# The Effect of Slab Curvature on IRI Values for Jointed Concrete Pavements

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## Abstract

This paper presents the results of a study showing the effect pavement slab curvature has on International Roughness Index (IRI) values for jointed concrete pavements. A set of idealized curved slab profiles were generated using connected circular arcs having varying lengths and magnitudes of constant curvature covering the range of curvature encountered in real pavements. IRI values are calculated for these profiles and a simple regression equation that approximates IRI for varying slab length and curvature magnitude is presented. The ideal slab curvature vs. IRI trends are then compared to existing profile curvature estimates and IRI data for the LTPP GPS3 test sections for over 1000 profiles. The IRI trends for the ideal profiles match well with the curvature vs. IRI trends for the GPS3 data. A discussion regarding how to fairly take into account varying slab length when analyzing slab curvature data for profiles is provided.

## Introduction

The Federal Highway Administration's (FHWA) Long Term Pavement Performance (LTPP) study is the largest and most comprehensive pavement study ever undertaken. The pavement profile data within LTPP is an excellent large controlled data set of pavement profiles and has great research potential. This study compares slab curvature data from the LTPP GPS3 pavement profiles to hypothetical ideal profiles comprised of repeating constant curvature arcs having varying slab length and curvature magnitude. This data is used to quantify the effect of profile wheel path slab curvature on International Roughness Index (IRI) values for jointed concrete pavements.

Figure 1 shows a pavement elevation profile from the LTPP GPS3 pavement group for a rough JPCP, which has unusually high locked-in curvature in the slabs. It is the GPS3 test pavement identified as 55-3009, which was very rough and faulted at less than ten years old. Site 55-3009 is the test pavement with the most rapid development of roughness (International Roughness Index) in the FHWA's LTPP GPS3 jointed concrete pavement research data. The elevation difference between the

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joint and center slab along the wheel path is as high as 10 mm (0.4 inches) for slab lengths of about 5.5 m (18 feet). Temperature gradients (curling effects) required to cause this much uplift at joints for a flat slab would be around +0.22 C°/mm (10 F°/in) from the slab surface downward. For a flat 254 mm (10-inch) thick slab, the top of slab would have to be about 67 C° (120 F°) cooler than the bottom, an unrealistic thermal gradient (Byrum, 2001a). It is a combination of long-term creep, warping, and construction related locked-in curvature that caused such large overall curvature to develop in the pavement slabs shown in figure 1. By the 1920's, Westergaard had noted that based on the general understanding of concrete shrinkage existing at that time, warping curvatures equivalent to that caused by temperature gradients of 0.11 C°/mm (5 F°/in) were possible (Westergaard, 1927). Obviously, locked-in curvatures in slabs can be many times greater than curvature caused by typical weather related temperature gradients, which are typically less than about ±0.07 C°/mm (3 F°/in). It is well known that high degrees of locked in curvature in concrete pavement slabs will lead to premature deterioration of the slabs.

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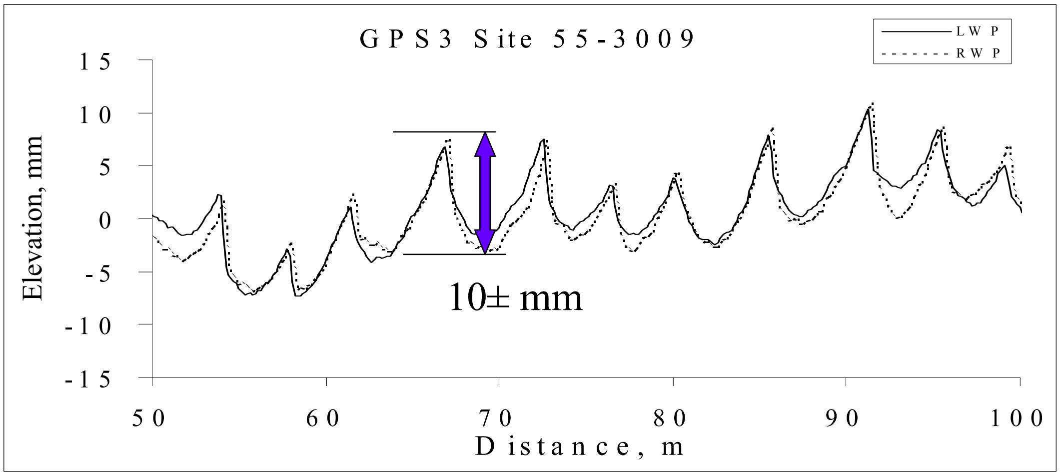

NOTES:
1. Highest IRI of all GPS3 pavements less than 10 years old.
2. High faulting at an early age.
3. Sandy clay subgrade (PI=14.5, w%=13), sand and gravel with 11% P200 base.
4. Built in 1984, 300-350 KESAL/yr, 220 mm PCC, no dowels.
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**Figure 1.** Profile data from a GPS3 JPCP with large curvature.
(average curvature for the 152.4 m profile ≈ 1.62 1/mx1000)

In the 1940's, Hveem referred to slabs having significant locked-in upward warped shape as "man-made pumping machines" susceptible to faulting (Hveem, 1951). Although it has long been accepted that slab shape factors affect long-term performance, clear statistical trends showing the relative contributions slab curvature on IRI have not been established. This fact and because IRI is the roughness statistic used by FHWA to track the overall condition of the United States of America's freeways were the motivating forces for this research. This research uses the FHWA LTPP GPS3 pavement profile data to perform one of the first known studies showing the effect of average slab curvature on IRI values

## Effect of Pure Curved Slab Wheel Paths on IRI Values

Figure 2 shows a set of idealized pavement profiles used for this study. The profiles shown consist of repeating connected segments of circular arcs all having constant curvature magnitude of 0.00231 $m^{-1}$ (0.000065 $ft^{-1}$) simulating up-warped pavement slabs. It is important to note that for the same magnitude of slab curvature, longer slab lengths result in more joint uplift and steeper slopes at joints. The mid-slab to joint elevation differences for the 4.9 m, 6.1 m, and 7.3 m (16-ft, 20-ft and 24-ft) slabs are 6.4 mm, 9.9 mm, and 14.2 mm (0.25-in, 0.39-in and 0.56-in), respectively, increasing as a function of length squared. Slope values near the joints are about 0.50%, 0.63%, and 0.76%, respectively, increasing linearly with slab length. For this study, profiles made of the three arc (slab) lengths were generated with varying magnitudes of arc segment curvature. For each slab length, idealized repeating arc segment profiles with curvature magnitudes of 0.000164, 0.000656, 0.001148, 0.001640, and 0.002133 $m^{-1}$ (0.00005, 0.0002, 0.00035, 0.00050, and 0.00065 $ft^{-1}$) were developed. These three slab lengths shown all have a common repeating pattern length of 73.152 m (240 feet). The ideal profiles analyzed were 146.304 m (480 feet) in length, which includes two of the common repeating pattern segments.

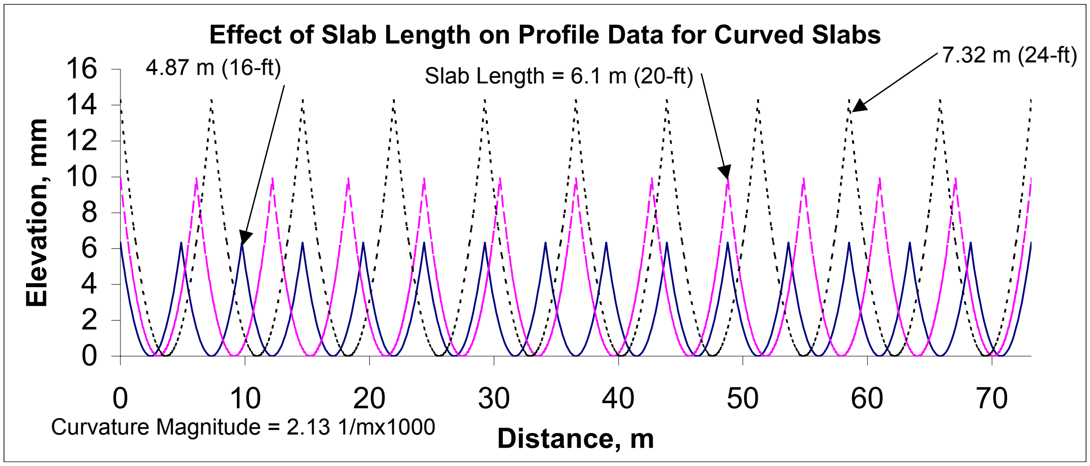


**Figure 2.** Idealized profile elevations for jointed concrete roadways having varying slab length with constant wheel path curvature magnitude.

IRI values were then calculated for all of the idealized profiles. Figure 3 shows the resulting IRI trends for the three slab length classes, for increasing magnitudes of curvature. The IRI model responds linearly to increasing slab curvature for a given slab length. IRI increases roughly exponentially with respect to slab length at a constant curvature magnitude.

The 15 data points shown in figure 3 were used to develop an equation to predict IRI caused by slab curvature for slab curvature magnitude and slab (arc) length combinations. The following simple regression expression can be used to predict the idealized IRI for any combination of slab length (4m<length<8m) and wheel path curvature magnitude:

$$\text{IRI}_{\text{curvature}} = 0.5945(\textit{Curvature Magnitude})e^{0.1595(\textit{Arc Length})}$$

Where,

$\text{IRI}_{\text{curvature}}$ = International Roughness Index of idealized repeating arcs, m/km.
*Curvature Magnitude* = repeating arc (slab) curvature in units of 1000/m.
*Arc Length* = Length of the repeating arcs (slabs) in meters (4 m < L < 8 m).
*e* = 2.7182818245904, the base of the natural logarithm.

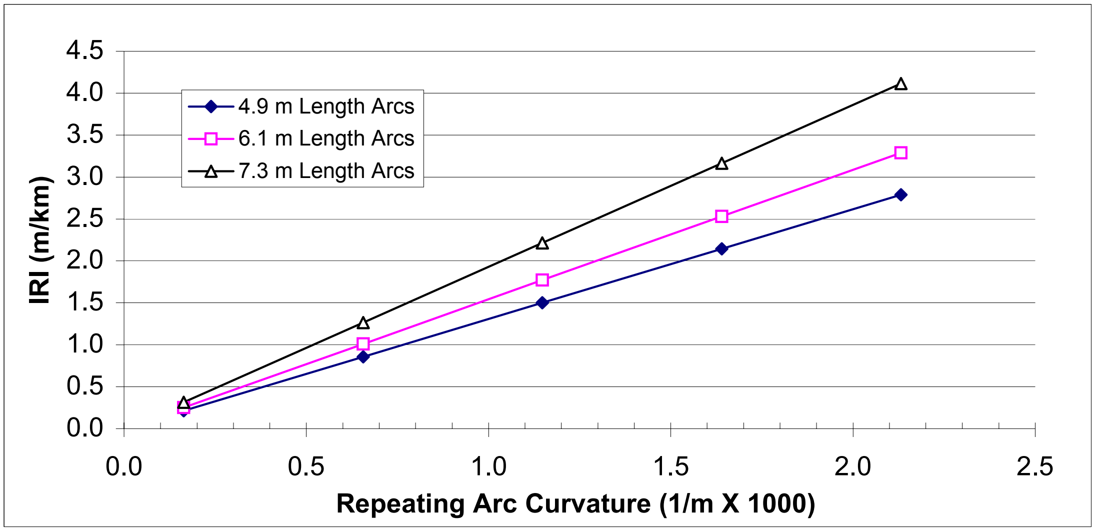
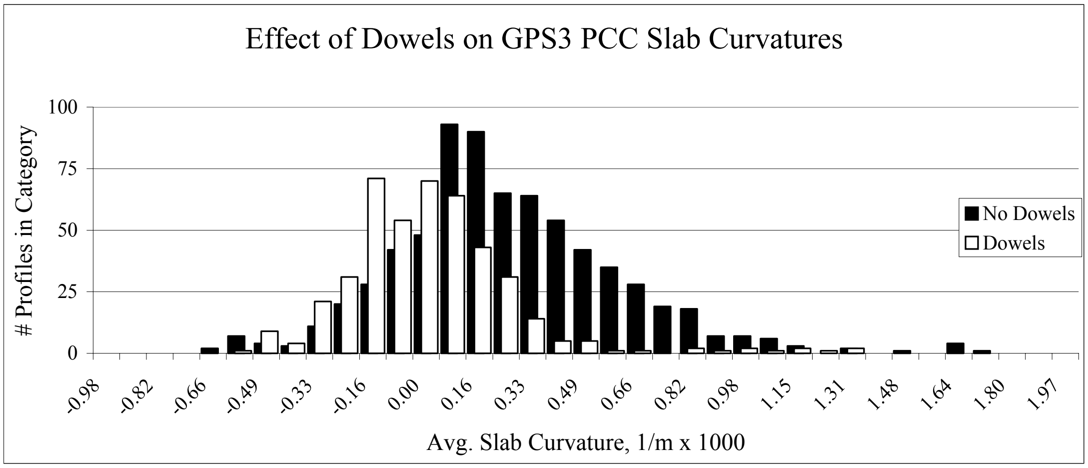


**Figure 3.** Resulting IRI trends for the idealized repeating arc profiles.

## Curvature in the LTPP GPS3 Jointed Concrete Pavements

The author has developed a method for obtaining what is referred to as the Curvature Index, CI, for road profile data (Byrum, 2001a; Byrum, 2001b; Byrum, 2001c; Byrum, 2004). The CI provides an estimate of the average slab curvature present within a 152.4 m (500-ft) pavement profile sample. The method used for establishing the curvature index is described elsewhere and is based on establishing the frequency distributions of finite difference arc curvature magnitudes for the continuous profile segments between obvious cracks and joints, using many arc samples ranging from 0.305 m to 2.438 m (1-ft to 8-ft) in length. Curvature statistics were obtained for most of the 152.4 m (500-ft) long LTPP GPS3 and GPS4 jointed concrete pavement profiles obtained during the 1990's. The overall curvature index for a given profile is the average of several arc sampling methods for estimating the slab segment curvatures. These curvature statistics are summarized below and compared to the reported IRI values for the profiles.

Figure 4 shows the frequency distributions for average slab curvatures observed in the GPS3 pavement test sections. The plot is broken down into two distributions, one for doweled pavements and one for pavements with no dowels at joints. The addition of dowels at joints provides restraint to the development of slab curvature and faulting. Pavements without dowels have a greater tendency to develop an upward warped shape, where the joints are lifted relative to the interior portion of the slabs. Notice that both of the frequency distributions do not have mean values in the downward curved (negative) region even though the pavement profiling was typically performed during daytime conditions. Given that thermal gradients during daytime conditions are almost always warm on top, the frequency distributions show that there is a general condition of locked in upward curvature for both doweled and non-doweled jointed concrete pavements, because the average values are about zero (flat) for doweled pavements, and about 0.00066 $m^{-1}$ (0.0002 $ft^{-1}$) for slabs without dowels. Note how the negative curvature sides of the two frequency distributions are similar, where as the positive curvature sides of the distributions are significantly different. The primary effect that dowels have on slab curvatures is to



| **No Dowels** | LCI | RCI |
|---|---|---|
| Minimum | -0.68 | -0.68 |
| Maximum | 1.62 | 1.70 |
| Average | 0.21 | 0.22 |
| Std Dev | 0.34 | 0.35 |
| Count | 351 | 351 |

| **Dowels** | LCI | RCI |
|---|---|---|
| Minimum | -0.54 | -0.61 |
| Maximum | 1.30 | 1.28 |
| Average | -0.03 | -0.02 |
| Std Dev | 0.27 | 0.26 |
| Count | 218 | 218 |

LCI = Left wheel path average curvature
RCI = Right wheel path average curvature

**Figure 4.** Frequency distributions for average slab curvature in the wheel paths for each of the GPS3 pavement profiles, along with summary data for doweled and non-doweled jointed concrete pavements.

reduce the chance of developing unusual upward slab curvature and lifted joints. This effect along with the load transfer provided by the dowels will significantly reduce the rate at which faulting develops at joints between slabs. This GPS3 frequency data can be used for reliability modeling of curvature in jointed plain concrete pavements.

## Results

Figure 5 shows the overall scatter plot for GPS3 IRI vs. the average 1.219 m (4-ft) long moving arc based slab curvature estimates. A key point regarding figure 5, is that pavement deterioration is represented by upward vertical movement within the scatter data. When analyzing a scatter plot for pavement data, it must be understood how aging is present within the plot trends. The most significant trend from this scatter plot is the lower boundary trend, which represents smooth younger pavements with low amounts of other types of age related roughness features. Fitting a trend line through the center of mass of this data is not of much use. That trend would constantly change as the pavements age and more data points are accumulated in the higher IRI region of the plot. When a pavement has no other roughness except slab curvature, the IRI values would be down near the lower boundary and roughly along the ideal pure curvature lines. Then as faulting and other deformations develop in addition to curvature, IRI will increase above the curvature only trend lines shown. Please note that the lines representing the ideal slab curvatures shown in figure 5 all initiate from an initial IRI of about 0.5 m/km (32 in/mi). This value of 0.5 m/km (32 in/mi) is the apparent lower bound for the initial IRI values for the LTPP GPS3 at a zero curvature condition and was added to the trend lines shown in figure 3 prior to plotting them in figure 5. This value of 0.5 m/km (32 in/mi) is the apparent GPS3 lower bound for the contribution to IRI from the typical jointed concrete pavement texture and construction techniques used to build the test sites. Actually, each individual roadway has its own unique initial “zero-curvature and zero-faulting” roughness level, and the curvature vs. IRI trend lines branch off from that point based on the effective slab lengths.

The lower boundary trend line generally follows the ideal 5-meter (16.4-ft) arc trend for low values of curvature and eventually ends up following the ideal 4-meter (13.1-ft) arc trend line for high curvature magnitude. This makes sense because about 60% of the LTPP GPS3 pavement test sites have slab lengths between 4.26 meters and 5.18 meters (14 feet and 17 feet), with an average slab length of 5.1 meters (16.6 feet). The LTPP GPS3 test sections have slab lengths ranging from 3.47 m to 9.14 m (11.4 feet to 30 feet) with only 13% of test sites having joint spacing less than 4.26 meters (14 feet). The observed lower boundary trend for the author’s 1.219 meter (4-ft) arc based LTPP GPS3 slab curvature estimates vs. IRI data set is what would be theoretically expected given the slab lengths used in the GPS3 pavements.

Real pavement slab wheel paths wont respond to gradients quite like ideal constant curvature arc segments. As thermal and moisture gradients develop that would cause curvature, pure constant curvature over the slab area would only develop in a zero-gravity and zero edge restraint condition. In the presence of gravity, the slabs are pressed against the earth and the middle portions of the slabs have reduced curvature and increased internal stresses. The bending stress can be considered anti-curvature in this case, where the flattened interior portions of slabs exposed to gradients are stressed (Westergaard, 1927; Byrum & Hansen, 1994). These flatter middle portions of slabs result in regions of lesser curvature and lesser joint uplift compared to the ideal pure arc curvature profiles. The greater the curvature causing forces become, the greater percentage of those forces that get expressed in the form of stress rather than curvature. Only short slabs can maintain high levels of average slab curvature. For longer slabs, a greater percentage of the slab area will be stressed and flattened. This general behavior could explain the general downward curvature for the lower boundary trend line observed for the real pavements compared to the ideal arc curvature profiles. The lower boundary trend line shown is unique to the LTPP GPS3 data set and is based on the slab lengths within.

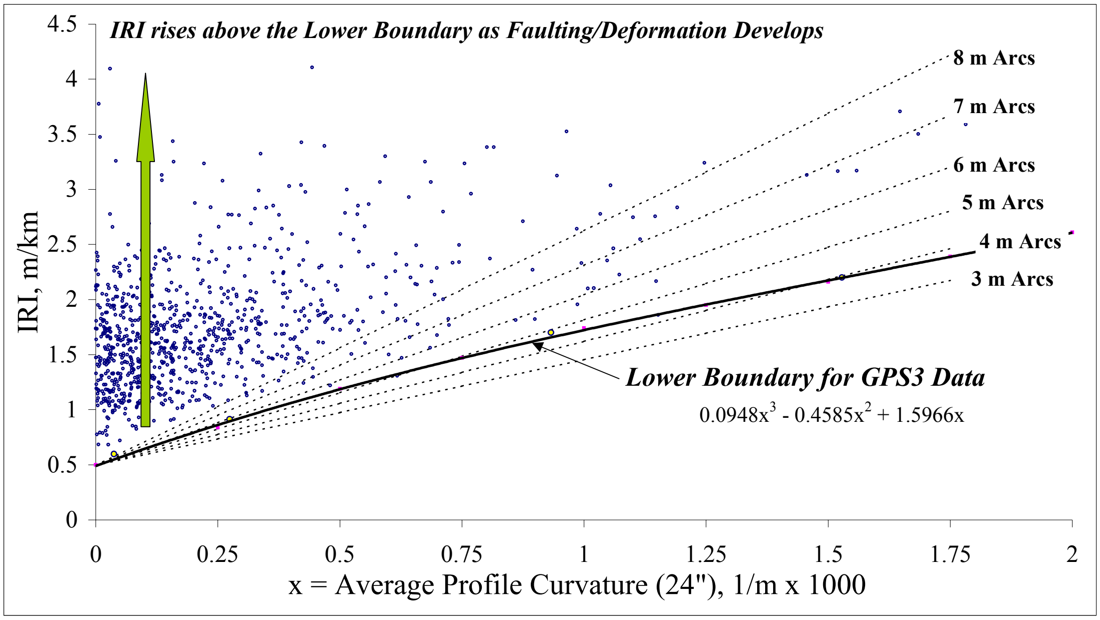


**Figure 5.** Scatter plot for the LTPP GPS3 1.219 m (4-ft) arc length based profile curvature magnitude compared to the profile IRI values and showing the ideal arc curvature profile IRI trends and the lower boundary trend for the LTPP GPS3 pavements.

Figure 5 demonstrates an important difficulty with accounting for slab curvature for initial smoothness specifications and profile evaluations in general. Pavement design engineers use a wide range of slab lengths. For a constant magnitude of curvature, IRI values will be higher for longer slabs compared to shorter slabs. If, for example, a contractor uses the same construction techniques on two roadway segments having two different slab lengths, and then equal magnitudes of construction related curvature are locked in to the slabs, the pavement segment with longer joint spacing would have higher IRI than the one with short joint spacing. This difference in IRI is not at all related to the contractor, but is related to the designer's joint spacing. Would it be fare to hold these two pavement segments, one with shorter slabs and one with longer slabs, to the same IRI smoothness bonus/penalty scheme? Is it necessary to adjust the bonus/penalty scheme as a function of the design joint spacing? It is not the purpose of this paper to answer these questions, but to provide clear data regarding these issues.

Figure 5 also shows a key observation regarding loss of serviceability for a roadway when significant slab curvature is present. Notice that regardless of the magnitude of slab curvature present, there are no roadways with IRI greater than about 4 m/km (250 in/mi), a typical limiting threshold for allowable roughness for highways. Pavement segments with high locked in curvature in slabs will have higher initial IRI values and, therefore, a smaller range of serviceability available between initial construction and the end of useful service life. There is also much evidence available that if large locked in slab curvature is present, premature cracking and faulting will occur for the roadway segment indicating more rapid loss of the already diminished available serviceability (Byrum, 2001a, 2001b; Westergaard, 1927; Hveem, 1951; Byrum & Hansen, 1994; Sixbey et al, 2001; Hansen et al 2002, Byrum, 2004). Locked in slab curvature of high magnitude must be avoided.

To summarize this discussion on the effect that slab curvature has on IRI values, consider drawing the general shapes of the positive sides of the frequency distributions shown in figure 4, onto the ideal IRI vs. curvature trends shown in figure 3. This allows a view of the relative percentages of pavements being affected by slab curvature of varying magnitudes. About 85% of the GPS3 pavements with non-reinforced joints having no dowels have locked in curvature values less than about 0.00065 $m^{-1}$ (0.0002 $ft^{-1}$). The IRI due to slab curvature for these flatter 85% of test sections without dowels will be between about zero m/km and 0.8 m/km (up to about 50 in/mi) .

Doweled pavements have reduced measured slab curvature values. About 85% of the GPS3 pavements with reinforced doweled joints have locked in curvature values less than about 0.00035 $m^{-1}$ (0.00011 $ft^{-1}$). The IRI due to slab curvature for these flatter 85% with dowels at joints will be between about zero m/km and 0.5 m/km (up to about 32 in/mi).

The IRI values from slab curvature for the two high values in the doweled and non-doweled pavements (0.0013 $m^{-1}$ (0.0004 $ft^{-1}$) and 0.0017 $m^{-1}$ (0.00052 $ft^{-1}$), respectively) are about 2 m/km and 2.5 m/km (125 in/mi and 160 in/mi), respectively. For the flatter 85% of the GPS3 test sections, adding dowels at joints will apparently reduce potential slab warping by about 40% to 50%. In extreme cases, IRI from slab curvature can reach 2.5 m/km (160 in/mi). Extreme locked in curvature can develop in both doweled and non-doweled slab systems.

## Conclusions

This paper presents a detailed comparison of the International Roughness Index (IRI) trends for ideal repeating arc profiles and the observed curvature vs. IRI trends for the LTPP GPS3 jointed concrete pavement profiles. The study quantifies the effect that slab curvature has on jointed concrete pavement IRI values.

Frequency distributions describing the magnitude of average slab curvature encountered in the LTPP GPS3 jointed concrete pavements are provided, which can be used for reliability modeling of jointed concrete pavements. Practicing pavement engineers and researchers can compare their measurements of slab curvatures from in service pavements to these frequency distributions to assess the relative severity of the curvature observed.

Ideal repeating arc profiles were developed covering the range of curvature and slab lengths observed in typical GPS3 type jointed concrete pavements. IRI values are calculated for the ideal profiles and a regression model developed from the results, which can predict the IRI caused by typical combinations of slab curvature and slab length. These ideal trends for IRI vs. slab curvature are compared to the LTPP GPS3 scatter plot for 1.219 m (4-ft) arc based slab curvature (Byrum, 2001a) vs. IRI. The ideal profile trends match well with the GPS3 data trends. The lower boundary IRI vs. slab curvature trend from the LTPP GPS3 data matches the ideal curved profile trends for 4-meter to 5-meter (13.1 to 16.4 feet) long constant curvature arc profiles, which matches the joint spacing for the majority of the GPS3 test sections.

For any constant magnitude of slab curvature, IRI increases exponentially with increasing slab length. Therefore, two pavement sections, one with short joints and one with long joints, constructed in the same way under the same environmental conditions could have significantly different initial IRI values if slab curvature develops. This would not be the result of the contractor's actions, but is the result of a design decision put in place long before construction. This joint spacing effect should be considered in initial smoothness specifications having very high smoothness requirements that can be affected by typical locked in slab curvature values.

Maximum slab curvature is different than wheel path curvature. A road profiler moving at high speeds is measuring the "wheel path view" of slab curvature. The curvature measured along a wheel path is a subdued and distorted image of the maximum slab curvature. Slab curvature is generally a radial-symmetric phenomenon occurring radial outward from the centroid of the slab area. In the presence of gravity, curvature is generally never constant over a slabs area, as self-weight stress will tend to keep the middle portions of slabs flatter than the edges, especially free edges. Maximum slab curvature is best estimated by profiling diagonally across an individual slab, from a slab corner, through the center of the slab area, and across to the opposing corner. Wheel path curvature magnitudes will generally be less than the maximum slab curvature magnitude. All the data in this study is from high speed profiling devices and is, therefore, referring to the slightly subdued "wheel path view" of slab curvature. However, this is the vector component of the slab elevation that the moving vehicle will actually experience, and which is contributing to the IRI values. The range of maximum slab curvatures is, therefore, slightly greater than the wheel path curvature frequency distributions shown in this paper.

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