Methodology for Computing Pavement Ride Quality From Pavement Roughness Measurements

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ABSTRACT

The objective of this paper is to report on the development of a methodology for computing pavement ride quality from pavement roughness measurements. This methodology is based on a statistical transform between physical profile measures and subjective panel ratings that allows the mean panel rating for a given pavement section to be accurately predicted from the profile measure of the pavement section. The physical profile measure, denoted the Profile Index (PI), is a measure of pavement roughness in the frequency band extending from 0.125 to 0.630 cycles/ft (10 to 51 Hz at 55 mph). A second transform has been developed from a pavement section's mean panel rating that provides an accurate prediction of its need for repair.

The objective of this paper is to report on the development of a methodology for predicting pavement ride quality from pavement roughness measurements. This methodology is based on research performed by Ketron, Inc., for the Transportation Research Board National Cooperative Highway Program (NCHRP) (1). The goals of the research were to (a) develop a scale that accurately reflects the public's perception of pavement roughness, (b) develop transforms that relate pavement profiles to this scale, and (c) show how roughness statistics produced by various response-type road roughness measuring systems (RTRRMS) relate to this scale.

BACKGROUND

During the AASHO Road Test, serviceability was defined as the ability of a pavement to serve the traveling public (2). 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. However, this PSI 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, as originally defined, is not exclusively a measurement of pavement ride quality or 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 or ride quality 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 (Project Statement, NCHRP Project 1-23).

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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.

DEFINITIONS AND CONCEPTS

In addition to rideability and roughness, defined in the preceding section, a number of related concepts should be explained.

For the physical roughness data, a profilometer was used to compute a profile index (PI) defined as the square root of the mean square of the profile height, with units in inches. PI is defined in this paper for specific frequency bands of roughness.

For the subjective rideability data, two terms were used: (a) a mean panel rating (MPR) of a given pavement section, which is the mean value (i.e., the average) of a group of subjective panel ratings for a given test section, and (b) a pavement section's rideability number (RN), which is equivalent to its MPR but is derived from a pavement section's PI by using a statistical transformation. One additional concept is the needs repair rating (NR), which represents the percentage of the driving public that believes a given pavement section should be repaired.

In the later part of this paper it is demonstrated how the concepts PI, RN, MPR, and NR are related.

RESULTS

Main Panel Rating Experiment

The main panel rating experiment was designed with the following components:

1. Fifty-two test sections including all three surface types [bituminous concrete (BC), portland cement concrete (PCC), and composite] and spanning a wide range of roughness.

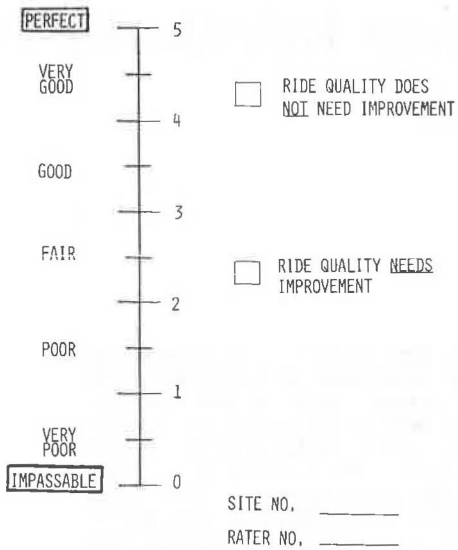

FIGURE 1 Rater form.

2. Thirty-six panel members spanning a wide range of ages and driving experience.
3. The Weaver/AASHO rating scale (Figure 1), including the subjective rating of rideability and 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 or not each pavement section requires repair or maintenance.
4. A detailed set of instructions that were uniformly given to all panel members (Figure 2).
5. A carefully designed and controlled experimental protocol.
6. Data reduction and analysis methods.

This experiment was implemented in the fall of 1983 in the Columbus, Ohio, area with the cooperation and help of the Ohio Department of Transportation (DOT).

Concurrent with the experiment, the Ohio DOT obtained profile information measuring each test section using a profilometer and a Mays meter. The experimental design is summarized as follows:

Test sections	52 test sections, 1/2 mi each in Columbus, Ohio, area, including 18 BC, 17 PCC, and 17 composite, spanning a range of roughness of 32.6 to 661.3 in./mi
Panel members	36 employees of Ohio DOT with 1 to 50 years of driving experience
Test vehicles	Four K-cars of similar age and mileage
Rating scale	Weaver/AASHO plus secondary rating (Figure 1)
Instructions	Figure 2
Profilometer	KJ Law noncontact
RTRRMS	Mays meter
Time	2 days per group (12 subjects) 6 days total

Data Analysis

The primary objective of the data analysis was to identify the frequency band at which MPR is most highly correlated with PI and then to derive a regression equation relating MPR and PI (i.e., a statistical transform) that can be used to predict

Highway Improvement Study

Purpose

To survey typical Ohio drivers in order to determine what they think of the quality of the ride provided by the roads in the state. The Ohio DOT will use this information to help decide which roads it 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 that we believe are representative of the roads as they exist throughout the state. 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 that you believe best describes the ride provided by each road.

Definitions of Endpoints

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

Impassable:

A road that 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.

FIGURE 2 Panel instructions.

Perfect:

A road that 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.

Because 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 that could be used to describe how the riding sensation appears 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 that 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 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 state should improve the ride quality of the road.

When making this decision you should take into account the fact that because 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 believe 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 that give identically rough rides but, if you had your choice, you would rather see only one of them improved because the type or character of that road appears to you to make it more worthy of improvement.

Procedure for Survey

- For this survey we are going to ask you to evaluate 81 road sections.

Note: You will not 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 rating of ride quality should be, based on how the ride feels to you.
- 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.
- Because some sections are only 3 to 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 6 hours the first day and 5 hours the second.

Special Instructions

- When making your rating of ride quality, do not consider any of the road before or after a test section. We are only interested in a rating for a small section of road.
- When making your decision concerning the need for improvements

FIGURE 2 (continued)

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. Do not let the appearance of the road surface influence your ratings. Judge only how the road feels!

• Do not be distracted by conversations in the car or by pretty scenery.

• Do not reveal your ratings to the other raters. There is no right or wrong answer, so do not "cheat." We are interested only in your 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 that 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 perfect. The road could (a) be so bumpy that it rattles your bones and makes your teeth chatter, (b) have bumps or undulations that makes the car heave up and down as if it were a roller coaster, or (c) have other imperfections in the surface that you believe detract from the ride quality.

FIGURE 2 (continued)

RNs from PIs measured in this frequency band. Secondary objectives included development of statistical transforms between response-type roughness measures and RNs and between NR and RN.

To meet the primary objective, the PI for each profile for each of the 26, one-third octave bands of frequencies were computed from 0.0025 to 0.8 cycles/ft (0.2 to 64 Hz at 55 mph). The PI values were then correlated with the MPRs for each test section, for all three surfaces combined, and for the three types of surfaces individually. Figure 3 shows the results for all three surfaces combined [the results for the three individual surface types are similar and available in NCHRP Report 275 (1)]. [Note that the graph in Figure 3 was extended beyond 0.8 cycles/ft (dashed line) using data collected with the Pennsylvania State University profilometer. The upper limit of the Ohio DOT profilometer was 0.8 cycles/ft.]

The abscissa in Figure 3 shows the 26 different frequency bands and the ordinate shows the correlation coefficient that results when PI in an individual band is correlated with MPR for the test section. From the figure it can be seen that between the frequencies 0.125 and 0.63 cycles/ft (10 to 51 Hz at 55 mph), the correlation coefficients (r) remain better than -.85 but that outside this band the correlation coefficients decline rapidly.

If PI is computed for each profile within this entire band of frequencies (0.125 to 0.630 cycles/ft) and correlated with MPRs, the resulting correlation coefficient is -.85. When the raw data are plotted (Figure 4) it is evident that an exponential curve is revealed and a log transform of the PI measures increases the correlation to -.94. The resulting equation

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

accounts for 88 percent of the variance. This equation is shown in Figure 5.

The NR rating was also found to be highly correlated with MPR ($r = -.93$) and yielded a regression equation

$$NR = 132.6 - 33.5\ MPR \tag{2}$$

This equation is shown in Figure 6.

Note that Equations 1-4 are based on only the Ohio data; in other states they could change slightly. [See NCHRP Report 275 (1).]

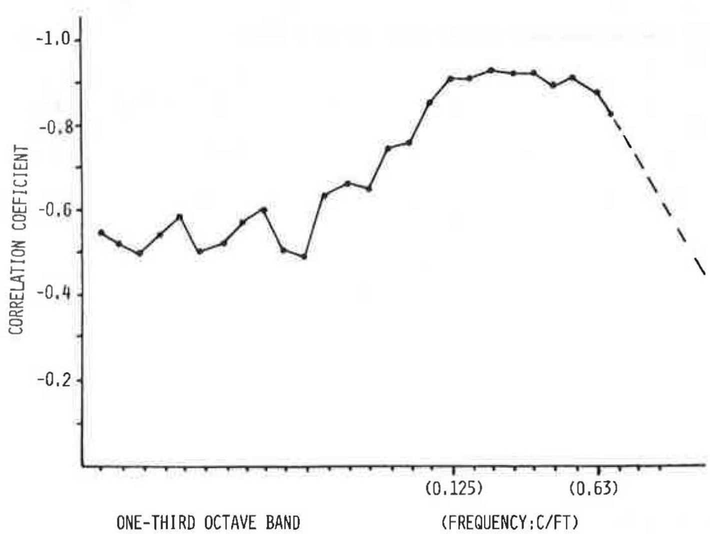

FIGURE 3 Correlation of MPR with PI for all surfaces.

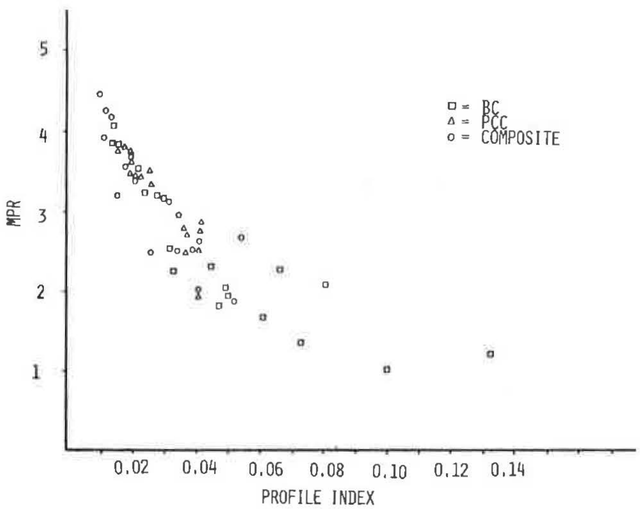

FIGURE 4 Profile index versus MPR, all surface types.

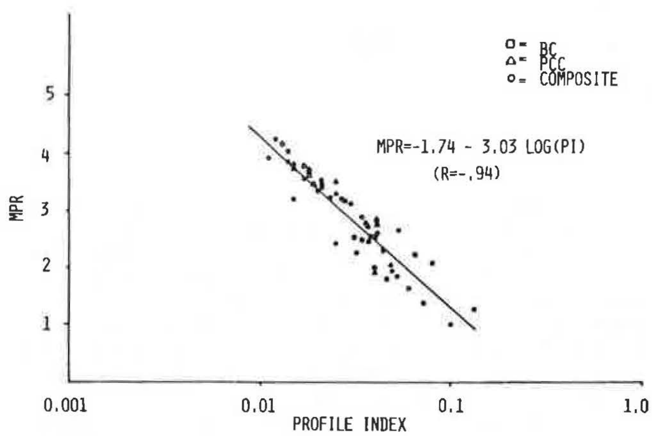

FIGURE 5 Log transform of raw data.

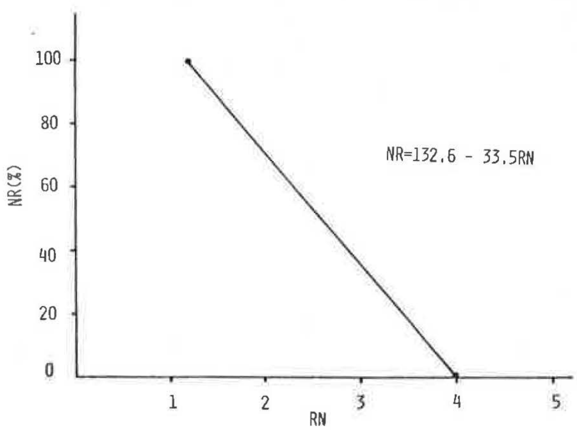

FIGURE 6 Needs repair versus ride number.

CONCLUSION

The implications of the primary analysis are that assuming an agency is able to compute PI for the band of frequencies 0.125 to 0.63 cycles/ft, then by applying the transform

$$RN = -1.74 - 3.03 \log (PI) \quad (3)$$

it can compute the ride number of a given pavement section. The ride number is an accurate approximation of the true mean panel rating of the pavement section ($r = -.94$).

From RN, NR can be computed by using

$$NR = 132.6 - 33.5 RN \quad (4)$$

to determine the exact percentage of the driving public that believes a given pavement section should be repaired.

ACKNOWLEDGMENT

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1. M.S. Janoff et al. Pavement Roughness and Rideability. NCHRP Report 275, TRB, National Research Council, Washington, D.C., 1985, 69 pp.
2. W.N. Carey and P.E. Irick. The Pavement Serviceability Performance Concept. In HRB Bull. 250, TRB, National Research Council, Washington, D.C., 1960, pp. 40-58.

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Discussion

R. M. Weed and R. T. Barros*

This discussion is not intended to detract from the author's excellent work but, instead, to suggest how the choice of more appropriate mathematical models might enhance it further.

From examination of the raw data in Figure 4, the author notes that an exponential function of some sort is suggested. He then proceeds to do a log transformation on the X-axis data (PI) and obtains Equation 1 by linear regression. The relatively high correlation coefficient of -0.94 indicates that a good fit of the data has been obtained.

In spite of this good fit, there are some drawbacks to the mathematical model that has been used. As shown conceptually in Figure 7, if the model is

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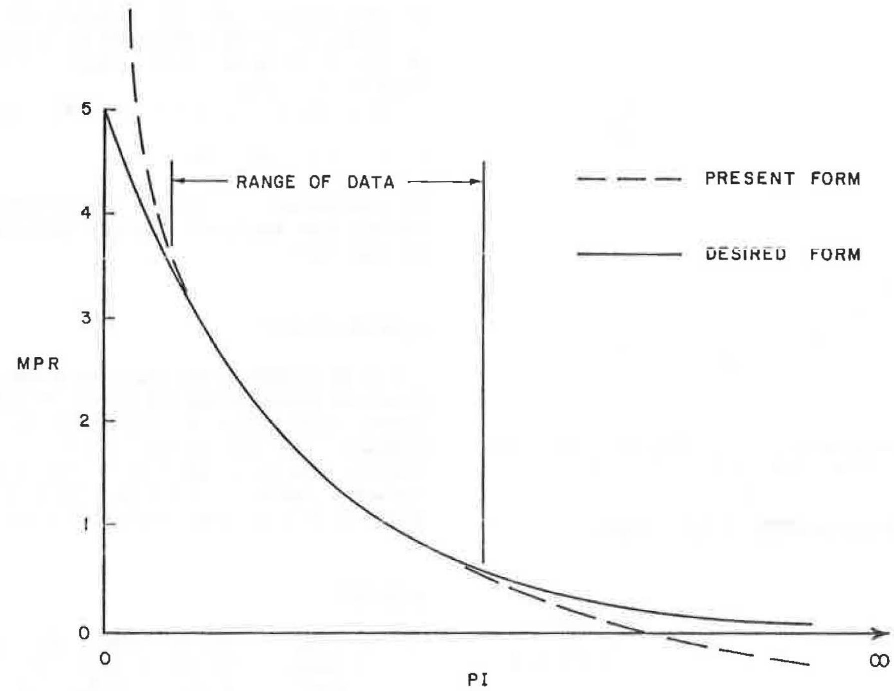

FIGURE 7 Comparison of two conceptual models.

extended beyond the range of the data, it violates two known constraints: (a) it rises above MPR = 5 at low PI values and (b) it eventually goes below MPR = 0 at very high PI values. This is the result of doing the log transformation on the X-axis data rather than on the Y-axis data. Although this model may be empirically useful within the range of the data, better models are available that do not violate these basic constraints.

The primary goal is to find the mathematical model that most accurately describes the process being investigated. To this end, it is appropriate to use every resource available, including any prior knowledge of that process. In this particular case, it is known that PI = 0 must correspond to MPR = 5 because both these points represent the best that can be obtained on the two scales. At the other extreme, there is essentially no difference between a very high PI value and a still higher PI value; for all practical purposes, both would correspond to MPR = 0. This suggests that the appropriate curve will originate at PI = 0, MPR = 5 and fall exponentially to eventually become asymptotic to the X-axis. As a check, visual inspection of Figure 4 strongly supports this conclusion.

A basic exponential decay function that is capable of satisfying the known constraints is given by Equation 5. Two additional candidate models are given by Equations 6 and 7. These models are capable of assuming the general shapes shown in Figure 8, depending on the values of the coefficients that are used. For this particular application, it can be seen by inspection that the first coefficient must be A = 5 in order for the curves to originate at the point x = 0, y = 5.

$$y = Ae^{Bx} \quad (5)$$

$$y = Ae^{Bx^{C}} \quad (6)$$

$$y = Ae^{Bx^{C+Dx}} \quad (7)$$

The next step is to fit these models using least-squares techniques. There are two ways that this can be done and one is somewhat preferable to the other. The less desirable method is to do a logarithmic transformation (two transformations are required for Equations 6 and 7) followed by linear regression and a transformation back to the original parameters. This method is considered less desirable because the least-squares technique may not be fully optimal when operating on transformed data. A preferable technique is the use of nonlinear regression, a standard feature included in SAS (1) and other computerized statistical analysis packages. With nonlinear regression, the least-squares procedure is applied directly to the raw data after first imposing the appropriate constraints. The data in Table 1 compare the author's results with those obtained by nonlinear regression.

TABLE 1 Comparison of Four Models

Model	Form	Equation	Residual Sum of Squares
Equation 1	$y = A - B \log x$	$MPR = -1.74 - 3.03 \log PI$	4.33
Equation 5	$y = Ae^{Bx}$	$MPR = 5e^{-17.4\ PI}$	5.39
Equation 6	$y = Ae^{Bx^{C}}$	$MPR = 5e^{-10.6 PI^{0.852}}$	4.75
Equation 7	$y = Ae^{Bx^{C+Dx}}$	$MPR = 5e^{-304 PI^{1.55+8.29\ PI}}$	4.17

The "goodness of fit" of the four models, as measured by comparatively low residual sums of squares, has been included in Table 1 as a matter of interest. This should not be the primary factor of consideration, however, when deciding among competing models. When it is possible to identify fundamental mathematical constraints, these constraints should be satisfied before any statistical procedures are applied. By this reasoning, any of the alternate models (Equations 5-7) is preferable to Equation 1, although only Equation 7 produces a lower residual sum of squares.

The three alternate models are compared to the author's original model in Figures 9-11. All three satisfy the known constraints and Equation 7, in particular, appears to provide an exceptionally good fit of the data.

In summary, the primary goal is to obtain the mathematical model that best describes the physical process. To accomplish this, it is necessary to impose any known constraints before regression analysis, or any other statistical technique, is applied. There are two advantages to this approach. First, by satisfying these constraints, it is more likely that a fundamentally correct model will be obtained. Second, because the equation may eventually be applied by users unfamiliar with its development, it will be more likely to produce correct results if it should subsequently be used outside the range of data from which it was derived.

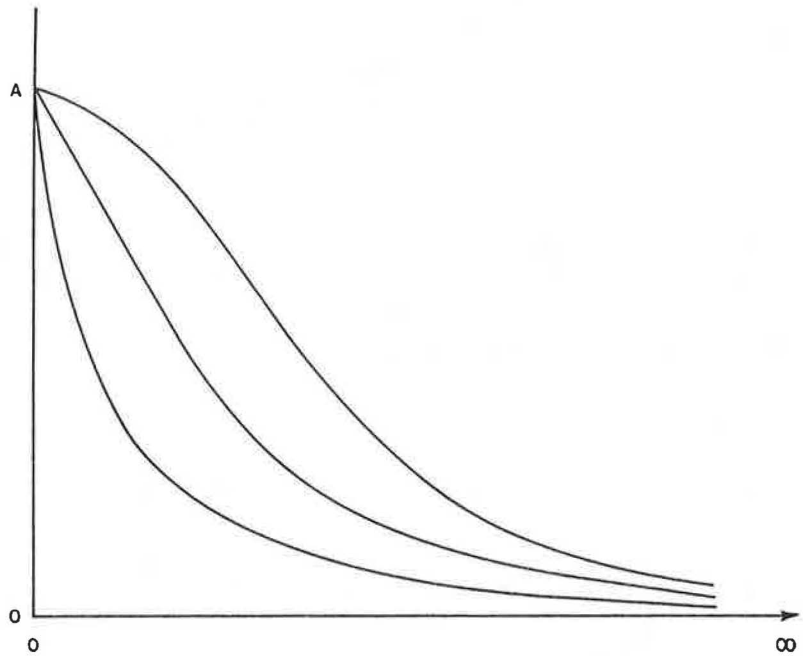

FIGURE 8 Various forms of exponential decay curves.

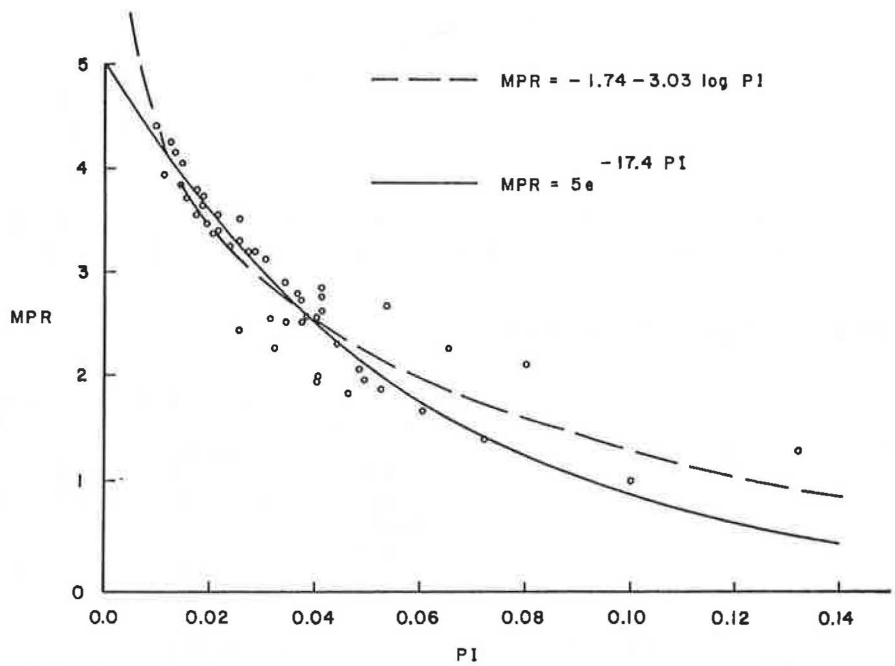

FIGURE 9 Equation 5 compared with Equation 1.

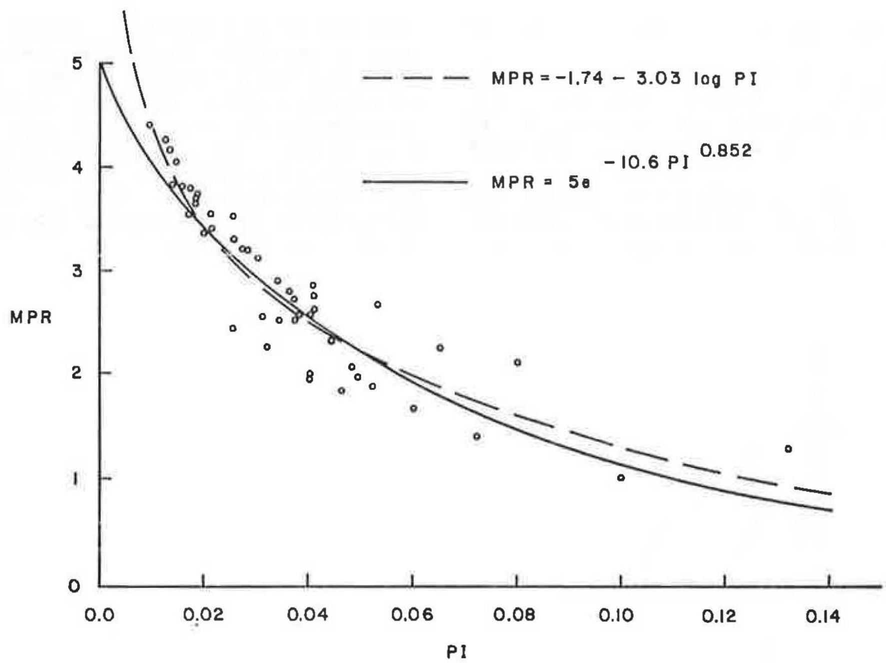

FIGURE 10 Equation 6 compared with Equation 1.

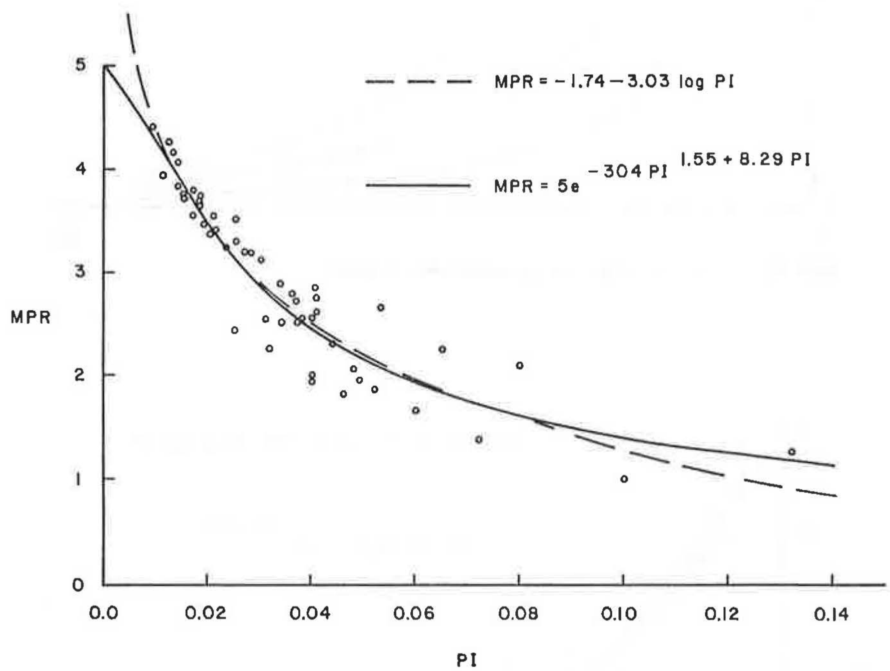

FIGURE 11 Equation 7 compared with Equation 1.

REFERENCE

1. SAS User's Guide. SAS Institute, Cary, N.C., 1979.

Author's Closure

I would like to thank Weed and Barros for their discussion of my paper. Although their comments are valid, I believe that a response on my part is necessary for completeness.

Their comments primarily address my choice of model and the fact that my model does not accurately predict ride quality (RN) either less than 1.0 or greater than 4.5. Their analysis develops a model that is theoretically correct (i.e., from an engineering point of view) for all levels of ride quality.

A number of points should be noted:

1. My research (NCHRP Project 1-23) has indicated that on roads with ride quality less than 1.0, 100 percent of the raters agree that the road should be repaired; for ride quality greater than 4.5, 100 percent of the raters agree that the road requires