Effect of Pavement Deterioration Types on IRI and Rehabilitation

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A study of the relationships between present serviceability rating (PSR), international roughness index (IRI), and selected pavement distress types was conducted. A predictive model was developed between PSR and the IRI. Relationships between IRI and selected asphalt pavement and jointed concrete pavement distress types were developed. Some of the distress types have stronger effects on IRI than do others, and the severity of these distresses is also very important. The relationship of IRI to critical levels of rehabilitation was evaluated. It was found that as distress amounts increase in number and in severity, the IRI increases also. It is believed that in addition to IRI, visible distress is an important aspect to proper selection of timing and type of rehabilitation techniques. It is recommended that the Highway Performance Monitoring System utilize both the IRI and selected pavement distress types as trigger values for more consistent and realistic results in predicting future rehabilitation needs on the nation's highways.

The second phase of a research study conducted to develop relationships between the international roughness index (IRI) and pavement condition is documented in this paper. The first phase of this research concentrated on the development of a relationship between IRI and the present serviceability rating (PSR) for pavement types included in the Highway Performance Monitoring System (HPMS) database. A predictive model for PSR as a function of profile IRI was developed for flexible, rigid, and composite (asphalt over concrete) pavements. The results of the first phase have been documented (*1*).

The second phase of this research concentrated on the relationships between IRI and various pavement distress types. In this second phase, data from the Long-Term Pavement Performance (LTPP) database, including IRI and pavement distresses, were analyzed to determine the relationships of key distress types to IRI and critical levels for rehabilitation. These results will be very useful in the HPMS analytical process to achieve improved and consistent estimates of the current conditions and the future highway pavement rehabilitation needs in the United States.

Currently, the states are required to report both IRI and PSR to FHWA. The PSR ranges from 0 (very poor) to 5 (very good). The levels of PSR are defined according to HPMS, which include descriptions of ride quality, physical distress such as cracking, and rehabilitation needs. The PSR is determined by the states, on the basis of this general definition but also by other methods. The PSR concept is important since it is built into the HPMS analytical software and is a vital part of the procedures used to estimate long-term pavement rehabilitation needs. The PSR is also well known in the highway community as an indicator of pavement condition. Visual distress also is a widely used indicator of pavement condition and is strongly related to rehabilitation needs. Not much is currently known about the IRI on the nation's highways, especially critical levels at which pavements should be rehabilitated. If correlations can be made between the objectively measured IRI (an index of pavement profile) and the PSR and visual distress, the IRI could become a more reliable indicator of pavement condition and rehabilitation needs.

CORRELATION OF IRI AND PSR

In the first phase of this research the primary objective was to develop a predictive model for PSR as a function of profile IRI that was applicable to flexible, rigid, and composite (asphalt over concrete) pavements. Relationships between IRI and PSR were analyzed for data from the states of Louisiana, Michigan, New Jersey, New Mexico, and Ohio. These data were obtained from the NCHRP Project 1-23 database, with some additional data obtained from Indiana. Data for all six states were entered into a Statistical Analysis System data set, and the following nonlinear model was found to best fit the boundary conditions and the actual data:

$$\mathrm{PSR} = 5 * e^{(-a*\mathrm{IRI})} \qquad (1)$$

Regression analysis was conducted for all possible sets of data considering different states and pavement types. No significant difference was found between the models for different states and pavement types. Therefore, the following model was recommended for all pavement types:

$$\mathrm{PSR} = 5 * e^{(-0.0026*\mathrm{IRI})} \qquad (2)$$

where IRI is in units of cm/km, or

$$\mathrm{PSR} = 5 * e^{(-0.0041*\mathrm{IRI})} \qquad (3)$$

where IRI is in units of in./mile.

Figure 1 shows the plot of the recommended model with all the data (*3*).

CORRELATION OF IRI AND DISTRESS—ASPHALT-SURFACED PAVEMENTS

Two approaches were followed to analyze the effect of asphalt concrete (AC) pavement distresses on IRI and/or PSR. The first approach used profile and distress data from the available test sections in the Strategic Highway Research Program's Long-Term Pavement Performance (SHRP LTPP) database. The second approach used "manufactured profiles" developed mathematically

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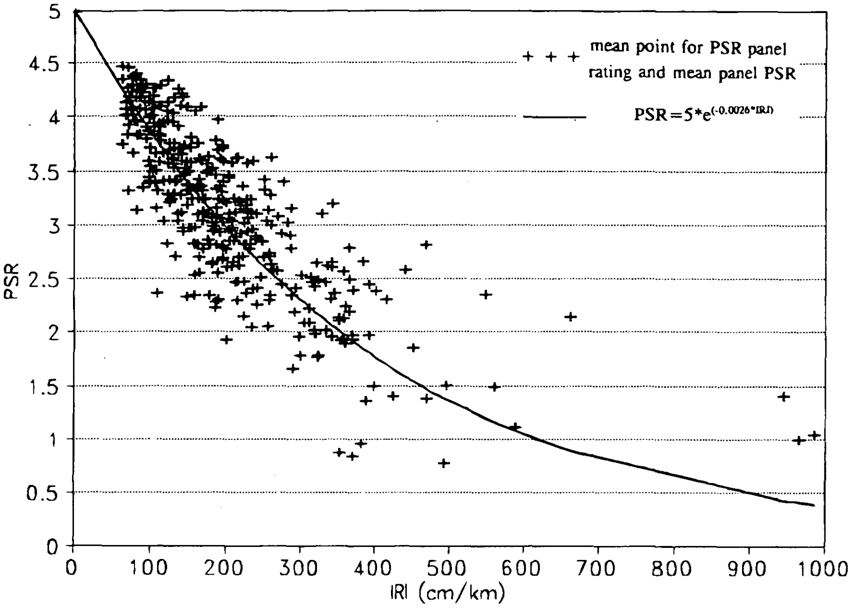

FIGURE 1 PSR versus IRI data and model recommended for all pavement types (*3*).

to incorporate different additional distresses to examine how these distresses affect the values of IRI and PSR. Computation of the IRI for various profiles was accomplished using a computer program named PROFILE, prepared by using standard procedures described by Sayers et al. (*1*).

After summarizing and testing all the available LTPP data, it was found that rutting was the only distress for which a sufficient number of test sections showing distress were available, from which reasonable results were obtained. Very few sections contained fatigue cracking, for example. Rutting was therefore the only distress analyzed on the basis of LTPP data.

Rutting, transverse cracking, potholes, depressions, and combined distresses were analyzed using manufactured profiles. Fatigue cracking was not considered directly in the analysis because there were no distinctive profile characteristics available, and its effect on the pavement profile is already considered as an associated distress with rutting. When fatigue cracking occurs, rutting normally develops also. The effect of each distress on IRI was analyzed first. Then the effect of combined distresses on IRI was determined.

Rutting

Correlation Based on LTPP Data

No significant correlation was found between the IRI and either the average rut depth (RD) or the RD standard deviation when individual pavement sections were considered.

However, when the data were grouped for ranges of IRI and RD means and standard deviations were averaged over these ranges, it was found that the midpoints of IRI for those ranges correlate with both mean RD and RD standard deviation, with R^2 values of 0.93 and 0.94, respectively. The following linear equation was obtained by regression for IRI as a function of RD:

$$\mathrm{IRI} = 57.56 * \mathrm{RD} - 334.28 \quad (4)$$

where IRI is in units of cm/km and RD is in units of mm. This equation gives an IRI of about 250 (PSR = 2.6) if rutting is 10 mm (0.4 in.).

The following linear equation was obtained for IRI as a function of RD standard deviation:

$$\mathrm{IRI} = 136.19 * \mathrm{SD} - 116.36 \quad (5)$$

where IRI is in units of cm/km and SD is in units of mm.

A correlation also was found between average RD and RD standard deviation with an R^2 of 0.80.

Correlation Based on Manufactured Profile Analysis

The LTPP data were reviewed to find sections with no distresses other than rutting. There were a few sections that satisfied this criterion, and three of these were used in the profile analysis with a range of IRI from low to high. The three sections had the following IRI, estimated PSR, mean RDs and standard deviation of RD along the section.

Estimated		*Mean*	*Rut_Depth*
PSR	*IRI*	*Rut Depth*	*Standard Deviation*
4.54	37.5 cm/km	6.46 mm	0.0445 mm
3.37	151.0	8.43	0.0773
2.35	289.9	10.48	0.1175

The PSR values were estimated from Equation 2. Therefore, three sections that contain only rutting with known IRI, mean RD, and RD standard deviation were obtained.

The section having a PSR value of 4.54 (IRI = 37.5 cm/km) and no other distresses is in excellent condition. The profile of this section was used in the remaining flexible pavement analyses to determine the effect of each of the other distresses on the IRI value. This profile will be referred to as the "smooth" profile.

Transverse Cracking (Thermal or Reflection)

To examine the effect of transverse cracking on the value of IRI, the "smooth" profile section was utilized. A typical deteriorated transverse crack with a width of 50 mm (2 in.) and a maximum depth of 25 mm (1 in.) was added to this smooth profile. The effect of transverse cracking on IRI was determined by adding deteriorated transverse cracks to the profile and computing the IRI using the PROFILE software, as shown in Table 1.

It was found that the IRI value increases nearly linearly as the number of cracks in the 50-m (164-ft) section increases.

The specific shape of the transverse crack will have a major effect on IRI. The crack dimensions used in this analysis are typical of cracks that have settled, which would generally be rated as high severity. These results show that high severity transverse cracks have a significant effect on IRI.

Potholes

The effect of potholes on the IRI and the corresponding PSR was determined by adding potholes to the "smooth" profile over a range of frequencies (0, 1, 2, 3, and 4 potholes per 50 m). Each pothole had a diameter of 400 mm (15.75 in.) and a depth of 25 mm (1 in.). The IRI and calculated PSR values are shown in Table 1.

It was found that as the number of potholes in the section increases, the IRI increases in an approximate linear relationship. The specific dimensions of the pothole will have a major effect on IRI. The dimensions used in this analysis are typical of potholes that would be rated high severity. Potholes have a very strong effect on IRI.

Depressions and Swells

The effect of depressions and/or swells on the IRI and the corresponding PSR was determined by adding a number of depressions to the "smooth" profile. The depressions have a depth of 25 mm (1 in.) and a length of 2 m (6.56 ft). After adding the depressions and/or swells to the section, the new IRI and PSR values were calculated as shown in Table 1.

Note that depressions have exactly the same effect as swells since IRI measures the absolute difference between the elevations of the consecutive points. This measurement is not affected by the direction of upward or downward movement. A swell and a depression of the same shape and dimensions will have the same value of IRI.

It was found that as the number of depressions per given length increases, the IRI increases with an approximate linear relationship. The specific shape of the depression and/or swell will have a major effect on IRI. The depression dimensions used in this analysis are typical of depressions that would be rated high severity. These depressions and/or swells have a large effect on IRI.

Combination of Distresses

Most pavements contain more than one distress. Thus, it is desirable to be able to determine the effect of combined distresses on IRI and PSR values. To find the effect of combined distresses on IRI and PSR, the three sections that contain different amounts of rutting with known IRI and PSR values were used. After combining the distresses in different combinations, their corresponding IRI and PSR values were calculated. A set of 81 sections was obtained as shown in Table 2.

Regression analysis was applied to the data to find a model representing the relation between PSR and the combined distresses. Two models were obtained, one considering the mean RD and the other considering the RD standard deviation.

The model that includes mean RD is as follows:

$$\mathrm{PSR} = 4.95 - 0.685\,\mathrm{D} - 0.334\,\mathrm{P} - 0.051\,\mathrm{C} - 0.211\,\mathrm{RD} \qquad (6)$$

where

D = high severity depressions (number per 50 m);
P = high severity potholes (number per 50 m);

TABLE 1 Calculated PSR and IRI Values for Sections with Individual Distresses

Distress	Number per 50 m	IRI (cm/km)	PSR
Transverse Cracking	0	37.5	4.54
	1	52.0	4.37
	2	64.0	4.23
	3	78.3	4.08
	7	129.5	3.57
	15	205.2	2.93
Potholes	0	37.5	4.54
	1	117.7	3.68
	2	191.6	3.04
	3	273.1	2.46
	4	339.3	2.07
Depressions and Swells	0	37.5	4.54
	1	174.9	3.17
	2	335.4	2.09
	3	468.9	1.48

TABLE 2 PSR Values for Sections with Combined Distresses

D	P	C	RD=6.46 SD=4.45	RD=8.43 SD=7.73	RD=10.84 SD=11.75
0	0	0	4.54*	3.37*	2.35*
		3	4.08	3.18	2.23
		7	3.57	2.99	2.11
0	1	0	3.68	2.78	2.13
		3	3.30	2.58	1.95
		7	2.90	2.43	1.85
0	2	0	3.04	2.47	1.83
		3	2.73	2.33	1.72
		7	2.37	2.11	1.60
1	0	0	3.17	2.33	1.82
		3	2.76	2.16	1.67
		7	2.43	2.04	1.58
1	1	0	2.54	1.92	1.56
		3	2.28	1.78	1.43
		7	2.02	1.68	1.35
1	2	0	2.09	1.71	1.36
		3	1.89	1.60	1.28
		7	1.65	1.46	1.19
2	0	0	2.09	1.78	1.21
		3	1.87	1.60	1.11
		7	1.66	1.49	1.06
2	1	0	1.71	1.46	1.10
		3	1.52	1.30	0.98
		7	1.35	1.22	0.94
2	2	0	1.41	1.26	0.94
		3	1.26	1.13	0.86
		7	1.10	1.02	0.81

Where: D = depressions per 50 m
P = potholes per 50 m
C = transverse cracks per 50 m
RD = average rut depth, mm
SD = standard deviation of rut depth, x 100 mm
R^2 = 0.92 & SEE = 0.226 (standard error of the estimate of PSR)

C = high severity transverse cracks (number per 50 m);
RD = average RD (mm);
$R^2 = 0.92$; and
SEE = 0.226 (standard error of the estimate of PSR).

The model that includes the standard deviation of RD is as follows:

$$PSR = 4.151 - 0.685\,D - 0.334\,P - 0.051\,C - 0.127\,SD \qquad (7)$$

where

D = depressions (number per 50 m);
P = potholes (number per 50 m);
C = transverse cracks (number per 50 m); and
SD = RD standard deviation (× 100 mm).

PSR can be predicted for a pavement section if the depressions, potholes, transverse cracking, and average RD (or RD standard deviation) are known and no other distresses exist. As mentioned before, the models assume generally high severity levels for the distresses. Similar models could be developed for IRI.

CORRELATION OF IRI AND DISTRESS—CONCRETE-SURFACED PAVEMENTS

A similar analysis was conducted to determine the effect of several distresses on IRI and PSR of jointed concrete-surfaced pavements. The distresses considered include joint faulting, transverse cracking, and joint spalling. The effects of depressions and/or swells and potholes would be the same on concrete pavements as on asphalt pavements. Joint faulting was analyzed based on both LTPP data and manufactured profiles, while the other distresses were analyzed using manufactured profiles, since the LTPP sections did not have sufficient quantities of the other distresses.

Joint Faulting

Correlation Based on LTPP Data

The following linear equation was developed for IRI as a function of faulting ($R^2 = 0.5$):

$$\text{IRI} = 147.1 + 27.94 * \text{F} \tag{8}$$

where IRI is in units of cm/km and average section faulting F is in units of mm.

However, it is known that those sections have distresses other than faulting, which means that no pure relationship can be found between IRI and faulting.

Correlation Based on Manufactured Profile Analysis

A slab length of 5 m (16.4 ft) was used to find the effect of faulting on IRI and PSR. The depth of the faulting "y" was assumed as a constant value at all slab joints to represent the average faulting in the assumed section. The IRI value for the section was calculated for different values of average faulting. The calculated IRI and its corresponding PSR value are as shown in Table 3.

The following linear relationship between IRI and mean joint faulting was developed for a joint spacing of 5 m (16.4 ft).

$$\text{IRI} = 35.816 * \text{F} \tag{9}$$

Where IRI is in units of cm/km and faulting F is in units of mm.

Comparison of Manufactured Profile Analysis with the LTPP Analysis

The manufactured profile analysis provides a relationship between IRI and mean joint faulting, and the LTPP data provide another relationship. The relationship determined from the manufactured profile is considered to accurately show the effect of joint faulting as the only distress type, while in the LTPP data, joint faulting was not the only existing distress type. By comparing the two relationships, the effect of other profile deviations on IRI may be determined. At each value of mean joint faulting the non-joint faulting share of the IRI can be determined by taking the difference between the two values. This difference decreases as the mean joint faulting value increases. This indicates that as the mean value of joint faulting increases, its effect becomes increasingly larger than the other profile deviations on the calculated value of IRI.

Transverse Cracking

It is impossible, in practice, to find a section of roadway with an IRI of 0 (PSR = 5.0). A new pavement usually has a PSR value of approximately 4.5. Therefore, for this analysis a manufactured profile was produced with a mean joint faulting of 1 mm (0.04 in.), which was found previously to produce an IRI value of 4.06 cm/km and a corresponding PSR value of 4.5. This profile is referred to as the "smooth" profile. Transverse cracking was added to this profile to find its effect on IRI and PSR values. Each transverse crack was assumed to be spalled, with a width of 50 mm (2 in.) and an average depth of 25 mm (1 in.). The transverse crack was placed in the center of the slabs. In addition, each transverse crack was faulted 2.5 mm (0.1 in.), which is typical of high severity cracks. The calculated IRI and PSR values for different percentages of slabs with transverse cracks are shown in Table 4. Joint spacing was assumed to be 5 m (16.4 ft).

It was found that as the percentage of transverse cracking increases, IRI increases with an approximate linear relationship. The specific dimension of the transverse crack will have a major effect on IRI. The crack dimensions and faulting used in this analysis are typical of cracks that would have a medium to high rating of severity.

TABLE 3 Calculated IRI and Corresponding PSR Values

Mean faulting, y (mm)	IRI (cm/km)	PSR
1	35.8	4.50
2	71.6	4.15
4	143.3	3.45
6	214.9	2.86
8	286.5	2.37
10	358.2	1.97

Joint spacing = 5 m (16.4 ft), 1 in = 25.4 mm

TABLE 4 Calculated PSR and IRI Values for Sections with Individual Distresses

Distress Type	(% Slabs/Joints)	IRI (cm/km)	PSR
Transverse cracking	0	40.6	4.50
	20	80.0	4.06
	50	134.5	3.52
Joint Spalling	0	40.6	4.50
	20	75.8	4.11
	50	128.5	3.58

Joint Spalling

The analysis of the effect of joint spalling was conducted using the "smooth" profile, and IRI and PSR values calculated for different percentages of joints spalled. The spalling width across the joint was 100 mm (4 in.) and its depth was 37.5 mm (1.48 in.). The calculated IRI and PSR values are shown in Table 4. The joint spacing used was 5 m (16.4 ft).

It was found that IRI increases approximately linearly as the percentage of joints spalled increases. The specific dimensions of the joint spalling will have a major effect on IRI. The dimensions used in this analysis are typical of spalled joints that would be rated as having high severity.

Combination of Distresses

After determining the effect of each distress on both IRI and PSR values, the effect of combined distresses was determined. The PSR value was calculated for different combinations of distresses, as shown in Table 5.

Regression analysis was performed to find a relationship between PSR and the combined distresses, and the following equation was obtained for a joint spacing of 5 m (16.4 ft):

$$\mathrm{PSR} = 4.115 - 0.01083\,S - 0.00949\,TC - 0.22667\,F \tag{10}$$

where

S = high severity joint spalling (percent of joints);
TC = high severity transverse cracking (percent of slabs cracked);
F = average joint faulting (mm); and
$R^2 = 0.91$
$\mathrm{SEE} = 0.183$.

The PSR can be predicted for a pavement section if the joint spalling, transverse cracking, and average joint faulting are known and no other distresses exist. A similar equation could be developed for IRI.

SELECTING CRITICAL LEVELS OF IRI FOR REHABILITATION

As a pavement ages and is loaded by traffic, distresses such as rutting, faulting, and cracking develop that often adversely affect the longitudinal profile so that the IRI increases and the PSR decreases. Some of the relationships between IRI and distresses were explored in this study and it was found that, all other things being equal, several distress types at their high severity levels have a significant effect on IRI. It is important to point out, however, that at lower severity levels and for a variety of other distresses (e.g., raveling, "D" cracking), the longitudinal profile (and thus IRI) may not be affected very much until a large amount of pavement deterioration has occurred. In other words, a pavement could be relatively smooth and still have a significant amount of distress. If the pavement was not rehabilitated until it became relatively rough (high IRI), the resulting rehabilitation cost might be very large. The amount and quality of maintenance applied to keep distresses at low levels of severity are also a major factor.

The key point to be made is that although the longitudinal profile (as measured by the IRI) may be a good indicator of the highway user ratings (as indicated by the PSR), it may not be a good indicator of when the pavement should be rehabilitated from a structural viewpoint to develop a cost-effective rehabilitation program for pavements relying only on the longitudinal profile (IRI). Visible distress is another important aspect in proper selection of rehabilitation type and timing.

The HPMS analytical software currently uses minimum PSR trigger values for rehabilitation and reconstruction. The trigger values vary depending on pavement functional class and urban or rural location. It is desired to use the IRI and other pavement condition indicators as trigger values for more consistent and realistic results. This is an excellent goal for HPMS to strive to achieve, but there remains a lot of additional research work needed to accomplish it. For example, if rutting were added as a distress in the HPMS database to improve the rehabilitation selection procedure, there would need to be a methodology for predicting rutting into the future so that trigger values could be set for rehabilitation, as trigger values are currently specified for PSR.

With this broader background in mind, this section addresses the potential problem of using only IRI as a trigger value for resurfacing and reconstruction work for different functional classes, pavement types, and urban or rural locations. Both the highway user and the structural integrity of the pavement must be considered. It is well known that some distresses (and severity levels) significantly influence IRI, but there are other important distresses that, at least at lower levels of severity, do not have much effect on longitudinal profile and, thus, IRI. For these types of distresses, to wait until the IRI is at a high trigger value would be to wait too long past the time when the distresses can be repaired cost-effectively. Complete high-cost reconstruction may be required at this point. In the following section some results obtained herein are presented to illustrate these results.

Highway User IRI Trigger Levels

The conventional way of selecting rehabilitation trigger values for PSR is to determine the level at which approximately 50 percent of highway users decide that a pavement ride is unacceptable for a given functional class of highway and pavement type. The upper values in Table 6 are the mean PSR ratings from several studies at which 50 percent of the panel in the study indicated yes or no as an answer to the question: Is the pavement acceptable? As can be seen from the table, there is a difference between the PSR value at which 50 percent of the panel indicated "yes" and the PSR at which 50 percent of the panel indicated "no." This is because some panel raters made no decision about the acceptability of some pavement sections. Also, the PSR trigger values were taken from the best fit of the data or the fraction of the panel stating "yes" or "no" versus PSR. The lower values in Table 6 are the corresponding calculated IRI values, which were calculated from PSR values using Equation 2.

Additional information was obtained in the second phase of NCHRP Project 1-23, in which the following equation was obtained showing that the mean panel rating is a predictor of the public's subjective perception of whether a pavement surface needs repair (*6*):

$$\mathrm{NR} = 131.7 - 33.9\,\mathrm{RN} \tag{11}$$

where NR is percentage of drivers who believe a pavement requires repair, and RN is the riding number, an approximation to the mean panel rating (PSR). By substituting Equation 2 in Equation 11 the following equation is obtained:

TABLE 5 PSR Values for Jointed Concrete Pavement Sections with Combined Distress [Joint Spacing 5 m (16.4 ft)]

Spalling (% Joints)	Transverse Cracking (% Slabs)	Fault=0mm	Fault=2.5mm	Fault=5mm
0	0	4.50	3.45	2.65
	20	4.06	3.38	2.62
	50	3.52	3.27	2.55
20	0	4.11	3.30	2.59
	20	3.69	3.14	2.51
	50	3.19	2.96	2.42
50	0	3.58	3.07	2.48
	20	3.22	2.85	2.38
	50	2.75	2.56	2.22

$$NR = 131.7 - 169.5\, e^{(-0.0026*IRI)} \qquad (12)$$

where IRI is in units of cm/km and NR is as defined before.

This equation results in a *RN* (or approximate PSR) = 2.4 and IRI = 2.81 for the 50th percentile of highway users. Considering all of this information collectively shows that about 50 percent of the highway users believe a pavement is unacceptable when PSR values and corresponding IRI values are at the following levels:

Highway Class	*PSR*	*IRI*	
		cm/km	*in./mile*
Secondary	2.0	352	223
Primary	2.5	267	169
Interstate	3.0+	196+	124

PHYSICAL DETERIORATION OF PAVEMENT IRI TRIGGERS VALUES

Given the above highway user criteria for triggering rehabilitation, what is the consequence of these levels on pavement deterioration and rehabilitation costs? The following data show how the PSR and IRI change for asphalt-surfaced pavements as the amounts of individual distresses change independently. For example, 40 potholes per kilometer would result in an IRI of only 196 and a PSR of 3.0, whereas it requires 24 depressions or swells per kilometer for the same IRI and PSR.

PSR	*IRI*	*Rutting*	*Transverse cracks*	*Potholes*	*Depressions and swells*
2.0	352	11.9	533	84	43
2.5	267	10.5	408	58	32
3.0	196	9.2	283	40	24
3.5	137	8.2	160	26	14

These results show that individual distresses do not reduce the PSR lower than 2.5 to 3.0 (IRI greater than 196 to 267) until a large amount of deterioration is present. For primary and Interstate highways, RDs in excess of about 10 mm (0.4 in.) would generally be considered maximal for preventing hydroplaning, and rehabilitation should be performed, which occurs at a PSR = 2.5 and IRI = 267. There are no such criteria for the other types of distress. However, for PSR less than 2.5 for primary highways and less than 3.0 for Interstate highways, the levels of these distress severity types

TABLE 6 PSR and Estimated IRI (cm/km) at Which 50 Percent of Panel Indicated Yes or No for Acceptability

Data Source	Secondary and Primary Classes Combined				Pavement Types Combined			
	Rigid		Flexible		Secondary		Primary	
	Yes	No	Yes	No	Yes	No	Yes	No
AASHO Road Test (2)	2.9 210	2.5 267	2.9 210	2.5 267	- -	- -	- -	- -
Purdue University (4)	2.2 316	1.5 463	2.2 316	1.7 415	2.0 352	1.5 463	2.4 282	- -
Nakamura (4)	- -	- -	- -	- -	2.0 352	1.5 463	2.5 267	2.0 352
Texas DOT (5)	- -	- -	- -	- -	1.9 372	- -	3.4* 148	- -

**Interstate highway*

appear to be quite excessive. For example, 40 potholes per kilometer is equivalent to an average pothole spacing of 25 m (83 ft).

The other important aspect to note is the relative increase in distress types as the PSR and IRI change from level to level. For example, a PSR decrease from 3.5 to 3.0 corresponds to an increase of 14 potholes per kilometer, whereas a drop in PSR from 3.0 to 2.5 corresponds to 18 additional potholes per kilometer, and 2.5 to 2.0 corresponds to 26 additional potholes per kilometer. This large increase in deterioration would cause a significant increase in maintenance and rehabilitation costs.

Of course, there are many different combinations of these distress types that could also lead to the various levels of PSR and IRI. Equations 6 and 7 may be used to show how a combination of distress types can result in different levels of PSR (and IRI). The following table shows how the PSR and IRI change for jointed concrete pavements as the levels of individual distress change. For example, 89 percent joints spalled would reduce IRI to 196 and PSR to 3.0. It requires 5.5 mm (0.217 in.) mean faulting for the same IRI and PSR.

PSR	*IRI*	*Faulting*	*Transverse cracks*	*Joint spalling*
2.0	352	9.8	100	100
2.5	267	7.5	100	100
3.0	196	5.5	82	89
3.5	137	4.0	50	55

where IRI is in units of cm/km.

These results show that a high level of faulting, cracking, or spalling is required to reduce individually the PSR to below 3.0. As these distresses increase, rehabilitation costs also increase. For example, when the PSRs drop from 3.0 to 2.5, the mean faulting increases from 5.5 to 7.5 mm (0.217 to 0.295 in.), which would increase diamond-grinding costs. Of course, there are many different combinations of these distress types that could also lead to the various levels of PSR and IRI. Equation 10 may be used to show how a combination of distress types can result in different levels of PSR (and IRI).

These results show that for PSR levels typically recommended for triggering rehabilitation based upon the 50th percentile of highway users, a substantial amount of pavement deterioration may be present. These levels may not be the most cost-effective points at which to perform rehabilitation.

The current HPMS PSR trigger values for selection of resurfacing are shown in Table 5 along with the corresponding IRI values (*7*). Also shown in Table 5 are comments on the level of physical deterioration that is expected to exist and whether or not repair at this level appears to be cost-effective.

As can be seen from Table 7, several of the levels of PSR are believed to be too low for cost-effective resurfacing of AC pavements. However, detailed cost studies are needed to actually demonstrate that these levels are too low. As a general guide, a minimum PSR of 3.0 (IRI = 196 cm/km) is recommended for principal arterials and above. A minimum PSR of 2.5 (IRI = 267 cm/km) or greater is recommended for all other classes. If IRI is to be used as a trigger for resurfacing, then it should be set at a reasonably high level to avoid extreme deterioration. Further research into the most appropriate levels based on economic analysis is needed. The relationships provided in this study among PSR, IRI, and visible distresses provide some useful results to assist in that analysis.

CONCLUSIONS

A study of the relationships among PSR, IRI, and selected pavement distress types was conducted. A predictive model was developed between PSR and the IRI in the first phase of this work, as reported by Al-Omari and Darter (*3*). The second phase of the study concentrated on the relationships between IRI and selected asphalt pavement and jointed concrete pavement distress types. For asphalt pavements, correlations were identified between IRI and mean RD, RD standard deviation, potholes, transverse cracks, and depressions and/or swells. For concrete pavements, correlations were determined between IRI and joint faulting, transverse cracking, and joint spalling (depressions and/or swells would be the same as with asphalt pavements). Some of these distress types have stronger effects on IRI than others, and the severity level of these distresses is also very important. Large quantities of some of these distress types could develop without reducing the PSR (or increasing the IRI) below conventional levels for resurfacing, especially if exten-

TABLE 7 HPMS Analytical Process Recommended PSR trigger values (with Estimated IRI) and Comments on Level Pavement Deterioration for Resurfacing

Functional System		PSR	IRI (cm/km)	Physical Deterioration
RURAL	Interstate	3.0	196	Reasonable
	Principal Arterials (ADT>6000)	3.0	196	Reasonable
	Principal Arterials (ADT<6000)	2.8	223	Reasonable
	Minor Arterials (All ADT)	2.4	282	Excessive
	Major Collectors (ADT> =400)	2.0	352	Reasonable
	Major Collectors (ADT<400)	1.8	393	Excessive
	Minor Collectors (ADT> =400)	2.0	352	Excessive
	Minor Collectors (ADT<400)	1.8	393	Excessive
URBAN	Interstate	3.2	172	Reasonable
	Other Freeways, Expressways	3.0	196	Reasonable
	Other Principal Arterials	2.8	223	Reasonable
	Minor Arterials	2.4	282	Excessive
	Collectors	2.0	352	Excessive

sive maintenance was applied that maintained distresses at lower severity levels.

The relationship of IRI to critical levels of rehabilitation was evaluated. As distress quantities increase in number and severity, the IRI increases also. However, a pavement could be relatively smooth and still have a significant amount of distress. If the pavement was not rehabilitated until it became relatively rough (low PSR or high IRI), the resulting rehabilitation cost might be very high.

Although the longitudinal profile (as measured by the IRI) may be a good indicator of highway-user acceptance of the pavement (as indicated by the proportion of a panel of users), it may not be a good indicator of when the pavement should be rehabilitated from a structural viewpoint or from a rehabilitation cost standpoint. Thus, it is not believed possible to develop a cost-effective rehabilitation program for pavements by relying only on the longitudinal profile (or IRI). Visible distress is another important aspect in proper selection of rehabilitation type and timing.

It is recommended that HPMS utilizes both the IRI and selected pavement distress types as trigger values for more consistent and realistic results in predicting rehabilitation needs. Several of the trigger levels of PSR currently recommended in HPMS for resurfacing are believed to be too low for cost-effective resurfacing of AC pavements. Relationships provided in this study among PSR, IRI, and visible distresses provide some useful results to assist in further detailed analysis of this subject.

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