ENHANCEMENTS TO THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE:

A MANUAL OF PRACTICE, JULY 2008 INTERIM EDITION

ADDENDUM NUMBER: **FY2015.4**

ADDENDUM TITLE: **REFLECTION CRACKING ENHANCEMENT TO THE MEPDG**

Addendum Date: August 28, 2015

Reflection cracks were predicted using an empirical regression equation in earlier versions of the Pavement ME Design software. The regression equation was only applicable to transverse cracks and/or joints. As part of a recent enhancement to the software in fiscal year (FY) 2015, the regression equation was replaced with a mechanistic-empirical (ME) based procedure to predict reflection cracks. The procedure developed under NCHRP 1-41 and documented in NCHRP Report 669 was added to the software. This addendum provides a brief overview of the methodology and inputs to the ME-based procedure.

CHAPTER 5 – PERFORMANCE INDICATOR PREDICTION METHODOLOGIES

5.3 Distress Prediction Equations for Flexible Pavements and HMA Overlays

5.3.5 Reflection Cracking in HMA Overlays

The MEPDG predicts reflection cracks in HMA overlays or HMA surfaces of semi-rigid pavements using a fracture mechanics-based model based on three response mechanisms: (1) shear, (2) bending, and (3) tension. The three response mechanisms are graphically illustrated in Figure 5.6a of this addendum. The tension related response mechanism is thermally induced (see Figure 5.6b), while the bending and shear response mechanisms are traffic induced (see Figure 3).

The Paris-Erdogan's law is used to model crack propagation expressed in equation 5-13a, and is similar to the one used to predict transverse cracks caused by a low-temperature event. The transfer function is used to estimate the amount of fatigue and transverse cracks exhibited in a non-surface layer that reflect to the AC surface or overlay after a certain period of time. This transfer function predicts the percentage of area of cracks that propagate through the AC as a function of time as shown in equation 5-13a due to wheel loads and in equation 5-13b for temperature changes. Both were calibrated as part of this enhancement.

$$\frac{dc}{dN} = A(\Delta K)^n \qquad (5\text{-}13a)$$

$$\frac{dc}{dT} = A(\Delta K)^n \qquad (5\text{-}13b)$$

Where:

- C = Crack length and dc is the change or growth in crack length.
- N = Number of loading cycles and dN is the increase in loading cycles during a time increment.
- T = Temperature and dT is the increase in thermal cycles during a time increment.
- ΔK = Stress intensity amplitude that depends on the stress level, the geometry of the pavement structure, the fracture model, crack length, and load transfer efficiency across the crack or joint.
- A,n = Fracture properties of the asphalt concrete mixture.

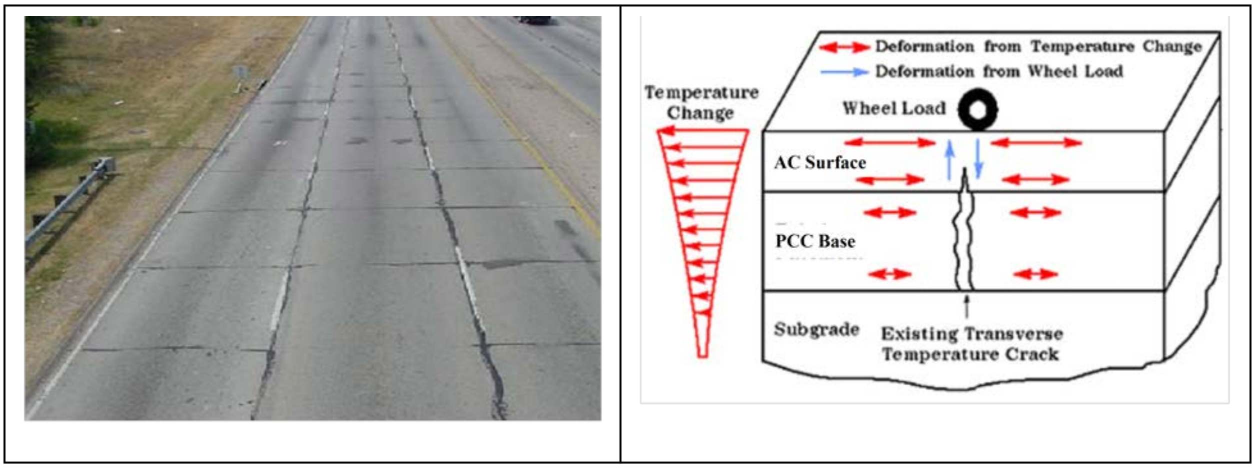


Figure 5.6a. Response Mechanisms used in Reflection Cracking Prediction Methodology

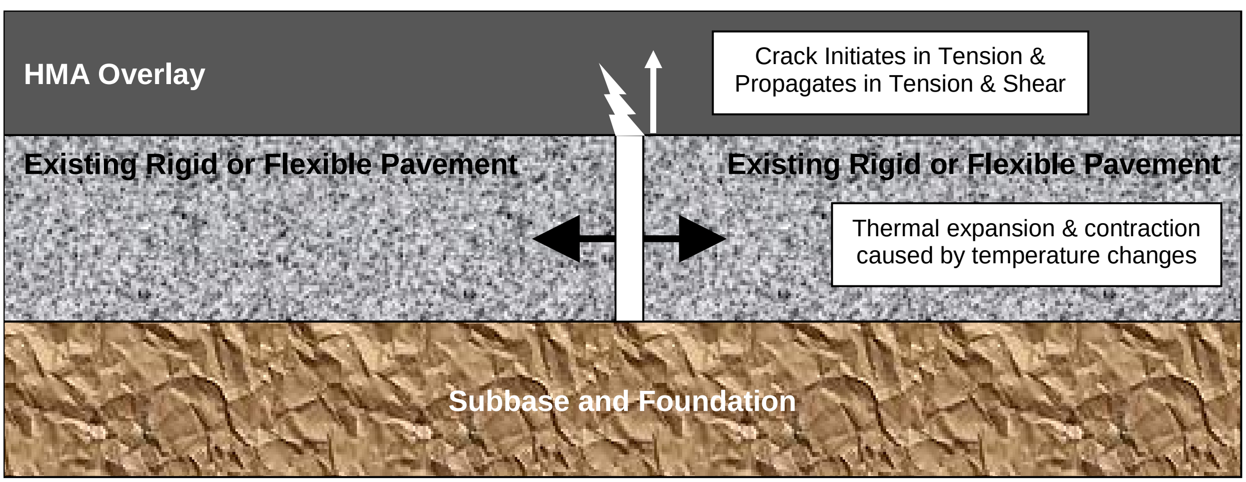
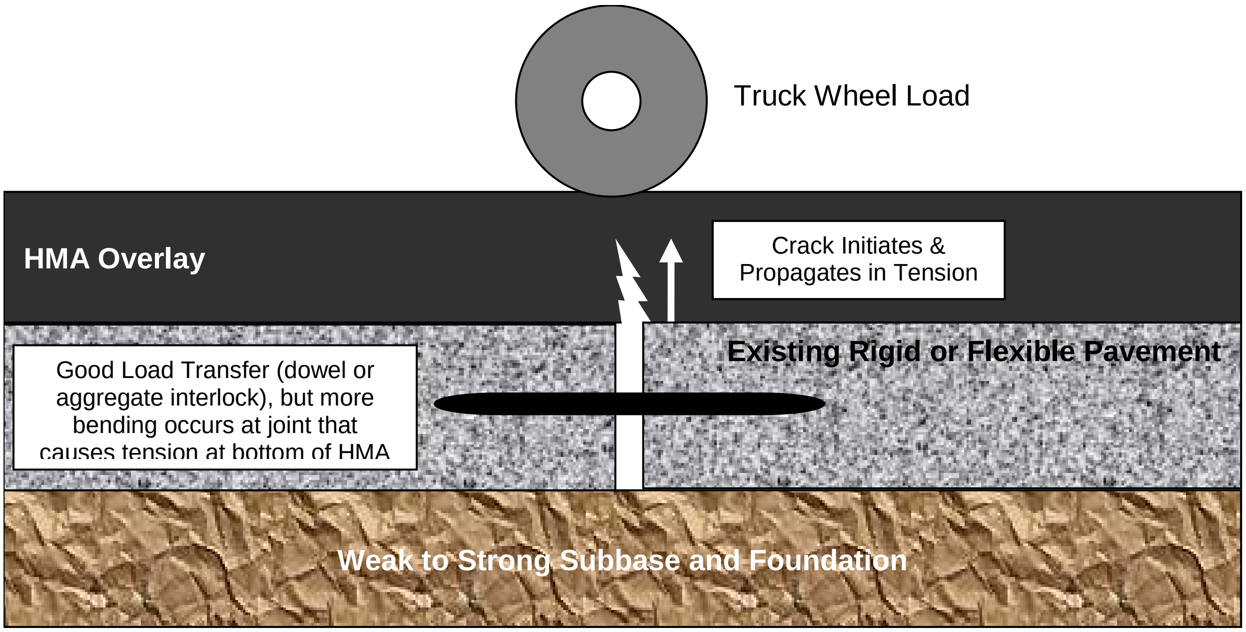
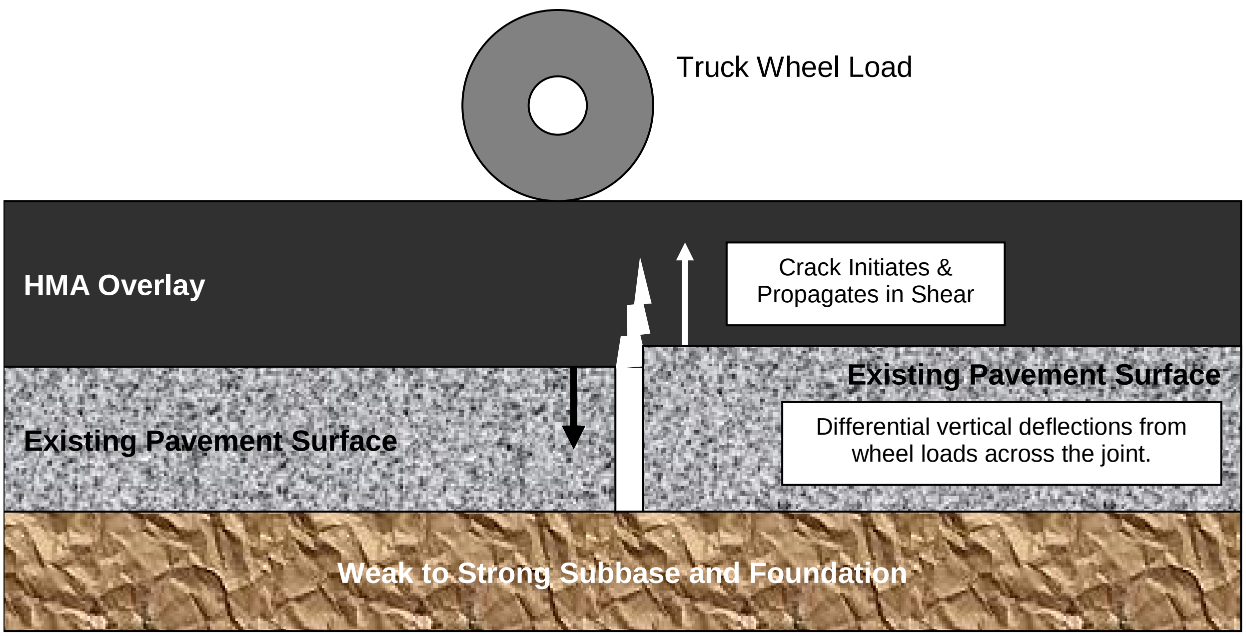


Figure 5.6b. Mechanisms of Thermally Induced Reflective Cracks of HMA Overlays



Bending Response Mechanism



Shear Response Mechanism

Figure 5.6c Mechanisms of Traffic Induced Reflective Cracks of HMA Overlays

The fracture properties A and n are calculated from the indirect tensile creep-compliance and strength of the asphalt concrete mixture in accordance with equations 5-13.c and 5-13.d.

$$A = g_2 + \frac{g_3}{m_{mix}}\left(LogD_1\right) + g_4 \log \sigma_t \qquad \text{(5-13.c)}$$

$$n = g_0 + \frac{g_1}{m_{mix}} \qquad \text{(5-13.d)}$$

Where:

g_0, g_1, g_2, g_3, g_4 = Mixture regression coefficients.
m_{mix} = The log-log slope of the mixture creep compliance versus loading time relationship for the current temperature and loading time.
D_1 = Coefficient of the creep compliance expressed in the power law form.
σ_t = Tensile strength of the asphalt concrete mix at the specific temperature.

The three response mechanisms are used to estimate the change in crack length over time: bending, shear, and tension. The crack growth or damage increment from each mechanism is provided below.

$$\Delta_{Bend} = A\left(\Delta K_B\right)^n \qquad \text{(5-13e)}$$

$$\Delta_{Shear} = A\left(\Delta K_S\right)^n \qquad \text{(5-13f)}$$

$$\Delta_{Tension} = A\left(\Delta K_T\right)^n \qquad \text{(5-13g)}$$

The loading time for the bending and shear mechanisms (equations 5-13e and 5-13f) are defined similar to the loading time for the alligator fatigue cracking model, while the loading time for the tensile mechanism (equation 5-15g) is defined similar to the low temperature cracking model. The stress intensity factors (ΔK) for each mechanism are determined using neural networks; similar in concept to those developed for the rigid pavement distress prediction models. The reflection cracking neural network models were developed from finite element analyses for the MEPDG family of pavements: conventional and deep strength flexible pavements, semi-rigid pavements, CRCP, intact JPCP, and fractured JPCP.

The methodology assumes the damage from each mechanism is uncoupled, but additive – similar to Miner’s hypothesis for fatigue damage. As such, the following equations are used to estimate the growth of a reflection crack with increasing number of load applications and thermal cycles.

$$\frac{dc}{dN} = A\left[k_1\left(\Delta K_B\right)^n + k_2\left(\Delta K_S\right)^n\right] \qquad \text{(5-13h)}$$

$$\frac{dc}{dT} = A\left[k_3\left(\Delta K_T\right)^n\right] \qquad \text{(5-13i)}$$

Where:

$k_{1,2,3}$ = Calibration coefficients for reflection cracking

Thus:

$$C = \sum_{i=1}^{m} \left(\frac{dc}{dN} + \frac{dc}{dT} \right)_i \quad (5\text{-}13j)$$

Equation 5-13j was rewritten in the form of the common fatigue damage index accumulation relationship for HMA layers and overlays over chemically stabilized layers, PCC and existing HMA layers with continued truck and temperature loadings. The continual fatigue damage accumulation of these layers is considered in the MEPDG HMA overlay analysis procedure in the following form.

$$C = h_{HMA} \left(DI_{RC} \right) \quad (5\text{-}13k)$$

Where:

h_{HMA} = Total thickness of the hot mix asphalt (HMA) layers that the reflection crack will have to propagate through, inches.

DI_{RC} = Total damage index for reflection cracks.

For any given month, *i*, the total fracture damage is estimated by equation 5-13l.

$$DI_{RC} = \sum_{i=1}^{m} \Delta DI_i \quad (5\text{-}13l)$$

Where:

DI_{RC} = Total damage index for reflection cracks in time increment *m*.

ΔDI_i = Increment of damage index in month *i*.

The incremental damage index within month i, is defined below.

$$\Delta DI = \Delta DI_N + \Delta DI_T$$

$$\Delta DI_i = \sum_{i=1}^{m} A \left[\left(c_1 k_1 \left(\Delta K_B \right)^n + c_2 k_2 \left(\Delta K_S \right)^n + c_3 k_3 \left(\Delta K_T \right)^n \right) \right]$$

Where:

$C_{1,2,3}$ = Calibration coefficients for reflection cracking

As noted above the k-value or model coefficients for the reflection cracking transfer functions are the global calibration factors and defined in Table 5.1 for transverse cracks and in Table 5.2 for fatigue cracks. The area (fatigue cracks) and length (transverse cracks) of reflection cracks from the underlying layer at month or time increment i (RCR_i) is given by equation 5-13m.

$$RCR_i = Ckg\left(\frac{100}{c_4 + e^{c_5 LogDI_i}}\right) \quad (5\text{-}13m)$$

Where:

Ckg = Total area or length of cracks in the existing pavement surface prior to overlay.
$C_{4,5}$ = Calibration coefficients for reflection cracking.

The reflective fatigue and transverse cracks are calculated separately but based on the same mathematical relationship using the appropriate calibration coefficients for fatigue and transverse cracks. The k and c-value model coefficients are included in Table 5.1a for transverse cracks and in Table 5.1b for fatigue cracks.

For each month *i*, there will be an increment of damage ΔDI_i which will cause an increment of cracking area and/or length CA_i to the wearing surface or overlay. To estimate the amount of cracking reflected from the non-surface layer to the surface of the pavement for month m, the reflective cracking prediction equation is applied incrementally.

The standard deviation equations for the standard error are listed in Table 5.1c for transverse cracks and in Table 5.1d for fatigue cracks.

Table 5.1a Global Calibration Coefficients for the Reflection Cracking Transfer Functions for Transverse Cracks

Calibration Coefficients	Pavement Type				
	AC over AC	AC over Intact JPCP	AC over Intact CRCP or Fractured JPCP	Semi-Rigid	AC over Semi-Rigid
K1	0.012	0.012	0.012	0.45	0.012
K2	0.005	0.005	0.0002	0.05	0.005
K3	1.00	1.00	0.1	1.0	1.0
C1	3.22	0.1	1.0375	0.1	3.22
C2	25.7	0.52	1.8929	0.9809	25.7
C3	0.1	3.1	0.1	0.19	0.1
C4	133.4	79.3	262.1	165.3	133.4
C5	-72.4	-27.1	-9.6645	-5.1048	-72.4

Table 5.1b Global Calibration Coefficients for the Reflection Cracking Transfer Functions for Fatigue Cracks

Calibration Coefficients	Pavement Type				
	AC over AC	AC over Intact JPCP	AC over Intact CRCP or Fractured JPCP	Semi-Rigid	AC over Semi-Rigid
K1	0.012	NA	NA	0.45	0.012
K2	0.005	NA	NA	0.05	0.005
K3	1.00	NA	NA	1.00	1.00
C1	0.38	NA	NA	1.64	0.38
C2	1.66	NA	NA	1.1	1.66
C3	2.72	NA	NA	0.19	2.72
C4	105.4	NA	NA	62.1	105.4
C5	-7.02	NA	NAA	-404.6	-7.02

Table 5.1c Standard Deviation Equations for the Transverse Cracks

Pavement Type	Standard Deviation Equation
AC over AC	70.98*Pow(TRANSVERSE,0.2994) + 30.12
AC over Intact JPCP	5.1025*Pow(TRANSVERSE,0.6513) + 30.12
AC over Intact CRCP or Fractured JPCP	52.54*Pow(TRANSVERSE,0.39) + 283.3
Semi-Rigid	0.000027* Pow(TRANSVERSE,2.1187) + 399.9
AC over Semi-Rigid	70.98*Pow(TRANSVERSE,0.2994) + 30.12

Table 5.1d Standard Deviation Equations for the Fatigue Cracks

Pavement Type	Standard Deviation Equation
AC over AC	1.1097*Pow(FATIGUE,0.6804) + 1.23
AC over Intact JPCP	Not Applicable
AC over Intact CRCP or Fractured JPCP	Not Applicable
Semi-Rigid	1.3897*Pow(FATIGUE,0.2960) + 0.4212
AC over Semi-Rigid	1.1097*Pow(FATIGUE,0.6804) + 1.23

CHAPTER 8 – SELECTING DESIGN CRITERIA AND RELIABILITY LEVEL

8.1 Recommended Design-Performance Criteria

The following reflection cracking criteria should be added to Table 8-1.

- The criterion for the reflective fatigue cracks should be the same as for the alligator cracking of new HMA pavements and overlays.

- The criterion for the reflective transverse cracks should be the same as for the transverse cracking length for New HMA pavements and overlays.

CHAPTER 10 – PAVEMENT EVALUATION FOR REHABILITATION DESIGN

10.2. Data Collection to Define Condition Assessment

10.2.3 Conduct Condition or Visual Survey

A key factor to determine the condition or strength of the existing pavement layers is the result from a detailed visual survey. Pavement visual surveys are performed to identify the types, magnitudes, and severities of distress. The visual survey needs to be performed on the pavement, shoulders and on any drainage feature along the project site. Automated distress surveys are adequate for rehabilitation design purposes, for most cases.

Table 10-4 provides a summary of the visual survey data needed for determining the inputs to the MEPDG software related to the condition of the existing pavement. Additional rows should be included in Table 10-4 for Flexible and Semi-Rigid Pavements, which are listed below.

Flexible Pavement	Load transfer efficiency (LTE) across transverse cracks	Conduct FWD testing across the transverse crack to determine the LTE or use crack severity level to determine the default LTE to be used in design.
Semi-Rigid Pavements	Transverse crack lengths	Input level 1 and 2: conduct visual survey along design lane of project and measure length of all severities of transverse cracking.
	Alligator cracks (bottom-up) cracking plus previous repair of this distress	Input level 1 and 2: conduct visual survey along design lane of project and measure area of all severities of alligator fatigue cracking plus any previous repair of this cracking. Compute percent area affected (cracked and repair).
	Load transfer efficiency (LTE) across transverse cracks	Conduct FWD testing across the transverse crack to determine the LTE or use crack severity level to determine the default LTE to be used in design.

For the MEPDG, distress identification for flexible, rigid, and composite pavements is based on the *Distress Identification Manual* for the LTPP program (FHWA, 2003). This LTPP manual was used to identify and measure the distresses for all pavement segments that were included in the global calibration process.

10.2.6 Conduct Deflection Basin Tests

The deflection basin data measured along the project is used in several ways to help select adequate rehabilitation strategies and to provide input for backcalculating layer moduli. The backcalculated layer moduli are helpful in establishing the in-place structural condition of the pavement layers. Table 10-5 lists some of the specific uses of the deflection basin data for eventual inputs to the MEPDG software. Additional rows should be included in Table 10-5 for HMA layers, which are listed below.

HMA	Transverse crack (LTE)	Input for determining need for selecting reflection cracking mitigation techniques and estimating the HMA thickness.

For JPCP, deflections are measured at the mid-slab (intact condition), across the transverse joints, and along the edge of the slabs to evaluate the load transfer efficiency and check for voids beneath the PCC layer. For flexible and semi-rigid pavements, deflections can also be measured across the transverse cracks to evaluate the load transfer efficiency of the transverse cracks in the same manner or method used for JPCP transverse joints. The loading plate should be located adjacent to the joint or crack so that the crack or joint is about equal distance between the center of the plate and first sensor location. Figure 10.2 shows the location of the loading plate and sensor in relation to the joint or crack.

The deflections are used to compute the load transfer efficiency of the joint and/or transverse cracks for use in the reflection cracking analysis and prediction of transverse reflective cracks in the HMA overlay. The load transfer efficiency is calculated as defined by the LTPP calculated parameter presented in section 10.3.4.

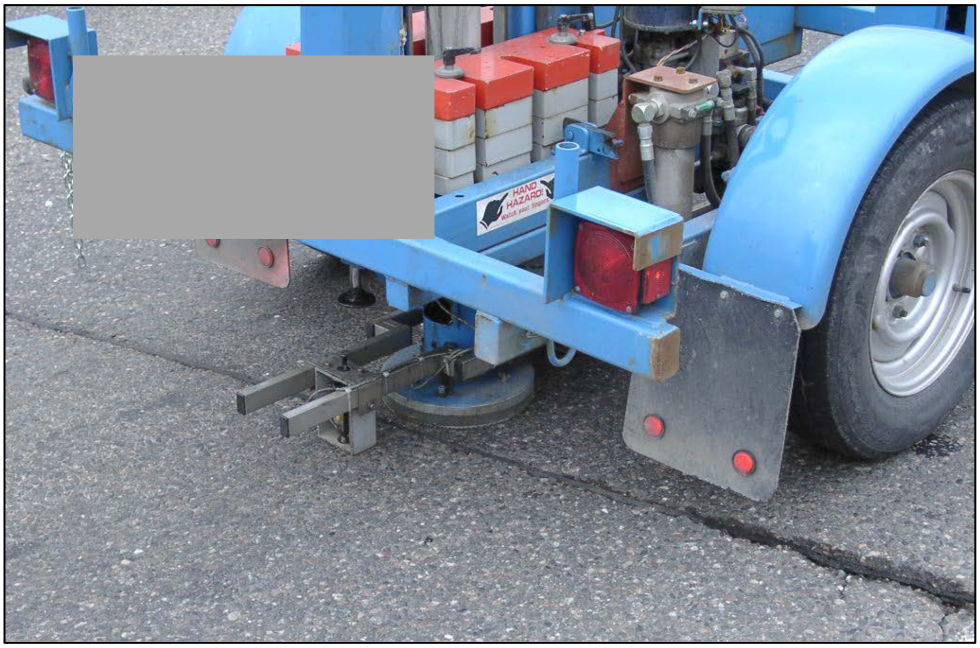


Figure 10.2 Location of the Loading Plate and Sensor relative to the Joint or Transverse Crack for Measuring LTE

10.3. Analysis of Pavement Evaluation Data for Rehabilitation Design Considerations

10.3.4 Joint and Crack Load Transfer Efficiency

Deflection testing can be used to evaluate the LTE of joints and cracks in rigid pavements. This information is used in selecting rehabilitation strategies, needed repair (e.g., retro fit dowels), and in assessing the reflection cracking potential if the jointed concrete pavement is overlaid with an HMA overlay. The same method of deflection testing can be used for transverse cracks in semi-rigid pavements and flexible pavements. The LTE represents input level 1 for the rehabilitation design using HMA overlays of rigid, flexible, and semi-rigid pavements.

The LTE is calculated in accordance with equation 10.1, where the joint or transverse crack is located midway between the loading plate and the first sensor from the loading plate as illustrated in Figure 10.2. Figure 10.3 includes a schematic of the two extreme and opposite cases for the LTE.

$$LTE = \frac{\Delta_U}{\Delta_L} 100 \qquad (10.1)$$

Where:

Δ_L = Deflection measured by the sensor at the loading plate on the loaded side of the slab.

Δ_U = Deflection measured by sensor closest to the loading plate but on the unloaded side of the slab.

Table 10.9 summarizes the different rehabilitation input levels for the LTE when using an HMA overlay of intact and fractured PCC slabs, as well as for the transverse and fatigue cracks for flexible and semi-rigid pavements. Table 10.10 lists the LTE default values used in the global calibration for the reflection cracking transfer functions. An important point or assumption made within the rehabilitation design or analysis period is that the LTE is assumed to be constant after overlay.

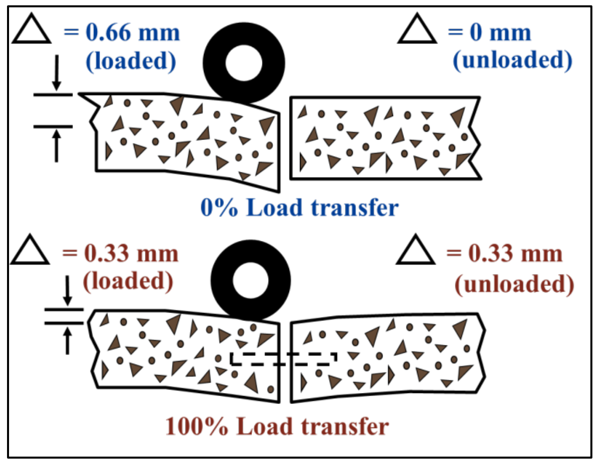


Figure 10.2. Schematic of the LTE for Two Cases

Table 10.9 LTE Values for Rehabilitation Design

Type of Discontinuity in the Existing Pavement	Input Level		
	1	2	3
Transverse Cracks, Mid-Slab Crack, or Transverse Joint	Average LTE from the FWD deflection basins	Same as input level 3	Tied to crack severity level (see Table 9.2)
Fatigue Cracks	Same as input level 3	Same as input level 3	Tied to crack severity level (see Table 9.2)

Table 10.10 LTE Default Values for Input Level 3 Tied to Crack Severity Level

Type of Pavement	Type of Crack	Condition of Crack/Joint	Crack Severity Level (See Note 1)		
			Low	Moderate	Severe
Flexible	Transverse Crack	Confined to wearing surface or does not propagate through entire bound layers (See Note 2)	85	NA	NA
		Propagates through the entire bound layers.	85	50	30
	Alligator Fatigue Cracks	Confined to wearing surface or does not propagate through entire bound layers (See Note 2)	85	NA	NA
		Propagates through the entire bound layers.	85	50	30
Semi-Rigid	Transverse Crack	Confined to wearing surface or does not propagate through entire bound layer (See Note 2)	85	NA	NA
		Assumed to propagate through entire CTB layer	85	50	30
JPCP	Intact JPCP: transverse joint	Dowelled joints	LTE = 90; if not measured		
		Non-dowelled joints	LTE = 75; if not measured		
	Fractured JPCP; transverse crack	Crack and Seat	NA	50	NA
		Rubblized, JPCP	NA	NA	NA
CRCP	Intact CRCP transverse cracks	No steel corrosion	85	NA	NA
		Steel corroded	NA	50	NA
	Fractured CRCP; transverse crack	Rubblized, CRCP)	NA	NA	NA

NOTE 1: The values listed are the average LTE values assumed for the different conditions or crack severity level.

NOTE 2: If the wearing surface is milled and all cracks are removed, the area and/or length of cracks become zero.

CHAPTER 11 – DETERMINATION OF MATERIAL PROPERTIES FOR NEW PAVING MATERIALS

11.2 HMA Mixtures; Including SMA, Asphalt-Treated or Stabilized Base Layers, Asphalt Permeable Treated Base Mixes

The following rows should be added to Table 11-2.

Table 11-2. Asphalt Materials and the Test Protocols for Measuring the Material Property Inputs for New and Existing HMA Layers

Design Type	Measured Property	Source of Data		Recommended Test Protocol and/or Data Source
		Test	Estimate	
Existing HMA mixtures, in-place properties at time of pavement evaluation	FWD backcalculated layer modulus	X		AASHTO T 256 and ASTM D 5858
	LTE Transverse Cracks	X		AASHTO T 256 and ASTM D 5858 (See section 10.3.4)

11.4 Chemically Stabilized Materials, Including Lean Concrete and Cement-Treated Base Layers

The following rows should be added to Table 11-6.

Table 11-6. Chemically Stabilized Materials Input Requirements and Test Protocols for New and Existing Chemically Stabilized Materials

Design Type	Material Type	Measured Property	Source of Data		Recommended Test Protocol and/or Data Source
			Test	Estimate	
Existing Semi-Rigid Pavements	All	Calculated modulus from FWD deflection basins	X		AASHTO T 256 & ASTM D 5858
		LTE Transverse Cracks	X		AASHTO T 256 & ASTM D 5858 (See section 10.3.4)

CHAPTER 13 – REHABILITATION DESIGN STRATEGIES

13.2 Rehabilitation Design with HMA Overlays

13.2.1 Overview

The MEPDG includes specific details for selecting the designing HMA overalys to improve the surface condition or to increase the structural capacity of the following pavements (refer to Figure 3-2 under Subsection 3.3).

1. HMA overlays of existing HMA-surfaced pavements, both flexible and semi-rigid.
2. HMA overlays of existing PCC pavements that has received fractured slab treatments; crack and seat, break and seat, and rubbvlization.
3. HMA overlays of existing intact PCC pavements (JPCP and CRCP), including composite pavements or second overlays of original PCC pavements.

With the reflection cracking enhancement added to the software, two additional pavement types were added to the rehabilitation strategies, which include:

4. HMA overlays with seal coats over existing HMA-surfaced pavements.
5. HMA overlays with interlayers over existing HMA-surface pavements.

Properties of the seal coat included in the MEPDG software represent typical values and the seal coat is placed directly over the existing HMA-surfaced pavements. Properties of the interlayer represent those of a leveling course typically used when a geo-grid or geo-textile is used to mitigate reflection cracks. If is important to note that the test sections used to globally calibrate the reflection cracking transfer function did not exhibit any consistent difference between the use of seal coats or interlays, milling and overlay, or just a simply overlay of an existing HMA-surfaced pavement. Some agencies have reported an extended service life when using seal coats and interlayers. Local calibration is recommended for those agencies that have observed increases in service life or reduced reflection cracking when using these mitigation techniques.

13.2.7 HMA Overlays of Existing HMA Pavements, Including Semi-Rigid Pavements

HMA overlays of flexible and semi-rigid pavements may be used to restore surface profile or provide structural strength to the existing pavement. The trial overlay and pre-overlay treatments need to be selected considering the condition of the existing pavement and foundation, and future traffic levels. The HMA overlay may consist of up to four layers, including three asphalt layers and one layer of an unbound aggregate (sandwich section) or chemically stabilized layer.

The same distresses used for new flexible pavement designs are also used for rehabilitation designs of flexible and semi-rigid pavements (refer to subsection 5.3). For overlaid pavements, the distress analysis includes considerations of distresses (cracking and rutting) originating in the HMA overlay and the continuation of damage and rutting in the existing pavement layers. The total predicted distresses from the existing pavement layers and HMA overlay are used to predict the IRI values over time (refer to subsection 5.3).

Longitudinal and thermal cracking distresses in the HMA overlay are predicted at the same locations as for new pavement designs. Fatigue damage is evaluated at the bottom of the HMA layer of the overlay using the alligator fatigue cracking model. Reflection cracking is predicted by applying the ME-based reflection cracking model to the cracking at the surface of the existing pavement.

The continuation of damage in the existing pavement depends on the composition of the existing pavement after accounting for the effect of pre-overlay treatments, such as milling or in-place recycling. For existing flexible and semi-rigid pavements where the HMA layers remain in place, fatigue damage will continue to develop in those layers in the existing structure using the damaged layer concept. All pavement responses used to predict continued fatigue damage in the existing HMA layers remaining in place are computed using the damaged modulus as determined from the pavement evaluation data using the methods discussed in Section 10. The pavement responses used to predict the fatigue damage of the HMA overlay use the undamaged modulus of that layer.

Plastic deformations in all HMA and unbound layers are included in predicting rutting for the rehabilitated pavement. As discussed in Section 5, rutting in the existing pavement layers will continue to accumulate but at a lower rate than for new materials due to the strain-hardening effect of past truck traffic and time.

13.2.8 HMA Overlays of Existing Intact PCC Pavements Including Composite Pavements (one or more HMA overlays of existing JPCP and CRCP)

Reflection Cracking of JPCP through HMA Overlay

The transverse joints and cracks of the underlying JPCP will reflect through the HMA overlay depending on several factors. The ME-based reflection cracking transfer function included in the MEPDG may be calibrated to local conditions prior to use of the software (refer to subsection 5.3). The transfer function has been globally calibrated. The global calibration model coefficients are included in Tables 5-1 through 5-4. Both the time in years to 50 percent of reflected joints and the rate of cracking may be adjusted depending on the HMA overlay thickness and local climatic conditions.

It is recommended that reflection cracking be considered outside of the MEPDG by means such as fabrics and grids or saw and sealing of the HMA overlay above joints. The MEPDG only considers reflection cracking treatments of fabrics through empirical relationships (refer to subsection 5.3).

For CRCP, there is no reflection cracking of transverse joints. The design procedures assumes that all medium and high severity punchouts will be repaired with full depth reinforced concrete repairs.

13.2.9 HMA Overlay of Fractured PCC Pavements

The HMA overlay has a very significant effect on thermal gradients in the PCC slab. Even a thin HMA overlay greatly reduces the thermal gradients in the PCC slab, thereby reducing the amount of fatigue damage at both the top and bottom of the slab. This typically shows that even thin HMA overlays have a sufficient effect as to reduce future fatigue damage in the PCC slab. The extent of reflection cracking, however, is greatly affected by HMA thickness and this often becomes the most critical performance criteria for overlay design.