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ABSTRACT

Every agency responsible for the maintenance of roadway systems faces the problem of insufficient funding to perform all of the necessary repairs on all pavement sections. Therefore, highway agencies must adopt a pavement management system (PMS) to help set priorities. The PMS includes a method for evaluating pavement performance on a routine basis and identifying sections with a need for rehabilitation or maintenance. Some states in the U.S. use a pavement rating system that is based solely on visible surface distresses, while others use an index based on ride quality alone, to perform the regular evaluation of pavements and to select projects. Increasingly, many states are using a combination of distress and ride quality. The Ohio Department of Transportation (ODOT) utilizes the Pavement Condition Rating (PCR), which is based on surface distress, for project selection.

This paper outlines the development of a new performance index for pavements that incorporates aspects of ride quality together with surface distress, for possible adoption by ODOT. The proposed index is called the Pavement Quality Index (PQI). The PQI does not require any new measurements or methods; rather, it simply utilizes procedures that are already in place and well established in Ohio. The PQI is an amalgam of the PCR and the International Roughness Index (IRI). The development of the new index is the natural extension of the growing trend that transportation agencies are placing increased emphasis on customer satisfaction, and also introducing performance-based specifications.

INTRODUCTION

Problem Statement

With a limited amount of funding available for the maintenance of pavements, responsible agencies must rely on a pavement management system (PMS) to identify priorities for maintenance and rehabilitation *(1)*. The question of how to evaluate the performance of a pavement for the purposes of a PMS is a difficult one and even within the U.S. there are differing practices from state to state. It could probably be agreed upon that a comprehensive assessment of the condition of a pavement would involve the characterization of:
1. Surface friction characteristics i.e. skid resistance,
2. Structural adequacy,
3. Roughness (ride quality), and
4. Surface distress.

A survey of 50 states, the District of Columbia and 9 Canadian provinces, giving a total of 60 agencies, was performed in 1994 by the National Cooperative Highway Research Program (NCHRP) to determine the prevailing practices in pavement condition evaluation *(2)*. The survey considered all four criteria mentioned above. It showed that is was not common practice to use friction and structural adequacy in routine evaluation of pavements, probably because of the prohibitive costs. Regarding the other two criteria, there was no consensus and there were widely differing practices between agencies. In the case of distress, the field survey procedures and the type, extent and severity of distresses collected varied greatly. Distress types tended to fall into three general categories, regardless of roadway surface type: cracking, surface deterioration, and distortion. In the case of roughness, there was more standardization with many states using the International Roughness Index (IRI). A total of 58 agencies collected distress data and 59 collected roughness data. Seventeen combined distress ratings with roughness ratings, 6 combined distress with roughness and average daily traffic (ADT), 8 combined distress with roughness and structural number or data, and 5 combined distress with roughness and friction number or accident data.

The Ohio Department of Transportation (ODOT) utilizes a measure of pavement distress, namely the Pavement Condition Rating (PCR), to evaluate pavements on a routine basis. Roughness measurements are taken but are independent considerations and not used in the PMS. Recently at ODOT, there has been a climate of attaching increasing importance to the role of roughness in pavement serviceability. ODOT has implemented an incentive program for contractors who achieve pavements with a certain level of smoothness, and are in the process of developing performance-based smoothness specifications for new construction *(3)*.

A major disadvantage of using the PCR as the only performance indicator is that pavement management decisions may not correspond with user satisfaction. A distressed pavement with a low PCR will often have poor ride quality as well. In this case, the problems are minimal since the rehabilitation of the pavement to address the PCR usually also improves the ride quality. The other end of the spectrum is often more problematic. In this case, a pavement with a high enough PCR may have poor ride quality. Under the current ODOT operational procedures, there are no provisions for identifying the pavement in question for rehabilitation or

maintenance. Thus, the pavement would continue to be used with a low ride quality and increased public dissatisfaction.

The primary objective of this research was to develop a composite index of pavement performance that incorporates ride quality together with surface distress. The new index was named the Pavement Quality Index (PQI). The new index could be used in ODOT's PMS to target roads with high PCR values but rough rides, and to provide greater user satisfaction. The PQI could also be used to provide a generalized idea of pavement quality in the network. A composite index such as PQI could also be useful on a national level to rate the quality of the National Highway System (NHS).

Methods for Including Roughness in the PMS

There are several possible methods for incorporating roughness in the PMS. Three of these are discussed below:

1. *Roughness as a deduction from PCR*: The PCR is obtained by deducting points from 100 based on the weight, severity and extent of visible distresses. Under this method, IRI could simply be treated as an additional deduct. In this way, PCR would still be the primary trigger variable; thus, PQI would never be higher than PCR, and pavements with poor PCR would still be selected for rehabilitation and maintenance as under the current system. However, pavements with a poor ride quality beyond a certain limit would incur a deduct penalty, which could be large enough to cause the pavement to be selected for rehabilitation or maintenance.

2. *Roughness and PCR combined into one index*: In this method, both indexes would contribute to the overall composite index, but the relative weight could still be higher for the PCR. Pavements with poor PCR might still be targeted for rehabilitation as under the current system. In this case, however, pavements with a very low IRI could actually be rewarded and the overall PQI could be higher than the PCR. Examples of agencies employing this type of practice include Mississippi *(4)*, Utah *(5)* and Alberta, Canada *(6)*.

3. *Roughness and PCR as separate indexes*: In this method, roughness would be a separate consideration of enough importance to trigger rehabilitation or maintenance on its own regardless of PCR. This could be accomplished by using a remaining service life concept, for example. A pavement performance curve could be used to determine the remaining service life for a pavement for both PCR and IRI. The shorter remaining service life would control. Examples of agencies employing this type of practice include Colorado *(7)* and Florida *(8)*.

Practicality and potential for quick implementation were guiding principles in this study. Methods that represent the least deviation from the current state-of-practice are most likely to be successfully implemented. In addition, the current thinking in Ohio is that the priority for pavement management decisions should be on distress rather than roughness. The third method probably represents the biggest change from the current state-of-practice. Furthermore, it depends on accurate prediction models of long-term pavement performance. In order to utilize this method, additional research would be needed to develop performance curves for both IRI and PCR. The second method has the potential problem that an index with a good value might wash out the effect of an index with a poor value. ODOT has a long history of using PCR in pavement management. Policy makers and field personnel are thoroughly familiar with the

concept of deducting points as used in this rating system. The first method provides the guarantee that any pavements that were classified as poor under the PCR system would still be classified as poor using PQI. For these reasons, the researchers chose to concentrate on the first method.

Description of Ohio's PCR

When stress or strain exceeds a certain limit, distress may occur. The survey of the distress is performed by visual inspection by walking along the pavement section. ODOT uses a PCR to characterize surface distress *(9)*. The PCR is calculated using Equation (1).

$$PCR = 100 - \text{Sum of Deducts} \qquad (1)$$

Figure 1 shows a sample rating form used by ODOT to calculate PCR for a flexible pavement. It shows the types of distresses considered, the weight assigned to each, the multipliers for severity level (low, medium or high), and the multipliers for extent (occasional, frequent or extensive). Note that rutting is also included as a distress. Figure 2 shows a similar rating form for jointed concrete pavements. Once the PCR is calculated using Equation (1), a qualitative description of the pavement is made according to the chart in Figure 3 (a). A PCR of 100 represents a pavement in perfect condition while a PCR < 55 indicates a pavement in poor condition.

LITERATURE REVIEW

Importance of Including Roughness in PMS

A research study was conducted to evaluate measures of client satisfaction with pavements *(10)*. It was found that ride quality was the most important issue for customer satisfaction, followed by surface distress. On a scale of 0-100, ride quality would contribute about 25% to overall customer satisfaction, surface distress nearly 20% and all the other measures between 5 and 10 percent each. The other measures that were considered were cost-effectiveness, structural adequacy, user delays, surface friction, noise, and surface drainage.

Research suggests that roughness can lead to a cycle of increasing deterioration rates with increasing roughness severity *(11,12)*. On a smooth road, loads from trucks are relatively constant but on a rougher road, the pavement receives higher impact loads at the point of roughness. The magnitude of the increase in load can be thought of as a dynamic load effect. Another article *(13)* published by FHWA provides data showing that by decreasing the initial roughness of a pavement, its expected service life becomes longer.

Performance-based Specifications in Pavement Construction

It has been reported that transportation agencies have become much more customer oriented over the past 15 years *(14)*, and this is evident in the number of agencies now focusing attention on

roughness issues. There is a growing trend toward introducing performance-based specifications for smoothness in new pavement construction. Traditionally, states have used the Profile Index (PI), which is measured with a profilograph, to determine roughness but there is an increasing trend toward using IRI. Arizona has implemented an incentive/disincentive program for smoothness and is moving to replace Mays ride meter with IRI *(15)*. In their experience contractors are putting real effort into producing smoother pavements to earn incentives. Some contractors are taking potential incentive payments into account when preparing their bids. Louisiana has implemented a smoothness specification for asphalt concrete in terms of IRI replacing their old specifications using PI *(16)*. The specifications include 100% pay if IRI < 65 in/mile (1.03 m/km) and 50% pay or removal if IRI > 75 in/mile (1.18 m/km) for multi-lift new construction. There is also a bonus pay of 10% if IRI < 45 in/mile (0.71 m/km). Ohio is in a trial phase of a smoothness incentive program. The contractor is required to report roughness using both PI and IRI for each 0.1 mile of pavement. The incentive is paid based on whichever index gives the larger pay adjustment. It is anticipated that PI will eventually be phased out. The bonus pay for asphalt concrete is 5% if IRI < 45 in/mile (0.71 m/km) and 1% if IRI is between 55-60 in/mile (0.87-0.95 m/km) *(3)*.

A paper outlining the development of a pavement smoothness specification for hot-mix asphalt in New Jersey has been published *(17)*. It makes use of estimates of percentage increase in service life as a function of percentage decrease in initial roughness. A useful table was generated that could be used to develop a relationship between expected service life and initial IRI. In New Jersey, the average level of IRI on satisfactory jobs is about 75 in./mile (1.18 m/km) and overlays typically last about 10 years. The very best jobs have average IRI values around 50 in./mile (0.79 m/km) and have expected lives of 11.1 years, and the worst jobs have approached 100 in./mile (1.58 m/km) with expected lives of 8.8 years.

Roughness Thresholds Based on User Perception of Ride Quality

The Federal Highway Administration (FHWA) requires that states must collect and report IRI values for roadways within the National Highway System (NHS). The FHWA has established criteria for defining "acceptable ride quality" *(18)*. Under the old system, pavements were designated "very good" if IRI < 60 in./mile (0.95 m/km) and "poor" if IRI > 170 in./mile (2.68 m/km) for interstates or 220 in./mile (3.48 m/km) for other routes. Under the new system, there are simply two categories - "good" corresponding to IRI < 95 in./mile (1.50 m/km), and "acceptable" corresponding to IRI not greater than 170 in./mile (2.68 m/km).

Several papers have appeared on the topic of correlating subjective user rating of pavement roughness with IRI, and determining IRI thresholds of acceptable ride quality. A study was conducted by Kuemmel et al. using pooled funds from Wisconsin, Iowa and Minnesota *(19)*. Participants were asked to drive their own vehicles over selected rural highway segments and indicate their agreement with the statement: "I am satisfied with the pavement on this section of the highway". It was interesting to note that the public seems to demand higher ride quality with asphalt pavements than concrete. The ratings for all pavement types combined showed that 60% of participants found IRI of 63 in./mile (0.99 m/km) satisfactory, and only 10% found IRI of 184 in./mile (2.90 m/km) satisfactory.

Another study was conducted in Washington to test the threshold for acceptable IRI *(20)*. It was speculated that the FHWA picked IRI of 170 in/mile (2.68 m/km) because it corresponds

to a PSR of 2.5. Traditionally, a PSR of 2.0 to 3.0 has been used to define failure in the AASHTO pavement structural design method. The PSR of 2.5 would represent a mid-range value. In the study, 56 participants were asked to evaluate 40 highway segments using one of four provided vehicles. The participants were asked the question, "Is this level of roughness acceptable to you?" The results showed that 99% of all observations made for IRI < 63 in./mile (0.99 m/km) were "acceptable". This would seem to indicate that an IRI threshold of 60 in./mile (0.95 m/km) is an excellent level for determining "very good" pavements. At an IRI value around 170 in./mile (2.68 m/km), approximately 68% of observations were "acceptable" and 32% were "unacceptable". Thus, the FHWA guideline of IRI < 170 in./mile (2.68 m/km) seems to be quite reasonable.

An investigation was performed in Sweden to test the correlation between public perception of roughness and IRI for relatively smooth roads (i.e. roads with low IRI) *(21)*. Twenty-two observers evaluated 45 highway sections while first traveling as passengers in a car and then in a truck. Most of the stretches were in the IRI range of 32-190 in./mile (0.50-3.0 m/km). Participants were asked to gauge the tested sections with respect to a very bad pavement section with IRI of 395 in./mile (6.23 m/km). The study found a linear relationship between subjective and objective roughness. The participants were able to distinguish between roughness levels even down at the lower end of the IRI scale.

Researchers in Pennsylvania completed a study to identify roughness thresholds based on user perception of ride quality *(22)*. Four functional classes of highways were studied, namely, interstates, other NHS roads, secondary roads with over 2,000 AADT, and secondary roads with under 2,000 AADT. The study showed that the relationship between motorists' satisfaction and pavement roughness resembled a fan-shaped pattern rather than parallel functions. In other words, the percentage of those satisfied decreased at a moderate rate as IRI increased on secondary roads; it decreased more sharply as IRI increased on NHS roads; and it dropped off at an even steeper rate with higher IRI values on interstates. Also, the IRI value at which 100% of the subjects rating any class of road believed ride quality to be satisfactory was somewhat convergent to a value in the range of 40-70 in./mile (0.63-1.10 m/km). As a result of the study, suggestions were made that the IRI threshold for "excellent" pavements should be < 60 in./mile (0.95 m/km) for all NHS roads and < 95 in./mile (1.50 m/km) for all secondary roads. For the case of "unacceptable" pavements, the IRI thresholds range from > 115 in./mile (1.81 m/km) for interstates to > 200 in./mile (3.16 m/km) for secondary roads with low AADT.

2004 ONU Survey

In October 2004, the research team conducted a survey of all state departments of transportation to assess the prevailing practices in pavement condition evaluation. The survey was conducted by sending an electronic mail to the list server NATIONALRAC with a link to a web page at Ohio Northern University (ONU). The survey consisted of five questions:
1. Do you currently use the IRI or any other measure of ride quality in your PMS?
2. Do you currently use the PCR or any other measure of surface distress in your PMS?
3. Do you currently use a combination of ride quality (roughness) and visible surface distress measurements (e.g. IRI and PCR) in your PMS?
4. If yes, please provide the equation and/or direct us to where we can find resources describing your current procedures.

5. If possible, please provide information for a person whom we may contact for additional information if necessary.

The summary responses for questions 1-4 have been compiled in Table 1. A total of 21 states, 2 Canadian provinces and FHWA LTPP responded to the survey. In addition, the authors have added responses from four other states based on published literature, giving a total of 28 agencies. Twenty-five agencies reported that roughness was used in their PMS; of these 20 indicated that they used IRI. Twenty-five agencies used some form of distress rating. Eighteen agencies combined distress with roughness. Some general conclusions that can be drawn from the survey results are that:

1. Almost every agency considers both distress and roughness very important.
2. IRI is almost a standard.
3. No two agencies follow the same procedures for assessing pavement condition.
4. More agencies combine roughness and distress than do not.

A discussion of two of the agencies' procedures follows. Mississippi's procedure can be considered as an example of combining roughness and distress into one index. Both IRI and a distress rating are obtained which are then combined into a composite index (PCR) on a 0-100 scale *(4)*.   For new pavements, IRI is expected to range between 13-127 in./mile (0.20-2.00 m/km), and 64-222 in./mile (1.01-3.50 m/km) for old pavements. The PCR is calculated using Equation (2).

$$PCR = 100 \left(\frac{12 - IRI}{12} \right)^a \left(\frac{D_{max} - DP}{D_{max}} \right)^b \tag{2}$$

Where   IRI   = Measured IRI, m/km
               D_{max} = Maximum possible deduct points due to distress
               DP   = Actual total of deduct points
               a, b   = constant

The maximum possible value for IRI is taken to be 12 m/km (760 in./mile). The original concept was that the constant *b* would be approximately 2 and the constant *a* would be 1. Expert panel ratings were used to subsequently calibrate the coefficients. The panel also determined the rating scale corresponding to pavements requiring routine maintenance, overlay, and structural strengthening. A panel size of 12 was used. A total of 8 flexible, 6 jointed concrete, 6 continuously reinforced concrete and 6 composite sections were selected for the ratings ranging from poor to very good. Finally, the coefficients were determined to be, *a* = 0.9567 and *b* = 1.4857 for flexible and concrete pavements. The *b/a* ratio greater than 1 indicates that the Mississippi equation gives more weight to the deduct points due to distress than to the measured IRI.

Colorado's procedures are an example of the method of keeping roughness and distresses as separate indexes. Colorado historically used an Overall Pavement Index (OPI) which combined ride quality, rutting and cracking *(7)*. The OPI had a tendency to skew the apparent condition of the network towards ride and relied heavily on the apparent surface condition of the pavement. Colorado then moved towards a Remaining Service Life (RSL) concept. Current raw

condition data (IRI, rut, cracking etc.) are converted to individual indexes on a scale of 0-100 using Equation (3).

$$Index = 100 - \left(\frac{\text{Avg Distress} - \text{Min Distress}}{\text{Max Distress} - \text{Min Distress}} \right) \times 100 \qquad (3)$$

Statewide maximum and minimum distresses are used. An index value of 50 indicates failure. Pavement performance (forecasting) curves are utilized. At age 0, the index would be 100. The threshold age is the age where the index value deteriorates to 50. The RSL is simply the threshold age minus the current age. The final RSL is the lowest of the individual distress RSLs rounded to the nearest whole number. The RSLs are grouped into categories (> 10 years = good, 6-10 years = fair, < 6 years = poor).

DEVELOPMENT OF OHIO'S PAVEMENT QUALITY INDEX

The ODOT PMS database that was used for this research spanned from 1998 to 2003 and included 179,934 data records. It should be noted that although ODOT classifies pavements into five types for PCR rating, only three types were found on the database, namely flexible, jointed concrete, and composite. Some screening of the data was performed. Records that did not have complete PCR and IRI records for all six years were eliminated. Next, records which showed an increase in PCR of a pavement from one year to the next (probably because the pavement received some maintenance) were removed. Finally, the records from 1998 and 1999 were removed because of a change in IRI profiling equipment after 2000. The remaining valid data were limited to 9,972 data records (2,493 pavement sections).

Practicality and potential for implementation were significant considerations in this research. The PQI makes use of existing ODOT procedures so that additional equipment and training are not needed. The PQI is an amalgam of PCR and IRI. It treats IRI as a deduction from PCR. Primary control is given to PCR, and PQI cannot be greater than PCR. This guarantees that pavements rated poor by just using the PCR would still be poor under the new system.

There are three functional classes of roadways in ODOT's network. These are the Priority System (consisting of interstates, freeways and multi-lane portions of the NHS), Urban System (consisting of state and federal routes in cities where the speed limit is usually < 40 mph), and General System (the remaining two-lane routes outside the cities). It was decided that for the Urban System there should be no deduction due to IRI, that is, the PCR would be the only rating method. This is due to questions regarding the validity of IRI measurements made at speeds < 40 mph (64 km/h). The mathematical model for calculating IRI uses a simulation vehicle speed of 50 mph (80 km/h). A study was performed regarding the applicability of IRI for roads that are used at speeds above or below this simulation speed (23). The investigation used simulated quarter-car speeds between 25-75 mph (40-120 km/h) on profiles of both asphalt and concrete pavements. For simulation speeds between 37-68 mph (60-110 km/h), the response from the IRI model was within ±13 in./mile (±0.2 km/h) of the actual IRI for 80% of the asphalt sections and 61% of the concrete sections. When measuring roughness on city streets for which the speed limits are typically less than 50 mph (80 km/h), it was recommended that a panel-rating study to obtain user opinion be performed. Thereafter, a correlation of user opinion with both IRI

(simulation speed of 50 mph) and IRI (simulation speed of actual speed limit) could be performed. The one giving the better correlation should then be used in subsequent applications.

The other two categories, General and Priority Systems, will be rated using the PQI. The PQI takes a slightly different form between these two systems because the threshold for failure is different. Failure is at PQI = 65 for priority systems and at PQI = 60 for general systems. The qualitative rating scale for PQI is similar to a proposed scale for PCR being considered by ODOT. The proposed scale for PCR would move failure from 55 up to 65 and 60 for priority and general systems, respectively. Figure 3 (a) is the current qualitative rating scale for PCR while Figures 3 (b) and 3 (c) are the proposed new qualitative rating scale to be adopted for PQI in priority systems and general systems, respectively.

In developing the equation for the priority system, it was felt that no deduction should be taken for ride quality if IRI is below 60 in./mile (0.95 m/km). This is logical because contractors receive awards for IRI < 60 in./mile (0.95 m/km) under ODOT's incentive program for smoothness. Studies have shown that this level of roughness would be acceptable to almost all users (20,22), and this was also the old threshold used by FHWA to classify pavements as "very good". Another threshold to be determined was the IRI corresponding to "unacceptable" roughness. Various studies (20,22) and the old FHWA guidelines put this value somewhere around 200-220 in./mile (3.16-3.48 m/km). In the present study the value was taken as 250 in./mile (3.95 m/km). It was felt that as ODOT gains more experience with incorporating roughness into the PMS, the requirements could be gradually tightened in the future. Note that this implies that even a brand new pavement (with PCR of 100) with an IRI of 250 in./mile (3.95 m/km) should be considered failed i.e. the PQI should be 65. The development of the PQI equation can be explained with reference to Figure 4. The graph shows PCR versus IRI for all priority pavement sections. From the preceding discussion, the easy way to define the trigger line for failure (i.e. PQI = 65) would be to draw a flat line at PCR = 65, from IRI = 0 to IRI = 60. Then a straight line could be drawn from the point (60, 65) to the point (250, 100). The disadvantage of this method would be that a piecewise function would be created. Furthermore, an increasing rate of deduct with increasing IRI (i.e. a nonlinear curve) is probably more rational than a flat rate of deduct. This pattern reflects the nonlinear curve of user satisfaction versus IRI observed in some studies, as well as the probable nonlinear dependence of deterioration on roughness stemming from the dynamic load effect. Thus, a single equation for PQI consisting of a linear PCR term and a power IRI term was used as given by Equation (4).

$$PQI = PCR - a\left(IRI\right)^{b} \tag{4}$$

Since we desire an essentially flat curve until IRI exceeds 60 in./mile (0.95 m/km), it follows that one of the points on the curve of PQI = 65 should be (60, 66). Note that the PCR corresponding to IRI of 60 in./mile had to be slightly higher than 65, otherwise the function would have a minimum at a point other than (0, 65). The second boundary condition corresponds to the maximum allowable IRI value for new pavements. Thus, another point on the curve of PQI = 65 should be (250, 100). These two boundary conditions can be solved to determine the coefficients a = 0.00003716 and b = 2.4913.

The graph of PQI = 65 for priority systems is shown in Figure 4. Also shown in Figure 4, are the curves for PQI = 75 and PQI = 90. These values were chosen because they represent thresholds for overlay and maintenance actions. As observed in Figure 4, the curve for PQI remains essentially flat until IRI equals 60 in/mile (0.95 m/km), and an increasing amount of

deduction is applied as IRI gets larger. Developing an equation that will be perfectly constant until IRI equals 60 in./mile can only be achieved with either a piecewise function or a mathematically intractable solution. The simple function of Equation (4) performs extremely well in this regard. At an IRI of exactly 60, the PQI would be only one point less than the PCR. In other words, for all practical purposes, the curve can be considered flat up to IRI = 60 in./mile (0.95 m/km).

For general systems, the threshold for failure is set at PQI = 60. It is appropriate to use the same IRI value of 60 in./mile for both priority and general systems because it has been shown that user perception of roughness corresponding to "excellent" ride quality seems to converge for different functional classes *(22)*. Since we desire an essentially flat curve until IRI exceeds 60 in./mile (0.95 m/km), it follows that one of the points on the curve of PQI = 60 should be (60, 61). Again, the PCR corresponding to IRI of 60 in./mile (0.95 m/km) had to be slightly higher than 60, otherwise the function would have a minimum at a point other than (0,60). The second boundary condition corresponds to the maximum allowable IRI value for new pavements. If we use the equation developed for the priority system, the curve crosses the line of PCR = 100 at an IRI of 265 in./mile (4.19 m/km). Logically though, tougher standards should be imposed on the priority system than the general system. The roughness value should be higher in the general system to cause the same amount of drop in PQI as in the priority system. Thus, the second boundary condition point on the curve of PQI = 60 was taken at (275, 100). These two boundary conditions can be solved to determine the coefficients, yielding a = 0.00004915 and b = 2.4230. The graph of PQI = 60 for general systems is shown in Figure 5, together with the curves for PQI = 75 and PQI = 90.

An analysis was performed to determine what ODOT might expect to see if the new PQI is implemented as the rating method for pavements instead of the PCR. The biggest impact will be in the low range with approximately three times as many pavements being considered poor than under the current system. Although this will pose a significant strain on ODOT's pavement management budget, these are clearly bad pavements (with low range PCR and high IRI), and being able to target them for rehabilitation will have an enormous benefit in terms of user satisfaction. In the range of fair pavements (66-75 for priority systems and 61-75 for general systems), there will be very little impact. Another relatively significant impact would be felt in the range of very good pavements i.e. PCR or PQI > 90. About 25% of the pavements currently considered very good in the priority system and 50% of those in the general system would now fall out of this category. Many of these pavements have little distress but marginally bad ride quality. There are currently no maintenance solutions that are designed to target only roughness; therefore no action would be taken on them. The authors believe that if ODOT implements smoothness specifications, then as a result of the higher ride quality of newly constructed pavements, this problem will be minimized or eliminated.

DISCUSSION AND CONCLUSIONS

Transportation agencies are becoming more customer-oriented and are striving to increase user satisfaction. For this reason, much emphasis is being placed on pavement roughness considerations. Many agencies are writing performance-based smoothness specifications and/or incentive/disincentive clauses. Additionally, many agencies are including roughness in making pavement management decisions about rehabilitation and/or maintenance. Another major

consideration for project selection under a pavement management system is distress. This paper outlined the development of a simple method to combine both roughness and distress into one index. The composite index, named the Pavement Quality Index, treats IRI as a deduction from PCR (the distress index). It applies essentially zero deduction when IRI is < 60 in./mile (0.95 m/km). The PQI is given by

$$PQI = PCR - a\left(IRI\right)^{b}$$

The values of the constants are $a = 0.00003716$, $b = 2.4913$ for priority systems and $a = 0.00004915$, $b = 2.4230$ for general systems. Higher standards for roughness are incorporated in the priority system compared to the general system. It is recommended that ODOT use the PQI instead of the PCR alone for pavement management decisions.

The FHWA currently ranks pavement quality in the NHS based on IRI only. However, they state: "To continue improving our pavement evaluation, FHWA has been working with AASHTO and States to establish standards for measuring roughness, cracking, rutting and faulting" *(18)*. If indeed a national standard for distress measurement could be achieved, then an index such as the PQI could prove to be very useful on the national level to rate the overall quality of the NHS system.

ACKNOWLEDGMENT

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TABLE 1 Summary Results of 2004 ONU Survey

State/Agency	Use Ride Quality?	Use Distress?	Combined?	Equation
Arizona	Yes, IRI.	Yes. Cracking (in %)	Yes	Rate = Cracking + IRI/10 + Rut*10 + 0.015 *(Average Maintenance cost for last 3 years)
Arkansas	Yes	No.	No	Collect pavement distress data and are working towards developing a form of PCR
California	Yes	Yes	No	N/A
Colorado	Yes, IRI	Yes	Yes	IRI, rut, cracking etc. converted to 0-100 scale. Index of 50 = failure. Performance curves are used to get Remaining Service Life. The lowest RSL controls
Delaware	No	Yes. OPC (overall pavement condition) rating based on visual surface distress	No	One of the distresses available for surface treated roadways is an index for roughness/crown. All our ratings are based on visual severity and extents of distresses based on pavement type. Not yet published.
Florida	Yes, Ride Number from high speed laser profiler with six inch sampling interval.	Yes, a Pavement Condition Rating	Yes	Ride, cracking and rutting rated independently on 0 to 10 scales. The overall Pavement Condition Rating for a section is the lowest rating of these three categories. http://www.dot.state.fl.us/statematerialsoffice/ administration/resources/library/publications/reseachreports/ PavementResearch/2003flexhandbook.pdf
Idaho	Yes, IRI.	Yes, PCR.	No	Each index is used separately.
Kansas	Yes, use right wheelpath IRI.	No	Yes, use distress state.	DISTRESS STATE: Condition of the segment at the time of the survey. This is usually expressed as a three digit code where: First digit. The Roughness Level on all pavement types based upon the IRI. "1" indicates IRI value less than 1.66 m/km (105 in/mi). "2" indicates IRI value of 1.66 to 2.59 m/km (105 to 164 in/mi). "3" indicates IRI value of more than 2.59 m/km (164 in/mi). Second digit. Distress type varies with the pavement type. - PCCP: An indicator of joint distress. - Full and Partial design bituminous and Composite: An indicator of transverse cracking distress. Third digit. Distress type varies with pavement type. - PCCP: Indicates faulting distress level. - Full design bituminous and Composite: An indicator of block cracking distress. - Partial design bituminous: An indicator of fatigue cracking distress. In the rating system, distress is based on 7 criteria consisting of rutting, fatigue cracking, transverse cracking, block cracking, faulting, joint distress.

Louisiana	Yes. Additionally we have implemented IRI based specification for ac pavements	Yes. Distresses such as cracking, rutting, patching, jt faulting (pcc), roughness (IRI) are collected.	No. Not necessarily	N/A
Maine	Yes	Yes	Yes.	Using our ARAN (automatic road analyzer) vehicle we collect IRI, rut depths and cracking. All of this information is used in determining the PCR for Maine roads
Maryland	Yes	Yes	Yes	Currently in the process of developing an overall condition index for pavement that includes ride quality, cracking, friction, and rutting. Procedures are still in the development and testing stage as of Fall of 2004.
Minnesota*	Yes, PSR	Yes, Surface Rating (SR)	Yes, PQI	PSR obtained from IRI is on 0-5 scale. The SR is crack and surface distress index on 0-4 scale. $PQI = \sqrt{(PSR)(SR)}$ http:www.mrr.dot.state.mn.us/pavement/PvmtMgmt/DistressManual.pdf
Mississippi	Yes, IRI.	Yes	Yes, PCR (0-100 scale)	PCR=100*[(12-IRI)/12]^a*[(Dmax-DP)/Dmax]^b where IRI is in mm/m for full depth flexible: a=.9567, b=1.4857, Dmax=205 for jointed concrete (JCP): a=.9567, b=1.4857, Dmax=185 for continuous concrete (CRCP): a=.9567, b=1.4857, Dmax=145 for composite (i.e. HMA over PCC): a=1.1111, b=1.5429, Dmax =230 DP for all pavements is the arithmetic mean of the total distress deduct points for all 500' samples within the section.
Missouri	Yes	Yes	Yes	Use a 40-point scale. Ride or IRI comprises half for 20 maximum possible points. A combination of different visual distresses for flexible and rigid pavements comprises the other half for 20 maximum possible points.
Montana*	Yes, IRI	Yes	Yes, Overall Pavement Index (OPI)	Ride, rut, distresses are each on 0-100 scale. 40 is failure. OPI is based on multiplicative deducts. Weights: alligator A 0.3, alligator B 0.6, alligator C 0.2, block cr. 0.2, transverse cr. 0.2, longitudinal cr. 0.2, ravel 0.2,rutting 0.6, patching 0.2, IRI 0.6. http://www.mdt.state.mt.us/materials/pavemgmt/opi_def.shtml
New Jersey	Yes, IRI. Also use Ride Quality Index on a scale of 0 to 5.	Yes, Surface Distress Index on a scale of 0-5. SDI is based on severity & extent of various distresses: multiple, transverse, and longitudinal cr.; patching; shoulder condition & drop	Yes, Final Pavement Rating	Project selection triggers – Interstates: RQI ≤ 3.5, SDI ≤ 3.5, Rut depth ≥ 0.5 in; Other routes: RQI ≤ 3.0, SDI ≤ 3.0, Rut depth ≥ 0.5 in. The Final Pavement Rating is established as follows: 1. If both RQI and SDI are > 2.51, they are weighed at 50% each. 2. If RQI and/or SDI are < 2.00, then the lower of the two ratings is weighed at 100%. 3. If the lowest value of RQI and/or SDI is ≥ 2.00 and ≤ 2.50, then the lower number is weighed at 75% and the other value is weighed at 25%.

New York	Yes, IRI used informally in decision-making/ assessing condition	Yes, use a 1-10 scale Surface Score which is essentially a cracking index.	Yes, PCI	We have a draft Pavement Condition Index (PCI) that combines Surface Score, IRI, rut, fault and dominant distress. It is still in draft form.
Ohio*	No	Yes, PCR	No	N/A
Oregon	No	Yes	No	N/A
South Dakota	Yes, IRI converted to 0-5 scale.	Yes, on 0-5 scales	Yes, Surface Condition Index (SCI)	IRI: 0 if > 225 in/mi and 5 if < 50 in/mi. SCI = Mean – 1.25 x SD. SCI ≥ 0 and ≥lowest individual index. SD is standard deviation. http://www.sddot.com/pe/planning/docs/Synopsis2003.pdf

Texas	Yes, mainly for construction specs. Our main ride quality index is Serviceabiity Index (SI), converted from IRI. SI ranges from 0.1 (roughest) to 5.0 (smoothest).	Yes. We use a weighted index ("Distress Score")of all distress types on each section. Distress Score ranges from 1 (most distress) to 100 (least distress).	Yes. Index is called "Condition Score." It ranges from 1 (worst condition) to 100 (best condition).	The equation is:
				CScore = DScore*RideUtility
				
				where CScore = Condition Score
				  DScore = Distress Score
				  RideUtility = utility factor for ride quality, adjusted for ADT and Speed Limit

Utah	Yes, RIDE (based on IRI) on 0-100 scale	Yes, several distresses on 0-100 scale	Yes, Overall Combined Index (OCI)	OCI is mean of four indices. For concrete: RIDE, concrete cracking, faulting and joint spalling. For asphalt: RIDE, environmental cracking, wheelpath cracking, and rutting.
Vermont	Yes. IRI in 0.1 mile sections. IRI is converted to a Roughness Index on a 0 to 100 scale	Yes. Structural crack index, transverse crack index & rutting index are tracked seperately to enable the triggering of treatments based on distress mechanisms occuring	Yes - This composite index is not used to trigger treatment options, but as the index that benefits are generated from	Vermont DOT pavement management section is currently upgrading our performance models and the calculation of this index is under review as are the methods to derive the individual distress index's from the raw data. The current composite index is felt to give unstable results.
Virginia	Yes, IRI data is collected every alternate years on all the Interstate network and on all HPMS designated sections	Yes. Load-related Distress Rating (LDR): Condition index affected mostly by distresses resulting from wheel load e.g. fatigure cracking, rutting etc. & Non-Load Related Distress Rating	No	N/A

Washington*	Yes, IRI	Yes, Pavement Structural Condition (PSC) on 0-100 scale	No	PSC includes cracking. Value of 100 is very good. Rehabilitation when projected PSC < 50. Rehabilitation when projected rut depth > 1/3 inch. Rehabilitation when projected IRI > 220 inches/mile. http://www.wsdot.wa.gov/biz/mats/pavement/Pavement%20Plan.pdf
Alberta	Yes, IRI	Yes, (SCR) surface condition rating to measure surface distress, which is then converted to a surface distress index (SDI)	Yes, the composite index is PQI (Pavement Quality Index)	PQI=(10*EXP(-0.2221*IRI))^0.7 * SDI^0.3
British Columbia	Yes, IRI	Yes	Yes	50% IRI and 50% distress
FHWA - LTPP	Yes	No	No	N/A

*These states did not participate in the survey. The authors have filled in the responses based on literature review.

Section: _____   **FLEXIBLE**   Date: _____
Log mile: _____ to_____   Rated by: _____
Sta: _____ to_____   # of Utility Cuts _____

PAVEMENT CONDITION RATING FORM

DISTRESS	DISTRESS WEIGHT	SEVERITY WT.*			EXTENT WT.**			DEDUCT POINTS***
		L	M	H	O	F	E	
RAVELING	10	0.3	0.6	1	0.5	0.8	1	
BLEEDING	5	0.8	0.8	1	0.6	0.9	1	
PATCHING	5	0.3	0.6	1	0.6	0.8	1	
DEBONDING	5	0.4	0.7	1	0.5	0.8	1	
CRACK SEALING DEFICIENCY	5	1	1	1	0.5	0.8	1	
RUTTING	10	0.3	0.7	1	0.6	0.8	1 ✓	
SETTLEMENT	0	0.0	0.0	0.0	0.0	0.0	0.0	
POTHOLES	10	0.4	0.8	1	0.5	0.8	1 ✓	
WHEEL TRACK CRACKING	15	0.4	0.7	1	0.5	0.7	1 ✓	
BLOCK AND TRANSVERSE CRACKING	10	0.4	0.7	1	0.5	0.7	1	
LONGITUDINAL CRACKING	5	0.4	0.7	1	0.5	0.7	1 ✓	
EDGE CRACKING	10	0.4	0.7	1	0.5	0.7	1 ✓	
THERMAL CRACKING	10	0.4	0.7	1	0.5	0.7	1	

*L = LOW   **O = OCCASIONAL   TOTAL DEDUCT = _____
M = MEDIUM   F = FREQUENT   SUM OF STRUCTURAL DEDUCT (✓) = _____
H = HIGH   E = EXTENSIVE   **100 - TOTAL DEDUCT = PCR =** _____

*** DEDUCT POINTS = DISTRESS WEIGHT X SEVERITY WT. X EXTENT WT.
REMARKS:

FIGURE 1 Sample PCR form for flexible pavements.

Section: _____   Date: _____

Log mile: _____ to_____   **JOINTED CONCRETE**   Rated by: _____

Sta: _____ to_____   # of Utility Cuts _____

PAVEMENT CONDITION RATING FORM

DISTRESS	DISTRESS WEIGHT	SEVERITY WT.*			EXTENT WT.**			DEDUCT POINTS***
		L	M	H	O	F	E	
SURFACE DETERIORATION	10	0.4	0.7	1	0.6	0.8	1	
LONGITUDINAL JOINT SPALLING	5	0.4	0.7	1	0.6	0.8	1	
PATCHING	10	0.4	0.7	1	0.5	0.8	1	
PUMPING	15	1	1	1	0.3	0.7	1 ✓	
FAULTING (JOINTS AND CRACKS)	10	0.4	0.7	1	0.5	0.8	1 ✓	
SETTLEMENTS	0	0.0	0.0	0.0	0.0	0.0	1	
TRANSVERSE JOINT SPALLING (CIRCLE IF D-CRACKED)	10	0.4	0.7	1	0.5	0.8	1	
TRANSVERSE CRACKING (Plain Concrete)	15	1	1	1	0.5	0.8	1 ✓	
PRESSURE DAMAGE	5	1	1	1	0.5	0.8	1	
TRANSVERSE CRACKING (Reinforced Concrete)	15	0.1	0.8	1	0.4	0.8	1 ✓	
LONGITUDINAL CRACKING	10	0.5	0.7	1	0.4	0.9	1 ✓	
CORNER BREAKS	10	0.4	0.8	1	0.5	0.8	1 ✓	

*L = LOW   **O = OCCASIONAL   TOTAL DEDUCT = _____

M = MEDIUM   F = FREQUENT   SUM OF STRUCTURAL DEDUCT (✓) = _____

H = HIGH   E = EXTENSIVE   **100 - TOTAL DEDUCT = PCR =** _____

*** DEDUCT POINTS = DISTRESS WEIGHT X SEVERITY WT. X EXTENT WT.
REMARKS:

FIGURE 2 Sample PCR form for jointed concrete pavements.

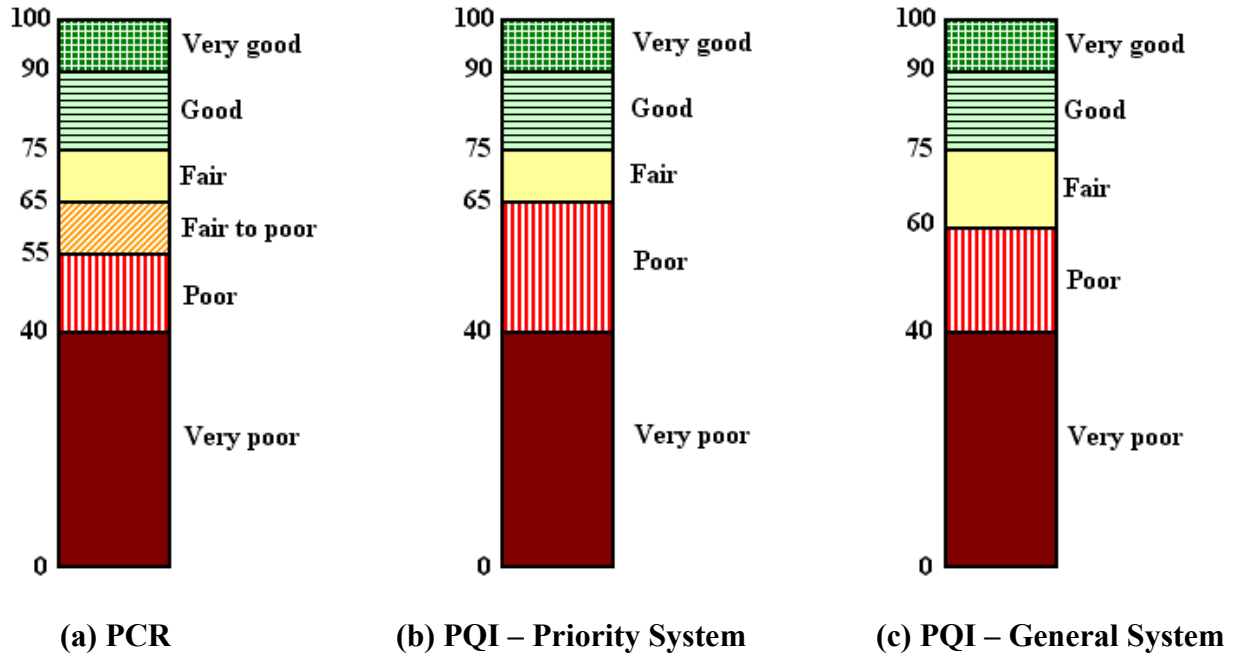(a) PCR   (b) PQI – Priority System   (c) PQI – General System

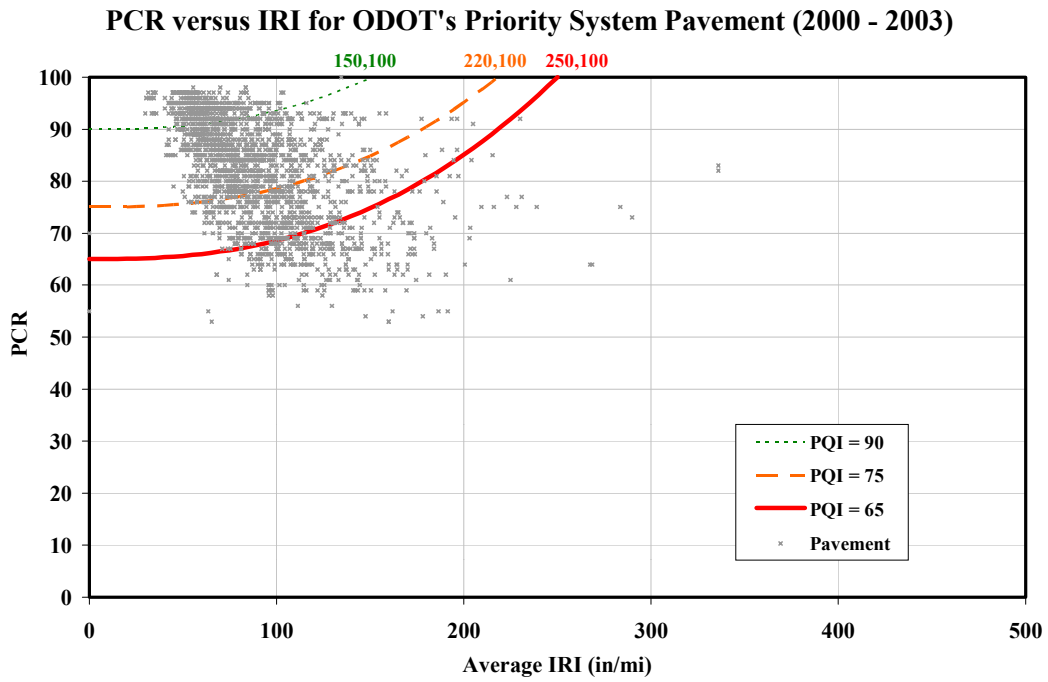**FIGURE 3 Qualitative pavement performance descriptions for each pavement system.**

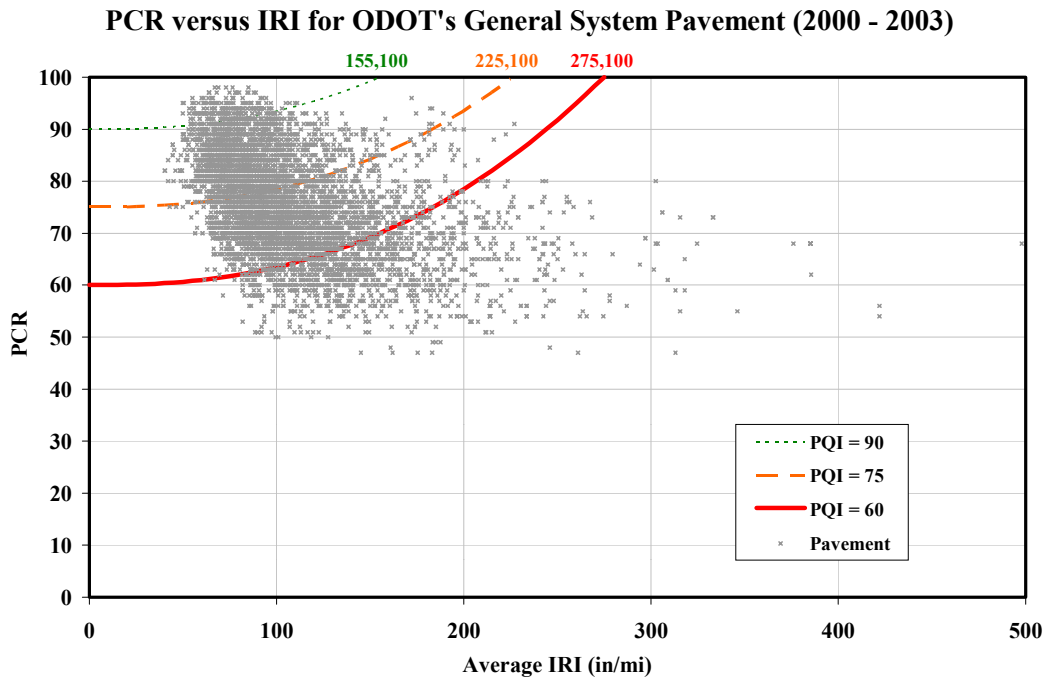**FIGURE 4 PQI curves for ODOT's pavements in the priority system.**

FIGURE 5 PQI curves for ODOT's pavements in the general system.