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EVALUATING THE EFFECTS OF CONCRETE PAVEMENT CURLING AND WARPING ON RIDE QUALITY

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16. Abstract

Construction of a jointed concrete pavement on US 34 near Greeley, Colorado in 2012 led to an investigation of slab curling and warping that appeared to be contributing to undesirable levels of pavement roughness. Specifically, the westbound lanes that were constructed in July appeared to exhibit significantly higher roughness than the eastbound lanes that were constructed in September. Furthermore, smoothness testing by the contractor at three different times of the day on one of the westbound lanes revealed significant differences in roughness values depending on the time of day. In response, CDOT initiated the investigation under this study to determine the effects of slab curling and warping on ride quality for the US 34 project with the expectation that the findings from this study can also be applied to jointed concrete pavement projects in general. The outcomes of this study are recommendations for improvements in construction practices to help minimize the effects of curling and warping on jointed concrete pavement ride quality as well as recommendations for the collection of ride quality data for acceptance.

Implementation

Implementation recommendations include potential modifications to concrete pavement construction practices and/or specifications, particularly for hot weather paving, as well as recommendations for modifications to the collection of pavement smoothness acceptance data for jointed concrete pavements. The recommendations for smoothness acceptance data collection can be implemented on pilot projects or as shadow specifications in the coming construction seasons. After each construction season, the recommended procedures can be further evaluated before being included in the Standard Specifications. Recommendations for construction practices/specifications are less substantial and may only require minor modifications to standard practices and specifications.

17. Keywords
jointed concrete pavement, pavement smoothness, slab curvature

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EXECUTIVE SUMMARY

Construction of a jointed concrete pavement on US 34 near Greeley, Colorado in 2012 led to an investigation of slab curling and warping that appeared to be contributing to undesirable levels of pavement roughness. Specifically, the westbound lanes that were constructed in July appeared to exhibit significantly higher roughness than the eastbound lanes that were constructed in September. Furthermore, smoothness testing by the contractor at three different times of the day on one of the westbound lanes revealed significant differences in roughness values depending on the time of day.

In response to the above observation, CDOT initiated the investigation under this study to determine the effects of slab curling and warping on ride quality for the US 34 project with the expectation that the findings from this study can also be applied to jointed concrete pavement projects in general. The outcomes of this study are recommendations for improvements in construction practices to help minimize the effects of curling and warping on jointed concrete pavement ride quality as well as recommendations for the collection of ride quality data for acceptance.

For this investigation, profile data were collected on the US 34 project for in-depth analysis. Profile data were collected during two site visits, one in the winter and one in the summer, to examine the effects due to extreme seasonal conditions. During each site visit, profile data were collected at four different times during the day to cover daily temperature extremes. The intent was to identify changes in slab curling that were occurring over the course of a given day as well as from season to season. During the profiling survey, temperature sensors were installed in the pavement slab at different depths in order to measure temperature gradients across the slab thickness. In situ temperature gradient, slab built-in curling, joint restraint, and slab-base friction all affect slab curling.

Several different analyses were performed on the profile data and construction information from the project. The most valuable information resulted from quantifying slab curvatures from the profile data and correlating curvature to roughness using ProVAL and the Second Generation Curvature Index (2GCI) curvature-fitting tool developed under a previous FHWA curl/warp study. Additionally, HIPERPAV was used to compute slab temperature gradients at construction and to evaluate alternative scenarios to help minimize slab curling.

Based on the above analyses, the difference in roughness between the westbound and eastbound lanes was not significant. On the other hand, the effects of diurnal (or changes during the day) slab curling on roughness were very significant for both the eastbound and westbound lanes. Up to 40 in/mi of roughness can be attributed to slab curling on the US 34 project. These drastic effects of slab curling on roughness over the course of a given day emphasize the need for changes to practices for collection of pavement smoothness data for acceptance. The findings from this study also highlight the need for modifying construction requirements during hot weather to minimize slab curling. Thus, recommendations were made for modifications to existing construction

practices/specifications for jointed concrete pavements as well as recommendations for modifications to collection of smoothness acceptance data.

IMPLEMENTATION STATEMENT

Recommendations are provided for modifications to concrete pavement construction practices and/or specifications, particularly for hot weather paving, as well as recommendations for modifications to the collection of pavement smoothness acceptance data for jointed concrete pavements. The recommended profile data collection method includes: 1) Collect profile for acceptance during at least two times of the same day to cover extreme temperature conditions; 2) Set acceptance thresholds for ride quality based on two parameters, a) average roughness for the two profiles that were collected at different times of the day, and b) maximum absolute difference in roughness between the two profiles.

The recommendations for smoothness acceptance data collection can be implemented on pilot projects or as shadow specifications in the coming construction seasons. After each construction season, the recommended procedures can be further evaluated before being included in the Standard Specifications. Recommendations for construction practices/specifications are less substantial and may only require minor modifications to standard practices and specifications.

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BACKGROUND AND INTRODUCTION

In 2012, a section of US Highway 34 near Greeley, Colorado was reconstructed between approximate mileposts 113.4 to 115.3, as shown in Figure 1. The existing asphalt concrete pavement was replaced with a new 9-inch-thick jointed plain concrete pavement (JPCP). The westbound (WB) lanes, constructed in July 2012 exhibited noticeably different ride quality from the eastbound (EB) lanes, constructed in September 2012, and CDOT was seeking to understand the cause of this difference in ride quality for a pavement constructed with an identical design and materials. Slab curling and warping were suspected to be the primary cause of the difference in ride quality, and this study was initiated to determine whether this was the case or not. In addition, CDOT is seeking recommendations for changes to existing jointed concrete pavement construction and profile data collection practices to mitigate this issue on future projects.

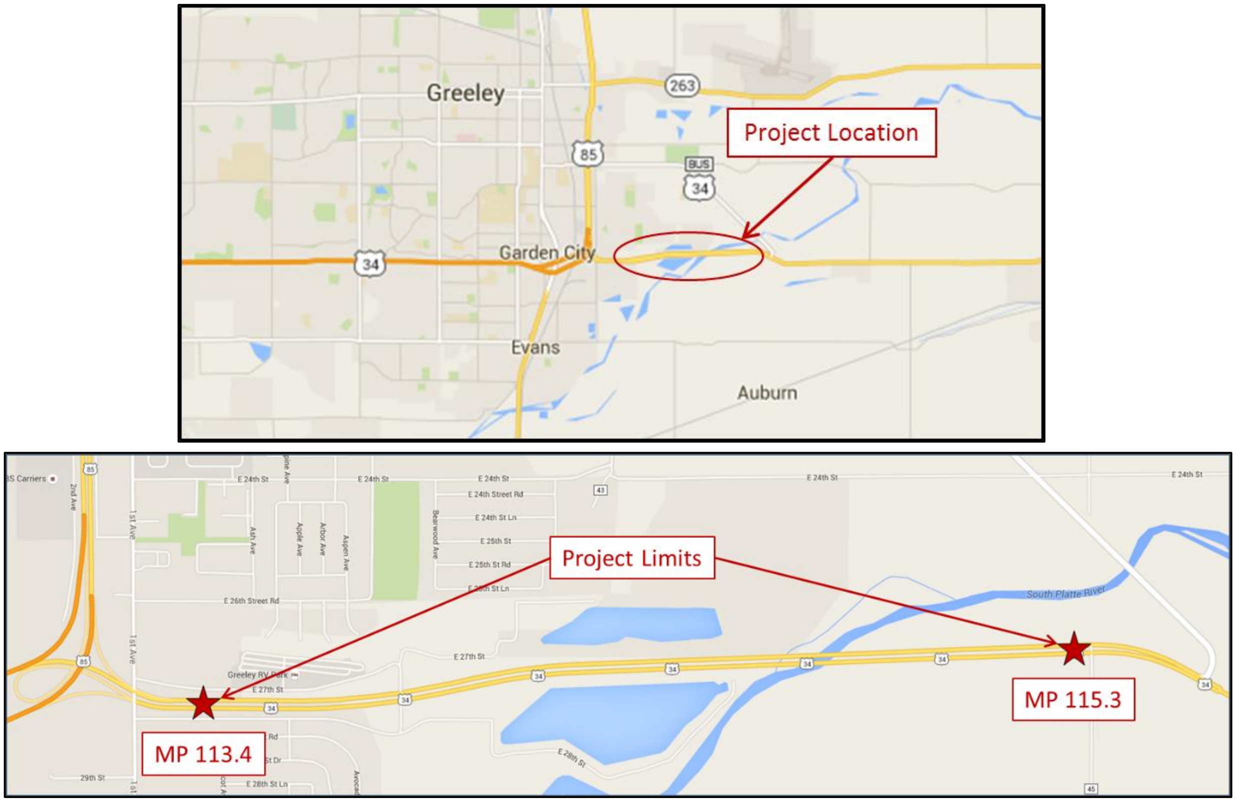

Figure 1. Location of the US 34 curling and warping study site.

Jointed Concrete Pavement Curling and Warping

Curling and warping of jointed concrete pavement slabs is a complex issue, and still not fully understood within the concrete pavement industry to the point where accurate predictions of its effect on pavement smoothness can be made. The two primary factors which affect curling and warping are temperature and moisture gradients, or differentials in temperature and moisture between the top and bottom of the slab. Although terminology is used interchangeably throughout current literature, curling is generally associated with the effects of temperature gradients and warping with moisture gradients. For the purposes of this report, curling and warping will be referred to as simply *curling* herein. Regardless of the cause, curling and warping deformations of jointed concrete pavement slabs effectively impose a curvature on the slab, which can significantly affect ride quality of the pavement.

The phenomenon of "built-in" slab curling, while well documented, is still difficult to predict with certainty. Built-in curling is effectively a permanent curling propensity of the concrete slab resulting from temperature and moisture gradients over the depth of the slab when the concrete reaches final set, or transitions from a plastic to hardened (elastic) state. If the top of the slab is warmer than the bottom at final set, a negative built-in temperature gradient will result, meaning that when the temperature gradient is zero the edges of the slab will curl upward as if the top of the slab were cooler than the bottom (i.e., a negative temperature gradient). The converse occurs when the bottom of the slab is warmer than the top at final set, leading to a downward-curled slab shape from a positive built-in temperature gradient. Effects of moisture gradients almost always result in a negative built-in gradient as the bottom of the slab generally stays moist while drying shrinkage occurs at the top of the slab due to evaporation of moisture from the pavement surface, resulting in differential shrinkage strain and a curled-up shape. Moisture-related curling is commonly quantified as an effective (negative) temperature gradient for simplicity.

The built-in effects of temperature and moisture gradients can effectively cancel each other out, but more often are additive, resulting in an overall curled-up slab shape. For pavement design using the AASHTOWare Pavement ME software, the default value for "permanent curl/warp effective temperature difference" which accounts for both temperature and moisture effects, is -10°F (Vandenbossche, 2011).

Dowelled joints can help restrain curling, and creep effects can reduce curling stresses as movement is restrained, but curling has also been documented to increase over the life of the pavement (Karamihas, 2012) due to creep deformation caused by sustained moisture gradients where the bottom of the slab remains moist while the top goes through continual wetting and drying cycles.

While the slab temperature gradient changes over the course of a day with changes in ambient temperature, moisture gradients generally remain constant (in the absence of precipitation). Therefore, diurnal changes in slab curling are generally the result of changes in temperature gradients only. These changes in slab curling can have a significant impact on pavement smoothness, as will be discussed with regard to the US 34 project herein.

US 34 Project Background

Initial concerns about the effects of slab curling on ride quality were raised after ride quality values for profile data collected by the contractor, and values collected by CDOT on the same section of pavement were substantially different. Testing of a calibration site by both profilers at the same time confirmed that both profilers were measuring the same values and functioning properly. Table 1 shows an example (three 0.1 mi. lots) of the difference between roughness values from contractor testing and CDOT testing over a section of the WB Lanes (note: LWP = left wheelpath, RWP – right wheelpath). The CDOT values were collected in the early morning on two consecutive days, giving the same results. The contractor tests were run in the afternoon. Note that CDOT results are reported as half-car roughness index (HRI) and contractor results as mean roughness index (MRI). The difference between the contractor and CDOT numbers are even more significant when considering the fact that HRI is typically 90-95 percent of the international roughness index (IRI) for jointed concrete pavements (Karamihas, 2012).

Table 1. Comparison of initial measurements on WB Lane 2 by the contractor and CDOT.

Station		**Contractor - Lane 1**			**CDOT Lane 1**	**Contractor - Lane 2**			**CDOT Lane 2**
Start	***End***	***LWP***	***RWP***	***MRI***	***HRI***	***LWP***	***RWP***	***MRI***	***HRI***
554+99	549+71	62.8	59.3	61.0	89.4	61.3	63.4	62.3	103.2
549+71	544+43	61.5	54.1	57.8	77.1	59.3	54.9	57.1	96.3
544+43	539+15	55.3	43.6	49.5	74.5	50.7	55.5	53.1	87.0

Suspecting that the time of day of profiling could be the cause of the difference between CDOT and contractor measurements, the contractor subsequently measured a section of WB Lane 2 at three different times during the same day. Table 2 shows the results from this testing, confirming that time of day of profile data collection had a significant effect on IRI values. Also shown are the CDOT measurements from the final acceptance testing on the same section of pavement, collected on a different day in the early afternoon.

Table 2. Diurnal IRI values on WB Lane 2 measured by the contractor.

Station		**8:00 AM**			**1:00 PM**			**5:00 PM**			**CDOT Acceptance HRI**
Start	***End***	***RWP***	***LWP***	***MRI***	***RWP***	***LWP***	***MRI***	***RWP***	***LWP***	***MRI***	
554+99	549+71	109.5	99.2	104.4	80.9	71.0	75.9	78.6	71.1	74.9	60.5
549+71	544+43	98.4	95.8	97.1	66.7	66.8	66.7	65.7	67.8	66.8	59
544+43	539+15	89.9	88.5	89.2	61.0	61.2	61.1	59.4	62.7	61.0	64.8
539+15	533+87	92.8	88.7	90.7	63.8	59.1	61.5	63.6	59.4	61.5	65.4

Investigation of Curling and Warping on US 34

Based on these varying measurements on the US 34 project, CDOT initiated the research study described herein. The objective of this study was to provide CDOT with a better understanding of concrete pavement curling and warping which can be used to modify pavement specifications and acceptance testing methodologies to help improve pavement smoothness performance. The ultimate benefit of this study will be improved concrete pavement performance in Colorado, both structurally and functionally, based on the recommendations provided from this investigation of the US 34 project. The key aspects of this investigation included:

Literature Search

A literature search was completed in order to identify recent efforts investigating the jointed concrete pavement curling and warping phenomenon, particularly as it relates to ride quality.

Data Collection

The project team collected additional profile data on the US 34 project for analysis, and requested detailed information related to construction of the project from CDOT.

Analysis

Several analyses were completed using the data collected on US 34 to further understand the causes of curling and warping and the potential impacts on performance. These analyses included a comprehensive evaluation of profile data collected during the study, including assessment of slab curvature, roughness, and any potential correlations to construction conditions or slab temperatures during profiling. Analyses also included a HIPERPAV simulation of the project using actual construction conditions and a Mechanistic-Empirical prediction of pavement performance based on actual construction conditions and as-constructed roughness.

Recommendations and Implementation Plan

From the analyses completed under this study, recommendations for concrete pavement construction practices and pavement smoothness data collection were compiled and steps for implementation provided.

LITERATURE SEARCH

Curling and warping of jointed concrete pavement has been the focus of significant research, particularly over the past 15-20 years. Below is summarized more recent literature related to this subject, classified by topic. This is by no means an exhaustive compilation of curling and warping literature, but it provides some of the more relevant information as it relates to this project.

Built-in Curling

Analysis of Concrete Pavement Responses to Temperature and Wheel Loads Measured from Instrumented Slabs (Yu, 1998). This report presents the findings of a study conducted in Colorado to verify the actual field response of jointed concrete pavements. Curling and temperature measurements were conducted along test sections constructed on I-70 near the Kansas-Colorado border during the summer of 1994. The test sections were part of a jointed plain concrete overlay on an existing asphalt pavement. Figure 2 and Figure 3 present the curling and temperature gradient measurements, respectively. The analysis of these measurements indicated a significant built-in negative temperature gradient close to -20^{o}F in order to match the calculated and measured curling values.

Additional findings of the study indicate that: “the effects of temperature gradients on the critical edge stresses may not be as great as previously thought and that the corner loading, in some cases, may produce more critical conditions for slab cracking.” Also, “a physical bond between pavement layers is not required to obtain a bonded response from concrete pavements.”

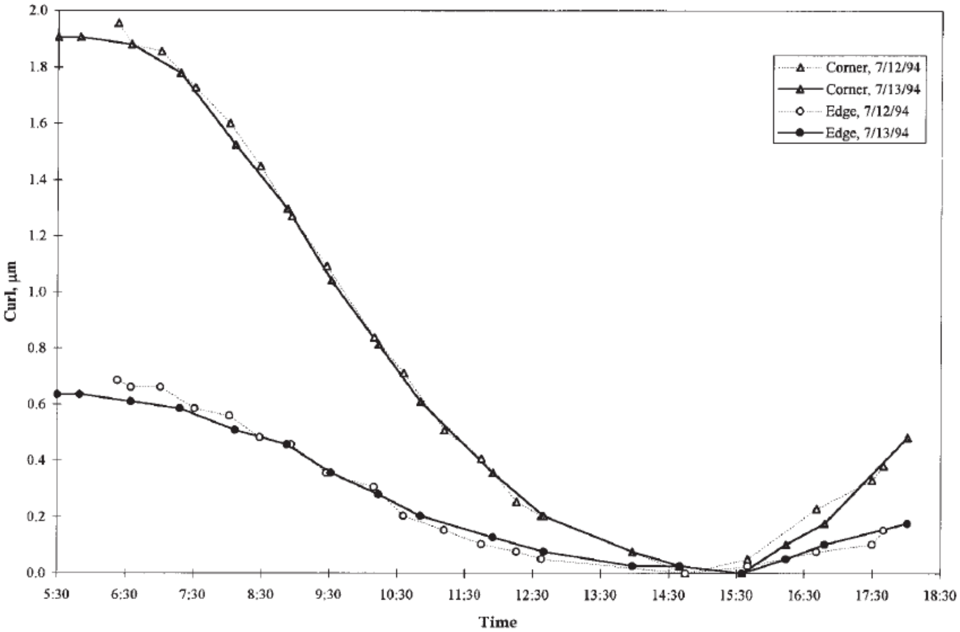

Figure 2. Measured curling of JPCP in Colorado (Yu, 1998).

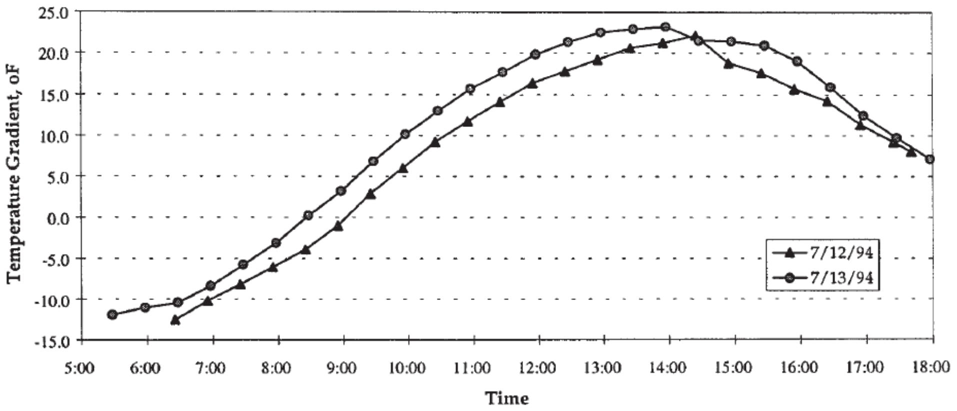

Figure 3. Variation of temperature gradients for Colorado JPCP (Yu, 1998).

Effects of Construction Curling on Concrete Pavement Behavior (Yu, 2001). The abstract summarizes this article as follows, where construction curling is synonymous with built-in curling:

"This paper illustrates the effects of construction curling on critical stresses in JPCP and the consequent effects on slab cracking. The effects of construction curling on pavement deflections and surface profile are also discussed. Also presented is a procedure for estimating the magnitude of construction curling based on curling deflections monitored over a range of temperature conditions. Field data from I-80 Pennsylvania are presented to illustrate the effects of construction curling and the procedure for estimating the magnitude of construction curling."

This report mentions that, "if the magnitude of built-in curling is sufficiently high, multi-axle loading under nighttime temperature conditions becomes more critical, and the slabs can crack from top-down, rather than bottom-up." However, the authors explain that built-in curling is difficult to quantify and furthermore, it varies throughout the length of a project according to the temperatures during paving as shown in Figure 4, below.

The authors explain that the effect of built-in curling cannot be evaluated on pavement surface profile alone, and needs to be assessed in conjunction with pavement response data such as deflections. A procedure to estimate built-in curling based on pavement deflections and slab temperatures is presented using field data from I-80 in Pennsylvania.

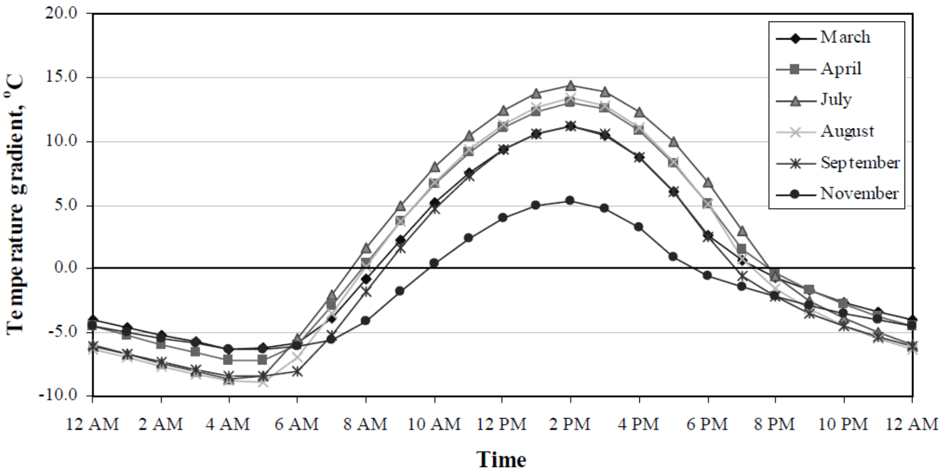

Figure 4. Daily and seasonal variation in temperature gradients through 13-in slab (Yu, 2001).

Impact of Curling, Warping, and Other Early-Age Behavior on Concrete Pavement Smoothness: EFD Study (Ceylan, 2007). The abstract for this report states:

"The purpose of this project is to obtain detailed information about factors affecting pavement smoothness during the critical time immediately following construction by conducting a controlled field evaluation of three concrete pavement construction projects. Both field and laboratory testing of the materials and construction process were conducted. Extensive pavement profiling was also performed during strategic times after placement. This study shows that the curling and warping behaviors at early ages are influenced not only by temperature variation but also by other environmental effects such as the moisture variation, drying shrinkage, and temperature conditions during pavement construction. Within the scope of this project, it can be concluded that measurable changes of early-age pavement smoothness do occur over time from the standpoint of smoothness specifications."

The major findings of the study include:

- Based on the limited field data, it appears that morning paving produces smoother JPCP pavements (in terms of measured smoothness indices) compared to afternoon paving.
- The measured smoothness index values between morning and afternoon measurement times showed some variations.
- The measured smoothness index values were different at different measurement locations within a pavement test section.
- Within the scope of this project, it can be concluded that measurable changes of early-age pavement smoothness do occur over time from the standpoint of smoothness specifications.

- The changing slab curvature conditions at early ages are influenced not only by temperature variation but also by other environmental effects, such as the moisture variation, drying shrinkage, and wind conditions during pavement construction.
- The permanent curling/warping effective temperature difference identified from this study ranged approximately from –8°F to –12°F on different sites, measurement methods, and FE-programs. (Note that –10°F is defined as permanent curl/warp effective temperature difference in the newly released MEPDG through national calibration results.)
- A linear relation was observed between the actual measured temperature difference and the equivalent temperature difference associated with actual slab displacement under pure environmental loading.
- Pavement temperature differences are usually positive at daytime and early nighttime and negative at late nighttime and early morning.
- Pavement temperature is generally higher than ambient temperature and follows a pattern that is similar to that of ambient temperature with one- to two-hour lag.

Recommendations of this study include considering nighttime or morning paving when feasible, using HIPERPAV to analyze the specific daily project conditions before these paving schedule changes are made, and utilizing a curing method with uniform and adequate coverage over the entire surface to prevent the loss of mixing water from the surface of concrete.

PCC Pavement Acceptance Criteria for New Construction When Built-In Curling Exists (Hansen, 2008). This report presents a project conducted to: 1) determine the magnitude of built-in curling for Michigan conditions, and 2) develop acceptance criteria to quantify built-in curling during and after construction. To accomplish the first objective, temperature measurements were conducted from instrumented slabs on I-94 in June 2005 and also US 23 in late October 2005.

The study found that in Michigan a temperature gradient as high as -20°F can be expected during summertime construction, and +3°F for late fall. The recommendations of the study include:

- Temperature monitoring of the concrete pavement during hot weather paving to determine its temperature gradient at the time of set in order to calculate the extent and severity of built-in curl that may have occurred.
- Temperature monitoring should continue after construction to determine average daily temperature fluctuations through the slab.

Field Evaluation of Built-In Curling Levels in Rigid Pavements (Lederle, 2011). This report presents the findings of a study to evaluate the factors that cause built-in curling, and assess the methods to determine built-in curling in existing slabs. An extensive literature review was conducted as part of this study, and it was found that material, geometric, restraint, curing and local ambient relative humidity affect both construction curl and drying shrinkage, leading to built-in curl of concrete slabs.

Relevant to this literature search for CDOT, this report includes a section that focuses on construction practices that are known to directly affect the magnitude of built-in temperature gradient, including paving season, time of day, curing techniques, and mix design. The following conclusions from previous research are noted in the report:

- Paving Season: "In general, constructing concrete pavements in a hot, dry climate or during the summer season will result in high negative built-in temperature gradients. Conversely, constructing pavements in a cool, wet climate or during the spring and fall will result in little or no built-in curl."
- Paving time: "Paving in the morning on a hot, sunny day will result in the maximum built-in temperature gradient because the slab will harden in the afternoon during the time of maximum heat and solar radiation (Hansen, 2006). One study looked at the effects of constructing a concrete pavement during the night and found that a significantly lower built-in curl developed compared to slabs constructed during the day (Rao, 2001). *It can be concluded that constructing pavements late in the day or during the night in cloudy conditions will prevent significant built-in curling from occurring."*
- Curing techniques: "The effective temperature difference that is built into the slab is highly dependent on the types of curing techniques that are used…The use of wet curing has also been shown to have many beneficial effects with regard to built-in curling."

After the literature review, the main focus of the research was to back calculate built-in curling from pavement deflection measurements with a Falling Weight Deflectometer (FWD) and temperature profiles. To accomplish this task the researchers developed an artificial neural network (ANN) using a finite element program. Pavement deflection and surface profile data were collected at the MnROAD facility. Comparisons between the back calculated curling and the measured slab curvature with different surface profiling methods were conducted.

Impact of Curling and Warping on Ride Quality

KDOT Investigation of the Effect of Curling on As-Constructed Smoothness and Ride Quality of PCC Pavements (Siddique, 2004). This report presents a study to evaluate and quantify the effect of slab curling on initial and short-term smoothness and to identify the factors affecting both curling and roughness. Smoothness and construction history data were collected and analyzed for twelve test sections on six newly built segments of Interstates 70 and 135. The research results include recommendations to modify design and/or construction techniques. Findings relative to this literature search include:

- A large temperature gradient (as high as 29°F) between the top and bottom of the concrete pavement slab can build up during concrete placement in Kansas.
- Double curing compound application tends to decrease the temperature differential between the top and the bottom of the slab in freshly placed concrete pavement slab. The temperature gradients were 2°F to 11°F lower when compared to the slabs with a single application of curing compound.

Impact of Temperature Curling and Moisture Warping on Jointed Concrete Pavement Performance (Chang, 2010). The abstract for this document is as follows:

"This Tech Brief summarizes the results of a study on curling and warping in jointed concrete pavement (JCP). Profile measurements, following quality assurance plans developed under the study, were collected in all U.S. climate zones, diurnal periods, and seasons of the year to obtain sufficient data to fully characterize slab curvatures. Both functional and structural pavement performance were measured to correlate performance to curling and warping. Products of the study include a new technique that quantifies the magnitude of JCP curling and warping and a system to assess the influence of diurnal and seasonal changes on JCP curvature and pavement unevenness."

Relevant to this literature research, Chang et al. found that:

- Diurnal impacts of slab curling on the Half-car Roughness Index can be as high as 0.63 m/km (40 in/mi.) with an average around 0.16 m/km (10.1 in/mi.).
- It may be prudent for more emphasis to be placed on the timing of roughness measurements within specifications, particularly for agencies working under incentive–disincentive specifications.
- This issue must be dealt with on a site-by-site basis since it has been demonstrated that diurnal and seasonal effects vary significantly between sites.

Evaluating the Effect of Slab Curling on IRI for South Carolina Concrete Pavements (Johnson, 2010). The abstract summarizes this report as follows:

"This research project measured the magnitude of concrete pavement slab curling of two newly constructed jointed plain concrete pavements in South Carolina and the effect of the slab curling on rideability of the pavements. Three methods were used to measure the amount of slab curling: digital indicators suspended over the pavement surface, a terrestrial laser scanner, and a high-speed inertial profiler. It was found that the pavements showed small changes in curvature as the temperature increased during the day. These changes also correlated to increases in the International Roughness Index (IRI) measurement of the pavement, the IRI increase were found to be less than 10 inches/mile on days with large swings in temperature. The change in IRI from seasonal temperature variations was in the range of 1 to 4 inches/mile. *Based on this research project, it is recommended that SCDOT schedule its quality acceptance rideability testing of concrete pavements for the same time of day (i.e. afternoon) to reduce the variation in the IRI."*

The following excerpts from the report are also relevant to this literature search:

- Based on the data collected in this research project, the change in IRI due to daily temperature change in South Carolina is expected to be less than 10 inches/mile. The change in IRI resulting from pavement curvature due to seasonal variations is expected to be less than 5 inches/mile. These changes are fairly small, especially when considering the variability in single-point laser profiler measurements due to the surface texture of a diamond ground concrete pavement.

- In general, the pavements showed an increase in the roughness as the temperature increased towards the middle of the day and the roughness would decrease in the evening as the temperature gradient in the pavement diminished. This is a generalization because there are other factors contributing to the pavement curvature, most notably the built-in curl from when the conditions when the pavement was constructed.
- The terrestrial laser scanner showed the ability to measure small changes in the pavement surface. The surface texture of the pavement is an important factor for the accuracy of the scanner.

Curl and Warp Analysis of the LTPP SPS-2 Site in Arizona (Karamihas, 2012). This report documents the investigation of the roughness progression of a Long-Term Pavement Performance SPS-2 (jointed concrete pavement) site in Arizona over the 16-year period after construction. The 21 sections evaluated varied in thickness, lane width, flexural strength, and base type. The analysis showed that curl and warp contributed to, and in some cases dominated, the roughness on many of the test sections. Curling was measured using profile data collected over the 16-year period and quantified on a slab-by-slab basis as a pseudo strain gradient (PSG) value. The PSG and changes in PSG over time were compared to changes in roughness to identify any correlations. The study was able to demonstrate the potential for isolating the effects of concrete pavement curling and warping from other sources of roughness (faulting, cracking, etc.) using the IRI-PSG relationship. The study also concluded that long-term increases in IRI may be caused by changes (i.e., progression) in curling and warping over time.

Mitigation Strategies

Concrete Pavement Curling and Warping: Observations and Mitigation (Van Dam, 2015). This technical summary provides an overview of the work by Karamihas and Senn (Karamihas, 2012). In addition, strategies to mitigate curling and warping during design and construction are provided as summarized in the following excerpts:

- Alter the concrete constituents to reduce the ultimate drying shrinkage. Reducing the cementitious materials content through increasing aggregate volume will reduce the ultimate shrinkage of the concrete, not only because of the reduction in water but also because aggregates provide internal resistance to shrinkage. In recent years, shrinkage-reducing admixtures (SRAs) have been developed that can significantly reduce drying shrinkage in concrete. Yet SRAs have not seen widespread use in pavements due to their high cost and unproven long-term effectiveness in pavement applications.
- Establish better curing practices that minimize moisture loss at early ages. Proper use of effective membrane-forming curing compounds that hold free moisture in the concrete for long periods of time and wet curing methods delay the onset of shrinkage, although their impact on ultimate drying shrinkage is less clear. Recent research has suggested that wet curing can actually increase warping in concrete slabs and thus might not be the best approach for curing slabs in dry environments (Hajibabaee, 2015). The use of saturated lightweight aggregates (SLWA) has shown promise to improve curing and reduce ultimate

drying shrinkage in concrete, but additional work is needed to determine the effectiveness of SLWA in reducing long-term upward curvature in concrete pavements.

- Use concrete pavement design elements that minimize the impact of long-term curvature on ride quality. The use of shorter slabs, dowelled joints, and bonding of the concrete slab to an underlying stabilized base are design elements that can help mitigate the magnitude of long-term upward curvature in jointed concrete pavements, reducing its impact on IRI.

2014 NCDOT Construction Manual, Division 7 – Concrete Pavements (NCDOT, 2014). The 2014 North Carolina DOT Construction Manual limits concrete paving as stated below in Item 4. This measure possibly addresses concerns for concrete curling and shrinkage amongst other issues.

Section 700-5, Placing Concrete: Because proper construction practices are critical to the concrete pavement's service life, the Roadway Technician and the Laboratory Technician should ensure that placement of concrete shall not begin or shall be suspended when the following conditions occur:

1. When the descending air temperature in the shade away from artificial heat reaches 35°F, paving shall be suspended until an ascending temperature in the shade away from heat reaches 35°F.
2. When the subgrade or base course is frozen.
3. When the aggregates to be used in the mix contain frozen particles.
4. When air temperature in shade is 90°F and rising or the concrete temperature is greater than 95°F.

2011 Florida DOT PCC Pavement Specifications: State of the Practice (Nazef, 2011). This report presents a review of specifications and practices for seven lead State DOTs in concrete pavement construction, and notes methods and techniques that can possibly strengthen Florida's specifications. The section on Subgrade and Base Preparation lists the following practice that may assist in preventing slab curling and warping during hot weather paving:

"Treat top of Asphalt-Treated Permeable Base (ATPB) with lime solution before paving to keep base temperature low and prevent flash set of concrete mixture."

Other Related References

Volume II – Design and Construction Guidelines and HIPERPAV II User's Manual (Ruiz, 2005). This report presents design and construction guidelines for concrete pavements. In addition, this document contains the user's manual and examples for the HIgh PERformance PAVing (HIPERPAV II) software. Chapter 2, Early-Age Pavement Behavior, outlines the factors that affect concrete pavements shortly after construction and ultimately long-term performance.

The report lists the following as the primary factors that influence concrete pavements at the early ages:

- Generated heat from hydration of the cement.
- Climatic conditions such as air temperature, solar radiation, relative humidity of the air, and wind speed.
- Concrete temperature and subbase temperature during placement.
- The concrete coefficient of thermal expansion (CTE).
- Slab-subbase interface restraint.
- Concrete shrinkage as a result of the drying process.
- Curling and warping of the concrete slab as a result of temperature gradients.
- Creep/relaxation phenomena.
- Construction procedures.

Climatic conditions and concrete/subbase temperature during placement are particularly relevant to this literature search and investigation of the US 34 project. The impact of climatic conditions on built-in curling is covered in this reference; however, note there is little information on the effect of the base/subbase temperature on slab curling. The following excerpt from Volume II, Section 2.1.1.2 touches briefly on this subject:

"In the early ages, concrete temperature is a function of the heat of hydration and climatic conditions. The heat generated due to hydration results in a temperature rise in the concrete as a function of the thermal conductivity and specific heat of the paste and aggregate. On the other hand, climatic conditions such as air temperature, solar radiation, cloud cover, and convection due to wind speed affect the amount of heat lost or gained through the surface of the pavement. This heat loss or gain is transported through the depth of the slab, as a function of the concrete thermal conductivity and specific heat. Heat conduction to or from the subbase also affects the temperature of the concrete."

Later in the report, the initial subbase temperature is defined as one of the construction inputs in the software, even though emphasis is placed on paving during cold weather as opposed to hot weather. From Section 5.4.5 Initial Subbase Temperature:

"Ideally, the temperature of the subbase should be as close as possible to the temperature of the concrete when placing the concrete during cold weather concreting. The ground should not be frozen, but could be thawed by steaming, covering with insulation, or spreading a layer of hot sand, gravel, or another material."

Alternative Failure Modes for Long-Life JPCP (Hiller, 2006). Hiller and Roesler describe the development of a software program (RadiCAL) that takes into account alternative fatigue modes such as longitudinal and corner fatigue cracking in addition to the traditional bottom-up midslab transverse cracking. The authors explain that this approach is now possible due to "the characterization of built-in construction curl and differential drying shrinkage, which primarily affect permanent curling of these slabs," which allows designers to consider alternative failure modes. They note that “in low volume roads, with thinner slabs and aggregate interlock joints, alternative fatigue failure modes become more likely.”

In addition, this article presents an overview of the “equivalent built-in temperature difference” (EBITD) developed by Rao and Roesler. The authors explain, “This value can be back-calculated in a variety of ways including falling weight deflectometer testing, joint deflection measuring devices, multi-depth deflectometers, or surface profiling (Byrum, 2000). This value, as defined by Rao and Roesler, takes into consideration the built-in temperature difference from construction, permanent differential shrinkage, and reversible moisture gradients, as well as creep of the concrete, which could negate some of this permanent curl.”

DATA COLLECTION

Data collection for this effort included detailed information from construction of the US 34 project and additional data collected by the project team, as summarized below.

Construction Information

Design

The US 34 project was a reconstruction of an existing asphalt pavement following the same footprint of the original pavement. The pavement consists of two 12-ft lanes, 4-ft inside, and 10-ft outside tied concrete shoulders. The pavement structure consists of 9-inch jointed plain concrete pavement over a (full-depth) reclaimed asphalt base. The depth of the asphalt varied from 6-8 inches and the full-depth reclamation process mixed in approximately two inches of the underlying aggregate base into the reclaimed asphalt. No treatment was applied to the reclaimed material except water in order to achieve density requirements.

The design joint spacing was 15 feet with 18-inch-long, 1.25-inch-diameter epoxy-coated dowels. Dowels were placed in the wheelpaths only, with 5 dowels per wheelpath, spaced 12 inches apart. Tie-bars were No. 5 epoxy-coated bars, 30 inches in length placed at the three longitudinal joints at 30 inches on center.

Current traffic on this highway is 12,500 vehicles per day with 9 percent trucks, and 20-year traffic is anticipated as 21,580 vehicles per day.

Materials

Table 3 summarizes the concrete mix design and physical properties of the concrete that were approved by CDOT for the US 34 project. The concrete mixture was an optimized mix with three coarse aggregate used to achieve the optimized aggregate gradation.

Table 4 summarizes the average values for the quality assurance data collected during construction for thickness and flexural strength. Incentive payment was applied for thickness and disincentive pay adjustment for flexural strength.

Equipment

Paving was completed with a 4-track slipform paver with dowel bar inserter in a single pass, 38 ft. wide, in both directions. Dual string lines were used for grade control. Concrete was placed on the grade with end dumps and side dumps, and a spreader was used to distribute concrete directly in front of the paver. A tie-bar inserter was used to insert tie-bars at the three longitudinal joints from the top of the slab. Concrete was batched on-site approximately 2,000 ft. from the west end of the project.

Burlap drag texture was applied behind the paver, followed by longitudinal tining from a separate texture/cure machine. A single coat of curing compound was applied by the texture cure machine immediately after tining at a rate of one gallon per 150 square-ft. Joint sawing was completed using conventional joint saws, cut in a single pass. Diamond grinding was used to correct localized roughness, and joints were sealed after completion of grinding.

Table 3. US 34 concrete mixture design and properties.

Material	**Quantity (lb./CY)**
Cement (Type I)	422
Fly Ash (Class F)	108
Coarse Aggregate 1 (#4)	403
Coarse Aggregate 2 (#57/67)	992
Coarse Aggregate 3 (#9)	403
Fine Aggregate	1302
Water	215
Admixture (Air Entraining)	4 oz.
Admixture (Water Reducer)	29 oz.
Mixture Properties	
Water/Cementitious Ratio: 0.41	
Compressive Strength: 4,070 (7 day); 5,480 (28 day)	
Flexural Strength: 560 (7 day); 680 (28 day)	
Air Content: 6 percent	
Slump: 1.75 in.	
Unit Weight: 142.8 lb./CF	
Workability Factor: 37.3	
Coarseness Factor: 63.1	

Table 4. Summary of US 34 thickness and strength acceptance testing results.

	Thickness, in. Design = 9 in.	**Flexural Strength, psi (28 day) Design = 680 psi**
EB Lanes	9.6	604
WB Lanes	9.5	585

Paving Sequence, Dates, and Temperatures

The full-depth reclamation process took approximately three weeks to complete prior to concrete paving. Paving began at the east end of the project paving westward, for both the EB and WB lanes. Table 5, below, summarizes the paving sequence, daily paving window, and ambient high and low temperatures during the paving window each day.

Table 5. US 34 paving sequence and temperature data.

Date	Paving Day	From	To	Distance (ft.)	Side of Bridge	Paving Window	Ambient High Temp (°F)	Ambient Low Temp (°F)
WB Lanes								
7/20/2012	1	593+90 *(MP 115.3)*	570+98	2292	East	7:00-19:15	102.2	62.6
7/23/2012	2	560+04.4	553+96	608	West	7:30-11:14	87.8	68
7/24/2012	3	553+96	529+49	2447	West	7:21-19:10	98.6	66.2
7/25/2012	4	529+49	515+04	1445	West	7:27-14:20	93.2	73.4
7/26/2012	5	515+04	502+50 *(MP 113.5)*	1254	West	7:20-13:58	84.2	60.8
EB Lanes								
9/13/2012	1	593+99.5 *(MP 115.3)*	577+00	1699.5	East	7:40-18:00	71.6	51.8
9/14/2012	2	577+00	570+03	697	East	7:20-11:30	69.8	44.6
9/17/2012	3	559+10	535+44	2366	West	7:15-17:15	68	48.2
8/18/2012	4	535+44	512+29	2295	West	7:15-18:00	80.6	42.8
9/19/2012	5	512+29	496+58 *(MP 113.4)*	1571	West	8:30-17:12	82.4	50

Grinding

Only spot grinding, primarily at construction joints, had been completed on US 34 at the time of profile data collection for this effort.

CDOT Smoothness Acceptance Data

Pavement smoothness acceptance data were collected on August 22 and October 31, 2012 for the WB lanes and on October 4 and 10, 2012 for the EB lanes. Tables showing the actual acceptance data are provided in Appendix C.

Smoothness Category II was used to compute incentives and disincentives for ride quality. For Category II, incentive pay adjustments are applied for lots with HRI less than 58 in/mi and disincentive pay adjustments are assessed for HRI greater than 67 in/mi. Corrective work is required for lots with HRI greater than 85 in/mi. Areas of localized roughness are identified as areas with an HRI exceeding 125 in/mi. when evaluated using a continuous roughness report with a 25 ft. base length. Table 6 summarizes the percent of lots receiving incentive and disincentive pay adjustments at acceptance.

Table 6. Summary of US 34 smoothness testing pay adjustments.

Location		**Pay Adjustment (Percent of Lots)**	
		Incentive	***Disincentive***
EB (17 lots)	*Lane 1*	59	0
	Lane 2	29	6
WB (16 lots)	*Lane 1*	6	19
	Lane 2	19	6

Curling/Warping Study Data Collection

Profile Data

Profile data for this study were collected by CDOT using their high-speed profiler with line lasers in each wheelpath. Profile data were reported approximately every one inch within each data file. Reflective tape was placed on the pavement surface during each site visit to automatically trigger profile data collection at the same locations for each run.

In order to evaluate daily and seasonal changes in roughness, profile data were collected at two times during the year and at four different times of the day. Profile data were collected in February and August, traditionally two of the coldest and warmest months of the year at this location, in order to examine the two extreme conditions. Diurnal profiling during each of these site visits sought to capture the effects of daily temperature cycles on pavement curling by collecting data at the following times:

- Early AM – just before sunrise when the maximum negative slab temperature gradient is expected.
- Mid-AM – a few hours after sunrise when a near-zero slab temperature gradient is expected.
- Early-PM – near or shortly after noon when the maximum positive slab temperature gradient is expected.
- Late-PM – shortly before sunset when a near-zero slab temperature gradient is expected.

Table 7 summarizes the profile date collected by CDOT for this effort during the two site visits in February and August 2014. Due to the time required to collect data on all four lanes at each diurnal period, only one run was made in each lane. However, for the early afternoon runs, a second repeat was collected the following day during both site visits.

Unfortunately it was not possible to profile the full length of the US 34 project. Due to flooding in fall 2013, a portion of lane 1 on the EB lanes and a portion of lane 2 on the WB lanes at the eastern end of the project were closed to traffic. Approximately 700-900 ft. of the eastern end of each direction could not be profiled, but the data that were collected provided more than enough for analysis.

Table 7. Summary of profile data collected for the US 34 evaluation.

Site Visit 1: February 2014							Site Visit 2: August 2014						
Date	**Time**	**Dir.**	**Lane**	**Diurnal Period**	**Repeat**	**Length (ft)**	**Date**	**Time**	**Dir.**	**Lane**	**Diurnal Period**	**Repeat**	**Length (ft)**
2/12	13:05	WB	1	Early PM	1	7367	8/5	13:59	WB	1	Early PM	1	7115
2/12	13:12	EB	1	Early PM	1	7958	8/5	14:05	EB	1	Early PM	1	7703
2/12	13:16	WB	2	Early PM	1	7365	8/5	14:09	WB	2	Early PM	1	7110
2/12	13:24	EB	2	Early PM	1	7957	8/5	14:18	EB	2	Early PM	1	7706
2/12	15:24	WB	1	Late PM	1	7370	8/5	19:47	WB	1	Late PM	1	7139
2/12	15:32	EB	1	Late PM	1	7961	8/5	19:52	EB	1	Late PM	1	7730
2/12	15:35	WB	2	Late PM	1	7365	8/5	19:57	WB	2	Late PM	1	7132
2/12	15:48	EB	2	Late PM	1	7959	8/5	20:05	EB	2	Late PM	1	7728
2/13	10:29	EB	1	Mid-AM	1	7958	8/6	5:46	WB	1	Early AM	1	7145
2/13	10:32	WB	1	Mid-AM	1	7364	8/6	5:51	EB	1	Early AM	1	7735
2/13	10:41	EB	2	Mid-AM	1	7958	8/6	5:57	WB	2	Early AM	1	7139
2/13	10:45	WB	2	Mid-AM	1	7362	8/6	6:03	EB	2	Early AM	1	7732
2/13	12:26	EB	1	Early PM	2	7979	8/6	8:18	WB	1	Mid-AM	1	7140
2/13	12:29	WB	1	Early PM	2	7365	8/6	8:27	EB	1	Mid-AM	1	7730
2/13	12:39	EB	2	Early PM	2	7958	8/6	8:32	WB	2	Mid-AM	1	7135
2/13	12:43	WB	2	Early PM	2	7363	8/6	8:38	EB	2	Mid-AM	1	7730
2/13	5:40	EB	1	Early AM	1	7959	8/6	12:44	WB	1	Early PM	2	7156
2/13	5:46	WB	1	Early AM	1	7366	8/6	12:49	EB	1	Early PM	2	7733
2/13	5:51	EB	2	Early AM	1	7960	8/6	12:53	WB	2	Early PM	2	7140
2/13	5:55	WB	2	Early AM	1	7366	8/6	13:03	EB	2	Early PM	2	7734

Temperature Data Collection

In order to examine the relationship between slab curling and slab temperature gradients, temperature sensors were installed in the pavement slab prior to profiling. Sensors were installed at one location in both the EB and WB lanes during the first profiling site visit. Self-contained logging temperature sensors were installed at approximately one inch from the top, one inch from the bottom, and at mid-depth of the pavement. Holes were drilled to the proper depth, the sensors inserted, and then bonded in place using a rapid hardening resin which has similar thermal conductivity properties to concrete. Sensors recorded temperature every three minutes during profiling and remained in place between the two site visits. Figure 5 shows one set of temperature sensors during and after installation.

Figure 5. Data logging temperature sensors installed prior to profiling.

In addition to the sensors in the pavement slab, two additional sensors were hung on sign posts within the project limits in order to capture ambient temperature data. Ultimately, however, temperature data from Greeley-Weld County Airport was used for ambient temperature records.

The top-bottom slab temperature gradient was of most interest for this study. Figure 6 and Figure 7 show the slab temperature gradient data collected by the project team during the two site visits. The shaded bars show the window during which diurnal profile data were collected at each site visit. Although the goal was to collect profile data when slab temperature gradients were maximum negative, maximum positive, and near zero, the timing of the zero temperature gradient was difficult to predict and therefore was not achieved for most of the runs. The average of the EB and WB gradient was used for the curling data analysis, with the exceptions of the February site visit when only the WB sensor data were used (due to significant differences in EB and WB) and the mid-AM data on August 6 during the August site visit, where only the EB sensor data were used.

While it is recognized that concrete pavement slab temperature profiles are normally non-linear, a linear gradient using the top and bottom temperature sensors was used in the analysis for lack of more detailed slab temperature measurement over the depth of the slab.

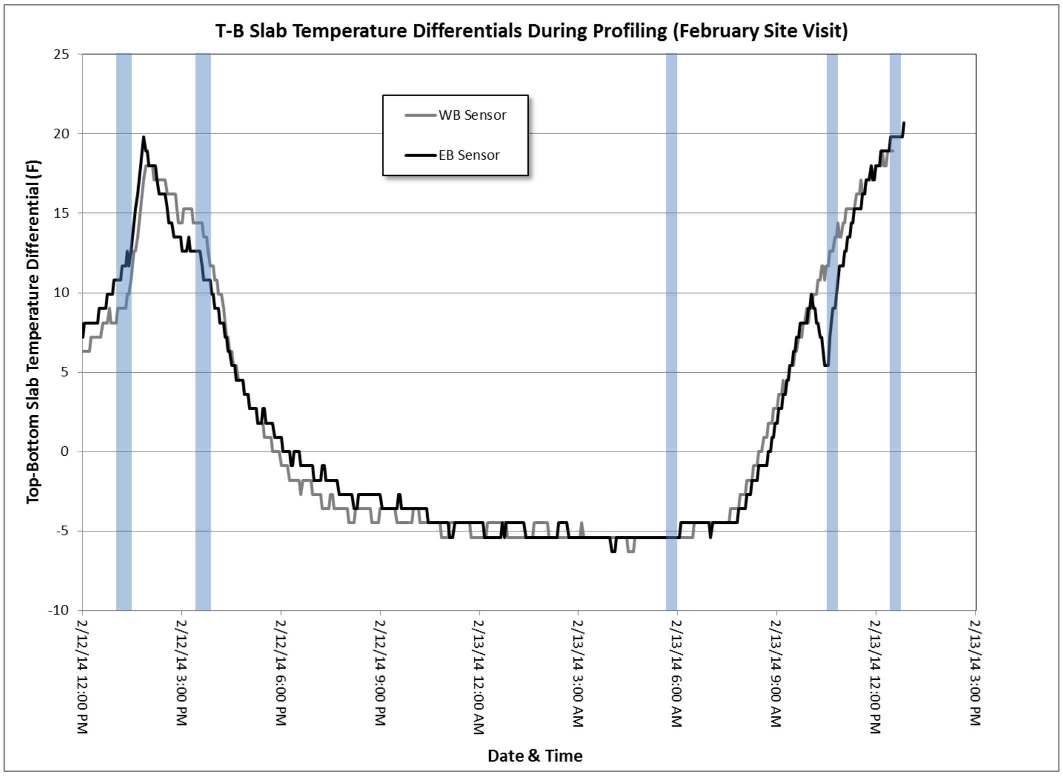

Figure 6. Top-Bottom slab temperature differentials during February site visit profiling.

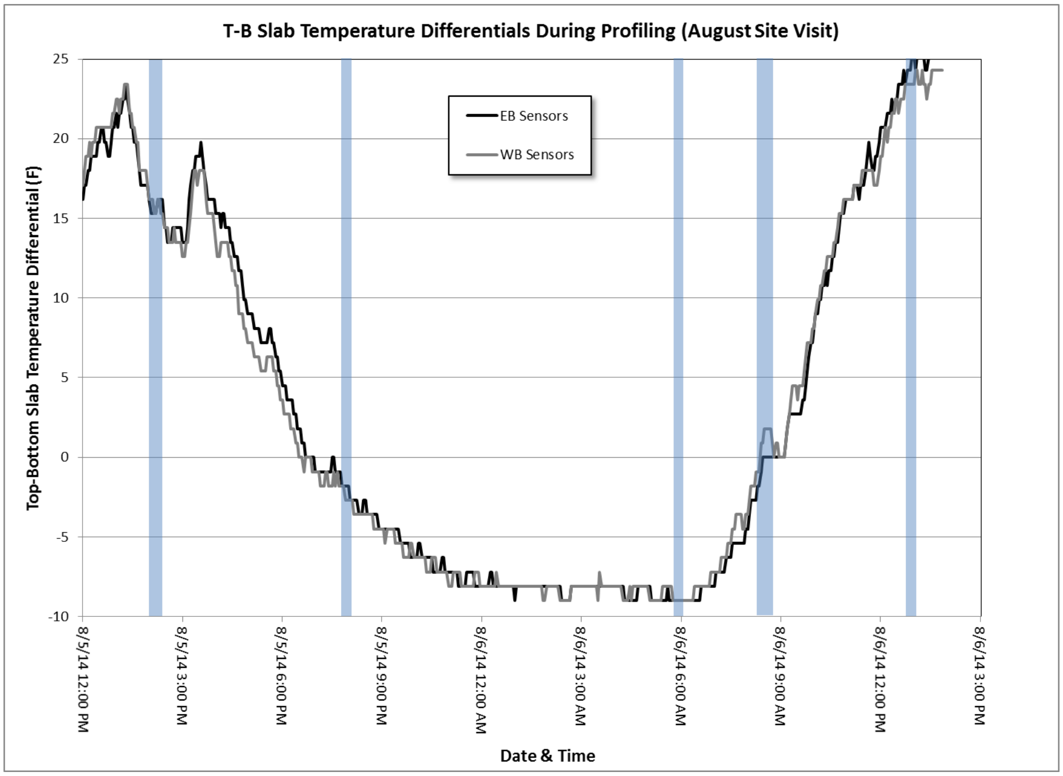

Figure 7. Top-Bottom slab temperature differentials during August site visit profiling.

Strain Data

In addition to the profile and slab temperature data collected during each site visit, strain data were collected by mounting Demec strain gage measurement points to the pavement surface at several locations. Two pavement joints near the temperature sensors on both the EB and WB lanes were instrumented in order to monitor joint movement. Additionally, the end of the bridge approach slab (near the bridge expansion joint) was also instrumented in order to measure slab movement at an essentially unrestrained joint. Unfortunately, the very limited amount of data collected from the strain measurements did not prove to be of value for the analysis, and is therefore not discussed further.

ANALYSIS

Several analyses were conducted using the profile data, temperature data, and construction information in order to investigate the slab curling issues on US 34. The various analyses conducted are summarized below.

Profile Data Analysis

Profile data analysis was the first step in evaluating the roughness of the EB and WB lanes of the US 34 project. Profile data were evaluated in several ways, as described below.

Overall Roughness

Overall roughness was evaluated by computing the overall IRI and HRI values for each lane in each direction during the four diurnal periods and the two (winter and summer) site visits. Data were also separated by location within the project, namely east of the South Platte River Bridge and west of the bridge, in order to examine any differences in roughness on either side of the bridge. Table 8 summarizes the overall roughness evaluation by wheelpath (IRI) and by lane (HRI). Figure 8 and Figure 9 present this data graphically for HRI. Some key observations from this evaluation include:

- Trends in roughness between diurnal periods across both lanes, both sides of the bridge, in both directions, and during both site visits, are similar (Figure 8 and Figure 9). This is an indication that profile data were collected in a consistent manner between seasonal periods, and seeming anomalies in profile data (e.g., WB lane 1, east of bridge) are not the result of measurement issues.
- Roughness values for the two "near zero" temperature gradient conditions (Mid-AM and Late PM) are similar in value consistently across all lanes.
- Roughness of the WB lanes is consistently higher than EB lanes for both profiling periods and all diurnal measurements. WB roughness (HRI) is up to ~16.5 in/mi higher than EB lane roughness, depending on the time of day of profiling, with an overall average of 6 in/mi higher. The only exception is lane 2 on the east side of the bridge in which the EB lane is marginally rougher than the WB lane.
- Overall roughness west of the bridge is consistently higher than east of the bridge for all lanes, in both directions, with the exception of WB lane 1. This is likely due to a contribution to overall roughness from localized roughness at construction joints. For both EB and WB directions, 2-3 construction joints, at least one driveway, and one intersection are present on the west side of the bridge. Only one construction joint is present east of the bridge for the EB lanes, and none for the WB lanes.
- Roughness is consistently higher for the August profile data than February. This may be due to differences in slab temperature gradient during profiling (-9 to +24 in August vs. 5 to +19 in February), but may also be due to a larger moisture gradient in the slab which would be more likely in August (rainy/wet subbase) than February (frozen subbase).

- Diurnal changes in roughness are also greater for August than February. This again could be due to differences in slab temperature gradient, but could also be due to greater solar warming of the pavement surface in August.
- With the exception of WB lane 1, east of the bridge, Early AM roughness is significantly higher than subsequent times of the day. This confirms observations from diurnal testing by the contractor shortly after construction. Diurnal differences in roughness (HRI) range from 0.9 in/mi (EB lane 1) up to 31.1 in/mi (WB lane 2), with an overall average of 14.1 in/mi. The largest difference is generally between the Early AM profiles and Early PM profiles.
- The diurnal variation in roughness, as well as between seasons (February to August) clearly indicate that temperature gradients in the slab are causing the slabs to curl, significantly impacting pavement smoothness.

Roughness by Wheelpath

In order to examine differences within individual lanes, Figure 10 through Figure 14 show overall roughness values for individual wheelpaths along with HRI, separated by the time of day of profiling.

With the exception of WB lane 2, LWP roughness is consistently higher than RWP roughness in both directions. In some cases LWP roughness is as much as 18 in/mi higher, with an overall average of 7.7 in/mi higher. This is not believed to be caused by measurement/profiler error as the trend was the same for both the February and August profiles, and was also observed with the contractor's profile data (Table 2). While the reason for this is not obvious from the data, it is speculated that it could be related to whether or not the longitudinal joint between the lanes and the longitudinal joint between the lanes and shoulders have formed (cracked) through the slab. For joints that have formed, the slabs on either side of that joint may be curling independently, whereas for joints that have not formed, the slabs would be curling monolithically with each other or with the shoulder. Figure 14 shows some possible scenarios that could lead to the difference in LWP and RWP smoothness, although none of these scenarios has been confirmed for US 34.

In order to further examine the cause of roughness differences between RWP and LWP, the ProVAL Power Spectral Density (PSD) module was used to compare WB lane 1, which had significant difference in roughness between wheelpaths, and WB lane 2, where wheelpath roughness was similar. For simplicity, only one diurnal period from the August profile data was analyzed: Early PM, west of the bridge. Figure 15 shows the PSD plot for WB lane 1 and lane 2 (with a 100-ft high-pass filter applied). All four PSD plots show dominant spectral density content at the joint spacing (~14.5 ft.). However, despite lower overall roughness, the 14.5-ft spectral density content for lane 2 is higher than lane 1. This is an indicator that the effect of the joints (due to slab curing) is more pronounced on lane 2 than lane 1, and the roughness for lane 1 is not as affected by curling. Also of note, the LWP and RWP spectral density content is virtually identical for lane 2, but somewhat different for lane 1, which may indicate more uniformity of slab curling across the lane for lane 2 than lane 1. This may be an indicator of whether the longitudinal joints on either side of lane 1 and lane 2 had formed.

Table 8. Overall ride quality values from profile data collected during US 34 evaluation.

Direction	Lane	Diurnal Period	Side of Bridge	February Site Visit			August Site Visit		
				HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)
EB	Lane 1	Early AM	E	54.5	62.3	56.5	59.7	63.0	65.1
			W	60.8	69.9	63.6	65.5	72.9	70.0
EB	Lane 1	Mid-AM	E	46.2	56.8	46.5	50.3	57.2	53.2
			W	53.5	65.6	54.9	57.1	68.2	59.7
EB	Lane 1	Early PM	E	45.9	59.8	43.5	47.8	61.5	45.1
			W	51.3	65.6	50.1	51.0	66.3	49.0
EB	Lane 1	Late PM	E	45.6	57.7	44.7	44.8	54.2	46.4
			W	51.9	65.4	51.7	53.1	65.4	54.5
EB	Lane 2	Early AM	E	58.9	66.8	58.6	68.4	75.0	67.6
			W	68.6	78.0	65.6	75.5	86.8	69.9
EB	Lane 2	Mid-AM	E	48.1	58.2	46.5	57.5	66.2	55.4
			W	58.7	69.1	56.4	64.4	75.0	60.6
EB	Lane 2	Early PM	E	44.6	55.9	43.4	44.0	54.3	42.9
			W	52.5	62.0	52.1	50.0	59.7	50.3
EB	Lane 2	Late PM	E	46.2	56.9	45.5	52.7	62.8	49.8
			W	57.5	68.3	54.5	59.6	70.9	56.6
WB	Lane 1	Early AM	E	61.5	78.4	64.4	64.5	78.0	73.6
			W	65.3	74.0	73.3	72.1	77.3	81.6
WB	Lane 1	Mid-AM	E	62.2	80.0	63.9	60.7	74.7	69.1
			W	60.3	72.4	66.8	66.7	75.4	75.7
WB	Lane 1	Early PM	E	62.4	83.0	65.1	63.0	82.3	65.4
			W	57.9	71.9	63.3	56.0	72.0	59.4
WB	Lane 1	Late PM	E	62.1	80.5	64.6	61.2	78.2	64.5
			W	59.3	72.7	65.8	61.9	72.2	69.7
WB	Lane 2	Early AM	E	52.3	57.1	58.3	62.9	67.2	67.8
			W	72.7	77.1	75.1	83.2	86.2	85.9
WB	Lane 2	Mid-AM	E	48.1	53.1	53.7	53.9	58.0	59.5
			W	63.3	66.9	68.0	73.0	77.0	75.7
WB	Lane 2	Early PM	E	48.7	56.0	52.7	44.6	49.4	50.2
			W	57.7	63.2	61.3	52.1	57.4	56.4
WB	Lane 2	Late PM	E	47.0	53.8	52.0	52.1	57.5	56.7
			W	61.7	68.2	64.1	67.8	71.7	70.9

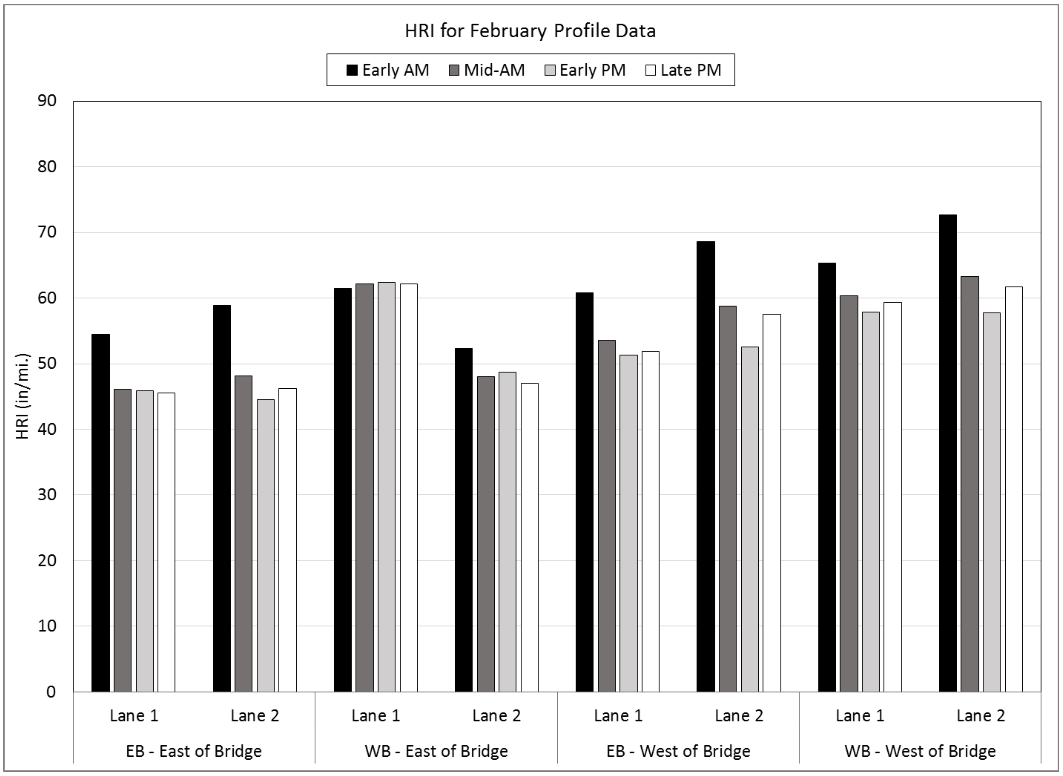

Figure 8. Overall diurnal HRI values from February profile data.

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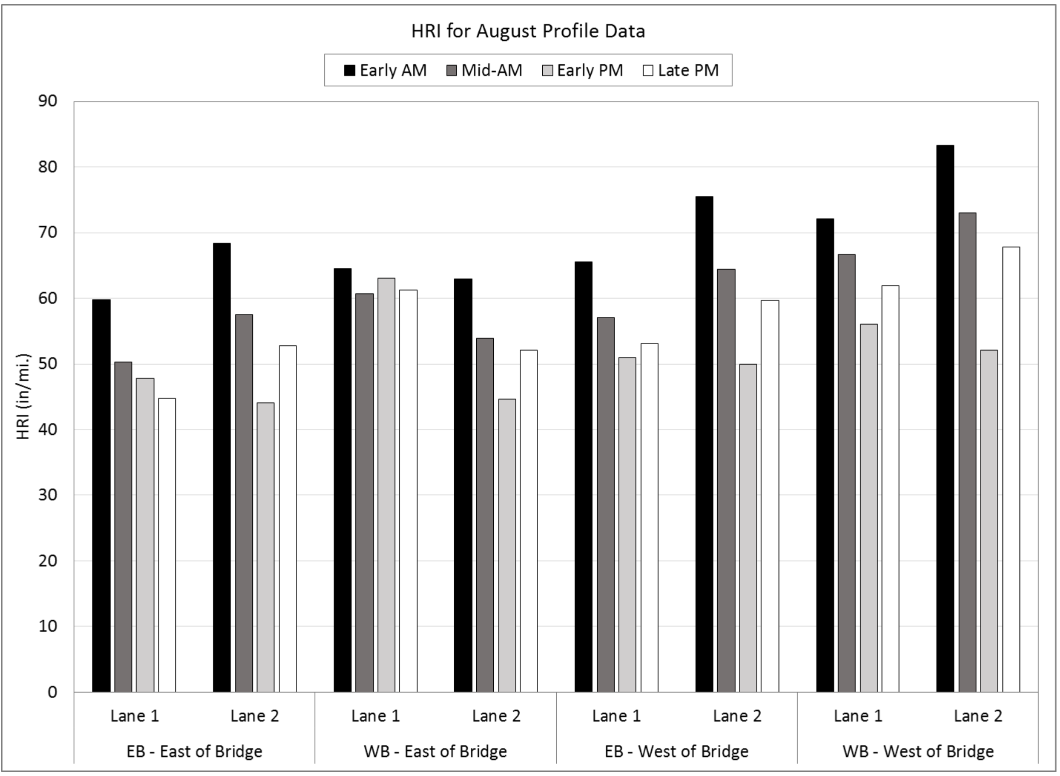

Figure 9. Overall diurnal HRI values from August profile data.

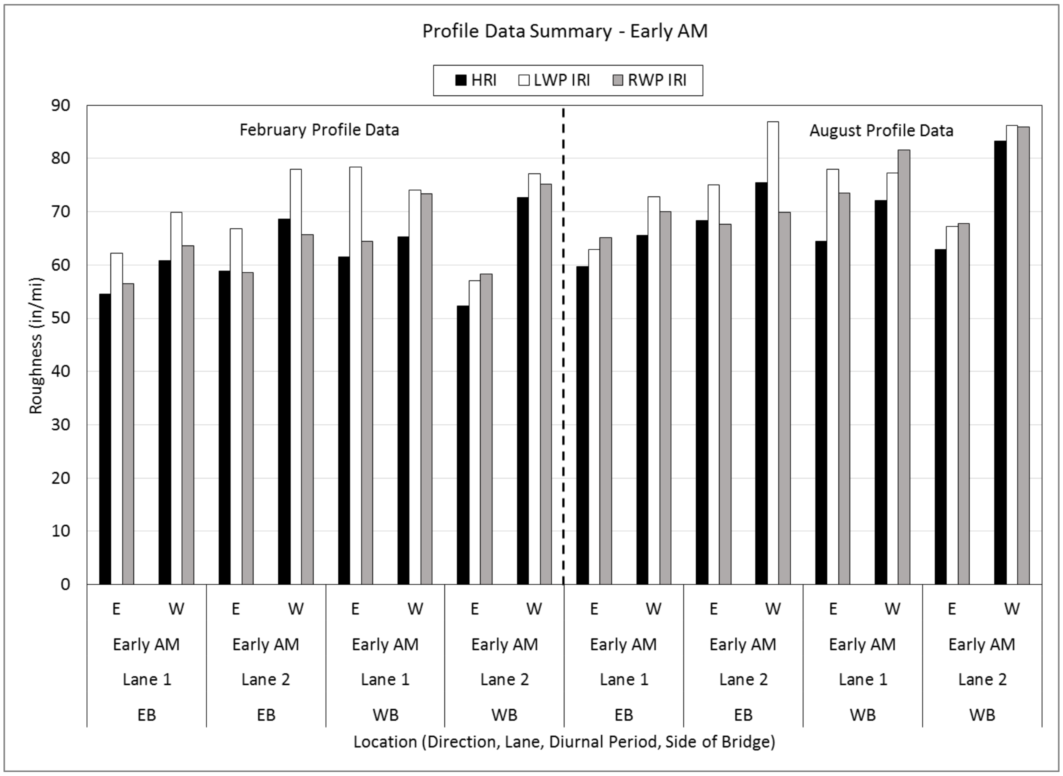

Figure 10. Summary of early AM ride quality from US 34 evaluation.

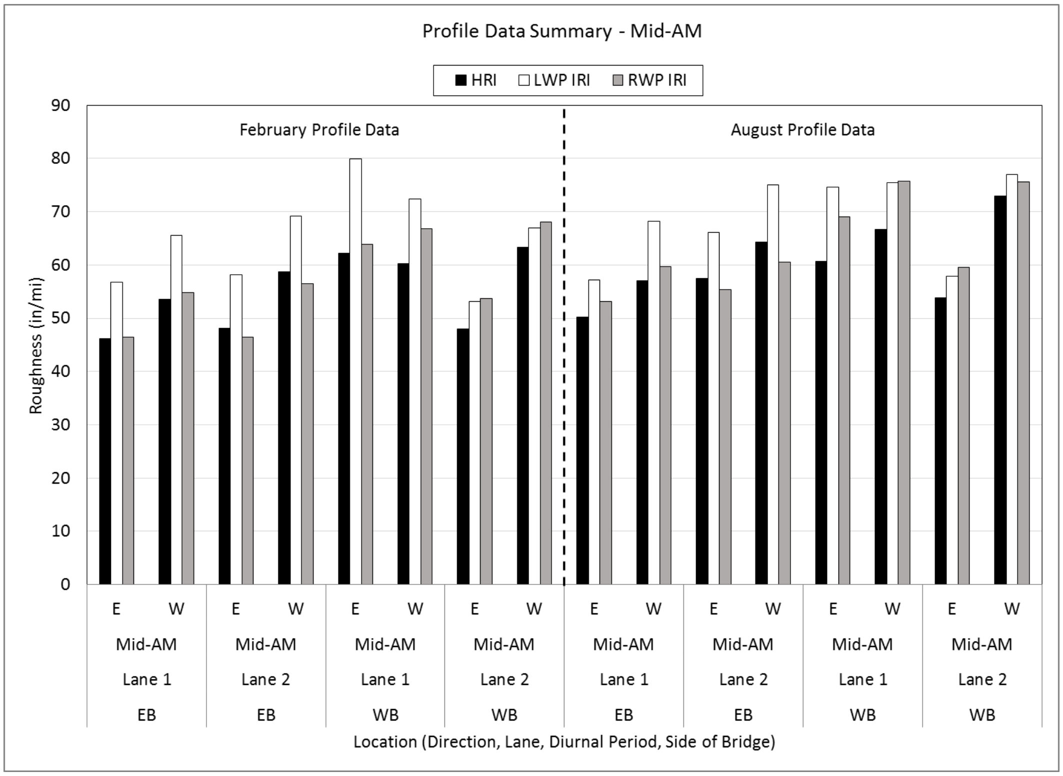

Figure 11. Summary of mid-AM ride quality from US 34 evaluation.

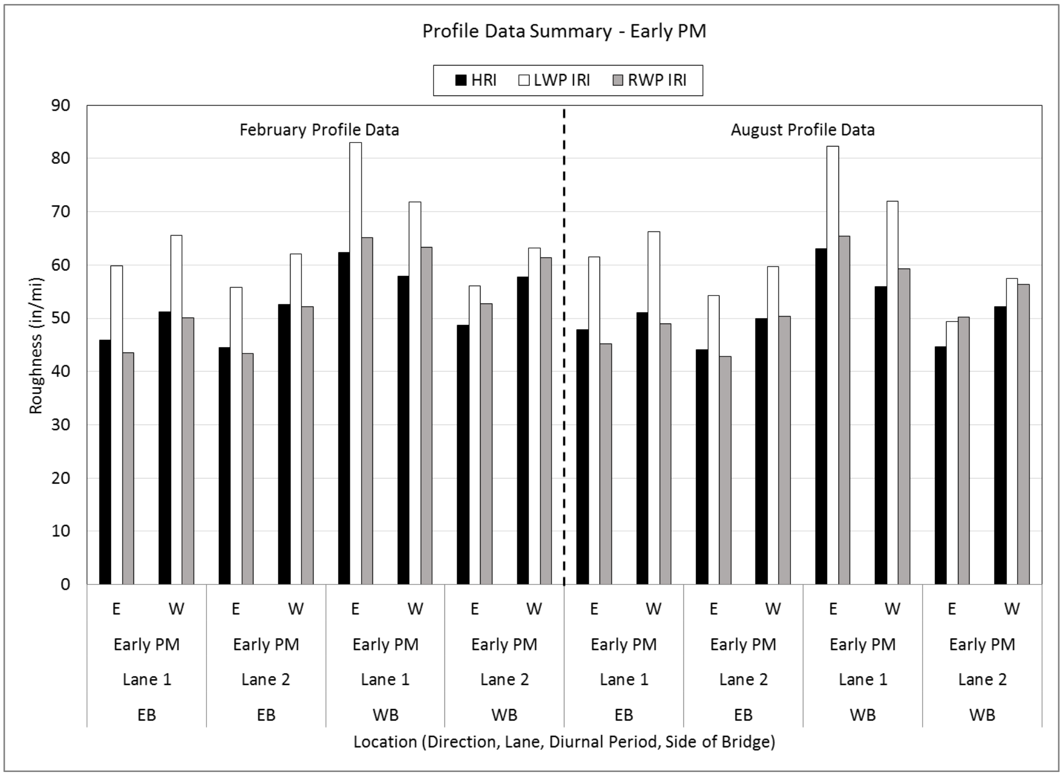

Figure 12. Summary of early PM ride quality from US 34 evaluation.

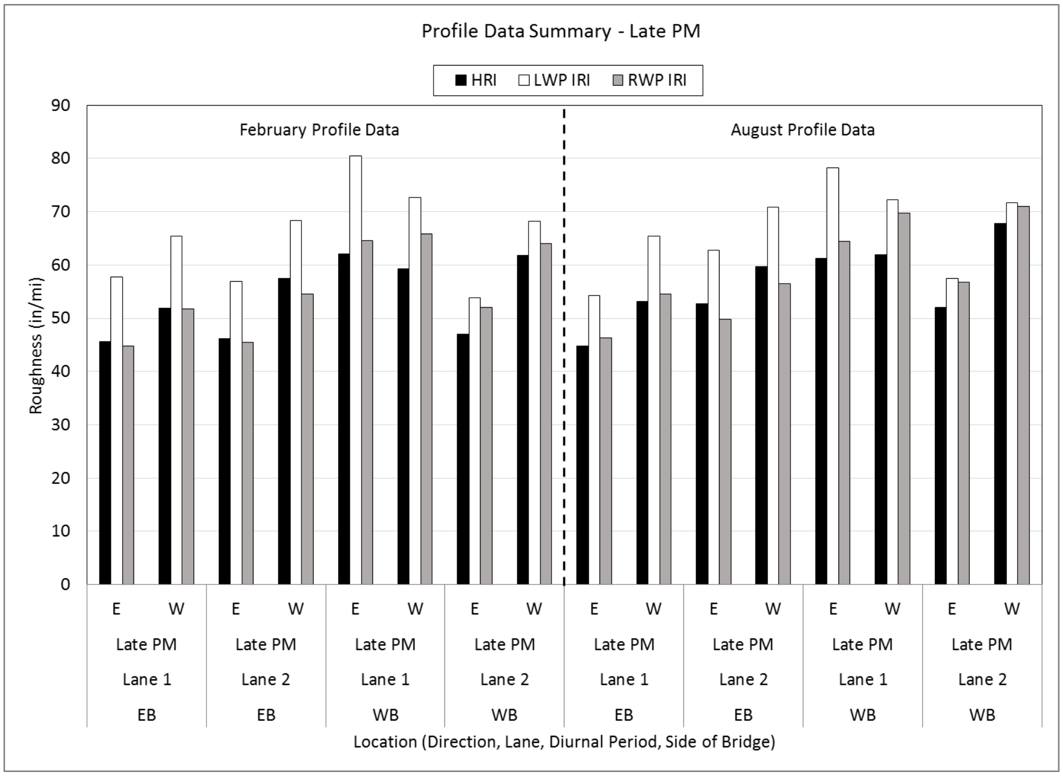

Figure 13. Summary of late PM ride quality from US 34 evaluation.

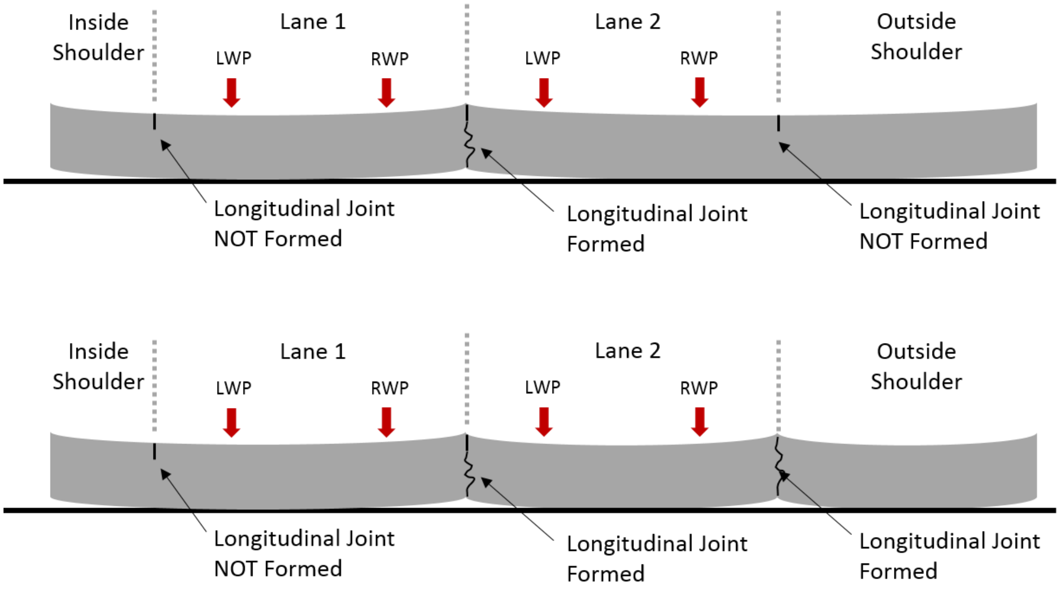

Figure 14. Longitudinal joint formation scenarios that could lead to variations in ride quality between lanes.

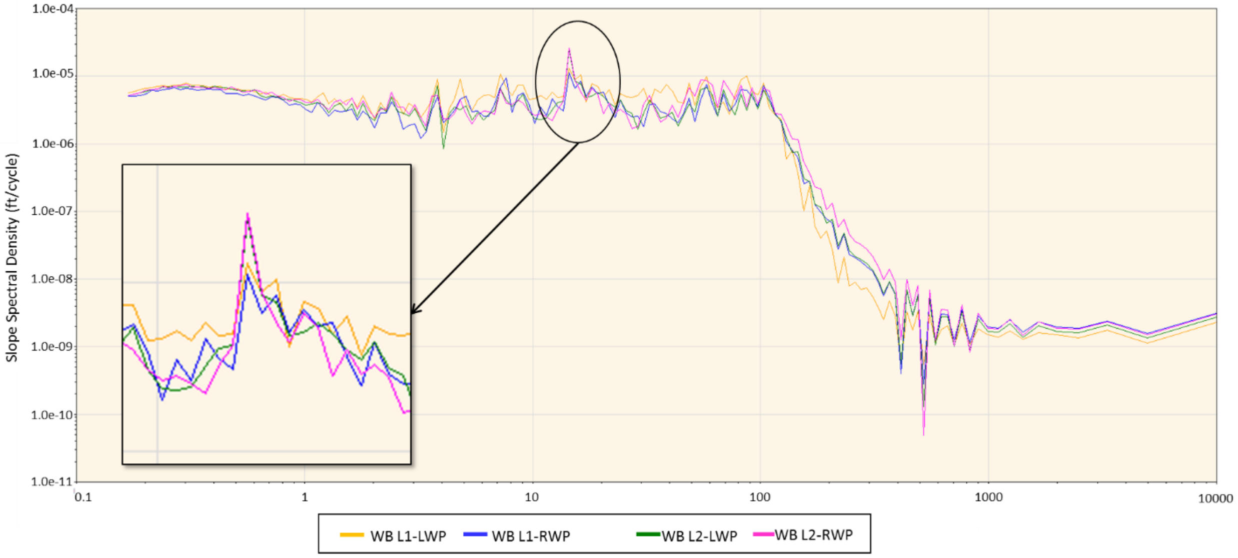

Figure 15. ProVAL PSD plot for WB lane 1 and WB lane 2.

Effect of Slab Temperature Gradient

In order to examine the effect of the slab temperature gradient (during profiling) on roughness, Figure 16 shows a plot of HRI values versus top-bottom slab temperature differentials by lane (excluding WB lane 1, east of the bridge which showed little change in roughness with temperature). The trend for each lane shows increasing roughness with increasingly negative temperature gradient and decreasing roughness with increasingly positive temperature gradient, but not necessarily linearly across negative and positive temperature gradients. This trend confirms the effect of slab temperature differentials on roughness and also confirms a built-in upward slab curl that becomes more severe, increasing roughness, as the negative temperature differential increases, and becomes less severe, decreasing roughness, as a positive temperature differential increases. While the trend is clear, a definitive correlation between HRI and temperature gradient is not very strong, even separated by lane.

When examining temperature gradient versus roughness by wheelpath IRI (since LWP and RWP were generally quite different), a reasonable – but still not very strong for all lanes – correlation was observed for the RWP profiles (Figure 17), but not for the LWP profiles (not shown). The overall trend observed when comparing HRI to slab temperature gradient is still the same for the RWP data, but was not the same for the LWP data.

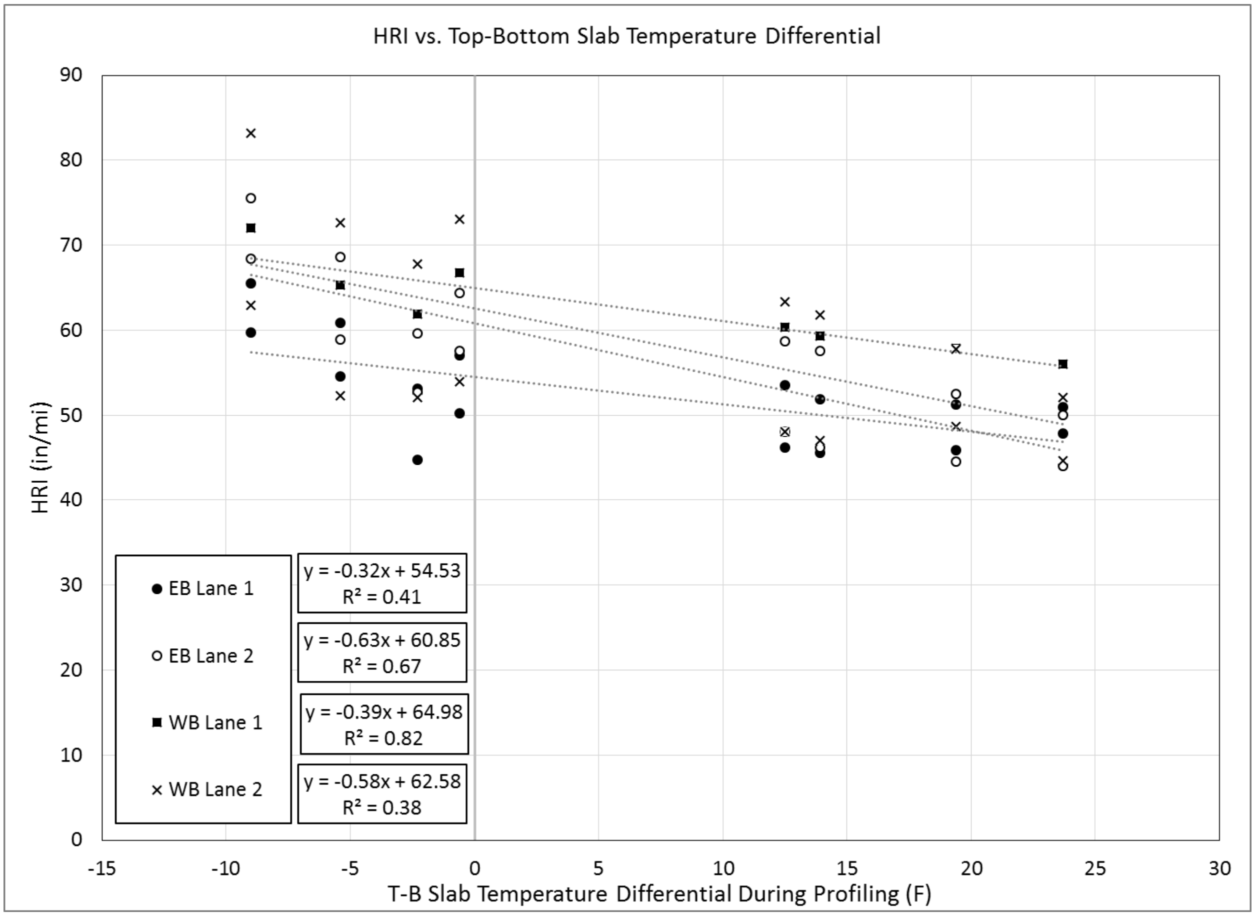

Figure 16. Relationship between HRI and top-bottom slab temperature differential.

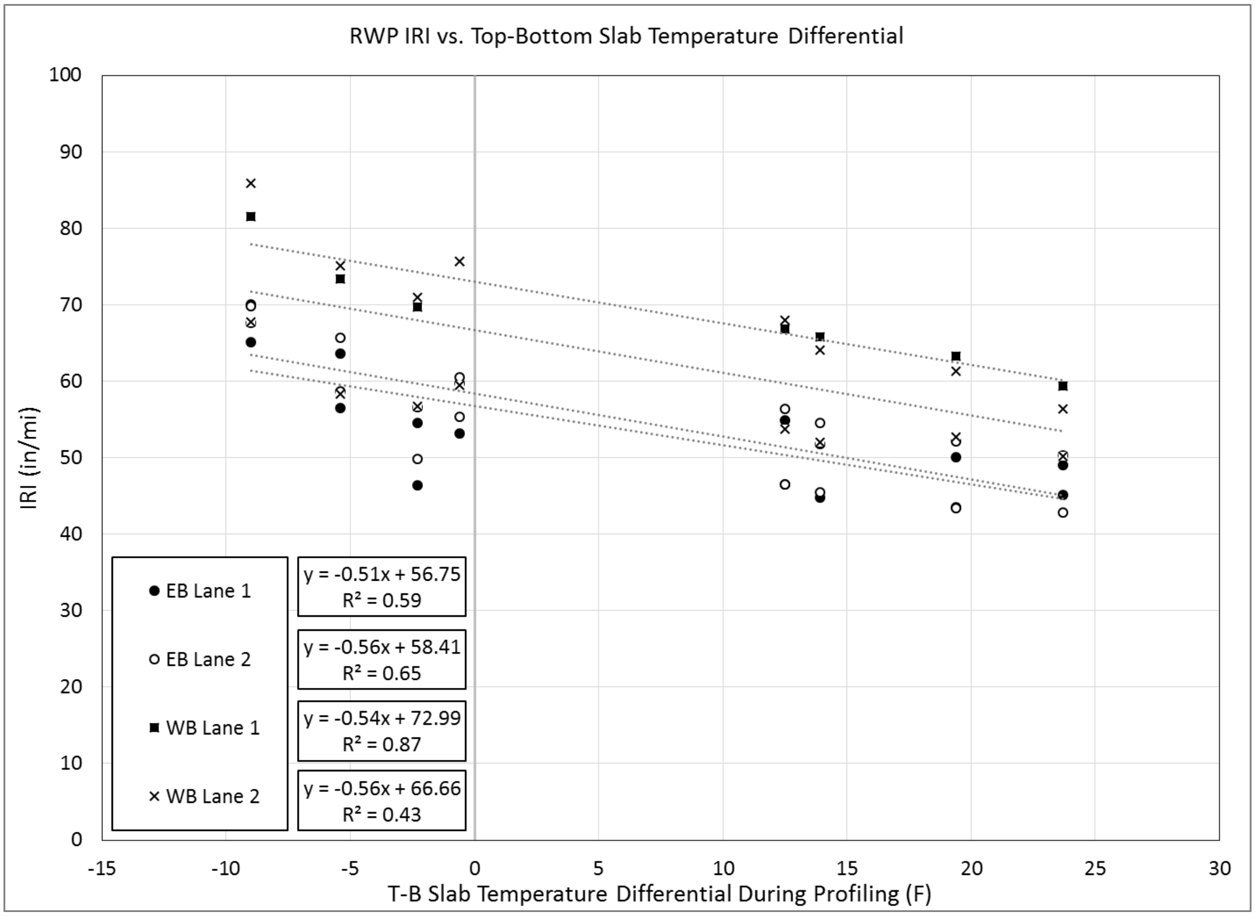

Figure 17. Relationship between RWP IRI and top-bottom slab temperature differential

Roughness by Paving Day

One of the key questions surrounding this evaluation was related to the effect of climatic conditions during construction on roughness. As discussed previously, the WB lanes were constructed primarily during warm to abnormally hot days, whereas the EB lanes were constructed under much cooler temperatures (see Table 5).

Table 16 in the Appendix summarizes profile data collected under this effort by paving day, and Figure 18 shows this information graphically for HRI. For simplicity, only the August profile data (which showed the most variation during the day) and only the Early AM profile data (which was consistently the highest for each lane) is shown. Figure 19 shows the maximum diurnal change in HRI for each lane by paving day. Again for simplicity, only the August profile data is shown. Maximum HRI values were all from the Early AM profiles while minimum HRI values were from either the Early PM or Late PM profiles. It is important to note that roughness shown in these plots should not be affected by localized roughness related to construction joints since construction joints only occurred at the end of each day of paving. Some key observations from this data include:

- Although there are differences in roughness between paving days for both EB and WB lanes (Figure 18), roughness does not appear to be correlated to either the ambient high/low temperatures or the difference between high and low temperatures on the days of paving. For example, Day 1 had the lowest roughness for both EB and WB lanes, yet was very different in terms of ambient conditions. WB Day 1 was the hottest day (high of 102.2°F) with the largest temperature change throughout the day (39.6°F), while EB Day 1 was one of the cooler days (high of 71.6°F) with the lowest temperature change throughout the day (19.8°F).
- The difference between lane 1 and lane 2 for several of the paving days (particularly WB Day 2) confirms what was previously observed, and the cause of this difference is not evident.
- The diurnal changes in roughness (Figure 19), likewise, do not appear to be correlated to either the ambient high/low temperatures or the change in ambient temperature during the day.
- The difference in diurnal change in roughness between lanes (Figure 19) is not readily explainable, but as discussed previously, could be related to whether longitudinal and/or transverse joints had formed.

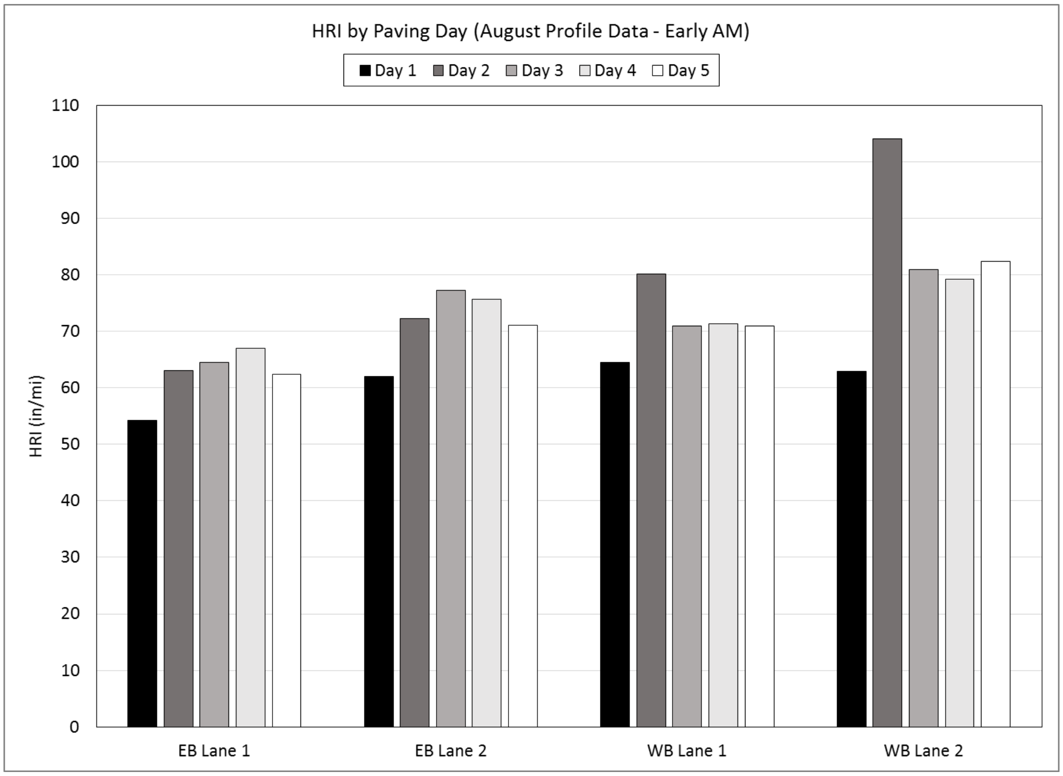

Figure 18. Overall HRI by paving day Early AM August profile data.

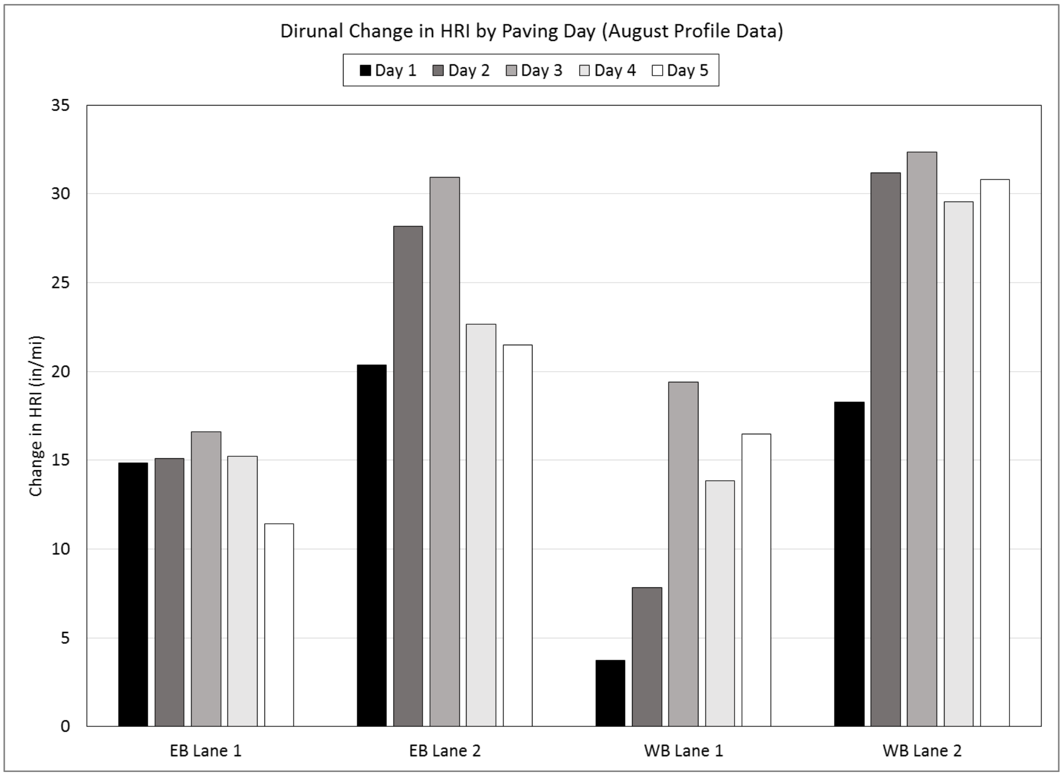

Figure 19. Diurnal change in HRI for August profile data.

Evaporation Rate by Day

As discussed previously, moisture gradients in jointed concrete pavement slabs due to surface moisture loss from evaporation are also known to contribute to slab curling, and generally upward slab curling. While the moisture gradient in a pavement slab is difficult to predict, at early age it is highly dependent upon the evaporation rate at the top surface of the pavement during construction, along with curing methods that are used. As such, the evaporation rates for each day of paving for US 34 were computed in accordance with the ACI Guide to Hot Weather Concreting (ACI, 2010) and are summarized in Table 9. Shown in the table are evaporation rates during the daily paving window and for the first 24 hours from the start of paving. Note that for hot weather paving an evaporation rate exceeding 0.2 lb/ft^2/hr is considered the threshold at which precautions are needed to prevent plastic shrinkage cracking (ACI, 2010).

Evaporation rate is affected by the temperature of the concrete, and therefore two different concrete temperatures were evaluated: 90°F (CDOT maximum placement temperature) and 75°F. Although the actual concrete temperatures are not known, the WB lanes were likely placed at temperatures closer to 90°F, and the EB lanes were likely placed at temperatures closer to 75°F. Assuming this is the case, the evaporation rate for the WB lanes was potentially much higher than that for the EB lanes, which could have resulted in higher moisture gradients and additional upward curling and associated roughness in the WB lanes. In theory, proper curing practices will greatly reduce the effects of the evaporation rate on surface moisture loss, and it must be assumed that the contractor followed CDOT curing protocols. However, because moisture-related curling/warping of hardened concrete is not known to vary during a given day, its effects on curling-related roughness would effectively be the same throughout the day, and could explain at least part of the non-curvature roughness discussed below.

Table 9. Computed evaporation rates for various days of paving.

		Evaporation Rate (lb/ft^2/hr)					
		Paving Window				First 24 hrs.	
		Tc = 90°F		Tc = 75°F		Tc = 90°F	Tc = 75°F
WB lanes	**Paving Day**	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Avg.
7/20/2012	1	0.225	0.129	0.114	0.071	0.207	0.105
7/23/2012	2	0.153	0.057	0.068	0.026	0.203	0.101
7/24/2012	3	0.173	0.097	0.084	0.048	0.221	0.105
7/25/2012	4	0.238	0.142	0.110	0.067	0.192	0.089
7/26/2012	5	0.134	0.048	0.061	0.022	0.178	0.086
EB lanes	**Paving Day**	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Avg.
9/13/2012	1	0.157	0.063	0.082	0.035	0.141	0.074
9/14/2012	2	0.068	0.022	0.035	0.012	0.165	0.090
9/17/2012	3	0.231	0.093	0.124	0.051	0.185	0.100
9/18/2012	4	0.223	0.084	0.122	0.048	0.179	0.098
9/19/2012	5	0.091	0.123	0.091	0.071	0.251	0.140

Slab Curvature Analysis

Analyzing slab curvature from profile data provides a method for isolating the effects of slab curvature on roughness from non-curvature related roughness. In order to do this, multiple sets of profile data are needed, ideally from different times of the day and different seasons of the year, as was done for the US 34 evaluation.

For the slab curvature analysis, profile data were used to approximate the curled slab shape that was then quantified in terms of the Second Generation Curvature Index or 2GCI per the procedure developed by Chang et al. (Chang, 2008). The median curvature values from each set of profile data were then used for correlations with roughness (IRI and HRI) and slab temperature gradients to examine any possible differences between the EB and WB lanes.

Procedure

The procedure for estimating 2GCI values for each set of profile data is described in more detail elsewhere (Chang, 2008; Chang, 2010), and summarized briefly below.

Synchronization of Profile Data

The first step in the curvature analysis was to synchronize repeat sets of profile data for each lane. The ProVAL Profile Synchronization module was used to synchronize repeat measurements from the various diurnal periods. Because automated triggering was used for profile data collection, synchronization required only very minor adjustments/offsets of the profile data. Unfortunately, it was not possible to synchronize profile data between the February and August site visits with a high level of confidence, so February and August profile data were analyzed separately.

Isolation of Individual Slabs

The next step was to isolate individual slabs within each set of profile data. This was done using the Automated Faulting Module (AFM) within the ProVAL software which uses various algorithms to identify joint locations. In general, the “Spike” joint detection method provided the most comprehensive list of joint locations. However, it was still necessary to manually input joint locations where they were missing from the ProVAL analysis. Missing joint locations could generally be identified visually from the high-pass filtered profile data. Joint locations were used to create joint files used by the 2GCI software to isolate individual slabs within each set of profile data for analysis.

2GCI Computation

Using the synchronized profile data and joint files, the 2GCI software program, developed by Transtec, was used to compute a curvature index for each wheelpath of each slab of each set of profile data collected under this effort. The 2GCI algorithm uses Westergaard’s curling equations (Westergaard, 1926; Westergaard, 1927) and real-world joint restraints to derive a curvature metric that fits hypothesized slab geometries to their measured slab profile. The model parameters of the 2GCI have connection to the physical parameters that describe a jointed concrete pavement system subjected to curling and warping. Since these model parameters characterize effects beyond what the Westergaard model considers directly (such as slab restraint due to joint reinforcement), they are termed “pseudo” parameters, and as such the “pseudo strain gradient” (herein referred to as the 2GCI) is computed.

While some idealized slab shapes fit the actual data very well, as shown in Figure 20, other approximations were not as good, as shown in Figure 21. Because so many slabs are analyzed for each profile, however, these seeming anomalies are averaged out. In general, most slabs exhibited a curled-up shape, but for a number of slabs, collected during the Late AM profiling period in particular, a downward-curled slab shape resulted in positive curvature indices, as shown in Figure 22.

In total, 80 sets of profile data and corresponding joint files were analyzed, resulting in 2GCI computation for roughly 520-540 slabs for each set of profile data or approximately 21,000 slabs total. In order to reasonably assess the results from so many slabs, summary statistics, including the minimum, maximum, median, and 1st and 3rd quartile summary statistics were computed for each wheelpath of each profile.

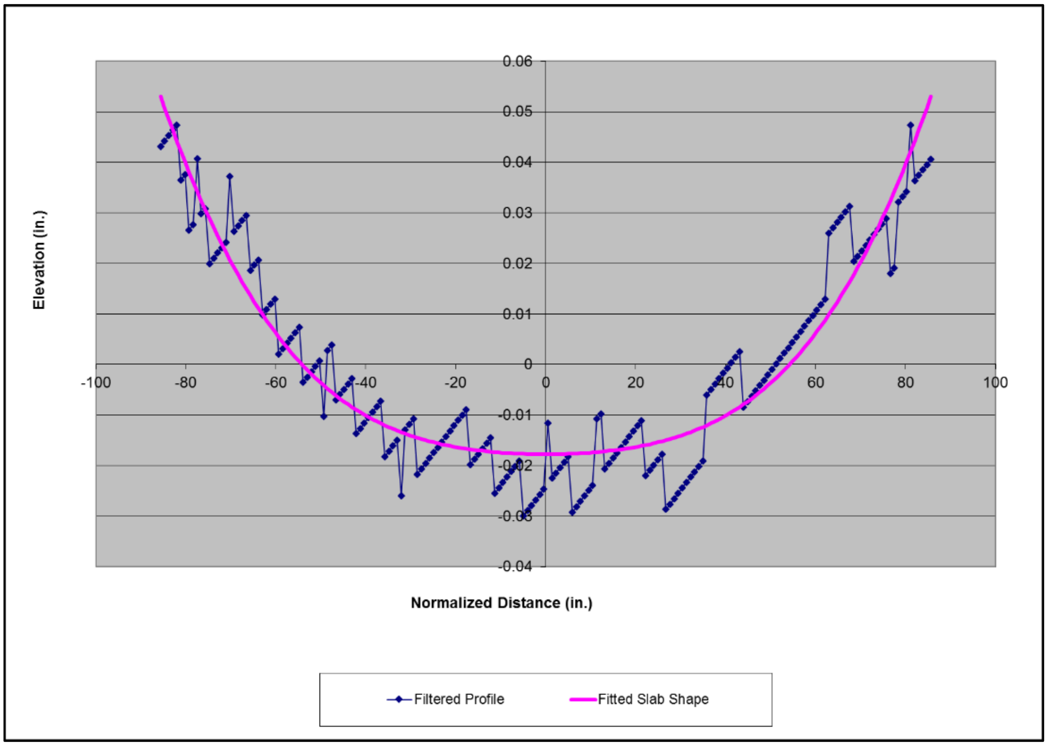

Figure 20. Example of upward curvature slab fitting from 2GCI analysis.

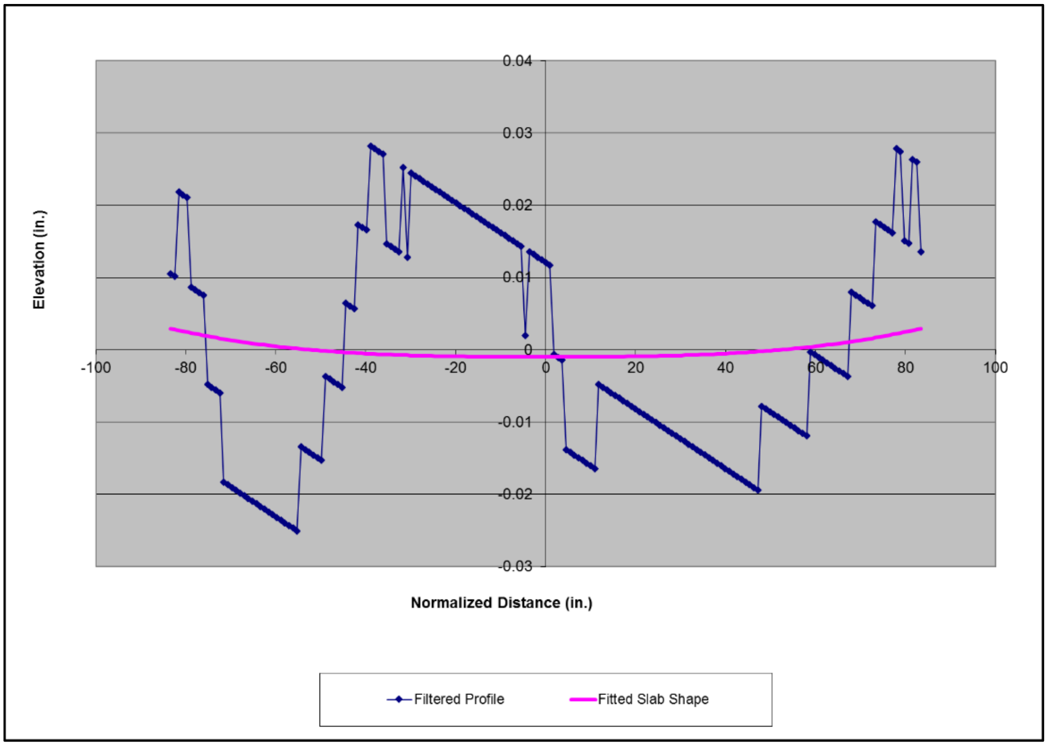

Figure 21. Example of poor slab fitting from 2GCI analysis.

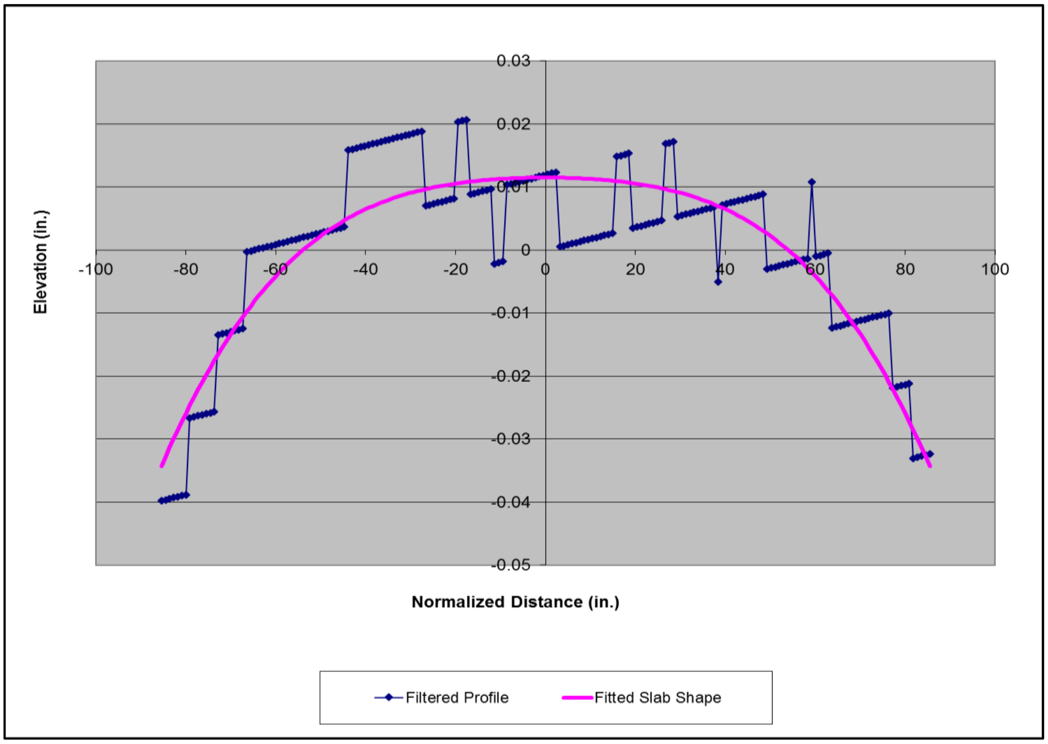

Figure 22. Example of downward curvature slab fitting from 2GCI analysis.

Results

Table 17 in Appendix B provides the summary statistic 2GCI values for each set of profile data. Because of the potentially large variation in curvature index within a given profile, the summary statistic used for analysis was the median value for each wheelpath. The two wheelpath median values were averaged when computing the 2GCI value for each lane.

As Table 17 shows, with a few exceptions, the curvature indices were essentially all negative, indicating a curled-up slab shape at all times of the day in both summer and winter seasons and in both EB and WB directions. This built-in curled up shape is typical for jointed concrete pavements constructed during the daytime in a dry, sunny climate. The severity of this curled-up slab shape varies by time of day, as reflected in the 2GCI, affecting roughness as discussed below.

Curvature vs. Roughness

In order to evaluate the effect of slab curvature on roughness, the 2GCI values from each set of profile data were correlated to ride quality values for the same profile data. The correlation between curvature and roughness were summarized statistically by wheelpath, lane, direction, and side of the bridge as shown in Table 10. Data were analyzed for each wheelpath using the IRI for the wheelpath and curvature index for the corresponding wheelpath. Data for each lane were analyzed using the HRI data for the lane and average of the median LWP and RWP curvature indices for the lane.

Figure 23 shows the roughness-curvature relationship by direction (EB lanes vs. WB lanes), and Figure 24 and Figure 25 show the curvature-roughness relationship based on individual wheelpaths. A clear trend is seen in these plots – that of increasing roughness with an increasingly negative curvature value. Looking at the HRI for the EB and WB lanes overall, the change in roughness with curvature (“Slope” in Table 10) is very similar for both, indicating that despite differences in ambient conditions during construction, changes in slab curvature with temperature are very similar.

As implied by these plots, the “zero curvature” roughness, or y-axis intercept, is the estimated non-curvature-related roughness. Table 10 summarizes this zero-curvature roughness in the “Intercept” column. The zero-curvature roughness for the overall EB and WB lanes is also very similar (within 3 in/mi), again indicating that the difference in WB and EB is not substantial when looking at the data as a whole.

As might be expected, the standard error and R-squared coefficient (Table 10) improve as the data are further parsed by direction, lane, side of the bridge, and wheelpath, thereby reducing the sample size. However, the data also show the relationship between curvature and roughness by specific locations, indicating for example, how curvature has virtually no impact on roughness for the LWP of WB lane 1. When looking at the roughness-curvature relationship by wheelpath, the left wheelpath data for both EB and WB is more erratic, particularly for the WB lanes. This confirms what was observed previously, when looking just at roughness data.

Table 10. Summary statistics for curvature-ride quality correlation.

lane	Profile	Overall				East of Bridge				West of Bridge			
		Slope	Intercept	R^2	Std. Error	Slope	Intercept	R^2	Std. Error	Slope	Intercept	R^2	Std. Error
EB lanes (Both)	***lane (HRI)***	**-0.49**	**41.6**	**0.79**	**3.61**	**-0.49**	**38.5**	**0.90**	**2.28**	**-0.46**	**45.3**	**0.94**	**1.78**
	Left	-0.36	55.2	0.57	4.93	-0.36	51.2	0.84	2.25	-0.30	60.3	0.68	3.62
	Right	-0.48	41.7	0.76	3.80	-0.52	37.5	0.88	2.69	-0.43	45.7	0.93	1.80
EB lane 1	***lane (HRI)***	**-0.39**	**44.0**	**0.65**	**3.56**	**-0.49**	**38.3**	**0.93**	**1.63**	**-0.35**	**47.4**	**0.92**	**1.52**
	Left	-0.19	60.0	0.17	5.03	-0.26	53.7	0.77	1.65	-0.18	64.2	0.78	1.30
	Right	-0.51	40.0	0.78	3.54	-0.63	33.6	0.94	2.05	-0.47	43.6	0.95	1.69
EB lane 2	***lane (HRI)***	**-0.55**	**40.0**	**0.85**	**3.58**	**-0.49**	**38.7**	**0.89**	**2.83**	**-0.52**	**43.5**	**0.98**	**1.27**
	Left	-0.53	48.0	0.87	3.20	-0.41	49.3	0.89	2.36	-0.56	49.2	0.97	1.61
	Right	-0.46	42.5	0.76	4.08	-0.49	38.7	0.89	2.94	-0.40	47.2	0.96	1.37
WB lanes (Both)	***lane (HRI)***	**-0.51**	**44.7**	**0.60**	**5.84**	**-0.29**	**47.4**	**0.22**	**6.46**	**-0.49**	**47.5**	**0.71**	**4.16**
	Left	-0.36	56.8	0.24	8.82	0.16	65.1	0.04	11.03	-0.16	66.8	0.14	6.53
	Right	-0.61	44.6	0.78	4.38	-0.53	45.6	0.64	4.67	-0.57	47.2	0.73	4.08
WB lane 1	***lane (HRI)***	**-0.35**	**54.5**	**0.83**	**1.59**	**-0.16**	**58.8**	**0.61**	**1.30**	**-0.45**	**51.3**	**0.97**	**0.87**
	Left	0.00	75.3	0.00	2.52	0.05	77.8	0.07	2.11	-0.17	69.3	0.80	0.91
	Right	-0.50	52.4	0.90	1.77	-0.56	50.5	0.99	0.63	-0.48	53.0	0.86	2.30
WB lane 2	***lane (HRI)***	**-0.65**	**37.2**	**0.87**	**4.00**	**-0.40**	**41.2**	**0.90**	**1.81**	**-0.68**	**37.8**	**0.87**	**3.62**
	Left	-0.59	44.3	0.85	3.87	-0.34	48.2	0.85	1.98	-0.62	45.2	0.90	2.82
	Right	-0.60	42.7	0.87	3.66	-0.40	46.3	0.87	2.03	-0.64	42.0	0.83	3.85

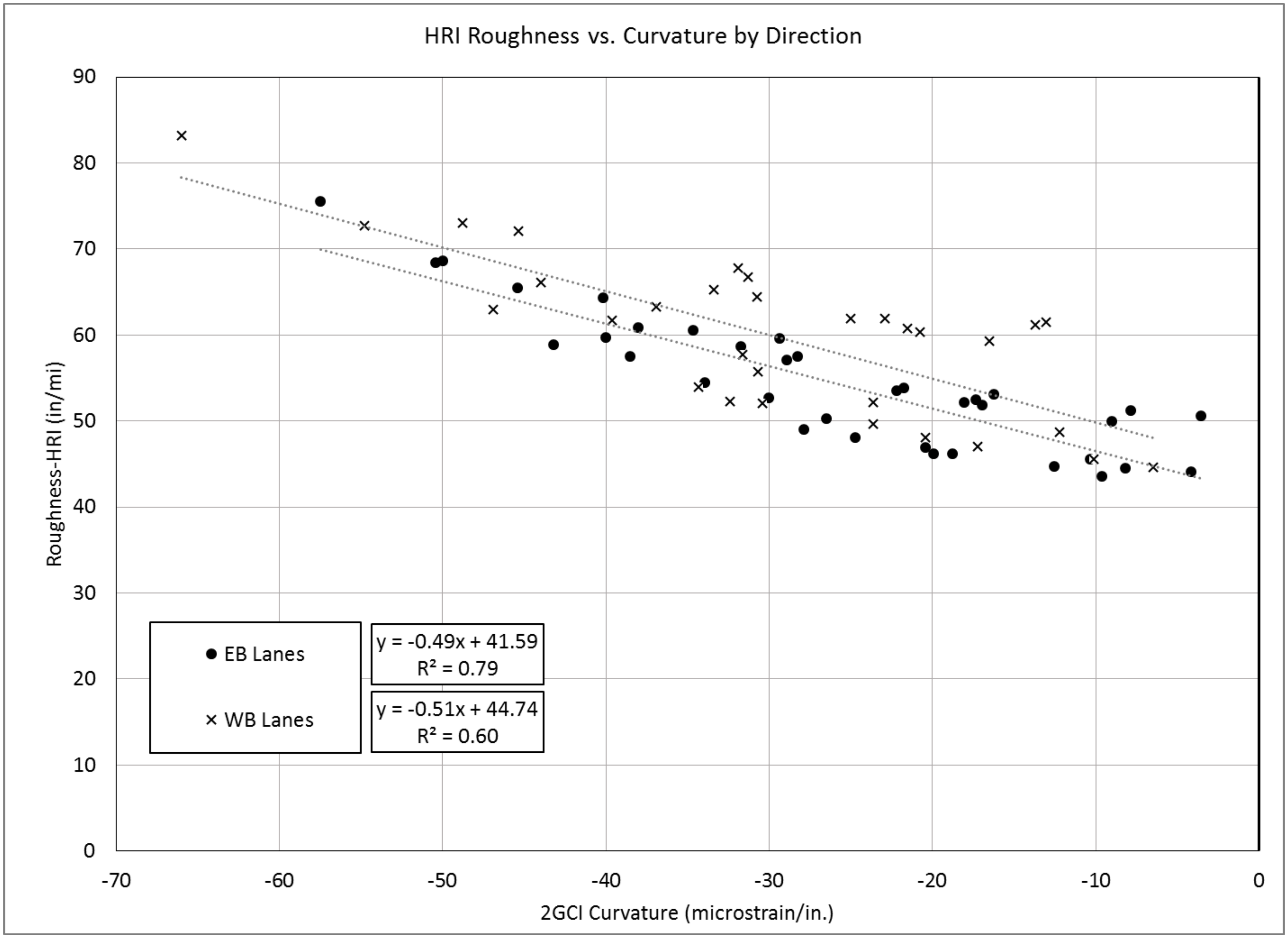

Figure 23. Plot of HRI vs. curvature for EB and WB lanes.

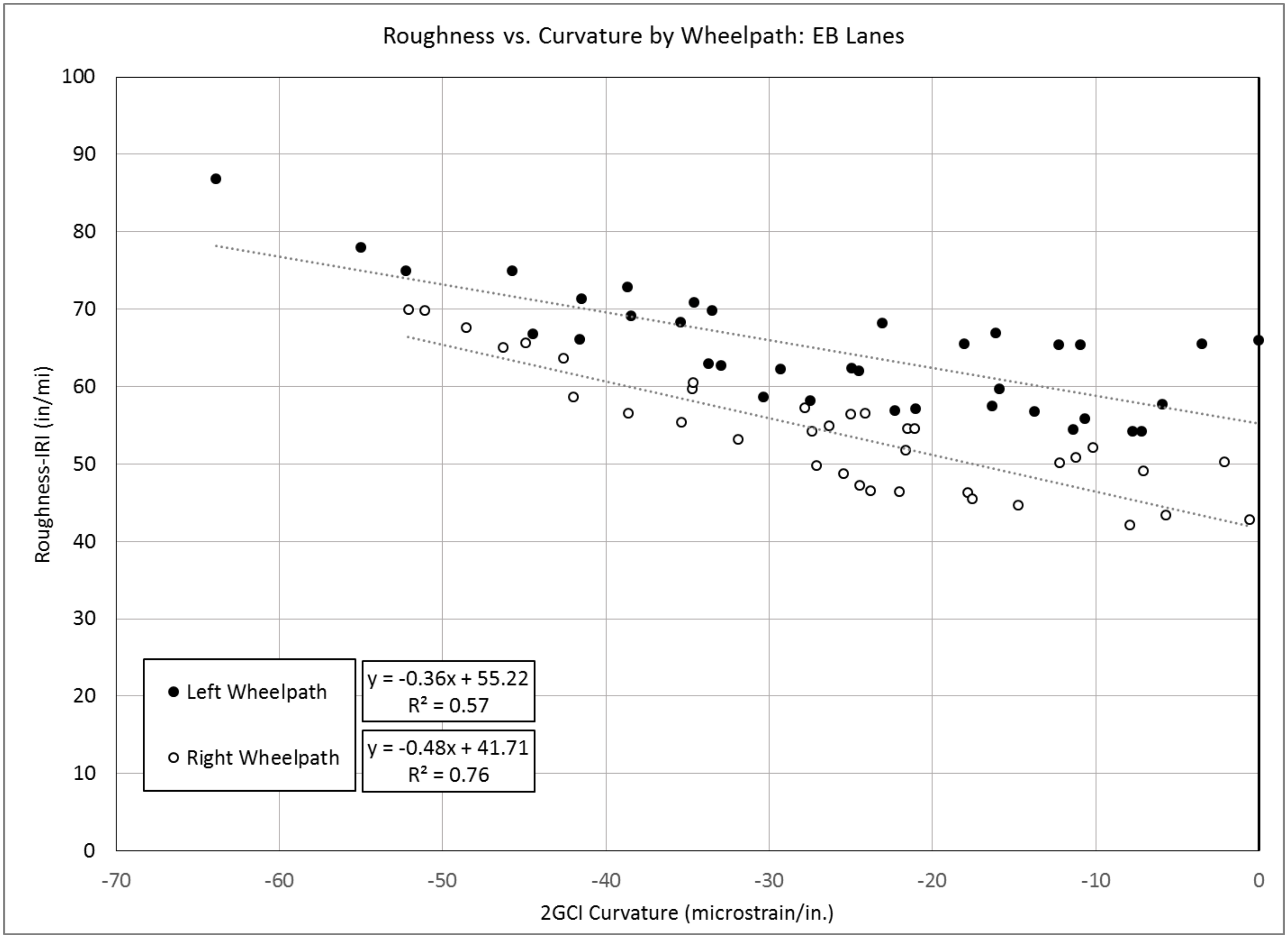

Figure 24. Plot of IRI vs. curvature by wheelpath for EB lanes.

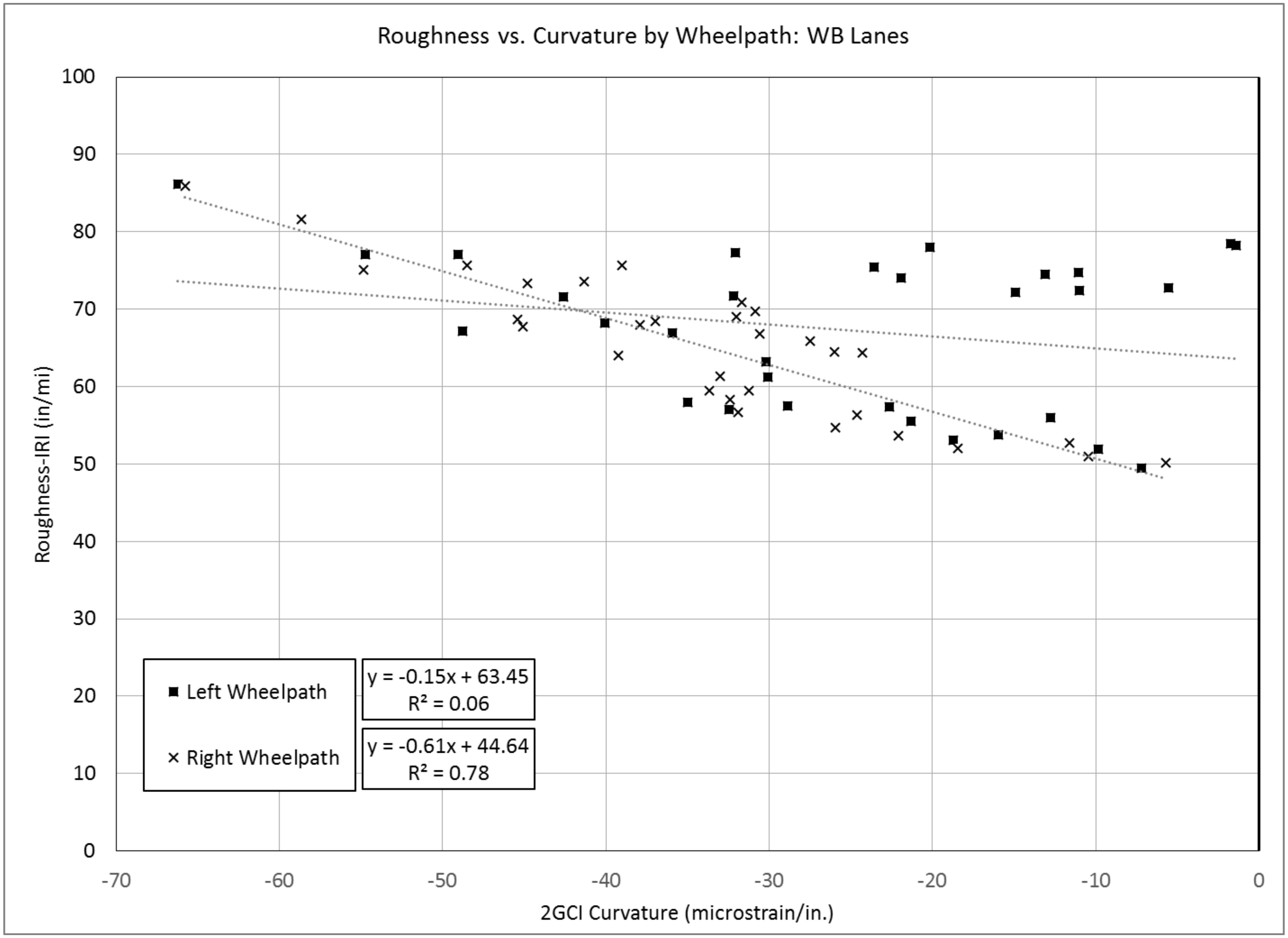

Figure 25. Plot of IRI vs. curvature by wheelpath for WB lanes.

Curvature and Non-Curvature Roughness

Using the relationships between curvature and roughness shown above, curvature-related roughness and non-curvature-related roughness can be separated. Figure 26 shows curvature-related roughness in terms of HRI, and Figure 27 shows non-curvature-related roughness by lane (as HRI) and by wheelpath (IRI). Non-curvature-related roughness was computed by subtracting curvature-related roughness (“Intercept” in Table 10) from overall roughness.

As Figure 26 shows, the effect of curvature on roughness over the course of a given day can be substantial. For WB lane 2, nearly 40 in,/mi. of roughness can be attributed to slab curling when profile data is collected in the early morning but only 17 in./mi. when profile data is collected in the early afternoon. The reason for the significant difference between lanes for a given direction and side of the bridge is not readily evident, but may be related to formation of longitudinal and transverse joints, as discussed previously, or it may be related to the width of the tied shoulder.

In each case, curling-related roughness was higher for lane 2 than lane 1 for all periods of the day. It should be noted, however, that curvature-related roughness is not higher for the WB lanes than the EB lanes in all cases. Lane 1 and lane 2 east of the bridge, for example, show higher curvature-related roughness for the EB lanes than WB lanes.

Figure 27 shows the non-curvature roughness for each lane on either side of the bridge in both directions. Note that non-curvature roughness is not affected by changes in slab curling, and is therefore a constant for each lane. As noted previously, there is a significant difference between the LWP and RWP for most, but not all, of the lanes. When examining HRI, the WB lanes generally show higher roughness, with the exception of lane 2 west of the bridge. All of the HRI data, however, fall well below the CDOT smoothness specification upper limit for full pay.

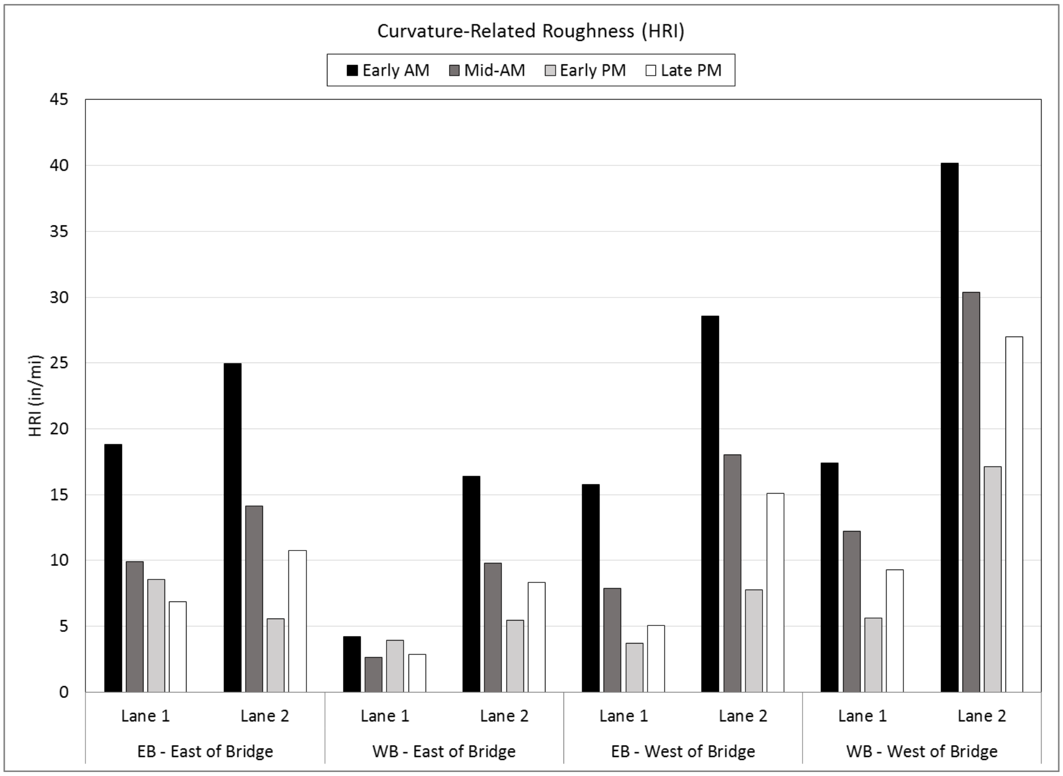

Figure 26. Summary of diurnal curvature-related roughness.

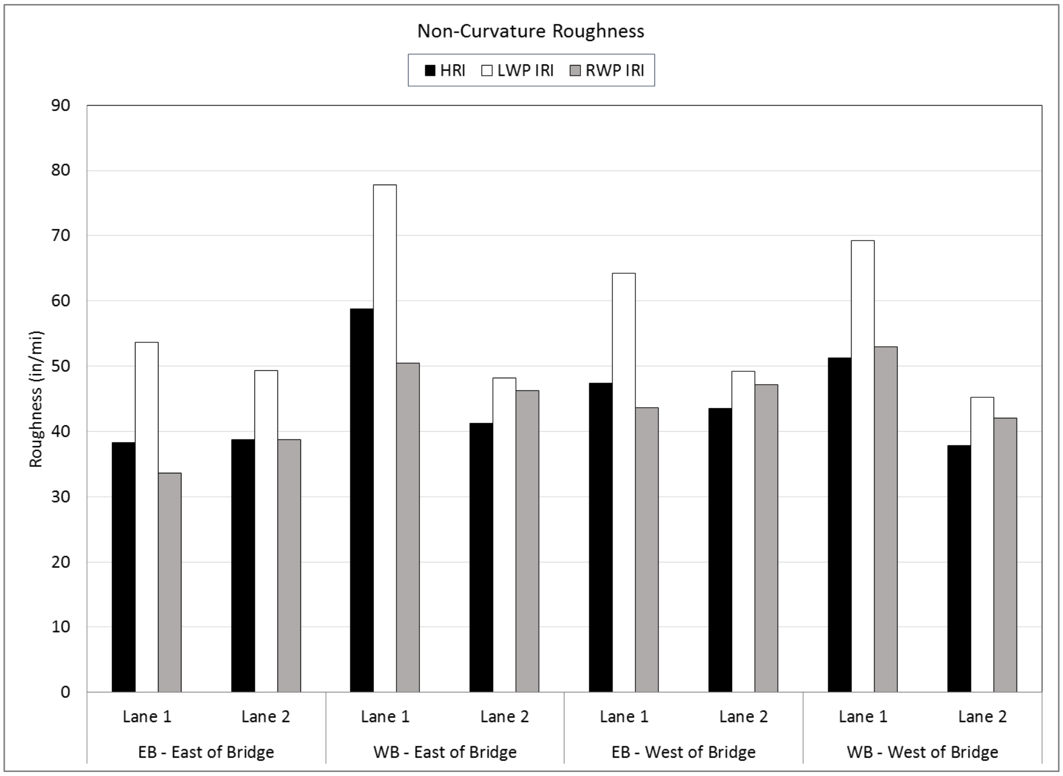

Figure 27. Summary of non-curvature roughness

Curvature and Temperature Gradient

In addition to examining the relationship between roughness and slab curvature, top-bottom slab temperature gradients were plotted against curvature to determine if any correlation could be identified. Table 11 shows the statistical results from this analysis and Figure 28 shows the relationship for the EB and WB lanes.

As Table 11 and Figure 28 show, no reliable relationship can be determined between slab temperature gradient and curvature. Standard errors are significant, even when the relationship is examined for individual wheelpaths (not shown). The lack of any reasonable correlation between temperature differential and slab curvature is likely the result of a non-linear temperature gradient in the pavement slab, which is not captured by the gradients measured during the data collection effort.

Although a correlation between top-bottom slab temperature gradient and slab curvature is not well defined, a definite trend is reflected in the data. As the temperature differential becomes more negative, negative (upward) curvature generally increases, and as the temperature differential increases positively, curvature decreases towards zero. This trend once again confirms the built-in negative temperature gradient and curled-up slab shape observed previously.

Table 11. Summary statistics for curvature-slab temperature gradient correlation.

Lane	Profile	Slope (in/mi/ microstrain/in)	Intercept	R^2	Std. Error (°F)
EB lanes	*Left*	0.43	17.6	0.42	8.07
	Right	0.66	23.4	0.80	4.71
	lane	**0.60**	**22.0**	**0.66**	**6.19**
WB lanes	*Left*	0.23	10.9	0.12	10.11
	Right	0.52	22.3	0.42	8.18
	lane	**0.40**	**16.7**	**0.27**	**9.23**

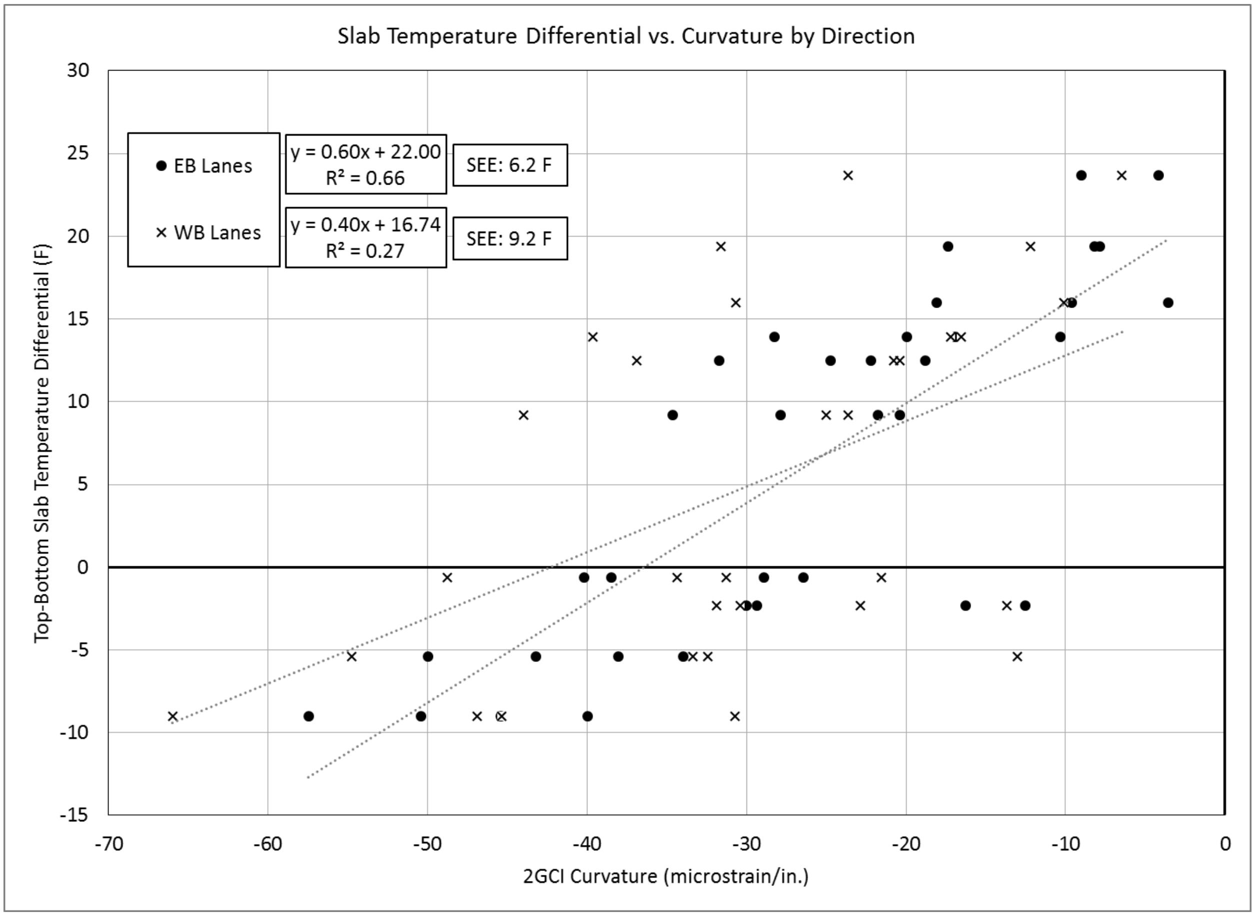

Figure 28. Plot of slab temperature differential vs. curvature.

HIPERPAV Analysis

HIPERPAV is a tool used to predict early-age concrete pavement behavior based on various design and construction inputs. The program predicts early-age stresses in the pavement slab and concrete strength development, in order to determine the optimal time to saw cut joints for jointed concrete pavement. The program can be used to evaluate different scenarios based on construction conditions and concrete design parameters in order to prevent early-age cracking and help ensure long-term pavement performance.

Evaluation Parameters

HIPERPAV was used for the US 34 evaluation to estimate temperature gradients in the pavement slab during construction. Actual concrete design parameters (slab thickness, joint spacing, base type, and subgrade support), concrete mixture design, and climatic conditions for the EB and WB lanes were used by HIPERPAV to compute slab temperature gradients during construction.

With the structural and concrete mixture design and climate inputs fixed, variables that were examined included the initial concrete mix temperature, the support layer (reclaimed asphalt base) temperature, and the curing method (i.e., single vs. double coat of liquid curing compound). Because actual concrete and base temperatures were not known, assumptions were made within reasonable limits and alternative strategies were also examined. Table 12 summarizes the as-constructed scenarios that were analyzed for the EB and WB lanes.

Table 12. HIPERPAV evaluation inputs.

Construction Factor	**EB lanes**	**WB lanes**
Paving Start Time	7 AM	7 AM
Actual ambient temperature range during first 72 hours	Low: 44.6 High: 84.2	Low: 60.8 High: 100.4
Base Temperature (at paving start)	52°F	63°F
Concrete temperature at placement (note: 90°F is CDOT limit)	75°F 90°F	75°F 90°F
Curing	Single Coat Double Coat	Single Coat Double Coat

Results

Table 13 summarizes the results from the evaluation of slab temperatures for the EB and WB lanes based on actual construction conditions. As these results show, the predicted top-bottom temperature gradients at final set are positive; meaning the top of the slab is warmer than the bottom. After final set, as the top of the slab cools and the gradient returns to zero, a curled-up slab shape results. This is consistent with the curvature observed from profiling, which was essentially always curled upwards, or a negative built-in temperature gradient.

The difference in top-bottom slab temperature differentials at final set are significant. This may account for some of the differences in roughness between the EB and WB lanes. However, it must also be recognized that the roughness measured during the site visits nearly two years after construction will inherently be different from that measured during or shortly after construction due to creep effects which may reduce the severity of curling measured at construction over time. It is also important to remember that temperature gradients are not the only cause of slab curling. Curling from moisture gradients in the pavement slab can also have a significant effect, and is not reflected in the HIPERPAV temperature prediction models.

Using the worst-case difference in top-bottom slab temperature differential between the EB and WB lanes of 16.1, the range of difference in curvature from the correlations shown in Figure 28 would be 27-40 microstrains/in, keeping in mind the significant standard error of these predictions. Using the correlations between curvature and HRI from Figure 23, this equates to a difference in HRI of 13 to 20 in/mi, depending on which curvature index is used. The difference in HRI measured during certain periods of the day, of up to 16.5 in/mi, falls within this range.

It is important to note also that both the EB and WB lanes experienced a 40°F ambient temperature swing in the first 72 hours. However, the WB lanes were exposed to much higher temperatures immediately after concrete placement, leading to higher temperatures in the top of the slab, and a larger temperature gradient, at final set.

Some additional observations from the HIPERPAV analysis of as-constructed conditions include

- concrete temperature at placement (75°F vs. 90°F) had little effect on the top-bottom slab temperature gradients,
- a double coat of curing compound had virtually no effect on slab temperature gradients, and
- the hardened concrete (72 hour) slab temperature differentials, both positive and negative, were not substantially different between the EB and WB lanes, but the WB gradient tended to be slightly higher.

Table 13. Slab temperature gradient at final set predicted by HIPERPAV.

	Concrete Temperature	**EB lanes**	**WB lanes**
Estimated top-bottom slab temperature gradient at final set	75°F	+2.8	+18.9
	90°F	+3.9	+15.6
Maximum (+) top-bottom slab temperature differential, first 72 hours		-17.7	-21.1
Maximum (-) top-bottom slab temperature differential, first 72 hours		+16.6	+18.9

Alternate Scenarios

For the purposes of providing recommendations for mitigating potential slab curling issues that were encountered on the US 34 project, additional scenarios were evaluated to determine the effect on slab temperature gradient. These scenarios were evaluated for the WB lane construction conditions (ambient temperatures) as a way to see if these factors could help mitigate the temperature gradients actually experienced during construction. Combinations of the following variables were examined for these alternate scenarios:

1. Night paving (start time of 7 PM).
2. High base temperature of 120°F to simulate a bituminous base temperature in the late afternoon/early evening.
3. Moderate base temperature of 90°F to simulate late morning/early afternoon base temperatures.
4. Cooler concrete temperature at placement (65°F), achieve by adding ice or cold water to the mix.

The results of these alternative scenarios revealed the following

- Nighttime paving (start time of 7 PM) resulted in a negative temperature gradient at final set for all cases. This is due to placing concrete over a warm or hot base, which has been heated up during the day, combined with the heat from concrete hydration being trapped in the bottom of the slab while the top of the slab cools at set during the night and early morning hours. A negative temperature gradient at set will generally result in downward curling of the slab, but this effect is also counteracted by moisture warping due to a higher moisture content at the bottom of the slab.
- Cooler concrete temperature at placement (65°F) had only a very marginal effect on slab temperature gradients, regardless of whether paving started at 7 AM or 7 PM.
- Base temperature had a significant effect on the slab temperature gradient at final set. For the scenario with 120°F base temperature, the temperature gradient at set was -15.5°F, while it was only -8.5°F for the scenario with 90°F base temperature.

While this analysis showed the effect of certain factors on slab temperature gradients, it is difficult to establish a single best practice as paving conditions for any project change throughout the day. General best practice, however, is to help minimize the temperature gradient in the pavement slab by taking into account the actual construction conditions. If paving on a hot, dry day, delaying paving until night can help reduce the built-in temperature gradient. Also, when paving over a base that tends to get hotter due to solar radiation, such as a bituminous material, measures to help cool the base will also help minimize the temperature gradient.

Mechanistic-Empirical Pavement Design Guide Analysis

A mechanistic-empirical pavement design analysis of the US 34 project was used to predict the long-term performance of the US 34 project to determine if any differences in performance can be expected for the EB and WB lanes. For this analysis, the AASHTOWare Pavement ME Design program was used to predict performance of the US 34 project based on the local climatic data, and based on varying the built-in slab temperature gradients and initial roughness (IRI).

Inputs

The analysis was performed following the design input guidance in the CDOT 2015 M-E Pavement Design Manual, along with the actual project construction information available, as described below. The software default values were used for all other inputs.

General Information

- Design life: 30 years
- Design type: Jointed Plain Concrete Pavement
- Pavement construction dates: July 2012 (westbound) and September 2012 (eastbound)
- Traffic opening: September 2012 (westbound) and November 2012 (eastbound)
- Initial IRI: 67 (baseline design) and 85 in/mi. These limits correspond to the upper limits for full pay and to values measured by the contractor after construction. (Note: although it

is recognized that the CDOT specification is for HRI the Pavement ME software does not provide the option to predict HRI.)

Traffic

- Initial two-way AADTT: (AADT x %Trucks): 12,500 x 0.09 = 1,125
  (Note: project plans show 2014 ADT=12,500, DHV truck=9% and 2034 ADT=21,580.)
- Number of lanes: two lanes each direction
- Directional distribution factor (%): 50
- Lane distribution factor (%): 90
- Traffic load spectra: Level 2 and Level 3 inputs provided in the CDOT 2015 M-E Pavement Design Manual (based on CDOT's automated vehicle classification and weigh-in-motion historical measurements). These traffic adjustment factors include vehicle class distribution and growth, monthly adjustment, axles per truck, and hourly truck distribution factors. The vehicle class for “Cluster 1” corresponding to 4-lane rural principal arterial - Non-Interstate (US Highways and State routes) was used. A growth rate of 2.77% with compound growth function was used for all the vehicle classes.

Climate

- Climatic data (air temperature, solar radiation, wind, humidity) in the software were used for a weather station near the project location, Greeley, CO.
  (Note: this information in the software is from October 1991 until March 2010, and does not cover the exact dates for construction in 2012. An alternate analysis was conducted using only the July 2002 to 2003 climate data since it represents the “hottest year” in the available data for that weather station. The intent was to simulate the hot weather observed in 2012 and continue the entire analysis repeating that climate information.)
- Estimated (from Web Soil Survey) the annual average water table depth: 10 ft.

JPCP Design Properties

The project specific design features were used as follows:

- Slab geometry
  - Joint spacing: 15 ft
  - Slab width: 12 ft
- Joint and shoulder type
  - Dowel diameter: 1.25 in
  - Dowel spacing: 12 in
- Assumed a preformed joint sealant
- Tied shoulders
- A “PCC-base full friction contact” condition was selected as the interface condition that exists between the bottom of the JPCP and the reclaimed base. An erodibility index of 4 was used to represent a fairly erodible base material.

- Permanent curl/warp effective temperature difference, ºF (“the equivalent temperature differential that corresponds to the effective permanent curl-warp locked into the pavement”): -10°F (default in the Pavement ME software); -2.5°F and -20°F (to simulate the approximate temperature gradients at final set predicted by HIPERPAV)

Structural Layers

- PCC Layer:
    - Thickness: 9 in
    - Unit weight: 142.8 pcf (from Concrete Mix Design Report)
    - Coefficient of thermal expansion (CTE): $4.8\text{x}10^{-6}$/°F (per Table G.6 CTE values of Typical CDOT PCC Mixtures in the CDOT 2015 M-E Pavement Design Manual)
- PCC mix properties (from Concrete Mix Design Report):
    - Cement type: Type I
    - Cementitious material content: 530 lb/yd^3
    - Water/cement ratio: 0.42
    - Aggregate type: granite (from Martin Marietta’s website)
    - 28-Day PCC modulus of rupture: 595 psi
- Reclaimed base layer:
    - Thickness: 8 in
    - Material type: non-stabilized base, cold recycled asphalt – RAP pulverized in place
    - Resilient modulus: 26,000 psi (default for material type)
- Subgrade:
    - Material type: A-4 (estimated from Web Soil Survey)
    - Resilient modulus: 18,200 psi (per Table 4.5, Level 3 Resilient Modulus For Embankments and Subgrade in the CDOT 2015 M-E Pavement Design Manual)

Results

Table 14 shows the results from the Pavement M-E analysis. Varying the built-in slab temperature gradient input to -2.5°F showed the most significant difference in performance predictions using the AASHTO Pavement ME Design Guide. The predicted gradients using HIPERPAV result in “failing” cracking performance predictions at 30 years. As expected, using a higher initial IRI has an impact on smoothness predictions as well, but still passed CDOT criteria.

Merely changing the construction and opening to traffic dates from July and September to September to November to represent the WB and EB lanes construction, respectively, did not make a significant difference in the performance predictions.

Site-specific weather data starting in 2012 to present is needed to create climatic files that can be used with Pavement ME to evaluate these designs based on the actual conditions during and after construction.

Table 14. Results from Pavement ME analysis of US 34.

Design	**Variables**	**30-Year Distress Predictions (90% Reliability)**		
		Terminal IRI (in/mi)	Mean Joint Faulting (in)	Transverse Cracking (% slabs)
WB lanes, baseline	N/A	166.95	0.03	4.88
EB lanes	Construction: September 2012 Traffic opening: November 2012	166.54	0.03	4.88
WB lanes, 2002-2003 weather	2002-2003 weather entire analysis	165.05	0.03	4.88
WB lanes, temperature gradients per HIPERPAV	deltaT = -2.5˚F deltaT = -20˚F	168.95 178.24	0.02 0.05	**11.83** 5.48
WB lanes, higher initial IRI	Initial IRI = 85 in/mile	189.94	0.03	4.88

Note: failure criteria recommended in the CDOT 2015 M-E Pavement Design Manual for JPCP: terminal IRI: 200 in/mi; transverse cracking: 7% slabs cracked; mean joint faulting: 0.14 in.

CONCLUSIONS AND IMPLEMENTATION RECOMMENDATIONS

The initial intent of this study centered on identifying the cause of differences in roughness between the EB and WB lanes, and differences in roughness over the course of a day. After analyzing the data collected under this effort, the differences between the EB and WB lanes turned out not to be as great as expected (WB lane 2 which caused the initial concern was the worst-case condition examined in this study). The study did reveal, however, that slab curling has a significant impact on both the EB and WB lanes, and provided insight as to how best to measure smoothness for acceptance. This issue is very important since jointed concrete pavement curling affects both functional performance (smoothness), but also the long-term structural performance of jointed concrete pavements.

Quantifying slab curvature from profile data using the 2GCI methodology provided much more insight into the effect of changes in slab curvature on roughness than the evaluation of roughness alone. The slab curvature analysis allowed curvature-related roughness to be separated from non-curvature-related roughness, so that the effect of slab curling could clearly be seen. Depending on the time of day of profiling, up to 40 in/mi (HRI) of roughness can be attributed to slab curling on the US 34 project. While it may not be practical to compute slab curvature indices in regular practice, there are some practical recommendations from this study that should be considered for improving construction practice and the collection of smoothness data on jointed concrete pavements.

Implementation Recommendations for Construction Practices

Through the HIPERPAV analysis, the effect of base temperature and time of day of paving appears to have greatest impact on slab temperature gradients. The effect of lower concrete temperature in hot weather paving was minimal, as was the effect of additional (e.g., second coat) curing compound. It is recommended that CDOT maintain the requirement for maximum concrete temperature at placement for hot weather paving, as well as the curing procedures that require membrane curing to be applied within 30 minutes of concrete placement. However, some potential modifications to current construction practice that should be considered, particularly for hot weather paving conditions, include:

1) **Nighttime Paving and/or Maximum Ambient Temperature Restrictions**
   Consider a requirement for night paving under certain hot weather paving conditions (or allow for provision for night paving if there are currently any restrictions on it). As the HIPERPAV analysis showed, night paving resulted in a negative temperature gradient at final set, which would likely be at least partially offset by the effects of the moisture gradient, resulting in a lower overall built-in temperature gradient. Alternatively, consider restricting paving based on ambient conditions, not just concrete temperature at placement. Many states have hot weather paving provisions that do not allow placement of concrete pavement when air temperatures are 90-95°F and rising, regardless of concrete temperature.

2) **Maximum Base Temperature**
   Consider a requirement for maximum base temperature for paving. This is particularly important for paving over bituminous base materials (either asphalt-treated base or reclaimed asphalt), which absorb significant heat from solar radiation during daytime hours. Although the literature search did not reveal any other state specifications with requirements for maximum base temperature, the HIPERPAV literature discusses the importance of keeping the base temperature as close to the concrete temperature as possible to limit the effects of base temperature on slab temperature gradients (Ruiz, 2005). Florida DOT mentions a recommendation for treating the top of asphalt-treated bases with a superficial lime solution to lower the base temperature (Nazef, 2011). White-pigmented curing compound has also been used for this purpose.

3) **Membrane Curing Compound**
   Consider a requirement for more effective curing compounds for hot weather paving conditions, such as Poly-Alpha Methylstyrene (PAMS). Minnesota DOT testing found that PAMS had 5 to 10 times less water loss at 1 and 3 days than conventional (wax or resin-based) membrane curing compounds (Zeller, 2014). Testing by Oklahoma State University also found PAMS to provide the best performance in terms of water loss and curling from shrinkage (Hajibabaee, 2015), while wax-based compounds essentially provided results similar to no curing compound at all. Although this material is more costly than resin-based compounds, the requirement for its use could potentially be limited to paving under certain hot weather conditions.

These recommendations for construction practices should help to reduce built-in temperature gradients and associated curling for jointed concrete pavements, particularly for hot-weather paving.

Implementation Recommendations for Collection of Profile Data

There are no known state DOT specifications for the collection of smoothness acceptance data on jointed concrete pavements which specifically address the slab-curling phenomenon. As such, there are no other models that can be used as a starting point, making modification of CDOT practices for collecting acceptance profile data on jointed concrete pavements the most challenging aspect of implementing the findings from this study. While it is important for CDOT to protect their investment, the desire is also to not burden the contractor with unduly harsh requirements for pavement smoothness acceptance because of factors that may be beyond the contractor’s control. However, the data from this project confirms what is well known about most jointed concrete pavements – that smoothness changes throughout the day, sometimes dramatically, as a result of slab curling, and this should somehow be reflected in the profile data collected on projects. Below are summarized recommendations for changes to practices for collection of smoothness acceptance data.

Overall Smoothness Acceptance

A requirement for simply profiling under the “worst case” condition (generally early morning), without adjusting smoothness specification thresholds to account for this, could potentially unduly penalize the contractor unless CDOT also provided the contractor with the maximum flexibility in selecting materials and even adjusting pavement design (e.g., joint spacing) to ensure they can minimize the effects of slab curling on smoothness. On the other hand, profiling under the “best case” condition (generally early afternoon) effectively ignores the fact that early morning levels of roughness better reflect slab curling effects that impact both user (driver) satisfaction and pavement structural performance.

To balance these factors, the recommended modification to collection of profile data for jointed concrete pavements includes the following two components:

1) **Collect profile during at least two times of the (same) day for acceptance**.
   Ideally, profile data would be collected during the early AM and early PM time periods to capture the potential “worst case” and “best case” conditions. Early AM profiling should be completed just prior to sunrise, regardless of the season of the year. Early PM profiling will vary depending on the season of the year, but a window between 1 PM and 3 PM will likely capture the other extreme condition. Should a contractor wish to determine this optimal time to maximize the “best case” condition, they should be permitted to instrument the pavement slab to determine when to collect profile data.

   It will be important that this data is collected on a day when these extreme conditions will most likely be encountered. In particular, it should be a sunny, dry day when the ambient temperature is expected to vary at least 20°F over the course of the day. Overcast days with ambient temperature change less than 20°F will not likely provide the necessary conditions for capturing changes in slab curvature. If it is not possible to collect data during both periods of the same day (e.g., should it become overcast following the early AM run), it may be necessary to allow the second data run the following day(s), assuming similar temperature conditions are present.

2) **Set acceptance thresholds for ride quality based on two parameters.**
   Rather than setting acceptance thresholds based on the two sets of profile data, a more reasonable approach would be to set thresholds based on the following two parameters:

   Average roughness (HRI) for the two profiles that were collected at different times of the day.

   The average HRI for each lot from the two (early AM and early PM) profile runs should be used for acceptance. This threshold will likely need to be slightly higher than current CDOT specification thresholds, but pilot project or shadow specification testing of this requirement on upcoming projects would help determine the most appropriate threshold. One of the main challenges will be to ensure profile data are collected in the same manner (e.g., same starting and ending point) to ensure that the same lot is compared between the two time periods. The

> use of automated triggering and ProVAL's Profile Synchronization module can help overcome this challenge.
>
> *Maximum absolute difference in HRI between the two profiles.*
>
> The difference between the HRI values for each lot from the two profiling periods will be the other criteria for acceptance. This parameter is perhaps the biggest indicator of the effect of slab curling on roughness. By setting a limit on the difference between the two extreme conditions, this can help eliminate accepting any pavement with very extreme diurnal differences that may in fact meet the average HRI value. A recommended starting point for this would be 15-20 in/mi maximum absolute difference per lot.

The primary drawbacks of this change in practice will be doubling the amount of profiling required for acceptance, while also restricting the timing of profile data collection to specific windows of time each day. This will add significant effort for acceptance testing for CDOT, but will help address a very pressing issue related to smoothness acceptance of jointed concrete pavements.

Localized Roughness

Additional consideration will also need to be given for areas of localized roughness (ALRs). The current CDOT ALR requirement which utilizes continuous roughness reporting with a 25 ft base length is good practice and should be maintained. However, for the purposes of deploying the "two stage" acceptance procedure described above, modification to the ALR procedure will likely be needed as well since ALRs might appear in the early AM profile data but not in the early PM profile data. A reasonable approach to ALR would be to require correction of ALRs that appear in *both* the early AM and early PM profile data. The challenge will be synchronizing the continuous roughness plots from the two profile runs to determine which ALRs appear in both roughness plots, but the use of the ProVAL Profile Synchronization module can help overcome this challenge.

Mitigation

Mitigation methods (diamond grinding) should still be permitted to correct overall roughness and localized roughness. The challenge for the contractor will be determining the optimal time to diamond grind to maximize grinding benefit to achieve the specification requirements. In most cases, this will likely mean grinding only during early morning hours (e.g., 12 AM-6 AM), which will limit daily grinding production and require flexibility from CDOT in allowing the contractor to determine the necessary window for grinding.

Deployment

Deploying these acceptance testing specification changes should initially be done on pilot projects or as a shadow specification on an existing project. In a pilot project scenario, the specification changes should be included in the project up front, but the contractor asked not to deviate from normal practices (i.e., paving under the current CDOT smoothness specification). Some form of incentive would help ensure cooperation of the contractor in evaluating the specification changes.

In a shadow specification scenario, CDOT would conduct the two-stage profiling on existing or recently completed projects constructed under existing specifications to determine viable acceptance thresholds. The contractor (if the project is still under construction) would be aware of the shadow specification, but would not be held to the requirements of the two-stage profiling specification.

Ideally, thresholds for the average HRI and maximum absolute difference would be determined through testing of a number of projects (via pilot projects or shadow specifications) in various regions of the state over an upcoming construction season. Once viable thresholds have been established, the new requirements could be deployed on a select number of projects as a Project Special Provision/Special Specification for further evaluation. Inclusion into full standard specifications could potentially occur within 2-3 years.

Partnering with the Colorado concrete paving industry will be essential for successful implementation of specification changes. Contractors should be engaged in the process and encouraged to provide input to help ensure a practical solution to specification changes.

Validation of Recommended Procedures for Collection of Profile Data

Data collected from the US 34 project were analyzed to determine how many lots would pass or fail based on these modified procedures for collecting smoothness acceptance data (although it is recognized that the data were collected more than a year after construction). Early AM and early PM profile data from both the February and August site visits were analyzed on a fixed interval (0.1-mi segment) basis. The current CDOT Category II full pay upper limit of 67 in/mi was utilized for overall roughness, and the localized roughness requirement of 125 in/mi in a 25 ft base length were used for the thresholds. For this initial analysis the criteria for absolute difference in HRI between the early AM and early PM profiles was 15 in/mi.

Table 15 summarizes the results from this validation analysis. The table summarizes the number of 0.1-mile segments within each lane (partial segments were excluded) and the percent of those segments that passed the two criteria discussed above. Also summarized are the number of locations of localized roughness for each lane from each of the time periods of the day and the number that matched (similar location limits) between the early AM and early PM runs.

For the overall roughness criteria, while a few lanes showed 100 percent of segments passing the Average HRI criteria, and at least one lane passing the Absolute Difference criteria, no lanes had all segments passing both criteria. Most interesting is the fact that there was a significant variation in the number of segments that passed between the February and August profile data. This emphasizes the need for setting thresholds that will be appropriate no matter what time of year profile data is collected.

For localized roughness, only WB lane 2 (February profile data) had the same number of localized roughness locations in both the early AM and early PM profiles, but all lanes had at least one location that matched between them. It should be noted, however, that areas of localized roughness vary greatly in length. In some instances they are only a few feet in length, and in others may be over 100 ft in length. Therefore, it is difficult to simply use the number of locations of localized roughness for comparison. A more detailed analysis of the exact locations and lengths of localized roughness would be more appropriate.

Because WB lane 2 showed such poor results for the criteria provided, ProVAL's Grinding Simulation was used to see if WB lane 2 could be improved with grinding. The early AM profile, which had exceptionally high overall roughness (all segments defective) and 26 localized roughness locations, was the primary contributor to the poor results. After a full (blanket) grind simulation was applied to the early AM profile, no defective segments remained in the early AM profiles, and 26 areas of localized roughness were reduced to just two.

Table 15. Summary of results from validation of recommended smoothness acceptance procedures.

		Overall Roughness			Localized Roughness		
		Number of 0.1-mile Segments	Percent Passing Average HRI Criteria	Percent Passing Absolute Difference Criteria	Number of Early AM Localized Roughness Locations	Number of Early PM Localized Roughness Locations	Locations Matching Early AM and Early PM
February Profile Data							
EB	**lane 1**	14	100	93	3	5	3
	lane 2	14	100	43	2	1	1
WB	**lane 1**	13	69	100	5	10	4
	lane 2	13	69	62	9	9	5
August Profile Data							
EB	**lane 1**	13	100	54	4	2	1
	lane 2	13	92	8	9	1	1
WB	**lane 1**	12	67	58	8	2	2
	lane 2	12	58	0	26	3	3

This validation analysis revealed some additional challenges that will need to be addressed should it be deployed, but demonstrated the methodology is viable and will help to capture differences in roughness related to slab curvature during acceptance testing. Pilot project testing or shadow specification evaluation of these recommendations will help to resolve these challenges and set the most appropriate thresholds.

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APPENDIX A: SUMMARY OF PAVEMENT SMOOTHNESS BY DAY

Table 16. Summary of overall ride quality by paving day.

Dir.	Lane	Diurnal Period	Paving Day	February Site Visit				August Site Visit			
				HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	MRI (in/mi)	HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	MRI (in/mi)
EB	1	Early AM	1	51.2	61.2	51.6	56.4	54.2	60.4	58.5	59.5
			2	56.9	61.8	61.1	61.5	63.0	63.0	70.0	66.5
			3	58.6	66.7	61.3	64.0	64.5	70.2	69.8	70.0
			4	63.8	74.9	66.2	70.5	67.0	77.5	70.4	74.0
			5	56.6	64.1	60.1	62.1	62.4	67.5	67.4	67.5
EB	1	Mid-AM	1	43.4	55.5	43.0	49.2	45.2	55.5	46.5	51.0
			2	48.1	57.6	49.1	53.3	53.2	57.3	57.8	57.5
			3	49.9	62.0	51.2	56.6	55.4	65.0	59.0	62.0
			4	55.8	70.5	56.4	63.4	59.3	72.9	60.6	66.7
			5	52.4	60.8	54.9	57.8	53.4	62.9	56.6	59.7
EB	1	Early PM	1	44.0	58.6	42.6	50.6	44.6	61.0	41.1	51.1
			2	46.8	60.5	42.9	51.7	49.0	59.7	47.7	53.7
			3	46.3	59.8	46.2	53.0	47.9	63.9	44.6	54.3
			4	53.1	70.9	50.6	60.8	51.8	69.4	49.6	59.5
			5	52.6	63.3	51.9	57.6	52.0	62.7	52.1	57.4
EB	1	Late PM	1	43.6	57.1	42.5	49.8	39.4	51.2	39.4	45.3
			2	46.6	57.7	45.8	51.8	47.9	55.3	51.1	53.2
			3	48.4	60.9	48.6	54.8	49.7	60.5	52.1	56.3
			4	53.7	70.7	51.9	61.3	55.9	71.7	55.9	63.8
			5	51.6	61.3	53.2	57.3	51.0	60.2	53.5	56.9
EB	2	Early AM	1	54.7	61.0	57.5	59.2	61.9	66.9	64.4	65.7
			2	62.1	72.2	58.1	65.1	72.3	80.5	68.5	74.5
			3	68.0	77.5	64.0	70.7	77.3	87.7	71.3	79.5
			4	69.1	78.2	67.3	72.8	75.6	90.3	67.5	78.9
			5	67.0	77.0	63.7	70.3	71.0	79.2	69.2	74.2
EB	2	Mid-AM	1	47.2	57.6	47.0	52.3	52.6	59.3	54.2	56.7
			2	47.0	57.1	43.3	50.2	60.2	71.0	54.5	62.7
			3	57.0	67.4	53.5	60.5	65.7	76.6	60.2	68.4
			4	60.5	71.6	58.3	64.9	64.0	75.3	60.5	67.9
			5	56.7	66.5	56.1	61.3	61.3	70.8	59.1	64.9
EB	2	Early PM	1	42.5	54.5	42.0	48.3	41.6	51.9	42.0	46.9
			2	45.0	55.6	43.2	49.4	44.1	54.9	41.4	48.1
			3	50.3	60.5	47.8	54.2	46.3	57.5	44.2	50.9
			4	53.9	63.4	54.4	58.9	53.0	61.7	54.6	58.2
			5	51.9	60.6	53.3	57.0	49.6	58.7	51.4	55.1

Dir.	Lane	Diurnal Period	Paving Day	February Site Visit				August Site Visit			
				HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	MRI (in/mi)	HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	MRI (in/mi)
EB	2	Late PM	1	44.5	55.9	44.9	50.4	48.2	56.8	48.4	52.6
			2	46.1	56.0	43.9	50.0	54.9	66.6	48.8	57.7
			3	55.0	65.5	51.3	58.4	59.8	69.8	56.1	63.0
			4	59.7	71.3	56.7	64.0	59.6	70.6	57.9	64.2
			5	56.5	66.9	54.4	60.7	57.8	71.4	53.7	62.5
WB	1	Early AM	1	61.5	78.4	64.4	71.4	64.5	78.0	73.6	75.8
			2	74.7	78.1	92.3	85.2	80.1	82.6	97.3	90.0
			3	63.2	71.8	71.2	71.5	70.9	76.7	78.7	77.7
			4	66.5	78.2	73.2	75.7	71.3	78.3	81.8	80.0
			5	63.5	71.4	68.4	69.9	70.9	74.1	79.0	76.5
WB	1	Mid-AM	1	62.2	80.0	63.9	71.9	60.7	74.7	69.1	71.9
			2	73.1	79.0	89.5	84.3	78.6	81.7	98.5	90.1
			3	57.0	69.3	62.5	65.9	64.9	75.1	72.2	73.6
			4	61.5	76.8	67.6	72.2	65.7	76.3	75.3	75.8
			5	59.3	69.8	63.6	66.7	65.5	71.5	72.0	71.8
WB	1	Early PM	1	62.4	83.0	65.1	74.1	63.0	82.3	65.4	73.9
			2	72.0	79.6	89.4	84.5	73.6	82.8	89.7	86.2
			3	54.0	68.7	58.2	63.5	51.5	68.8	53.3	61.1
			4	59.3	77.3	64.2	70.7	57.5	77.1	59.2	68.2
			5	56.9	67.4	59.7	63.6	54.4	66.4	56.4	61.4
WB	1	Late PM	1	62.1	80.5	64.6	72.5	61.2	78.2	64.5	71.4
			2	70.8	77.1	89.4	83.3	72.3	78.6	85.8	82.2
			3	55.8	69.7	61.5	65.6	59.5	70.2	66.7	68.4
			4	61.0	77.9	66.8	72.3	62.5	75.8	70.8	73.3
			5	58.0	69.4	61.5	65.4	61.0	68.6	66.7	67.6
WB	2	Early AM	1	52.3	57.1	58.3	57.7	62.9	67.2	67.8	67.5
			2	88.8	90.6	94.2	92.4	104.0	104.4	109.8	107.1
			3	70.8	74.5	73.3	73.9	80.9	82.9	83.7	83.3
			4	71.1	76.0	74.0	75.0	79.2	83.7	81.4	82.5
			5	70.5	76.6	71.1	73.8	82.4	86.7	83.4	85.0
WB	2	Mid-AM	1	48.1	53.1	53.7	53.4	53.9	58.0	59.5	58.7
			2	79.9	80.1	88.8	84.5	93.5	93.3	100.0	96.7
			3	61.1	64.2	65.5	64.9	70.0	73.3	73.0	73.1
			4	62.0	67.8	66.4	67.1	69.2	74.7	71.5	73.1
			5	60.9	65.1	64.2	64.7	74.0	79.5	74.5	77.0

Dir.	Lane	Diurnal Period	Paving Day	February Site Visit				August Site Visit			
				HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	MRI (in/mi)	HRI (in/mi)	LWP IRI (in/mi)	RWP IRI (in/mi)	MRI (in/mi)
WB	2	Early PM	1	48.7	56.0	52.7	54.4	44.6	49.4	50.2	49.8
			2	74.3	77.8	80.9	79.3	72.8	74.8	80.4	77.6
			3	55.0	60.2	58.3	59.3	48.5	53.1	52.8	52.9
			4	55.6	62.2	60.2	61.2	49.6	57.0	53.9	55.5
			5	57.6	63.5	59.3	61.4	51.6	57.8	54.0	55.9
WB	2	Late PM	1	47.0	53.8	52.0	52.9	52.1	57.5	56.7	57.1
			2	77.4	86.6	78.1	82.4	89.6	90.0	95.7	92.8
			3	59.8	65.2	62.4	63.8	64.8	67.9	68.5	68.2
			4	59.7	67.0	63.1	65.1	63.3	70.1	65.0	67.5
			5	60.4	66.6	61.7	64.1	68.5	72.6	71.1	71.8

APPENDIX B: SUMMARY OF CURVATURE VALUES

Table 17. Summary of 2GCI values from curvature analysis.

Dir.	Lane	Time[1]	Month	Repeat	Side of Bridge	2GCI (Pseudo Strain Gradient), microstrain/in									
						LWP Q1	LWP Min.	LWP Med.	LWP Max.	LWP Q3	RWP Q1	RWP Min.	RWP Med.	RWP Max.	RWP Q3
EB	L1	1	2	1	E	-43.97	-94.01	-29.30	11.54	-16.01	-52.10	-103.43	-38.60	16.26	-29.50
EB	L1	1	2	1	W	-47.18	-127.84	-33.49	65.41	-15.96	-56.79	-99.20	-42.57	28.93	-30.40
EB	L1	2	2	1	E	-29.54	-78.16	-13.78	16.69	0.16	-32.86	-90.77	-23.79	26.86	-12.47
EB	L1	2	2	1	W	-31.73	-111.98	-18.08	77.39	0.61	-38.86	-103.58	-26.34	31.91	-12.00
EB	L1	3	2	1	E	-30.95	-85.96	-16.36	19.05	-0.39	-34.54	-82.90	-24.44	28.22	-13.88
EB	L1	3	2	1	W	-31.73	-112.92	-16.14	69.90	-0.19	-40.52	-87.83	-27.39	37.19	-13.84
EB	L1	3	2	2	E	-10.53	-64.53	0.30	44.97	16.57	-18.11	-70.04	-4.16	50.28	5.70
EB	L1	3	2	2	W	-19.15	-90.54	-3.51	91.84	12.17	-26.33	-85.62	-12.19	51.51	-0.42
EB	L1	4	2	1	E	-19.49	-67.74	-5.92	25.04	8.06	-25.93	-77.96	-14.72	37.36	-2.60
EB	L1	4	2	1	W	-27.62	-94.53	-12.27	78.99	5.25	-34.51	-85.92	-21.63	36.63	-7.92
EB	L2	1	2	1	E	-58.18	-126.26	-44.45	51.12	-26.28	-52.19	-86.94	-41.97	31.00	-28.04
EB	L2	1	2	1	W	-72.24	-138.76	-55.02	25.37	-39.78	-57.35	-117.14	-44.93	61.43	-28.03
EB	L2	2	2	1	E	-40.28	-89.30	-27.49	55.47	-10.21	-32.43	-68.83	-22.00	46.69	-10.40
EB	L2	2	2	1	W	-53.44	-136.81	-38.44	43.28	-21.96	-38.63	-95.54	-25.02	68.55	-10.86
EB	L2	3	2	1	E	-43.22	-88.84	-30.33	42.61	-16.06	-35.37	-76.63	-25.47	50.81	-13.60
EB	L2	3	2	1	W	-55.84	-138.30	-41.47	45.57	-25.35	-42.74	-98.01	-27.81	51.36	-12.90
EB	L2	3	2	2	E	-23.37	-86.18	-10.68	53.93	6.02	-15.23	-59.38	-5.72	77.01	6.16
EB	L2	3	2	2	W	-37.87	-108.62	-24.53	66.15	-6.66	-24.58	-75.94	-10.16	91.62	4.35
EB	L2	4	2	1	E	-36.25	-84.19	-22.31	49.56	-6.68	-27.22	-65.43	-17.55	60.75	-5.45
EB	L2	4	2	1	W	-51.21	-125.28	-35.42	43.92	-17.99	-35.09	-95.17	-21.09	80.71	-5.15
WB	L1	1	2	1	E	-23.30	-93.00	-1.76	87.63	16.32	-41.23	-93.12	-24.28	27.74	-8.93
WB	L1	1	2	1	W	-43.67	-102.40	-21.91	64.51	-1.47	-61.09	-134.47	-44.81	32.14	-24.50

Dir.	Lane	Time[1]	Month	Repeat	Side of Bridge	2GCI (Pseudo Strain Gradient), microstrain/in									
						LWP Q1	LWP Min.	LWP Med.	LWP Max.	LWP Q3	RWP Q1	RWP Min.	RWP Med.	RWP Max.	RWP Q3
WB	L1	2	2	1	E	-10.02	-75.06	9.43	97.07	26.48	-30.67	-85.43	-14.81	44.66	-0.22
WB	L1	2	2	1	W	-30.33	-86.01	-11.01	97.43	11.08	-47.04	-123.11	-30.55	46.56	-12.75
WB	L1	3	2	1	E	-13.18	-85.15	4.19	95.40	26.73	-30.09	-84.63	-15.83	40.74	-0.27
WB	L1	3	2	1	W	-34.79	-101.10	-13.07	79.03	7.13	-52.31	-126.60	-36.96	31.62	-15.53
WB	L1	3	2	2	E	-7.09	-73.16	13.27	101.28	34.85	-22.83	-78.12	-6.36	54.40	7.93
WB	L1	3	2	2	W	-21.31	-82.34	0.74	103.58	20.14	-37.30	-115.34	-22.69	45.60	-2.31
WB	L1	4	2	1	E	-2.49	-84.42	14.48	94.72	31.53	-23.47	-76.49	-4.81	50.38	8.57
WB	L1	4	2	1	W	-25.36	-97.68	-5.53	82.97	16.92	-44.09	-98.60	-27.51	60.03	-8.07
WB	L2	1	2	1	E	-48.25	-94.98	-32.46	15.85	-18.98	-48.60	-88.33	-32.37	16.52	-20.00
WB	L2	1	2	1	W	-69.42	-123.93	-54.72	56.96	-35.98	-72.00	-134.39	-54.82	74.31	-37.70
WB	L2	2	2	1	E	-32.63	-84.67	-18.73	27.95	-8.03	-34.90	-81.63	-22.08	20.64	-8.01
WB	L2	2	2	1	W	-53.58	-101.76	-35.93	58.03	-17.96	-55.00	-112.98	-37.90	109.38	-20.20
WB	L2	3	2	1	E	-36.89	-84.02	-21.32	29.15	-9.61	-37.50	-89.84	-25.96	19.96	-9.64
WB	L2	3	2	1	W	-58.57	-116.18	-42.59	74.00	-25.63	-59.40	-126.99	-45.41	89.37	-28.10
WB	L2	3	2	2	E	-26.69	-71.97	-12.75	44.72	-0.74	-25.70	-79.27	-11.63	34.50	3.57
WB	L2	3	2	2	W	-46.70	-93.10	-30.18	75.15	-14.89	-48.10	-110.75	-33.02	80.52	-16.10
WB	L2	4	2	1	E	-29.37	-82.78	-15.94	30.53	-4.70	-30.90	-80.21	-18.46	24.34	-4.57
WB	L2	4	2	1	W	-55.15	-119.79	-40.05	78.62	-22.09	-54.00	-118.31	-39.24	89.11	-22.20
EB	L1	1	8	1	E	-46.93	-97.99	-33.69	47.88	-18.90	-60.07	-107.36	-46.30	39.69	-34.57
EB	L1	1	8	1	W	-54.16	-129.99	-38.70	83.97	-21.28	-64.60	-114.64	-52.11	37.80	-38.90
EB	L1	2	8	1	E	-33.54	-100.39	-21.05	63.94	-5.04	-44.60	-103.24	-31.89	43.27	-20.90
EB	L1	2	8	1	W	-38.49	-132.39	-23.07	121.15	-5.13	-49.00	-115.57	-34.73	65.46	-22.40
EB	L1	3	8	1	E	-1.46	-73.45	10.99	93.78	25.09	-14.40	-80.54	-2.73	66.57	9.30
EB	L1	3	8	1	W	-10.73	-102.06	0.00	126.18	18.32	-22.10	-98.71	-7.09	82.81	1.96
EB	L1	3	8	2	E	5.89	-84.94	16.98	109.08	30.69	-13.40	-87.07	3.12	78.93	15.70
EB	L1	3	8	2	W	-6.85	-79.36	6.71	124.31	23.75	-19.65	-77.05	-4.23	85.56	7.48

Dir.	Lane	Time[1]	Month	Repeat	Side of Bridge	2GCI (Pseudo Strain Gradient), microstrain/in									
						LWP Q1	LWP Min.	LWP Med.	LWP Max.	LWP Q3	RWP Q1	RWP Min.	RWP Med.	RWP Max.	RWP Q3
EB	L1	4	8	1	E	-17.94	-85.37	-7.21	80.69	7.97	-32.28	-99.95	-17.81	50.99	-8.10
EB	L1	4	8	1	W	-25.59	-125.75	-10.96	139.39	7.36	-35.78	-112.15	-21.54	85.55	-7.19
EB	L2	1	8	1	E	-67.42	-123.44	-52.26	18.36	-37.61	-61.70	-97.94	-48.55	32.59	-35.00
EB	L2	1	8	1	W	-79.72	-156.43	-63.87	51.79	-46.17	-63.21	-126.82	-51.08	43.39	-31.79
EB	L2	2	8	1	E	-52.18	-102.71	-41.62	39.17	-24.19	-45.70	-79.67	-35.38	38.70	-22.00
EB	L2	2	8	1	W	-61.17	-141.67	-45.72	29.55	-29.62	-48.70	-110.64	-34.67	54.74	-17.00
EB	L2	3	8	1	E	-25.60	-90.50	-11.40	65.51	1.67	-15.80	-86.23	-7.88	79.33	6.15
EB	L2	3	8	1	W	-41.71	-118.60	-24.92	58.26	-8.70	-23.30	-89.89	-11.23	82.53	5.61
EB	L2	3	8	2	E	-19.27	-72.20	-7.76	55.39	7.05	-9.51	-62.86	-0.55	75.45	11.90
EB	L2	3	8	2	W	-34.13	-116.19	-15.90	65.23	-1.68	-16.20	-81.11	-2.12	86.30	11.90
EB	L2	4	8	1	E	-47.59	-94.87	-32.92	49.95	-13.70	-37.30	-79.34	-27.12	44.53	-15.10
EB	L2	4	8	1	W	-51.85	-111.64	-34.59	42.07	-21.33	-37.20	-99.09	-24.12	70.85	-7.33
WB	L1	1	8	1	E	-35.25	-98.84	-20.16	46.42	4.91	-58.30	-114.05	-41.30	13.96	-26.60
WB	L1	1	8	1	W	-54.00	-118.53	-32.05	51.64	-14.42	-74.40	-132.12	-58.62	13.51	-39.60
WB	L1	2	8	1	E	-27.60	-91.07	-11.04	56.74	7.19	-49.60	-94.22	-32.01	25.06	-17.20
WB	L1	2	8	1	W	-41.56	-106.45	-23.57	91.28	-1.57	-55.00	-108.85	-39.02	56.35	-22.70
WB	L1	3	8	1	E	1.19	-51.65	16.16	112.37	40.89	-21.20	-61.08	-3.41	58.08	10.40
WB	L1	3	8	1	W	-16.92	-81.84	5.35	109.06	23.14	-37.00	-92.66	-20.66	114.62	-1.31
WB	L1	3	8	2	E	7.40	-53.00	24.20	112.00	45.60	-17.70	-63.20	-0.86	58.60	12.50
WB	L1	3	8	2	W	-9.36	-70.95	12.29	94.53	29.63	-29.58	-86.97	-12.91	40.44	4.62
WB	L1	4	8	1	E	-18.68	-68.83	-1.42	90.43	22.25	-42.38	-97.81	-26.00	34.84	-10.72
WB	L1	4	8	1	W	-34.25	-95.54	-14.91	91.71	3.54	-45.60	-108.15	-30.86	65.17	-14.00
WB	L2	1	8	1	E	-66.15	-102.35	-48.75	-11.09	-35.59	-61.00	-97.31	-45.07	-5.03	-34.00
WB	L2	1	8	1	W	-81.73	-146.15	-66.22	27.09	-49.99	-79.90	-155.28	-65.76	59.46	-50.00
WB	L2	2	8	1	E	-49.46	-85.14	-35.00	14.68	-24.04	-50.60	-94.99	-33.67	4.23	-21.00
WB	L2	2	8	1	W	-63.47	-115.52	-49.05	66.37	-31.38	-65.50	-121.20	-48.49	80.79	-30.30

Dir.	Lane	Time[1]	Month	Repeat	Side of Bridge	2GCI (Pseudo Strain Gradient), microstrain/in									
						LWP Q1	LWP Min.	LWP Med.	LWP Max.	LWP Q3	RWP Q1	RWP Min.	RWP Med.	RWP Max.	RWP Q3
WB	L2	3	8	1	E	-24.71	-67.60	-9.81	41.42	0.14	-30.20	-73.03	-10.46	30.75	2.17
WB	L2	3	8	1	W	-45.64	-103.08	-30.08	73.61	-13.79	-46.10	-115.47	-31.25	96.03	-13.00
WB	L2	3	8	2	E	-23.90	-60.74	-7.20	30.63	5.57	-24.47	-60.58	-5.72	34.22	2.38
WB	L2	3	8	2	W	-38.06	-99.77	-22.63	70.48	-6.52	-37.40	-107.96	-24.63	103.48	-7.46
WB	L2	4	8	1	E	-46.68	-78.49	-28.88	19.74	-18.15	-48.50	-87.58	-31.89	12.83	-15.70
WB	L2	4	8	1	W	-49.42	-106.78	-32.16	65.71	-14.04	-53.30	-115.30	-31.66	117.43	-12.90

[1] 1 = Early AM, 2 = Mid-AM, 3 = Early PM, 4 = Late PM

APPENDIX C: CDOT ACCEPTANCE DATA AND PAY ADJUSTMENTS FOR RIDE QUALITY

EB Lane 1

18862							**HRI Category II**										
NH 0342-054							**Eastbound Passing Lane**							**Lane In**			
Region 4				🟩 Used in I/D Calculatio			🟥 ot Used in I/D Calculatio							$2,182.40			
			10/4/2012				**10/10/2012**				**Incentive Calculations**			**Length**			
							Final				Based on 12' Lane			1.6301			
Start	Stop	Dist	R1	R2	R3	Avg	R1	R2	R3	Avg				**Avg HRI**	Start	Stop	Distance
Mile	Mile	Mile	HRI	HRI	HRI	HRI	HRI	HRI	HRI	HRI	$/SY	SY	Incentive	57.9	Station	Station	Feet
0.0000	0.0056	Lead-In													496+53	496+83	29.57
0.0056	0.1056	0.1000	53.6	54.2	53.6	🟩 53.8	50.8	51.3	52.0	🟥 51.4	$0.25	704.0	$176.00		496+83	502+11	528.00
0.1056	0.2056	0.1000	54.6	53.4	55.0	🟩 54.3	56.6	54.4	53.4	🟥 54.8	$0.22	704.0	$154.88		502+11	507+39	528.00
0.2056	0.3056	0.1000	63.8	63.0	62.5	🟩 63.1	62.4	59.9	59.5	🟥 60.6	$ -	704.0	$ -		507+39	512+67	528.00
0.3056	0.4056	0.1000	58.2	57.4	57.6	🟩 57.7	56.0	55.7	54.4	🟥 55.4	$0.01	704.0	$ 7.04		512+67	517+95	528.00
0.4056	0.5056	0.1000	49.7	49.2	49.0	🟩 49.3	48.5	46.9	48.0	🟥 47.8	$0.52	704.0	$366.08		517+95	523+23	528.00
0.5056	0.6056	0.1000	62.3	61.0	62.6	🟩 62.0	62.6	60.2	60.9	🟥 61.2	$ -	704.0	$ -		523+23	528+51	528.00
0.6056	0.7056	0.1000	68.5	69.6	65.1	🟥 67.7	65.6	63.2	64.0	🟩 64.3	$ -	704.0	$ -		528+51	533+79	528.00
0.7056	0.8056	0.1000	68.2	67.9	70.9	🟥 69.0	60.9	60.5	60.7	🟩 60.7	$ -	704.0	$ -		533+79	539+07	528.00
0.8056	0.9056	0.1000	52.9	53.2	54.1	🟩 53.4	51.4	51.2	51.2	🟥 51.3	$0.27	704.0	$190.08		539+07	544+35	528.00
0.9056	1.0056	0.1000	52.4	55.8	55.4	🟩 54.5	52.8	53.3	52.3	🟥 52.8	$0.21	704.0	$147.84		544+35	549+63	528.00
1.0056	1.1056	0.1000	49.0	50.7	49.7	🟩 49.8	48.6	49.3	48.6	🟥 48.8	$0.49	704.0	$344.96		549+63	554+91	528.00
1.1056	1.1854	0.0798	78.2	72.9	75.0	🟥 75.4	59.0	60.9	59.2	🟩 59.7	$ -	561.8	$ -		554+91	559+12	421.34
1.1854	1.3917	Bridge													559+12	570+01	1,089.26
1.3917	1.4917	0.1000	59.5	59.4	58.3	🟩 59.1	48.6	48.2	48.6	🟥 48.5	$ -	704.0	$ -		570+01	575+29	528.00
1.4917	1.5917	0.1000	56.4	54.4	56.4	🟩 55.7	53.9	54.3	53.2	🟥 53.8	$0.13	704.0	$ 91.52		575+29	580+57	528.00
1.5917	1.6917	0.1000	44.9	45.4	45.1	🟩 45.1	41.8	41.6	41.1	🟥 41.5	$0.78	704.0	$549.12		580+57	585+85	528.00
1.6917	1.7917	0.1000	55.7	53.0	54.1	🟩 54.3	51.6	51.5	51.2	🟥 51.4	$0.22	704.0	$154.88		585+85	591+13	528.00
1.7917	1.8420	0.0503	68.3	68.3	69.5	🟥 68.7	55.8	54.6	56.3	🟩 55.6	$ -	354.1	$ -		591+13	593+79	265.58
1.8420	1.8476	Lead-Out													593+79	594+08	29.57

EB Lane 2

18862							**HRI Category II**										
NH 0342-054							**Eastbound Driving Lane**							**Lane In**			
Region 4				🟩 Used in I/D Calculatio			🟥 Not Used in I/D Calculatio							$919.64			
			10/4/2012				**10/10/2012**				**Incentive Calculations**			**Length**			
							Final				Based on 12' Lane			1.6310			
Start	Stop	Dist	R1	R2	R3	Avg	R1	R2	R3	Avg				**Avg HRI**	Start	Stop	Distance
Mile	Mile	Mile	HRI	HRI	HRI	HRI	HRI	HRI	HRI	HRI	$/SY	SY	Incentive	61.5	Station	Station	Feet
0.0000	0.0056	Lead-In													496+53	496+83	29.57
0.0056	0.1056	0.1000	56.0	56.9	53.0	🟩 55.3	54.3	52.8	54.2	🟥 53.8	$ 0.16	704.0	$ 112.64		496+83	502+11	528.00
0.1056	0.2056	0.1000	64.5	61.5	58.3	🟩 61.4	60.2	59.2	59.6	🟥 59.7	$ -	704.0	$ -		502+11	507+39	528.00
0.2056	0.3056	0.1000	68.5	68.5	64.7	🟥 67.2	63.5	64.6	63.4	🟩 63.8	$ -	704.0	$ -		507+39	512+67	528.00
0.3056	0.4056	0.1000	63.9	63.6	59.2	🟩 62.2	62.9	63.0	63.0	🟥 63.0	$ -	704.0	$ -		512+67	517+95	528.00
0.4056	0.5056	0.1000	53.3	55.7	56.7	🟩 55.2	55.5	55.7	54.3	🟥 55.2	$ 0.16	704.0	$ 112.64		517+95	523+23	528.00
0.5056	0.6056	0.1000	68.0	66.5	66.3	🟩 66.9	63.7	66.4	64.7	🟥 64.9	$ -	704.0	$ -		523+23	528+51	528.00
0.6056	0.7056	0.1000	66.3	67.9	65.7	🟩 66.6	68.8	69.8	66.8	🟥 68.5	$ -	704.0	$ -		528+51	533+79	528.00
0.7056	0.8056	0.1000	69.3	65.9	69.0	🟥 68.1	65.4	64.1	65.9	🟩 65.1	$ -	704.0	$ -		533+79	539+07	528.00
0.8056	0.9056	0.1000	53.7	51.5	53.2	🟩 52.8	51.7	51.6	51.5	🟥 51.6	$ 0.31	704.0	$ 218.24		539+07	544+35	528.00
0.9056	1.0056	0.1000	60.3	57.4	58.1	🟩 58.6	54.3	50.7	54.7	🟥 53.2	$ -	704.0	$ -		544+35	549+63	528.00
1.0056	1.1056	0.1000	58.9	58.4	58.3	🟩 58.5	58.9	51.6	55.1	🟥 55.2	$ -	704.0	$ -		549+63	554+91	528.00
1.1056	1.1861	0.0805	83.4	81.3	82.9	🟥 82.5	76.2	75.4	75.9	🟩 75.8	$(0.68)	566.7	$(192.68)		554+91	559+16	425.04
1.1861	1.3924	Bridge													559+16	570+05	1,089.26
1.3924	1.4924	0.1000	65.1	64.4	63.0	🟩 64.2	52.6	53.0	53.3	🟥 53.0	$ -	704.0	$ -		570+05	575+33	528.00
1.4924	1.5924	0.1000	60.5	60.9	57.9	🟩 59.8	54.8	56.9	55.5	🟥 55.7	$ -	704.0	$ -		575+33	580+61	528.00
1.5924	1.6924	0.1000	47.4	46.1	47.3	🟩 46.9	43.5	43.1	42.4	🟥 43.0	$ 0.67	704.0	$ 471.68		580+61	585+89	528.00
1.6924	1.7924	0.1000	54.0	53.1	52.4	🟩 53.2	50.4	50.2	50.0	🟥 50.2	$ 0.28	704.0	$ 197.12		585+89	591+17	528.00
1.7924	1.8429	0.0505	80.7	79.1	79.9	🟥 79.9	61.0	63.5	61.6	🟩 62.0	$ -	355.5	$ -		591+17	593+84	266.64
1.8429	1.8486	Lead-Out													593+84	594+14	30.10

WB Lane 1

18862							**HRI Category II**										
NH 0342-054							**Westbound Passing Lane**							**Lane In**			
Region 4				Used in I/D Calculatio			Not Used in I/D Calculatio							-$207.68			
			8/22/2012				**10/31/2012**				**Incentive Calculations**			**Length**			
							Final				Based on 12' Lane			1.5301			
Start	Stop	Dist	R1	R2	R3	Avg	R1	R2	R3	Avg				**Avg HRI**	Start	Stop	Distance
Mile	Mile	Mile	HRI	HRI	HRI	HRI	HRI	HRI	HRI	HRI	$/SY	SY	Incentive	65.6	Station	Station	Feet
0.0000	0.0057	Lead-In													593+95	593+65	
0.0057	0.1057	0.1000	69.2	69.6	71.2	70.0	61.7	60.8	62.1	61.5	$ -	704.0	$ -		593+65	588+37	-528.00
0.1057	0.2057	0.1000	61.9	61.3	61.6	61.6	55.5	56.3	55.6	55.8	$ -	704.0	$ -		588+37	583+09	-528.00
0.2057	0.3057	0.1000	69.0	70.6	70.7	70.1	72.7	73.0	72.1	72.6	$ (0.24)	704.0	$ (84.48)		583+09	577+81	-528.00
0.3057	0.4057	0.1000	60.2	59.9	59.5	59.9	55.2	56.7	55.5	55.8	$ -	704.0	$ -		577+81	572+53	-528.00
0.4057	0.4443	0.0386	75.7	76.6	75.3	75.9	53.2	55.7	58.2	55.7	$ -	271.7	$ -		572+53	570+49	-203.81
0.4443	0.6368	Bridge													570+49	560+33	
0.6368	0.7368	0.1000	84.6	84.6	86.7	85.3	72.1	71.4	69.8	71.1	$ (0.32)	704.0	$(112.64)		560+33	555+05	-528.00
0.7368	0.8368	0.1000	77.2	77.2	79.6	78.0	61.6	61.3	62.5	61.8	$ -	704.0	$ -		555+05	549+77	-528.00
0.8368	0.9368	0.1000	60.4	60.4	63.0	61.3	55.8	55.4	54.9	55.4	$ -	704.0	$ -		549+77	544+49	-528.00
0.9368	1.0368	0.1000	59.4	59.4	60.4	59.7	52.3	53.4	51.5	52.4	$ -	704.0	$ -		544+49	539+21	-528.00
1.0368	1.1368	0.1000	56.9	56.9	56.8	56.9	51.5	49.0	49.1	49.9	$ 0.06	704.0	$ 42.24		539+21	533+93	-528.00
1.1368	1.2368	0.1000	59.9	59.9	63.4	61.1	52.8	52.5	51.5	52.3	$ -	704.0	$ -		533+93	528+65	-528.00
1.2368	1.3368	0.1000	60.3	60.3	61.5	60.7	49.2	49.0	49.6	49.3	$ -	704.0	$ -		528+65	523+37	-528.00
1.3368	1.4368	0.1000	70.2	70.2	69.4	69.9	68.5	67.6	70.8	69.0	$ (0.15)	704.0	$ (52.80)		523+37	518+09	-528.00
1.4368	1.5368	0.1000	57.9	57.9	57.7	57.8	52.0	52.5	50.9	51.8	$ -	704.0	$ -		518+09	512+81	-528.00
1.5368	1.6368	0.1000	62.9	62.9	62.5	62.8	56.8	57.0	60.2	58.0	$ -	704.0	$ -		512+81	507+53	-528.00
1.6368	1.7283	0.0915	66.0	66.0	63.6	65.2	55.7	57.8	56.6	56.7	$ -	644.2	$ -		507+53	502+70	-483.12
1.7283	1.7341	Lead-out													502+70	502+39	

WB Lane 2

18862							**HRI Category II**										
NH 0342-054							**Westbound Driving Lane**							**Lane In**			
Region 4				Used in I/D Calculation			Not Used in I/D Calculatio							$309.76			
			8/22/2012				**10/31/2012**				**Incentive Calculations**			**Length**			
							Final				Based on 12' Lane			1.5305			
Start	Stop	Dist	R1	R2	R3	Avg	R1	R2	R3	Avg				**Avg HRI**	Start	Stop	Dist
Mile	Mile	Mile	HRI	HRI	HRI	HRI	HRI	HRI	HRI	HRI	$/SY	SY	Incentive	69.7	Station	Station	Feet
0.0000	0.0057	Lead-In													593+95	593+65	
0.0057	0.1057	0.1000	72.8	72.5	72.8	72.7	58.5	58.3	56.9	57.9	$ -	704.0	$ -		593+65	588+37	-528.00
0.1057	0.2057	0.1000	57.5	57.6	57.7	57.6	44.6	43.1	42.9	43.5	$ 0.02	704.0	$ 14.08		588+37	583+09	-528.00
0.2057	0.3057	0.1000	56.0	57.3	57.7	57.0	49.9	48.7	49.4	49.3	$ 0.05	704.0	$ 35.20		583+09	577+81	-528.00
0.3057	0.4057	0.1000	51.0	47.8	47.9	48.9	44.7	39.7	38.8	41.1	$ 0.55	704.0	$ 387.20		577+81	572+53	-528.00
0.4057	0.4445	0.0388	77.3	80.9	79.3	79.2	54.7	50.7	48.8	51.4	$ -	273.2	$ -		572+53	570+48	-204.86
0.4445	0.6369	Bridge													570+48	560+32	
0.6369	0.7369	0.1000	104.2	103.8	104.0	104.0	73.9	70.2	70.6	71.6	$ (0.36)	704.0	$(126.72)		560+32	555+04	-528.00
0.7369	0.8369	0.1000	82.8	82.1	80.8	81.9	62.2	60.6	58.7	60.5	$ -	704.0	$ -		555+04	549+76	-528.00
0.8369	0.9369	0.1000	71.2	71.2	71.2	71.2	62.0	57.4	57.5	59.0	$ -	704.0	$ -		549+76	544+48	-528.00
0.9369	1.0369	0.1000	65.2	62.1	67.1	64.8	54.6	52.0	51.7	52.8	$ -	704.0	$ -		544+48	539+20	-528.00
1.0369	1.1369	0.1000	65.4	64.8	65.9	65.4	50.2	52.1	50.2	50.8	$ -	704.0	$ -		539+20	533+92	-528.00
1.1369	1.2369	0.1000	67.4	67.3	67.2	67.3	50.3	50.3	50.1	50.2	$ -	704.0	$ -		533+92	528+64	-528.00
1.2369	1.3369	0.1000	71.2	71.6	71.5	71.4	55.9	54.8	55.4	55.4	$ -	704.0	$ -		528+64	523+36	-528.00
1.3369	1.4369	0.1000	70.6	67.7	67.2	68.5	62.4	58.5	61.2	60.7	$ -	704.0	$ -		523+36	518+08	-528.00
1.4369	1.5369	0.1000	66.4	66.0	65.2	65.9	49.6	50.5	49.5	49.9	$ -	704.0	$ -		518+08	512+80	-528.00
1.5369	1.6369	0.1000	76.0	76.8	76.6	76.5	58.4	59.0	58.3	58.6	$ -	704.0	$ -		512+80	507+52	-528.00
1.6369	1.7286	0.0917	70.1	67.8	67.2	68.4	58.4	57.2	56.1	57.2	$ -	645.6	$ -		507+52	502+68	-484.18
1.7286	1.7344	Lead-Out													502+68	502+37	