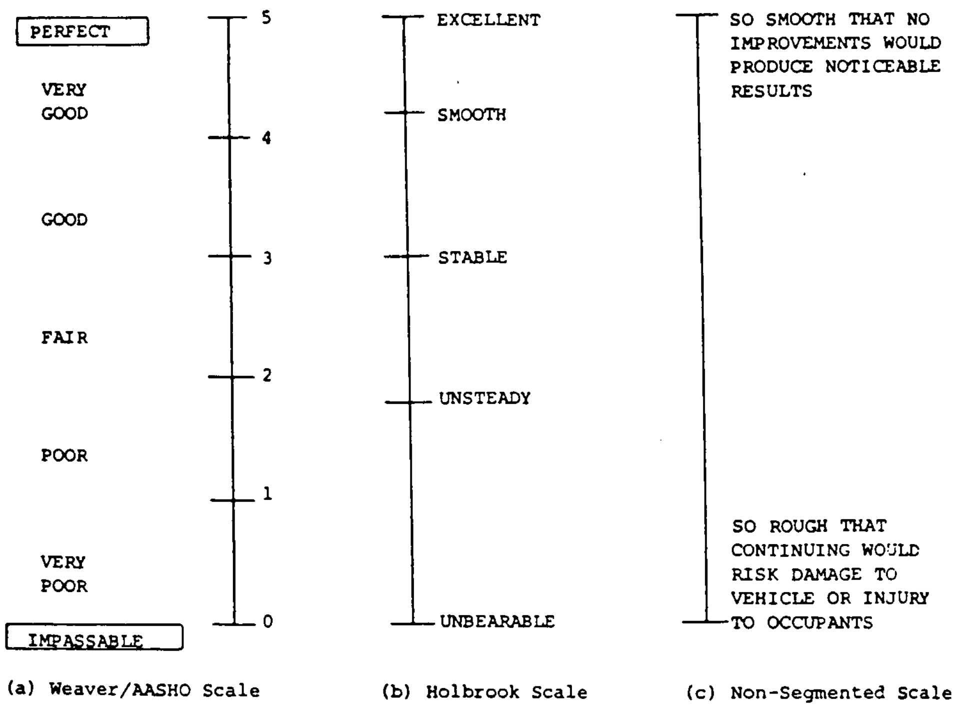

Figure 4. Three rating scales.

Statistical Methods

Analyses of roughness and rideability data fall into three categories: (1) analysis of physical roughness data, (2) analysis of subjective rideability data, and (3) comparative analysis of physical and subjective data.

Physical Data

Since measured records of roughness or profile data are recognized as random signals of finite durations, they can be described in terms of three domains: space (or time), amplitude, and frequency. Of the three, frequency domain descriptions are generally considered to contain the most information. The space domain description is the unprocessed signal-versus-space (or time). The various amplitude domain descriptions reduce the measured signal to a single number or table of values. This procedure is mathematically equivalent to computing an amplitude probability distribution for the signal (*7*). The PSI, the most commonly used method, represents the amplitude domain.

There are three basic frequency domain analysis methods that are applied to road roughness data: harmonic analysis, power spectral density (PSD), and amplitude-frequency distribution (AFD). Harmonic analysis assumes that the road roughness data are periodic and reduces a complex road roughness waveform to a harmonic series of sinusoid waveforms, which are considered to be the amplitude contributions of the various harmonics in the road roughness data. PSD representation assumes random road roughness data and shows the extent to which spatial wavelengths within a bandwidth contribute to road roughness. AFD provides a combination of the information contained in the PSD and the amplitude representations. The complete array of numbers of the AFD includes continuous or periodic makeup of singularities in the input.

Subjective Data

Beginning with Carey and Irick (*4*) a number of approaches have been followed to analyze the psychophysical data derived from the subjective ratings of pavements. Such analyses are dependent on the design of the experimental procedures and the form of the data collected. However, each analysis ultimately yields a single value (e.g., the MPR) for each test surface for the AASHO type of evaluation as developed by Carey and Irick (*4*). Weaver (*6*) extended this approach modeled on psychophysical theory developed by Guilford (*8*). His approach was based on the premise that raters are only capable of making ordinal judgments of ride quality rather than direct interval-scaled judgments.

Janoff and Nick (*2*) further evaluated this hypothesis and found that direct (e.g., MPRs) and indirect ratings (e.g., ratings for each test section derived using Guilford's theory) are almost perfectly correlated ($r = 0.99$).

Comparative Analysis

The main statistical analysis required for the study of rideability is that which compares the objective and subjective data to obtain a transform relating the two data types. The form of the subjective data has typically been in terms of a single numerical rating for each pavement surface. The objective data, however, can be as simple as a single number or as complex as AFDs. Many researchers have attempted to compare objective, physical roughness measurements with subjective measures (ratings) of user's perception of pavement serviceability (i.e., Pavement Serviceability Rating).

The original comparison of subjective and objective ratings was accomplished by Carey and Irick (*4*). A BPR roughometer and rut depth gauge were used to obtain roughness and profile characteristics (as well as measurement of cracking, etc.), and a panel was employed to subjectively rate the test sections. Carey and Irick hypothesized a linear model which would be a function of surface deformation and deterioration and which would predict Pavement Serviceability Rating as obtained from the panel ratings. They found correlation coefficients of 0.844 and 0.916 for flexible and rigid pavements. Weaver (*6*) developed similar models relating roughness alone to subjective ratings.

A number of other researchers have related subjective ratings to profilometer-derived measures of roughness (e.g., *9, 10*). Holbrook and Darlington (*11*) investigated the functional relationships between the spectral density frequencies of the road profile and subjective responses to road roughness, to disclose the underlying problems which had been previously ignored or missed, and suggested solutions for providing more accurate functional relationships. They demonstrated that when human subjective responses to road roughness were functionally related through multiple regression to PSD frequencies of the road profile, highly inaccurate or unreliable relationships could result. The problem was extremely high intercorrelation of many of the frequencies, resulting in part from the difference in elevation between the inner and outer wheelpaths, causing a roll component which could have a strong effect on ride quality. The problem was not alleviated by stepwise multiple regression in an attempt to capture only the most important frequencies. Their proposed solution included the development of a power function relating the two wheel profile signals.

Uses of Roughness and Rideability Data

Carey and Irick (*4*) pointed out four fundamental uses of pavement roughness measurements:

1. To maintain construction quality control.
2. To locate abnormal changes in the highway, such as drainage or subsurface problems, and extreme construction deficiencies.
3. To establish a systemwide basis for allocation of road maintenance resources.
4. To identify road serviceability-performance life histories for evaluation of alternative designs.

Wambold (*7*) expanded this list to include the following uses:

1. Specifications of surface profile limits and rideability of new road construction.
2. Evaluation of costs to improve the road.
3. Prediction of loss of rideability in existing roads.
4. Establishment of maintenance and replacement criteria.

5. Correlation with vibrational response and fatigue damage in vehicles.
6. Development of passenger comfort criteria.
7. Evaluation of roughness effects on vehicle steering and braking.

Some of these applications require highly sophisticated data processing, which lead to an entirely mathematical representation of the profile record. Other applications may require only an averaging or summing to establish a single roughness or rideability criterion.

PILOT STUDY

Panel Regionality Experiment

The objective of this experiment was to determine if drivers from culturally and geographically diverse backgrounds have different expectations regarding the quality of the ride provided by a particular highway system. Specifically, it was desired to determine if Pennsylvania drivers' perception of Florida roads was different from Florida drivers' perception of Florida roads.

Twenty-one Florida residents and 21 Pennsylvania residents rated the ride quality of 31 Florida road sites. Figure 5 shows the graphs of the means obtained from both groups of drivers. The horizontal axis is on an ordinal scale with the sites ordered according to increasing MRM readings which are listed under each site (sites CC, K, and L were not Mays metered, and their place in the order of sites was estimated by their MPRs). The vertical axis represents the MPRs obtained from the rating task. Data points plotted with circles represent the MPRs for the Pennsylvania (PA) drivers; triangles represent the MPRs for the Florida (FL) drivers.

A two-way analysis of variance (ANOVA) (2 geographic regions $\times$ 31 roughnesses) with repeated measures on the roughness factor was used to test the hypothesis that there was no difference between the ratings of PA and FL drivers. The main effects of both roughness and regionality were found to be significant at the 0.01 α-level. Additional analyses of the difference between PA and FL drivers for each site showed that there were no significant differences for 9 out of the first 13 sites, as indicated by the "ns" above the data points. All other differences were statistically significant.

Generally, regionality appears to have no effect when judging smooth roads; everyone seems to agree what the rating should be for very smooth roads. There is a statistically significant effect of regionality for rougher roads; PA drivers tended to give higher ratings (i.e., rated them as smoother) than FL drivers on the rougher roads. The average difference is approximately 0.5 scale unit.

Vehicle Size Experiment

The objective of this experiment was to determine if the size of the vehicle has an effect on the perception of ride quality.

Twenty-one PA subjects rated 11 PA BC sites in a 1982 Horizon while another group of 21 PA subjects rated the same sites in a 1982 Reliant. Figure 6 shows the MPRs for these two groups. The horizontal axis indicates cumulative axle displacements in inches per mile. The vertical axis indicates the MPRs. The circles represent the MPRs for the Horizon group; the triangles represent the Reliant group.

A two-way ANOVA (2 vehicle sizes $\times$ 11 roughnesses) with repeated measures on the roughness factor tested the hypothesis that there was no difference between car size. The main effects of size and interaction between car size and roughness were found not to be significant.

If one is willing to assume that the Horizon and the Reliant are representative of today's down-sized subcompact and compact/intermediate cars, respectively, it seems safe to conclude that different vehicle sizes within this range have no systematic impact on the perception of ride quality.

Vehicle Speed Experiment

The objective of this experiment was to determine if the speed at which a vehicle traverses a road alters the perception of roughness.

Twenty-one PA subjects were driven at 25 mph across 7 "speed change" sites embedded in the 34 Pennsylvania BC sites. Another group of 21 Pennsylvania subjects traversed these same sites at 45 mph. Figure 7 shows the results of this experiment. The X and Y axes are the same as in Figure 6. The data points plotted with circles represent the MPRs obtained at 25 mph; the triangles show the MPRs obtained at 45 mph.

A two-way ANOVA (2 speeds $\times$ 7 roughnesses) with repeated measures on the roughness factor was used to test the hypothesis that there were no differences between the two speeds. The main effect of speed was found not to be significant, but there was a significant interaction between speed and road roughnesses. Additional analyses showed that the significant interaction is due only to the difference in MPRs for the site with 639 in./mi cumulative axle displacement.

Since traversing a road having a measured roughness of 639 in./mi at 45 mph is quite abnormal, it is concluded that driving across roads at any speed within a *normal* driving range appears to have no systematic impact on the perception of roughness.

Panel Training

The objective of this experiment was to determine if a panel of trained raters' perception of the ride quality provided by roads was different from the laymen's perception.

One panel of 21 Pennsylvania-trained professionals was driven over 11 Pennsylvania BC sites spanning a wide range of roughness. The MPRs obtained from the panel were compared with those given by laymen for the same sites using a two-way, repeated measures ANOVA (2 levels of expertise $\times$ 11 roughnesses).

Figure 8 shows the result of this experiment. There was no statistical difference between the laymen (circles) and the trained Pennsylvania raters (squares).

Both laymen and trained professionals subjectively rate roads the same, and it is believed that a state could employ either type of individual for panel rating experiments.

A small group of regionally diverse experts (actually eight members of the NCHRP Panel on Project 1-23) was also employed to rate the same 11 test sections. However, since the panel size was so small, the group was so regionally diverse, and such a trained group would never all be found employed

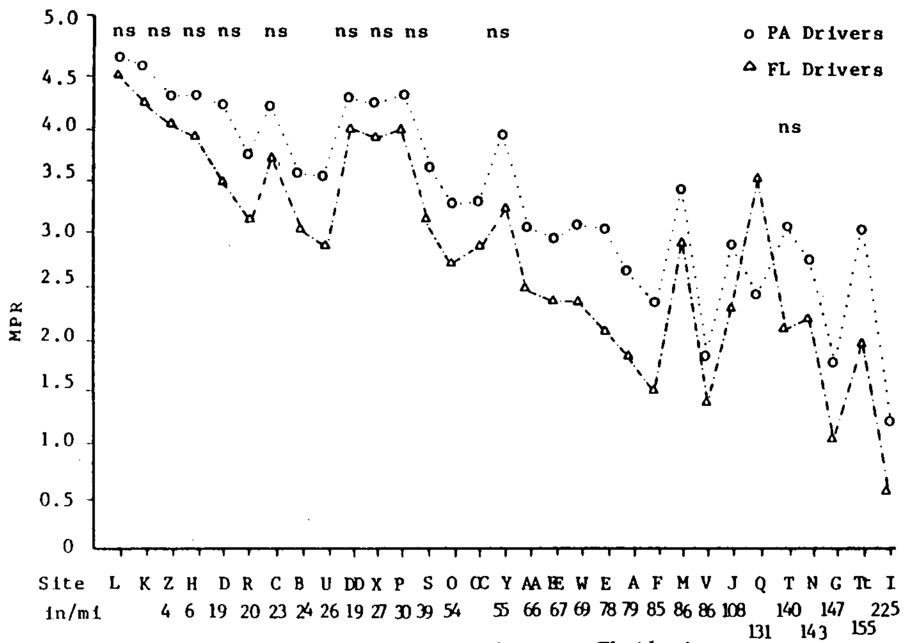

Figure 5. MPRs for Pennsylvania and Florida drivers on Florida sites.

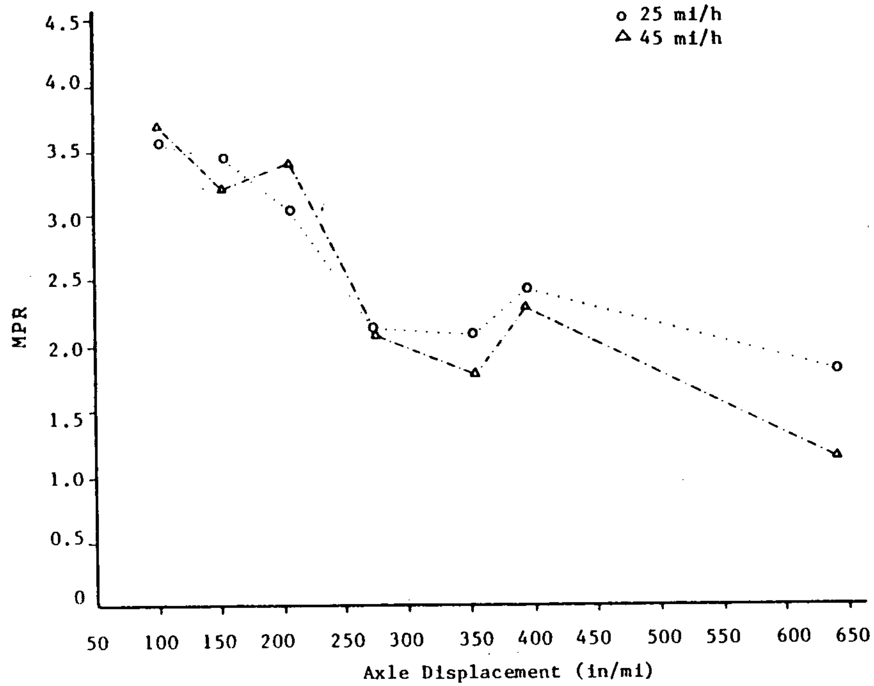

Figure 7. Effect of vehicle speed.

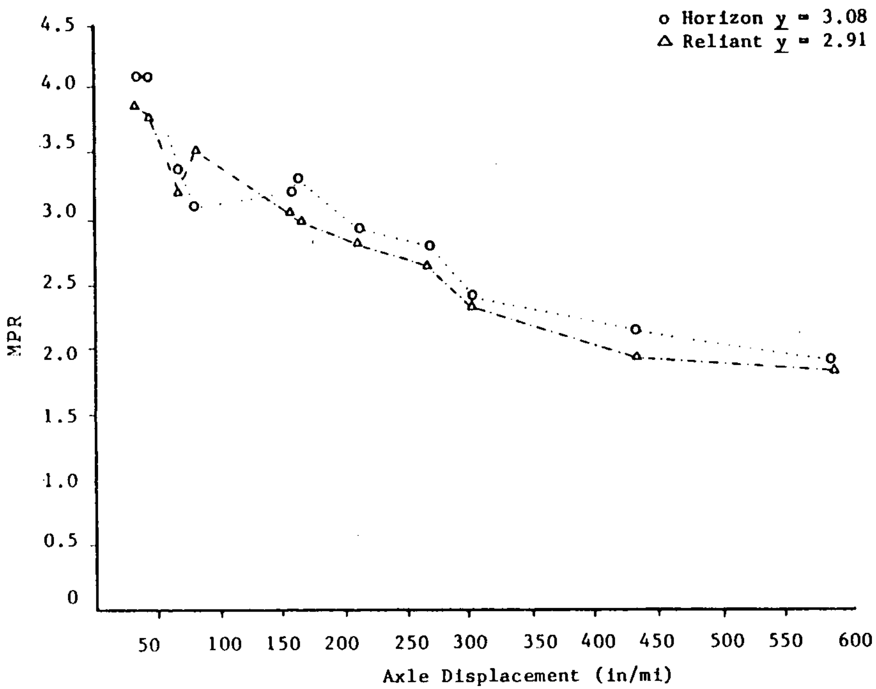

Figure 6. Effect of vehicle size.

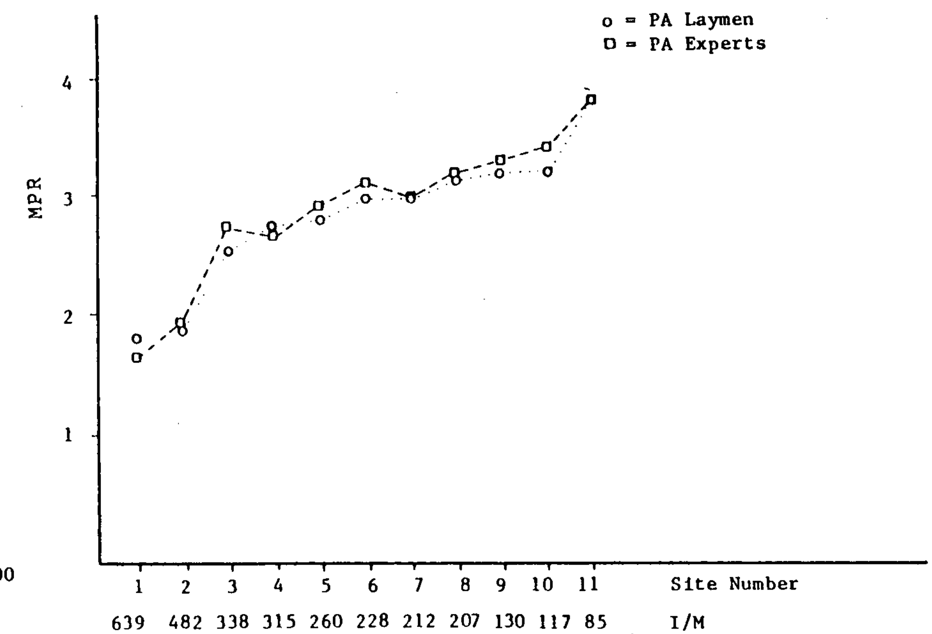

Figure 8. Effect of trained raters versus laymen.

by the same state, no firm conclusions were drawn. (This last group actually rated the 11 test sections somewhat lower (i.e., more critically), ranging from 0.2 scale units to 0.6 scale units.)

Development of Analysis Methods

The intent of these analyses was to develop preferred methods of analyses that both combined subjective ratings of ride quality and physical profiles, and could be used to develop transforms that would allow subjective ratings to be predicted from physical measures. Eighteen Florida test sections (Table 3), spanning a wide range of roughness, were used for all of these analyses. Twelve Pennsylvania test sections were also profiled, but these data were not used in the analyses.

Graphical Analysis

Figures B-3 through B-6 of Appendix B show four of these plots. It can be seen from the four curves that as the MPRs decrease, the area under the curves increases (i.e., total roughness, defined in terms of PI, increases)—although not uniformly over all frequencies. This led to the first proposed comparative analysis: the correlation of broad-band roughness (i.e., total area under the curve) with MPRs.

Further visual inspection of the graphical data indicated that there may be two or three broad bands of frequencies that are related to the subjective ratings. Frequently the graphs would rise (or fall) within a narrower range of frequencies (e.g., the center frequencies in Figures B-3 through B-6 of Appendix B) as the rating fell (or rose). This led to the second method of analysis: establishing various cutoff frequencies to derive two or three narrower frequency bands. The resulting roughnesses (i.e., PI) in these individual bands were then correlated with the MPRs. Different crossover points were selected based on the work of Gillespie (*12*). In addition, there was some evidence to indicate that the subjects may have been responding differentially to audible frequencies above 30 Hz (0.4 c/ft) and to kinesthetic motion imparted by frequencies below 30 Hz. This led to the selection of a third crossover frequency at 30 Hz. (The results of the one-half and one-third octave analyses to be described below yielded a fourth crossover point, 108 Hz (1.48 c/ft).)

Comparative Analyses,

Based on the graphical analysis described above, past work by the same authors (e.g., *2*) and suggestions by the NCHRP project panel, correlations were computed to determine the relationship between the PI in the following individual bands of frequencies and the MPRs for the 18 test sections:

1. Broad band (0.009 to 3.0 c/ft).
2. All frequencies above 0.09, 0.2, 0.4, or 1.5 c/ft (i.e., upper part of two-band analysis).
3. All frequencies below those listed in (2) (i.e., lower part of two-band analysis).
4. Frequencies within the following ranges (i.e., center band of three-band analysis): 0.09 to 0.2, 0.09 to 0.4, 0.09 to 1.5, 0.2 to 0.4, 0.2 to 1.5, and 0.4 to 1.5 c/ft (all frequency bands defined by the four crossover points defined above).
5. Individual one-half and one-third octave bands for the entire broad band of frequencies from 0.009 to 3.0 c/ft.

Table 3. Mean panel ratings of 18 Florida test sections.

Section Number	Mean Panel Rating	Mays Ride Meter (Roughness: in/mi)
1	1.20	327
2	1.73	220
3	2.00	152
4	2.64	127
5	2.74	215
6	2.91	111
7	3.03	270
8	3.03	101
9	2.09	210
10	3.25	93
11	3.31	93
12	3.43	137
13	3.51	55
14	3.62	84
15	3.73	46
16	3.92	137
17	4.24	56
18	4.26	25

Intercorrelations between the separate bands were then computed. In addition, regression analyses were performed to relate MPRs to the PI in two bands, three bands, and 9 (of 19) one-half octave bands (the 9 bands where roughness (PI) was found to be most correlated with subjective ratings—see one-third and one-half octave analysis). For completeness, MPRs were correlated with ¼ car roughness derived from the profilometer output and actual MRM measurements for all 18 sites.

The PI in the band of frequencies from 0.009 to 3.0 c/ft was computed for each test section, and the MPRs were correlated with these values. A correlation coefficient of −0.33 was obtained, indicating poor agreement between the two types of data. Even when the roughness was transformed using a log function, the coefficient remained low. (Previous research has indicated that the relationship between these two measures would tend to obey Fechner's law: $R = -b \log S + a$, where R = rating, b = slope of line, S = physical stimuli, and a = scale constant (*2*).)

The PI in each of four different bands of frequencies above the cutoff frequencies was computed and correlated with the MPRs. The results are summarized in the top third of Table 4. Generally, the correlation decreases as the cutoff frequency increases. Note, however, that the first three bands had exceptionally high correlation coefficients.

The PI in each of the four different bands of frequencies below the cutoff frequencies was computed and correlated with the MPRs. The results are summarized in the middle section of Table 4. All correlations were quite low, especially the three lowest bands.

The PI in each of the six different bands of center frequencies was computed and correlated with the MPRs. The results are summarized in the bottom third of Table 4. All six center bands of frequencies resulted in very high correlations, indicating excellent agreement between the objective and subjective data.

The PI in each of 19 one-half octave bands and in each of 28 one-third octave bands was computed. Each of these values was then correlated with the MPRs. Figure 9 shows the results for the one-half octave analysis. (The results of the one-third octave analysis were similar.) For both analyses, the PI in each of the one-half or one-third octave bands from 0.09 to 1.48 c/ft (7 to 120 Hz) was highly correlated with the MPRs. The correlations for bands above and below this center band fell off rapidly, indicating poor agreement between such PI and the MPRs for frequencies outside this center band.

It was found that all nine one-half octave bands in the center frequency band (0.09 to 1.48 c/ft) were highly intercorrelated, indicating a lack of independence as predictors in a multiple regression equation. There was low intercorrelation between one-third or one-half octave frequency bands inside this center band and one-third or one-half octave frequency bands outside the center band.

For the two-band analysis, the intercorrelations were found to be quite low. However, the incorporation of the roughness in the lower band as an additional predictor of MPRs did not improve the correlation coefficient when compared to the use of only the roughness in the higher band.

For the three-band analysis the higher two bands were highly intercorrelated, but neither was very intercorrelated with the lower band. Again, using all three bands as predictors did not significantly improve the correlation (and yielded an impractical regression equation; i.e., with at least one positive regression coefficient which would imply that roads which are physically rougher in such a frequency range would be subjectively rated smoother).

Using the PI in all nine one-half octave bands from 0.09 to 1.48 c/ft as 9 independent predictors of MPRs increased the correlation coefficient to −0.99. However, the resulting regression equation was again impractical because a number of the regression coefficients were positive. More sophisticated data analysis methods would be required to derive more practical predictive transforms (see, for example, Ref. *11*), but because the correlations are already so high (e.g., better than −0.9 in many bands), improvements would be marginal.

For completeness, the roughness of all 18 sites was measured with an MRM and also computed from the profiles using a ¼ car simulated roughness index. A correlation coefficient of −0.76 was derived from the MRM; the ¼ car index provided a correlation coefficient of −0.69. Log transforms improved both correlations, but only slightly.

Table 4. Effect of frequency restrictions on correlation.

Frequency Range (c/ft)	Correlation Coefficient
Delete Low Frequencies	
Greater Than 0.09	-.92
" " 0.2	-.90
" " 0.4	-.87
" " 1.5	-.66
Delete High Frequencies	
Less Than 0.09	-.33
" " 0.2	-.33
" " 0.4	-.33
" " 1.5	-.66
Delete High and Low Frequencies	
0.09-0.2	-.87
0.09-0.4	-.91
0.09-1.5	-.92
0.2-0.4	-.92
0.2-1.5	-.91
0.4-1.5	-.88

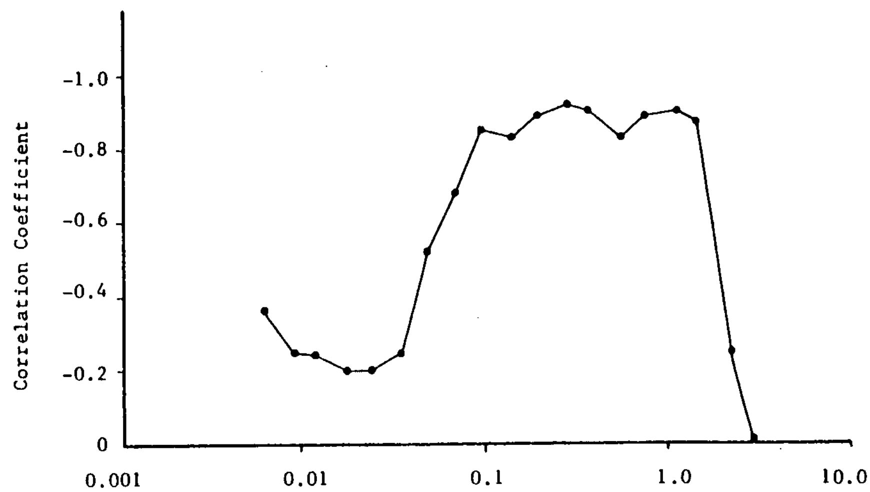

Figure 9. Results of correlating PI with MPRs for individual one-half octave bands.

Summary of Data Analysis

Table 5 summarizes and compares the correlation analyses, presenting them in decreasing order of correlation coefficient. Table 6 presents the results of the regression analyses. Note that for the regression analysis only the two predictor cases (i.e., the two-band analyses) yielded practical predictive transforms.

The highest correlations (i.e., the best transforms between profiles and subjective ratings) result from use of PI in the band above 0.09 c/ft (above 7 Hz) or in the center bands between 0.09 and 1.5 c/ft (120 Hz) or between 0.2 (16 Hz) and 0.4 c/ft (32 Hz).

The major conclusions of these analyses are as follows:

Table 5. **Summary of correlation analyses.**

Correlation Coefficient	Predictor
-.92	Roughness in frequency band 0.09 c/ft Roughness in frequency band between 0.2 and 0.4 c/ft Roughness in frequency band between 0.09 and 1.5 c/ft
-.91	Roughness in frequency band between 0.09 and 0.4 c/ft Roughness in frequency band between 0.2 and 1.5 c/ft
-.90	Roughness in frequency band 0.2 c/ft
-.88	Roughness in frequency band between 0.4 and 1.5 c/ft
-.87	Roughness in frequency band 0.4 c/ft Roughness in frequency band between 0.09 and 0.2 c/ft
-.76	MRM roughness
-.69	1/4 car derived roughness index
-.66	Roughness in frequency band 1.5 c/ft Roughness in frequency band 1.5 c/ft
-.50	Log of roughness in band of frequencies between 0.009 and 3.0 c/ft
-.33	Roughness in band of frequencies between 0.009 and 3.0 c/ft Roughness in frequency band 0.09 c/ft Roughness in frequency band 0.20 c/ft Roughness in frequency band 0.40 c/ft

Table 6. **Summary of regression analyses.**

Correlation Coefficient	Predictor
-.99	Roughness in 9 one-half octave bands* from 0.09 to 1.48 c/ft
-.93	Roughness in three bands;* crossover at 0.2 and 0.4 c/ft
-.92	Roughness in two bands; crossover at 0.09 c/ft Roughness in two bands; crossover at 0.2 c/ft Roughness in three bands;* crossover at 0.09 and 0.2 c/ft Roughness in three bands;* crossover at 0.09 and 1.5 c/ft
-.91	Roughness in two bands; crossover at 0.4 c/ft

*High intercorrelations

1. It is possible to determine those specific frequency bands—both narrow and wide—that are most related to subjective ride quality.
2. The correlations between the PI within these frequency bands and the MPRs are typically greater than −0.9, indicating excellent agreement.
3. If these PI values are used as predictors of MPRs (i.e., as transforms), approximately 85 percent of the variance is accounted for (i.e., $r^2 = 0.85$).
4. The use of regression equations with more than one predictor is probably unnecessary because the correlation coefficient does not significantly increase and high intercorrelations exist between the predictors (i.e., the individual frequency bands).

MAIN EXPERIMENT

Table 7 summarizes the ranges of roughness (inches per mile) and ride quality (MPR) for all sites and for each specific surface type.

Table 8 summarizes the first four sets of analyses, which considered only simple roughness measures. The findings are that for BC surfaces, either ¼ car index or MRM index predicts subjective ratings with high precision. For PCC, composite, or all surfaces combined, the predictions are only poor to fair. A discussion and possible interpretation for this lack of high correlation on PCC and composite surfaces are provided in Chapter Three.

The "needs repair" rating is highly correlated with the MPR for all surfaces, but is highly correlated with the ¼ car index or MRM index only for BC surfaces. For PCC and composite surfaces, "needs repair" is not well correlated with ¼ car or MRM.

The ¼ car and MRM are highly correlated for all surfaces except PCC.

Functional class of road did not affect the correlation, and a log transform on ¼ car or MRM improved the correlation with MPRs by 5 to 10 percent for all surface types.

Because of the low correlation between MPRs and response-type measures of roughness for PCC and composite surfaces, it is clearly necessary to analyze the full profiles instead of the simple roughness measures.

Graphical Analysis

The graphical analysis was begun on seven of the right profiles of the BC surfaces, spanning an MPR range of 1.0 to 4.05. These graphs are included in Appendix C.

In general, as the MPR increased, indicating a better ride quality, the total area under the graphs decreased, indicating less total roughness. These results were expected. There are some reversals and frequent intercepting and crossovers, but these results were also expected inasmuch as the pilot study analysis revealed that total roughness was not a good predictor of ride quality. Graphs of PCC and composite surfaces were generally similar.

One-Third Octave Analysis

The second step in the analysis was the one-third octave analysis, again using right wheel profiles. The Ohio profilometer only provided data out to about 0.8 c/ft (the PSU profilometer provided it out to 6 c/ft, and data were analyzed out to 3 c/ft in the pilot study). Therefore, a more limited range of frequencies was analyzed in the main study than in the pilot study.

An initial one-third octave analysis was performed using the right profiles of the BC surfaces. Correlation coefficients were derived for each of the 26 one-third octave bands from 0.0025 to 0.7937 c/ft (0.2 to 64.0 Hz; center frequency). Each correlation coefficient was derived from regressing the PI in each one-third octave band (one band for each test section) with the MPRs.

The results indicated a nearly constant correlation of about −0.55 over all frequency bands and appeared questionable. The pilot analyses revealed high correlations within a restricted band of frequencies (0.09 to 1.48 c/ft; 7.3 to 119.4 Hz) and low correlations both outside of this band and for total PI. The main study findings were completely the reverse, with total PI in every one-third octave band predicting MPRs equally poorly.

It was suspected that there were problems with the raw profile data, and a number of approaches were selected to correct these problems. These included (1) careful examination of the raw profile data (the analyses were fully tested using the Florida data; hence, it was doubtful that the problem resulted from them), its labeling and format; (2) use of left plus right wheelpath instead of only the right profile (as in Florida); and (3) use of transforms (filters) applied to the profile data to eliminate possible low-frequency noise which could contaminate the data.

After careful examination of the profiles and their graphs, it was disclosed that 2 BC, 3 PCC, and 3 composite test sections had erroneous data (e.g., mislabeled) and these were deleted, leaving 18 BC, 17 PCC, and 17 composite sections for analysis. One-third octave PI in the left plus right profile was then computed for each of the remaining 52 test sections for all 26 frequency bands and correlated with MPRs for each surface individually and all three surfaces combined. (Appendix C describes the exact calculations.) This is illustrated in Figure 10.

Figure 10 clearly shows that the correlations are low for low frequencies and extremely high (better than −0.85) in the frequency band ranging from 0.125 to 0.630 c/ft (10.1 to 50.8 Hz) for each of the three surface types individually and all three combined. It is also evident that the correlations fall off at frequencies above 0.630 c/ft. (This will be discussed again later in this chapter—see Figures 16 and 17.) Only the BC surfaces reveal correlations that remain generally high (better than −0.7) for almost all frequency bands. This agrees with the high correlation between MPR and either ¼ car index or MRM number for this one surface type.

Table 7. Summary statistics for Ohio sites.

Type of Site	Number	Range of Mean Rating	Range of In/Mi (MRM)
All	81	1.0-4.4	32.6-661.3
BC	25	1.0-4.1	42.0-661.3
PCC	22	1.9-3.8	66.1-236.3
Composite	34	1.9-4.4	32.6-221.5

Table 8. Simple roughness analyses.

Analysis	Correlation Coefficient	Result
MPR correlated with 1/4 car index	-.71	Correlation good for BC; poor for other two surfaces and three combined
BC	-.89	
PCC	-.31	
Composite	-.60	
MPR correlated with log (1/4 car)	-.75	Correlation good for BC; poor for other two surfaces and three combined
BC	-.91	
PCC	-.42	
Composite	-.75	
MPR correlated with MRM	-.74	Correlation good for BC; poor for other two surfaces and three combined
BC	-.86	
PCC	-.48	
Composite	-.70	
MPR correlated with log (MRM)	-.77	Correlation good for BC; poor for other two surfaces and three combined
BC	-.91	
PCC	-.55	
Composite	-.76	
MPR correlated with % NR	-.93	High correlations for all surfaces
BC	-.97	
PCC	-.97	
Composite	-.94	
NR correlated with 1/4 car index	.58	Good for BC; poor for others
BC	.83	
PCC	.15	
Composite	.61	
NR correlated with MRM index	.59	Good for BC; poor for others
BC	.81	
PCC	.46	
Composite	.63	
MRM correlated with 1/4 car	.88	Excellent for BC; good for composite and three combined; poor for PCC
BC	.99	
PCC	.42	
Composite	.82	

Note: NR = "needs repair"

Regression Analyses

When the total PI in the band of frequencies from 0.125 to 0.630 c/ft was correlated with MPRs, the data in Table 9 were derived. This table reveals high correlations between the MPRs and PI in this band of frequencies for all surface types. In addition, the results are generally similar (i.e., the *a* and *b* coefficients are similar) for all four cases in Table 9.

Two additional analyses were performed to investigate whether the correlation would be improved or this important band of frequencies would change: (1) a double differentiation of the profile with respect to distance before computer PI (to eliminate potential low-frequency noise in the profiles) and (2) a log transform of the physical profile data (PI) before performing the regression analyses. The results of the double differentiation are given in Table 10, the results of the log transform are given in Table 11, and the combined results are given in Table 12.

For the double differentiated transform, bands 18 to 26 (from 0.125 to 0.7937 c/ft) were used for the analysis, because the

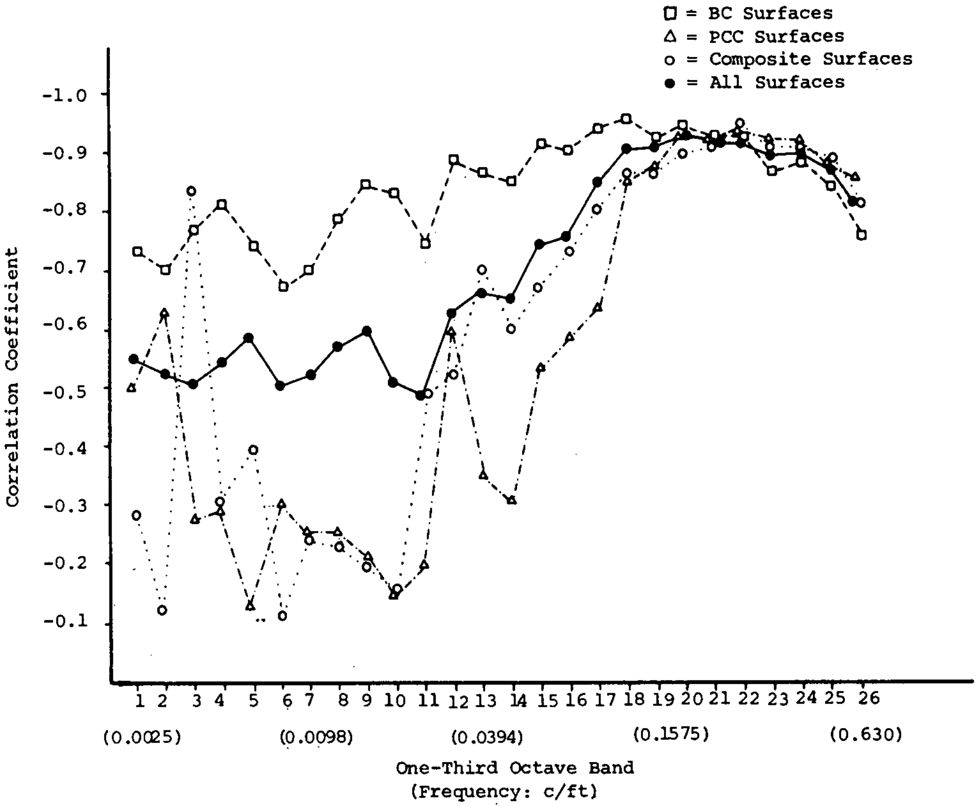

Figure 10. Effect of correlating PI in one-third octave bands with MPR.

Table 9. Correlation of profile index (0.125–0.630 c/ft) with mean panel ratings.

Surface Type	Regression Analysis*		
	r	a	b
BC	-.85	3.70	-24.88
PCC	-.93	4.56	-50.70
Composite	-.87	4.42	-47.55
All	-.85	3.95	-30.22

*MPR = a + b PI

Table 10. Effect of double differentiation of profiles.

Surface Type	r	a	b
BC	-.93	4.34	-12.52
PCC	-.92	4.37	-10.87
Composite	-.89	4.46	-12.12
All	-.92	4.45	-12.34

graphs of correlation coefficient versus PI in one-third octave bands revealed that the correlation coefficients were better than −0.85 for this slightly wider band of frequencies.

Table 13 illustrates the effect of each transform on the correlation coefficient. In general, the log transform is best.

Figures 11 to 14 show the relationship between PI in the band of frequencies 0.125 to 0.630 c/ft and MPR for all three surfaces combined and each separately. For all surfaces and the BC surfaces, the graph is exponential, and a log transform (Figure 15) clearly converts them into a straight line, as predicted by the regression analyses summarized in Tables 9–13.

The graph for PCC surfaces is nearly straight (Figure 13); hence, there is no effect of the log transform as predicted in the regression analysis (Table 13). For composite surfaces there is some improvement when the log transform is applied (Table 13), and Figure 14 shows some exponential curvature, as expected.

Table 11. Effect of log transforms.

Surface Type	r	a	b
BC	-.94	-1.79	-3.04
PCC	-.93	-2.01	-3.25
Composite	-.91	-1.58	-2.89
All	-.94	-1.74	-3.03

Table 12. Effect of double differentiation and log transforms.

Surface Type	r	a	b
BC	-.95	-1.05	-4.03
PCC	-.92	0.29	-2.89
Composite	-.94	-0.01	-3.08
All	-.92	-0.41	-3.47

Table 13. Effect of transformations on correlation coefficients (percent changes).

Surface Type	Log	Double Differentiation	Double Differentiation and Log
BC	10.6	9.4	11.8
PCC	00.0	-1.1	-1.1
Composite	4.5	2.2	8.0
All	10.6	8.2	8.2

The Ohio data were then compared with the Florida data collected in the pilot study. Figure 16 presents the Florida data plus the graphs from Figure 10. The range of important frequencies (i.e., high correlations) for the Florida data is slightly broader by about one octave; however, within the band from 0.125 to 0.630 c/ft, the correlations are almost identical. The Florida data are based only on data from the right profile and were not processed in exactly the same way as the Ohio data (see Appendixes B and C). This may account for some of the differences. However, since the Ohio data are based on a greater number of pavement sections (52 profiles instead of 18), a larger panel (36 instead of 18), and a broader range of surfaces, more confidence is given to the Ohio analyses.

Comparison of the Ohio and PSU Profilometers

The next analysis was a comparison of profile data collected on 11 sites by both the Ohio and PSU profilometers. There were two objectives: (1) evaluation of the relative accuracy of both profilometers (it was hoped that they would provide nearly identical data) and (2) extension of the relationship disclosed in Figures 10 and 16 between PI in one-third octave bands and MPRs, in order to better identify the most important band of frequencies for predicting MPRs from physical profiles.

To evaluate the relative accuracy of the two profilometers, profiles were measured on 10 test sections—4 BC, 3 PCC, and 4 composite—spanning a range of ride quality from 1.01 to 4.41 (MPR). PI was computed in one-third octave bands from 0.0031 c/ft to 3.0 c/ft for the PSU profilometer and from 0.0025 to 0.7937 c/ft for the ODOT profilometer, for all 10 test sections. The PI in the one-third octave bands was then correlated with MPRs and the correlation coefficients were plotted, as indicated in Figure 17.

Within the frequency band from 0.0313 to 0.7937 c/ft, the two graphs are almost identical. Within the frequency band from 0.125 to 0.630 c/ft, identified previously as most important, the two graphs never differ by more than 0.05 units of r (i.e., 0.9 versus 0.95), approximately 5 percent, and typically the differences are only 2 to 3 percent.

It is also evident that the correlations are dropping above 0.630 c/ft, and below 0.125 c/ft, reinforcing the previous relationships between MPR and PI.

Regression equations were developed for both data sets (ODOT and PSU) for these 10 test sections using PI in the band of frequencies between 0.125 to 0.630 c/ft, as given in Table 14. All of the values (a, b, r) are very similar for both sets of data, again reinforcing the previous findings. In addition, since the regression equations are so similar and both predict MPRs as a function of PI, the two profilometers are thus recording similar roughness in this frequency band.

To further evaluate the relative accuracy, total PI was computed for both profilometers in the frequency band 0.125 to 0.630 c/ft using these same 10 test sections. This is illustrated in Table 15.

The PSU and ODOT measures were then correlated to yield an r of 0.99, indicating almost perfect agreement. The regression equation is

$$\text{ODOT} = 0.00^{*} + 0.84\ \text{PSU}$$

* The a coefficient, to four decimal places, is actually −0.0006.

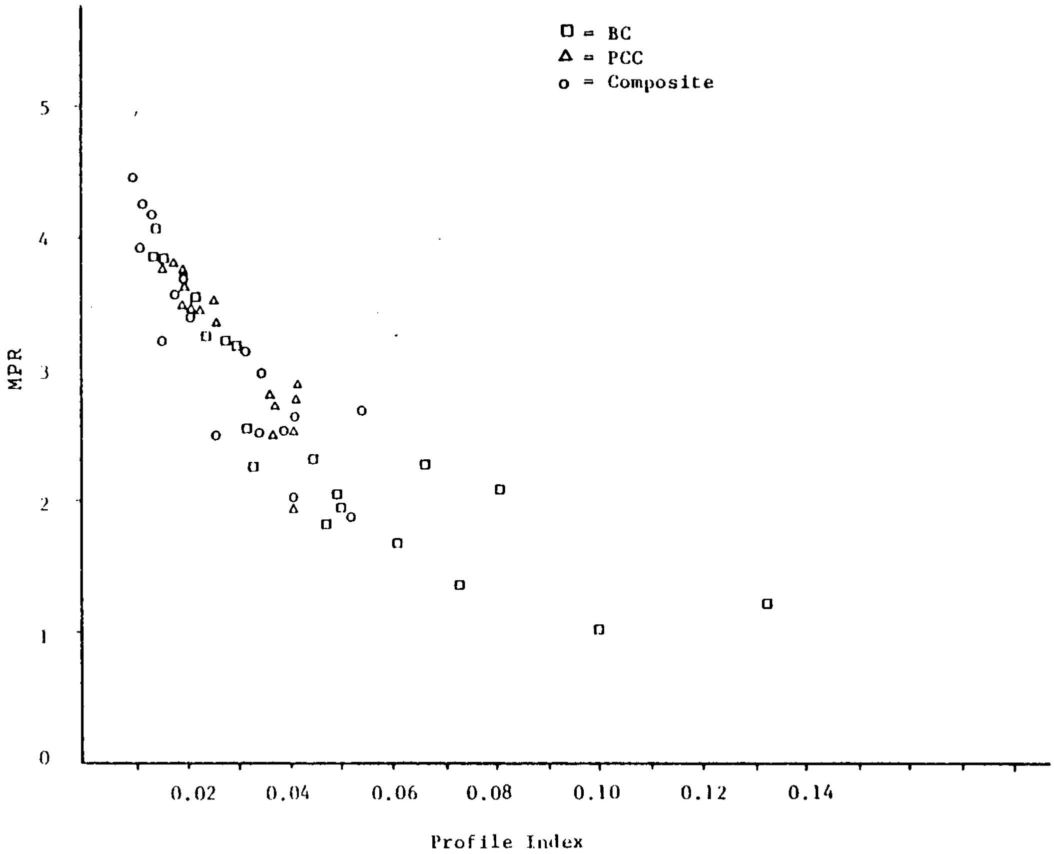

Figure 11. PI versus MPR—all surface types.

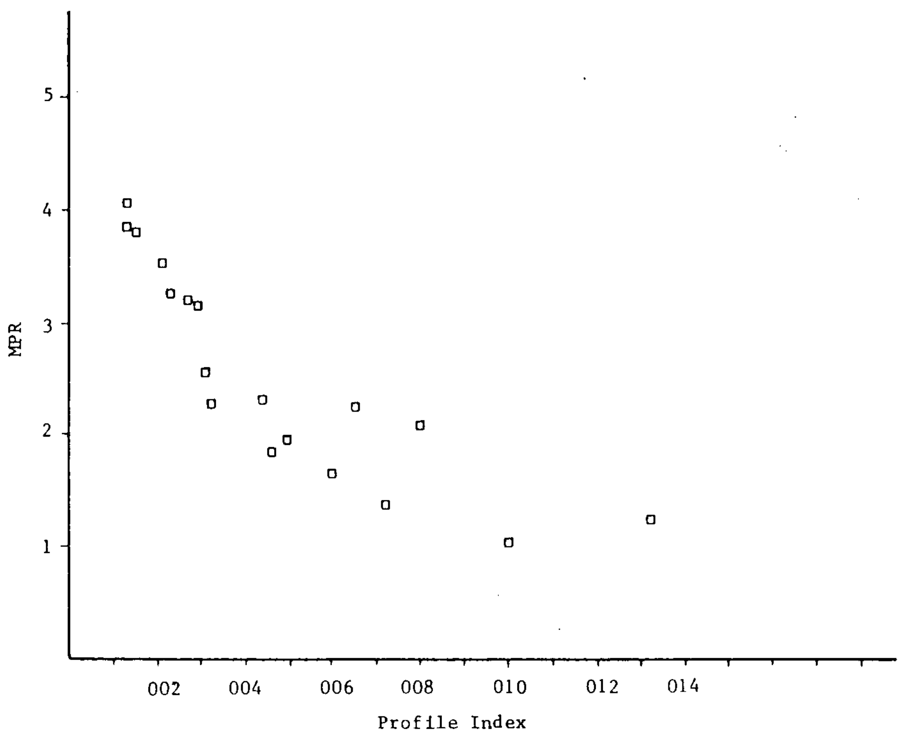

Figure 12. PI versus MPR—bituminous concrete surfaces.

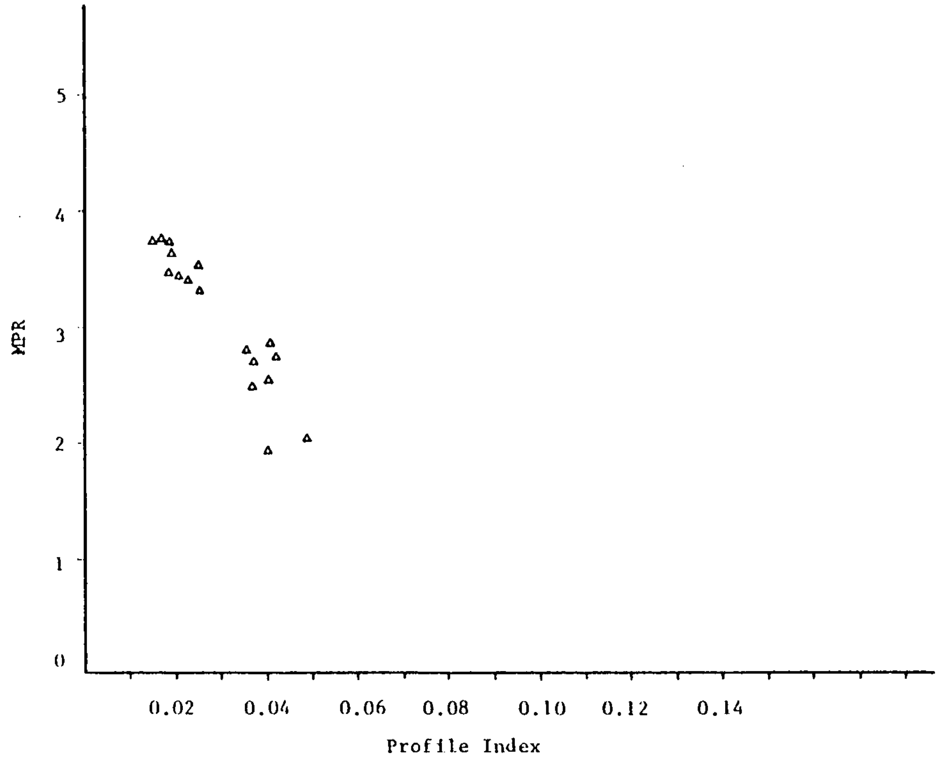

Figure 13. PI versus MPR—portland cement concrete surfaces.

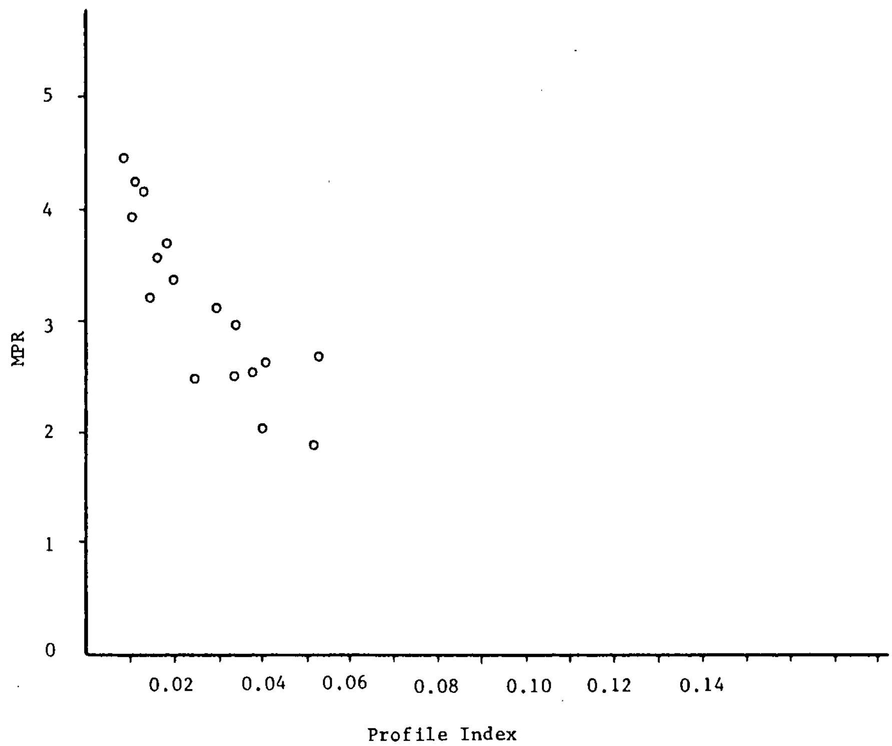

Figure 14. PI versus MPR—composite surfaces.

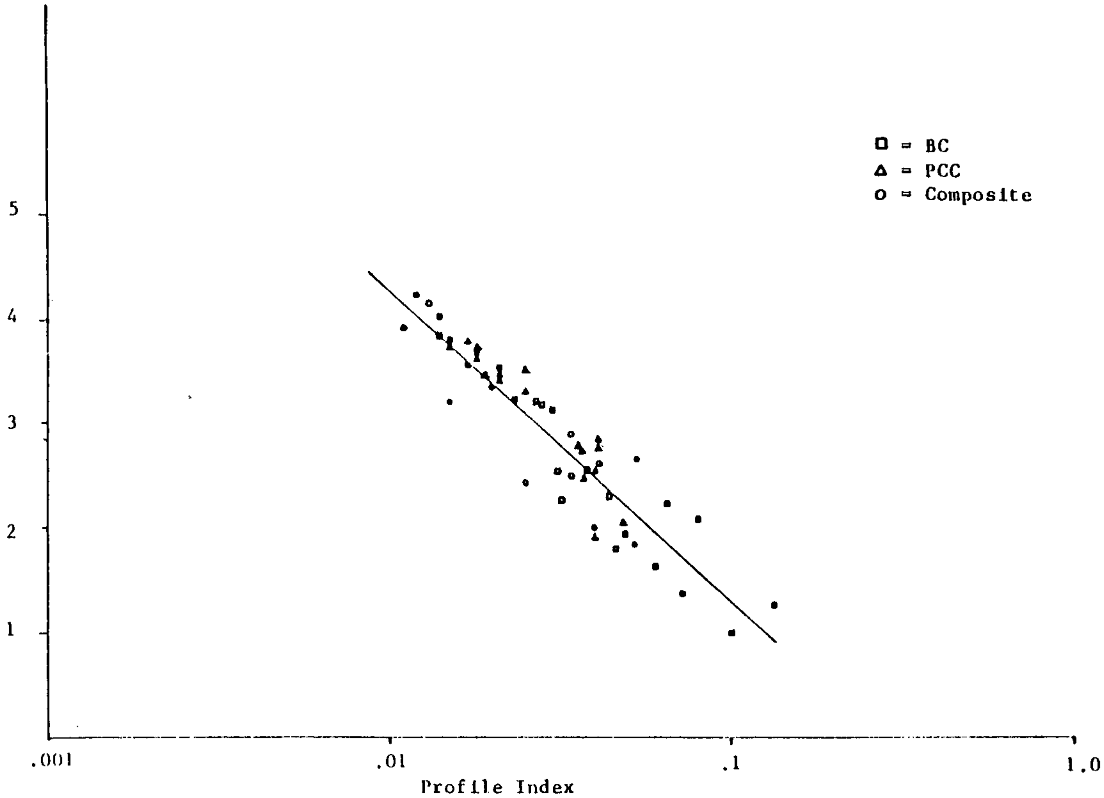

Figure 15. Log (PI) versus MPR—all surface types (MPR = −1.74−3.03 log (PI).

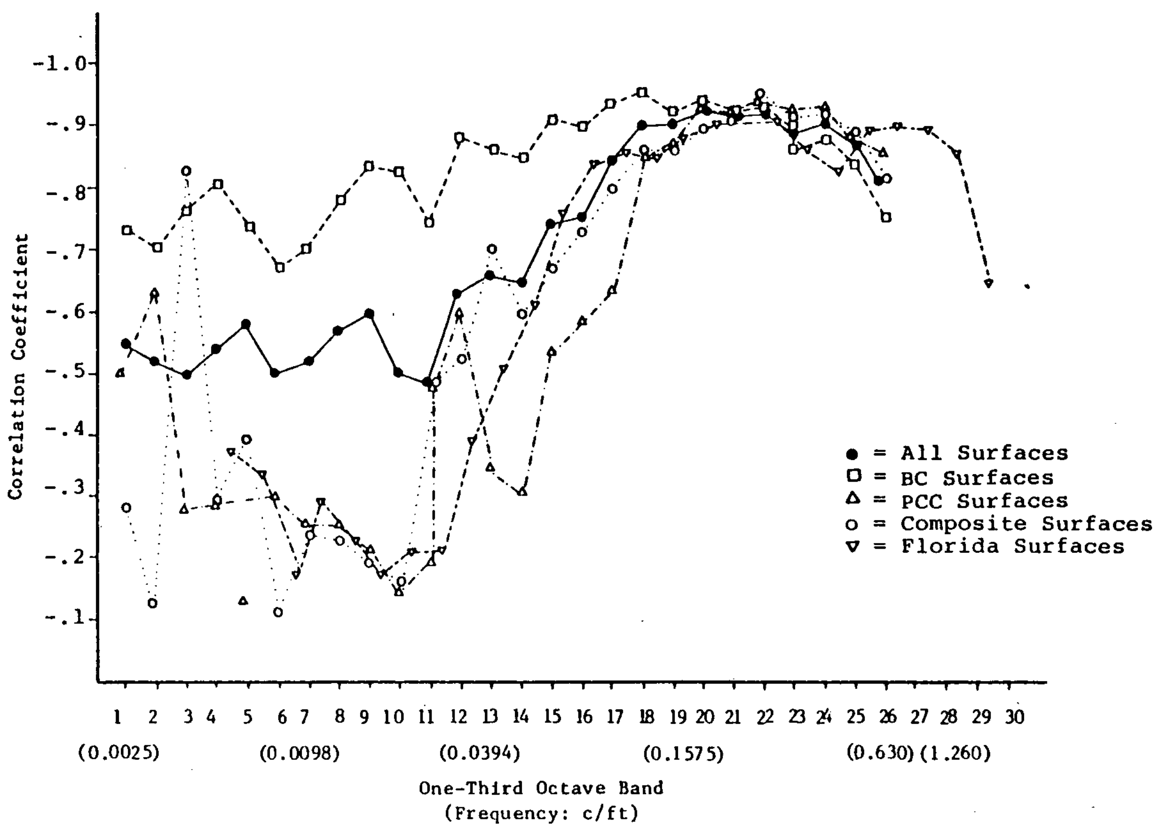

Figure 16. Effect of correlating PI in one-third octave bands with MPR—Ohio and Florida.

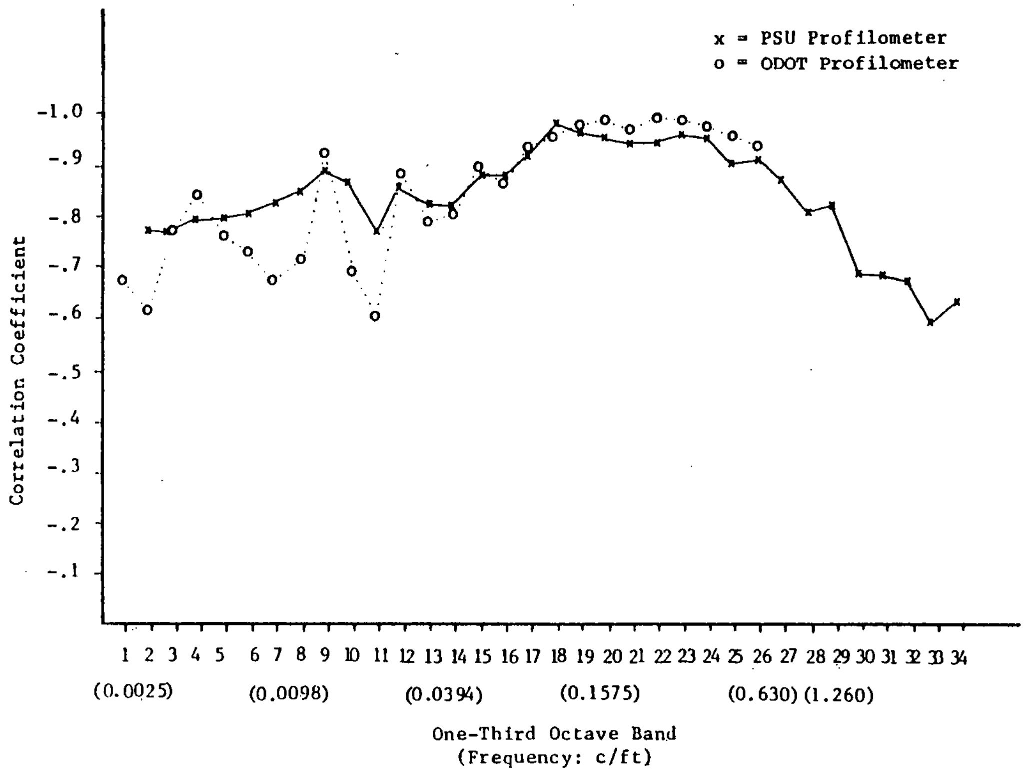

Figure 17. Comparison of PSU and ODOT profilometers: correlation between PI and MPR.

Table 14. Comparison of PSU and ODOT profilometers.

Profilometer	Regression Analysis r	a	b
Ohio	-.98	-3.374	-1.384
PSU	-.96	-3.058	-1.380

MPR = a + b log (PI)

Table 15. Comparison of profile index in frequency band 0.125–0.630 c/ft for 10 test sections.

Test Section	PI PSU	ODOT
1	.0708	.0585
2	.0336	.0262
3	.0126	.0108
4	.0355	.0336
5	.0178	.0109
6	.0117	.0095
7	.0195	.0165
8	.0055	.0042
9	.0197	.0150
10	.0061	.0052

which implies that the ODOT measures are 84 percent of the PSU ones. The regression equation and the plot of the raw data from Table 15 are illustrated in Figure 18.

It is suspected, but not proven, that the filters in the ODOT profilometer reduce the actual measured PI, thus providing uniformly lower readings than the PSU profilometer but almost perfect correlation between the two instruments in the frequency band of greatest importance.

Graphs of PI in one-third octave bands were generated for a few of the test sections for both profilometers. They showed that the profilometers measured roughness very similarly in the frequency band above 0.03 c/ft, but provided different roughness values below this value. This is also revealed in Figure 17, which showed disagreement in the correlations between PI in one-third octave bands and MPRs in this same low frequency band.

Transforms Between PI and Panel Ratings

The data in Tables 9 to 12 provide transforms between the PI (in the frequency band from 0.125 to 0.630 c/ft) and MPRs in the form:

$$\text{MPR} = a + bp$$

where MPR = mean panel rating, a,b = coefficients in Tables 9 to 12, and p = PI (or log PI or dd PI, etc.) in the referenced band (see Appendix C).

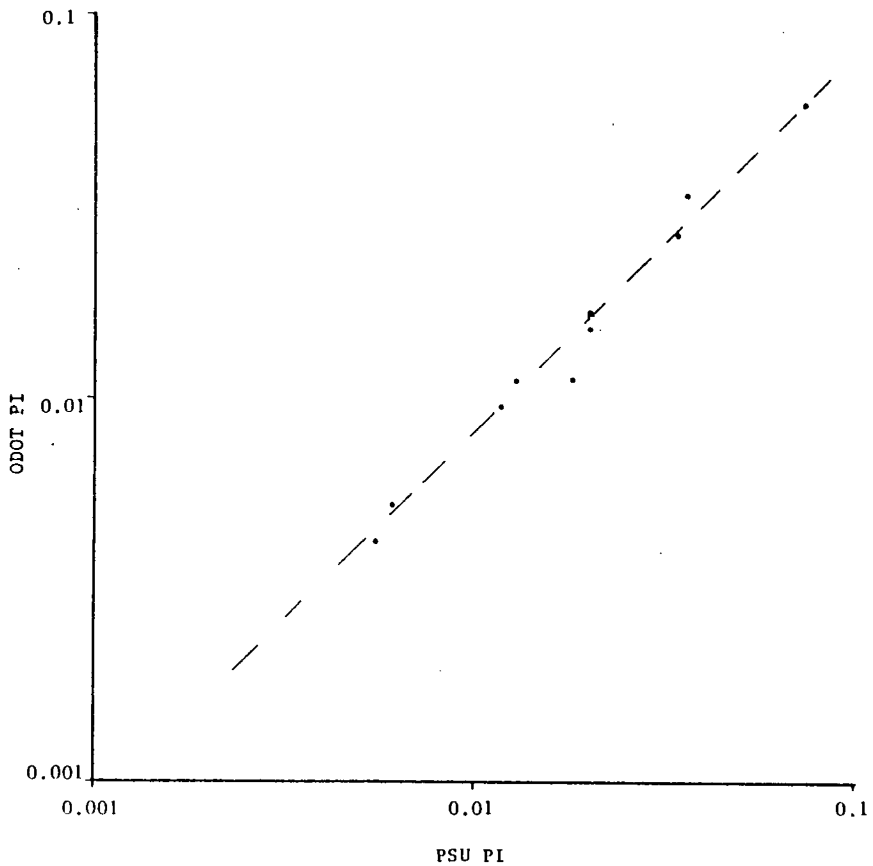

Figure 18. Correlation between PSU and ODOT profilometers (ODOT = 0.84 PSU).

For example, for all three surface types combined, and using the log transform of profile index, the regression equation is:

$$RN = MPR = -1.74 - 3.03 \log (PI)$$

(last row of Table 11)

Others would be formatted in a similar manner.

The correlation coefficient for this regression equation is −0.94, indicating that 88 percent (r^2) of the variance is accounted for by this equation. The residual error after linear regression is 0.12 ($1 - r^2$). A graph of this regression equation, with the raw data points, is provided in Figure 15.

Additional regression analyses were performed to investigate further the relationships between the following variables: MPR, profile index in the band of frequencies from 0.125 to 0.630 c/ft, ¼ car index, and MRM index. In addition, the effect of log and square root transforms on these relationships was investigated. No significant improvements were obtained from those described previously. The results are presented in Appendix C.

Needs Repair Rating

The last analysis compared the needs repair (NR) ratings and the MPRs. The two sets of data (Appendix C, Table C-1 columns headed "M" and "NR") were correlated for all 52 test sections to derive the regression equation

$$NR = 132.6 - 33.5 \text{ MPR} \qquad (r = -0.93)$$

$$\text{or} \quad NR = 132.6 - 33.5 \text{ RN}$$

Similar equations were derived for the three individual surface types. These are given in Tables C-3 through C-5 in Appendix C. The preceding equation is plotted in Figure 19, and Table 16 summarizes the values of RN for NR percentages from 0 to 100.

This equation reveals that on pavement sections with RN $\geq$ 3.96 no panel members feel that the section should be repaired, whereas on pavement sections with RN $\leq$ 0.97 100 percent of the panel members feel the section should be repaired. A RN of 2.46 represents a value where one-half believe it should be repaired and one-half believe it should not be repaired.

Figure 20 provides a graph of PI versus NR, by combining the two equations:

$$NR = 132.6 - 33.5 \text{ RN}$$

$$RN = 1.74 - 3.03 \log (PI)$$

Using the foregoing equation, NR can be predicted directly from PI rather than from RN. The combined equation is

$$NR = 190.9 + 101.5 \log (PI)$$

The preceding equations are valid for pavement sections with MPRs (RNs) between about 1.0 and 4.4, the limits of the test data.

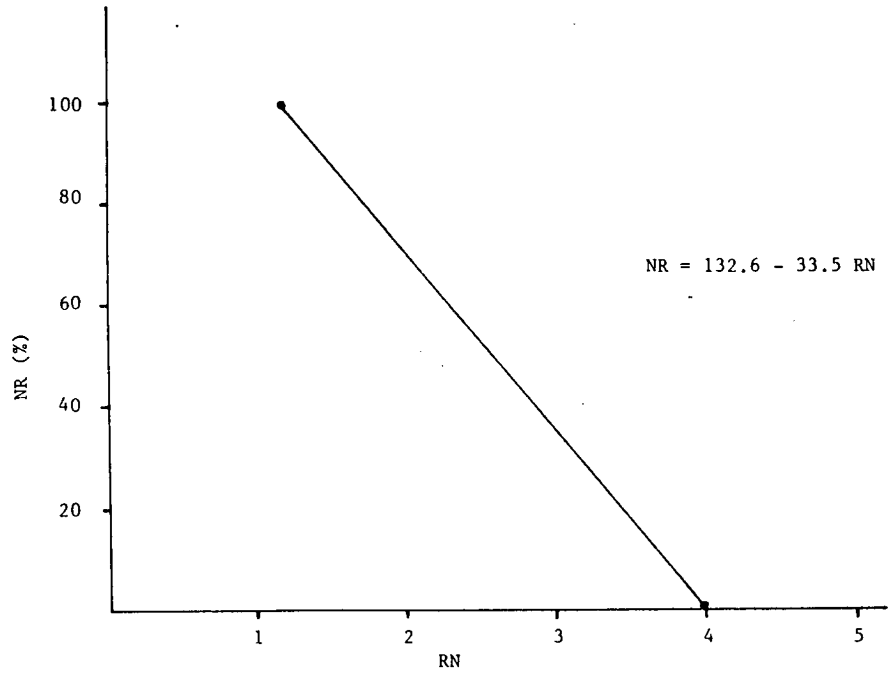

Figure 19. Needs repair versus rideability number.

Table 16. Needs repair versus rideability numbers.

NR (%)	RN
0	3.96
10	3.66
20	3.36
30	3.06
40	2.76
50	2.47
60	2.17
70	1.87
80	1.57
90	1.27
100	0.97

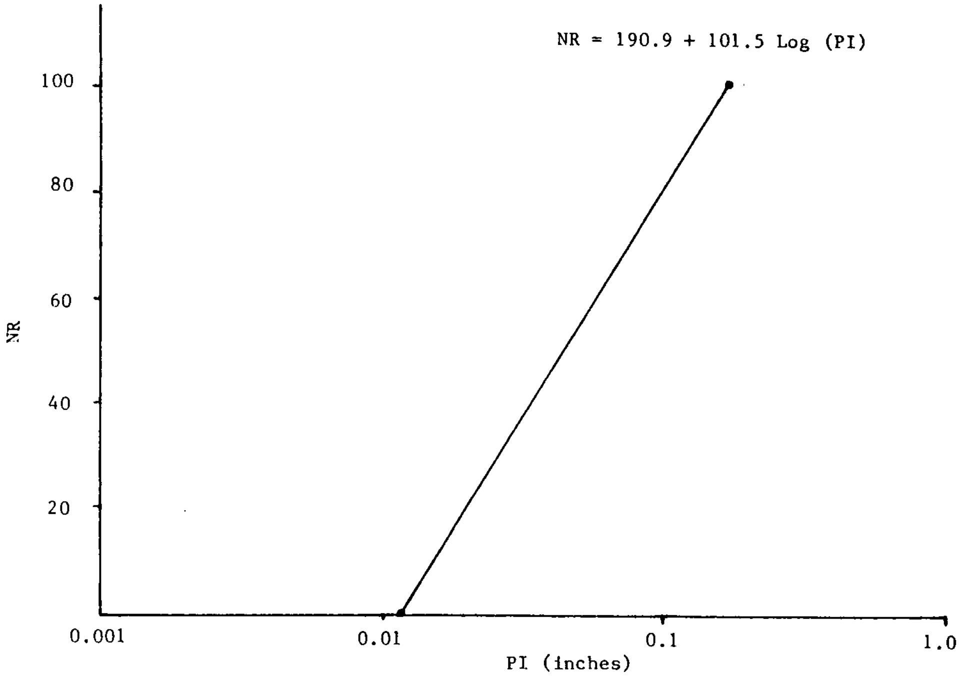

Figure 20. Needs repair versus PI.

CHAPTER THREE

INTERPRETATION AND APPLICATION

The objective of this chapter is to interpret the findings of Chapter Two and to discuss their implications and applications. These include:

1. The preferred transforms between physical profile measures and subjective panel ratings, their limitations and suggested uses.
2. The possible transforms between response-type roughness measures and subjective panel ratings, their limitations and uses.
3. Specifications for a simple roughness meter that would provide data which are highly correlated with MPRs and which could be used to accurately predict ride quality from physical measures of roughness.
4. The preferred transform between NR and RN, its use and limitations.
5. The effect of vehicle and driver characteristics on the subjective evaluation of ride quality.

TRANSFORMS BETWEEN PHYSICAL PROFILE MEASURES AND SUBJECTIVE RATINGS

The preferred transform between physical profile measures and subjective panel ratings is

$$RN = -1.74 - 3.03 \log (PI)$$

for frequencies between 0.125 and 0.630 c/ft. This equation is based on profile data collected on 52 test sections spanning a range of MPRs of 1.0 to 4.4 and a range of roughness of 32.6 to 661.3 in./mi (MRM). It is considered to be a statistically valid transform within the ride quality range of 1.0 to 4.4, which spans the vast majority of surfaces. Roads with ride quality over 4.4 are of little importance from a practical or maintenance viewpoint, and road sections of ride quality less than 1.0 are rarely found, especially on Federal or State designated highways, and obviously require some type of repair.

The foregoing equation can be directly used by agencies that are able to measure the PI in the band of frequencies from 0.125 to 0.630 c/ft (e.g., those that have a profilometer). In addition, the equation leads to performance specifications for a simple roughness meter that could measure only these frequencies. These specifications will be addressed after the discussion of response-type roughness measures.

Given that a highway agency is able to measure profiles and compute PI for a given pavement section, RN is calculated directly from the preceding equation. Figure 21 presents a graph of this equation. It is valid for all surface types for RN between 1.0 and 4.4, the limits of our data.

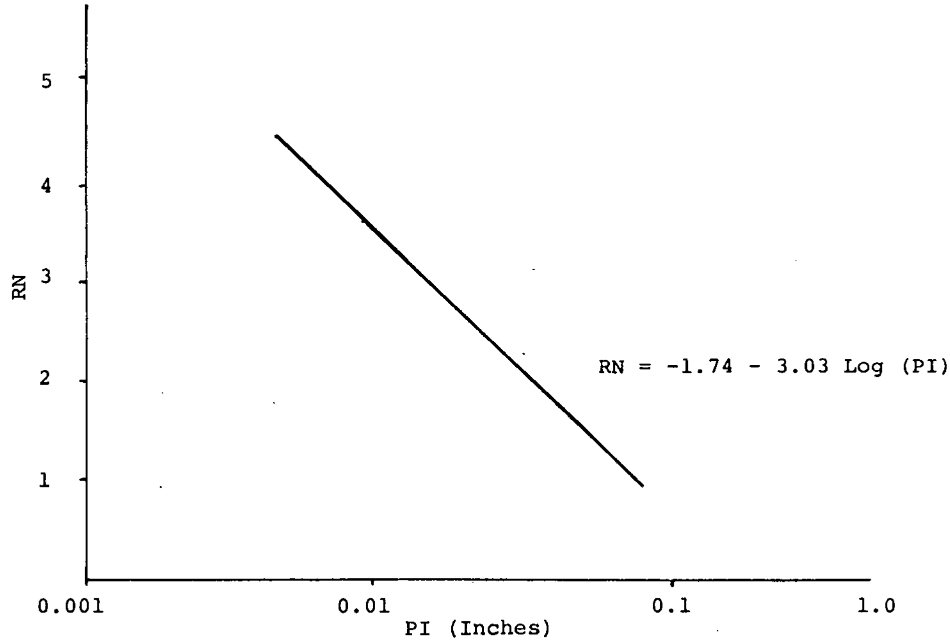

Figure 21. RN versus PI—all surfaces.

After the profile is measured, and PI is computed as described in Appendix D, RN is computed directly from the above equation.

One additional point is the fact that there may exist pavement sections that have predominate roughness in frequency bands outside of this study's preferred band (0.125 to 0.630 c/ft). For such sections, the transform developed in this study might be invalid and additional analyses would be warranted to check its validity.

TRANSFORMS BETWEEN RESPONSE-TYPE ROUGHNESS AND SUBJECTIVE RATINGS

As discussed in the beginning of Chapter Two, high correlations were found between response-type roughness and MPRs only for BC surfaces. Employing a log transform of the roughness data, correlation coefficients as high as −0.92 were found using either MRM or the ¼ car index as the measure of roughness.

The resulting transform between MRM index (see Appendix C for other equations) and MPR is

$$RN = MPR = 8.66 - 2.70 \log (MRM)$$

This equation has a regression coefficient (r^2) and 0.85 and a residual error of 0.15. It is almost as good a predictor of RN as the previous equation relating PI to RN.

This equation can be directly used by agencies that employ response-type meters. For other surface types, the resulting transforms are much less valid (i.e., low r). Figure 22 illustrates this equation, which is valid between RN = 1.0 and RN = 4.4, the limits of the data.

An alternative approach for deriving transforms would be to use the combination of two transforms: (1) PI versus RN and (2) simple roughness versus PI to yield one transform: simple roughness versus MPR. The first type, discussed in the previous section of this chapter and summarized fully in Tables 9 to 13, has high correlation coefficients and high validity. The second type, however, is much less valid.

Table 17 summarizes the results of correlating PI in the band of frequencies from 0.125 to 0.630 c/ft with MRM and ¼ car indexes. For PCC surfaces the predictions are poor (r^2 as low as 0.22); for BC and all surfaces combined the predictions are fair (r^2 about 0.6); and for composite surfaces they are slightly better (r^2 = 0.74), but still far poorer than the correlation between PI and MPR (r^2 = 0.88). Implementation of such transforms is thus not suggested.

The basic problem in this approach is that response-type meters, such as the MRM, respond to frequencies from 0.01 to about 0.2 c/ft, while MPRs are highly correlated with frequencies from 0.125 to 0.630 c/ft. (Only the BC surface has a relatively high correlation at lower frequencies.) The only common range is in the narrow band 0.125 to 0.2 c/ft, about two-thirds of an octave, and even in this band the response of the simple road meter is very low (*12*).

In NCHRP Report 228, Gillespie discusses the other problems associated with response type roughness measuring systems (stability, calibration, differences in dynamic response, hysteresis and quantization effect, dependency on host vehicle, inability to discriminate between roughness and tire/wheel nonuniformities) which must be considered if a RTRRMS is used to compute RN.

A preferred approach is to develop specifications for a simple response-type meter that would measure only the roughness in the frequency range dictated by the one-third octave analyses.

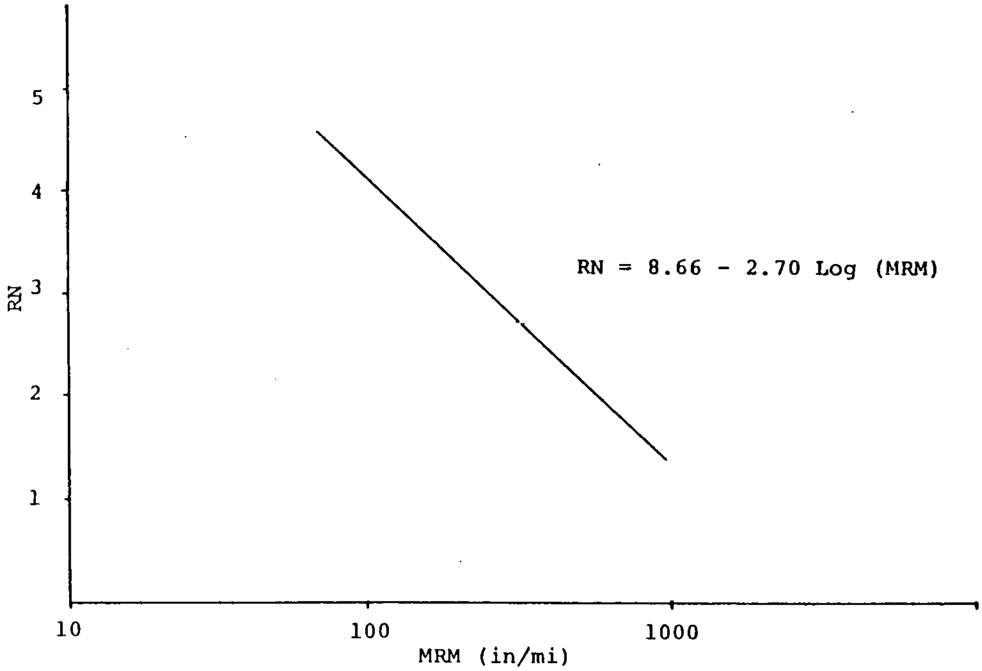

Figure 22. RN versus MPR—bituminous concrete surfaces.

Table 17. Correlation (r) between profile power and response-type roughness.

Surface Type	Roughness	
	1/4 Car	MRM
BC	.79	.75
PCC	.63	.47
Composite	.87	.86
All	.81	.78

Performance Specifications for a Response-Type Roughness Meter

Based on the results of the one-third octave analysis, the regression analyses summarized in Tables 9 to 13, and the preferred transform that relates physical profile measures to subjective panel ratings, performance specifications can be developed for a meter that would provide roughness data that are highly correlated with MPRs:

1. This instrument should measure roughness only in the range of 0.125 to 0.630 c/ft.
2. Frequencies outside this range should be filtered out by the meter and the associated equipment.
3. Both wheelpaths should be measured, or if only one wheelpath is measured, a correlation should be derived between the measurements in one wheelpath and the measurements in both wheelpaths.
4. The instrument should be calibrated against a profilometer to ensure that it is responding accurately to the roughness in the preferred frequency band.
5. The instrument should, preferably, be independent of the host vehicle.
6. The recommendations provided by Gillespie in NCHRP Report 228 should be considered.

A suggested practical implementation of these performance specifications is presented in Appendix E.

OTHER IMPLICATIONS

In addition to the recommended transform between PI and RN, the results of the pilot study and main experiment provide additional implications and recommendations.

First, the use of either trained professionals or laymen as panel members is recommended for evaluation of the subjective appraisal of ride quality.

Second, the statistical equivalence of MPR and "needs repair" rating ($r = -0.93$) obviates any requirement for an additional subjective rating to assess the public's desire for improvement of a given section of pavement surface. The RN (or PI) can be used as an accurate predictor of the percentage of the driving public that feels a specific surface should be improved.

Using the data in Table 15 or the graph in Figure 19 one can easily determine the exact percentage of the driving public that would be satisfied by a given RN (i.e., would not feel the section needs repair). For example, if it is desired to satisfy 85 percent of the public, an RN of 3.51 would be required; if only 50 percent were desired, an RN of 2.47 would be required. (This is based only on the data collected in Ohio; other areas may yield slightly different values.)

Third, the fact that (reasonable variations in) vehicle speed does not influence the subjective appraisal of ride quality implies that the effect of this variable need not be measured in future panel ratings. Since this study evaluated the effect of only two vehicle sizes (subcompact/compact), this variable should be fixed in any given panel rating study (i.e., use only one size). In Chapter Four recommendations are provided for further evaluations of this variable.

Finally, the small effect of panel regionality on subjective appraisals of ride quality will influence the design of future panel rating studies, and State agencies desiring to implement the results of this study should be aware that the preferred transforms may be slightly different in different areas of the country.

If a State highway agency wishes to implement a panel rating study to compute RNs directly from the MPRs and fine-tune the preferred equation to fit its specific state, Appendix F provides guidelines for implementing such a study. It includes a discussion of site selection and marking, panel selection, rating procedures, data reduction and analysis, and physical measures of roughness. It also gives the numbers and types of sites, panelists, vehicles, forms, etc., that are required.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The most important conclusion of this research is that subjective appraisals of pavement ride quality can be accurately predicted from physical measurements of the pavement's profile. The preferred regression equation accounts for 88 percent of the variance and is applicable to all three surface types.

The resulting transform is based on physical and subjective measurements made on 52 pavement sections spanning a wide range of roughness; a rating panel of 36 Ohio drivers spanning a wide range of experience; and use of the Weaver/AASHO rating scale with explicit panel rating instructions.

Other important conclusions are as follows:

1. The specific band of frequencies where roughness is most highly correlated with subjective appraisals of ride quality was identified: it is 0.125 to 0.630 c/ft (10 to 50 Hz).
2. The preferred transform that allows RN to be predicted from PI in the preceding band of frequencies is

$$RN = -1.74 - 3.03 \log (PI)$$

3. The performance specifications for a response-type roughness meter that would measure roughness only within this band of frequencies were developed.
4. For BC surfaces, a transform that relates RN to MRM index is

$$RN = 8.66 - 2.70 \log (MRM)$$

5. For PCC, composite, and all surfaces combined, MRM measures did not accurately predict RN.
6. For all surfaces, a transform that relates need for repair to RN (and hence, to roughness) is

$$NR = 132.6 - 33.5\ RN$$

7. Vehicle size (of two), (reasonable) vehicle speed, and training of panel members did not influence the subjective appraisal of ride quality.
8. A small, but statistically significant, effect of panel regionality on the subjective appraisal of ride quality was found.
9. Important frequency bands identified for Ohio surfaces were also important for Florida surfaces.

The lack of high correlation between MRM and MPR for PCC and composite surfaces is discouraging, in that interim recommendations using MRM values to accurately predict RNs for these surface types are not forthcoming. However, when one considers that this important band of frequencies, 10 to 50 Hz, includes a range of frequencies well above those that the MRM responds to, it is not surprising that the MRM measures are uncorrelated with the subjective ratings. It appears that PCC surfaces, and composite surfaces to a lesser degree, have considerable roughness in the frequency band above the limits of the MRM and that subjects respond to this roughness in providing lower ratings when such roughness is present.

It should also be noted that most of the literature on ride quality indicates that the human is most sensitive to frequencies in the range of 1 to 6 Hz (*13*). However, this is the range that an automobile manufacturer tries to filter out, so that it is reasonable to expect that the important band of frequencies has shifted to the 10 to 50-Hz range. Thus, one must not be led to believe that the range of 1 to 10 Hz can be forgotten, especially since trucks behave (as filters) quite differently.

RECOMMENDATIONS FOR FURTHER RESEARCH

A number of questions were raised by the research and the conclusions, and, as in many large studies of this type, hindsight has indicated other tasks that could have been performed to address those questions. Recommendations for further research include:

1. The use of a broader range of vehicle types for evaluation of ride quality, possibly also including trucks.
2. Further evaluation of panel regionality (residence area) effects. Subjective ratings (and their relationships to physical measures) will probably be slightly different in different areas of the country. (In other research no significant effect of statewide panel regionality (east-central-west) was found, so a total state can probably be considered to be the same for panel rating purposes (*2*).) Pennsylvania and Florida drivers were used to rate roads in Florida; it would have been preferable to use these drivers to also rate roads in Pennsylvania, but costs prevented it.
3. The addition of profile and panel rating data from other states to further validate the frequency band identified as most important.
4. Additional analyses to correlate PI derived from the profiles on two wheelpaths with PI derived from a single wheel profile.
5. Development and testing of a simple roughness meter that can be used on all types of vehicles and that would measure roughness in one or both wheelpaths in the important band of frequencies, development of calibration procedures for this meter, and field testing of the meter in a few states.

Care must be employed in applying the results of this study, especially the preferred transforms. The small effect of regionality should be considered by any agency that desires to apply these equations. A small panel rating experiment might be considered as a first step to fine-tune the transform; in particular, the subjective ratings for given roughness levels.

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APPENDIX A

LITERATURE REVIEW

INTRODUCTION

This appendix summarizes the results of a literature review of recent research on pavement roughness and rideability. The subjects reviewed are as follows:

- Definitions and concepts.
- Subjective rating methods.
- Objective (physical) measurements.
- Statistical methods.
- Uses of road roughness, profile and rideability data.
- Effects of road roughness.

The final sections of this appendix are a discussion of on-going research, conclusions, and a list of references.

DEFINITIONS AND CONCEPTS

NCHRP (*1*) has defined *rideability* as the subjective evaluation of pavement roughness and defined *roughness* as the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, and dynamic pavement loads. The reason for this latter definition is to exclude those factors of surface defects such as cracking, potholing, spalling, and patching and to ultimately develop separate measures for rideability and surface defects. However, it is clear from the extensive literature related to this problem that before one can even begin to define subjective measures of rideability, it is necessary to understand its basis (i.e., the entire notion of pavement serviceability).

The modern concept of pavement serviceability was initially developed at the AASHO road test and reported by Carey and Irick (*2*). Before that time, design systems in use by highway departments did not include consideration of the desired level of performance, and design engineers varied widely in their concept of desirable performance. Systems in use then were based on pavement stresses, pavement cracking, required maintenance, and other surface defects, but rational descriptions of the relative serviceability of pavements and how well they serve traffic were unspecified.

Carey devised a system "performance" measure that was rational and free of many of the biases due to strong personal opinion of groups or individuals. This system was based on five fundamental assumptions:

- The only valid reason for any road or highway is to serve the highway users.
- The opinion of a user as to how he is being served by a highway is largely subjective (with some exceptions).
- There are characteristics of the highway that can be measured objectively and are related to the user's subjective evaluation.
- The serviceability of a given highway may be expressed as the mean evaluation given it by its users.
- Performance is assumed to be an overall appraisal of the serviceability history of a pavement.

The actual system consists of 10 steps:

1. Establishment of definitions.
2. Establishment of rating panel.
3. Orientation and training of the rating panel.
4. Selection of pavements.
5. Field ratings.
6. Replication of field ratings.
7. Validation (replication) of panel.
8. Physical measurements.
9. Summaries of measurements.
10. Derivation of present serviceability index (PSI).

Carey pointed out that once a large number of roadway sections were so evaluated (including a wide range of each of the selected features such as very rough to very smooth and deep ruts to no ruts) and physical measurements were made on these surfaces, any section of highway could then be measured using the objective measurements without the necessity of the panel visiting the highway sections.

The heart of the subjective portion of the system was the individual present serviceability rating (PSR), illustrated in Figure A-1, from which all data are collected and from which all serviceability indices (SIs) are derived.

The main result of the AASHO study was the determination that serviceability is quantifiable and is a psychological quality or experience, not a physical measurement derived from pavement surface roughness (although it may be correlated with such measurements). Applications of this subjective rating technique have been accomplished in Virginia (*3*); Indiana (*4*);

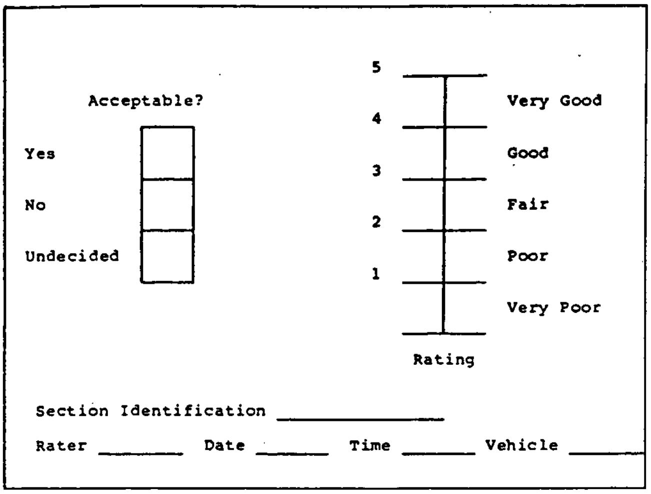

Figure A-1. Individual present serviceability rating form: Carey and Irick (*2*).

Minnesota, Indiana, and Illinois (*2*); Pennsylvania (*5*); and other areas (*6*). Although the subjective rating systems used in these states have been primarily based on the AASHO road test, the objective measurements have been taken with a wide range of instruments, including profilometers, BPR-type roughometer, Autoflect, Mays meter, and others.

The basic definition of pavement serviceability has been reiterated by numerous researchers and engineers, including Weaver (*7*), Corvi and Bullard (*8*), Phang (*9*), and Hudson (*10*). Weaver points out that the concept of serviceability (and performance) defined for the AASHO road test is beyond challenge. Serviceability and performance must be quantified and a rating system was devised to do it.

Problems arose in the application of the original concepts, primarily related to the principles and methods of psychophysics. These problems were not overcome in the original AASHO study (and in many later applications). The following section describes some of these problems and reviews possible methods to overcome them.

SUBJECTIVE RATING METHODS

The basic subjective rating system for evaluating pavement serviceability developed by Carey (*2*) and illustrated in Figure A-1 employs an adjective comparison scale (ACS) of 0 to 5. Slightly different rating systems have been employed by Holbrook and Darlington (*11*), Phang (*9*), and others. However, all are basically similar to the original AASHO scale with either the method of recording changed (graphic instead of numeric), the scale changed (AASHO uses 0 to 5, others 1 to 5 or 1 to 10), or the descriptive word cues changed.

Even in areas of research somewhat removed from pavement serviceability (e.g., Richards and Jacobson (*12*) for aircraft, trains, and buses; Park and Wambold (*13*) for buses), the same type of ACS procedures have been employed. L. G. Richards (University of Virginia, Charlottesville) has conducted extensive research on ride quality of many different types of vehicles and recently has considered scales of 9 or even 11 choices (much greater than the original AASHO scale of 6 numbers of 5 descriptive words). He is finding them much more accurate for subjective ride quality assessments.

The most extensive analysis of the AASHO subjective rating system was performed by Hutchinson (*14*). He reviewed the basic principles of subjective rating scale construction with emphasis on the subjective measurement of pavement serviceability. His findings included the following:

- Pavement serviceability is subjective.
- A panel or observers should be employed to evaluate serviceability.
- Bias of observers must be controlled.
- Systematic errors such as leniency, anchoring, central tendency, and halo effect must be minimized.
- Exact definitions and cues must be formulated and employed.
- Reliability (reproducibility) must be ensured (e.g., reliability coefficient).
- The number of rating categories must be optimized.
- The ability of raters must be evaluated.

Although Hutchinson pointed out that some of the more common distortions and biases to which rating scales are vulnerable have been shown to be present in the AASHO road test ratings, a complete evaluation of the ratings was not accomplished. The need still exists for the design of suitable experiments to evaluate some of the factors concerning scale format, anchoring, etc., that have been described. He explained that a more rigorous scale of pavement serviceability cannot be established until a suitable physical correlate of pavement serviceability is established. It is still not known whether the AASHO road test, as formulated by Carey, is the optimum choice for meeting the criteria described by Hutchinson.

Hutchinson also pointed out some of the basic problems or errors found in psychophysical ratings. These are summarized in Table A-1. His most important conclusions were as follows:

- For proper measurement of the attribute of serviceability, the panel-rating procedures must incorporate well-established principles and methods of psychophysics and applied psychology.
- The subjective estimating procedures typified by the AASHO panel ratings were inappropriate for the task in that they tended to measure pavement distortion and deterioration rather than ride quality.
- A dilemma exists in that a rating of serviceability cannot be derived with assurance until one has derived a precise measurable physical correlate that varies one-to-one with serviceability. However, the physical correlate cannot be derived with assurance until one has the subjective rating.

Weaver (*7*) continued the analysis of Hutchinson for the New York Department of Transportation to find objective, reproducible means of measuring pavement condition and deterioration and to implement the AASHO road test serviceability-performance concept in some manner. He stated that either (1) people make astonishingly poor "measuring instruments," (2) highway users are not served by highway pavements in any simple or uniform way according to the definition of serviceability, or (3) the panel-rating procedure *previously used* was not an effective means of finding out how people are affected by pavement conditions (Hutchinson's suggestion). Weaver concluded that the last possibility is now known to be the case.

Table A-1. Psychophysical problems.

Problem	Description	Method to Prevent/Overcome
Error of leniency	Constant tendency of a rater to rate too high or too low	Statistical transformation of rater variance
Halo effect	Tendency of raters to force the rating of a particular attribute in the direction of the overall impression of the object rated	Accurate definitions and exactness in direction
Error of central tendency	Raters hesitate to give extreme judgments and displace individual ratings toward the mean	Introduction of the judgment continuum as distinct from the sensory continuum
Anchoring	End point of continuum being rated	Accurate definitions

The requirements for change include a larger number of raters and better instructions. Weaver's proposed method includes the following items:

- Minimum of 90 test sections.
- No fewer than 60 raters.
- Maximum and minimum test section lengths and each test section homogenous.
- Rapid transition between sections.
- No atypical surroundings.
- Exclusion of nondrivers and engineers who study pavement distress.
- Very specific rater instructions and scale anchoring.
- New rater form (different from the original AASHO form).
- Specific procedures/techniques for actual field measurements.
- An extensive (13-step) analysis method to ultimately compute the scale value for each test section.

Weaver concluded his analysis by stating that the serviceability of a pavement, as perceived by the highway user, can be precisely measured. The principles of psychophysics provide a solution to the problem of measuring basic human responses to the range of physical stimuli generated by travel speed and pavement conditions. Although panel ratings have long been regarded as the most ambiguous and irreproducible means of evaluating pavement serviceability, *they may accomplish that purpose with precision and reproducibility if they are properly devised, conducted, and analyzed.*

Weaver's method, which produces test-section serviceability scale values that are shown to be independent of time, place, and differences in rating panels, differs in many ways from the classical AASHO road test PSR procedures. Unfortunately, the nature of PSR methods precludes any retrofit of AASHO road test data.

Requirements for applications of the new methodology are as follows:

- The raters should be 60 to 80 ordinary highway users, each rating all test sections.
- Rater instructions, which differ considerably from the PSR type of instructions, must firmly anchor the endpoints of the rating scale and fully describe the attribute of serviceability.
- Travel speed is a vital serviceability variable. Each test section must maintain a defined travel speed for all raters, thus constituting not merely a profile but a "travel experience" whose serviceability is rated. The serviceability scale value that is computed is thus the serviceability of a test section profile at its rating speed.
- The method of analysis encompasses the entire set of judgments and test sections from its onset.
- Combinations of test section and speed must provide a full range of serviceability experiences as well as profile conditions.

This method was developed to obtain a precise measure of serviceability on test sections at any time or place and permits calibration or recalibration of vehicle-mounted profile-measuring systems whose output is to be correlated with scalar serviceability at the posted travel speed. Thus, this method may also be used to evaluate the merits of various profile-measuring systems.

Since the interaction of profile, speed, and serviceability variables has been found to be sensitive to pavement type (rigid, flexible, and flexible-over-rigid overlay), Weaver recommended approximately 90 test sections (6 serviceability levels × 3 pavement types × 5 speeds) for a single experimental plan. The advantage of this method, which requires a great deal of effort to apply, is that it transforms the serviceability-performance concept from a somewhat abstract idea into a realistic tool yielding precise results. These results measure serviceability in terms of its original definition—how the pavement serves the highway user.

Although Weaver (*7*) and Hutchinson (*14*) presented a powerful case in their analyses, it appears that such methods are not universally accepted. Hudson (*10*) recommended a 15-number rating panel similar to the original AASHO test; Karan (*15*) employed only 8 members. The number of test sections is also open to debate. Weaver (*7*) recommended 90, but Karan (*15*) used only 55 in Canada. Similar disagreements exist on the scale (0 to 5 vs. 0 to 10, etc.), the wording, and even the entire concept of panel rating. Different systems such as accelerometers mounted on subjects in cars, results of a physical tracing with a pencil of a line on a form while riding in a vehicle (i.e., deviation from straight), and even physical simulators incorporating road-induced vibration have all been tried (or proposed) for evaluating the subjective ride quality of surfaces and vehicles.

Holbrook and Darlington (*11*) reviewed and tested three different scale rating methods for obtaining subjective responses to road roughness: graphic, gray paper, and word scales. The 96 subjects were able to use all three scales with equal effectiveness, and no evidence was found to suggest that the type of scale had any bearing on subjective ratings. In addition, different cars, blindfolded versus not blindfolded, and noise suppressor (ear covers) versus no noise suppressor had no measurable effect on the ratings. Holbrook further analyzed the scale rating data to artificially develop rank-ordered scale responses (equivalent to performing paired comparison ratings).

OBJECTIVE (PHYSICAL) MEASUREMENTS

Road roughness is measured by two types of equipment, one measuring the responses to roughness (response-type equipment) and the other measuring actual profiles (profilometers).

Response-Type Equipment

Response-type equipment records the dynamic response of a mechanical system traveling over a pavement surface at a constant speed; therefore, the characteristics of the mechanical system and the speed of travel affect this measurement.

The first widely used response-type device was the BPR roughometer, introduced in 1925. The roughometer is a single-wheel trailer which measures the unidirectional vertical movements of the damped, leaf sprung wheel (with respect to the frame) by a mechanical integrator. Counters record the results by producing an inches-per-mile count of roughness. Modifications of the BPR roughometer, intended to provide more information, include a cumulative tape recorder, an oscillograph, and the use of several resonance beams that are excited at different frequencies, giving an indication of the wavelength content of the surface at a given speed.

The great disadvantage of the roughometer is that measurements are made at speeds much lower than average highway speeds because of the slow response of the electromechanical counter. This causes a safety problem when other traffic is present. Illinois has reported that this limitation can be corrected by replacing the electromechanical counter with an electronic one for operation at higher speeds; however, the operational characteristics of the roughometer are modified by the higher speed (*16*).

Response-type equipment also included meters such as the PCA (Portland Cement Association) meter and Mays meter, which measure the vertical movements of the rear axle of an automobile relative to the vehicle frame.

Response-type equipment is widely used because of its simplicity, low cost, and high-speed operation. However, it is known to be time unstable, and suitable calibration procedures must be employed to provide useful data.

Road meters measure a dynamic effect of the roughness, but do not define the profile of the roughness. The selection of the mechanical system is critical, because some wavelengths will be amplified while others will be attenuated. Road meters are normally most useful in survey work to predict the user's response to the quality of the road. However, profiling equipment must be used to further examine the condition of a road or to determine what characteristics of the road cause the poor condition.

Profiling Equipment

Profilometers are designed to provide accurate, scaled reproductions of the pavement profile along a straight line. Although in practice the range and resolution of any profiling device are limited, the measurement is absolute within these limits.

The advantage of a profilometer is that it provides complete information about the pavement profile (within the limits of the particular device), which can be evaluated according to specific needs. However, the initial cost and/or operation of this equipment is high, and extensive data processing is required.

The simplest profilometer is a straightedge. The equipment is operated either statically or at very low speed, and is not readily suitable for wide-scale profiling since it cannot measure wavelengths longer than its span and can distort wavelengths that are harmonics of its span. Low-speed systems, such as the CHLOE, are moving reference planes, which have few or no dynamic effects because of their slow speed. Some modern profilometry equipment requires highly trained technicians, but it must be done at slow speeds of about 3 mph (5 km/h) (*16*).

General Motors Research (GMR) Laboratories developed the first modern roadway profiling equipment, the GMR profilometer, in the 1960s. It uses two spring-loaded, road-following wheels, instrumented with a linear potentiometer to measure relative displacements between the vehicle frame and the road surface. The accelerometers, which are mounted on the frame over each of the follower wheels, measure the vehicle frame motion by double integration of the signal. The frame motion is then added to the relative displacement motion to yield two voltage signals, which in theory are the road profiles of the wheelpaths. This method (using a road wheel displacement signal plus the double integration of the body accelerations rather than just the double integration of wheel accelerations) provides greater accuracy in the measurement of long wavelengths and separates the higher frequency data (shorter wavelengths) from the lower frequency data (long wavelengths) by using the vehicle's suspension as a filter (with a natural frequency around 1.5 to 1.8 Hz). The frequencies below 1 Hz are measured primarily by the accelerometer; frequencies above 2 Hz are measured primarily by the linear potentiometer; and frequencies between 1 and 2 Hz are measured by a combination of the two signals. This method is extremely useful because it provides good resolution of both the short wavelengths with low amplitudes and the long wavelengths with much greater amplitudes (*16*).

The GMR profilometer was originally manufactured with analog processing equipment; however, the most recent profilometer has been manufactured with on-board mini-digital computer. In the later version, the road profile computation is performed on board the profilometer vehicle, and the computed road profile data points are stored on a digital magnetic tape recorder for subsequent data processing. The acceleration and displacement sensor signals are sampled and immediately converted to digital values for use in the profile computation. The road profile sampling and computation are performed as a function of distance, instead of time (as in the earlier analog system), making these computations independent of vehicle speed and much easier to interpret. The programming flexibility of the digital system means that less technical expertise is required to operate and maintain the sytem than was required for the analog system.

Despite its advantages, the GMR-type profilometer is not widely used in the highway community because of high purchase cost, limited use that has been made in the past of the information contained in the roughness profile, and rapid wearing of the contact wheel.

Other profiling equipment includes the French design dynamic profile analyzer from the Technical University of Berlin, and newer devices which incorporate noncontact probes (acoustic, infrared, white light, laser, and microwave). FHWA is presently evaluating devices incorporating both acoustic and infrared probes (*16*), and the K. J. Law Company has developed an ultrasonic, noncontact, profiling device.

Calibration of Road Roughness Measuring Devices

Calibration procedures are required to convert present performance of road roughness measuring devices to an established standard performance.

Profilometers can be statically calibrated directly on surfaces for which the absolute profile has been obtained, or, for the GMR-type profilometer, the complete system can be calibrated by bouncing the profilometer vehicle in a stationary position. In the digital version the computer program guides the calibration procedure, in contrast to the operator judgment required in the analog version (*16*).

Calibration of response-type equipment is a more difficult task. The problem was addressed by Gillespie (*17*), who evaluated the time instability of the response-type devices and developed standard calibration procedures. Gillespie proposed a primary procedure involving the use of a specially designed set of artificial road bumps. In the primary procedure the profilometer was used to measure a road profile, which was then used as an input to a simulation of a response-type device. Thus, the output of the simulation is what would be expected from a response-type device driven on that road profile. Since the output of a response-type device is also a function of road roughness, this same procedure must be done for a range of road roughnesses. A Mays meter calibration capability has been programmed into the digital profilometer calibration system developed by Gillespie and includes a simulation of a Mays meter vehicle.

The proposed secondary calibration procedure involves driving over a foreshortened set of specially designed artificial bumps at low vehicle speed. The theory is that the system output at the lower speed can be used to calibrate the system output at the normal 80 km/h operating speed.

Hudson (*10*) summarizes a number of other methods for calibration, including roughometer calibration course, TRRL Pipe calibration course, use of "Standard Device," use of Hydraulic Shaker Table, Texas calibration course plus profilometer and Rod and Level Surveys.

Road Roughness Evaluation

Measuring the profile of a road is a preliminary step in evaluating its performance as a riding surface for vehicles and in judging its surface geometry. In recent years the trend in road profilometer design has been toward instruments capable of sensing undulations in the road surface with wavelengths as long as 325 ft (100 m), and doing this accurately at highway speeds.

Because visual evaluation of the recorded road profile is difficult, the major problem in application is extracting useful roughness data, and the methods selected for the reduction of road profile data depend on the ultimate uses for which the roughness measurements are intended and on the inherent limitations of the equipment.

STATISTICAL METHODS

Analyses of roughness and rideability data fall into three categories: analysis of physical roughness data, analysis of subjective rideability data, and comparative analysis of physical and subjective data.

Physical Data

Since measured records of roughness or profile data are recognized as random signals of finite durations, they can be described in terms of three domains: space (or time), amplitude, and frequency. Of the three, frequency domain descriptions are generally considered to contain the most information. The space domain description is the unprocessed signal-versus-space (or time). The various amplitude domain descriptions reduce the measured signal to a single number or table of values. This procedure is mathematically equivalent to computing an amplitude probability distribution for the signal (*16*).

The PSI, the most commonly used method, represents the amplitude domain. Subjective evaluations determine the PSI equations, with one relation for flexible pavement, one for rigid pavement, and one for overlays. All three equations are developed to use physical data such as the mean slope variance or the roughness value in a reading of inches of displacement per mile of travel.

There are three basic analysis methods that are applied to road roughness data: harmonic analysis, power spectral density (PSD), and amplitude frequency distribution (AFD). Harmonic analysis assumes that the road roughness data are periodic and reduces a complex road roughness waveform to a harmonic series of sinusoid waveforms, which are considered to be the amplitude contributions of the various harmonics in the road roughness data. The computed amplitudes of the sinusoid waveforms can be shown graphically as a function of spatial wavelengths in a road surface that can produce time domain frequencies causing poor ride quality at certain vehicle speeds.

The PSD representation assumes random road roughness data and shows the extent to which spatial wavelengths within a bandwidth contribute to road roughness. A PSD estimate is made by accumulating the squared amplitude within a bandwidth over the length of the processed pavement, dividing by the pavement length to obtain mean variance over that pavement length, and then dividing by the bandwidth to obtain an average for the bandwidth. A graph of the roughness power spectrum can be plotted, with the spectral density in units of length squared per cycle per unit of length as the ordinate and the spatial frequency (inverse of the wavelength) in cycles per unit length as the abscissa. The area bounded by the curve, the horizontal axis, and any two selected abscissas represent the total mean square value of the roughness for wavelengths lying between the two ordinates. The total area under a power spectrum curve gives the total mean square roughness of the pavement in unit length squared. If the PSD of the road surfaces is plotted on log-log plots, one obtains straight lines with a slope at a certain angle. Furthermore, parallel shifting of these lines occurs for different road amplitudes with similar distributions, and changes in slopes show different distributions (*16*).

AFD provides a combination of the information contained in the PSD and the amplitude representations. The complete array of numbers of the AFD includes continuous or periodic makeup and singularities in the input.

Simulation of Response-Type Equipment

Although response-type equipment, if properly tuned and calibrated, is normally useful to highway departments for surveying at low cost, profiling equipment provides more detailed information. In fact, the response data are still available from the profilometer outputs by using prediction methods with a ¼-car simulation.

With the development of the digital GMR-type profilometer, data processing can be performed at the time the road profile is being measured or afterward by retrieving data stored on digital magnetic tape. The manufacturer of the West Virginia digital profilometer has provided several computer programs for this purpose (*18*). Two of the programs involve the simulation of low-speed inspection devices (BPR roughometer and moving straightedge) to produce the output of these devices. This approach permits measurement of road profiles at normal traffic speed (for safety purposes), sufficient time for computation of the output of the (simulated) low-speed inspection device, and the retirement of out-of-date equipment without losing continuity with historic inspection procedures. A third computer program developed by the same manufacturer involves simulation of the Mays meter. The Mays meter model used in the simulation was developed in an NCHRP project (*17*) and is the first implementation of the calibration procedure recommended in this project.

Other Analysis Methods for Physical Data

McKenzie and Hudson (*19*) developed a special class of profile statistics, termed root-mean-square vertical acceleration (RMSVA). This statistic has been shown to reveal many of the road surface properties normally associated with roughness. The RMSVA indices computed from a road profile can provide a "signature" that reflects roughness over a broad range of profile wavelengths.

In Europe, two different roughness analysis methods have been used. The first method, which is effective for research, is the determination of the spectral density of the variations in amplitude level, to calculate vibrations. This method is very accurate and makes use of a specialized analog computer. The minimum length of a section under study is about 2 mi (3 km) (*16*).

The second method used in Europe corresponds to analysis of the average variance of differences in level, classified by wavelength scales. By breaking down the whole scale of the results obtained into 10 categories of geometrically increased scales, a scale of values has been set up, allowing simple comparison of results of measurements performed on various roads. This method is less sophisticated than the first but more accessible and so is well adapted to systematic measurements on a section of at least 650 ft (200 m) (*16*).

Subjective Data

Beginning with Carey and Irick (*2*), a number of approaches have been followed to analyze the psychophysical data derived from the subjective ratings of pavements. Such analysis are dependent on the design of the experimental procedures and the form of the data collected. However, each analysis ultimately yields a single rating (e.g., the mean panel ratings) for each surface for the AASHO type of evaluation as developed by Carey (*2*). Weaver (*7*) extended this approach, as discussed earlier in this appendix, and developed a detailed 13-step analysis plan using 90 test sections and 80 raters. (The analysis method is fully described in Ref. *7.)* Weaver employed this 13-step procedure under the assumption that raters are unable to make direct judgments of ride quality (i.e., they only make ordinal judgments instead of direct interval judgments). His method is modeled on psychophysical theory developed by Guilford (*20*).

Since most of the research into subjective rideability and serviceability has employed some type of ACS for rating the pavement surfaces, most of the analyses are similar to that proposed by Carey and Irick (*2*) and Weaver (*7*). In the area of vehicle ride quality (bus, train, airplane), Richards (*12, 21, 22*) has done extensive work employing ACS rating systems (typically with a range of 1 to 7) and some simpler "like-don't like" stratifications. Similar (but simpler) analyses were used by Park and Wambold (*13*).

Holbrook and Darlington (*11*) developed a statistical transformation of the individual test section ratings based on the subjective responses (ratings) and their variances and intercorrelations (i.e., between two responses) to artificially derive a paired comparison scale. This scale was then used to rank order the test sections.

Ultimately, however, the objective and subjective data must be combined so that the former, which is more economical to obtain, can be used to predict the latter, which is the realistic appraisal of rideability.

Comparative Analysis

The main statistical analysis required for the study of rideability is that which compares the objective and subjective data to obtain a transform relating the two data types. The form of the subjective data has typically been in terms of a single numerical rating for each pavement surface. The objective data, however, can be as simple as a single number or as complex as AFDs.

Many researchers have attempted to compare objective, physical measurements derived from instruments such as surface profilometers, Mays-type road meters, or BPR-type roughometers (i.e., SI) with subjective measures (ratings) of user's perception of pavement serviceability (i.e., PSR). The derivation of subjective ratings or PSRs generally employs an ACS.

The original comparison of subjective and objective ratings was accomplished by Carey and Irick (*2*). A BPR roughometer and rut depth gauge were used to obtain roughness and profile characteristics (as well as measurement of cracking, etc.), and a panel was employed to rate the test sections on a 0 to 5 basis as illustrated in Figure A-1. Carey hypothesized a linear model for SI which would be a function of surface deformation and deterioration and which would predict PSR as obtained from the panel ratings. He found correlation coefficients of 0.844 and 0.916 for flexible and rigid pavements.

Nakamura and Michael (*4*) employed various rating panels (laymen, state highway professionals, and academic professionals) and used the 0 to 50 rating scheme of AASHO and the BPR roughometer for physical measurements to develop linear regression lines for rigid, flexibile, and overlay pavements. The correlation coefficient for the rigid type was found to be high (about 0.90), but for the other types was quite low (about 0.50).

In a study by Park and Wambold (*13*), a correlation between objective and subjective comfort ratings of vehicles (buses) traversing rough roads was made. The objective measure was absorbed power (acceleration at the interface of the passenger and vehicle), and the subjective rating was an ACS (1 to 5 or 1 to 6). When a sufficient sample size was taken, an "excellent correlation" (authors' phrase) was developed.

Williamson (*23*) characterized roughness through digital filtering methods on the basis of wavelength. Multiple regression analyses were then employed to relate the panel rating (ACS) to roughness as a whole and to individual types of roughness as measured by a GMR surface profilometer. A model was developed to obtain, for any given road surface, a measure of riding quality corresponding to each of a set of important aspects of roughness.

Similarly, Walker and Hudson (*24*) developed serviceability models relating slope variance profile data obtained with a GMR profilometer to ACS ratings derived from a panel of 15 raters. Walker also included pavement deterioration data. He employed power spectrum components to develop pavement SI prediction models.

Holbrook and Darlington (*25*) further investigated the functional relationships between the spectral density frequencies of the road profile and subjective responses to road roughness (using an ACS), to disclose the underlying problems which had been previously ignored or missed, and suggested solutions for providing more accurate functional relationships. They demonstrated that when human subjective responses to road roughness are functionally related through multiple regression to PSD frequencies of the road profile, highly inaccurate or unreliable relationships result. The problem was extremely high intercorrelation of many of the frequencies, resulting in part from the difference in elevation between the inner and outer wheelpaths, causing a roll component which may have a strong effect on ride quality. The problem was not alleviated by stepwise multiple regression in an attempt to capture only the most important frequencies.

Their proposed solution included the development of a power function relating the two wheel profile signals. They considered three configurations of power: (1) the average power between lanes, (2) the absolute difference in power between lanes, and (3) the product of (1) and (2).

The procedure they employed for their solution was as follows:

1. Filter the two wheelpath signals to eliminate all wavelengths outside the ban of 2 to 50 ft (0.6 to 15 m).
2. Sample filtered signals every 6 in. (15.2 cm) providing 4 points/cycle at the highest frequency present.
3. Compute 25 ordinates yielding 13 "independent" estimates of the power spectrum.
4. Smooth the final estimates using a Hanning spectral window.

The specific details are presented in Ref. *25.* When they compared their results for a sample of 14 test roads rated by 96 subjects, they found that ordinary multiple regression provided poor estimates, while the new approach yielded high (over 0.9) correlations.

In other laboratory tests by the same authors, they found that the 6 to 8 ft (1.8 to 2.4 m) wavelength bands caused maximum reactive forces on average vehicles. This result, in conjunction with the statistical analysis, implied that it would be sufficient to measure the 6 to 8 ft wavelength band or the 2 to 8 ft (0.6 to 2.4 m) band (easily measured by a device much simpler than a profilometer, e.g., a simple accelerometer) in order to locate areas of excessive roughness.

USES OF ROAD ROUGHNESS AND RIDEABILITY DATA

Carey and Irick (*2*) pointed out four fundamental uses of pavement roughness measurements:

1. To maintain construction quality control.
2. To locate abnormal changes in the highway, such as drainage or subsurface problems, and extreme construction deficiencies.
3. To establish a systemwide basis for allocation of road maintenance resources.
4. To identify road serviceability-performance life histories for evaluation of alternative designs.

Wambold (*16*) expanded this list to include the following uses:

1. Specification of surface profile limits and rideability of new road construction.
2. Evaluation of costs to improve the road.
3. Prediction of loss of rideability in existing roads.
4. Establishment of maintenance and replacement criteria.
5. Correlation with vibrational response and fatigue damage in vehicles.
6. Development of passenger comfort criteria.
7. Evaluation of roughness effects on vehicle steering and braking.

Some of these applications require highly sophisticated data processing (especially for the physical, objective data), which would lead to an entirely mathematical representation of the profile record. Other applications may require only an averaging or summing to establish a single roughness or rideability criterion. Transportation departments that have profiling equipment are able, in effect, to bring the road surface into the laboratory and to seek the most useful data-processing method.

EFFECTS OF ROAD ROUGHNESS

A number of authors have reported on the effect of road roughness on safety, vehicle behavior, vehicle braking, vehicle steering, vehicle ride, and fuel economy (*23, 27, 28, 29, 30, 31*). The consensus appears to be that as the roughness increases, safety, vehicle behavior, fuel economy, etc. all decrease.

Burns (*29*) provides an excellent example of the relationship between roughness and accident experience. He found an increase of between 35 percent and 82 percent in the wet pavement accident rate on untreated control sections and a decrease of 15 percent in the wet pavement accident rate on a treated section (surface grinding). The ride quality (PSI) of the treated section was improved from 2.1 to 3.6 (71 percent).

Quinn and Jones (*30*) found direct relationships between road roughness and steering wheel angle, vertical driver acceleration, and lateral tire forces—all measures of vehicle behavior.

Ross (*31*) reported that past work has revealed increases of fuel consumption of between 10 percent and 30 percent when comparing a broken asphalt pavement and a smooth surface.

In an experiment conducted by Wisconsin DOT, Ross found that fuel consumption increased as roughness increased, but only slightly (a change in PSI from 4.4 to 0.9 revealed a 3 percent increase in fuel consumption). Ross pointed out that other factors (speed, gradient, driving habit, wind velocity) can have more effect on fuel consumption than roughness and will mask the effect of roughness unless very accurate measurements are made.

ON-GOING RESEARCH

There is presently one research study related to the psychophysical aspects of ride quality. This project, which is being conducted by Ketron, Inc., for PennDOT (*32*) has the following objectives:

1. Perform a state-of-the-art survey of methods to relate subjective and objective measurements of pavement serviceability.
2. Design an experiment to evaluate and quantify user perception of pavement serviceability.
3. Conduct the experiment to quantify user perception of serviceability for each maintenance functional classification (MFC) and determine thresholds of serviceability.
4. Correlate user ratings of pavement serviceability with physical measurements of roughness.

The overall goal of this program is to correlate Mays meter measurements with road users' ratings of pavement serviceability.

An experimental plan has been developed (*33*) and an interim report, summarizing the results of a pilot study, is available in draft form (*34*).

Because the objectives of the PennDOT project and those of NCHRP Project 1-23 are so similar and because the results of the PennDOT pilot study will be extremely useful in the work in NCHRP Project 1-23, a detailed summary of the PennDOT pilot study is presented here.

Objective. The objective of the pilot study was to determine the best psychophysical scaling method to employ for pavement ride quality evaluations. (This is the same objective as the objective of the pilot study proposed for NCHRP Project 1-23.) The selection of the "best" rating scale for the PennDOT study was based on its correlation to Mays meter measurements of roughness (for the NCHRP pilot study the section of "best" scale is based on its correlation with profile data).

Scale Selection. Table A-2 presents the five major types of psychophysical scales with brief descriptions of their advantages and disadvantages. Figure A-2 illustrates the scales selected for testing (the last two scales were not tested for the reasons given in Table A-2).

Panel Size. Table A-3 gives the panel sizes required as a function of error, in scale units, for both an assumption of normalcy (i.e., unimodal, symmetric sampling distribution) and nonnormal. Although it was hypothesized that the panel would have a normal distribution, a conservative approach was followed and a panel size of 18 (equivalent to an error of slightly over 0.4 scale units for a nonnormal distribution and slightly less than 0.3 scale units for a normal distribution) was selected for each scale, yielding a total panel of 54.

Panel Composition. The panel was prestratified by sex (½ male, ½ female) and poststratified (unequal cell sizes) by age, driving experience, living area, type of vehicle normally driven, and socioeconomic factors. Panel members included Ketron staff, PennDOT staff, and volunteers from the driving public.

Table A-2. Advantages and disadvantages of five scaling methods.

Method	Type	Advantage	Disadvantage
Weaver/AASHO (Figure A-2)	Direct	None	This method was clearly a first attempt at quantifying pavement serviceability and violated many principles of psychometric methods.
Holbrook's Graphic Scale (Figure A-2)	Direct	Accurate placement of cues along the scale should aid the observers in making direct interval level judgments.	Connotative problems associeated with the intermediate cue words could bias the results.
Nonsegmented Scale (Figure A-2)	Direct	Eliminates any problems introduced by using intermediate cue words.	Many observers may find it difficult to make their ratings without the aid of cue words.
Magnitude Estimation	Direct	Avoids all problems associated with graphic rating scales and placement of cues.	May be impossible to implement due to the logistics of the anticipated experimental design.
Successive Categories	Indirect	Makes no assumptions about the ability of the observers to make direct interval or ration judgments.	Relies heavily upon untestable, hypothetical models of human judgment and requires a complicated analysis procedure to obtain scale values.

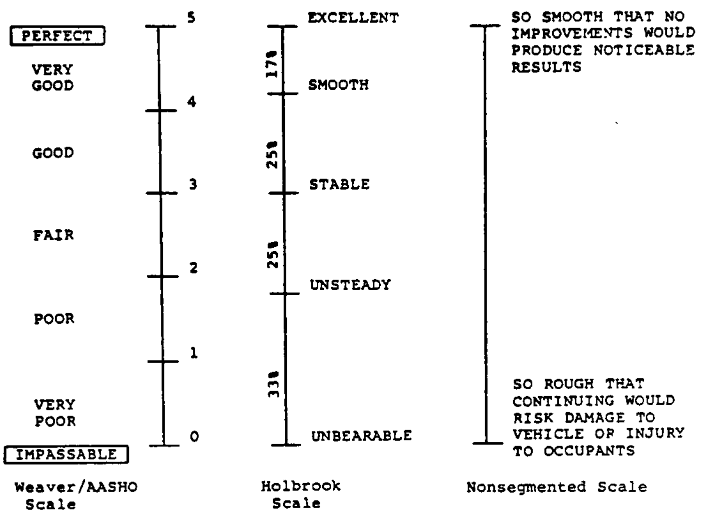

Figure A-2. Scales tested in pilot study.

Site Selection. Site selection was the most difficult part of the pilot study. Since it was only of interest to determine the "best" rating scale, certain important variables—which were fully analyzed in a later part of this study—were fixed. These included surface type (only flexible was employed) and area (all sites were in rural Chester county).

Four MFCs were employed (Pennsylvania has no MFC-A (interstate) roads with flexible surfaces), each with sites covering a wide range of roughness. Site length was specified to equalize the exposure time on each site (i.e., length of site divided by speed on site = constant).

Protocol. Panel members were grouped into sets of three (all of the same sex), assigned seat positions (one of three), provided with detailed instructions, and then driven over the route (one of three starting positions). Individual ratings were simply marked on prepared coded sheets and passed to the driver after each site was completed. One vehicle (1981 Chevrolet Citation) was used, and groups of three were taken twice a day for three weeks (a.m. and p.m.).

Statistical Analyses and Results. Two primary statistical analyses were performed: an analysis of concordance to assess how well the panelists agreed in their ratings for the three scales and

Table A-3. Panel size as a function of error.

Error (scale units)	"Non-normal" distribution	"Normal" distribution
0.1	319	138
0.2	80	35
0.3	36	15
0.4	20	9
0.5	13	6
0.6	9	4
0.7	7	3
0.8	5	-
0.9	4	-
1.0	3	-

a regression analysis between each of the three scales and the Mays meter measures.

Secondary analyses included a factor analysis to determine the effect of site characteristics, such as topography, curvature (vertical and horizontal), speed, and area type, and an analysis of demographic and other factors, such as sex, age, seating position, and starting point.

Table A-4 presents the results of the analysis of concordance. It reveals that there is basically no difference between the three scales.

Table A-5 presents the results (R^2) of the regression analysis using scale values obtained under two different assumptions: (1) people can make direct interval level judgments (i.e., a rating of 3 is twice as good as one of 1½); and (2) people can only make indirect judgments (a rating of 3 is better than one of 1½). Again there is virtually no difference between the three scales.

These results indicate that between 85 percent and 90 percent of the proportion of the variance is accounted for with the linear regression models. Conversely, only 10 percent to 16 percent of the proportion is not accounted for, highly significant results.

The major implication of these results is that either of the three scales can be successfully used if the experiment is well designed and controlled. Since the AASHO/Weaver scale has been used in most past research, it will be used in NCHRP Project 1-23 to preserve continuity and provide data that are generally comparable to that presently being collected by others (e.g., NYDOT).

The other analyses revealed the following effects:

1. There was no learning effect attributed to using different starting points.
2. There was no effect of sex; males and females rate pavements in an equivalent manner.
3. There was no significant effect of different seat positions (front/right, left/rear, right/rear).
4. There was no effect of vehicle type normally driven (subcompact to full size and truck/van).
5. More experienced drivers seem to rate with less variability, while inexperienced drivers may hesitate to provide extreme ratings.
6. There was no effect of average miles driven per year.
7. There were no significant effects of site characteristics other than roughness.

The implications for the NCHRP study are immediate. Since the Mays meter physical measures of roughness are a subset of the total profile of the road (i.e., the profilometer can predict the Mays meter measures) and since the Mays meter measures predict the subjective responses to well (only 10 percent of the variance is unaccounted for using the AASHO/Weaver scale), the use of a profilometer could only slightly increase the R^2 (e.g., up to 0.95—one rarely attains an R^2 closer to 1 for such experimental data). It therefore appears to be nonproductive to evaluate three or more psychophysical scales for NCHRP in a pilot study that would basically repeat that which was completed for PennDOT.

Table A-4. Analysis of concordance.

Scale	Chi-Square *	df	Coefficient of Concordance	Average Intercorrelation
Weaver	439.95*	32	.764	.750
Holbrook	461.61	32	.801	.790
Nonsegmented	427.66	32	.742	.727

*p <.001, CRIT $\chi^2_{.99}(32) \approx 51$

Table A-5. Regression analysis.

Scale	Assumptions on Judgments	
	Direct	Indirect
Weaver	.8964	.8993
Holbrook	.8436	.8869
Nonsegmented	.8942	.8907

CONCLUSIONS

Extensive work has been accomplished, both in the United States and in foreign countries, toward measuring the physical aspects of road roughness, analyzing the resulting data, and evaluating the (physical) riding performance of pavements. Instrumentation and analysis are well developed.

The subjective aspects of ride quality or rideability of pavements have been studied in a more limited context, primarily because of the time and costs of such evaluations. Even less information exists on the relationships between the physical measures of roughness and the subjective measures of ride quality. However, since ultimately it is the road user who must be served by highways, and users' criteria for acceptance of highways involve a subjective appraisal of its riding quality, one must know the relationships between these subjective appraisals and the physical measures of roughness. This will allow engineers to employ the more efficient physical measures of roughness, with its well-developed instrumentation and analysis, to evaluate the ride quality of such highways. On-going research will attempt to define these relationships, using both physical data derived from response-type road meters and complete road profiles.

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APPENDIX B

SUPPLEMENTAL MATERIAL FOR PILOT STUDY

This appendix contains supplemental material for the pilot study, including rater form, description of test sites, panel instructions, graphs of profiles, and a summary of the analysis of the profile data.

Figure B-1. Rater form.

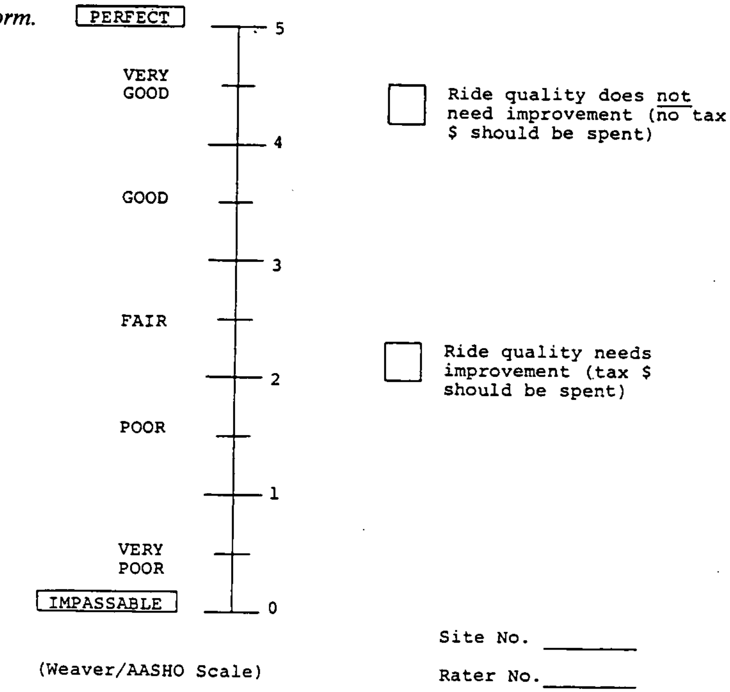

Table B-1. Pennsylvania test sites.

SITE NO.	MFC	TYPE	I/M	LR	TRAFFIC ROUTE	TEST STATIONS	COUNTY	LANE
33	B	BC	169	143	Rte. 252	445+20-460+20	Chester	North
29	B	BC	194	179	Rte. 352	30+56-45+56	Chester	North
1	B	BC	350	202	Phoenixville Pike	399+32-414+32	Chester	East
16	C	BC	88	137	Rte. 322	694+70-669+72	Chester	West
15	C	BC	105	270	Rte. 113	75+00-60+28	Chester	South
2	C	BC	130	202	Phoenixville Pike	469+72-484+72	Chester	North
8	D	BC	85	270	Rte. 113	350+56-370+56	Chester	North
10	D	BC	94	15139	Rte. 401	610+20-630+05	Chester	East
25	D	BC	103	134	Rte. 52	402+83-417+80	Chester	North
14	D	BC	108	15094	Whitford Rd.	185+28-195+28	Chester	North
28	D	BC	140	626	Rte. 926	49+50-64+50	Chester	East
23	D	BC	181	15002	Creek Rd.	99+80-84+80	Chester	South
7	D	BC	207	15139	Rte. 401	734+44-719+44	Chester	West
26	D	BC	283	15087	Birmingham Rd.	176+18-161+18	Chester	South
31	D	BC	341	15106	Surgartown Rd.	10+56-25+56	Chester	North
30	D	BC	352	15105	Delchester Rd.	59+84-74+72	Chester	North
4	D	BC	482	15009	Yellow Springs Rd.	165+00-155+00	Chester	West
24	D	BC	504	15002	Creek Rd.	55+02-45+02	Chester	South
17	D	BC	560	15211	Rock Raymond Rd.	58+08-44+80	Chester	South
3	D	BC	639	15009	Hollow Rd.	232+14-222+14	Chester	West
19	E	BC	153	15076	Shadyside Rd.	61+45-74+72	Chester	East
20	E	BC	187	15092	Conner Rd.	50+30-60+30	Chester	East
6	E	BC	212	15189	Seven Oaks Rd.	138+75-129+73	Chester	South
11	E	BC	228	15142	Byers Rd.	89+76-68+64	Chester	West
21	E	BC	229	15120	Creek Rd.	35+23-25+23	Chester	South
18	E	BC	244	15075	Glenside Rd.	179+14-160+28	Chester	South
9	E	BC	260	15216	Chester Springs Rd.	84+92-64+92	Chester	West
5	E	BC	315	15189	Foster Rd.	174+72-160+56	Chester	South
22	E	BC	329	15103	Creek Rd.	42+54-32+54	Chester	South
200D	E	BC	338	15142	Byers Rd.	30+00-15+00	Chester	West
27	E	BC	553	15221	Wylie Rd.	68+64-78+64	Chester	North
202D	TWP	BC	393	-	Frank Rd.	-	Chester	West
203D	TWP	BC	419	-	Thornbury Rd.	-	Chester	East
201D	TWP	BC	439	-	Harmony Hill	-	Chester	East

*LR = Legislative Route

Table B-2. Florida test sites.

SITE NO.	TYPE	I/M*	SPEED	TRAFFIC ROUTE	SITE LOCATION	COUNTY	LANE
aa	BC	60	35	121	0.1-0.9 from 121 and NW 16th Ave.	Alachua	North
A	BC	79	45	222	0.0-0.8 from 121 and 122	Alachua	East
B	BC	24	45	222	1.1-1.9 from 222 and 25/U.S. 441	Alachua	East
C	BC	23	45	26	1.5-2.3 from 222 and 26	Alachua	East
D	BC	19	45	26	0.9-1.7 from 26 and C-325	Alachua	East
E	BC	78	45	NE 58	0.2-1.0 from 26 and NE 58	Alachua	North
F	BC	85	45	C-219A	2.2-3.0 from 26 and C-219A	Alachua	South
G	BC	147	45	C-219A	1.5-2.3 from C-219A and C-234	Alachua	South
H	BC	6	55	20	1.6-2.4 from 20 and 200	Alachua	West
I	BC	225	30	C-234	0.6-1.2 from 20 and C-234	Alachua	South
J	BC	108	45	C-234	5.2-6.0 from 20 and C-234	Alachua	South
cc	BC	--	55	25/441	3.2-4.0 from C-234 and 25/U.S. 441	Marion	South
K	BC	--	45	318	2.1-2.9 from 25/U.S. 441 and 318	Marion	East
L	BC	--	45	200A	1.1-2.9 from 200A and 200/U.S. 301	Marion	South
M	BC	86	45	C-316	0.4-1.2 from 200A and C-316	Marion	West
N	BC	143	30	NW 21	0.1-0.9 from C-316 and NW 21 Terrace	Marion	South
O	BC	54	35	C-329	0.4-1.2 from NW 21 Terrace and C-316	Marion	West
dd	BC	27	45	C-25A	1.1-2.1 from C-329 and C-25A	Marion	South
P	BC	30	45	C-25A	4.6-5.4 from C-329 and C-25A	Marion	South
Q	BC	131	45	C-326	1.4-2.2 from C-326 and 93/U.S. 75	Marion	West
ee	BC	67	30	MC Road	0.1-0.6 from C-225A and MC	Marion	West
R	BC	20	45	C-225	1.4-2.2 from C-318 and C-225	Marion	North
S	BC	39	45	C-329	1.8-2.6 from C-318 and C-329	Marion	North
Tt	BC	155	45	C-320	1.5-2.3 from C-329 and C-320	Marion	East
T	BC	140	45	C-320	0.2-1.0 from C-320 and 93/U.S. 75	Marion	East
U	BC	26	45	25/441	1.4-2.2 from C-320 and 25/U.S. 441	Marion	North
V	BC	86	45	C-225	0.7-1.5 from C-10 and C-225	Alachua	North
W	BC	69	45	C-346	1.8-2.6 from c-225 and C-346	Alachua	East
X	BC	27	55	25/441	1.4-2.2 from C-346 and 25/U.S. 441	Alachua	North
Y	BC	55	45	SW 18	3.2-4.0 from 25/u.s. 441 and SW 18	Alachua	West
Z	BC	4	45	121	0.9-1.7 from SW 18 and 121	Alachua	South

*Florida DOT Mays Meter reading - sites cc, K, L were not Mays Metered. Site cc similar to site U, sites K and L were resurfaced and probably have a very low in/mi.

HIGHWAY IMPROVEMENT STUDY

Purpose: To survey typical Pennsylvania drivers in order to determine what they think of the quality of the ride provided by the roads in the Commonwealth. PennDOT will use this information to help decide which roads they should improve first with the limited funds available to make highway improvements.

Object of Ketron's Study:

We are going to drive you over a number of roads which we believe are representative of the roads as they exist throughout the Commonwealth. We will then ask you to make two judgments concerning each road. First, we want you to rate the roughness or smoothness of the ride provided by each road on a scale of 0 to 5, and second, we want you to indicate whether or not you think an effort should be made to improve the ride quality of each road.

MAKING YOUR RATINGS OF RIDE QUALITY

(A facsimile of the rating scale was shown to the subjects for this section).

The first thing we want you to consider as you drive down a road is the roughness or smoothness of the ride provided by the road and then to rate it on this scale (illustrated) which ranges from 0 to 5. You will indicate your rating by placing a small mark across the vertical line of the scale at the place which you think best describes the ride provided by each road.

DEFINITIONS OF ENDPOINTS

All the roads which you drive over in this survey will be between two extremes. That is, somewhere between impassable and perfect.

Impassable: A road which is so bad that you doubt that you or the car will make it to the end at the speed you are traveling -- like driving down railroad tracks along the ties.

Perfect: A road which is so smooth that at the speed you are traveling you would hardly know the road was there. You doubt that if someone made the surface smoother that the ride would be detectably nicer.

Since these roads probably do not exist you will probably not consider any road to be worse than impassable or better than perfect.

In order to help you make your rating, we have included a number of words along the scale which could be used to describe how the riding sensation seems to you. For example, if you should encounter a road for which you could describe the ride as FAIR but not quite GOOD, place your mark just below the line labeled "3" (illustrated). On the other hand, if you think the next road is still fair, but somewhat worse than the previous road, place your mark at a point which you think is the appropriate distance down in the FAIR category. To indicate small differences between the ride quality provided by the roads, you may place your mark anywhere you like along the scale.

NOTE: We are not asking you to place roads into one of five categories! You should use small differences in the position of your marks to indicate small differences between the ride quality provided by the roads. You may place your mark anywhere you like along the scale.

INDICATING THE NEED FOR THE IMPROVEMENT

After you have made your rating of the degree of ride quality provided by any particular road, we want you to check the appropriate box alongside the rating scale to indicate whether or not you think the Commonwealth should spend part of the money it receives from gasoline taxes, vehicle registration fees, etc. to improve the ride quality of the road.

When making this decision you should take into account the fact that since the state only has a certain, fixed amount of money each year to make road improvements, it must determine which roads should be improved first. Therefore, before deciding on the need for improvement, you should not only consider how rough a ride is provided by each road but whether you feel the road is important enough to be placed high on the state's list of roads needing improvement. For example, you may ride across two roads which give identically rough rides but, if you had your choice, you would rather see your tax dollars used to improve only one of them because the type or character of that road seems to you to make it more worthy of improvement.

PROCEDURE FOR SURVEY

- For this survey we are going to ask you to evaluate 34* road sections.

* 31 in Florida.

Figure B-2. Panel instructions.

NOTE: You will <u>not</u> be rating an entire road for its ride quality. We have carefully selected small test sections to represent each road. It is these sections that we want you to rate for ride quality.

- As you approach each section, the driver will call out the number of the section. Be sure you have the proper numbered form.
- When the driver says START, begin concentrating on what the <u>rating of ride quality</u> should be based on how the ride <u>feels to you</u>.
- It will only take about 30 seconds to drive over each section so maintain your concentration until the driver says STOP. At that point, place your rating mark on the scale.
- Next, while taking into account both the roughness of the ride through the representative test section, as well as the nature and type of the entire road, indicate whether or not you think the ride quality needs to be improved by checking the appropriate box next to the rating scale.
- Since some sections are only 3-4 minutes apart, make your decisions quickly and pass your forms to the person sitting in the front right seat.
- This procedure will be repeated for each site.
- We will be driving over a predetermined course in an ordinary passenger car. The trip will take *.

SPECIAL INSTRUCTIONS

- When making your rating of ride quality, do <u>not</u> consider any of the road before or after a <u>test</u> section. We are only interested in a rating for a small section of road.
- When making your decision concerning the need for improvements, assume that the ride provided by the entire road is the same as that for the test section.
- Concentrate only on the ride quality provided by the roads. Don't let the appearance of the road surface influence your ratings. Judge only how the road feels!

---
* Fill in appropriate time.

Figure B-2. Continued.

- Don't be distracted by conversations in the car or by pretty scenery.
- Don't reveal your ratings to the other raters. There is no right or wrong answer, so don't "cheat". We are interested only in <u>your</u> opinion which is as valid as anyone else's.
- Be critical about the ride quality provided by the roads. If they are not absolutely perfect as far as you are concerned, be sure to give it a rating on the scale which you think best reflects the diminished quality of the ride.
- Be aware that there are many ways that the ride could be considered less than <u>PERFECT</u>. The road could

  a) be so bumpy that it rattles your bones and makes your teeth chatter,

  b) have bumps or undulations which makes the car heave up and down as if it was a roller coaster, or

  c) have other imperfections in the surface which you think detract from the ride quality.

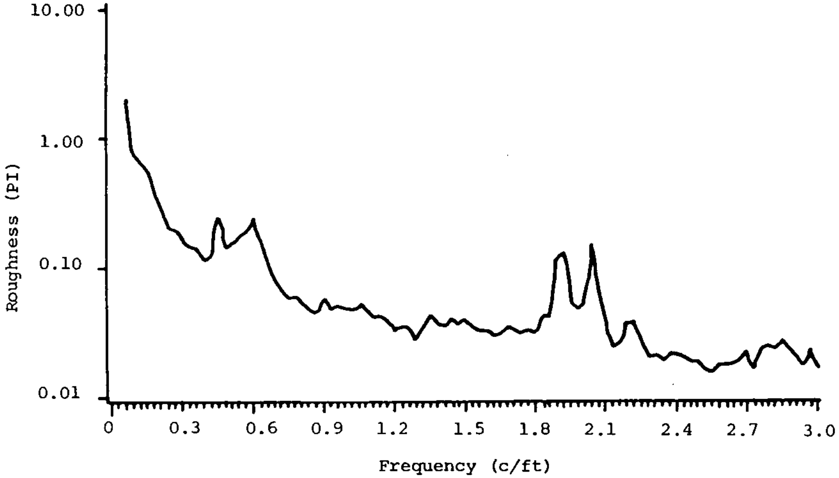

Figure B-3. Graph of left-wheel profile for Florida site 17 (MPR = 4.24).

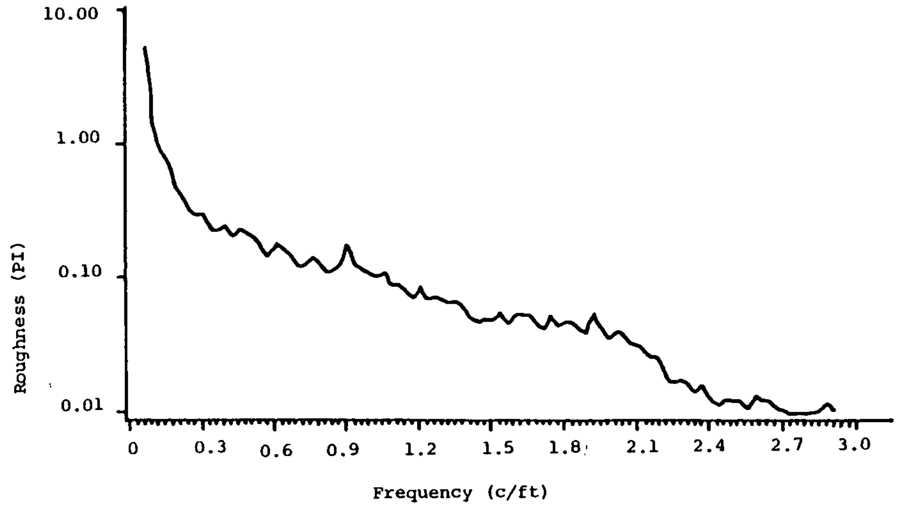

Figure B-4. Graph of left-wheel profile for Florida site 12 (MPR = 3.43).

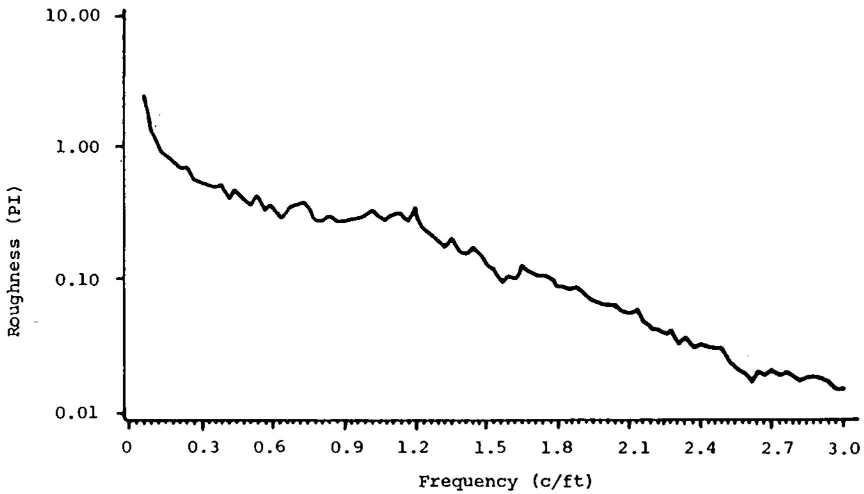

Figure B-5. Graph of left-wheel profile for Florida site 4 (MPR = 2.64).

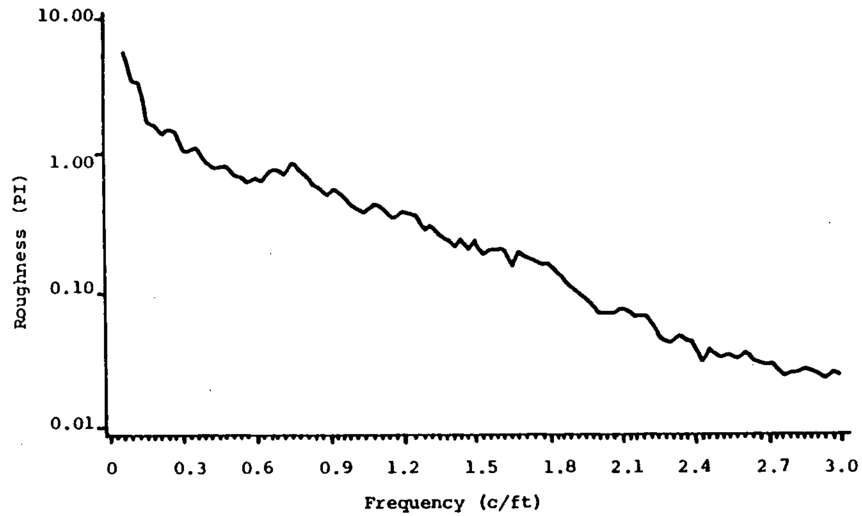

Figure B-6. Graph of left-wheel profile for Florida site 1 (MPR = 1.20).

DATA ANALYSIS OF PROFILES AND PANEL RATINGS -- PILOT STUDY

The raw profile data were first digitized and then a Fast Fourier Transform was applied to calculate the sine and cosine coefficients for each of the 2048 frequency bands from 0 to 6.0 c/ft.

Using the data from the right wheelpath, an SAS program was developed to transform the sine and cosine coefficients into a single roughness (PI)* reading for each of 1024 frequency bands from 0 to 3.0 c/ft. These data were processed into 100 frequency bands by combining the data in every 10 bands.

SAS/GRAPH, a computer graphics package, was used to generate plots of roughness (PI) versus frequency. These graphs illustrated amplitude of the roughness in each of the 100 combined frequency bands.

A third SAS program was then developed to combine the roughness data into 28 one-third octave bands between 0.005 and 3.0 c/ft (and 19 one-half octave bands).

The correlation between mean panel rating and roughness (PI) in one-third octave bands was computed directly from the previous data by correlating individual one-third octave band roughness with mean panel rating for all profiles. The correlation between mean panel rating and roughness in a specific frequency band (other than one-third octave) was obtained by summing the power in the approximate combined frequency bands (i.e., a subset of the 100 bands) and correlating this summed roughness with mean panel rating. For example, for the frequency band between 0.09 and 1.5 c/ft, the roughness was first summed over this frequency band for each profile, then correlations were computed using the mean panel rating and summed roughness for all profiles.

* See Appendix D for a complete description of PI.

APPENDIX C

SUPPLEMENTAL MATERIAL FOR MAIN EXPERIMENT

This appendix contains supplemental material for the main panel study, including rater form, description of test sites, test route, graphs of profiles, results of regression analyses, summary of the analysis of the profile data, list of center frequencies for the 26 one-third octave bands used in the analyses and a discussion of confidence limits.

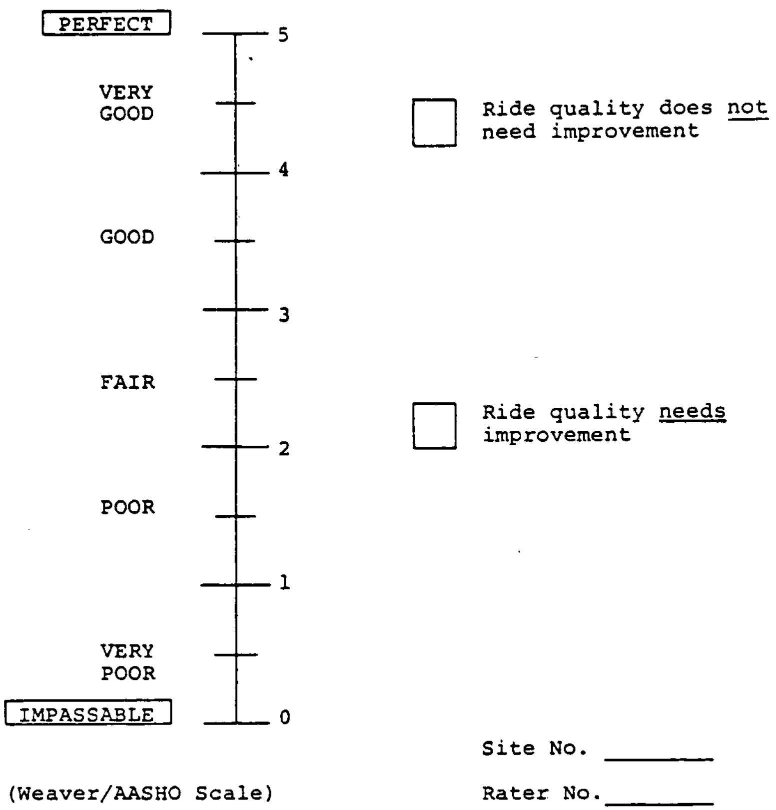

Figure C-1. Rater form.

Table C-1. Summary statistics, Ohio test sections.

BC					PCC					COMPOSITE				
#	M	1/4	MRM	NR	#	M	1/4	MRM	NR	#	M	1/4	MRM	NR
1 *	32.0	155	161.6	8.3	1*	28.5	198	219.0	30.6	1*	44.1	44	34.6	0
2 *	22.6	202	247.3	38.8	2*	33.1	140	236.3	25.0	2*	31.2	101	108.5	22.2
3	16.3	317	398.6	69.4	3	30.3	119	120.7	22.2	3	44.0	50	32.6	0
4 *	10.1	449	661.3	86.1	4*	34.2	77	66.1	13.9	4	35.2	75	66.1	5.6
5 *	22.5	213	221.9	41.7	5*	19.3	125	132.7	83.3	5*	32.1	56	55.8	19.4
6 *	20.9	351	441.3	47.2	6*	37.3	101	97.0	5.6	6	37.2	62	47.7	0
7	31.9	183	218.8	11.1	7*	27.6	151	172.3	57.6	7*	24.9	90	83.4	44.4
8 *	31.8	155	149.0	13.9	8	28.6	133	136.8	58.3	8	25.5	114	109.5	36.1
9 *	40.5	59	49.0	0	9*	27.2	138	147.9	61.1	9*	28.9	69	64.0	30.6
10 *	19.4	240	279.1	58.3	10*	27.9	196	217.6	44.4	10*	39.3	62	55.9	0
11 *	35.4	124	132.9	5.6	11*	25.6	178	188.9	72.2	11*	18.6	182	221.5	72.2
12	35.5	66	57.0	5.6	12*	24.9	161	138.1	72.2	12*	26.6	138	178.4	27.8
13 *	38.1	82	77.6	2.8	13*	34.7	141	134.5	13.9	13	38.3	57	44.1	2.8
14	37.6	96	93.1	0	14*	37.5	82	91.4	5.6	14*	36.8	66	59.2	2.8
15 *	25.4	129	142.2	44.4	15*	36.3	99	89.2	8.3	15*	42.5	57	42.0	0
16 *	16.4	247	286.0	83.3	16	34.0	102	91.6	19.4	16*	41.5	84	83.2	2.8
17 *	13.8	322	432.8	81.8	17	30.9	333	141.8	27.8	17*	33.5	117	101.1	13.9
18	19.8	214	251.7	58.3	18*	35.1	108	102.2	11.1	18	35.7	62	45.6	0
19 *	23.1	183	203.7	41.7	19*	37.9	112	105.2	2.8	19*	33.7	84	61.8	11.1
20 *	18.2	255	348.1	72.2	20*	34.1	123	110.9	19.4	20*	26.1	133	138.1	50.0
21 *	12.7	237	280.8	91.7	21	32.8	266	106.7	2.8	21	24.6	95	80.9	61.1
22 *	32.3	111	98.7	19.4	22*	20.7	166	150.5	88.9	22	35.4	67	49.3	11.1
23	26.6	N/A	183.3	25.0						23	20.7	92	91.3	88.9
24	26.6	N/A	155.3	25.0						24	26.3	108	91.8	48.5
25 *	38.4	63	42.0	0						25	27.2	89	73.3	45.5
										26*	20.0	108	106.0	75.8
										27*	25.6	102	96.6	55.6
										28	37.1	66	53.1	0
										29*	24.3	60	39.7	63.9
										30	18.8	386	196.9	88.9
										31	29.9	110	82.1	25.0
										32	32.8	74	66.0	13.9
										33	29.6	87	73.6	41.7
										34	40.1	56	40.7	0

* Included in Analysis

NOTE:

M = mean rating on a scale of 0-50. Divide by 10 to obtain rating on a scale of 0-5.

1/4 = index from profilometer.

MRM = Mays Ride Meter.

NR = % responding the section "needs repair."

NA = Not available.

Day 1

Begin: Central Garage
IR 70 West (drive in IR 70 lanes)

C-20 Start - Exit 95 sign at beginning of ramp to Hague Avenue
End - Beginning of ramp to Wilson Road

0-17 Start - mm 91 at entrance ramp
Stop - 55 mph sign (.54 mile)

C-11 Start - .3 mile past mm 88 at reflector
Stop - At reflector (60 mile)

SR 142 (Plain City - Georgesville) right
CR 44 - mm High Left (3rd road)

A-22 Start - 1/2 mile after culvert after "S" curves (pole left)
Stop - .6 mile (pole left)

US 42 - Left

0-18 Start - 1/4 mile past 1st road on left (telephone pole right)
Stop - .68 mile (pole left)

Taylor-Blair Road - Left (1st road) at church

King Pike - Left (1st road) (stone wall on left corner)

A-23 Start - .4 mile pole on left
Stop - POle at high tension line

Middle Pike - Right at dead end
Morgan Road - Left (1st road)

A-24 Start - After large oak tree right (at pole left)
End - Pole on left

Plain City-Georgesville - Right at dead end

IR 70 East, Left

C-12 Start - .25 mile past mm 87 (reflector)
End - .63 mile at patrol speed line

0-19 Start - .12 mile past bridge after mm 90 reflector
Stop - .65 mile reflector at ramp

IR 270 North

C-13 Start Center Lane .69 mile past mm 12 at reflector
End - At entrance ramp reflector

C-14 Start - .25 mile past mm 15 at reflector
Stop - at reflector (.60)

IR 270 East

C-15 Start - .15 mile past crash itinuator at overhead
Stop - End of concrete barrier on right

C-16 Stop - mm 29 stay in middle lane
Stop - at overhead (.59 mile)

SR 161 New Albany exit, Return to IR 270 West/North (turnaround)

IR 270 - North, West

C-17 Start - 55 mph sign past blacktop patch at overhead
Stop - at reflector (.59 mile)

C-18 Start - .15 mile past mm 28 at overhead
Stop - overhead (.57 mile)

US 23 South - Wilson Bridge Road left
fill up with gas - L&K
US 23 North

0-31 Start - mm 4
Stop - .61 mile (pole right)

0-30 Start - .30 mile from Delaware State Park 1 mile Sign opposite Penky Road (pole)
Stop - .60 mile at phone 1 mile sign

Turn around at Waldo exit

US 23 South

C-22 Start - .33 mile south of Marion at Jct 229 sign mml
Stop - .5 mile at end of guardrail

SR 229 East, Left

A-25 Start - .42 mile past mm 5 (pole)
Stop - .60 mile west of Ashley

Figure C-2. Route.

SR 61 South
IR 71 North

0-21 Start - .19 mile past mm 142
Stop - at overhead (.57 mile)

0-22 Start - .25 mile past mm 148 at reflector
Stop - .61 mile (reflector)

Rest Area

0-23 Start - .25 mile past mm 163
Stop - .54 mile

MacDonalds

SR 13

0-24 Start - .28 mile past mm 174
Stop - .60 mile

US 30 Left, West

0-27 Start - 1/4 mile west of mm 16
Stop - .55 mi. past Lavor Road at overhead

0-28 Start 1/4 mile past sign Crestline 6 mi. - Bucyrus 19 mile
Stop - .53 mile at sign Lexington-Springfield Road

0-29 Start - .25 mile west of Eckstein Road
Stop - .58 mile (US Route 30 sign)

Lunch Ponderosa, Burger King

IR 71 South (Left lane for exit)

MacDonalds

SR 13 South

0-25 Start - 1/4 mile South of mm 10
Stop - .72 mile

0-26 Start - .37 mile south of Do Not Pass sign at end of 4-lane highway (North end of guardrail)
Stop - .67 mile

SR 97 North, West follow signs in Bellvue

Figure C-2. Continued.

IR 71 South

0-32 Start - mm 152
Stop - relfector at Exit Ramp .63

0-20 Start - mm 139
Stop - .71 mile (reflector)

0-33 Start - mm 133
Stop - reflector (.67 mile)

0-34 Start - mm 126
Stop - overhead .75

IR 270 West

Start - .25 mile past mm 16
Stop - end of reflector

IR 70 East

Back to Central Garage

Day 2

Begin: Central Garage
IR 70 West
IR 270 South

C-1 Start - Beyond Broad St. at reflector
End - .10 mile before mm 6

C-2 Start - .3 mile past US 62 and 63 (Middle Lane)
TAPE ON LIGHT POLE AT RIGHT
End - mm 1

0-1 Start - mm 52
Stop - at reflector (.57 mile)

US 33 South/East

C-3 Start - Bridge South of Rager Road (3)
(SR 674 Exit Sign) church sign
Stop - (.62 mile) pole end of Entrance Ramp (light post)

0-2 Start - 55 mph sign past Cemetary Road
Stop - + sign before Wen Road

Diley Road left at Kingy's Pizza

A-1 Start - .22 mile pole on right
End - Pole on right
Busey (t-216) - 1st road right
Busey Road

A-2 Start - After covered Bridge, post route on fence post
Stop - .67 mile, on pole

Carroll Northern - Right at dead end
Pleasantville - Left (3rd road)
Carroll Southern - Right (1st road)
Carroll Eastern (CR 21) - Left
Sheets Road - Right (4th road)

A-3 Start - Big tree on left past culvert
Stop - .65 mile

Left at dead end
SR 158 - right
Coonpath Road (CR 31) Left at flashing lights

40 mph Stringtown Road 1st road left

A-4 Start - .26 mile pole left
End - .62 mile pole right

Marguette - Right (1st road)
Dead End - Left

Old Millersport - Right at dead end

A-5 Start - .24 mile south of culvert pole on right
End - .62 mile fence post left

Rest Area
Coonpath (CR 31) - Right
SR 37 - North, Right
Carroll Eastern - Left after Rest Area
Stringtown Road - Right

A-6 Start - .18 mile pole right
Stop - .66 mile fence post left

Pleasantville Road - Right at dead end
SR 37 - left
Bickel Church - Right after 4 miles

A-7 Start - .23 mile (Fence post left) (leaning)
End - Pole left (.64 mile)

Old Millersport (CR 58) left
SR 204 - Follow thru Millersport
SR 37 - Right
T 110 - Left (1st Road) Blacklick

2600/21J

Figure C-2. Continued.

A-8 Start - .13 mile after 2nd culvert (Eastern) pole right
Stop - .67 mile pole right

T-245 - Right (1st road)
T-36 - Right at dead end
Swamp Road (T-144) - Left 1st road
US 40 right

0-3 Start - .2 mile at pole on right
Stop - mm 12

SR 37 - Left

A-9 Start - .28 mile north of TR 35 (2nd crossroad) sign right
Stop - .60 mile crossroad sign right

CR 138 - Left 1-1/2 miles (1st road)

A-10 Start - 1/2 past RR at pole right
Stop - pole on right

T-141 - Left on gravel road

Blacks Road - Left after RR

A-11 Start - 2 miles pole on right after pines left
Stop - Fence right side

SR 37 - Left

SR 37 - North

A-12 Start - .4 mile North of RR at Park Entrance
Stop - .64 mile Pole

SR 16 East, Right

0-4 Start - .22 mile past traffic light at mm 17
End - .62 mile blue sign

C-4 Start - .2 mile East of Church Street Bridge (Pole left side) light
Stop - .63 Pole on left light

SR 16 (Left Lane)

C-5 Start - after blacktop (pole on right)
End - Pole before Bridge at Banyon

Section starts quickly

0-5 Start - .2 mile East of end of blacktop at (SR 16 sign)
End - Pole on right

SR 16 - Turnaround at Flashing Lights

SR 16 West

0-6 Start - 1/4 mile west of mm 25 at guardrail
Stop - .6 mile at Dayton Road

Lunch 21st Street North/Right
Follow for restaurants: Burger Chef
Captain D's
L & K
Wendy's
(Further up) Pizza Hut
Raz

SR 13 - Left at dead end from 21st

Start - .26 mile (marks on pole)
End - .66 mile Past M.B.

A-14 Start - 1/4 mile north of mm 21 (beside Olde Mill Swimming)
Stop - .66 mile

US 62 - East, Right

0-7 Start - .4 mile past Bridge at (Horse and Buggy sign)
Stop - .58 mile

US 62 - East

0-8 Start - .3 mile East of Lic/Kno C.L. Pole left
Stop - mm 1 (.69 mile)

(Turn around)

US 62 West

0-9 Start - .3 mile north of bridge (pole on right)
Stop - delineator right (.6 mile)

CR 19 - Left at main crossroads in Homer

A-16 Start - .2 mile after bridge out of town (pole right)
End - .54 mile pole on right
CR2
Bennington Chapen - Left (1st road)
continue past SR 657

A-17 Start - .17 mile after 2nd Road Pole on right
Stop - .68 mile at sign

T-56 Gravel Road - Right
C-19 Right at dead end

A-18 Start - Top of hill (.4 mile)
End - .61 mile (pole on left)

SR 657 - Right

A-19 Start - 1/2 mile past mm 12
End - .6 mile (pole on right)

US 62 right

0-10 Start - mm 12 (left side)
End - Deer crossing sign (.56 mile) on right

CR 21 Northridge - Left past school (2nd road)

CR 16 Sportsman Club Road - Left (2nd road)

A-20 Start - .73 mile at pole on right at pine trees
End - Top of crest at pole on right

A-21 Start - .26 mile past 2nd crossroad at Green Meadows Trailer
End - bump sign past pond on right

SR 661 - South right past,

0-11 Start - School - .26 mile past mm 6 at pole on right
End - .65 mile at cemetary (pole on left)

0-12 Start - 1/2 mile past mm 3 at pole on left at white wooden fence
End - mm2

Go to Granville. Follow SR 661 and SR 16 signs. Out of town past Granville Lumber.

SR 16 West, then around ramp to two-lane SR 16.

SR 16

0-13 Start - approx. 1/2 mile at 55 mph sign
Stop - mm 13

0-14 Start - mm 9
Stop Crossroads w/stop sign in island (58)

Figure C-2. Continued.

SR 310 South, left at Pataskala

0-15 Start - .4 mile past bridge out of town (At "Test Section 7" sign)
Stop - mm 3 on left

IR 70 West, right

0-16 Start - .3 mile from mm 115 at reflector
Stop - at reflector (.57 mile)

IR 270 North

Turn around at SR 16 and head South

IR 270 South

C-6 Start - .3 mile past mm 40 coming down ramp
Stop - .54 mile at pole on right

Section comes quick

C-7 Start - .22 mile past mm 44
Stop - .72 mile at reflector (33 Bexley Lancaster sign)

Section comes quick

Start - .5 mile past US 33 at IR 270 South sign on right
Stop at overhead Bridge

IR 270 South/West

Start - mm 1
End - .67 mile at reflector

Start - Bridge past mm 6
Stop - .6 mile at reflector

IR 70 East
Broad Street and Central Garage

Figure C-2. Continued.

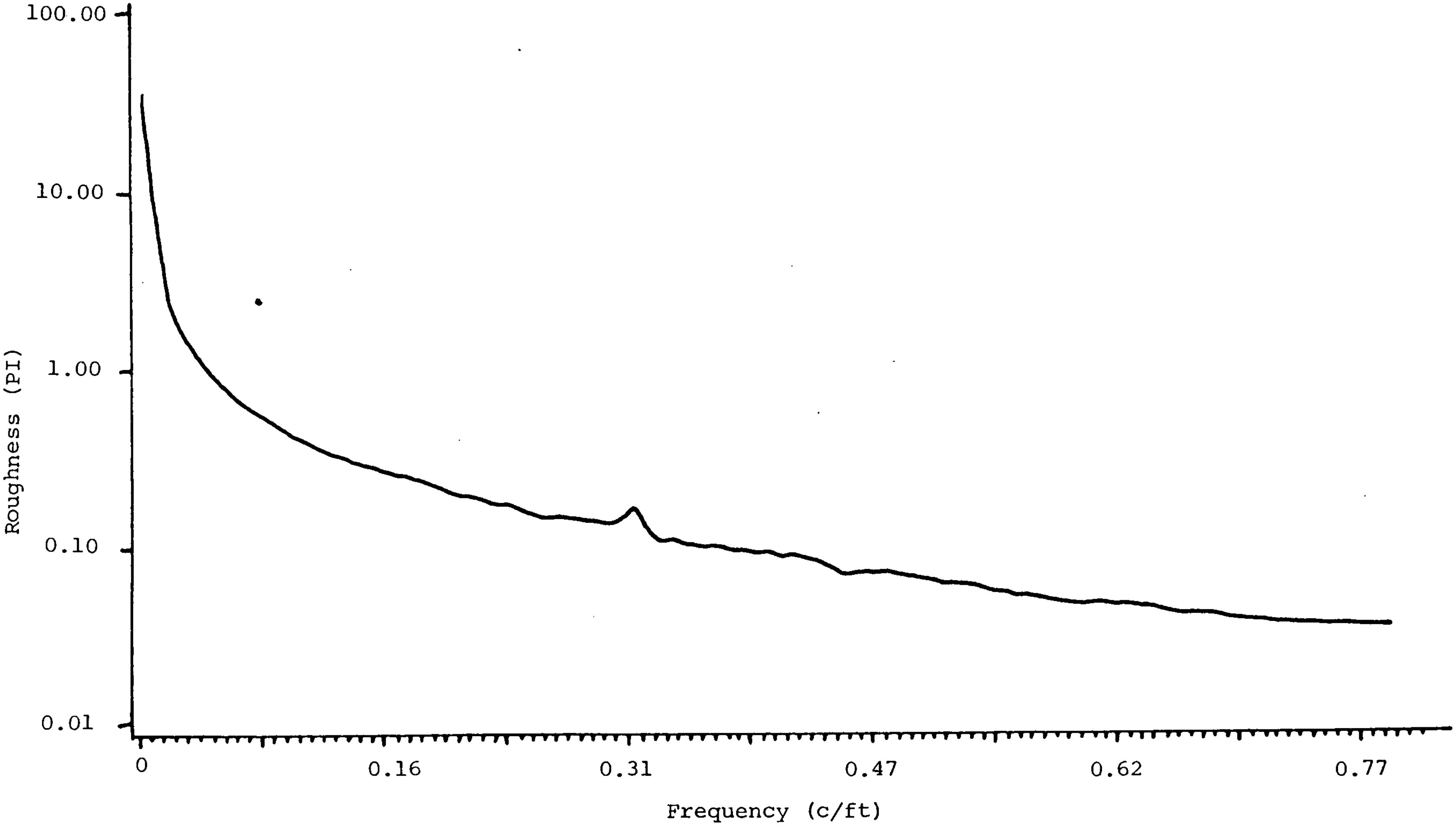

Figure C-3. Graph of right profile of site A9 (MPR = 4.05).

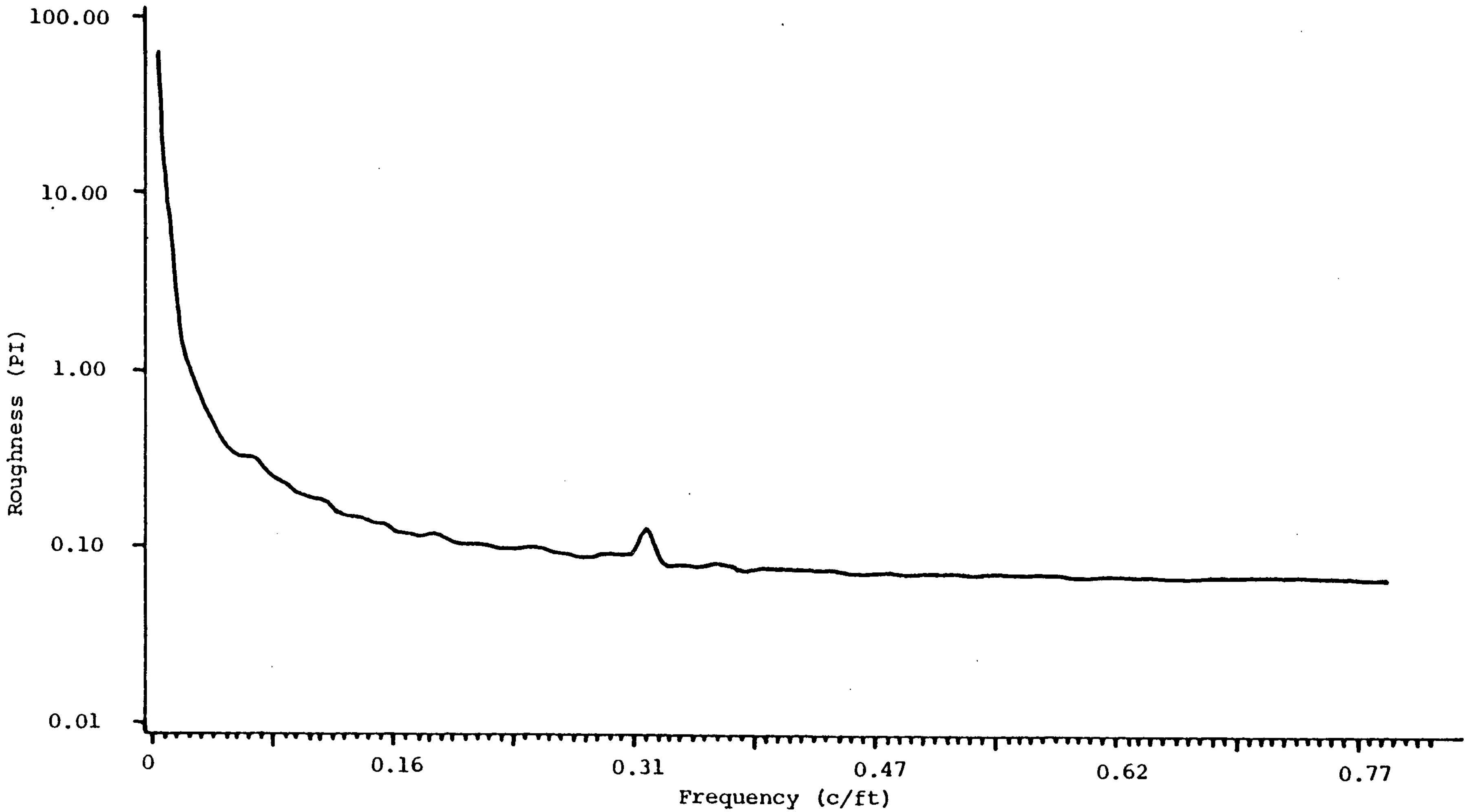

Figure C-4. Graph of right profile of site A25 (MPR = 3.84).

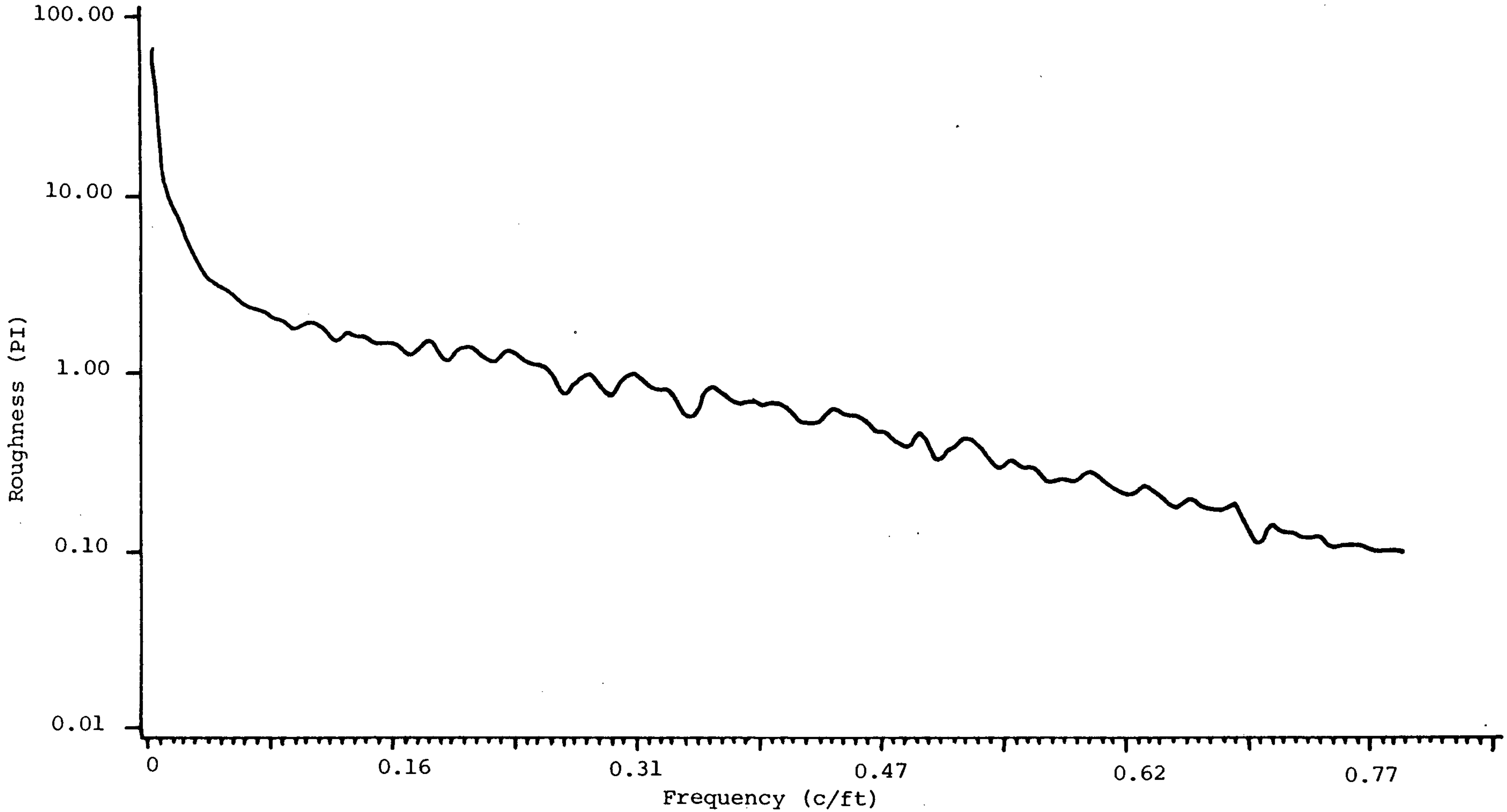

Figure C-5. Graph of right profile of site A23 (MPR = 2.66).

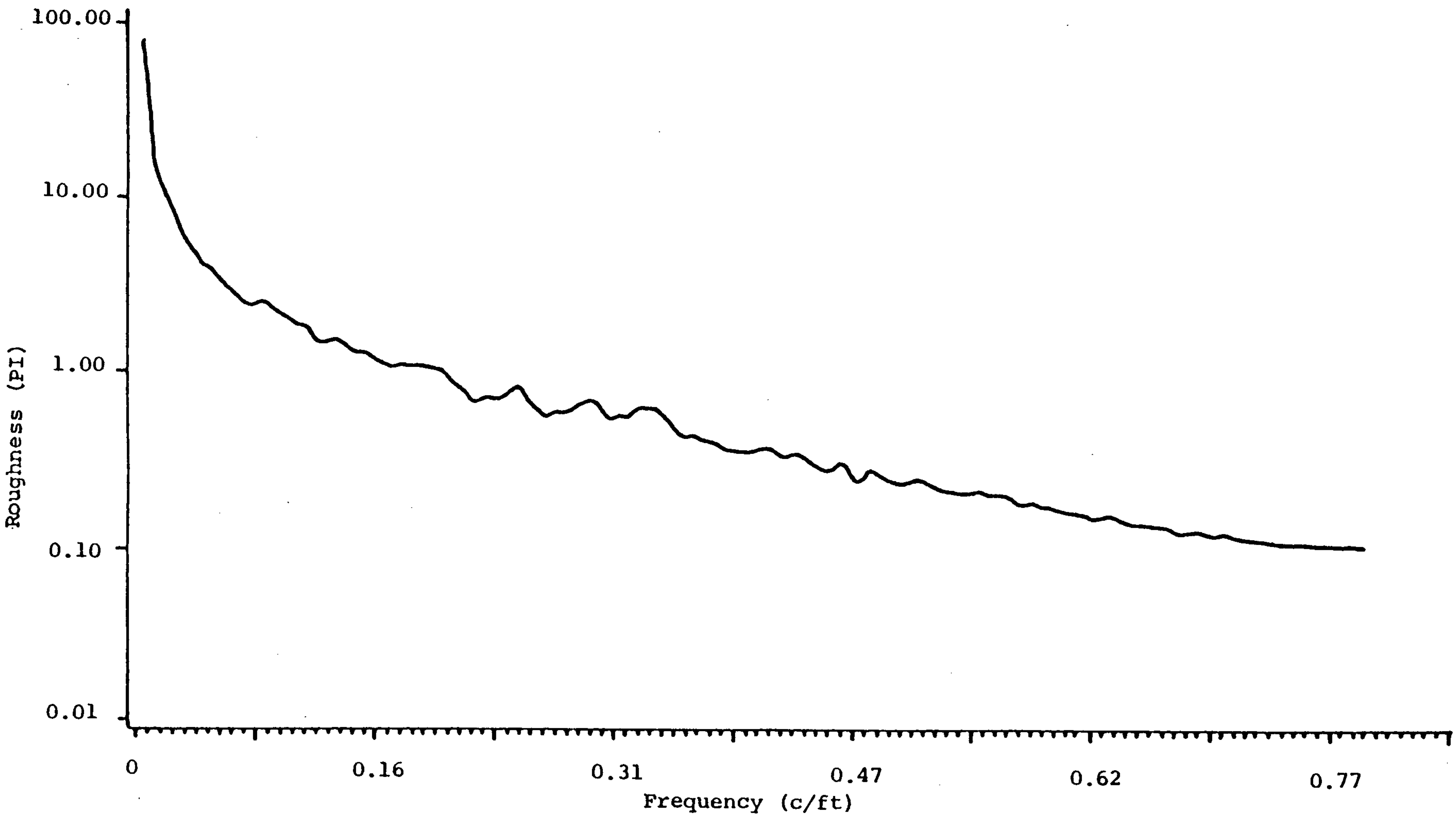

Figure C-6. Graph of right profile of site A24 (MPR = 2.66).

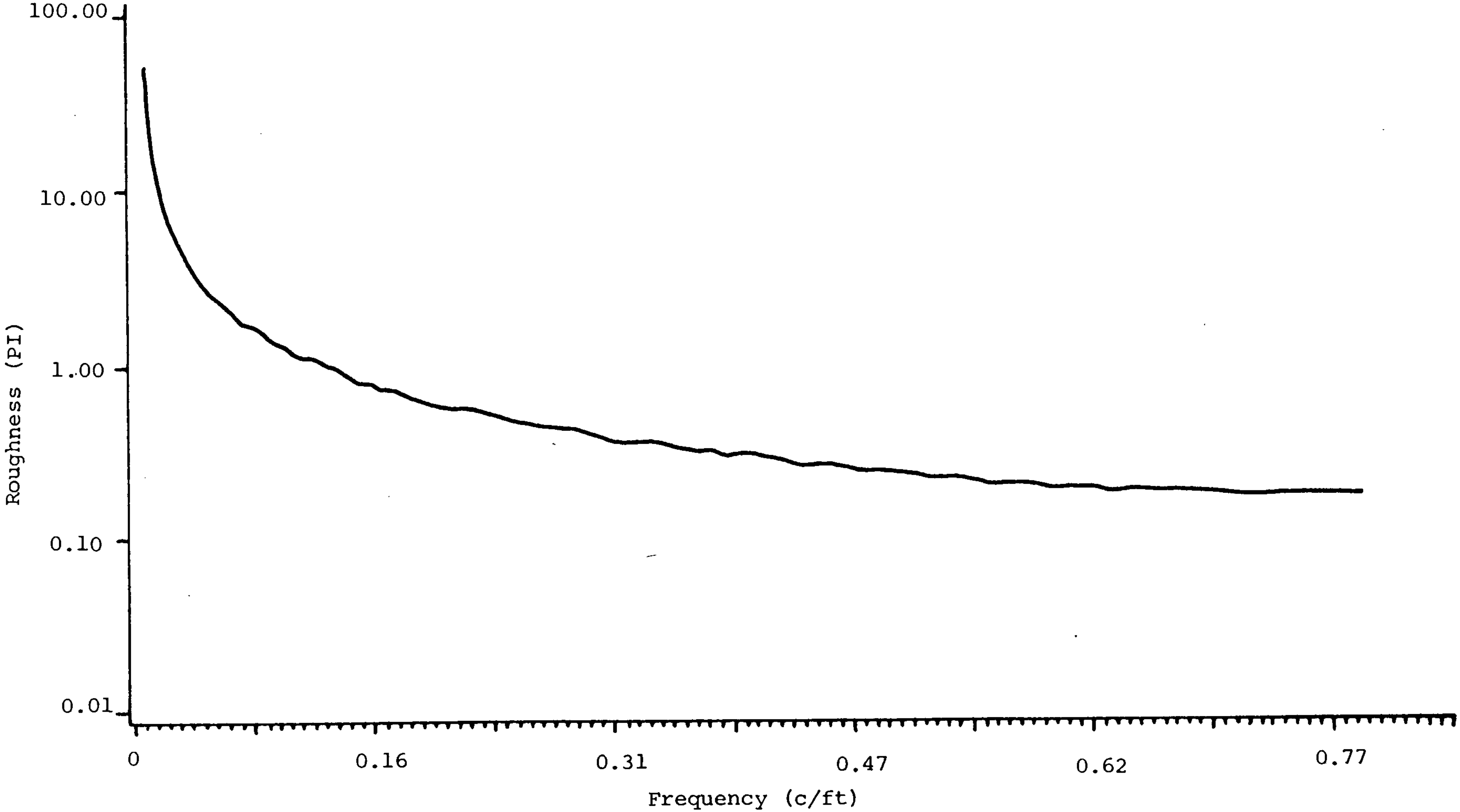

Figure C-7. Graph of right profile of site A2 (MPR = 2.26).

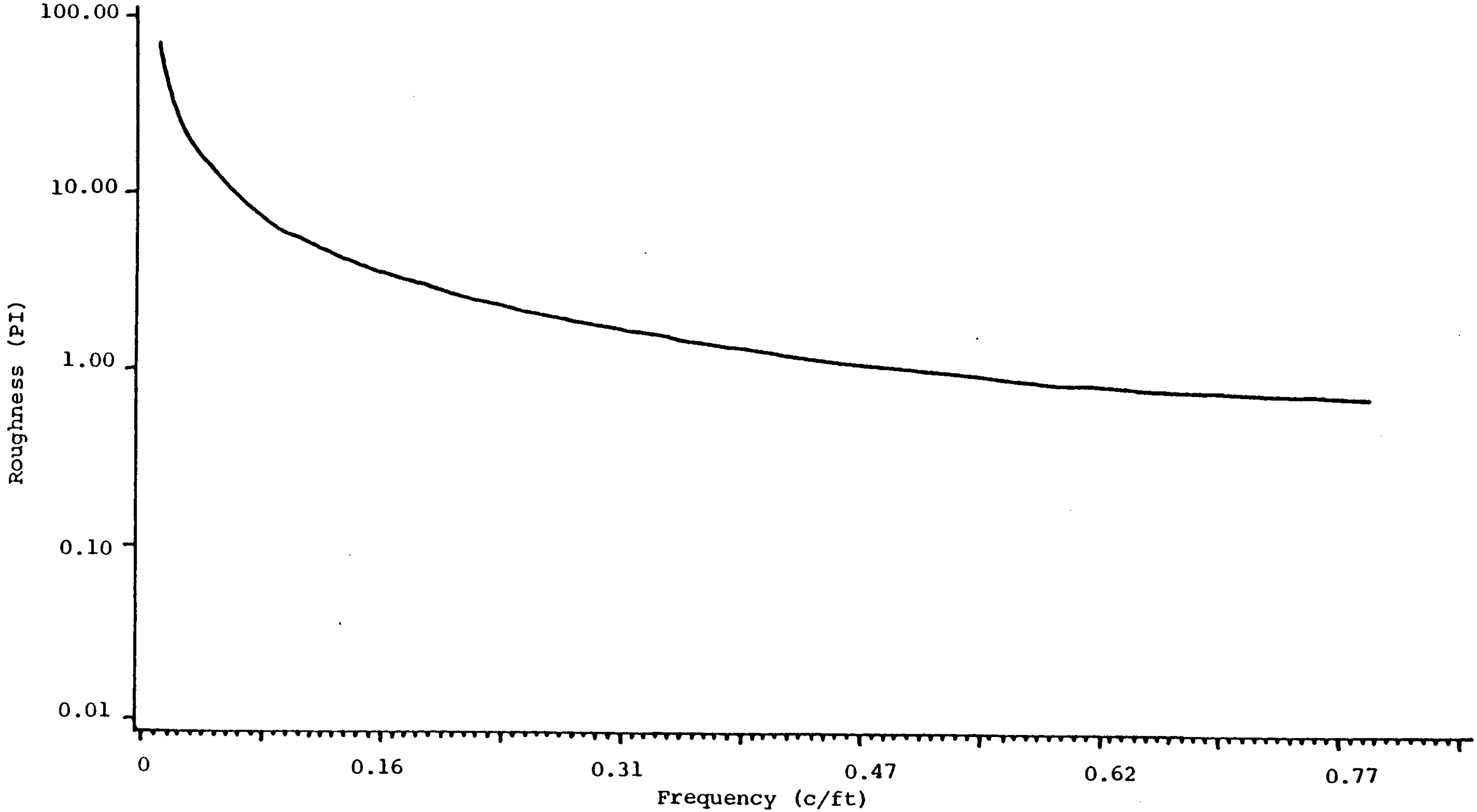

Figure C-8. Graph of right profile of site A21 (MPR = 1.27).

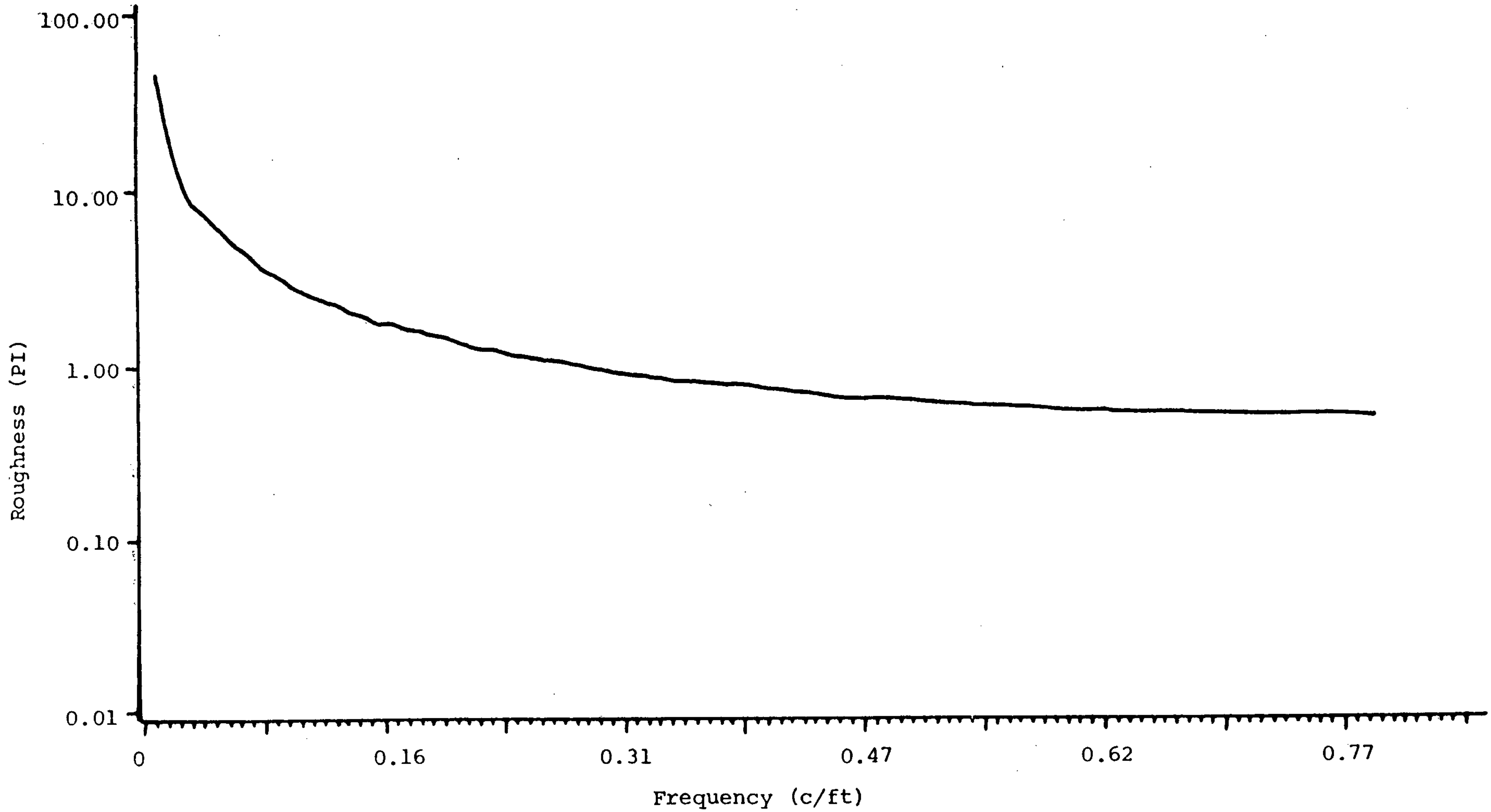

Figure C-9. Graph of right profile of site A4 (MPR = 1.01).

Table C-2. Effect of transforms on regression analyses for all surfaces combined.

MPR = 3.95 - 30.22 PI	R^2 = .72	r = -.85
MPR = -1.74 - 3.03 log (PI)	R^2 = .88	r = -.94
MPR = 3.67 - 0.005 MRM	R^2 = .53	r = -.73
MPR = 7.21 - 2.06 log MRM	R^2 = .54	r = -.73
MPR = 3.99 - 0.008 (1/4 car)	R^2 = .57	r = -.75
MPR = 8.65 - 2.75 (log 1/4 car)	R^2 = .57	r - -.75
MRM = 17.15 + 3985.73 PI	R^2 = .61	r = .78
1/4 car = 43.97 + 2802.48 PI	R^2 - .65	r = .81
MRM = -47.47 + 1.44 (1/4 car)	R^2 = .97	r = .98
MPR = 4.64 - 0.15 $\sqrt{MRM}$	R^2 = .56	r = -.75
MPR = 7.21 - 4.12 log $\sqrt{MRM}$	R^2 = .54	r = -.73
MPR = 5.23 - 0.20 $\sqrt{1/4\ car}$	R^2 = .59	r = -.77
MPR = 8.65 - 5.50 log $\sqrt{1/4\ car}$	R^2 = .61	r = -.78
NR = 132.6 - 33.5 MPR	R^2 = .86	r = -.93

Note: MPR = mean panel rating; MRM = Mays Ride Meter.
NR = needs repair (%)

Table C-3. Effect of transforms on regression analyses for bituminous concrete surfaces.

MPR = 3.70 - 24.88 PI	R^2 = .73	r = -.85
MPR = -1.79 - 3.04 log (PI)	R^2 = .89	r = -.94
MPR = 3.73 - 0.005 MRM	R^2 = .74	r = -.86
MPR = 8.66 - 2.70 log MRM	R^2 = .85	r = -.92
MPR = 4.12 -0.008 (1/4 car)	R^2 = .78	r = -.88
MPR = 10.46 - 3.55 (log 1/4 car)	R^2 = .85	r = -.92
MRM = 60.70 + 3708.88 PI	R^2 = .57	r = .75
1/4 car = 70.31 + 2519.90 PI	R^2 = .62	r = .79
MRM = -65.05 + 1.52 (1/4 car)	R^2 = .98	r = .99
MPR = 5.00 - 0.17 $\sqrt{MRM}$	R^2 = .83	r = -.91
MPR = 8.66 - 5.40 log $\sqrt{MRM}$	R^2 = .85	r = -.92
MPR = 5.73 - 0.25 $\sqrt{1/4\ car}$	R^2 = .84	r = -.92
MPR = 10.46 - 7.10 log $\sqrt{1/4\ car}$	R^2 = .85	r = -.92
NR = 124.5 - 33.1 MPR	R^2 = .94	r = -.97

Note: MPR = mean panel rating; MRM = Mays Ride Meter.
NR = needs repair (%)

Table C-4. Effect of transforms on regression analyses for portland cement concrete surfaces.

MPR = 4.56 - 50.70 PI	R^2 = .87	r = -.93
MPR = -2.01 - 3.25 log (PI)	R^2 = .86	r = -.93
MPR = 3.51 - 0.003 MRM	R^2 = .07	r = -.26
MPR = 4.98 - 0.90 log MRM	R^2 = .06	r = -.24
MPR = 4.01 -0.007 (1/4 car)	R^2 = .83	r = -.91
MPR = 6.98 - 1.85 (log 1/4 car)	R^2 = .15	r = -.39
MRM = 76.05 + 2194.34 PI	R^2 = .22	r = .47
1/4 car = 72.05 + 2134.70 PI	R^2 = .40	r = .63
MRM = -18.54 + 1.18 (1/4 car)	R^2 = .74	r = .86
MPR = 3.92 - 0.07 $\sqrt{MRM}$	R^2 = .07	r = -.26
MPR = 4.98 - 1.80 log $\sqrt{MRM}$	R^2 = .06	r = -.24
MPR = 4.82 - 0.115 $\sqrt{1/4 \text{ car}}$	R^2 = .17	r = -.41
MPR = 6.98 - 3.70 log $\sqrt{1/4 \text{ car}}$	R^2 = .15	r = -.39
NR = 188.6 - 49.6 MPR	R^2 = .94	r = -.97

Note: MPR = mean panel rating; MRM = Mays Ride Meter
NR = needs repair (%)

Table C-5. Effect of transforms on regression analyses for composite surfaces.

MPR = 4.42 - 47.55 PI	R^2 = .76	r = -.87
MPR = -1.58 - 2.89 log (PI)	R^2 = .83	r = -.91
MPR = 3.97 - 0.010 MRM	R^2 = .41	r = -.64
MPR = 7.37 - 2.26 log MRM	R^2 = .44	r = -.66
MPR = 4.46 -0.015 (1/4 car)	R^2 = .49	r = -.70
MPR = 9.67 - 3.42 (log 1/4 car)	R^2 = .51	r = -.71
MRM = 2.84 + 3094.60 PI	R^2 = .74	r = .82
1/4 car = 28.47 + 2205.60 PI	R^2 = .76	r = .87
MRM = -36.54 + 1.40 (1/4 car)	R^2 = .92	r = .98
MPR = 4.96 - 0.20 $\sqrt{MRM}$	R^2 = .43	r = -.66
MPR = 7.37 - 4.52 log $\sqrt{MRM}$	R^2 = .44	r = -.66
MPR = 5.95 - 0.31 $\sqrt{1/4 \text{ car}}$	R^2 = .50	r = -.71
MPR = 9.67 - 6.83 log $\sqrt{1/4 \text{ car}}$	R^2 = .51	r = -.71
NR = 129.2 - 32.2 MPR	R^2 = .88	r = -.94

Note: MPR = mean panel rating; MRM = Mays Ride Meter
NR = needs repair (%)

DATA ANALYSIS OF PROFILES AND PANEL RATINGS -- MAIN EXPERIMENT

The data from the Ohio profilometer were provided in digitized form. First, a fast fourier transform (FFT) was applied to compute the sine and cosine coefficients for the band of frequencies from 0.0025 to 0.8 c/ft.

Graphs of the right profile were developed as in the pilot study, and the one-third octave analysis, using the right profiles, was performed in the same manner as the pilot study except that only 512 values were available due to the more restricted range of the Ohio profilometer.

For the analysis employing the combined (L + R) profile data, the following steps were employed:

1. Compute FFT of each frequency band.
2. Square amplitude of each FFT frequency band.
3. Divide all FFT bands into one-third octave bands (see Table C-6).
4. Calculate sum of squared amplitudes in each one-third octave band.
5. Take square root of each sum to derive PI in each one-third octave band.

The transforms were next applied (e.g., log) and then the correlations were computed in the same manner as the pilot study.

The double differentiation of the total profile was applied before step 1 in those cases described in the main body of the text (e.g., Tables 10 and 12).

Table C-6. Center frequencies for one-third octave bands.

Band Number	Center Frequency (c/ft)
1	0.0025
2	0.0031
3	0.0039
4	0.0049
5	0.0062
6	0.0078
7	0.0098
8	0.0124
9	0.0156
10	0.0197
11	0.0248
12	0.0313
13	0.0394
14	0.0496
15	0.0625
16	0.0787
17	0.0992
18	0.1250
19	0.1575
20	0.1984
21	0.2500
22	0.3150
23	0.3969
24	0.5000
25	0.6300
26	0.7937

CALCULATION OF CONFIDENCE INTERVALS

The preferred regression equation

$$RN = -1.74 - 3.03 \text{ Log (PI)}$$

predicts a pavement section's RN from its PI. The RN is actually an approximation of the true MPR. Based on the methods in Snedecor & Cochran*, we can establish a confidence interval where given

$$\log(PI) = X \quad \text{and}$$

$$RN = Y = -1.74 - 3.03X$$

Then the true MPR will lie within the interval

$$RN - t \leqq MPR \leqq RN + t$$

where $t = (2.01)\sqrt{0.0065 + 0.1026\ (X+1.533)^2}$ (1)

For example, if Log (PI) = -1.533 (the mean of all panel ratings for all test sections in Ohio), then

$$t = (2.01)\sqrt{0.0065 + 0.1026\ (-1.533+1.533)} = 0.162$$

$$RN = -1.74 - 3.03 \cdot (-1.533) = 2.905$$

and $2.905 - 0.162 \leqq MPR \leqq 2.905 + 0.162$

or $2.743 \leqq MPR \leqq 3.067$

at the extremes of our data

(a) $X_1 = \log(PI)_1 = -0.9$

(b) $X_2 = \log(PI)_2 = -2.0$

the confidence intervals were computed from equation (1) to yield

(a) $0.555 = 0.987 - 0.439 \leqq MPR \leqq 0.987 + 0.439 = 1.419$

(b) $3.978 = 4.32 - 0.342 \leqq MPR \leqq 4.32 + 0.342 = 4.662$

* Snedecor, G.W. & cochran, W.G., "Statistical Methods", 6th Ed., Iowa State University Press, Ames, Iowa, 1967 (Chapter 6).

APPENDIX D

PROCESSING OF THE PROFILE DATA AND DEFINITION OF PROFILE DATA

This appendix includes a description of the processing of the raw profile data (both Ohio and Florida) and an explanation of the profile index that was computed from the raw profile data.

PROCESSING OF THE PROFILE DATA

Introduction

Two sets of profile data were obtained for use in the Ohio study. The first set consisted of profiles of 52 sites measured with the Ohio Department of Transportation (ODOT) profilometer. The second set consisted of an accelerometer and displacement sensor records of 12 sites measured with the Pennsylvania State University (PSU) profilometer.

The ODOT profile records had already been preprocessed on-board the profilometer by the normal procedure of high-pass filtering and double integrating the accelerometer signals and subtracting the result from the displacement sensor signals. Profile records were available for left and right wheel tracks at a sample spacing of 6 in. (15.25 cm). The ODOT profilometer measures displacement with noncontact displacement sensors.

Processing of the PSU data differed in a number of respects. The accelerometer and displacement sensor signals for both wheel tracks were recorded on an analog FM magnetic tape recorder on-board the profilometer. The analog tape signals were then digitized in the laboratory at a sample spacing of 1 in. (2.54 cm) and stored on disk for subsequent processing. The PSU profilometer measures displacements with wheel follower mechanisms and potentiometers.

Both sets of data were processed to find the root mean square (rms) profile height (i.e., PI) in one-third octave bands for all of the sites. A regression analysis of mean panel rating (MPR) versus PI in each one-third octave band over selected sets of sites was then made. The final regression analysis was made using all 52 ODOT sites, and the PSU data were used to extend the analysis over a wider frequency band, albeit with a smaller number of sites.

Processing for Third Octave Analysis

The general procedure used to find PI in one-third octave bands was as follows:

1. Find the Fourier coefficients of the pavement profiles with a Fast Fourier transform (FFT) program.
2. Find the mean squared (ms) profile height of (a) the sum of left and right profiles (vertical component) and (b) the difference between left and right profiles (roll component).
3. Find the sum of the ms profile height of the left and right wheel tracks.
4. Add the values of ms profile height over each third-octave band and take the square root.

The Fourier coefficients of both sets of data were computed using versions of Singleton's FFT procedure (Singleton, R. C., "On Computing the Fast Fourier Transform," *Comm. ACM,* 10 (10) 1967, 647–654). Data returned by the programs give scaled versions of the Fourier coefficients. That is, if

$$Z(X) = c_o + \sum_{n=1}^{N/2} (c_n e^{i2\pi nfX} + c_n^* e^{-i2\pi nfX}) \quad (1)$$

then $c_n, c_n^* = \frac{C_n}{N}, \frac{C_n^*}{N}$ where * denotes complex conjugate, c_n, c_n^* = Fourier coefficients, C_n, C_n^* = coefficients returned by the FFT program, N = number of samples in the profile record, f = frequency spacing of the (truncated) Fourier series, and $i = \sqrt{-1}$. Also, if ΔX = sample spacing, record length, $\lambda = N \Delta X$, and $f = 1/\lambda = 1/N \Delta X$.

The imaginary exponential form of the Fourier series given by Eq. 1 can be transformed to the real form with the identities:

$$e^{i\theta} = \cos\theta + i \sin\theta$$
$$e^{-i\theta} = \cos\theta - i \sin\theta$$
$$Z(X) = \frac{a_o}{2} + \sum_{n=1}^{N/2} (a_n \cos 2\pi nfX + b_n \sin 2\pi nfX)$$

where $a_n = 2R(c_n)$, and $b_n = -2I(c_n)$.

The Fourier coefficients of the vertical and roll components of a profile are, respectively,

$$a_{vn} = a_{ln} + a_{rn}$$
$$b_{vn} = b_{ln} + b_{rn}$$
$$a_{rln} = a_{ln} - a_{rn}$$
$$b_{rln} = b_{ln} - b_{rn}$$

where the subscripts denote: v = vertical component, rl = roll component, l = left wheel track, and r = right wheel track.

Now, if $Z(X) = A \sin(2\pi nfX + \varphi)$, then the mean squared value of $Z(X)$ measured over n periods ($X = \lambda = 1/f$) is given by: $\overline{Z}_n^2 = 1/\lambda \int_0^\lambda A^2 \sin^2(2\pi nfX + \varphi)\, dX = \frac{A^2}{2}$, and the mean squared value of each Fourier component is given by:

$$\overline{Z}_n^2 = \frac{a_n^2 + b_n^2}{2} = 2\, c_n \cdot c_n^* = 2\,\frac{C_n \cdot C_n^*}{N^2}$$

The rms profile height over a given bandwidth is found by summing values of $\overline{Z}_n^2$ and taking the square root. That is,

$$Z_{rms} = \sum_{n=j}^{k} \left(\frac{a_n^2 + b_n^2}{2}\right)^{1/2}$$

Note that estimates of the spectral density of a digitized signal at frequencies nf are given by $S_n = (\overline{Z}_n^2)/(f)$.

Spectral density is frequently called "power spectrum," irrespective of the true units (in this case in.^{2}/cy/ft), and the sum of spectral estimates over a given bandwidth multiplied by frequency spacing are correspondingly called "power." The terms "mean square" and "power" are therefore synonymous in the context of the present work and are used interchangeably in the text.

In a one-third octave analysis, the signal to be processed is filtered by a bank of band-pass filters whose center frequency doubles every third filter. The center frequency of the filters is given by the relationship:

$$f_{ci} = 2^{\frac{V_i}{3}}$$

where V_i is a sequence of real numbers increasing by 1's; i.e., $V_i + 1 = V_i + 1$ and f_{ci} is given in terms of spectrum band number, n.

Analog implementations of one-third octave filters have finite roll-off of the filter skirts, which can also be simulated if the filtering is to be done from a spectrum of the signal. In this work, however, rectangular filters were used with skirt frequencies calculated from the expression:

$$\text{low skirt frequency, } f_{li} = 2^{(V_i - 0.5)/3}$$
$$\text{high skirt frequency, } f_{hi} = 2^{(V_i + 0.5)/3}$$

RMS profile height within a given filter band is then given by:

$$Z_{ms} = \overline{Z}_{j-1}^2 (j - 0.5 - f_{li}) + \sum_{n=j}^{k} \left(Z_n^2\right) + \overline{Z}_{k+1}^2 (f_{hi} - k - 0.5)$$
$$Z_{rms} = \sqrt{Z_{ms}}$$

where

$$0 < (j - 0.5 - f_{li}) < 1.0$$
$$0 < (f_{hi} - k - 0.5) < 1.0$$

Spectral estimates have high variance and the above procedure gives estimates of rms profile height of increasing accuracy as the number of terms in the sum increases. The rms estimates therefore improve as the center frequency increases. Smoothing either the original records or the spectra also decreases the variance of the spectral estimates. The road profiles were smoothed by windowing as described below.

Ohio Profilometer Data Processing

One-third octave analysis of the preprocessed, digitized Ohio profilometer records was done on a DEC VAX 11/780 computer. Each site was processed as a complete record of length $I \times 1024$ sample points (I an integer value). The average value of each record was first subtracted from the record samples to remove dc bias and the samples windowed with a raised cosine Hamming window. The Hamming window is defined as follows:

$$Z'_k = Z_k\,[0.54 - 0.46 \cos(\pi\, k/N)]$$

where: Z_k = value of original sample, Z'_k = value of windowed sample, N = total number of samples, and k = sample number ($o \leq k \leq n - 1$).

Root-mean-square (rms) profile height in one-third octave bands was then found as described above. Windowing the data reduces the rms level of the original signal by a factor of 0.63, and the results from the third octave filtering should be multiplied by a factor of 1./0.63 (= 1.587). This was not done in the data processing programs and all values quoted in this appendix are for unfactored windowed data.

Frequency spacing of the Fourier coefficients calculated with the FFT program varied between 0.0003254 c/ft and 0.0004882 c/ft (λ = 3072 ft and λ = 2048 ft), depending on the length of the record. Root-mean-square (rms) profile height was found in one-third octave bands with center frequencies in the range 0.00246 c/ft to 0.794 c/ft.

PSU Profilometer Data Processing

The accelerometer and displacement sensor signals recorded with the PSU profilometer were digitized on a DEC LSI 11/23 computer system. Fourth order (24 dB/octave) low-pass Butterworth filters, with their 3 dB frequency set at one-fourth the sampling frequency, were used to band limit the analog signals prior to digitizing. Subsequent processing of the signals was also done on the LSI 11/23 system.

Each of the digitized records was processed in blocks of 4096 points according to the following general procedure (each step is an operation performed on individual 4096 sample blocks):

1. Subtract the average values from the accelerometer and displacement samples.
2. Find the Fourier coefficients of the accelerometer and displacement signals.
3. Find the Fourier coefficients of the second integral of the accelerometer signals.

$$\text{i.e., } a_{zan} = \frac{a_{an}}{U^2\,(2\,\pi\, n/N\,\Delta X)^2}$$
$$b_{zan} = \frac{b_{an}}{U^2\,(2\,\pi\, n/N\,\Delta X)^2}$$

where

a_{zan}, b_{zan} = Fourier coefficients of the second integral of the accelerometer signal with respect to distance;

a_{an}, b_{an} = Fourier coefficients of the accelerometer signal with resepct to time;

U = forward speed of the test vehicle (dividing by U^2 transforms time-based acceleration to distance-based acceleration);

N = number of samples in a block = 4096

ΔX = sample spacing = $1/12$ ft; and

$2\,\pi\, n/N\,\Delta X$ = angular frequency corresponding to the coefficients numbered n, rad/ft.

4. Find the Fourier coefficients of the road profiles by subtracting the Fourier coefficients of the displacement sensor signals from the Fourier coefficients of the second integral of the accelerometer signals.

$$\text{i.e., } a_n = a_{zan} - a_{zn}$$
$$b_n = b_{zan} - b_{zn}$$

where

a_n, b_n = Fourier coefficients of the (left or right wheel track) road profiles; and
a_{zn}, b_{zn} = Fourier coefficients of the displacement sensor signals.

5. Compute the mean squared profile heights as described in section 2.

6. Convolve the mean squared profile height components (raw spectral estimates) with the transfer function of the Hamming window function.

$$\text{i.e., } \overline{Z}_n^2 = (0.23)^2\, Z_{u,n-1}^2 + (0.54)^2\, Z_{u,n}^2 + (0.23)^2\, Z_{u,n+1}^2$$

where Z_u^2 = mean squared value of the unwindowed road profile.

The procedure is repeated for each 4096 block in a record, and the final mean squared values are found by averaging over blocks. Root-mean-squared (rms) profile height in one-third octave bands is then calculated as described in section 2. Frequency spacing of the Fourier coefficients was 0.00293 c/ft (λ = 341.3 ft). The rms profile height was found in one-third octave bands with center frequencies in the range 0.0031 c/ft to 5.04 c/ft. One-third octave band center frequencies for the Ohio and PSU data coincided where the two frequency ranges overlapped.

PROFILE INDEX

Profile Index (PI) is defined as the root-mean-square (rms) profile height of a section of highway calculated after the profile has been band-pass filtered to eliminate frequencies outside a specified range. PI has the units of length; inches, cm, etc.

If a true profile of the highway, measured from a fixed horizontal reference, is available and no filtering is performed, PI would be calculated as follows:

1. Find the average value of profile height and subtract it from the original record of profile height.
2. Square the new profile record and find the average value over the complete record.
3. Find the square root of the "mean square" calculated in 2.

In this case, PI would give a measure of the amount by which the profile deviates from a horizontal reference line over the length of the pavement section. (The reference line is the zero level of the profile, i.e., the average profile height measured from the reference is zero.) Obviously, the presence of very long wavelength components in the profile, such as grades, hills, and valleys, would have a great deal of influence on the calculated value of PI, even though they have little influence on the perceived roughness of the road. High-pass filtering the signal, however, forces the "reference line" (or zero level) of the resulting record to follow the long wavelength features. As the cut-off frequency of the filter is increased, the reference line follows the true profile more and more closely until, with the cut-off high enough to reject all frequency components, the output from the filter becomes zero over the full length of the record. The cut-off frequency should be set somewhere between these two extremes, at a value low enough to pass frequencies important in the perception of road roughness, but not so low that the long wavelength features provide erroneous measures of roughness. The profile record must also be low-pass filtered to eliminate noise and frequency components not important to road roughness. Band-pass filtering the profile provides the two operations of low and high-pass filtering in a single filter.

The use of a zero-mean level signal to calculate PI can lead to confusion in terminology because of the need to eliminate negative values by squaring or rectification. In electrical engineering, root-mean-square is the preferred way of characterizing such signals because it provides, directly, a measure of the power which would be dissipated by the physical quantity in a resistor of given value. That is

$$\begin{aligned}\text{Power} &= V \bullet I \\ &= V^2/R \\ &= I^2 \bullet R\end{aligned}$$

where R = resistance, V = voltage across the resistor, and I = current passing through the resistor.

Therefore, whether voltage or current is being measured, the rms level of the signal gives the square root of the power which the physical quantity is capable of dissipating, or is dissipating. Taking the square root is useful because it reduces the dynamic range required of the measuring instruments and it is of the same order of magnitude as the amplitude of the signal rather than its square. If the signal being measured is periodic, alternative measures (such as average rectified amplitude) are just as convenient because direct conversion can be made to mean-square or rms. But the same is not true of nonperiodic signals having unknown statistical properties and rms has become the standard by which electrical a.c. (zero mean) signals are measured.

Signal processing is an offshoot of electrical engineering and much of its terminology has been derived from electrical engineering practice. Consequently, the square of the amplitude of a measured signal, whatever physical quantity it represents, is frequently referred to as the "power" of the signal, or the "power" contained in the signal. Strictly speaking, however, the term "power" should not be used in reference to the square or the mean-square of the profile height.

PI, as defined above, is correctly described as *the square root of the mean square of profile height.*

Deriving a measure of road roughness from a band-pass filtered version of the road profile is reasonable in a physical sense because, to the occupant, the car behaves as a mechanical filter, amplifying or attenuating the pavement roughness profile in specific frequency bands according to the mechanical characteristics of the car and its components. For example, consider modeling a car as a simple base forced single degree of freedom system where the mass, damper, and spring of the system are represented by the body of the car, the sum of the suspension shock absorbers, and the sum of the suspension springs, respectively. The relative motion between the mass and the pavement, when the system is forced by the road profile moving the axle attachment ends of the springs and shock absorbers, is equivalent to the output of a simple second order band-pass electronic filter. The gain of the filter is equivalent to the relative amplitude of motion of the mass when the system is forced by a sine wave at the resonant frequency, and the center frequency of the filter is equivalent to the resonant frequency of the mechanical system. Filter bandwidth is usually defined by the 3 dB points and is represented in the mechanical system by the frequency range over which the relative amplitude of motion of the mass is greater than $1/\sqrt{2}$ of the amplitude at resonance. At very low frequencies, the body of the vehicle simply follows the road profile and the relative motion approaches zero. At high frequencies the mass tends to remain stationary in the vertical direction and relative motion approaches the value of profile displacement.

Although the foregoing model is useful for demonstrating the operation of a filter giving a zero-mean record, it does not reflect the motion experienced by a car's occupants. To do this, the body of the vehicle should be used as the system output, in which case the low and high frequency effects are reversed. At low frequencies the motion of the vehicle body is the same as the profile displacement, and at high frequencies the body motion tends to zero. Maximum response still occurs at resonance, unless damping is unusually high. A single degree of freedom model of this type gives a reasonable description of the vibrations experienced by someone riding in a car for frequencies below the resonant frequency, but body motion at frequencies above resonance are very poorly predicted. The reason is that a car has a large number of degrees of freedom, all of which, except, perhaps, for body pitch, have resonant frequencies above the body bounce frequency. The common ¼ car simulation model, for example, adds wheel bounce as a degree of freedom. Other degrees of freedom of a car which respond to road roughness inputs include body roll, engine bounce, pitch and roll, suspension fore-and-aft motion, and tire carcass motion (particularly for radial tires). Remembering that, for typical levels of damping, amplitude of response is amplified and a maximum at a resonant frequency, the first objective in vehicle design for a good ride is to make the body bounce and pitch frequencies as low as possible and to make the wheel bounce frequencies as high as possible. All other resonant frequencies tend to be higher than wheel bounce, which leaves a range of frequencies over which there are no resonances and vehicle body vibration is minimized. The range of frequencies is approximately 1 to 2 Hz to 12 to 15 Hz, depending on the vehicle. People are most sensitive to vibrations over the frequency range of approximately 2.5 to 10 Hz, and separating body and wheel bounce frequencies as described above minimizes the amplitude of vehicle body vibrations over this critical range. But this does not mean that vehicle body vibrations at frequencies higher than the wheel bounce frequency are not important; only that, for constant amplitude of body acceleration, their effect on ride quality diminishes with increasing frequency. The way that the vibrations are transmitted to the occupant of the car may also be important. For example, engine or longitudinal suspension vibrations excited by high frequency components of the road profile may be transmitted to the floor panels of the car body, or to the steering wheel, and may not be measured by an accelerometer mounted on a more rigid part of the car body even though they are felt by the occupant. It is quite reasonable, therefore, to expect components of the road profile which will excite vibrations in vehicle subsystems having natural frequencies higher than the wheel bounce frequency to also have an effect on ratings of road roughness.

APPENDIX E

SUGGESTED PRACTICAL IMPLEMENTATION OF A SIMPLE ROUGHNESS METER

INTRODUCTION

Practical implementations of a simple roughness meter are outlined to give an indication of the number of components and design effort required to apply the results of the research reported in the main body of this report. The first scheme uses analog components for all of the signal processing, followed by a voltage-to-frequency (V/F) converter and counter to perform the averaging operation. Digital implementations are then discussed, where the only need for analog components is in the preprocessing of the transducer signals prior to digitization. Advantages of the analog system are that the data reduction would be performed in real time and the components could be built into a small, compact package. The major disadvantage of the analog system is that the band-pass filter characteristics are specified as functions of spatial frequency whereas the analog filters operate in real time. The filter characteristics would therefore have to be varied as a function of vehicle speed, leading to a decrease in overall accuracy.

Whatever form the data processing takes, a full implementation of a roughness meter will require the measurement of vehicle acceleration in the vertical direction and the measurement of distance between the vehicle body and the pavement. The following discussion assumes that these measurements are available as analog signals from both wheel tracks. Alternative configurations may be used (such as direct digital distance measurement, low speed profile measurement, or acceleration and distance measured in only one wheel-track), but to consider all possible systems is beyond the scope of this project.

Analog System

Figure E-1 is a block diagram of a suggested road meter which could be built primarily from analog components. The first stage consists of band-pass filters for the accelerometer and displacement transducer signals. The filtered accelerometer signals are then double integrated with second order low-pass filters whose breakpoint is significantly lower than the high-pass breakpoint of the band-pass filters. Taking the difference between the integrated accelerometer signals and the displacement transducer signals, squaring, and adding gives the instantaneous square of total pavement profile height in the desired frequency band. Profile height squared is then passed to a V/F converter, which produces a pulse stream whose frequency is directly proportional to profile height squared. Counting the number of V/F pulses over the specified site length effectively gives the integral of the V/F input voltage, and the count value therefore gives, to within a scale factor, the mean squared profile height in the left and right wheel tracks.

Digital Systems

A large number of options are available for implementing a roughness meter using digital processing. System hardware could range from low-cost 8-bit single board computers to full-feature minicomputers, or, if off-board processing is acceptable, the processing could be done on a mainframe computer. For real-time, on-board processing a high-speed single board or full-feature computer would be required, possibly incorporating high-speed signal processing hardware. Once the hardware has been chosen, other options in the design process would include programming language, filter implementation—FIT, IIR type (Butterworth, etc.) and arithmetic precision, and storage medium.

The large number of possible implementations emphasizes the need for early standardization of the filter characteristics so that compatibility can be maintained between systems designed by different agencies.

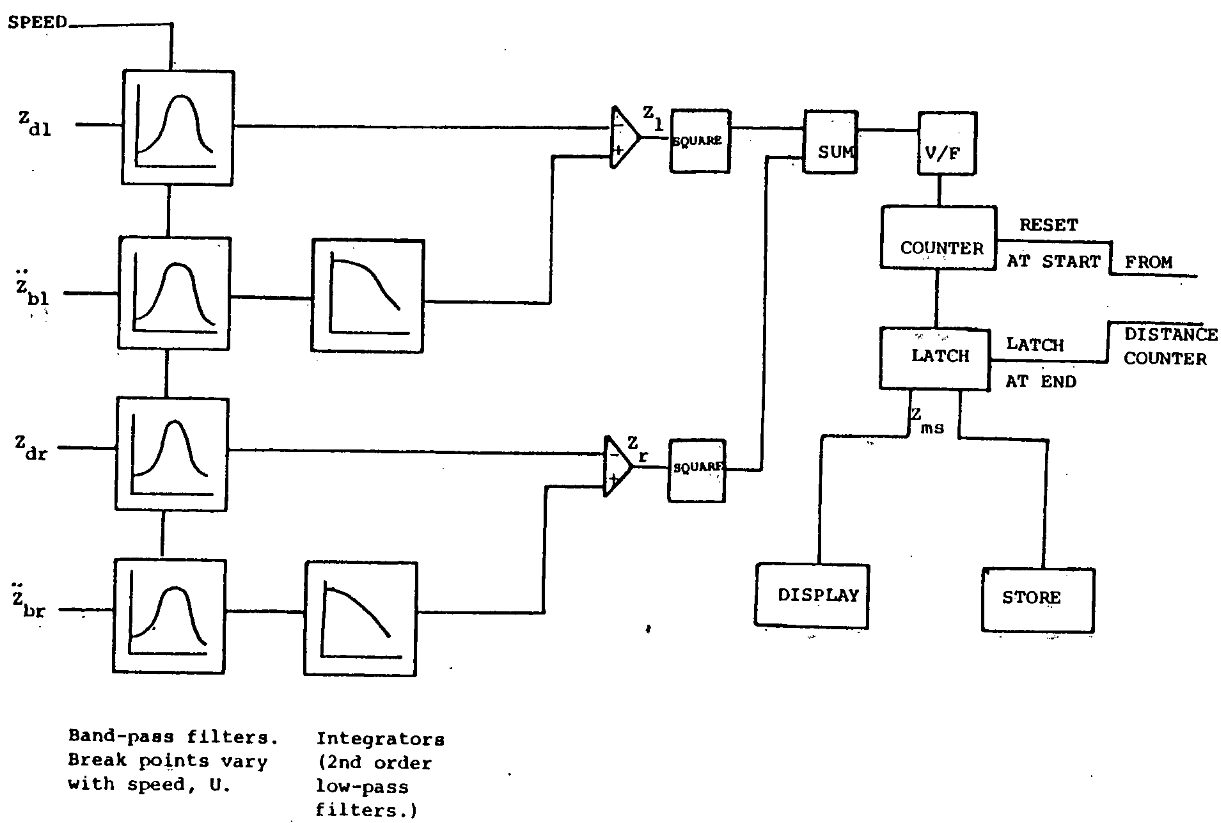

Figure E-1. Suggested analog road meter.

APPENDIX F

GUIDELINES FOR CONDUCTING PANEL RATINGS OF RIDE QUALITY

INTRODUCTION

The following discussion summarizes the key issues that must be addressed to conduct panel ratings of pavement ride quality and, concurrently, evaluate physical roughness. Five major issues are addressed:

1. Site selection and marking.
2. Panel selection.
3. Rating procedures.
4. Data reduction and analyses.
5. Physical measures of roughness.

SITE SELECTION

This is the most difficult and time consuming task. A recommended approach includes the following:

1. Identify potential test sections from historical roughness data. Each section should be at least ½-mile long, have uniform roughness over its entire length (no anomolous parts), and all sites together should span the widest range of roughness. The simplest method for estimating such roughness is to use a RTRRMS, although a profilometer (¼ car simulated roughness) or visual (subjective) estimates can be employed. Check roughness by measuring each section.

2. Link sections together into a route which (a) minimizes travel time, (b) equalizes time between test sections, and (c) allows sufficient time between test sections to mark the rating form and pass it to the front passenger.

Dummy sites might be necessary to fulfill (b). Such sections are treated in the experiment as real test sections, but can be ignored in the analysis. Twenty sections per surface type is a recommended value but as few as 10 can be used.

3. Mark all sections at the beginning and end and ¼ mile upstream (e.g., paint on road surface, shoulder or guardrail or plastic tape attached to vertical object (e.g., sign post).

4. Map entire route and prepare driving instructions (see e.g., Figure C-2). Mark all turns, decision points etc. on the route (e.g., paint, plastic tape).

5. Arrange for deferred maintenance on all test sections.

PANEL SELECTION

Panels are most efficiently selected from the state DOT or nearby (physically) agencies. Size should be at least 36 and should span all ages (not overrepresented by young drivers). All panel members should be licensed drivers.

Scheduling should be at the convenience of the subjects, but for routes requiring more than one day, the second day should immediately follow the first (e.g., Mon/Tues or Wed/Thur). Friday is preferred as a make-up day (e.g., rain cancellation).

Groups of three are preferred—the number of groups depending on the number of vehicles, as discussed below.

RATING PROCEDURES

Before the actual ratings are accomplished, the following steps should be taken:

1. Train drivers and ensure that they are familiar with the route (see 5 below).

2. Prepare rating forms (Figure C-1). The total number = number of panelists × number of sites. Length of line is exactly 5 in.; one inch per major division.

3. Pre-code forms (rater #, site #) and order by route—one complete ordered set per panel member.

4. Assign one individual to give all instructions and training, and practice instructions.

Prepare copy of instructions for each panel member and also on a large flip chart (or chalk board) in the room to be used for giving instructions.

5. Determine the number of vehicles to be used (all same size, type, age), and check appearance, tires, suspension, etc. daily.

At the scheduled meeting time for the first group (3 × number of vehicles) hand out instructions, rater forms, pens and clipboard to each panelist; give instructions in one room to all panelists in this group, assign seat positions (let panelists choose and retain these seat positions for entire route).

Other topics that should be covered include: meal stops and other breaks, number of days, number of hours per day, confidentiality of data, etc. Answer all questions uniformly to all groups.

The panel ratings include the following steps:

1. Board vehicles (driver + 3 raters).
2. Drive to beginning of route.
3. (Driver sets speed and announces Site # ____ coming up).
4. Panelists check that they have correct form.
5. Site is rated and form marked.
6. Forms collected (by right front panelist and placed in box or large envelope—DO NOT LOOK AT OTHER PERSON'S RATING AND DO NOT DISCUSS RATINGS).
7. Drive to next site.
8. Repeat 3-7.
9. Take breaks as necessary.
10. At completion of day (route) return to central site (or possibly hotel, etc. if a two-day route with no return on first day is planned).

DATA REDUCTION AND ANALYSIS

Data reduction consists of measuring to the nearest 0.1 in., the distance from the bottom of the scale to the rating mark for each form. A suggested tabulation procedure is a matrix of $n \times m$ cells where n = number of test sections and m = number of panelists; r_{ij} is the j^{th} rating (i.e., j^{th} test site) for the i^{th} panelist; t_j is the total for the j^{th} site (sum of all ratings for site j); and $t_{j/m}$ is the mean panel rating for the j^{th} site.

	TEST SECTIONS				
PANELISTS	1	2	3	4	n
1	r_{11}	r_{12}			r_{1n}
2	r_{21}		\		
3	r_{31}				
—					
—					
n	r_{m1}				r_{mn}
TOTALS	t_1	t_2	t_3		t_n
MEANS (MPR)	$t1/_m$	$t2/_m$			$tn/_m$

PHYSICAL MEASUREMENT

Concurrent with the panel ratings, profiles and/or RTRRMS should be accomplished for each test section. Such measures should begin after the panelists begin their ratings to ensure that no conflict will occur (or on a 2-day route, make physical measures on the opposite day—e.g., first ½ of route on day 2 and second ½ of route on day 1).

PI is computed as indicated in Appendix D.

APPENDIX G

ACRONYMS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AFD	Amplitude-frequency distribution
ANOVA	Analysis of variance
BC	Bituminous concrete
BPR	Bureau of Public Roads
FHWA	Federal Highway Administration
FLDOT	Florida Department of Transportation
GMR	General Motors Research
MPR	Mean panel rating
MRM	Mays ride meter
NCHRP	National Cooperative Highway Research Program
NR	Need for repair
ODOT	Ohio Department of Transportation
PCC	Portland cement concrete
PENNDOT	Pennsylvania Department of Transportation
PI	Profile index
PSD	Power spectral density
PSI	Present serviceability index
PSU	Pennsylvania State University
RN	Rideability number
RTRRMS	Response-type road roughness measuring system(s)
SI	Serviceability index
TRIS	Transportation Research Information Service
UFLA	University of Florida

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