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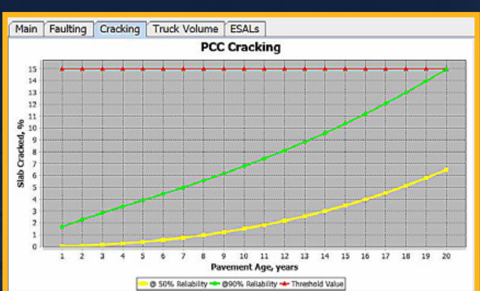
Development of Simplified Mechanistic-Empirical Design Tool for Pennsylvania Rigid Pavements

Summary Report



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Technical Report Document Page

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7. Abstract:

To accelerate the implementation of AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) in Pennsylvania, a simplified ME design method and a localized design tool are developed for concrete pavement. The new procedure, PittRigid ME, is based on the AASHTO MEPDG design procedure, but restricts design input parameters to the most influential and relevant for Pennsylvania conditions. It matches the MEPDG predicted performance at a fraction of the computational cost.

PittRigid ME can be used to predict pavement performance (i.e. fatigue cracking and joint faulting) or determine the concrete slab thickness and dowel diameters for given performance criteria and reliability level. It simplifies design process and reduces potential design errors from improper use of the AASHTOWare Pavement ME software.

The development of PittRigid ME procedure is documented in this report.

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Mechanistic-empirical Pavement Design Guide (MEPDG), Pavement ME, Rigid pavement design, Pavement performance prediction, Fatigue damage, Transverse cracking, Faulting, Calibration	Report available at: https://www.engineering.pitt.edu/IRISE/Research-Projects/Completed/

Development of Simplified Mechanistic-Empirical Design Tool for Pennsylvania Rigid Pavements

May 2020

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1 Introduction

The latest Mechanistic-Empirical Pavement Design Guide (MEPDG) [*1*] was developed under the National Cooperative Highway Research Program (NCHRP) 1-37A project [*2*]. MEPDG presents a new paradigm in how pavements are designed. It considers input parameters that influence pavement performance, including traffic, climate, pavement structure, and material properties, and applies principles of engineering mechanics to predict critical pavement responses. This gives designers the ability to select the optimal cost-effective combination of design parameters that meet long-term pavement performance requirements. MEPDG was adopted by AASHTO and implemented into the software tool, AASHTOWare Pavement ME.

Although MEPDG offers many improvements over the current pavement design guide, there are several concerns when implementing this procedure. MEPDG is substantially more complex than the previous design procedures. It requires significantly more inputs from the designer and some required data has not been commonly used in the past. Improper assignment of those parameters may lead to design errors. Moreover, AASHTOWare Pavement ME license fee is expensive. These and other factors create hesitation by states and local transportation agencies to implement MEPDG. Therefore, state and local engineers need a simplified M-E design alternative that is compatible with the AASHTO M-E procedure.

The objective of this project was to develop an efficient design tool for jointed plain concrete pavement (JPCP) that is compatible with AASHTO Mechanistic-Empirical Pavement Design Guide process but restricts design input parameters to the most influential and relevant for Pennsylvania conditions.

To achieve the objectives of this study, the research team conducted the following activities:

- Reviewed the latest version of the AASHTOWare Pavement ME software and various reports related to MEPDG sensitivity analyses.
- Conducted a sensitivity analysis for Pennsylvania conditions.
- Selected values or ranges of the MEPDG inputs parameters than can be changed by PittRigid ME’s users and values that are held constant for all projects and cannot be altered by PittRigid ME’s users.

- Performed a factorial of Pavement ME runs to develop a database of fatigue damages and differential energies for various Pennsylvania design and site conditions.
- Developed simplified fatigue cracking and joint faulting procedures.
- Developed PittRigid ME software that simplifies design process and reduces potential design errors from improper use of AASHTOWare Pavement ME software.

This document contains five major chapters and three appendixes. Chapter 1 gives a brief introduction to the research performed. Chapter 2 details the development of the PittRigid ME framework, including the selection of values or ranges of MEPDG inputs parameters. Chapter 3 presents the development and implementation of PittRigid ME simplified procedures for cracking and faulting. Chapter 4 provides illustrative case studies. Chapter 5 presents conclusions and recommendations for future research. Appendix A provides the results of the sensitivity analysis. Appendix B provides the MEPDG default parameters selected in this study. Appendix C contains the PittRigid ME User Guide.

2 Development of the PittRigid ME Framework

MEPDG procedure for designing JPCP uses an iterative approach. Designers must select a trial design and then analyze the design in detail to determine if it meets performance criteria. This includes the following steps [*3*]:

1. Define site conditions such as traffic, climate, and foundation.
2. Assemble a trial design (i.e. define layer arrangement, paving material properties, and design features).
3. Establish criteria for acceptable pavement performance at the end of the design period.
4. Select desired level of reliability for each of the performance indicators.
5. Process input to obtain monthly values of traffic, material, and climatic inputs needed in design evaluations for the entire design period.
6. Compute structural responses (stresses and deflections) using finite element based rapid solution models for each axle type and load and for each damage-calculation increment throughout the design period.
7. Calculate accumulated damage at each month of the entire design period.
8. Predict key distresses month-by-month throughout the design period using calibrated mechanistic-empirical performance models provided in the Guide.
9. Evaluate expected performance of the trial design at the given reliability level for adequacy.
10. If the trial design does not meet performance criteria, modify design and repeat steps 5 through 9 above until criteria are met.

The performance measures considered in MEPDG for JPCP include joint faulting, transverse cracking, and International Roughness Index (IRI). While JPCP transverse cracking and joint faulting models are mechanistic-empirical, the IRI model is purely empirical. MEPDG predicts IRI as a function of (1) JPCP cracking and faulting, (2) empirical site factors, and (3) the initial, as-constructed, profile of the pavement from which the initial IRI is computed. Since the initial profile in unknown at the pavement design stage, IRI prediction is only as accurate as the initial IRI guess. Due to these observations, PittRigid ME design process was limited to cracking and faulting analyses.

MEPDG requires thousands of stresses and deflection calculations (for different loads, joint stiffnesses, and equivalent temperature differences) to compute damage monthly over a design period of many years. It is not practical to perform these calculations manually, so a rudimentary software was developed that builds upon MEPDG. This software was later converted into AASHTOWare Pavement ME Design software.

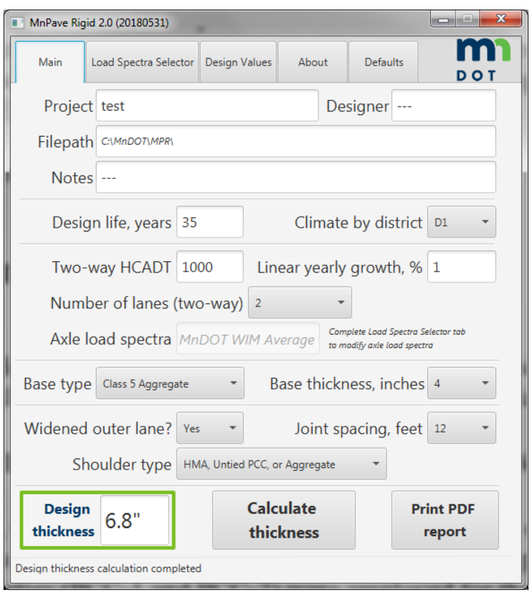
Pavement ME Design is a powerful, user-friendly program for pavement design. The program uses the designer-provided inputs (pavement structure, traffic, climate, and material parameters) and calculated pavement responses (stress and deflections) to predict the progression of pavement distress in hot-mix asphalt (HMA) and portland cement concrete (PCC).

Pavement ME requires the user to provide over one hundred inputs to characterize pavement materials, traffic loading, and environment for a single performance prediction. The following design features affect MEPDG performance predictions for JPCP:

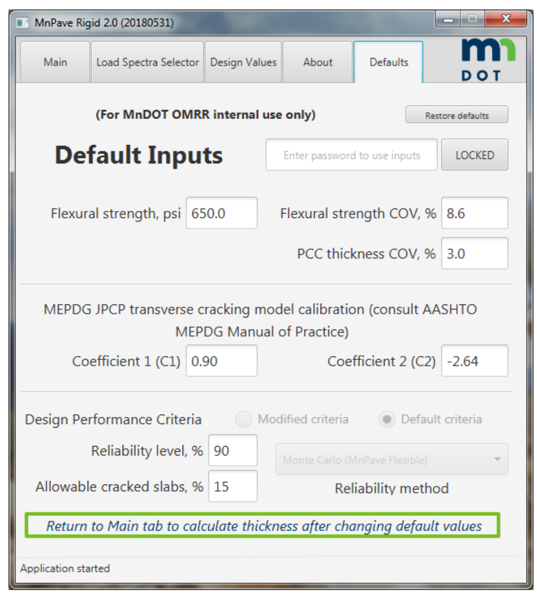
- Climate (hourly air temperature, precipitation, wind speed, and ambient relative humidity over the design period)
- Traffic volume and axle spectrum
- PCC properties
    - flexural strength
    - modulus of elasticity
    - coefficient of thermal expansion
- JPCP design features
    - PCC thickness
    - PCC joint spacing
    - dowel diameter
    - shoulder type
    - PCC slab width
- Base type and thickness
- Subgrade type and properties

Several reported sensitivity studies for the JPCP MEPDG process were reviewed by the research team [*4-7*]. These studies identified that MEPDG inputs have varying degrees of influence on the magnitude of distress; some of which are not significant to the results or are difficult to obtain for regular use. Several transportation agency-sponsored studies developed default values for these parameters for routine design [*8-11*]. The Minnesota Department of Transportation introduced a simplified mechanistic-empirical design tool, MnPave Rigid [*12-14*]. MnPave Rigid was developed by fixing a majority of MEPDG inputs to values appropriate for Minnesota conditions and only allowing the user to change key design inputs. Input parameters were selected to be both (1) important to Minnesota pavement engineers and (2) influential in M-E performance models for Minnesota conditions.

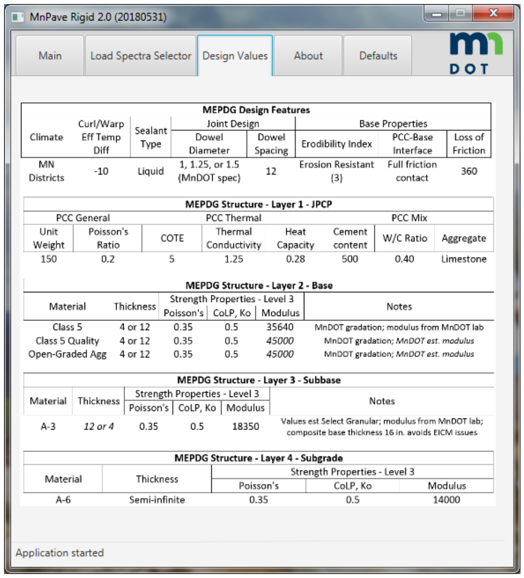
There are three tabs in the MnPave Rigid program. Figure 2-1 a) shows the main input/output screen. It allows the user to provide inputs such as design life, pavement location, daily truck traffic, joint spacing, shoulder type, etc., and display the required design concrete slab thickness as the output. Figure 2-1 b) shows password protected input variables that can be changed only by the authorized users. Figure 2-1 c) documents default MEPDG inputs used in the development of the MnPave Rigid software. These inputs cannot be changed by the user.



a) Main interface: variable input parameters



b) Password-protected variable parameters



c) Default design values

Figure 2-1. MnPave Rigid software

To assess the relative sensitivity of models used in MEPDG to individual inputs for Pennsylvania conditions, a sensitivity analysis was conducted in this study. This task was performed by fixing most input parameters and varying one parameter at a time and evaluating the results to determine if that variable has a significant, moderate, or minor effect on predicted pavement performance. AASHTOWare Pavement ME (version 2.5.3) software was used for the sensitivity analysis. The reports [*8*] and [15] were used to determine the ranges of design inputs for Pennsylvania conditions. The details of the sensitivity analysis process and its results are reported in Appendix A.

Based on the results of the literature review and sensitivity analysis, MEPDG inputs were divided into the following groups:

- Inputs that can be assigned by the user of PittRigid ME. These include parameters such as design life, daily truck traffic, traffic growth percentage, etc. Appropriate ranges for these inputs were recommended.
- Inputs that can be selected by the user from several predefined options, such as shoulder type, presence of widened lane, climate zone, and traffic pattern groups.

- Inputs for which the default values will be used. These inputs cannot be changed by the user.

Table 2-1 shows the recommended inputs that can be assigned by users along with allowable ranges or options. The default input parameters and corresponding default values are listed in the tables attached in Appendix B. Table 2-2 summarizes all the outputs of PittRigid ME for two different analyses, performance prediction and design, respectively. Moreover, PittRigid ME can output the visualized charts for distresses and cumulative traffic curves with respect to pavement age.

Table 2-1. PittRigid ME input parameters and corresponding ranges or options

Inputs Varied by Users	**Ranges or Options**
Climate Regions	• Region 1: Erie County • Region 2: PennDOT Districts D1 (except Eire County), D10, D11, and D12 • Region 3: PennDOT Districts D2 and D9 • Region 4: PennDOT Districts D3 and D4 • Region 5: PennDOT Districts D5, D6, and D8
PCC Thickness, in	6 – 14
Design Life, year	1 - 100
Cracking Reliability, %	50 – 99
Faulting Reliability, %	50 – 99
Two-way AADTT at Year 1	0 – 20000
Compound Yearly Growth Rate, %	0-10
Traffic Pattern Groups	• Urban Principal Arterial-Interstate (PA TPG 1) with Interstates Hourly Distribution Factor • Rural Principal Arterial-Interstate (PA TPG 2) with Interstates Hourly Distribution Factor • Minor Arterials, Collectors, and Recreational (PA TPG 5 to 10) with Non-Interstates Hourly Distribution Factor
Number of Lanes (Two-way)	• 2 • 4 • 6 • 8
Joint Spacing, ft	• 12 • 15

Inputs Varied by Users	Ranges or Options
Dowel Diameter, in	• Un-doweled • 1.0 • 1.25 • 1.5
Slab Width, ft	• 12 • 13
PCC Coefficient of Thermal Expansion, 10^{-6} in/in/°F	• 4.5 • 5.0 • 5.5
Shoulder Type	• Tied shoulder • HMA, Untied, and Aggregate
Base	• 6-in thick crushed stone • 4-in thick asphalt-treated permeable base (ATPB) and 6-in thick Class 2A subbase • 4-in thick cement-treated permeable base (CTPB) and 6-in thick Class 2A subbase
Modulus of Rupture, psi	400-1400

Table 2-2. Outputs for PittRigid ME

Output Parameters	Analysis Type	
	Performance Prediction	**Design**
Required PCC Thickness		×
Required Dowel Diameter		×
Cracking at Specified Reliability	×	×
Cracking at 50% Reliability	×	×
Faulting at Specified Reliability	×	×
Faulting at 50% Reliability	×	×
Cumulative Number of Heavy Trucks	×	×
Cumulative ESALs	×	×

3 PittRigid ME Procedure Development

In this study, a simplified procedure for design and analysis of Pennsylvania JPCP pavements was developed. AASHTOWare Pavement ME software was used to generate thousands of JPCP projects for Pennsylvania conditions. The information from these projects was used for development of simplified cracking and faulting procedures matching Pavement ME predictions.

3.1 JPCP Transverse Cracking Procedure Development

AASHTO M-E cracking analysis considers two modes of transverse cracking development: bottom-up cracking and top-down cracking. Under typical service conditions, the potential for either mode of cracking is present in all slabs, however a single slab cannot experience both modes. These modes of cracking are assumed to be caused by repeated application of excessive longitudinal tensile stresses in the concrete slab. The longitudinal stresses result from a combined effect of heavy axle loading and slab curling.

Repeated loadings of heavy axles cause fatigue damage along the edge of the slab, which eventually results in micro-crack propagation through the slab thickness and transversely across the slab. These cracks in JPCP eventually deteriorate, causing roughness, and require repairs. The AASHTO M-E cracking model accumulates the amount of fatigue damage caused by every truck axle load in time increments (i.e. month by month) over the entire design period.

Temperature variations from top to bottom through the JPCP slabs significantly affect critical stresses at the top and bottom of the slab. When the top surface is warmer than the bottom surfaces then slab curling causes tensile stress at the bottom of the slab. When the top surface is cooler than the bottom surface then slab curling increases tensile stress at the top of the slab.

The combined JPCP transverse cracking is determined using the following equation:

$$TCRACK = (CRACK_{BU} + CRACK_{TD} - CRACK_{BU} \cdot CRACK_{TD})\ 100\% \tag{3-1}$$

where:

$TCRACK$ = total cracking (percent),

$CRACK_{BU}$ = predicted amount of bottom-up cracking (fraction), and

$CRACK_{TD}$ = predicted amount of top-down cracking (fraction).

The following model is used to predict the amount of bottom-up and top-down transverse cracking:

$$CRACK_{BU\ or\ TD} = \frac{100}{1 + C_1 FD_{BU\ or\ TD}^{C_2}} \tag{3-2}$$

where:

$CRACK_{BU\ or\ TD}$ = predicted amount of bottom-up or top-down cracking (fraction),

$FD_{BU\ or\ TD}$ = calculated fatigue damage (bottom-up or top-down), and

C_1 and C_2 = calibration factors.

Fatigue damage is calculated incrementally to account for changes in factors that affect the result such as:

- PCC modulus of rupture
- PCC thickness and modulus of elasticity
- Axle weight and type
- Lateral truck wander
- Effective temperature difference
- Seasonal changes in base modulus, effective modulus of subgrade reaction, and moisture warping
- Axle type and load distribution

The incremental damage approach is used to predict fatigue damage at the end of each month. The total bottom-up and top-down fatigue is calculated according to Miner's hypothesis:

$$FD = \sum \frac{n_{i,j,k,l,m,n,o}}{N_{i,j,k,l,m,n,o}} \tag{3-3}$$

where:

$n_{i,j,k,\ldots}$ = applied number of load applications at condition $i,j,k,\ldots$,

$N_{i,j,k,\ldots}$ = allowable number of load applications at condition $i,j,k,\ldots$,

i = age (accounts for change in PCC modulus of rupture and modulus of elasticity),

j = season (accounts for change in base and effective modulus of subgrade reaction),

k = axle type (singles, tandems, and tridems),

l = load level (incremental load for each axle type),

m = temperature difference,

n = traffic offset path, and

o = hourly truck traffic fraction.

The allowable number of load applications is the number of load cycles at which fatigue failure is expected and is a function of applied stress and PCC strength. To predict cracking in JPCP, bending stresses should be determined for a very large number of combinations temperature and axle loading conditions, which is computationally expensive. This method has been implemented in the Pavement ME software.

In this study, the incremental Pavement ME analysis was replaced by a simplified estimation of fatigue damage using the following equation:

$$FDI_i = AADTT_i \, e^{(\alpha_1+\alpha_2 MR^* + \alpha_3 MR^{*2})} i^{(\beta_1+\beta_2 MR^*)} e^{\left(\gamma_1+\gamma_2 MR^*+\gamma_3 MR^{*2}\right)[\ln(i)]^2} \quad (3\text{-}4)$$

where:

FDI_i = fatigue damage increment for year *i* of the pavement life,

$AADTT_i$ = average annual daily track traffic for year *i*,

MR^* = the normalized 28-day concrete modulus of rupture (or flexural strength),

$= \frac{MR}{650}$, where *MR* is the 28-day concrete modulus of rupture (or flexural strength), and

$\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \gamma_1, \gamma_2,$ *and* γ_3 = regression coefficients depending on the PCC thickness, base type, PCC coefficient of thermal expansion, climatic region, traffic pattern, joint spacing, shoulder type, and lane width.

To obtain the coefficients of the damage model, a factorial of the AASHTOWare Pavement ME program run was performed. The research team created a factorial of 110,160 Pavement ME projects representing JPCP cracking design in Pennsylvania. The design life and average annual daily truck traffic (AADTT) were assumed to be equal to 40 years and 2,000 trucks, respectively. Since JPCP cracking predictions do not depend on dowel diameter, a 1.25 in dowel was arbitrary assumed. Appendix B summarizes the Pavement ME input parameters that were assumed to be the same in all cases. The following parameters were varied:

- Pavement location: 5 locations (see Table B.1)

- JPCP slab thickness: 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5, and 14 in
- Base type: aggregate base, permeable asphalt-treated base, and permeable cement-treated base (see Tables B.9 to B.12)
- Traffic pattern: 3 traffic patterns: Urban Principal Arterial-Interstate, Rural Principal Arterial-Interstate, and Minor Arterials, Collectors, and Recreational (see Tables B.2 to B.6)
- PCC 28-day modulus of rupture: 500, 600, 650, 700, 800, and 900 psi
- PCC coefficient of thermal expansion (COTE): 4.5×10^{-6}, 5.0×10^{-6}, and 5.5×10^{-6} 1/°F
- Shoulder type: tied PCC and asphalt shoulder
- Slab width: conventional width (12 ft) and widened lane (13 ft)

Table 3-1 illustrates the total number of projects required to execute. To predict cracking for these 110,160 cases, the following procedure was used:

- Pavement ME software version 2.5.4 was executed for all combinations of pavement locations, base type, PCC thickness, and modulus of rupture with the Pavement ME default traffic pattern, PCC coefficient of thermal expansion of 4.5×10^{-6} 1/°F, joint spacing of 12 ft, tied shoulder, and standard width lane.
- The batch mode process was later used to perform cracking analyzes for all combinations of traffic pattern coefficients, thermal expansion, joint spacing, shoulder types, and lane widths. The JPCP cracking model program version 8 was used. The only difference is that version 8 is written in Fortran while the current Pavement ME cracking model is written in C SHRP programming language.

Table 3-1 Cracking factorial of Pavement ME to represent Pennsylvania JPCP

5	×	3	×	17	×	6	×	3	×	2	×	2	×	3	×	2	=	110,160
Climate		Base		PCC thickness		Modulus of rupture		Traffic pattern		Joint spacing		Lane width		COTE		Shoulder type		Total projects

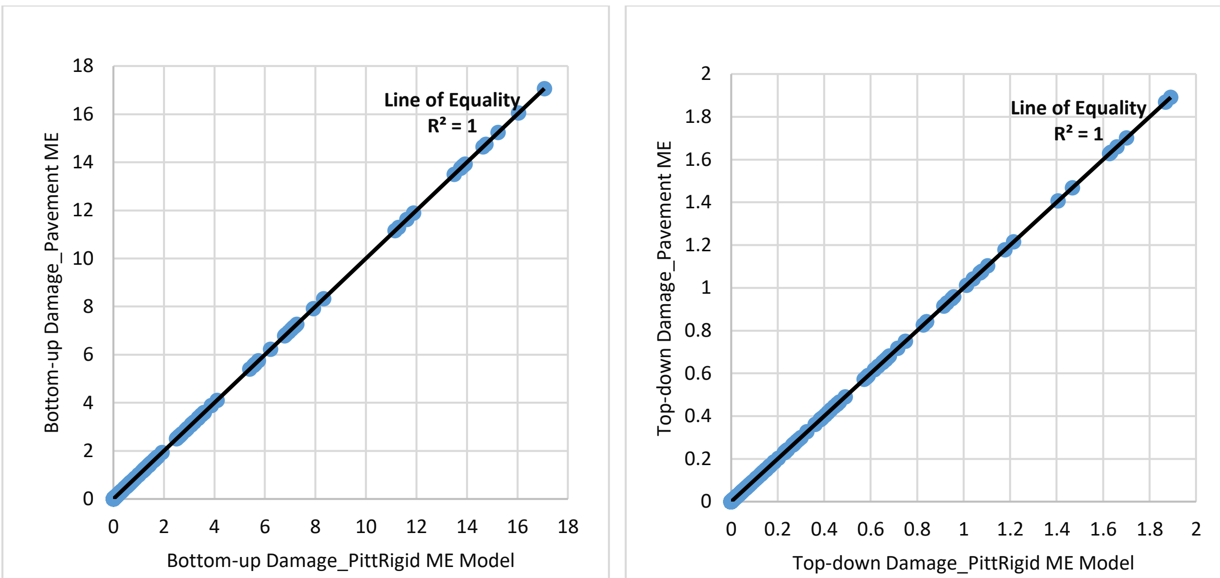
After completion of the cracking analysis for all cases, the resulting JPCP_cracking.csv files were screened to extract total top-down and bottom-up damages at the end of each month for the total pavement life. For each project, regression coefficients $\alpha_1, \alpha_2, \alpha_3,\ \beta_1, \beta_2, \gamma_1, \gamma_2, and\ \gamma_3$ were determined for top-down and bottom-up fatigue damage model described by Equation (3-4).

To verify the model, a factorial of Pavement ME runs was performed. Table 3-2 summarizes the Pavement ME input parameters that were assumed in the verification analysis. Figure 3-1 shows comparison of fatigue damages obtained from Pavement ME and the PittRigid ME model. Excellent agreements are observed for both bottom-up and top-down fatigue cracking.

Table 3-2 Pavement ME inputs for verification PittRigid ME fatigue cracking model

Pavement ME Input Variables	**Parameters**	**Ranges or Values**
Factorial Input Variables	**Climate Regions and Applied Stations**	• Region 1: Erie • Region 2: Pittsburgh (94823) • Region 3: Altoona • Region 4: Williamsport • Region 5: Philadelphia (94732)
	Base	• 6-in thick crushed stone • 4-in thick asphalt-treated permeable base (ATPB) and 6-in thick Class 2A subbase • 4-in thick cement-treated permeable base (CTPB) and 6-in thick Class 2A subbase
	PCC Thickness, in	• 6-14 with 0.5-in increments
	Modulus of Rupture, psi	• 500 • 600 • 650 • 700 • 800 • 900
Default Inputs	**Design Life, year**	40
	Two-way AADTT at Year 1	2,000
	Traffic Growth Rate, %	No growth
	Traffic Pattern Groups	Pavement ME default
	Number of Lanes	2
	Trucks in Design Lane, %	95
	Joint Spacing, ft	12
	Dowel Diameter, in	1.25
	Slab Width, ft	12
	PCC Coefficient of Thermal Expansion, 10^{-6} in/in/°F	4.5
	Shoulder Type	Tied shoulder

Pavement ME Input Variables	Parameters	Ranges or Values
	Cracking Calibration Coefficients	C1 = 2
		C2 = 1.22
		C3 = 0.52
		C4 = -2.17
	Standard Deviation	3.5522*Pow(Crack,0.3415)+0.75



a) Bottom-up damage comparisons b) Top-down damage comparisons

Figure 3-1. Comparison of fatigue damages between Pavement ME and PittRigid ME models

Fatigue damage obtained from the PittRigid ME fatigue model was used to compute transverse slab cracking using Equations (3-1) and (3-2). The predicted cracking modeled with the PittRigid ME damage model was compared to Pavement ME (shown in Figure 3-2). As it could be expected, there is an excellent agreement between these two predictions.

It should be noted that the process described above predicts JPCP cracking at 50% reliability. To predict JPCP cracking for other reliability levels, PittRigid ME adopted the MEPDG reliability analysis framework. It will be discussed in detail in Section 3.3.1.1.

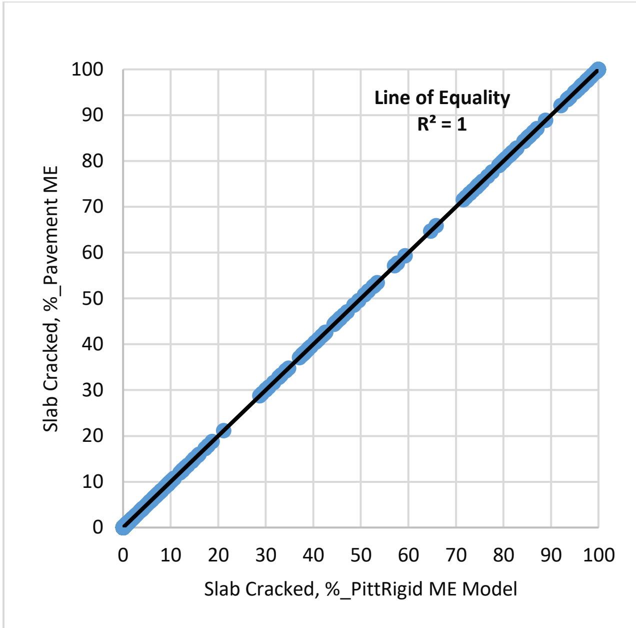


Figure 3-2. Comparison of PittRigid ME and Pavement ME transverse cracking predictions.

3.2 Faulting Model

Joint faulting is a major structural distress in JPCP that reduces the serviceability of a pavement. It is defined as the difference in elevation between adjacent joints at a transverse joint measured approximately one foot from the slab edge (longitudinal joint for a conventional lane width), or from the rightmost lane paint stripe for a widened slab.

Faulting is the result of excessive slab edge and corner deflections that cause erosion and pumping of fines from beneath a loaded leave slab. Fines are then deposited under the approach slab. A combination of poor load transfers across a joint or crack, heavy axle loads, free moisture beneath the pavement, and erosion of the supporting base, subbase, or subgrade material create necessary conditions for faulting development. Significant faulting impacts the life cycle cost of the pavement through early rehabilitation and vehicle operating costs.

Pavement ME faulting model uses a monthly incremental approach [*16*]. The faulting at each month is determined as a sum of faulting increments from all previous months in the pavement life using the following model [*16*]:

$$Fault_m = \sum_{i=1}^{m} \Delta Fault_i \quad (3\text{-}5)$$

$$\Delta Fault_i = C_{34} \times (FAULTMAX_{i-1} - Fault_{i-1})^2 \times DE_i \quad (3\text{-}6)$$

$$FAULTMAX_i = FAULTMAX_0 + C_7 \times \sum_{j=1}^{m} DE_j \times Log(1 + C_5 \times 5.0^{EROD})^{C_6} \quad (3\text{-}7)$$

$$FAULTMAX_0 = C_{12} \cdot \delta_{curling} \cdot \left[Log(1 + C_5 \times 5.0^{EROD}) \times Log\left(\frac{P_{200} WetDays}{P_s}\right)\right]^{C_6} \quad (3\text{-}8)$$

where:

$Fault_m$ = mean joint faulting at the end of month *m*, in.,

$\Delta Fault_i$ = incremental change (monthly) in mean transverse joint faulting during month *i*, in.,

$FAULTMAX_i$ = maximum mean transverse joint faulting for month *i*, in.,

$FAULTMAX_0$ = initial maximum mean transverse joint faulting, in.,

EROD = base/subbase erodibility factor,

DE_i = differential density of energy of subgrade deformation accumulated during month *i*, calculated by DE regression model,

$\delta_{curling}$ = maximum mean monthly slab corner upward deflection PCC due to temperature curling and moisture warping,

P_S = overburden on subgrade, lb,

P_{200} = percent subgrade material passing #200 sieve,

WetDays = average annual number of wet days (greater than 0.1 in. rainfall), and

$C_{1,2,3,4,5,6,7,12,34}$ = calibration constants.

The last two calibration constants, C_{12} and C_{34} can be calculated by the following equations [*16*]:

$$C_{12} = C_1 + C_2 \times FR^{0.25} \quad (3\text{-}9)$$

$$C_{34} = C_3 + C_4 \times FR^{0.25} \quad (3\text{-}10)$$

where:

FR = base freezing index defined as percentage of time the top base temperature is below freezing (32°F) temperature.

The differential energy of subgrade deformation is defined as the energy difference in the elastic subgrade deformation under the loaded slab (leave) and unloaded slab (approach):

$$DE = E_L - E_{UL} = \frac{k{\delta_L}^2}{2} - \frac{k{\delta_{UL}}^2}{2} \quad (3\text{-}11)$$

where:

DE = differential energy of subgrade deformation,

E_L = energy of subgrade deformation under the loaded slab corner,

E_{UL}= energy of subgrade deformation under the unloaded slab corner,

δ_L = corner deflection under the loaded slab, and

δ_{UL} = corner deflection under the unload slab.

Determining differential energy of subgrade deformation and load transfer efficiency parameters requires a prediction of deflections at the corner of loaded and unloaded slabs from a single, tandem, tridem, or quad axle located close to the approach slab corner. While many of the parameters remain constant through the design process (e.g., slab thickness and joint spacing), others vary seasonally, monthly, or with pavement age.

The incremental design procedure requires thousands of deflection calculations to compute damage monthly (for the different loads, joint stiffnesses, and equivalent temperature differences) over a design period of many years. This process has been implemented in the Pavement ME software.

In this study, the incremental Pavement ME analysis was replaced by a simplified estimation of the cumulative differential energy at the end of year *i* of the pavement life, CDE_i, using the following equation:

$$CDE_i = \max\left(\alpha \cdot {CumTruck_i}^2 + \beta \cdot CumTruck_i, 0\right) \quad (3\text{-}12)$$

where:

$CumTruck_i$ = cumulative number of trucks in the design lane for year *i* of the pavement life, and

α, β = regression coefficients.

To obtain regression coefficients for the differential energy model, a factorial of the AASHTOWare Pavement ME program run was performed. The research team created a factorial of 440,640 Pavement ME projects representing JPCP faulting design in Pennsylvania. The design life and AADTT were assumed to be equal to 40 years and 10,000 trucks, respectively. The remaining parameters are similar to the cracking damage factorial (see Appendix B), but unlike cracking, the faulting predictions are highly dependent on the dowel diameter. Because of that, the diameter was included in the factorial. The following parameters were varied:

- Pavement location: 5 locations (see Table B.1)
- JPCP slab thickness: 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5, and 14 in
- Base type: aggregate base, permeable asphalt-treated base, and permeable cement-treated base
- Traffic pattern: 3 traffic patterns: Urban Principal Arterial-Interstate, Rural Principal Arterial-Interstate, and Minor Arterials, Collectors, and Recreational
- PCC 28-day modulus of rupture: 500, 600, 650, 700, 800, and 900 psi
- PCC coefficient of thermal expansion: 4.5×10^{-6}, 5.0×10^{-6}, and 5.5×10^{-6} 1/ºF
- Shoulder type: tied PCC and asphalt shoulder
- Slab width: conventional width (12 ft) and widened lane (13 ft)
- Dowel diameter: un-doweled, 1 in, 1,25 in, 1,5 in

Table 3-3 illustrates the total number of projects required to execute.. To predict faulting for these 440,640 cases, the following procedure was used:

- Pavement ME software version 2.5.4 was executed for all combinations of pavement locations, base type, PCC thickness, and modulus of rupture with the Pavement ME default traffic pattern, PCC coefficient of thermal expansion of 4.5×10^{-6} 1/ºF, joint spacing of 12 ft, tied shoulder, and standard width lane, and 1.25 in dowel diameter.
- The same batch mode process used to perform the cracking analysis was used for the faulting analysis for all combinations of traffic patterns, coefficients of thermal expansion, shoulder types, joint spacing, lane widths, and dowel diameters. JPCP faulting model program version 5 was used.

Table 3-3. Faulting factorial of Pavement ME to represent Pennsylvania JPCP

5	×	3	×	17	×	6	×	3	×	4	×	2	×	2	×	3	×	2	=	440,640
Climate		Base		PCC thickness		Modulus of rupture		Traffic pattern		Dowel diameter		Joint spacing		Lane width		COTE		Shoulder type		Total projects

After completion of the faulting analysis for all cases, the resulting JPCP_faulting.csv files were screened to extract the differential energy at the end of each design year as well as the initial maximum faulting and base freezing index.

A comprehensive analysis comparing Pavement ME software version 2.5.4 and JPCP faulting model program version 5 was conducted. Figure 3-3 presents the results of comparison of the predicted faulting. Although the Pavement ME documentation does not report any modifications in the faulting prediction procedure, except re-coding it from Fortran into C SHRP, some minor discrepancies can be observed. Nevertheless, the overall agreement between these two tools is very good with the observed coefficient of determination, R^2, of 0.9982.

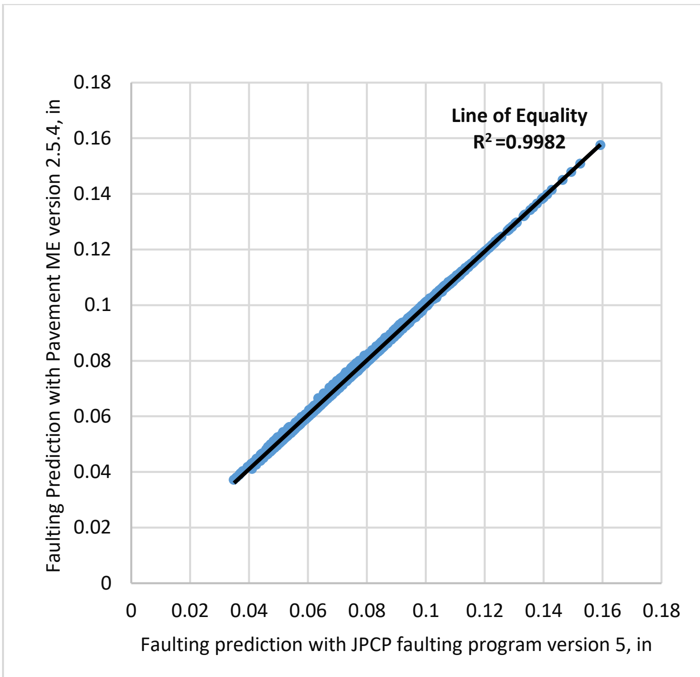


Figure 3-3. Comparisons of faulting predictions between using JPCP faulting program version 5 and Pavement ME version 2.5.4

It should be noted that the process described above predicts JPCP joint faulting at 50% reliability. To predict faulting for other reliability levels, PittRigid ME adopted the MEPDG reliability analysis framework. It will be discussed in detail in Section 3.3.1.2.

3.3 PittRigid ME Procedures

To facilitate implementation of the models described in Section 3.1 and 3.2, a Graphical User Interface (GUI) was developed using Java version 1.8.0. Figure 3-4 shows the main tab of PittRigid ME. The user may modify any shown design inputs. The ranges of input values that can be analyzed by the current version of the program are given in Table 2-1. Two types of analyses can be performed: design or performance prediction.

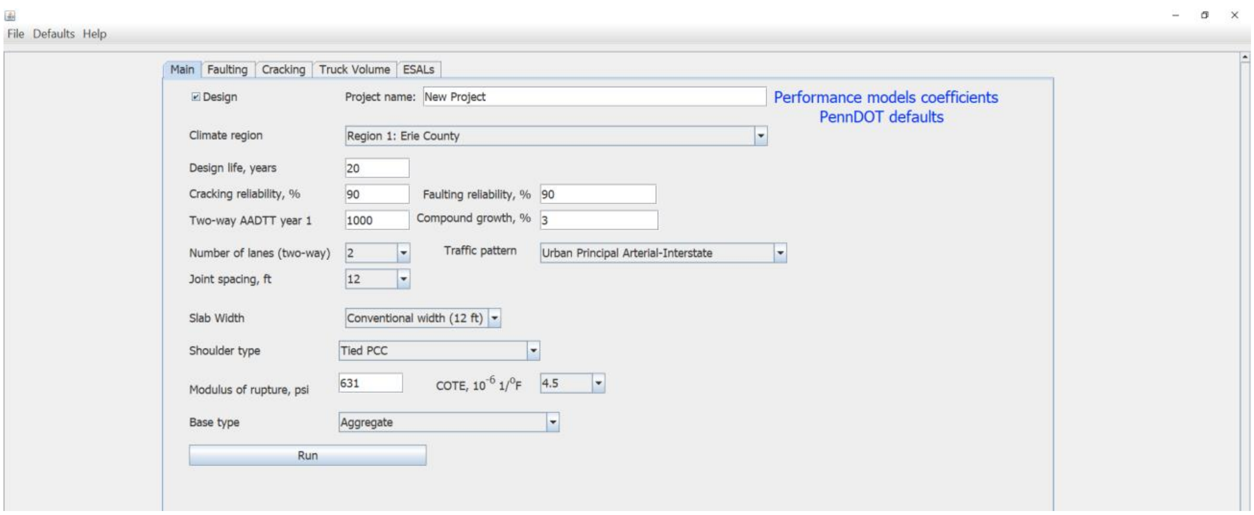


Figure 3-4. Main screen of PittRigid ME

3.3.1 *PittRigid ME Performance Prediction*

For performance prediction, the design checkbox should be unchecked (see Figure 3-5). The user should then provide PCC slab thickness and dowel diameter for the program to predict cracking and faulting levels for the pavement design life.

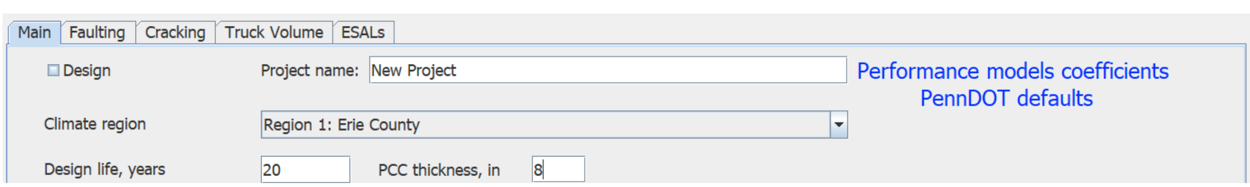


Figure 3-5. A portion of the PittRigid ME main screen with unchecked design checkbox.

By default, this program uses the calibration coefficients recommended by ARA [*15*] for Pennsylvania conditions (PennDOT default option), but the user can select Pavement ME software version 2.5.4 default values (National defaults option) or modify coefficients (Custom option).

3.3.1.1 PittRigid ME Cracking Prediction

To predict transverse fatigue cracking at 50% reliability, PittRigid ME will perform the following steps:

1. Predict average annual daily track traffic for each year *i* of the design life:

$$AADTT_i = (AADTT_1 \times LF)(1+g)^{i-1} \tag{3-13}$$

where:

$AADTT_i =$ average annual daily track traffic for year *i*,

g = compound traffic growth rate,

$AADTT_1$ = average daily track traffic in the first year, and

LF = lane distribution factor depending on the number of lanes (see Table B2).

2. Find the half-inch interval [h_1, h_2] containing the PCC slab thickness using the following equation:

$$h_1 = \frac{int(2 * h_{PCC} - 12)}{2} + 6$$
$$h_2 = h_1 + 0.5 \tag{3-14}$$

where:

h_{PCC} = PCC slab, in.

3. Using Equation (3-4), compute bottom-up and top-down fatigue damage for each year of the design life for axillary PCC thicknesses h_1 and h_2.
4. For each year of the design life compute bottom-up and top-down fatigue damage using the following equations:

$$BUFDI_i = \frac{BUFDI_{i1}(h_2 - h_{PCC}) + BUFDI_{i2}(h_{PCC} - h_1)}{h_2 - h_1}$$
$$TDFDI_i = \frac{TDFDI_{i1}(h_2 - h_{PCC}) + TDFDI_{i2}(h_{PCC} - h_1)}{h_2 - h_1} \tag{3-15}$$

where:

$BUFDI_i$ = bottom-up fatigue damage increment for year *i*,

$BUFDI_{i1}$ = bottom-up fatigue damage increment for year *i* computed in Step 2 for axillary PCC thickness h_1,

$BUFDI_{i2}$ = bottom-up fatigue damage increment for year *i* computed in Step 2 for axillary PCC thickness h_2,

$TDFDI_i$ = top-down fatigue damage increment for year *i*,

$TDFDI_{i1}$ = top-down fatigue damage increment for year *i* computed in Step 2 for axillary PCC thickness h_1, and

$TDFDI_{i2}$ = top-down fatigue damage increment for year *i* computed in Step 2 for axillary PCC thickness h_2.

5. Compute cumulative top-down and bottom-up fatigue damage for each year *i* of the design life:

$$FD_{BUi} = \sum_{k=1}^{i} BUFDI_k$$
$$FD_{TDi} = \sum_{k=1}^{i} TDFDI_k \tag{3-16}$$

where:

$FD_{TDi\ or\ BUi}$ = calculated fatigue damage (top-down or bottom-up) for year *i*.

6. Using Equation (3-2), compute predicted amount of bottom-up or top-down cracking for each year *i*.
7. Using Equation (3-1), compute 50%-reliability cracking, $TCRACK_i$, for each year *i*.

After 50% reliability cracking is predicted for each year, cracking at the specified reliability level is predicted using the MEPDG recommendations [*17*]:

$$CRACK\_P_i = TCRACK_i + STD_{Cri} \cdot Z_P$$
$$CRACK_{P_i} \leq 100\% \tag{3-17}$$

where:

$CRACK\_P_i$ = predicted cracking at the reliability level P for year *i*, percent of slabs,

Z_P = standard normal deviate (one-tailed distribution), and

STD_{Cri} = standard deviation of cracking at the predicted level of mean cracking for year *i*.

If the PennDOT default option is selected, then:

$$STD_{Cri} = \ 3.1306 \times TCRACK_i{}^{0.3582} + 0.5 \tag{3-18}$$

If the Nation default option or Custom option is selected, then:

$$STD_{Cri} = \ 3.5522 \times TCRACK_i{}^{0.3415} + 0.75 \tag{3-19}$$

3.3.1.2 PittRigid ME Faulting Prediction

To predict mean transverse joint faulting at 50% reliability, PittRigid ME performs the following steps:

1. Predict cumulative number of trucks in the design lane for year *i* of the design life, $CumTruck_i$,:

$$CumTruck_i = \frac{365 \times LF \times AADTT_1((1+g)^i - 1)}{g} \tag{3-20}$$

where:

g = compound traffic growth rate,

$AADTT_1$ = average annual daily track traffic in the first year, and

LF = lane distribution factor depending on the number of lanes (see Table B2).

2. For axillary PCC thicknesses h_1 and h_2 defined in Step 2 of the cracking procedure, compute the cumulative differential energy at the end of year *i* of the pavement life, $CDE_{1,i}$ and $CDE_{2,i}$, using Equation (3-12) and retrieve the corresponding initial maximum faulting.
3. Compute increment of the differential energy for year *i:*

$$\begin{gathered} DE_{k,1} = CDE_{k,1} \qquad k = 1,2 \\ DE_{k,i} = CDE_{k,i} - CDE_{k,i-1}, i > 1, \ \ k = 1,2 \end{gathered} \tag{3-21}$$

4. Using Equations (3-5) – (3-8), compute faulting, $Fault_{1,i}$ and $Fault_{2,i}$, for year *i* and axillary PCC thicknesses h_1 and h_2.
5. Compute 50% reliability faulting for year *i*, $Fault_i$, using the following equation:

$$Fault_i = \frac{Fault_{1,i}(h_2 - h_{PCC}) + Fault_{2,i}(h_{PCC} - h_1)}{h_2 - h_1} \quad (3\text{-}22)$$

After 50% reliability faulting is predicted for each year, faulting at the specified reliability level is predicted using the MEPDG recommendations [*17*]:

$$Fault\_Pi = Fault_i + STD_{Fi} \cdot Z_P \quad (3\text{-}23)$$

where:

$Fault\_P_i$ = predicted faulting at the reliability level *P* for year *i*, in., and
STD_{Fi} = standard deviation of faulting at the predicted level of mean faulting for year *i*, in.

If the PennDOT default option is selected, then:

$$STD_{Fi} = 0.08162 \times Fault_i^{\ 0.3481} + 0.008 \quad (3\text{-}24)$$

If the Nation default option or Custom option is selected, then:

$$STD_{Fi} = 0.07162 \times Fault_i^{\ 0.368} + 0.00806 \quad (3\text{-}25)$$

3.3.2 PittRigid ME Design Analysis

If the design analysis option is selected, PittRigid ME performs the following steps:

1. Conduct cracking performance prediction for PCC thicknesses starting from 6 in with a 0.01 in increment until predicted transverse cracking at the specified reliability level is less than the specified slab cracking requirements. The lowest PCC thickness to meet cracking performance criteria is the suggested PCC slab thickness for selected design features. If a 14-in PCC slab thickness does not meet performance requirement, the process stops and PittRigid ME reports that Pavement ME analysis should be performed.

2. Perform joint faulting performance prediction for un-doweled joints as well as dowel diameter 1, 1.25, and 1.5 in. The smallest dowel diameter that meets the joint faulting performance requirement is the suggested dowel diameter.
3. Report predicted cracking and faulting at the specified and 50% reliability as well as the required PCC slab thickness and dowel diameter.

4 Case Studies

Five examples below illustrate the use of the software to design a JPCP in Pennsylvania. Both the predicted performance and design analyses are presented to compare and verify PittRigid ME and Pavement ME.

4.1 Case 1

PittRigid ME pavement performance prediction analysis was conducted for a four-lane (two-way) interstate highway in Erie County. It has the following design features:

- PCC thickness: 6 in
- Design life: 20 years
- Daily truck traffic (two-way AADTT): 4000 trucks
- Compound truck growth rate: 3%
- Number of lane (two-direction): 4
- Truck pattern group: Urban Principal Arterial-Interstate
- Joint spacing: 12 ft
- Dowel diameter: 1.25 in
- Slab width: 12 ft
- Shoulder type: Tied shoulder
- Modulus of rupture: 675 psi
- Coefficient of expansion: 5.5×10^{-6} in/in/°F
- Base type: 4 in ATPB with 6 in Class 2A
- Target slab cracking: 10% at 95% reliability
- Target joint faulting: 0.12 in at 95% reliability
- Performance models coefficients: PennDOT defaults

Figure 4-1 shows the main screen of PittRigid ME with the corresponding inputs and main results of the analysis. Figure 4-2 and Figure 4-3 shows the screens with the results of faulting and cracking predictions, respectively. Figure 4-4 and Figure 4-5 present the computed cumulative number of trucks and cumulative equivalent single axle loads, ESALs, in the design lane, respectively. It should be noted that ESALs were not used for the design predictions and Figure 4-5 is provided for reference only.

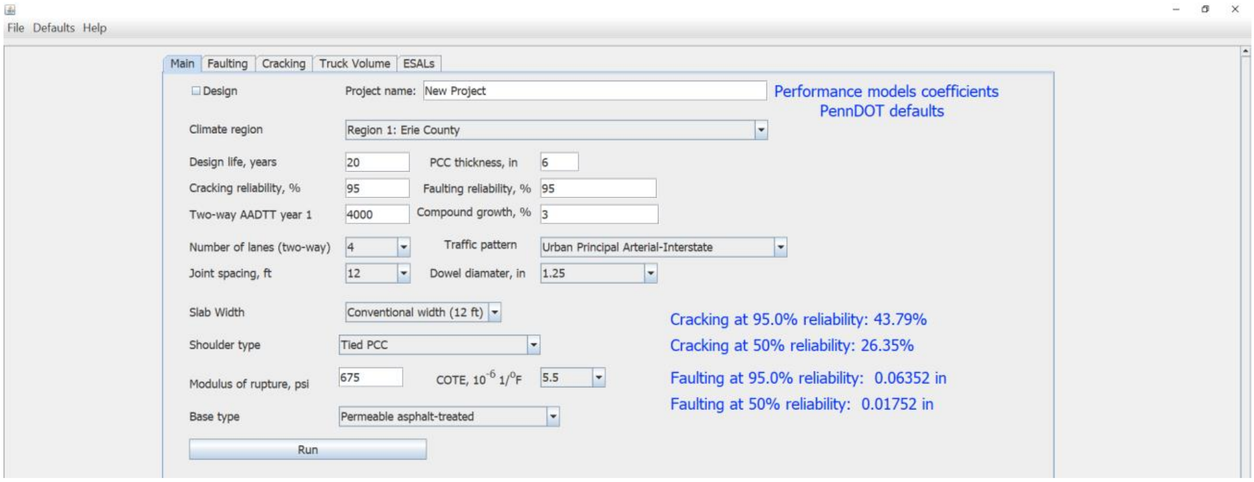


Figure 4-1. Main screen of PittRigid ME with the inputs and outputs for Case 1

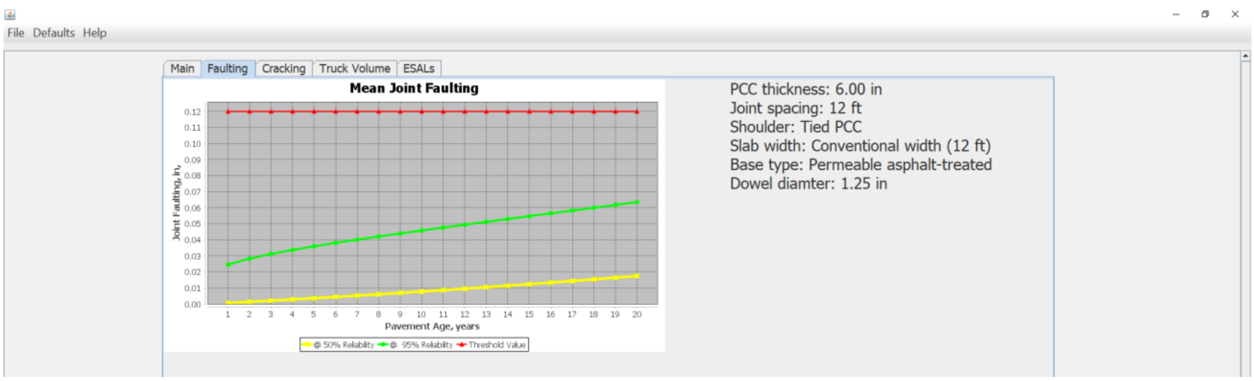


Figure 4-2. PittRigid ME screen with the results of faulting analysis for Case 1

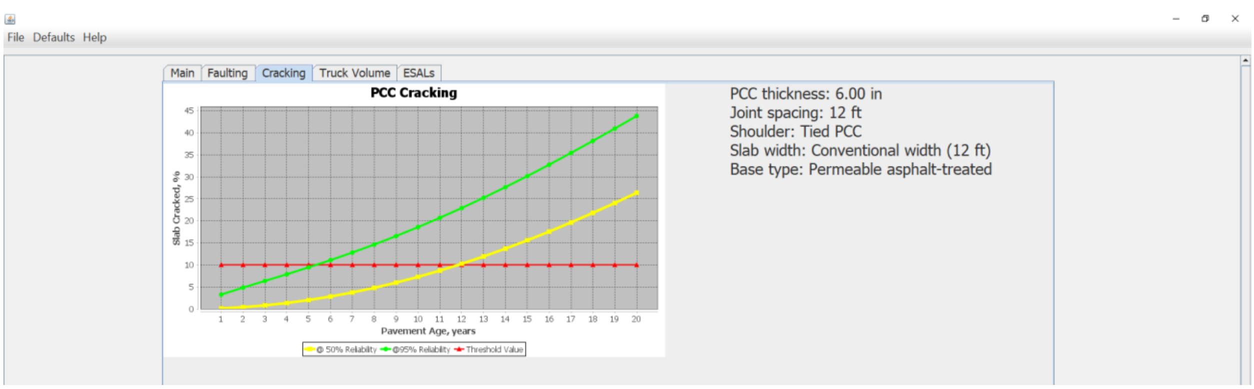


Figure 4-3. PittRigid ME screen with the results of cracking analysis for Case 1

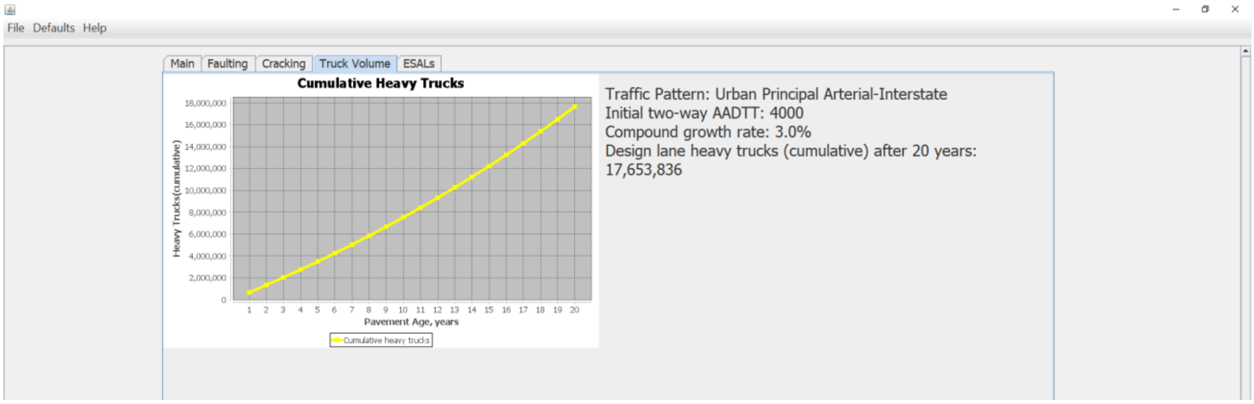


Figure 4-4. PittRigid ME screen with the results of design truck lane traffic prediction for Case 1

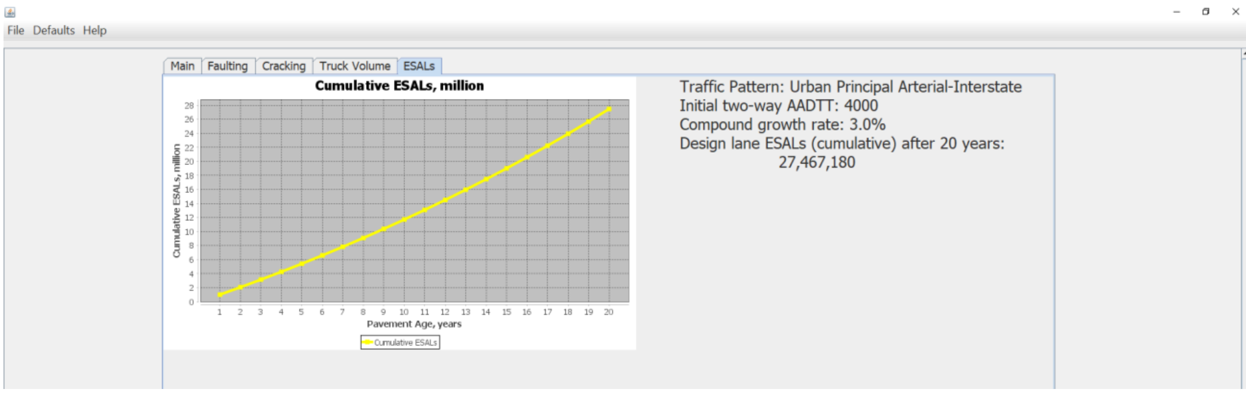
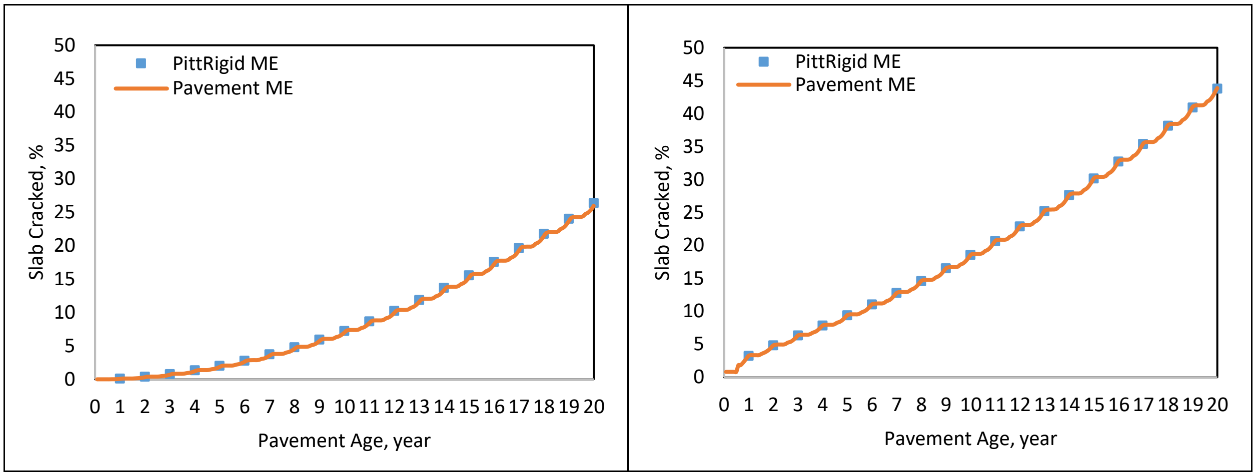


Figure 4-5 PittRigid ME screen with the results of ESALs prediction for Case 1

The results of PittRigid ME predictions were compared with the results of Pavement ME predictions. Figure 4-6 presents the results of the comparison of the cracking predictions. It should be noted that Pavement ME predicts cracking for each month of the pavement life while PittRigid ME predicts cracking at the end of each year. Nevertheless, an excellent agreement is observed for the Pavement ME cracking predictions at the end of each year and PittRigid ME cracking predictions.

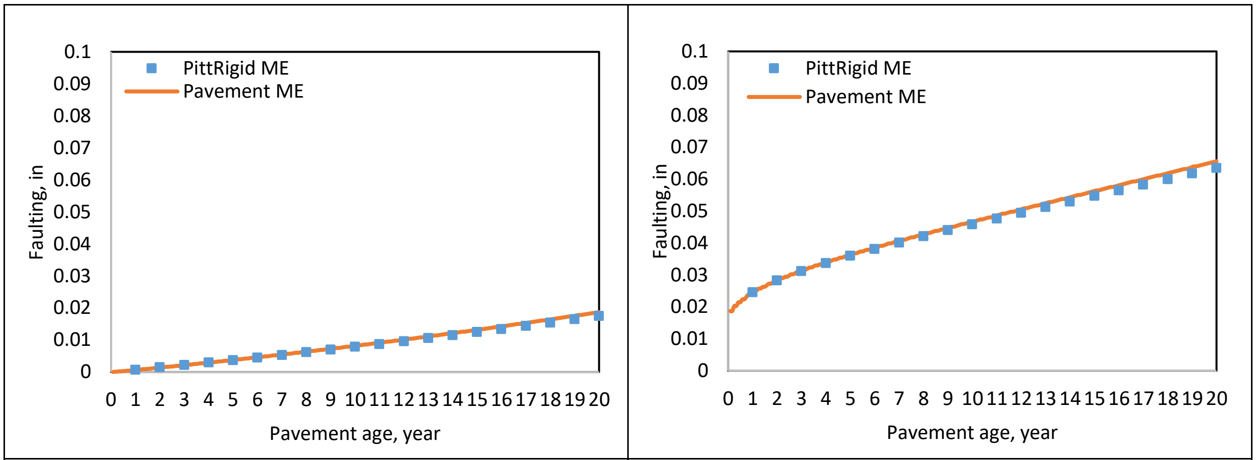
Figure 4-7 presents the results of the joint faulting predictions comparison. Similar to cracking, Pavement ME predicts faulting for each month of the pavement life while PittRigid ME predicts faulting at the end of each year of the pavement life. As it can be observed from Figure 4-7, the Pavement ME and PittRigid ME faulting predictions at the end of each year resulted in an excellent agreement between.



a) Slab cracking at 50% reliability

b) Slab cracking at 95% reliability

Figure 4-6. PittRigid ME and Pavement ME slab cracking prediction comparisons for Case 1



a) Faulting at 50% reliability

b) Faulting at 95% reliability

Figure 4-7. PittRigid ME and Pavement ME joint faulting prediction comparisons for Case 1

4.2 Case 2

PittRigid ME design analysis was conducted for a pavement with the design features and site conditions from Case 1. Figure 4-8 shows the main screen of PittRigid ME with the corresponding inputs and the main results of the analysis.

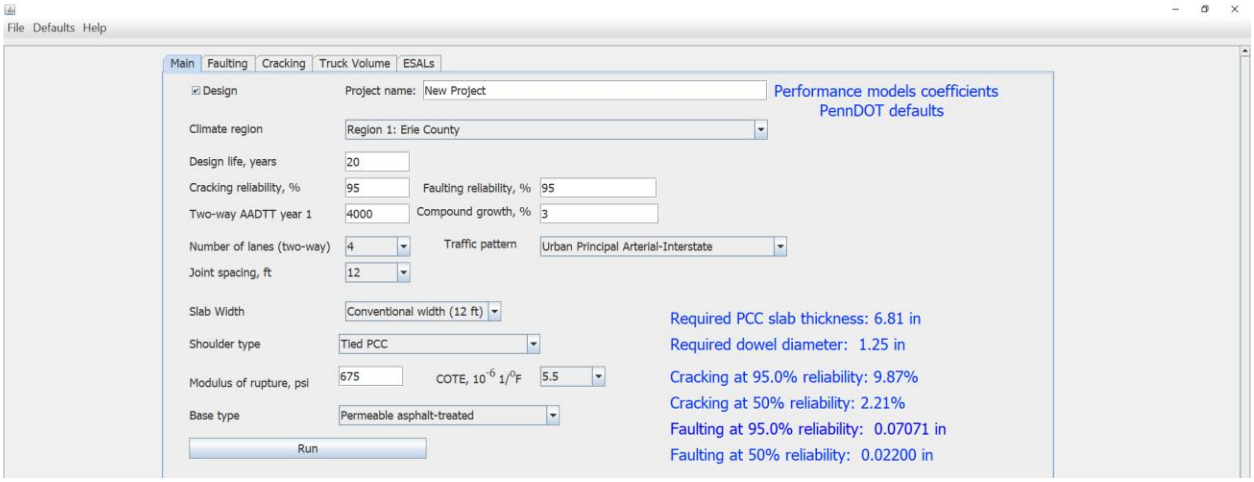


Figure 4-8. Main screen of PittRigid ME with the inputs and outputs for Case 2

Table 4-1 compares the design/optimization outputs between PittRigid ME and Pavement ME. Although Pavement ME requires a 7.0-in thick PCC slab and PittRigid ME requires a 6.81-in slab, it should be noted that Pavement ME varies PCC thickness with a 0.5-in increment, while PittRigid ME with a 0.01-in increment. Both programs require 1.25-in dowels to meets joint faulting performance requirements. Therefore, it can be concluded that both programs resulted in similar design requirements.

Table 4-1. Design analysis results comparisons for Case 2

Program	**Design/Optimized PCC Thickness, in**	**Dowel Diameter, in**	**Cracking at 95% Reliability, %**	**Faulting at 95% Reliability, in**
PittRigid ME	6.81	1.25	9.87	0.07
Pavement ME	7.0	1.25	7.39	0.08

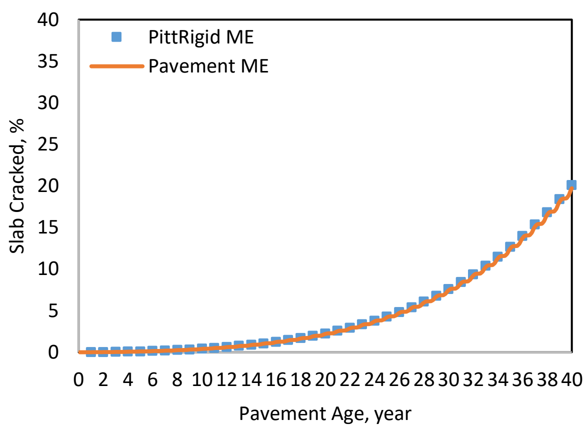
4.3 Case 3

PittRigid ME pavement performance prediction analysis was conducted for a two-lane (two-way) local road located in Williamsport, PA. The following design parameters were assumed:

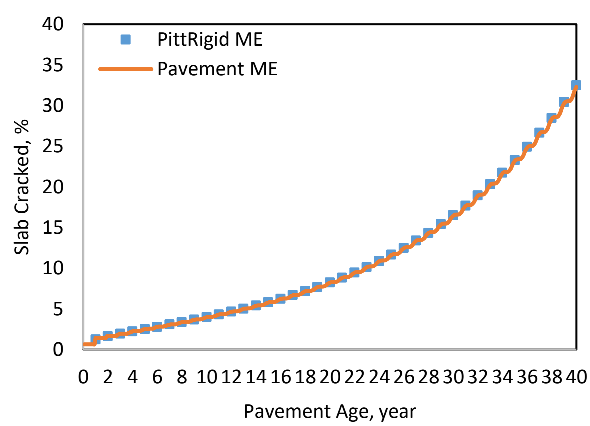
- PCC thickness: 8.0 in
- Climate region: Climate region 4: PennDOT Districts D3 and D4
- Design life: 40 years
- Daily truck traffic (two-way AADTT): 2000 trucks
- Compound truck growth rate: 5%
- Number of lane (two-direction): 2
- Truck pattern group: Minor Arterial-Interstate, Collectors, and Recreational

- Joint spacing: 15 ft
- Dowel diameter: 1.5 in
- Slab width: 12 ft
- Shoulder type: Asphalt shoulder
- Modulus of rupture: 750 psi
- Coefficient of expansion: 5.0×10^{-6} in/in/ºF
- Base type: 6 in aggregate
- Target slab cracking: 15% at 90 % reliability
- Target joint faulting: 0.15 in at 90 % reliability
- Performance models coefficients: PennDOT defaults

The results of PittRigid ME predictions were compared with the results of Pavement ME predictions. Figure 4-9 and Figure 4-10 present results of the cracking and faulting predictions. Similar to Case 1, excellent agreements are observed for the Pavement ME cracking and faulting predictions at the end of each year and the corresponding PittRigid ME cracking and faulting predictions. It confirms that PittRigid ME is capable to replicate Pavement ME slab cracking and faulting predictions for long life design scenarios.

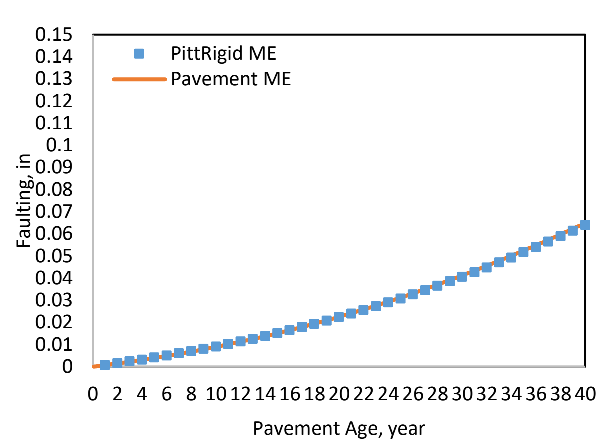


a) Slab cracking at 50% reliability

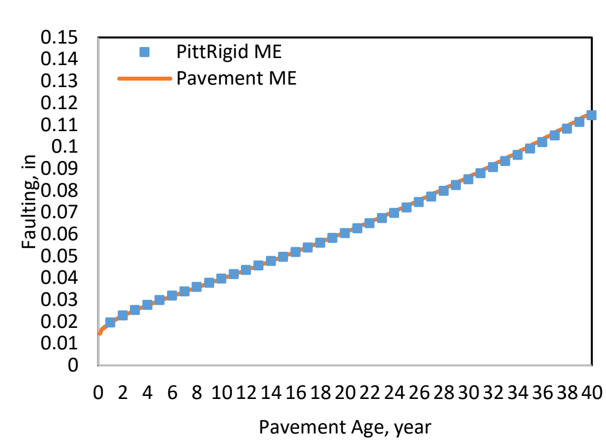


b) Slab cracking at 90% reliability

Figure 4-9. Slab cracking comparisons between PittRigid ME and Pavement ME for Case 3



a) Faulting at 50% reliability



b) Faulting at 90% reliability

Figure 4-10. Faulting comparisons between PittRigid ME and Pavement ME for Case 3

4.4 Case 4

PittRigid ME design analysis was conducted for a pavement with the design features and site conditions from Case 3. Table 4-2 compares the results of the design analysis and the results of the corresponding Pavement ME optimization. PittRigid ME resulted in an 8.33-in thick PCC slab while Pavement ME requires an 8.5-in thick PCC slab to meet transverse cracking performance. Both tools require 1.5-in dowels to meet joint faulting performance requirements. Considering that Pavement ME increments the PCC slab thickness with a 0.5-in interval, it can be concluded that both programs resulted in similar design requirements.

Table 4-2. Design analysis results comparisons for Case 4

Program	**Design/Optimized PCC Thickness, in**	**Dowel Diameter, in**	**Cracking at 90% Reliability, %**	**Faulting at 90% Reliability, in**
PittRigid ME	8.33	1.5	14.91	0.11
Pavement ME	8.5	1.5	10.23	0.12

4.5 Case 5

In response to the suggestions and recommendations from project Technical Advisory Panel (TAP), the factorial database simulating PittRigid ME cracking and faulting models was extended to increase the upper limit of PCC slab thickness from 12 in to 14 in. To verify the validation of the extended models implemented in PittRigid ME, an additional case study was performed. The PCC thickness varied at a 0.1-in increment from 12 in to 14 in. The remaining design features were selected as follows:

- Climate region: Climate region 4: PennDOT Districts D3 and D4
- Design life: 20 years
- Daily truck traffic (two-way AADTT): 20,000 trucks
- Compound truck growth rate: 8%
- Number of lanes (two-direction): 2
- Truck pattern group: Urban Principal Arterial-Interstate
- Joint spacing: 15 ft
- Dowel diameter: 1.5 in
- Slab width: 12 ft
- Shoulder type: Tied shoulder
- Modulus of rupture: 631 psi
- Coefficient of expansion: 5.5×10^{-6} in/in/^{o}F
- Base type: 4 in ATPB with 6 in Class 2A
- Target slab cracking: 15% at 90 % reliability
- Target joint faulting: 0.15 in at 90 % reliability
- Performance models coefficients: PennDOT defaults

It is important to note that an unrealistically high values of the two-way AADTT and compound growth rate were selected to predict appreciable amount of JPCP cracking. Comparisons between Pavement ME and PittRigid ME for slab cracking and faulting with respect to PCC slab thickness at 50% and 90% reliability, are shown in Figure 4-11 and Figure 4-12, respectively.

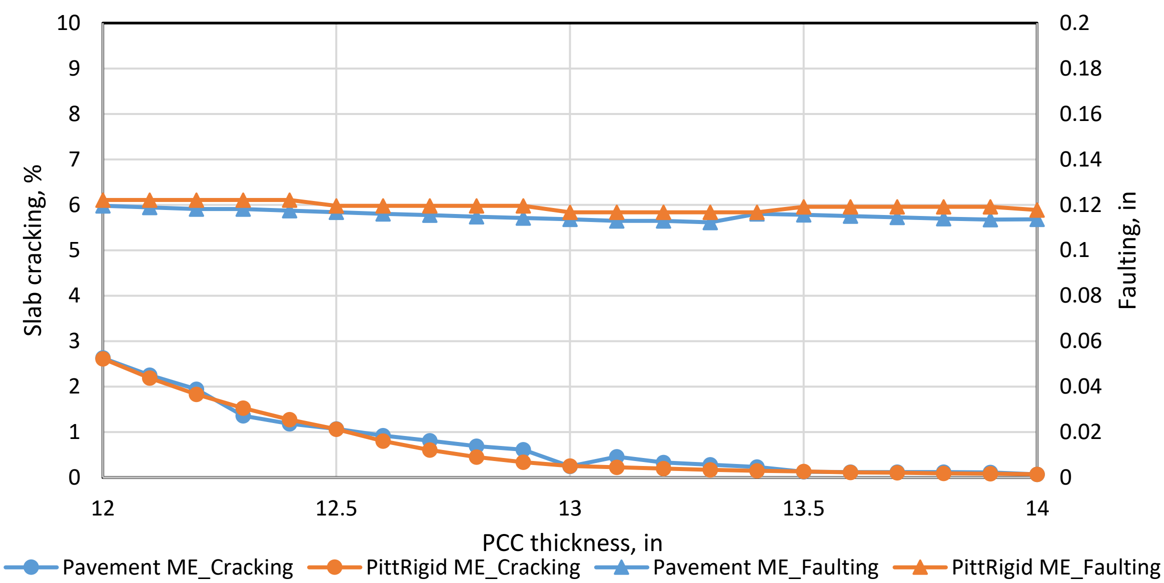


Figure 4-11. Comparing slab cracking and faulting predictions between Pavement ME and PittRigid ME at 50% reliability with respect to PCC thickness for Case 5

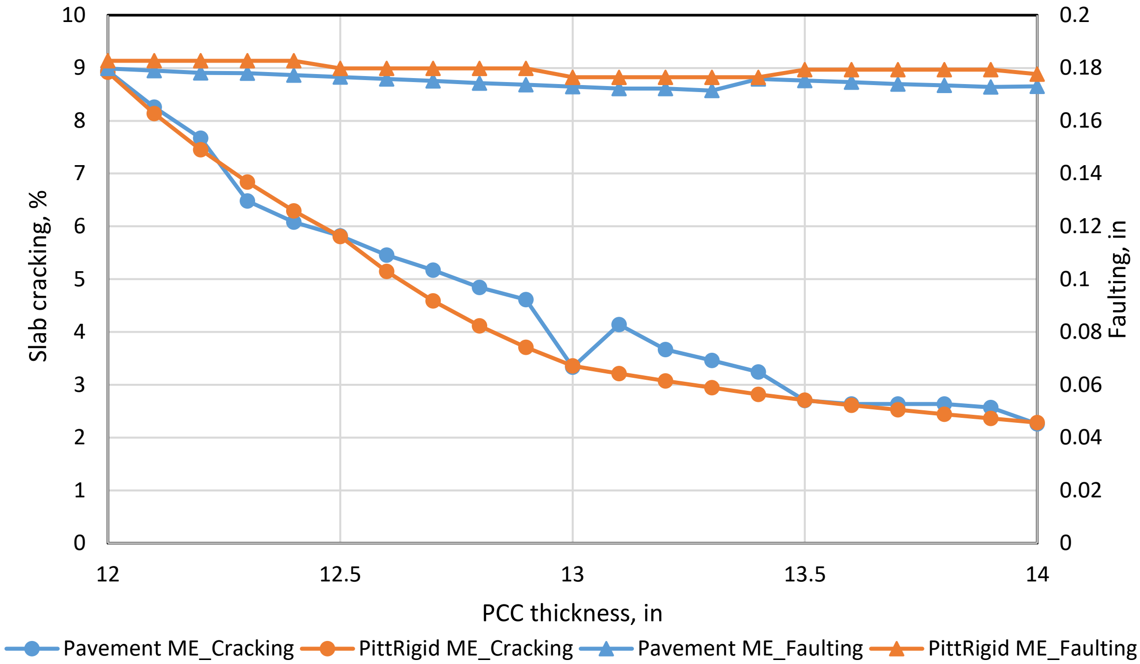


Figure 4-12. Comparing slab cracking and faulting predictions between Pavement ME and PittRigid ME at 90% reliability with respect to PCC thickness for Case 5

Figure 4-11 andFigure 4-12 show that the predictions from two programs have a good agreement for both distresses for PCC thicknesses of 12 in, 12.5 in, 13 in, 13.5 in, and 14 in. Some+ discrepancies are observed for intermediate PCC thicknesses, especially for cracking predictions at 90% reliability for PCC slab thicknesses around 13.0 in. However, the PittRigid ME seems to result in more reasonable slab cracking predictions as it can be observed from Figure 4-11 and Figure 4-12. Indeed, there is no good explanation why the Pavement ME-predicted slab cracking for a 13.0-in PCC slab thickness is significantly lower than for PCC thicknesses of 12.9, 13.1, and 13.2 in. This is an interesting phenomenon, and further investigation should be conducted to address this problem. PittRigid ME predicts a monotonic decrease in the predicted cracking with an increase in the PCC slab thickness. It should also be noted that even with these discrepancies the predictions from both programs are very similar.

5 Conclusions

This final report is intended to supplement the PittRigid ME software and User's Guide. It illustrates the research process and underlines several efforts made by the research team.

The developed simplified MEPDG design tool for rigid pavements, PittRigid ME, has many benefits for design and analysis of Pennsylvania pavements:

- PittRigid ME is portable and accessible. It does not need to access the Internet.
- The software is localized for Pennsylvania conditions.
- PittRigid ME requires users to provide only a limited number of critical input parameters.
- PittRigid ME performs and reports JPCP cracking and joint faulting predictions. The performance predictions closely match the performance predictions made with the most recent version of AASHTOWare Pavement ME software.
- PittRigid ME can determine the PCC thickness and dowel diameter required to meet the performance criteria established by the designer for the given site conditions and pavement design features.
- PittRigid ME provides flexibility to update the performance model calibration parameters if the latter is re-calibrated for Pennsylvania conditions.
- The PittRigid ME database can be extended or modified to include more design features or site conditions.
- The software can produce results instantaneously, which is much faster than Pavement ME.

PittRigid ME gives designers a practical tool for selecting the optimal cost-effective combinations of design parameters for Pennsylvania pavements that meet long-term pavement performance requirements using the advanced mechanistic-empirical design technology.

6 References

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Appendix A. Sensitivity Analysis of AASHTOWare Pavement ME

The main focus of the sensitivity study was to evaluate the effect of various design parameters on the JPCP cracking. The following model is used in the MEPDG to predict the amount of bottom-up and top-down transverse cracking:

$$CRACK_{TD\ or\ BU} = \frac{100}{1 + C_1 FD_{TD\ or\ BU}^{C2}} \quad \text{(A-1)}$$

where:

$CRACK_{TD\ or\ BU}$ = predicted amount of top-down or bottom-up cracking (fraction),

$FD_{TD\ or\ BU}$ = calculated fatigue damage (top-down or bottom-up), and

C_1 *and* C_2 = calibration factors.

The MEPDG employs an incremental damage approach to predict fatigue damage at the end of each month. The total bottom-up and top-down fatigue is calculated according to Miner's hypothesis as follows:

$$FD = \sum \frac{n_{i,j,k,l,m,n,o}}{N_{i,j,k,l,m,n,o}} \quad \text{(A-2)}$$

where:

FD = fatigue damage,

$n_{i,j,k,\ldots}$= applied number of load applications at condition $i,j,k,\ldots$,

$N_{i,j,k,\ldots}$ = allowable number of load applications at condition $i,j,k,\ldots$,

i = age (accounts for change in PCC overlay modulus of rupture and modulus of elasticity),

j = season (accounts for change in base and effective modulus of subgrade reaction),

k = axle type (singles, tandems, or tridems),

l = load level (incremental load for each axle type),

m = temperature difference,

n = traffic offset path, and

o = hourly traffic fraction.

Analysis of Equations (A-1) and (A-2) shows that the relationship between JPCP cracking and the number of load applications is highly nonlinear. This may cause misleading conclusions if the sensitivity of the design inputs on JPCP cracking is conducted only for a certain traffic level. At the same time, the cumulative damage is proportional to traffic volume. The relative effect of the design features on the cumulative damage does not depend on the traffic volume. Since the cumulative damage is directly related to cracking, it is more efficient to evaluate the relative effect of the design features on the cumulative damage than the cracking level (see Figure A.1).

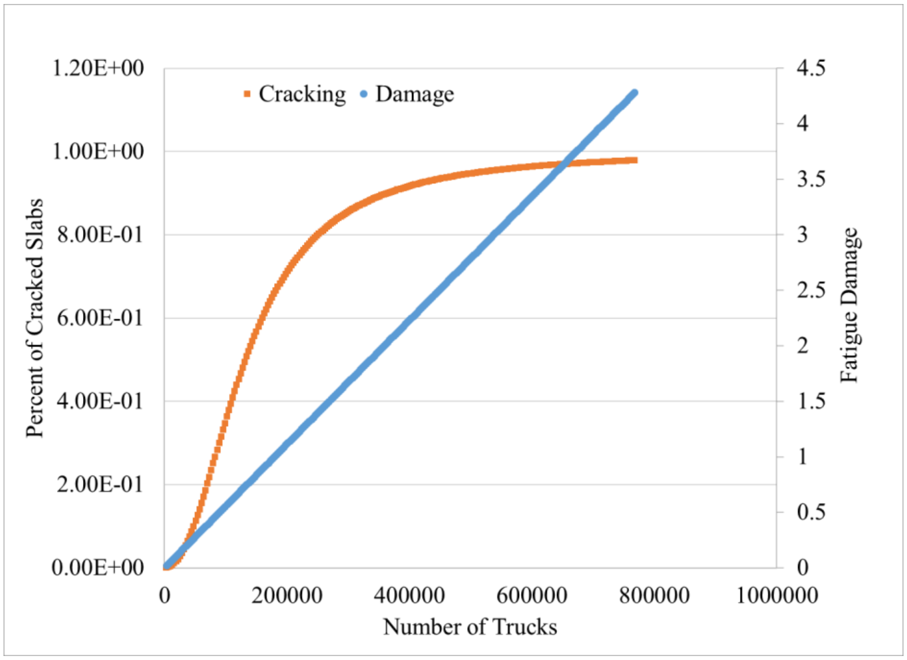


Figure A.1. Example of cracking and fatigue damage vs truck volume

In this study, a baseline Pavement ME design project (9-in JPCP at Pittsburgh), was selected and various design inputs were changed one input at a time. The reports [*8*] and [15] were used to determine the ranges of design inputs for Pennsylvania conditions. The selected default parameters in PittRigid ME software with detailed list of the input parameters, which are used in the Pavement ME sensitivity analysis, can be found in Appendix B. After the Pavement ME factorial runs were performed, the results were screened to determine the cumulative fatigue damages at the top and bottom PCC slab surfaces predicted by Pavement ME software. These damages were normalized to the cumulative damages for the baseline case. A summary of the sensitivity analysis results is provided below.

A.1 Traffic

A total of four traffic input parameters have been evaluated in this study:

- the average number of axles per truck class
- hourly distribution factor (HDF)
- monthly adjustment factor (MAF)
- traffic pattern groups (TPG)

If no site-specific information is available, Pavement ME used the default values determined from the data collected under the Long-Term Pavement Performance (LTPP) program for the pavement sections located around the entire Unites States. However, the MEPDG encourages the use of the site-specific or regional/statewide inputs. In this study, the MEPDG defaults were compared with the recommendations developed by ARA, Inc. [*15*] and the University of Pittsburgh for PennDOT [*8*].

Figure A.2 presents a comparison of the relative cumulative damages for the average number of axles per truck class assigned. It can be observed that MEPDG defaults and ARA-recommended input parameters resulted in very similar damage. Therefore, only one set of the average number of axles per truck class was recommended for use in the development of PittRigid ME.

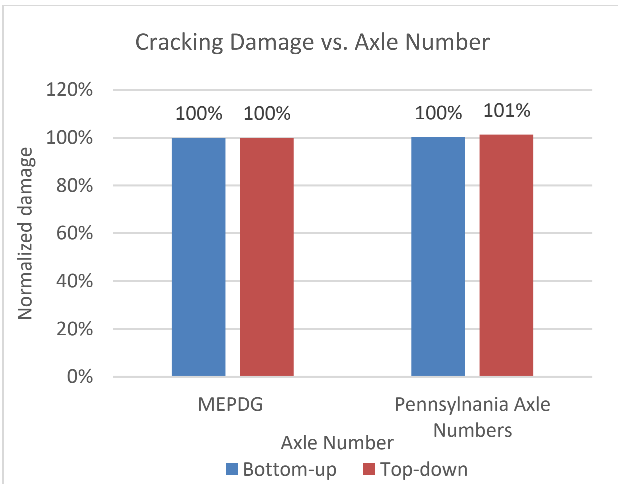


Figure A.2. MEPDG default vs. Pennsylvania-specific average number of axles per truck class

The hourly distribution factors, HDF, represent the percentage of the traffic volume within each hour of the day. Three sets of HDF were considered in this study:

- MEPDG defaults
- ARA-recommended HDF for the interstate roads
- ARA-recommended HDF for the non-interstate roads

Figure A.3. shows that the ARA recommendations for the HDF for non-interstate routes lead to significantly different damage predictions compared to the predictions using the MEPDG defaults. The difference is much less pronounced for the ARA recommendations for interstate roads. Based on this analysis, it was recommended to adapt ARA recommendations instead of the MEPDG defaults and use different HDF for interstate and non-interstate roads.

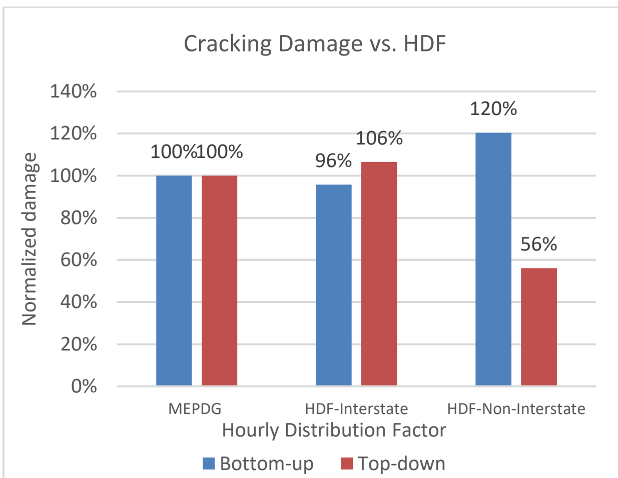


Figure A.3. Effect of hourly distribution factor (HDF) on predicted fatigue damage

Truck traffic monthly adjustment factors, MAF, simply represent the percent of the annual truck traffic for a given truck class that occurs in a specific month. A comparison of the fatigue damages predicted with the MEPDG defaults and ARA-recommended MAF show only a minor effect of the state-specific MAF on the damage (see Figure A.4). The ARA-recommended MAF will be adapted in this study.

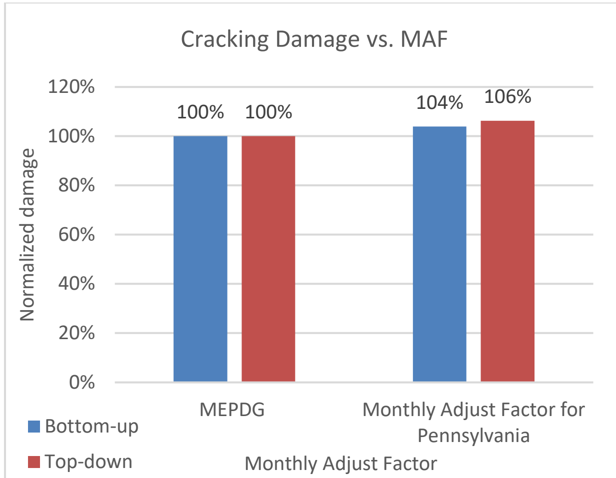


Figure A.4. Effect of truck traffic monthly adjustment factors on predicted fatigue damage

The traffic pattern groups (TPG) represent the percentage of each truck class (FHWA classes 4 through 13) within the truck traffic mix. The following TPG were considered in this study:

- AASHTO default vehicles class distribution
- ARA-recommended Urban Principal Arterial – Interstate (PA TPG 1)
- ARA-recommended Rural Principal Arterial – Interstate (PA TPG 2)
- ARA-recommended Other Principal Arterial (PA TPG 3 & 4)
- ARA-recommended Minor Arterials, Collectors, and Recreational (PA TPG 5 to 10)

As can be observed from Figure A.5, the damages for the interstate traffic pattern groups, PA TPG 1 and PA TPG2, are significantly different from the damages predicted with the MEPDG defaults. The difference between the two other patterns and the MEPDG defaults is less significant. Based on the results of this analysis, it is suggested to adapt ARA recommendations for both traffic patterns for interstate highways, but only one traffic pattern for non-interstate roads. Since bottom-up damage is pre-dominant for low volume roads, the PA TG 5 to 10 traffic pattern is recommended for analysis of non-interstate roads.

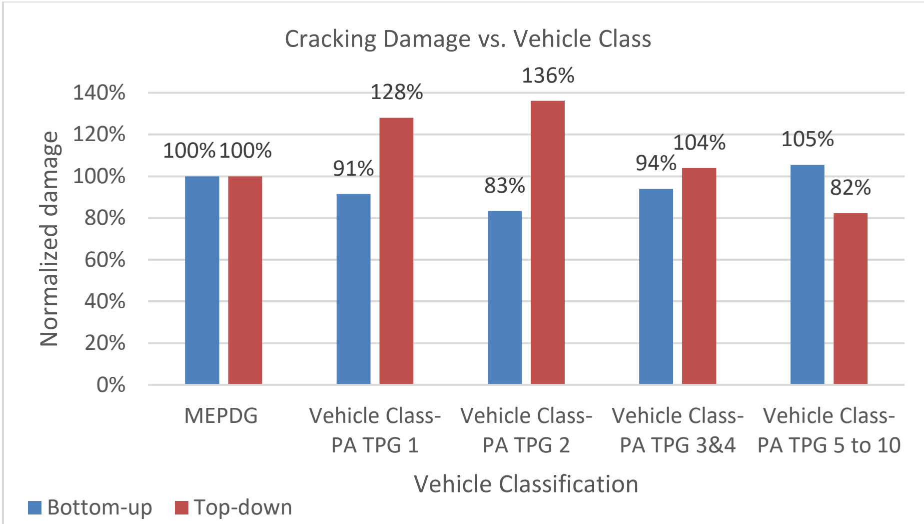


Figure A.5. Effect of the traffic pattern on predicted fatigue damage

A.2 Climate

The MEPDG procedure requires the designer to provide detailed climatic data for predicting pavement distresses. For ease of use, the Pavement ME database contains climatic data from a number of weather stations from the North American Regional Reanalysis (NARR) for JPCP. In this study, the Pavement ME simulations were performed for 33 weather stations located in Pennsylvania or neighboring states. Figure A.6 shows the geographic distribution of these weather stations. The location, latitude, longitude and elevation information are summarized in Table A.1.

Figure A.6. Climate stations in Pennsylvania and out of state surrounding stations [*15*]

Table A.1. Location, latitude, longitude and elevation data of climate stations

Region	Station	Location	Latitude	Longitude	Elevation
1	**Erie**	Pennsylvania	40.12	-76.29	400
2	**Pittsburgh (14762)**	Pennsylvania	40.36	-79.92	1240
	Pittsburgh (94823)	Pennsylvania	40.5	-80.23	1118
	Morgantown	West Virginia	39.64	-79.91	1220
	Meadville	Pennsylvania	41.63	-80.22	1407
	Youngstown	Ohio	41.25	-80.67	1172
	Ashtabula	Ohio	41.77	-80.69	918
	Wheeling	West Virginia	40.17	-80.64	1200
3	**Dunkirk**	New York	42.49	-79.27	665
	Bradford	Pennsylvania	41.8	-78.64	2109
	Johnstown	Pennsylvania	40.3	-78.83	2277
	Clearfield	Pennsylvania	41.05	-78.41	1511
	Wellsville	New York	42.1	-77.99	2085
	Du Bois	Pennsylvania	41.18	-78.9	1808
	Altoona	Pennsylvania	40.3	-78.32	1468
4	**Elmira/Corning**	New York State	42.15	-76.89	935
	Selinsgrove	Pennsylvania	40.82	-76.86	450

Region	Station	Location	Latitude	Longitude	Elevation
	Binghamton	New York	42.2	-75.98	1595
	Williamsport	Pennsylvania	41.24	-76.92	525
5	**Allentown**	Pennsylvania	40.65	-75.45	385
	Doylestown	Pennsylvania	40.33	-75.12	380
	Reading	Pennsylvania	40.37	-75.96	333
	Pottstown	Pennsylvania	40.24	-75.56	291
	Lancaster	Pennsylvania	40.12	-76.29	400
	Wilkes-Barre/Scranton	Pennsylvania	41.34	-75.73	953
	Harrisburg (14711)	Pennsylvania	40.19	-76.76	300
	Mount Pocono	Pennsylvania	41.14	-75.38	1892
	Wilmington	Delaware	39.67	-75.6	75
	York	Pennsylvania	39.92	-76.87	472
	Philadelphia (94732)	Pennsylvania	40.08	-75.01	101
	Philadelphia (13739)	Pennsylvania	39.87	-75.23	107
	Hagerstown	Maryland	39.7	-77.73	692
	Harrisburg (14751)	Pennsylvania	40.22	-76.85	336

Unlike the sensitivity study for other design inputs, the sensitivity analysis of the climatic data was conducted for two JPCP structures:

- 7-in thick JPCP pavement with an asphalt shoulder
- 9-in thick JPCP pavement with a tied PCC shoulder

A 15-ft joint spacing was assumed for both pavement structures. Figure A.7 and Figure A.8 present predicted fatigue damage for 7-in and 9-in thick JPCP, respectively. It has been observed from Figure A.7 that the dominant cracking damage for a 7-in thick JPCP is the bottom-up damage that is about 10 times greater than the top-down damage at every single climate station. For a 9-in thick JPCP, top-down and bottom-up damages have similar magnitudes as shown in Figure A.8.

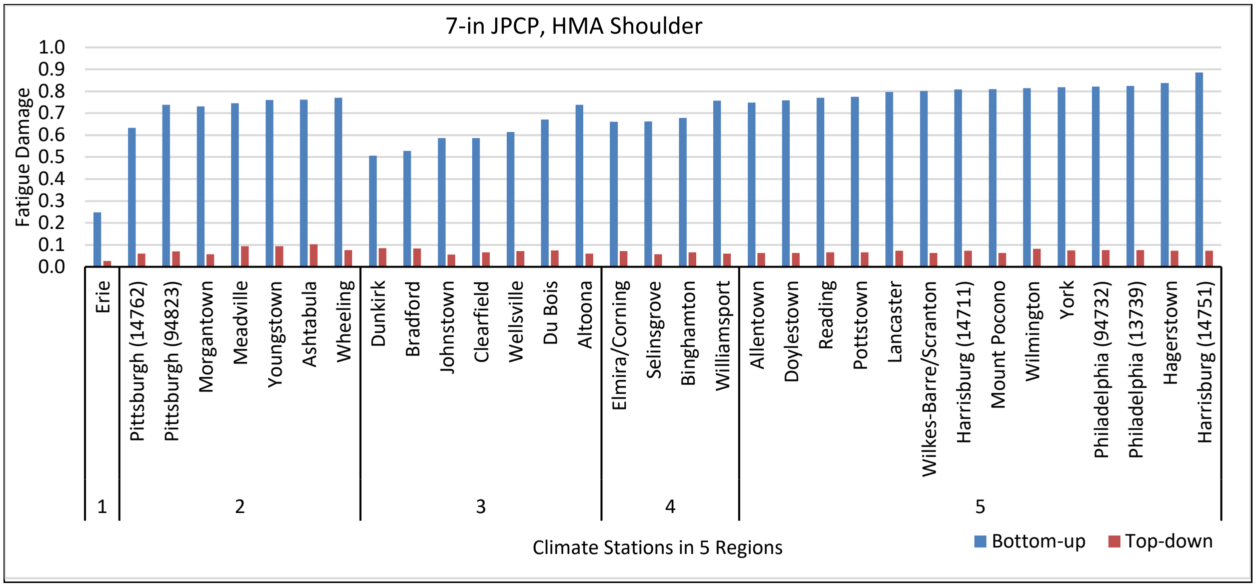


Figure A.7. Predicted fatigue damage for all climate stations, a 7-in thick JPCP

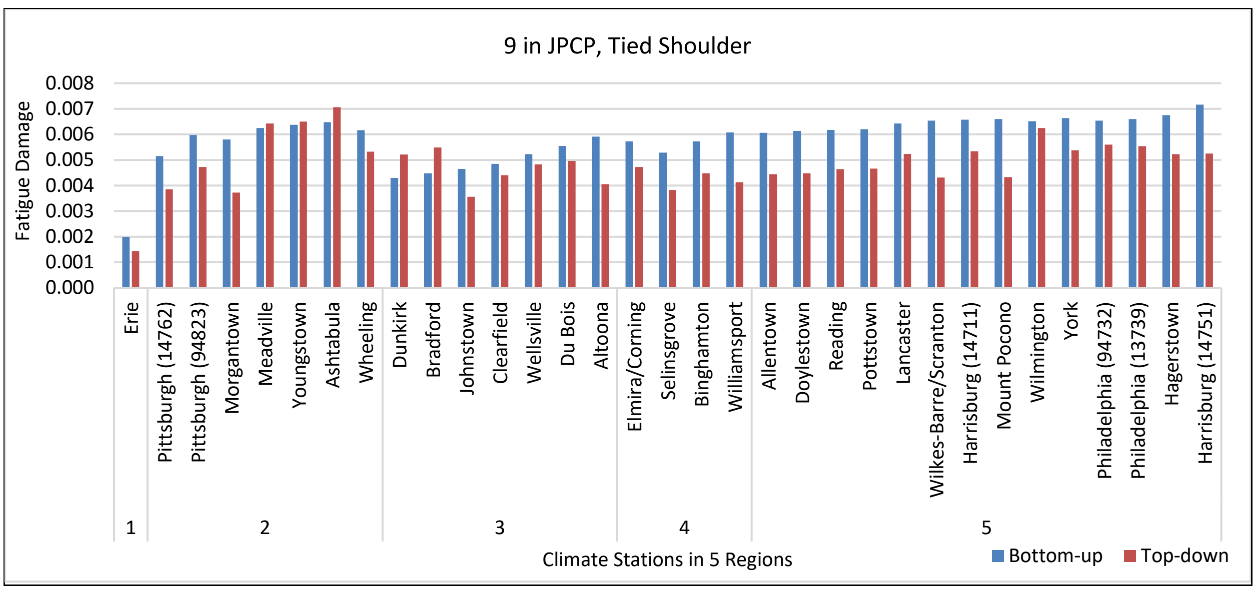
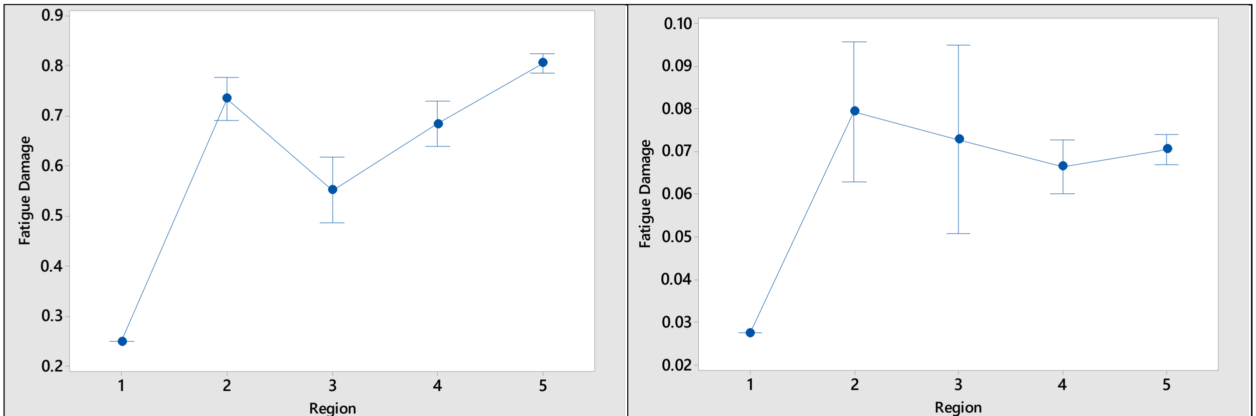


Figure A.8. Predicted fatigue damage for all climate stations, a 9-in thick JPCP

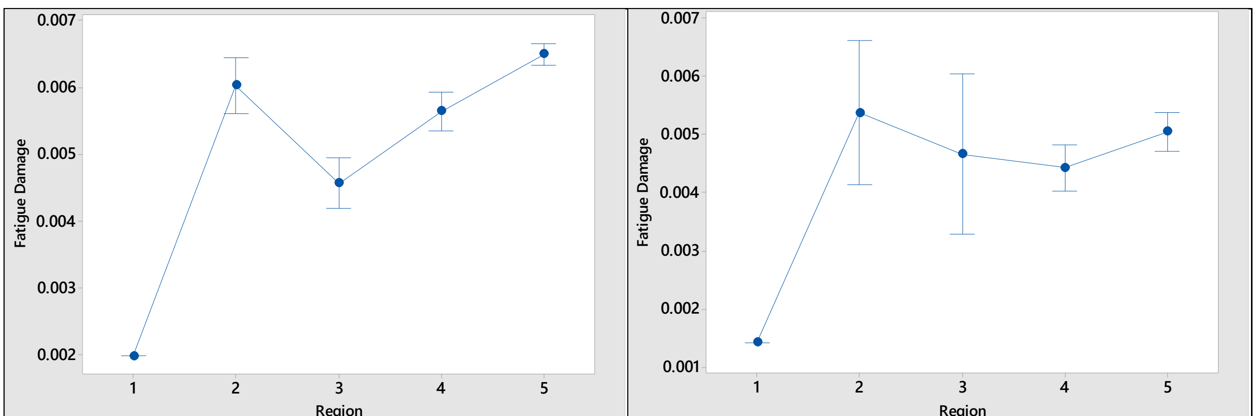
Based on the results of this analysis, the weather stations were divided into five groups based on geographic proximity and predicted damage level, as indicated in Table A.1. Figure A.9 and Figure A.10 show groups of statistical damage distributions for 7- and 9-in JPCP, respectively. It can be observed that the regions significantly differ by the predicted bottom-up damage. The difference in the top-down damage is less pronounced, except the Erie region that exhibited significantly lower both top-down and bottom-up damages than the remaining locations.

Based on the results of this analysis, Pennsylvania was divided into 5 regions (see Figure B.1) and the climate stations located in Erie, Pittsburgh (94823), Altoona, Williamsport, and Philadelphia (94732) were selected as representative climate stations for the corresponding regions (see Table B.1).



a) Bottom-up damage	b) Top-down damage

Figure A.9. Fatigue damages for 5 regions, a 7-in thick JPCP



a) Bottom-up damage	b) Top-down damage

Figure A.10. Fatigue damages for 5 regions, a 9-in thick JPCP

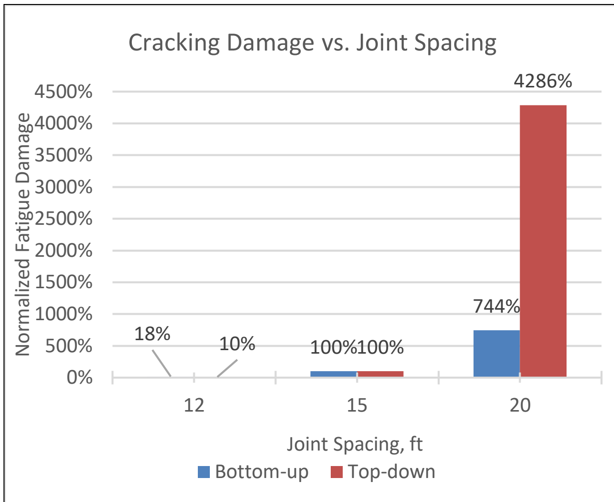
A.3 JPCP Design Features

The effect of the following four design inputs on the predicted pavement performance was evaluated:

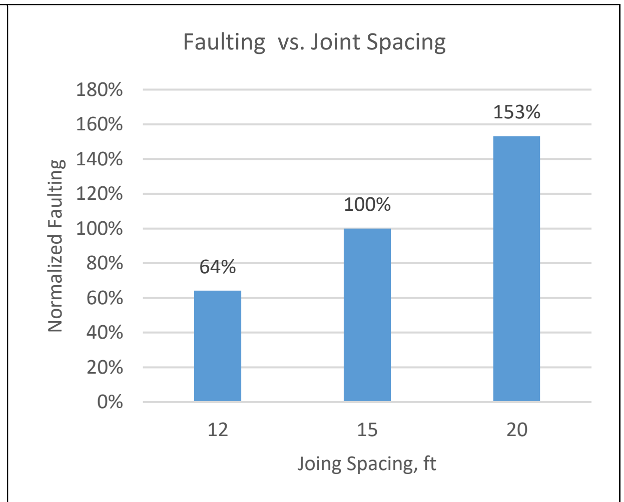
- Joint spacing
- PCC slab width
- Shoulder type

- Dowel diameter

Figure A.11 to Figure A.14 summarize the results of the Pavement ME sensitivity analysis of several JPCP properties. It can be observed that all the design features, except the dowel diameter, significantly affect the predicted fatigue damage. The dowel diameter does not affect fatigue damage but has a greater effect on the predicted joint faulting than all other design features.

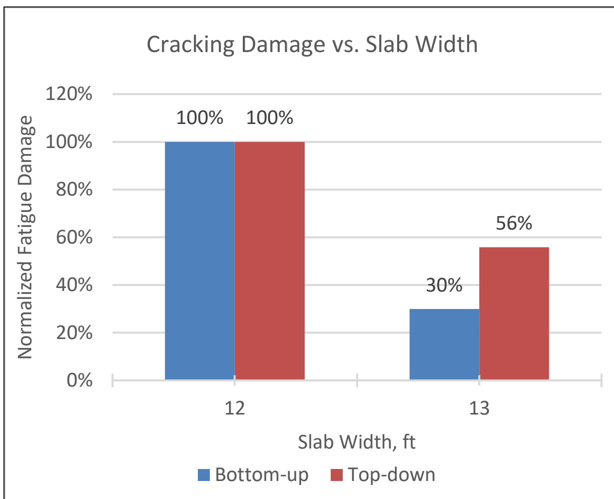


a) Joint spacing sensitivity for fatigue damage

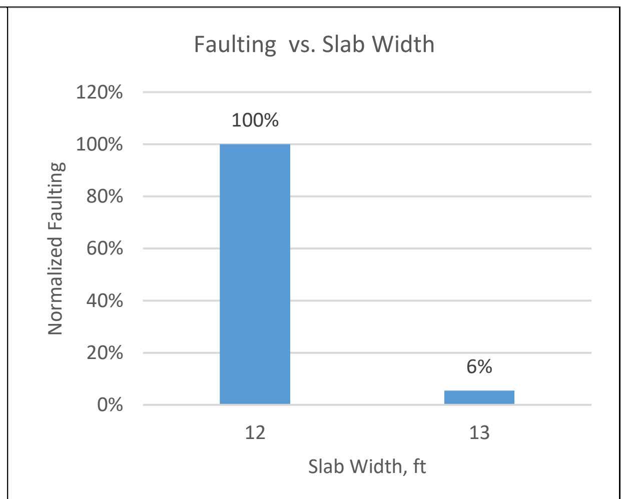


b) Joint spacing sensitivity for faulting

Figure A.11. Effect of joint spacing on predicted fatigue damage and joint faulting

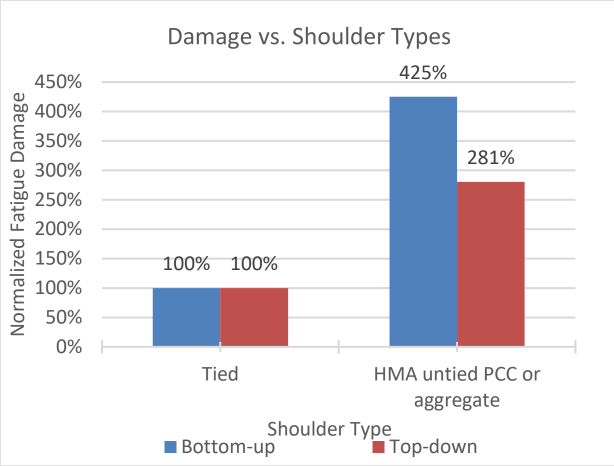


a) Slab width sensitivity for fatigue damage

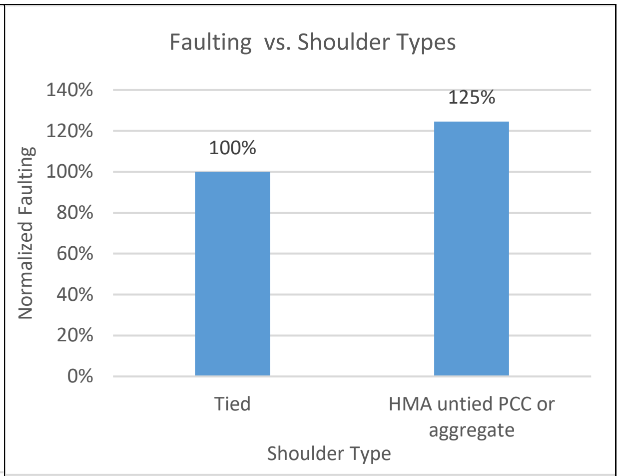


b) Slab width sensitivity for faulting

Figure A.12. Effect of PCC slab width on predicted fatigue damage and joint faulting

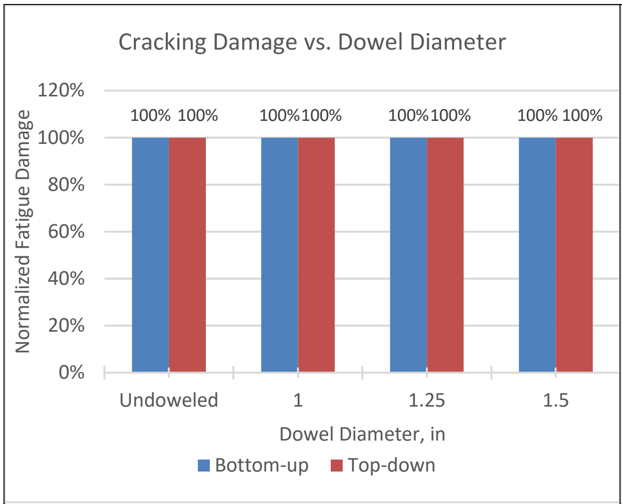


a) Shoulder type sensitivity for fatigue damage

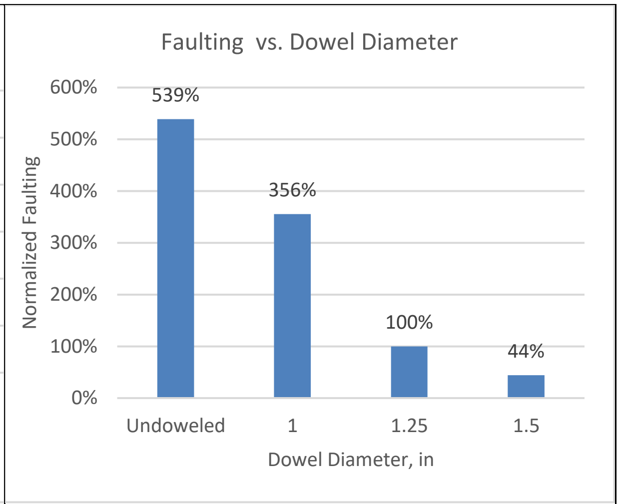


b) Shoulder type sensitivity for faulting

Figure A.13. Effect of should type on predicted fatigue damage and joint faulting



a) Dowel diameter sensitivity for fatigue damage



b) Dowel diameter sensitivity for faulting

Figure A.14. Effect of dowel diameter on predicted fatigue damage and joint faulting

A.4 PCC Properties

PCC properties are important input parameters of the MEPDG. Figure A.15 shows the effect of the coefficient of thermal expansion and concrete modulus of rupture (flexural strength) on the predicted fatigue damage. It can be observed that both parameters significantly affect pavement performance. It is recommended to include these parameters as direct inputs into PittRigid ME software.

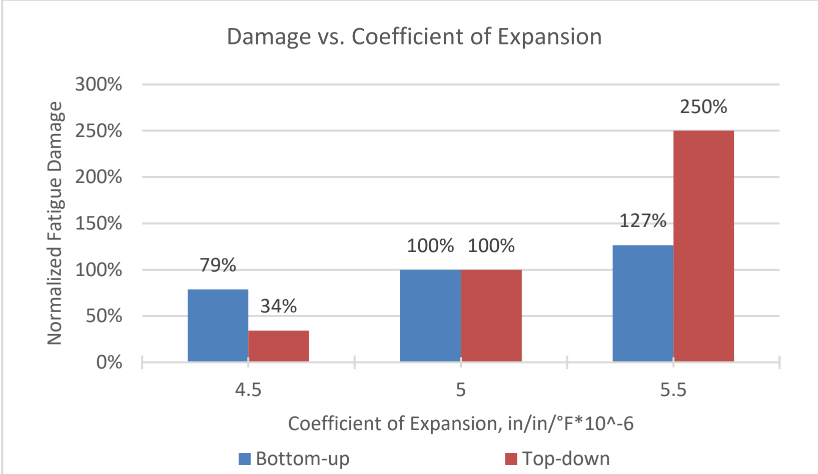
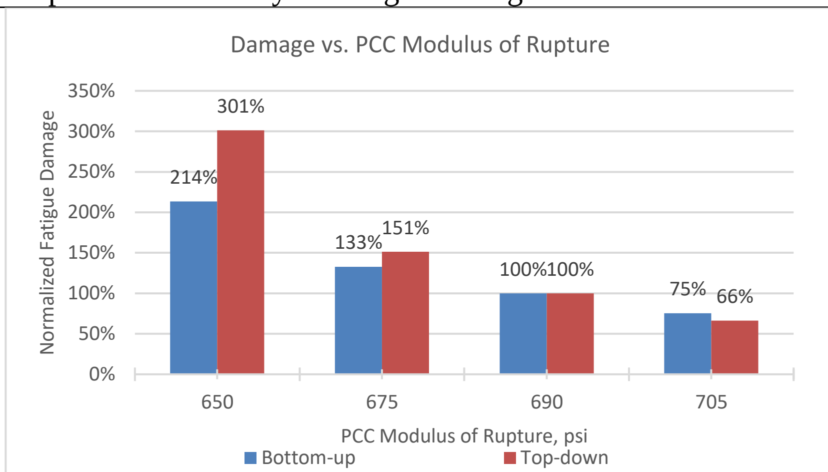
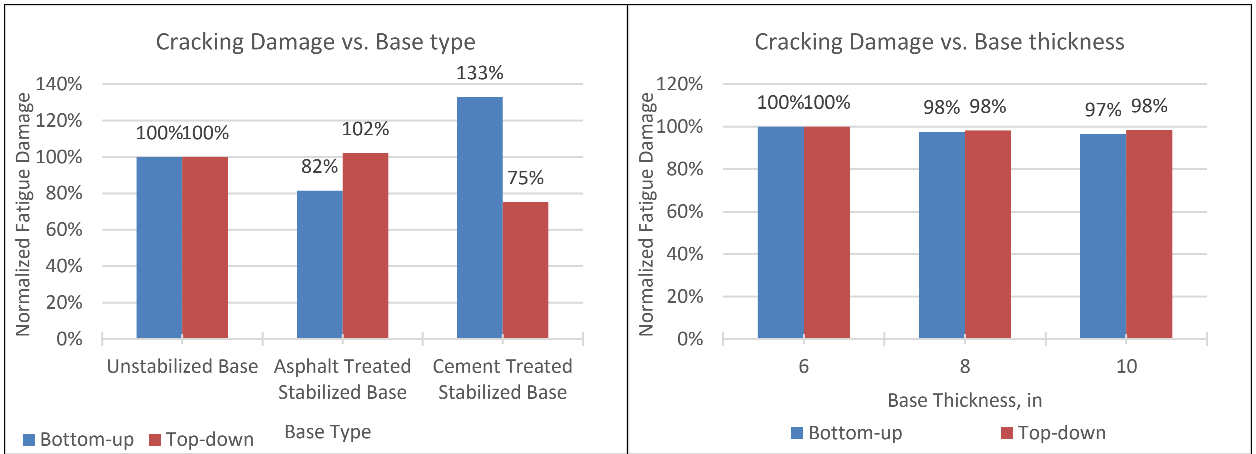

a) Coefficient of expansion sensitivity for fatigue damage

b) PCC Modulus of rupture sensitivity for fatigue damage

Figure A.15. Effect of concrete properties on predicted fatigue damage

A.5 Base

The effects of the base type and base thickness were investigated in this study. Figure A.16 a) shows a moderate difference between the predicted damages for the aggregate and asphalt-treated bases and a much greater difference between the aggregate base and the cement-treated base. At the same time, Figure A.16 b) shows that the thickness of the aggregate base has very little effect on the predicted damage. Based on this observation, it is recommended to incorporate the base type as an input parameter in PittRigid ME, but the user should not be allowed to change the base thickness.



a) Base type sensitivity for fatigue damage | b) Base thickness sensitivity for fatigue damage

Figure A.16. Effect of base type and thickness on predicted fatigue damage

A.6 Subgrade

Two types of subgrade: AASHTO A-6 and A-2-4 were considered in the sensitivity analysis. Figure A.17 shows the comparison of damages for these two cases. It can be observed that the subgrade type has only a minor effect on pavement damage. Therefore, the AASHTO A-6 soil is recommended as default soil type in the PittRigid ME.

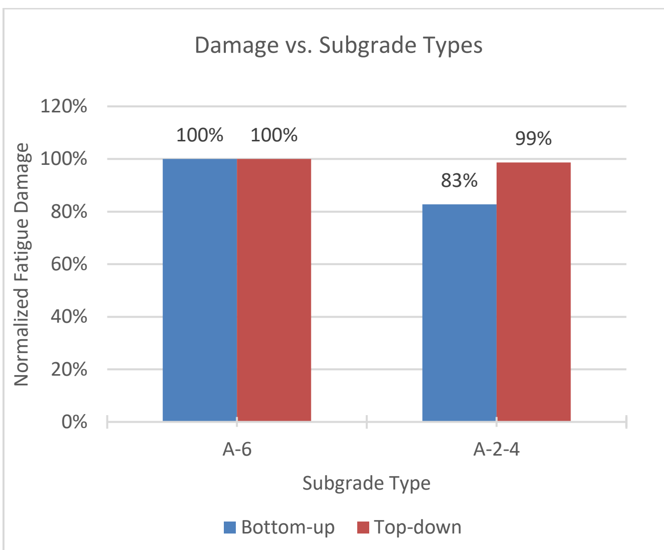


Figure A.17. Effect of subgrade type on predicted fatigue damage

Appendix B. Default MEPDG Parameters for PittRigid ME

B.1 Climate Regions

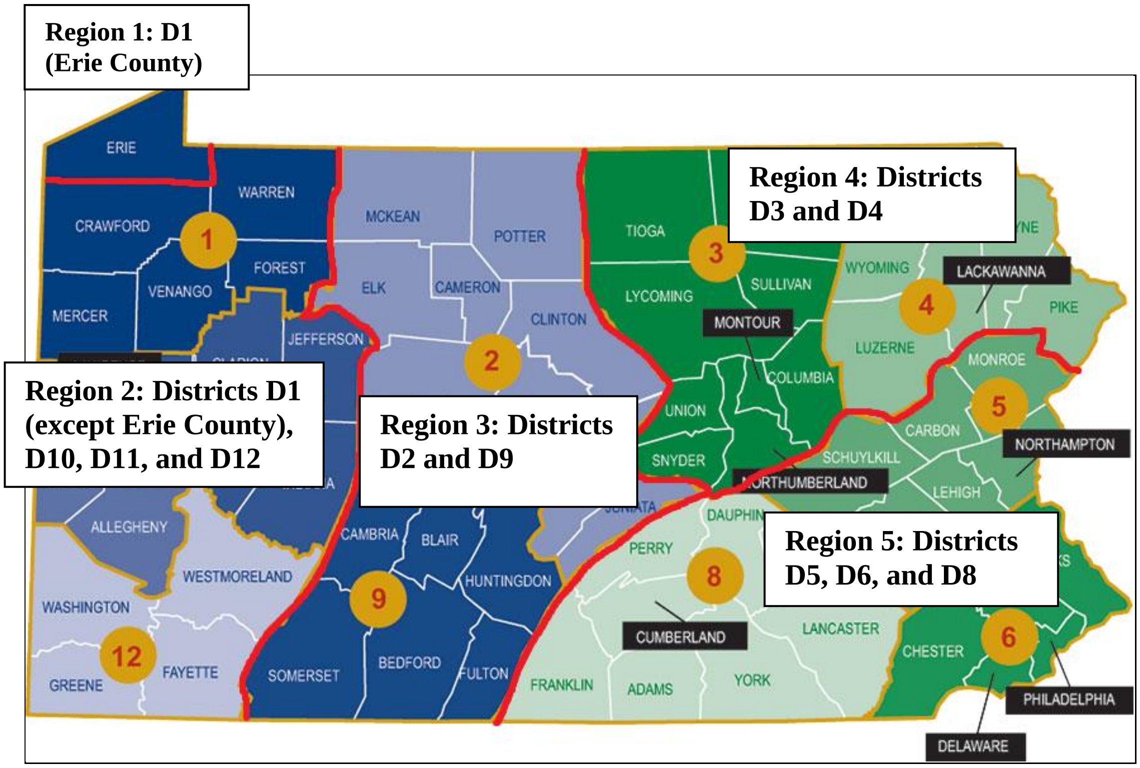


Figure B.1. Graphical five proposed climatic regions in Pennsylvania (Adapted from [*18*])

Table B.1. Climate regions and stations

Climate Region	Station	Location	Latitude	Longitude	Elevation
1	**Erie**	Pennsylvania	40.12	-76.29	400
2	**Pittsburgh (94823)**	Pennsylvania	40.5	-80.23	1118
3	**Altoona**	Pennsylvania	40.3	-78.32	1468
4	**Williamsport**	Pennsylvania	41.24	-76.92	525
5	**Philadelphia (94732)**	Pennsylvania	40.08	-75.01	101

B.2 Traffic Defaults

Table B.2. Recommended axle configuration for Pennsylvania roadways

Axle Configuration	Parameters	Default Values
Traffic	Lane distribution factor, two-way [*15*]	1.0 for 2 lanes 0.9 for 4 lanes 0.8 for 6 lanes 0.6 for >7 lanes
	Percent of trucks in design direction (%)	50.0
	Operational speed (mph)	60.0
Traffic Wander	Mean wheel location (in)	18.0
	Traffic wander standard deviation (in)	10.0
	Design lane width (ft)	12.0
Axle Configuration	Average axle width (ft)	8.5
	Dual tire spacing (in)	12.0
	Tire pressure (psi)	120.0
Average Axle Spacing	Tandem axle spacing (in)	51.6
	Tridem axle spacing (in)	49.2
	Quad axle spacing (in)	49.2
Wheelbase	Average spacing of short axles (ft)	12.0
	Average spacing of medium axles (ft)	15.0
	Average spacing of long axles (ft)	18.0
	Percent of trucks with short axles (%)	17.0
	Percent of trucks with medium axles (%)	22.0
	Percent of trucks with long axles (%)	61.0

Table B.3. Recommended vehicle class distributions for Pennsylvania roadways [*15*]

Vehicle Class	Urban Principal Arterial-Interstate (PA TPG 1)	Rural Principal Arterial-Interstate (PA TPG 2)	Minor Arterials, Collectors, and Recreational (PA TPG 5 to 10)
Class 4	2.79	0.9	3.5
Class 5	13.52	9.64	47.51
Class 6	5.68	3.53	12.92
Class 7	2.05	1.59	3.48
Class 8	7.29	3.63	10.39
Class 9	62.64	74.42	21.07
Class 10	0.91	0.58	0.67
Class 11	3.36	4.25	0.31
Class 12	1.37	1.31	0.04
Class 13	0.39	0.15	0.11
Total	100	100	100

Table B.4. Recommended hourly distribution factor inputs for Pennsylvania roadways [*15*]

Hour	Interstates	Non-Interstates
1	2.5	0.91
2	2.28	0.83
3	2.26	0.9
4	2.44	1.15
5	2.77	1.69
6	3.37	2.97
7	4.2	5.13
8	4.66	6.68
9	4.9	6.96
10	5.14	6.68
11	5.31	6.69
12	5.39	6.75
13	5.37	6.7
14	5.43	6.78
15	5.56	7.11
16	5.58	7.17
17	5.38	6.27
18	5.05	5.08
19	4.63	3.79
20	4.2	2.89
21	3.84	2.34
22	3.59	1.88
23	3.28	1.47
24	2.87	1.18

Table B.5. Recommended monthly adjustment factor inputs for Pennsylvania roadways [*15*]

Month	Truck Classification									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
January	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
February	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
March	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
April	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
May	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
June	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
July	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
August	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
September	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
October	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
November	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
December	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92

Table B.6. Recommended number of axles per truck class for Pennsylvania roadways [*15*]

Truck Class	Numbers of Axles per Truck Class			
	Single Axles	**Tandem Axles**	**Tridem Axles**	**Quad Axles**
4	1.61	0.39	0	0
5	2.03	0.06	0	0
6	1.03	0.98	0	0
7	1.05	0.02	0.97	0
8	2.24	0.79	0	0
9	1.28	1.84	0	0
10	1.13	1.02	0.92	0
11	4.94	0	0	0
12	3.37	1.28	0	0
13	1.39	0.77	0.81	0

B.3 JPCP Design Properties Defaults

Table B.7. JPCP design properties

Design Components	Parameters	Default Values
Pavement	Construction/Open	June/September
JPCP Design Properties	Sealant type	Type IV (Other)
	Dowel spacing if doweled (in)	12
	LTE for tied PCC shoulder (%)	50
	PCC curl/warp effective temperature difference (°F)	-10
	Shortwave absorptivity	0.85
	PCC-base full friction contact	No
	Months until friction loss, months	0

B.4 Layer Properties Defaults

Table B.8. PCC properties

PCC layer	Parameter	Default Values
PCC	PCC unit weight (pcf)	150
	Poisson’s ratio	0.2
	28-day PCC elastic modulus (psi)	4,200,000
Thermal	Thermal conductivity of PCC (BTU/ft*hr*°F)	1.25
	Heat capacity of PCC (BTU/lb*°F)	0.28
Mix	Cement type	Type 1
	Cementitious material content (lb/yd^3)	600
	Water to cement ratio	0.45
	Aggregate type	Limestone
	Reversible shrinkage (%)	50
	Time to develop 50% ultimate shrinkage (days)	35

	Curing method	Curing compound

Table B.9. Aggregate base layer properties

Base	Parameter	Default Values
Aggregate	Thickness (in)	6
	Poisson's ratio	0.35
	Coefficient of lateral earth pressure, k0	0.5
	Resilient modulus (psi)	30,000
	Erodibility index	3
Sieve	Liquid limit	6
	Plastic index	1
	Compacted layer	No
Moisture	Maximum dry unit weight (pcf)	127.2
	Saturated hydraulic conductivity	5.05E-02
	Specific gravity of solids	2.7
	Water content (%)	7.4
Gradation	#200	8.7
	#80	12.9
	#40	20
	#10	33.8
	#4	44.7
	3/8-in.	57.2
	1/2-in.	63.1
	3/4-in.	72.7
	1-in.	78.8
	1 1/2-in.	85.8
	2-in.	91.6
	3 1/2-in.	97.6

Table B.10. Permeable asphalt-treated base layer properties

Base	Parameter	Default Values
ATPB	Thickness (in)	4
	Unit weight (pcf)	150
	Poisson's ratio	0.35
	Erodibility index	1
Gradation	3/4-inch sieve	100
	3/8-inch sieve	77
	No. 4 sieve	60
	No. 200 sieve	6
Binder	Binder grade	Superpave Performance Grade

Base	Parameter	Default Values
	Binder type	64-22
	A	10.98
	VTS	-3.68
General Info	Reference temperature (ºF)	70
	Effective binder content (%)	11.6
	Air voids (%)	20
	Thermal conductivity (BTU/hr-ft-ºF)	0.67
	Heat capacity (BTU/lb-ºF)	0.23

Table B.11. Permeable cement-treated base layer properties

Base	Parameter	Default Values
CTPB	Thickness (in)	4
	Unit weight (pcf)	135
	Poisson's ratio	0.2
	Elastic/Resilient modulus (psi)	1,000,000
	Erodibility index	2
Thermal	Thermal conductivity (BTU/hr-ft-ºF)	1.25
	Heat capacity (BTU/lb-ºF)	0.28

Table B.12. Subbase properties under treated permeable base layer

Subbase	Parameters	Default values
Class 2A	Thickness (in)	6
	Poisson's ratio	0.35
	Coefficient of lateral earth pressure, k_0	0.5
	Resilient modulus (psi)	30,000
Sieve	Liquid limit	6.0
	Plasticity index	1.0
	Is layer compacted?	False
Gradation	#200	8.7
	#80	12.9
	#40	20
	#10	33.8
	#4	44.7
	3/8-in.	57.2
	1/2-in.	63.1
	3/4-in.	72.7
	1-in.	78.8
	1 1/2-in.	85.8
	2-in.	100

Table B.13. Subgrade properties

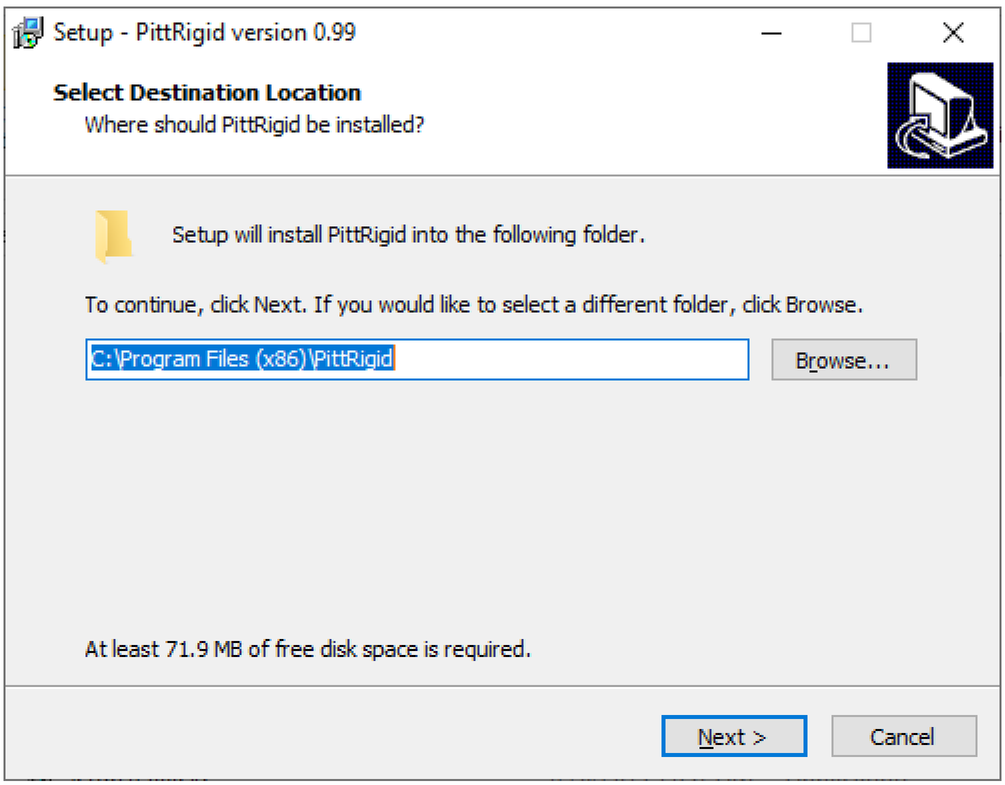
Subgrade	Parameters	Default Values
AASHTO Soil Classification A-6	Thickness	Semi-infinite
	Poisson's ratio	0.35
	Coefficient of lateral earth pressure, k_0	0.5
	Resilient modulus (psi)	14,000
	#200 sieve passing (%)	63.2

Appendix C. Software User's Guide

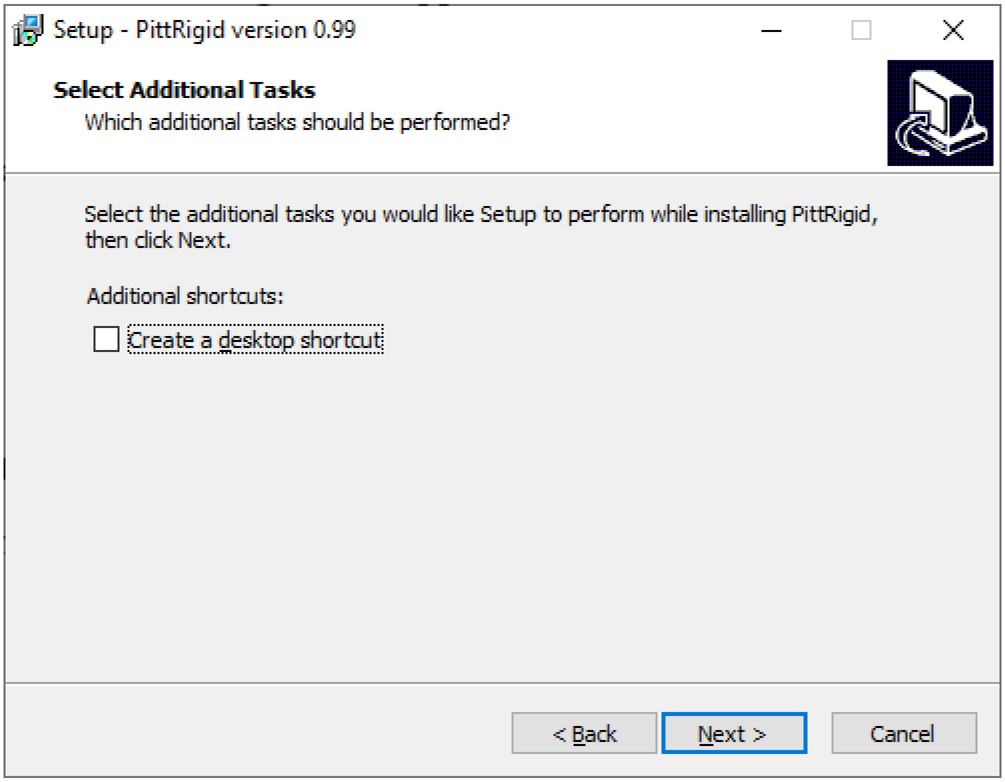
The program performs the design and analysis of concrete pavements based on the American Association of State Highway and Transportation Officials (AASHTO) mechanistic-empirical (M-E) pavement design procedure.

1 Setup Instructions

From Windows Explorer, double click on "setup.exe" file. The following screen will appear:



After clicking "Next", the following screen appears:

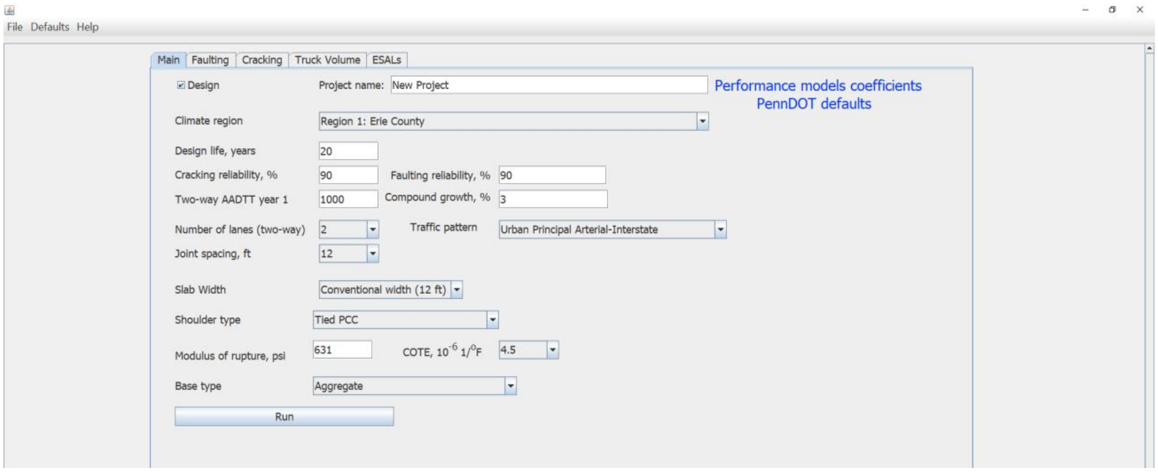


Click "Next" and follow the on-screen instructions to complete installation.

2 Execution of PittRigid ME Program

2.1 Design Inputs

The application starts with the following screen:

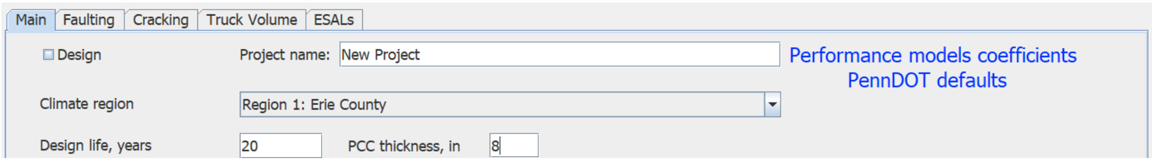


By default, a new empty project is created. The user should modify the default parameters. The following ranges of input values can be analyzed by the current version of programs:

- Project name: this information is used only for reference only.
- Climate Region:
    - Region 1: Erie County
    - Region 2: PennDOT Districts D1 (except Erie County), D10, D11, and D12
    - Region 3: PennDOT Districts D2 and D9
    - Region 4: PennDOT Districts D3 and D4
    - Region 5: PennDOT Districts D5, D6, and D8
- Reliability levels: 50 to 99 %
- Design life: from 1 to 100 years. Must be an integer value.
- Two-way annual average daily truck traffic (AADTT): from 0 to 20,000 (do not enter comma in the input).
- Compound growth rate: from 0% to 10%
- Traffic pattern:
    - Urban Principal Arterial-Interstate (PA TPG 1) with Interstates Hourly Distribution Factor
    - Rural Principal Arterial-Interstate (PA TPG 2) with Interstates Hourly Distribution Factor
    - Minor Arterials, Collectors, and Recreational (PA TPG 5 to 10) with Non-Interstates Hourly Distribution Factor
- PCC slab thickness: 6 to 14 in
- Joint spacing: 12 or 15 ft.
- PCC flexural strength: from 400 to 1400 psi
- Slab width: conventional width (12 ft) or widened lane
- Shoulder type: Tied PCC or asphalt
- Base type
    - 6-in thick crushed stone
    - 4-in thick asphalt treated permeable base (ATPB) and 6-in thick Class 2A subbase
    - 4-in thick cement treated permeable base (CTPB) and 6-in thick Class 2A subbase

Two types of analysis can be performed: design or performance prediction.

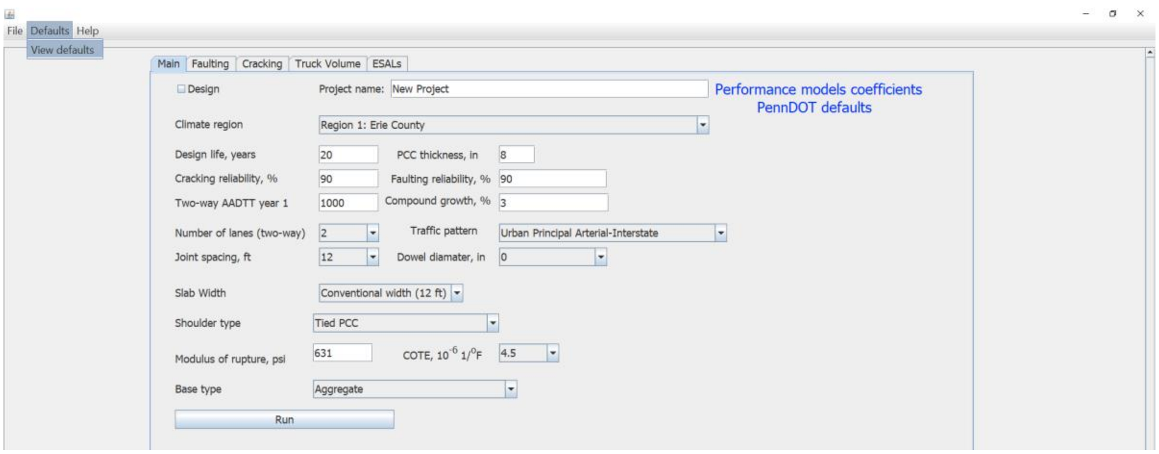
If the design checkbox is unchecked, the user should provide PCC slab thickness and dowel diameter, and the program will predict cracking and faulting levels for the pavement design life.



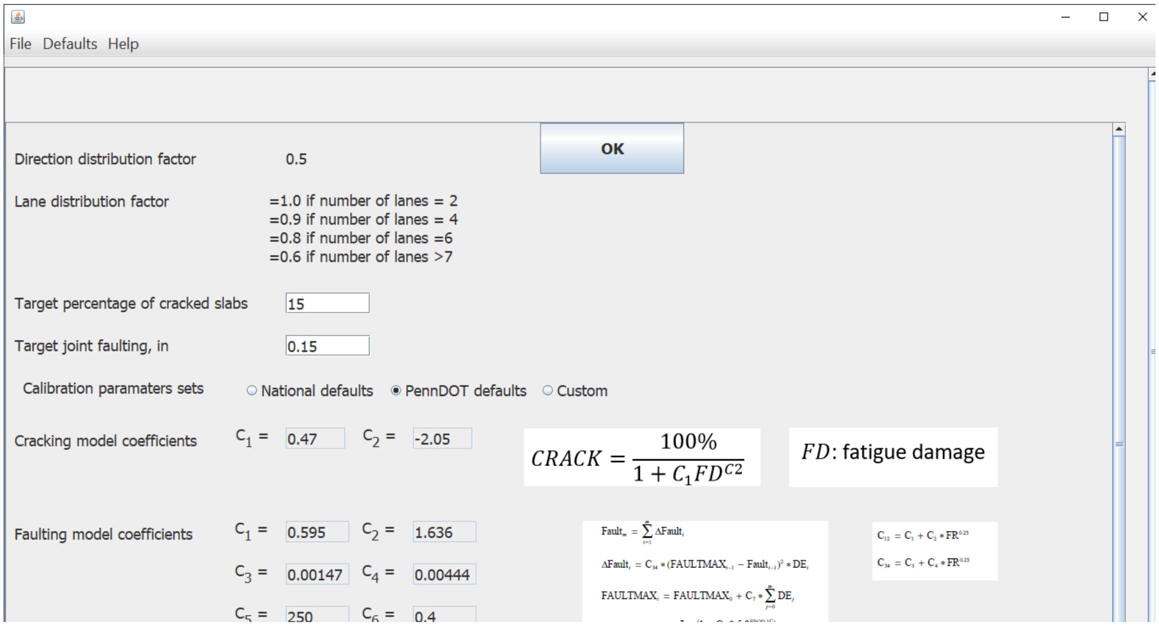
If the design checkbox is checked, the program will determine the required PCC slab thickness and dowel diameter to meet the required performance thresholds at the specified reliability levels at the end of the design life.

2.2 View/Modify Defaults

To view or modify default, select Defaults->View defaults option.

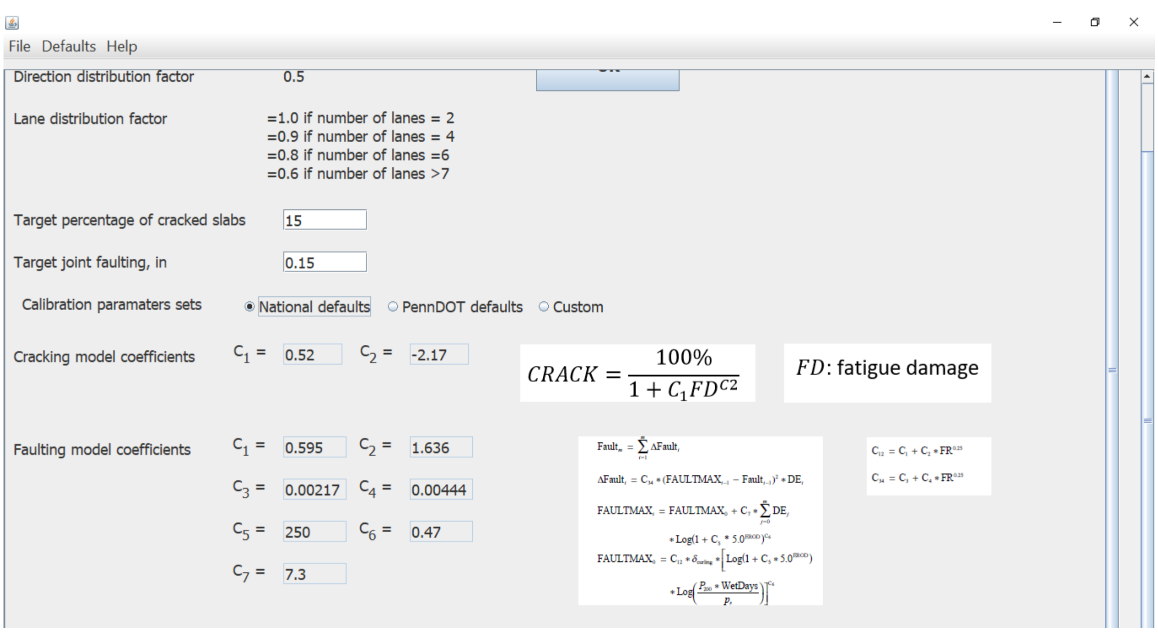


The following screen will appear:

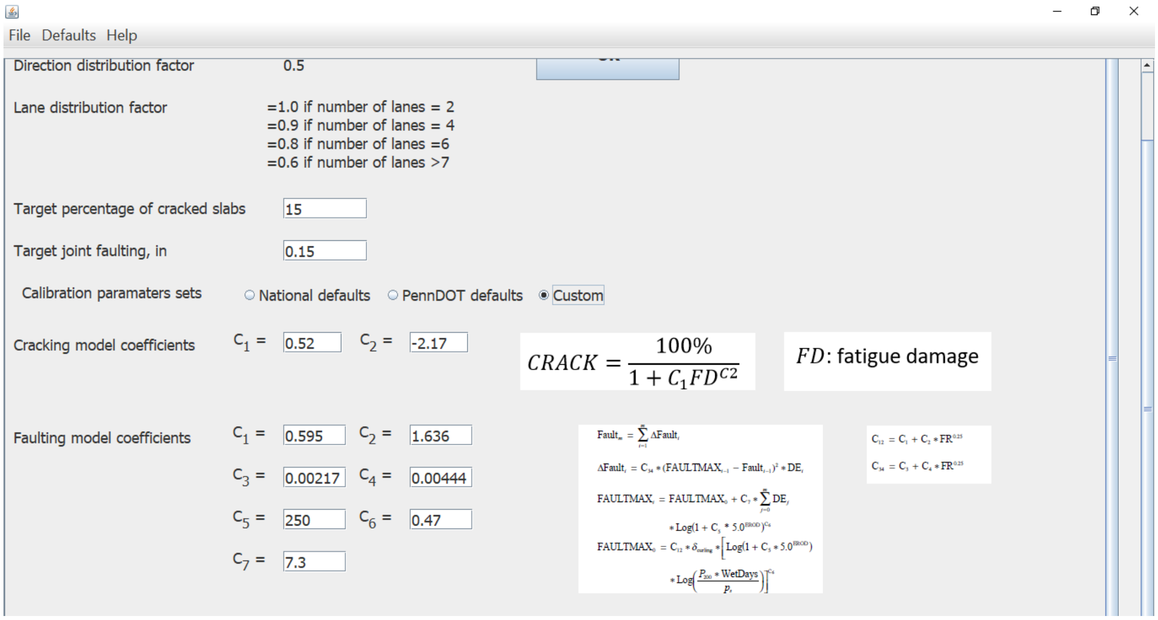


The user has an option to change the target performance criteria for slab cracking and joint faulting. By defaults, these parameters are set to 15% slabs cracks and 0.15 in mean joint faulting at the end of the design life.

The user may also select appropriate cracking and faulting model coefficients. The "PennDOT defaults" option refers to the calibration coefficients recommended to PennDOT by ARA, Inc. The user may switch to the current (as of January 19, 2020) Pavement ME coefficients by selecting the "National defaults" option as shown below:



If "Custom" option is selected, the user may change any model coefficient.

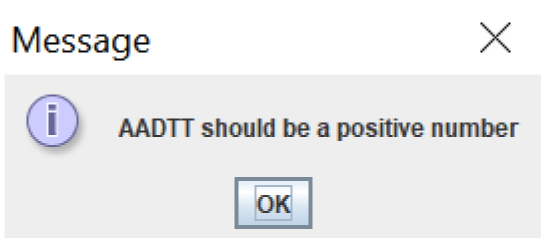


After the performance criteria and model coefficients are confirmed or modified, click the "OK" button to return to the main screen.

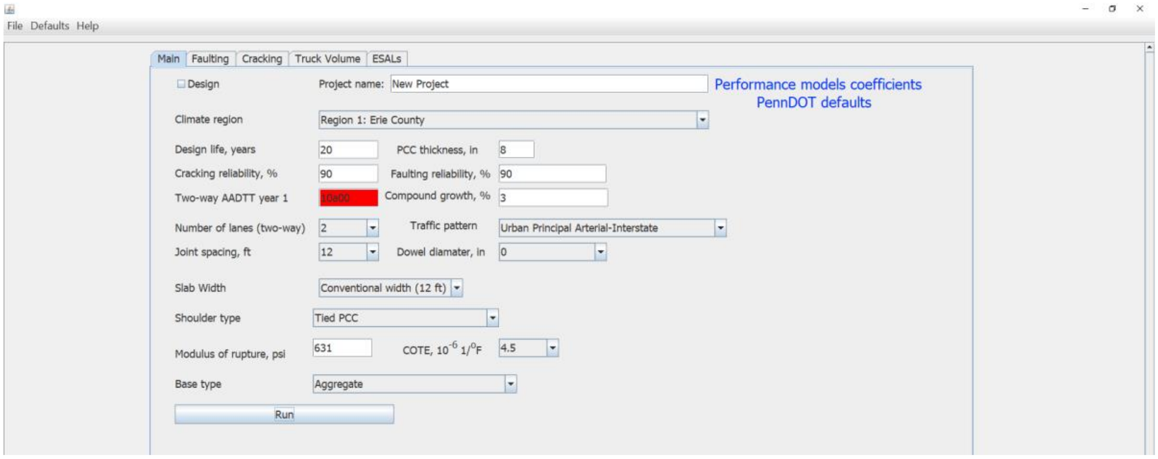
2.3 Executing the Analysis

Once the files and data options have been selected, the user can press the "Run" button. If the "Run" button does not appear on the screen, scroll to the bottom of the window.

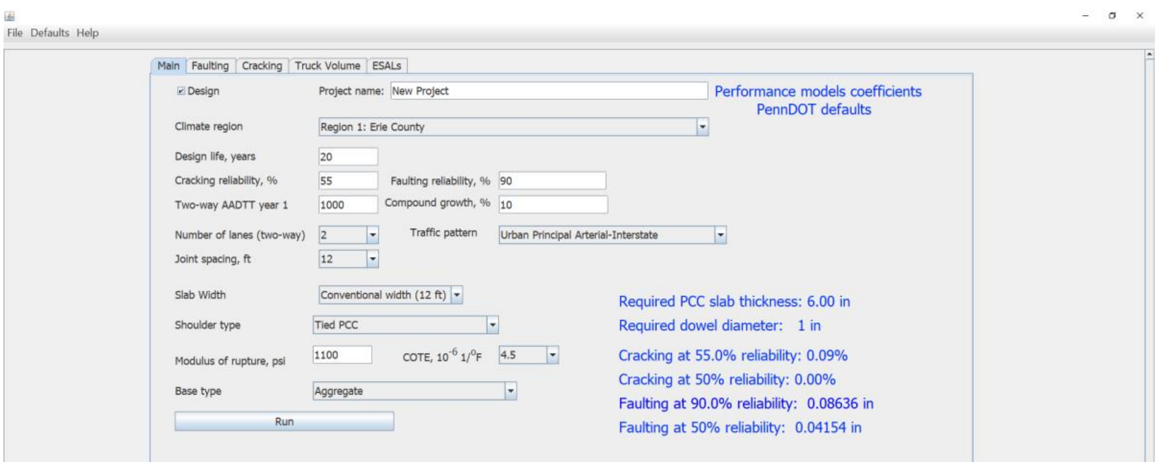
If the input value is out of range or the wrong type, an error message will appear. For example:



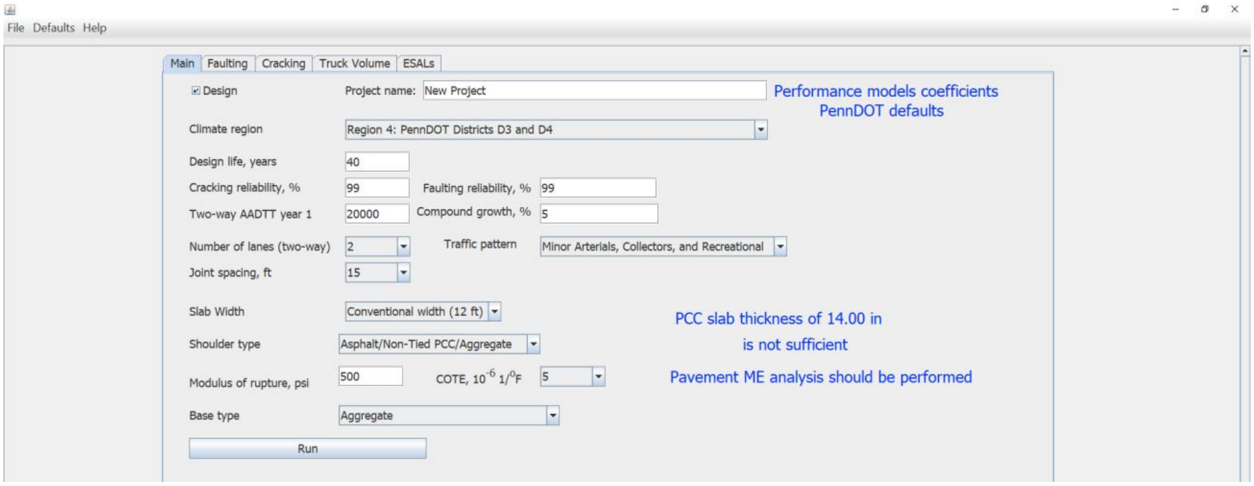
After the user clicks OK, the background of the corresponding input cell will turn red:



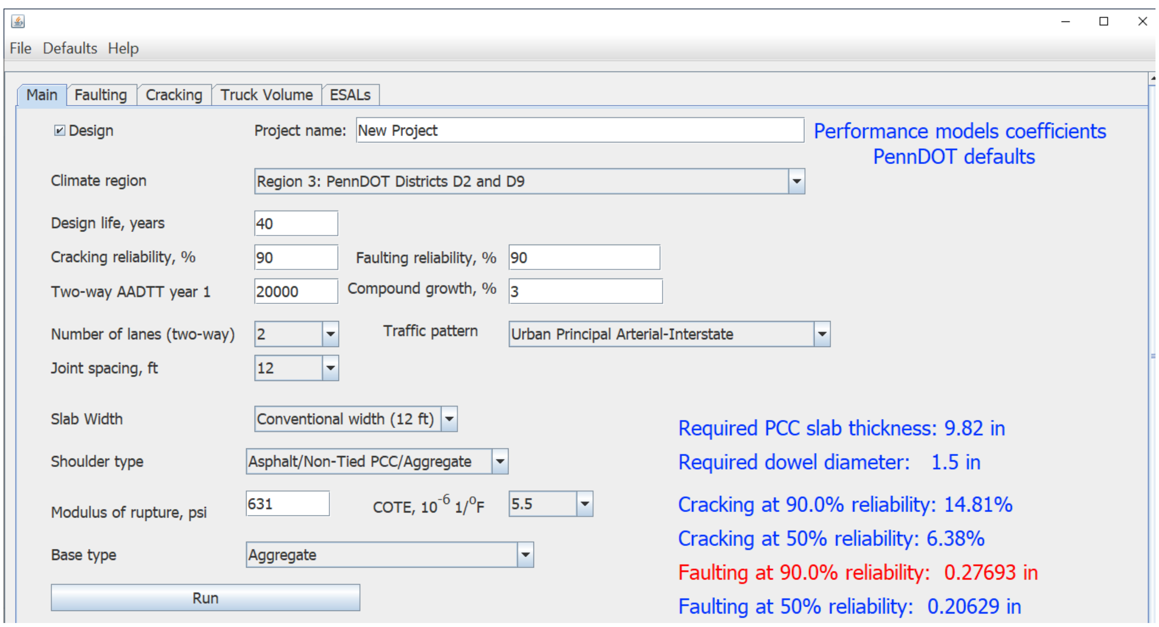
The user will need to correct the input(s) and press the "Run" button again. The results of the analysis will appear in the lower right part of the screen. If the design analysis is being performed, the resulting PCC slab thickness satisfying slab cracking requirements at the specified reliability level is displayed. Also displayed will be the predicted cracking at 50% reliability, predicted mean joint faulting at the specified reliability level, predicted mean joint faulting at 50% reliability level, and the required dowel diameter.



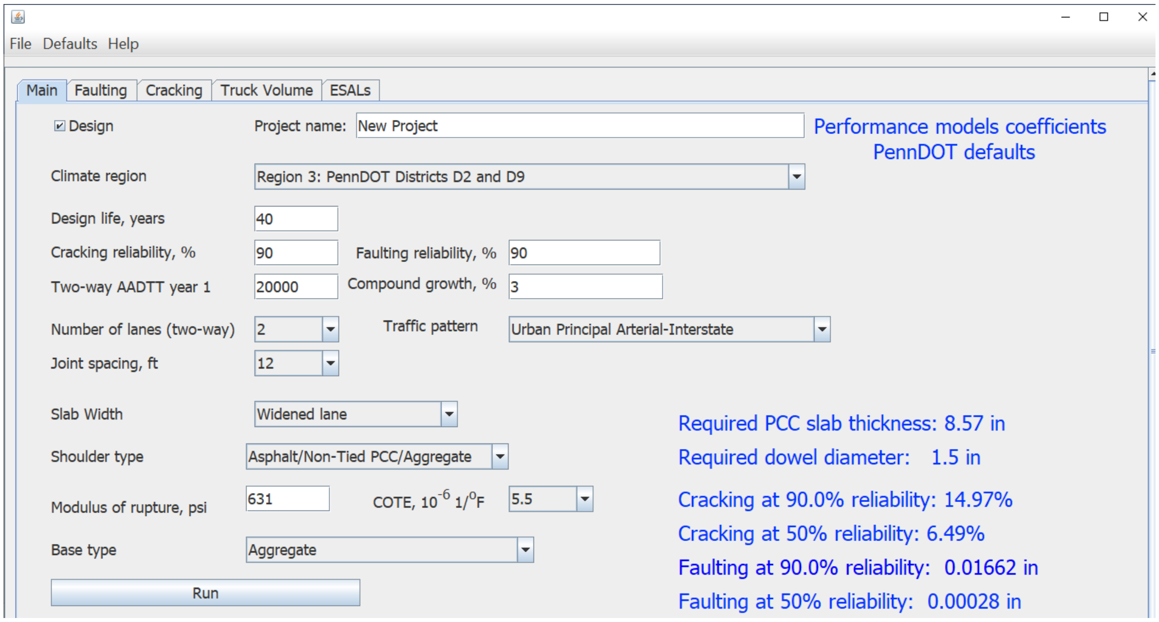
If the required PCC thickness exceeds 14 in then the following screen will appear:



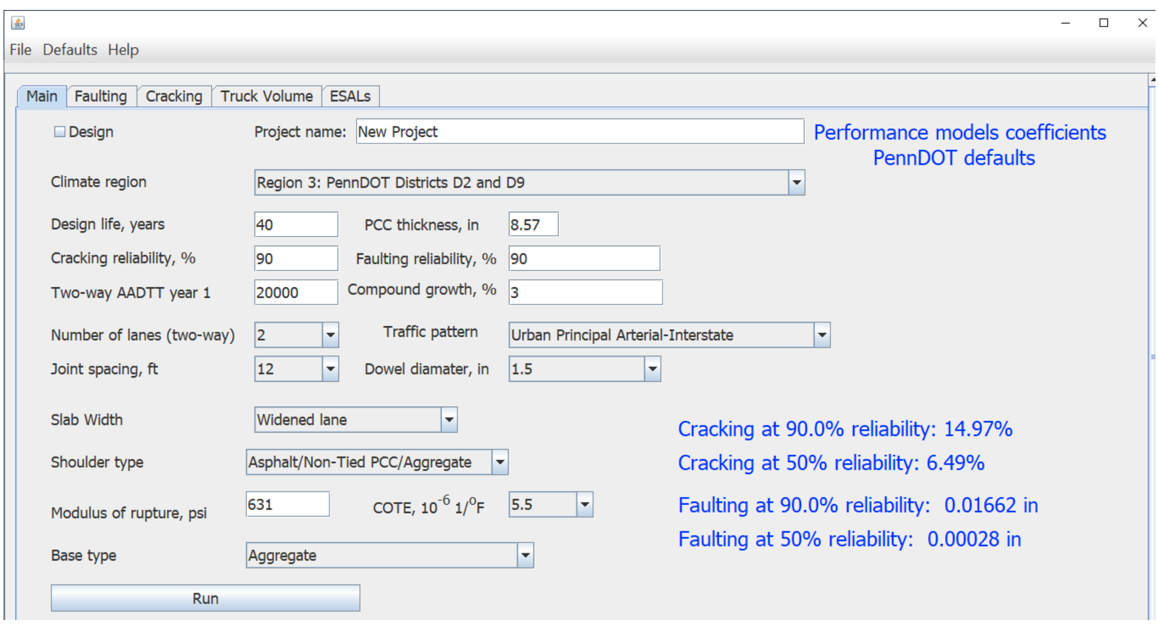
The user should either use Pavement ME software for the project or consider modification of design features, such as reduction of joint spacing, the use of a widened slab, or an increase in the modulus ruptures. For example, a decrease in joint spacing from 15 to 12 ft leads to the required PCC slab thickness of 9.82 in (see figure below). This means that this slab thickness is sufficient to meet the transverse cracking predicted performance requirement at the specified reliability level.



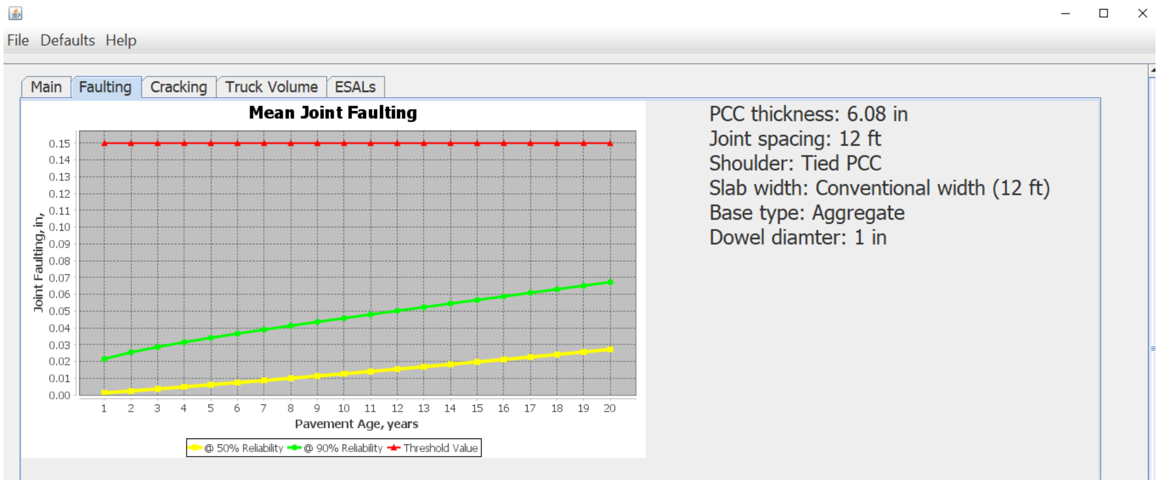
However, in this example, the predicted faulting performance does not meet the specified requirement even for the dowel diameter of 1.5 in. The use of a widened lane leads to a design solution meeting both cracking and faulting performance requirements.

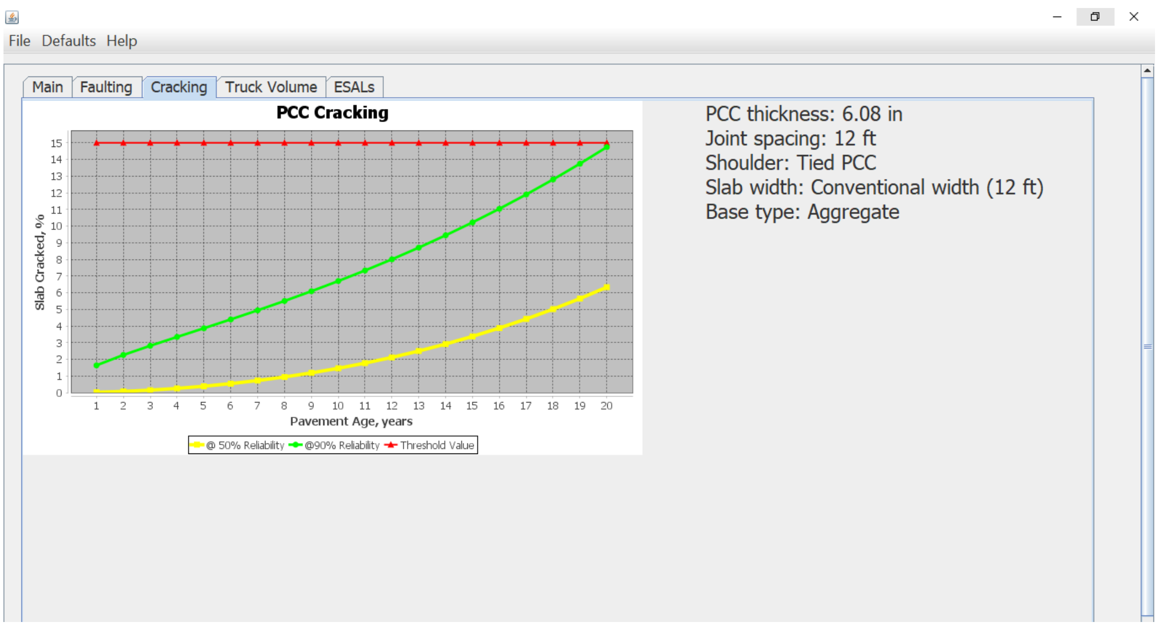


If the analysis option is not selected, only the predicted cracking at the specified reliability level, the predicted cracking at 50% reliability, the predicted mean joint faulting at the specified reliability level, and the predicted mean joint faulting at 50% reliability level are displayed.



After the analysis is complete, the user can select the tabs “Faulting” or “Cracking,” to view the predicted faulting and cracking, respectively.

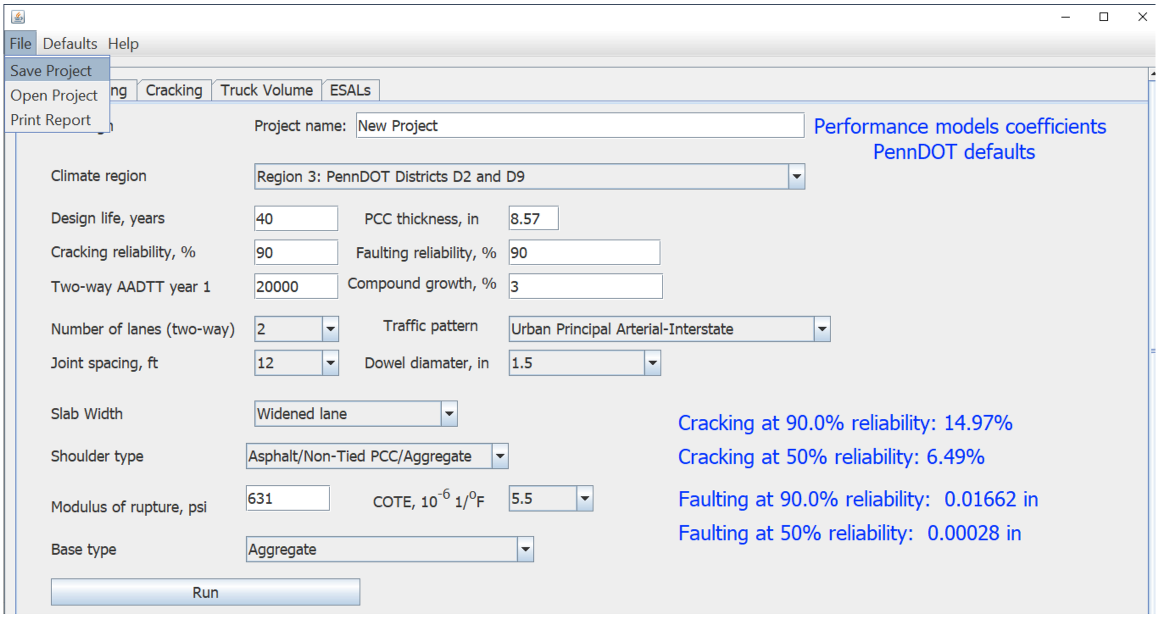




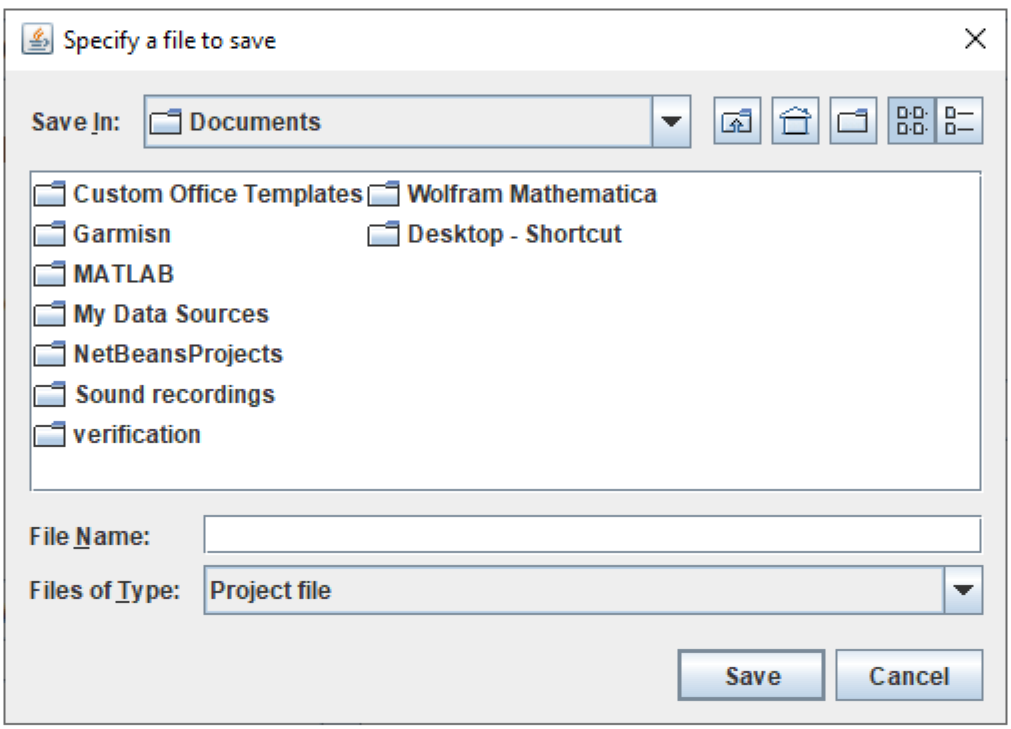
To see the analyzed cumulative traffic volume or ESAL over time, the user should select tabs "Truck Volume" or "ESALs," respectively.

2.4 Saving the Project

To save the project, select from the menu File->Save Project option:



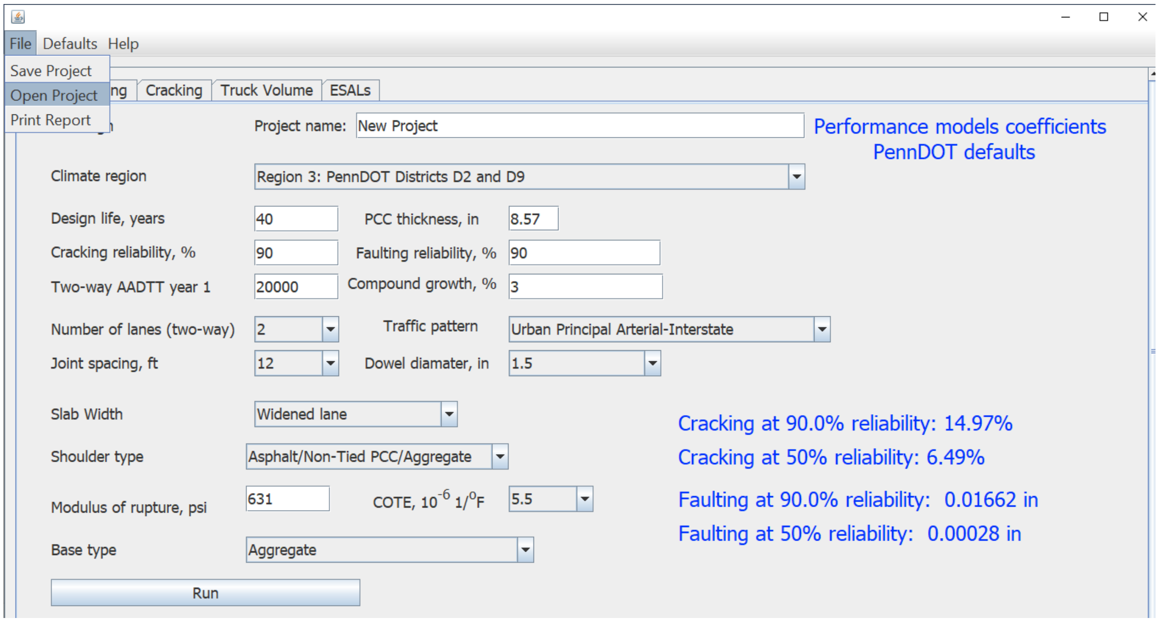
The following dialog box will appear:



Navigate to the desired location, provide the file name and click the “Save” button.

2.5 Opening Project

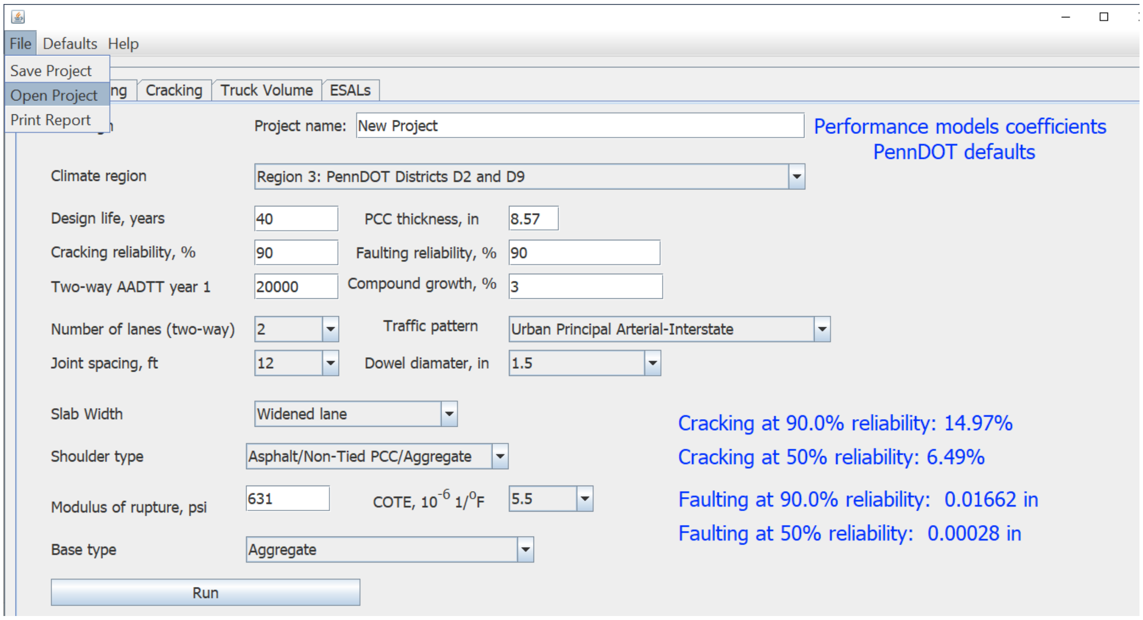
To open an existing project, select from the menu File->Open Project option.



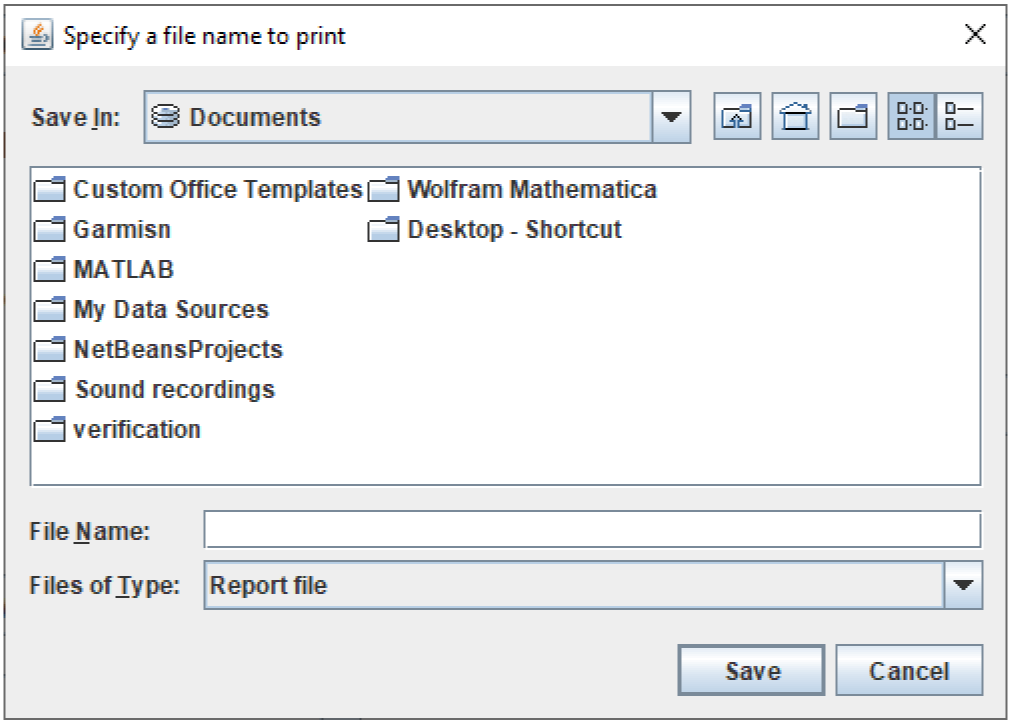
Find the desired file and click the "OK" button.

2.6 Printing Report

To create a report, select from the menu File->Print Report option.

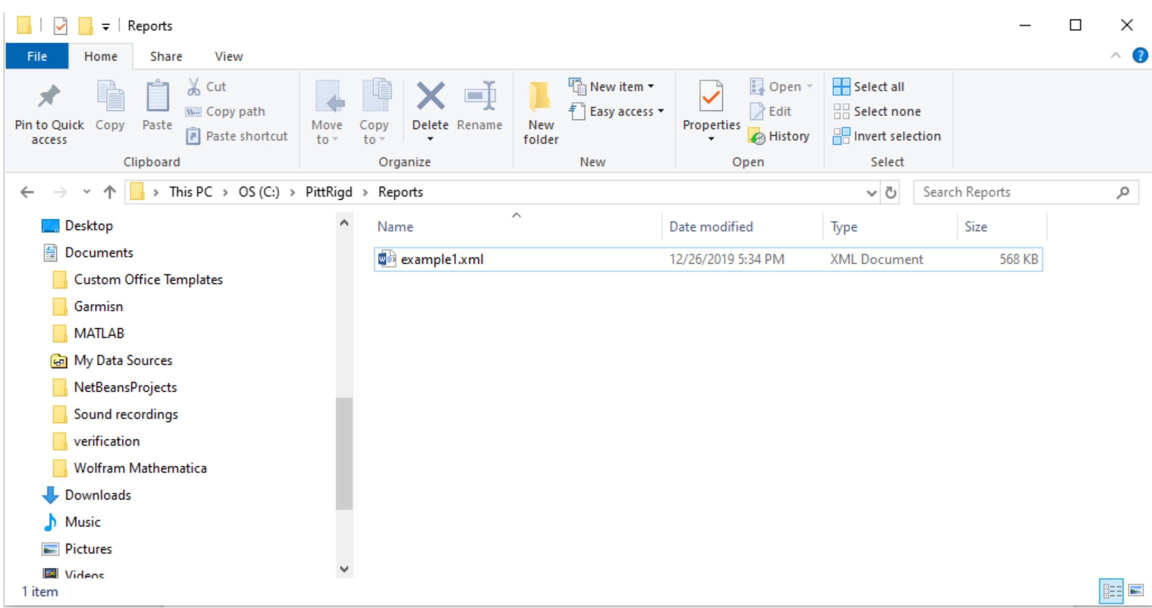


The following dialog box will appear:

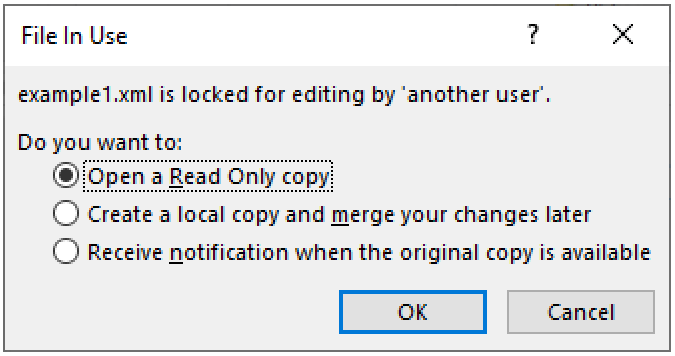


Navigate to the desired location, provide the file name and click the “Save” button.

The file will be saved with an extension “.xml”. It should be noted that the current version of PittRigid does not print the performance prediction plots. To add them to the report, the user can use the MS WORD and Windows snipping tool. When open the document with MS WORD, the file type option “All Word Documents (*.docx, *.docm, …) should be selected.



Until PittRigid program is closed, the following message will appear



Click “OK”. The opened file will have the “READ-ONLY” warning:

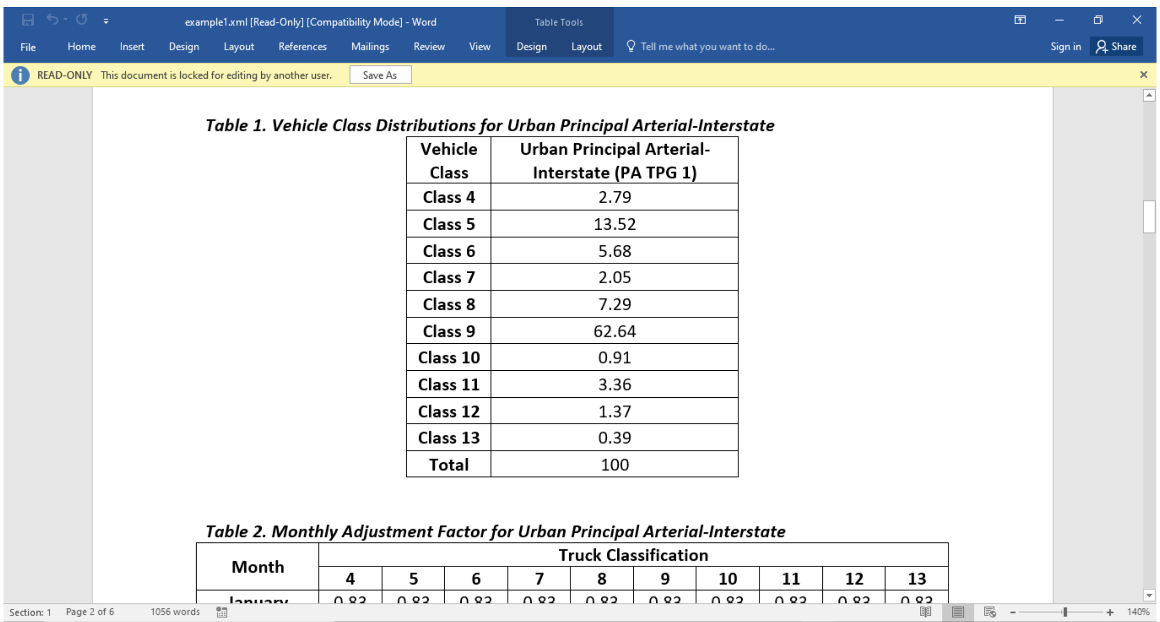


Table 1. Vehicle Class Distributions for Urban Principal Arterial-Interstate

Vehicle Class	Urban Principal Arterial-Interstate (PA TPG 1)
Class 4	2.79
Class 5	13.52
Class 6	5.68
Class 7	2.05
Class 8	7.29
Class 9	62.64
Class 10	0.91
Class 11	3.36
Class 12	1.37
Class 13	0.39
Total	100

Table 2. Monthly Adjustment Factor for Urban Principal Arterial-Interstate

Month	Truck Classification									
	4	5	6	7	8	9	10	11	12	13
January	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83

Save the file as a Word Document, *.docx” file. Using the Windows Snipping or Print Screen tool, add the faulting and transverse cracking prediction plots and save the report.

An example of an output file is shown below.

PittRigid ME *version 1.0*

Project: New Project

Main Inputs

Analysis type: Performance prediction

PCC thickness, in: 8.57 **Dowel diameter, in:** 1.5

Climate region: Region 3: PennDOT Districts D2 and D9

Cracking reliability, %: 90.00 **Faulting reliability, %:** 90.00

Design life, years: 40 **Two-way AADTT year 1:** 20000

Compound growth, %: 3 **Number of lanes (two-way):** 2

Traffic pattern: Urban Principal Arterial-Interstate

Joint spacing, ft: 12

Slab width: Widened lane

Shoulder type: Asphalt/Non-Tied PCC/Aggregate

PCC modulus of rupture, psi: 631

PCC coefficient of thermal expansion, 10^{-6} 1/°F: 5.5

Base type: Aggregate

Target cracked slabs, %: 15.00

Target joint faulting, in: 0.150

Outputs

Cracking at assigned 90.00% **reliability, %:** 14.97

Cracking at 50% reliability, %: 6.49

Faulting at assigned 90.00% **reliability, in:** 0.01662

Faulting at 50% reliability, in: 0.00028

Calculated cumulative heavy trucks over service life: 275,214,598

Calculated cumulative ESALs over service life: 428,199,786

Defaults

Traffic Pattern: Urban Principal Arterial-Interstate

Table 1. Vehicle Class Distributions for Urban Principal Arterial-Interstate

Vehicle Class	Urban Principal Arterial-Interstate (PA TPG 1)
Class 4	2.79
Class 5	13.52
Class 6	5.68
Class 7	2.05
Class 8	7.29
Class 9	62.64
Class 10	0.91
Class 11	3.36
Class 12	1.37
Class 13	0.39
Total	100

Table 2. Monthly Adjustment Factor for Urban Principal Arterial-Interstate

Month	Truck Classification									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
January	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
February	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
March	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
April	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
May	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
June	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
July	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
August	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
September	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
October	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
November	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
December	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92

Table 3. Number of Axles per Truck Class for Urban Principal Arterial-Interstate

Truck Class	**Numbers of Axles per Truck Class**			
	Single Axles	**Tandem Axles**	**Tridem Axles**	**Quad Axles**
4	1.61	0.39	0	0
5	2.03	0.06	0	0
6	1.03	0.98	0	0
7	1.05	0.02	0.97	0
8	2.24	0.79	0	0
9	1.28	1.84	0	0
10	1.13	1.02	0.92	0
11	4.94	0	0	0
12	3.37	1.28	0	0
13	1.39	0.77	0.81	0

Table 4. Hourly Distribution Factor for Urban Principal Arterial-Interstate

Hour	**Interstates**	**Hour**	**Interstates**
1	2.5	**13**	5.37
2	2.28	**14**	5.43
3	2.26	**15**	5.56
4	2.44	**16**	5.58
5	2.77	**17**	5.38
6	3.37	**18**	5.05
7	4.2	**19**	4.63
8	4.66	**20**	4.2
9	4.9	**21**	3.84
10	5.14	**22**	3.59
11	5.31	**23**	3.28
12	5.39	**24**	2.87

Table 5. Axle Configuration for Pennsylvania Roadways

Axle Configuration	**Parameters**	**Default Values**
Traffic	Lane distribution factor, two-way	• 1.0 for 2 lanes • 0.9 for 4 lanes • 0.8 for 6 lanes • 0.6 for >7 lanes
	Percent of trucks in design direction (%)	50.0
	Operational speed (mph)	60.0
Traffic Wander	**Mean wheel location (in)**	18.0
	Traffic wander standard deviation (in)	10.0
	Design lane width (ft)	12.0
Axle Configuration	**Average axle width (ft)**	8.5
	Dual tire spacing (in)	12.0
	Tire pressure (psi)	120.0
	Tandem axle spacing (in)	51.6

Axle Configuration	Parameters	Default Values
Average Axle Spacing	Tridem axle spacing (in)	49.2
	Quad axle spacing (in)	49.2
Wheelbase	Average spacing of short axles (ft)	12.0
	Average spacing of medium axles (ft)	15.0
	Average spacing of long axles (ft)	18.0
	Percent of trucks with short axles (%)	17.0
	Percent of trucks with medium axles (%)	22.0
	Percent of trucks with long axles (%)	61.0

JPCP Defaults

Table 6. JPCP Design Properties

Design Components	Parameters	Default Values
JPCP Design Properties	Sealant type	Type IV
	Dowel spacing if doweled (in)	12
	LTE for tied PCC shoulder (%)	50
	PCC curl/warp effective temperature difference (°F)	-10
	Shortwave absorptivity	0.85
	PCC-base full friction contact	No
	Months until friction loss, months	0

Layer Properties

Table 7. PCC Properties

PCC Layer	Parameters	Default Values
PCC	PCC unit weight (pcf)	150
	Poisson's ratio	0.2
	28-day PCC elastic modulus (psi)	4,200,000
Thermal	Thermal conductivity of PCC (BTU/ft*hr*°F)	1.25
	Heat capacity of PCC (BTU/lb*°F)	0.28
Mix	Cement Type	Type 1
	Cementitious material content (lb/yd^3)	600
	Water to cement ratio	0.45
	Aggregate type	Limestone
	Reversible shrinkage, (%)	50
	Time to develop 50% ultimate shrinkage (days)	35
	Curing method	Curing compound

Table 8. Aggregate Base Layer Properties

Base	Parameters	Default Values
Aggregate	Thickness (in)	6
	Poisson's ratio	0.35
	Coefficient of lateral earth pressure, k0	0.5
	Resilient modulus (psi)	30,000
	Erodibility index	3
Sieve	Liquid Limit	6
	Plastic index	1
	Compacted layer	No
Moisture	Maximum dry unit weight (pcf)	127.2
	Saturated hydraulic conductivity	5.05E-02
	Specific gravity of solids	2.7
	Water Content (%)	7.4
Gradation	#200	8.7
	#80	12.9
	#40	20
	#10	33.8
	#4	44.7
	3/8-in.	57.2
	1/2-in.	63.1
	3/4-in.	72.7
	1-in.	78.8
	1 1/2-in.	85.8
	2-in.	91.6
	3 1/2-in.	97.6

Table 9. Subgrade Properties

Subgrade	Parameters	Default Values
AASHTO Soil Classification A-6	Thickness	Semi-infinite
	Poisson's ratio	0.35
	Coefficient of lateral earth pressure, k_0	0.5
	Resilient modulus (psi)	14,000
	#200 sieve passing (%)	63.2

Other Defaults

Cracking model coefficients:

$$\boldsymbol{CRK = \frac{100\%}{1 + C_1(FD)^{C_2}}}$$

FD: Fatigue Damage

Cracking Coefficient	C_1	C_2
Values	0.47	-2.05

Faulting model coefficients:

$$\boldsymbol{C_{12} = C_1 + C_2 \times FR^{0.25}}$$
$$\boldsymbol{C_{34} = C_3 + C_4 \times FR^{0.25}}$$

$$\boldsymbol{\Delta Fault_i = C_{34} \times (FAULTMAX_{i-1} - Fault_{i-1})^2 \times DE_i}$$

$$\boldsymbol{FAULTMAX_i = FAULTMAX_0 + C_7 \times \sum_{j=1}^{m} DE_j \times Log\left(1 + C_5 \times 5.0^{EROD}\right)^{C_6}}$$

$$\boldsymbol{FAULTMAX_0 = C_{12} \times \delta_{curling} \times \left[Log\left(1 + C_5 \times 5.0^{EROD}\right) \times Log\left(\frac{P_{200}WetDays}{P_s}\right)\right]^{C_6}}$$

Faulting Coefficient	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Values	0.595	1.636	0.00147	0.00444	250	0.4	7.3

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