June 2021

Report No. 21-018

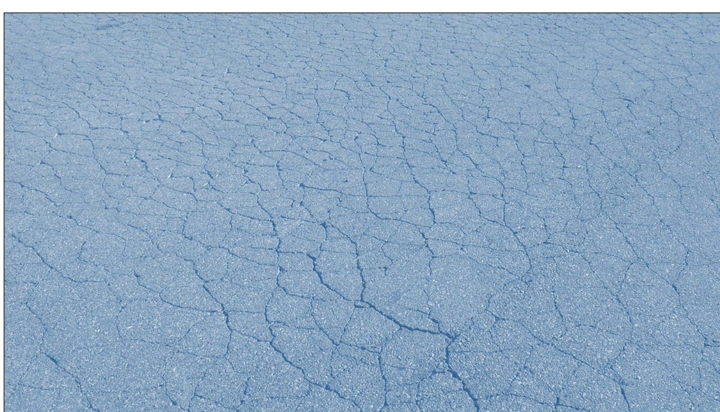
Charles D. Baker
Governor

Karyn E. Polito
Lieutenant Governor

Jamey Tesler
MassDOT Secretary & CEO

Improving the Long-Term Condition of Pavements in Massachusetts and Determining Return on Investment: Implementing the AASHTO Mechanistic-Empirical Pavement Design Guide PHASE I

Principal Investigator (s)
Dr. Walaa Mogawer
University of Massachusetts Dartmouth



Research and Technology Transfer Section
MassDOT Office of Transportation Planning

U.S. Department of Transportation
Federal Highway Administration

Technical Report Document Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
21-018	n/a	n/a

4. Title and Subtitle	5. Report Date
Improving the Long-Term Condition of Pavements in Massachusetts and Determining Return on Investment: Implementing the AASHTO Mechanistic-Empirical Pavement Design Guide - PHASE I	June 2021
	6. Performing Organization Code n/a
7. Author(s) Walaa S. Mogawer, Alexander J. Austerman, and James Pierce	8. Performing Organization Report No. 21-018
9. Performing Organization Name and Address University of Massachusetts Dartmouth 285 Old Westport Road North Dartmouth, MA 02747	10. Work Unit No. (TRAIS) n/a 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Massachusetts Department of Transportation Office of Transportation Planning Ten Park Plaza, Suite 4150, Boston, MA 02116	13. Type of Report and Period Covered Final Report June 2021 [April 2020 – June 2021] 14. Sponsoring Agency Code n/a

15. Supplementary Notes
Project Champion – Edmund Naras, MassDOT

16. Abstract
The goal of this study was to conduct a thorough literature review to determine the overall state-of-practice with regards to AASHTO Mechanistic Empirical Design Guide (MEPDG) implementation with focus on local verification and calibration. The literature review presented outlines the steps taken by other state agencies to perform local calibration. Specifically, the following key areas were addressed for each agency: distresses calibrated, steps followed for the calibration, sample size and sites selection, existing data utilized, laboratory and field testing to generate the required inputs, traffic data, climatic data, problems encountered, and any reported benefits from the calibration.

Additionally, initial testing was conducted on typical plant-produced mixtures sampled from across Massachusetts in an attempt to accelerate future phases of this research. The results were input into the AASHTOWare® Pavement M-E Design software to conduct trial designs.

This report outlines the work conducted in phase one of a four phase larger research project aimed at implementing the AASHTO MEPDG in Massachusetts.

17. Key Word	18. Distribution Statement
Mechanistic-Empirical, distress, prediction, pavement design	unrestricted

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
unclassified	unclassified	40	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

This page left blank intentionally.

Improving the Long-Term Condition of Pavements in Massachusetts and Determining Return on Investment: Implementing the AASHTO Mechanistic-Empirical Pavement Design Guide - PHASE I

Final Report

Prepared By:

Professor Walaa S. Mogawer, P.E., F.ASCE
Principal Investigator

Alexander J. Austerman, P.E.
Senior Research Engineer

And

James Pierce
Undergraduate Student

University of Massachusetts Dartmouth
Highway Sustainability Research Center
151 Martine Street – Room 131
Fall River, MA 02723

Prepared For:

Massachusetts Department of Transportation
Office of Transportation Planning
Ten Park Plaza, Suite 4150
Boston, MA 02116

June 2021

This page left blank intentionally.

Acknowledgements

Prepared in cooperation with the Massachusetts Department of Transportation, Office of Transportation Planning, and the United States Department of Transportation, Federal Highway Administration.

The Project Team would like to acknowledge the efforts of Edmund Naras (MassDOT Pavement Management Engineer), Mark J. Brum (MassDOT Materials Quality Systems Engineer), and Gregory Doyle (FHWA Massachusetts Division Construction Quality Engineer). Finally, the Project Team would like to thank graduate student Ibrahim Abdalfattah.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

This page left blank intentionally.

Executive Summary

MassDOT is striving to improve its highway infrastructure's resiliency to climate change, environmental impacts, and traffic loading by implementing new technologies. These improvements should begin with the pavement design process which currently utilizes antiquated empirical design methods from the 1960's. The development of the mechanistic-empirical pavement design guide (MEPDG) and the release of AASHTOWare® Pavement M-E Design software is a significant improvement to existing pavement design procedures. In pavement M-E design, pavement responses (stresses, strains, and deflections) are calculated and utilized as inputs in empirical distress prediction models called transfer functions. These models are then used to estimate cumulative pavement distresses over time. The various distress prediction models for flexible pavements include: total rutting, rutting in each layer (asphalt layer, base and subbase), top-down cracking, bottom-up fatigue cracking, thermal cracking, reflective cracking and international roughness index (IRI). The predicted distresses allow pavement engineers to define acceptable levels of performance and design pavements to address particular distresses. A key advantage of the M-E design methodology is that its individual components, like transfer functions and performance models, can be enhanced over time to reflect new research in the field.

The MEPDG performance prediction models were developed and nationally calibrated using in-service pavements. These in-service pavements were mainly selected from projects in the Long-Term Pavement Performance (LTPP) program. Accordingly, the prediction models may not accurately predict the performance for localized conditions (environment, traffic, and materials characterization) in Massachusetts. Therefore, prior to M-E design implementation, it will be crucial for MassDOT to recalibrate the standard M-E design guide prediction models to actual data from local projects located in Massachusetts (local calibration). Many states DOTs have already undertaken and completed this process. Local calibration is perhaps the most crucial aspect of implementation of the M-E design process. Local calibration will often remove bias present in the national model, as well as reduce some scatter in the results (i.e., improve precision). As illustrated in Figure ES1, local calibration is a systematic process expected to eliminate potential biases and increase the accuracy of the performance predictions.

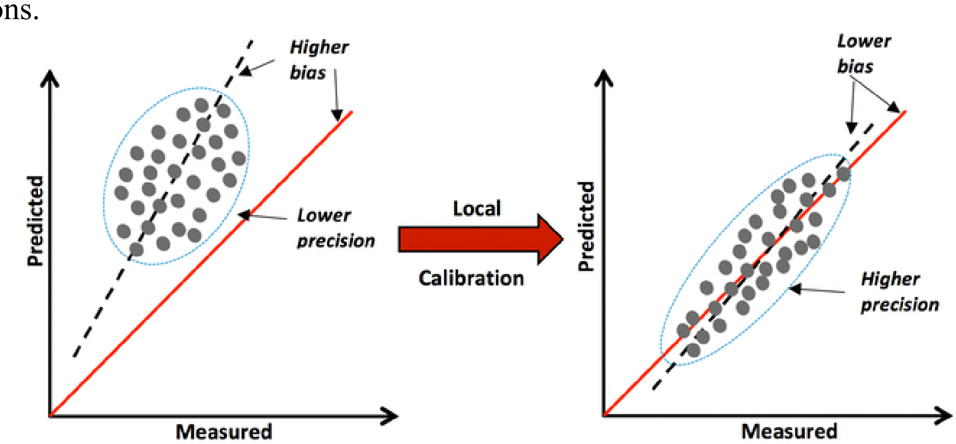
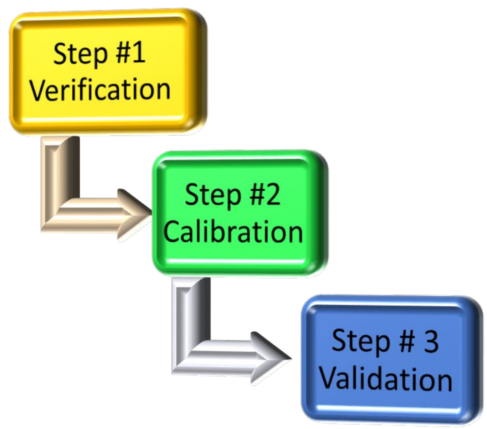


Figure ES1: Precision and bias in local calibration (*1*)

Local calibration of the distress prediction models helps bridge the gap, if any, between the predicted and the observed performance in the field. Otherwise, some pavements will be under-designed and others over-designed, translating to either premature failure or excessive costs. To date, many states (Arizona, Colorado, Indiana, Missouri, Montana, North Carolina, Ohio, Oregon, Utah and Washington) have completed local calibrations of M-E design guide asphalt concrete models (flexible pavements). The overall process of local calibration generally consists of three steps:



The first step involves verification or evaluation of the existing global models to determine how well the model represents actual distresses and to evaluate the accuracy and bias. The second step is calibration of the model coefficients to improve the model and reduce bias, typically using the same dataset as used in the verification step. This process of local calibration of the coefficients associated with the distress transfer functions is shown in Figure ES2. The third step is validation of the newly calibrated model using a separate dataset.

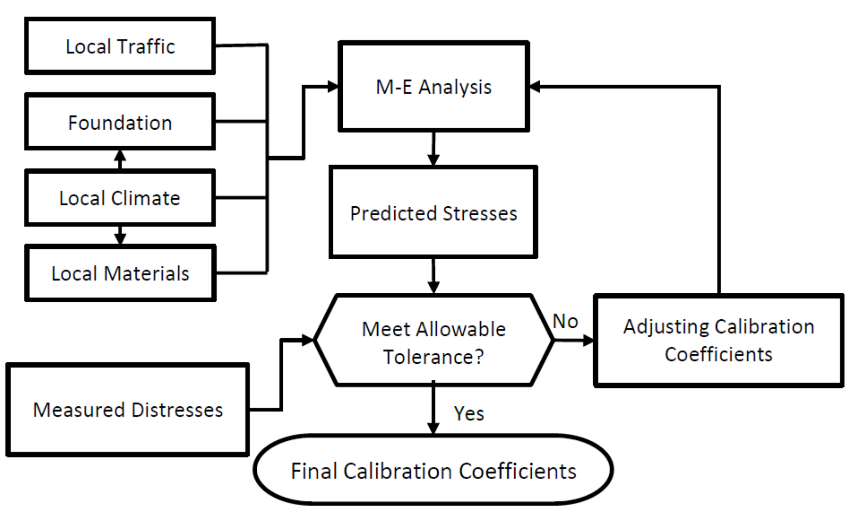


Figure ES2: Local Calibration of Pavement M-E Design (*2*)

Recognizing the importance of local calibration, this study was undertaken as a first step in the MEPDG implementation process for Massachusetts. The objective was to determine the overall state-of-practice with regards to AASHTO M-E design and implementation. This was accomplished by reviewing the general approach undertaken by other state highway agencies, the results of those efforts, and recommendations for implementing the nationally or locally calibrated models. The literature review addressed specifically the following key areas for each agency: distresses calibrated, steps followed for the calibration, sample size and sites selection, existing data that was used, laboratory and field testing to generate the required inputs, traffic data, climatic data, problems encountered, and any reported benefits from the calibration.

Based on the literature, it was found that a majority of agencies followed the local calibration guidelines in the AASHTO publication *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*). This publication has outlined a standard 11-step procedure for MEPDG local calibration. It should be noted that some agencies did not follow the AASHTO guide as their efforts were initiated prior to its publication or their efforts were ongoing when the guide became available. With regards to implementation, it was crucial to know what distresses have been verified or calibrated by other state agencies. A report published by the National Center of Asphalt Technology (NCAT) in 2017 inventoried the local verification and calibration efforts of state agencies as shown in Table ES1.

Table ES1: NCAT Summary of Local Verification & Calibration Efforts (*2*)

State	Verification (V) and Calibration (C) Efforts									
	Fatigue Cracking		Rutting		Transverse Cracking		IRI		Longitudinal Cracking	
	V	C	V	C	V	C	V	C	V	C
AZ	✓	✓	✓	✓	✓	✓	✓	✓		
CO	✓	✓	✓	✓	✓	✓	✓	✓		
IA	✓		✓	✓	✓		✓		✓	✓
MO	✓		✓	✓	✓	✓	✓	✓		
NY	✓	✓	✓	✓	✓		✓	✓	✓	✓
NC	✓	✓	✓	✓						
OH			✓	✓	✓		✓	✓		
OR	✓	✓	✓	✓	✓	✓			✓	✓
TN			✓	✓			✓	✓		
UT	✓		✓	✓	✓		✓			
WA	✓	✓	✓	✓	✓		✓		✓	✓
WI	✓		✓	✓	✓	✓	✓	✓		

V= Verification C = Calibration

In addition to the literature review, several plant-produced mixtures were tested in this study to generate the inputs necessary to run initial trial designs using the AASHTOWare® Pavement M-E Design software. The mixtures selected were those most produced on regular basis (based on tonnage) in Massachusetts and not developed for a specialized application. The testing of these mixtures included: measuring the dynamic modulus at different temperatures and different frequencies using the Asphalt Mixture Performance Tester (AMPT) and determining the complex modulus and the phase angle of the asphalt binder used in each mixture measured using the dynamic shear rheometer. This data was analyzed and combined with the as-built properties of the mixture obtained from production data to create cut-and-paste formatted data that can be directly input into the AASHTOWare® Pavement M-E Design software. Based on the reliability level selected for each distress that was predicted these mixtures will reach the pavement service life without exhibiting failures.

This page left blank intentionally.

Table of Contents

List of Tables

This page left blank intentionally.

List of Figures

This page left blank intentionally.

List of Acronyms

Acronym	Expansion
AADTT	Average Annual Daily Truck Traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ALF	Accelerated Loading Facility
AMPT	Asphalt Mixture Performance Tester
ARAN	Automatic Road Analyzer
ATRs	Automated Traffic Recorders
CIP	Capital Investment Plan
DSR	Dynamic Shear Rheometer
E*	Dynamic Modulus
ESAL	Equivalent Single Axle Load
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
HMA	Hot Mix Asphalt
HWT	Hamburg Wheel Tracking
IDT	Indirect Tension Strength
IRI	International Roughness Index
LTPP	Long-Term Pavement Performance
LVDT	Linear Variable Differential Transformers
MassDOT	Massachusetts Department of Transportation
M-E	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
M_R	Resilient Modulus
NCAT	National Center for Asphalt Technology
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resources Conservation Services
OTIS	Online Transportation Information System
Pa	Pascal
pcf	Pounds per Cubic Foot
PG	Performance Grade
PMS	Pavement Management System
psi	Pounds per Square Inch
RLT	Repeated Load Triaxial
RTFO	Rolling Thin Film Oven
SGC	Superpave Gyratory Compactor
SPR	State Planning and Research
SSURGO	Soil Survey Geographic
TRINA	Traffic Records Information Access
USDA	United States Department of Agriculture
WIM	Weigh-in-Motion

This page left blank intentionally.

1.0 Introduction and Objectives

This study entitled "Improving the Long-Term Condition of Pavements in Massachusetts and Determining Return on Investment: Implementing the AASHTO Mechanistic-Empirical Pavement Design Guide - PHASE I" was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Introduction

MassDOT is striving to improve its highway infrastructure's resiliency to climate change, environmental impacts, and traffic loading by implementing new technologies that can provide valuable return on investment. These improvements should begin with the pavement design process which currently utilizes antiquated empirical design methods from the 1960's. Implementing the American Association of State Highway Transportation Officials (AASHTO) new Mechanistic-Empirical (M-E) pavement design method currently used by at least 33 state agencies would be a significant improvement. The M-E design method incorporates performance models which are tailored to the region and form an important component of the design process. Additionally, because the AASHTO M-E design can predict pavement distresses, it could be used as a tool by MassDOT to measure the return on investment when using new technologies such as warm mix, bio-asphalts, modified asphalts, mixtures with increased recycled (sustainable) materials, etc. Furthermore, based on the predicted distresses, MassDOT can make decisions on which pavement preservation strategies should be implemented to improve and extend the pavement life of its road network. The AASHTO M-E design method predicts pavement distresses utilizing prediction models that were developed and nationally calibrated using in-service pavements. To accurately predict the performance in Massachusetts, these models will need to be calibrated according to local conditions.

Due to the complexity of the research problem, a multi-phase (four phases) approach over several years was suggested to complete this research. The four phases are:

Phase 1: Literature Review & State-of-Practice Assessment
Phase 2: Develop an AASHTOWare® Pavement M-E User Manual & Develop Local Experimental Plan and Sampling Template
Phase 3: Sample and Test Mixtures for Local Calibration/Collect Field Data
Phase 4: Calibrate/Validate the M-E Prediction Models (Local Calibration)

This report focuses solely on Phase 1: Literature Review & State-of-Practice Assessment.

1.2 Objectives

For Phase 1, the main objective is to determine the overall state-of-practice with regards to AASHTO M-E design and implementation. This will be achieved by conducting a thorough literature review on the steps taken by other DOTs to calibrate the AASHTO M-E Pavement Design. Additionally, initial testing of already sampled mixtures will be conducted to accelerate future phases of this research.

2.0 Overview & Experimental Plan

2.1 Overview

The development of the MEPDG and release of AASHTOWare® Pavement M-E Design software is a significant improvement to existing pavement design procedures. In pavement M-E design, pavement responses (stresses, strains, and deflections) are calculated and utilized as inputs in empirical distress prediction models. These models are then used to estimate cumulative pavement distresses over time. The various distress prediction models for flexible pavements include: total rutting, rutting in each layer (asphalt layer, base and subbase), top-down cracking, bottom-up fatigue cracking, thermal cracking, reflective cracking and international roughness index (IRI). The predicted distresses allow pavement engineers to define acceptable levels of performance and design pavements to address particular distresses. A key advantage of the M-E design methodology is that its individual components, like transfer functions and performance models, can be enhanced over time to reflect new research in the field.

The prediction models in the M-E design guide were developed and nationally calibrated using in-service pavements. These in-service pavements were mainly selected from projects in the Long-Term Pavement Performance (LTPP) program. Accordingly, the prediction models may not accurately predict the performance for localized conditions (environment, traffic, and materials characterization) in Massachusetts. Therefore, prior to M-E design implementation, it will be crucial for MassDOT to recalibrate the standard M-E design guide prediction models to actual data from local projects located in Massachusetts (local calibration). Many states DOTs have already undertaken and completed this process. Local calibration is perhaps the most crucial aspect of implementation of the M-E design process. Local calibration will often remove bias present in the national model, as well as reduce some scatter in the results (i.e., improve precision). As illustrated in Figure 2.1, local calibration is a systematic process expected to eliminate potential biases and increase the accuracy of the performance predictions.

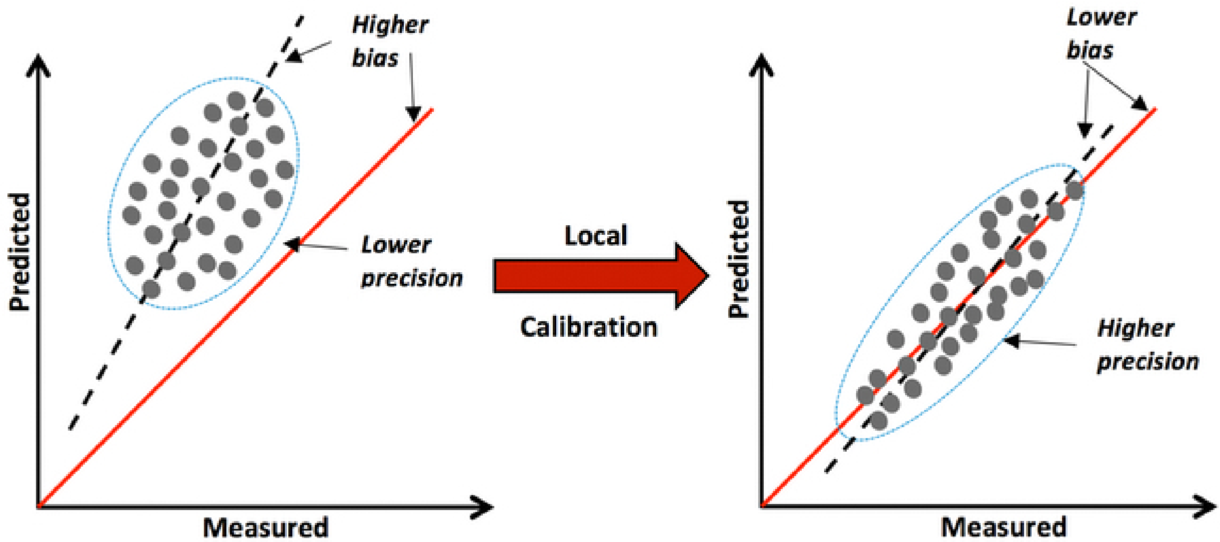


Figure 2.1: Precision and bias in local calibration (*1*)

Local calibration of the distress prediction models helps bridge the gap, if any, between the predicted and the observed performance in the field. Otherwise, some pavements will be under-designed and others over-designed, translating to either premature failure or excessive costs. To date, at least ten states (Arizona, Colorado, Indiana, Missouri, Montana, North Carolina, Ohio, Oregon, Utah and Washington) have completed local calibrations of M-E design guide asphalt concrete models (flexible pavements).

Implementation of the AASHTOWare® Pavement M-E Design advances the MassDOT mission to provide a reliable transportation system and supports the MassDOT Capital Investment Plans (CIPs). Utilizing this new design procedure will allow MassDOT to design better performing and cost-effective pavements using a procedure that is based more on the engineering properties of the materials and less on empirical relationships that are highly unreliable. The goals of all four phases of the research project addresses the most difficult and critical parts of M-E design implementation, thus allowing MassDOT to simply utilize the design procedure without the complications of determining how to set it up correctly. It should be noted that this research project would only calibrate/validate models for asphalt concrete pavements type, as Massachusetts has very limited sections of rigid pavement in the state.

Ultimately, pavement condition can be improved by implementing these designs. The design process allows for the identification of the design that will perform well in the field and help eliminate poorer performing options prior to construction, as well as serve as a measure to calculate the return on investment. Identifying the optimal design will allow for the maximization of funding resources, longevity of the pavement infrastructure, and improve overall pavement network condition. Finally, implementing the MEPDG will allow MassDOT to construct roads with enhanced durability to compensate for ongoing climatic changes.

Current design methods do not consider climatic changes, whereas as the MEPDG is heavily reliant on the climate of the regions for which it is placed.

2.2 Experimental Plan

As noted previously, due to the complexity of the research problem, a multi-phase (four phases) approach over several years was suggested to complete this research. The overall experimental plan for all phases of the project is shown in Figure 2.2.

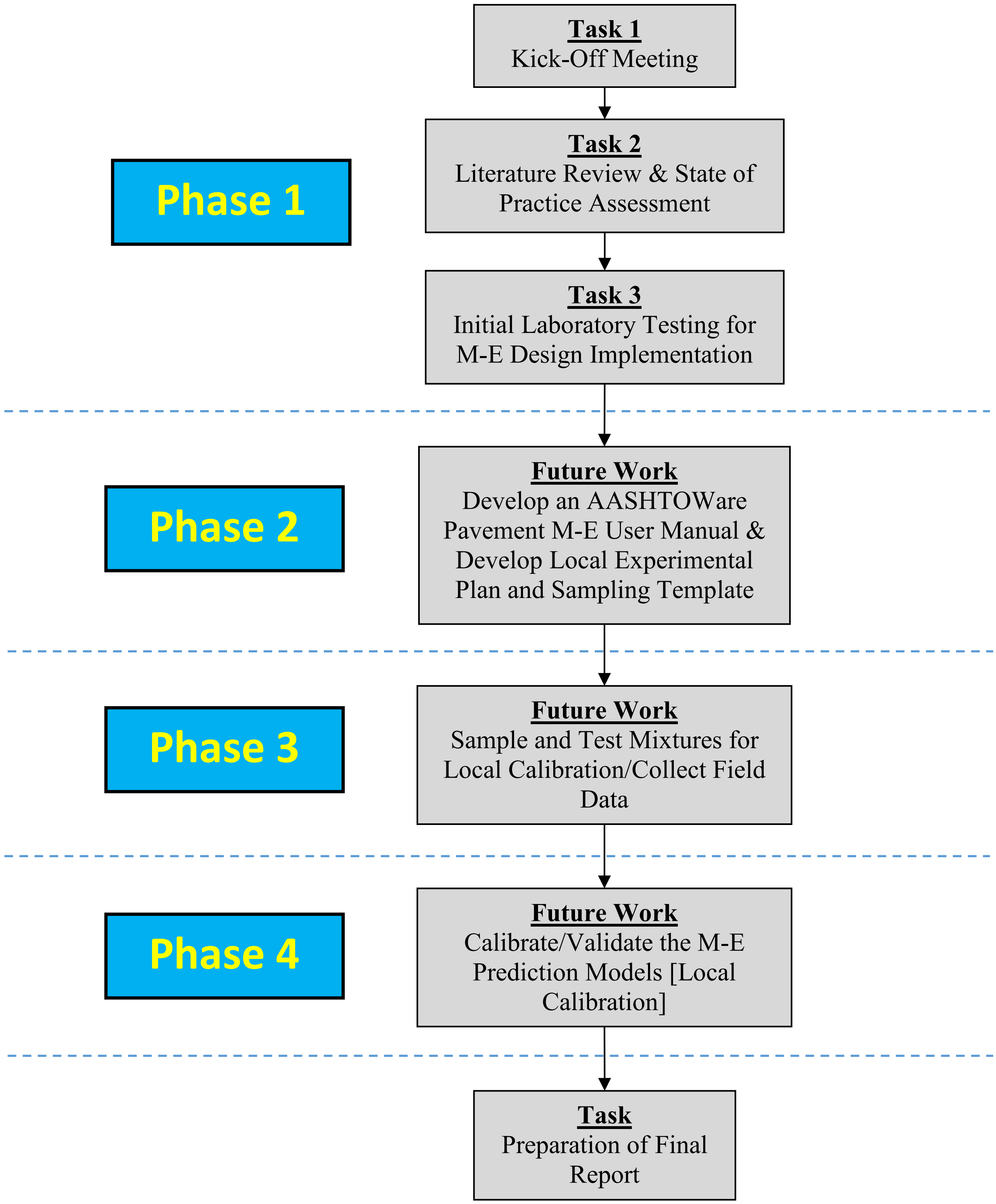


Figure 2.2: Experimental plan (All four phases)

3.0 Literature Review

3.1 Overview of Mechanistic-Empirical Design Method

The development of the mechanistic-empirical pavement design guide and release of AASHTOWare® Pavement M-E Design software is a significant improvement to existing pavement design procedures. The MEPDG was developed to design new and rehabilitated pavement structures based on mechanistic-empirical principles. Figure 3.1 illustrates the basic steps of the pavement M-E design method.

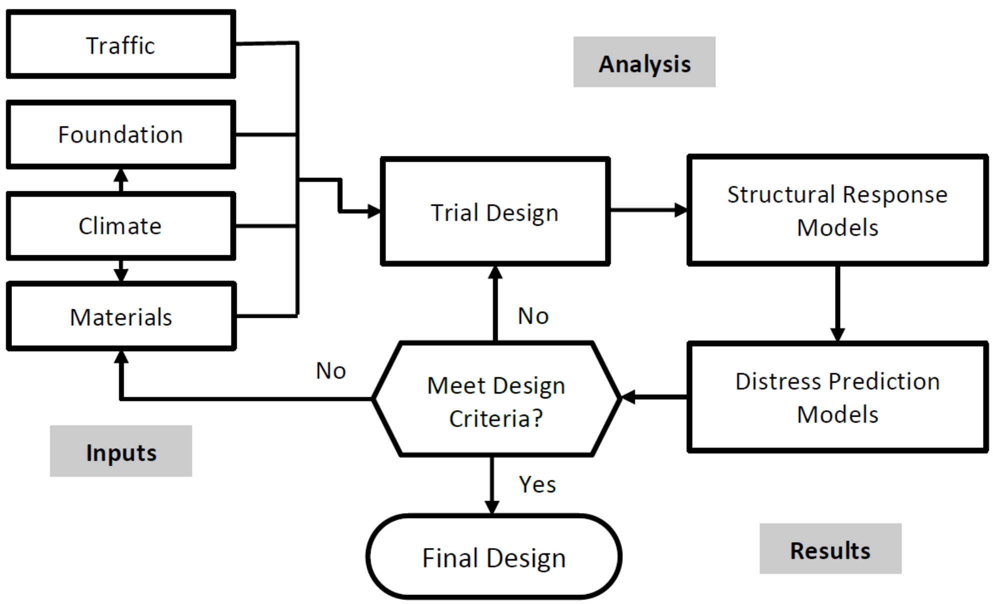


Figure 3.1: Basic Steps of Pavement ME Design (*2*)

Based on the inputs (traffic, subgrade, climate, and materials characteristics) and trial design structure (number of layers and thickness of each layer), the AASHTOWare® Pavement M-E Design software mechanistically calculates the pavement responses (stresses, strains, and deflections) and use the responses to compute incremental damage over time (*2*). The software then utilizes the cumulative damage to empirically predict pavement distresses for each trial pavement structure. The empirical analysis uses transfer functions to relate cumulative damage to observed pavement distresses. The various distress prediction models for flexible pavements include:

1. Total rutting
2. Rutting in each layer (asphalt layer, base and subbase)
3. Top-down cracking
4. Bottom-up fatigue cracking
5. Thermal cracking

6. Reflective cracking
7. International Roughness Index (IRI)

The predicted distresses allow the user to define acceptable levels of performance so that pavements can be designed to specifically address a particular distresses. Generally, the mechanistic models used in the software are assumed to be accurate. However, inaccuracies still exist and ultimately affect the computations and prediction of final distresses using the transfer functions (*3*). Therefore it essential to address these inaccuracies in both the mechanistic and empirical models.

The prediction models in the MEPDG were developed and nationally calibrated using in-service pavements. These in-service pavements were mainly selected from projects in the Long-Term Pavement Performance (LTPP) program. Other data was used that were generated from field experiments such the FHWA Accelerated Loading Facility (ALF). Accordingly, the MEPDG prediction models may not accurately predict the performance for the localized conditions (environment, traffic, and materials characterization) of Massachusetts. Therefore, prior to M-E design implementation, it will be crucial for MassDOT to recalibrate the standard M-E design guide prediction models to actual data from local projects located in Massachusetts (local calibration). Many states DOTs have already undertaken and completed this process.

Local calibration is perhaps the most crucial aspect of implementation of the M-E design process. Local calibration will often remove bias present in the national model, as well as reduce some scatter in the results (i.e., improve precision). As illustrated in Figure 2.1, local calibration is a systematic process expected to eliminate potential biases and increase the accuracy of the performance predictions. Local calibration of the distress prediction models helps bridge the gap, if any, between the predicted and the observed performance in the field. Otherwise, as stated earlier, some pavements will be under-designed and others over-designed, translating to either premature failure or excessive costs. Many states have completed local calibrations of M-E design guide asphalt concrete models (flexible pavements).

3.2 Definitions

AASHTO defines three methodologies related to determining how accurate the transfer functions relevant to local conditions (*2, 4*). These methodologies are: verification, calibration, and validation.

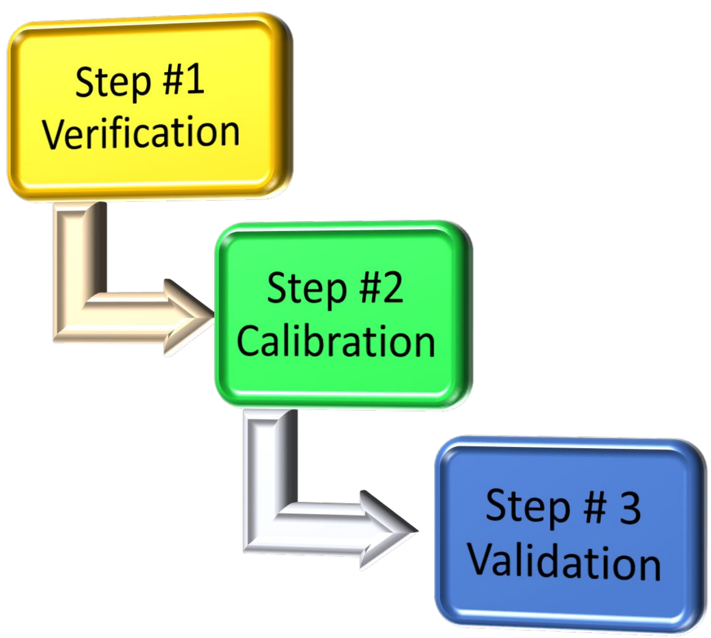
Verification: "Verification of a model examines whether the operational model correctly represents the conceptual model that has been formulated." It should also be noted that field data are not needed in the verification process, as it is "primarily intended to confirm the internal consistency or reasonableness of the model. The issue of how well the model predicts reality is addressed during calibration and validation." (*3*)

Calibration: "A systematic process to eliminate any bias and minimize the residual errors between observed or measured results from the real world (e.g., the measured mean rut depth in a pavement section) and predicted results from the model (e.g., predicted mean rut depth from a permanent deformation model). This is accomplished by modifying empirical calibration parameters or transfer functions in the model to minimize the differences between the predicted and observed results. These calibration parameters are necessary to compensate for model simplification and limitations in simulating actual pavement and material behavior." (*3*)

Validation: "A systematic process that re-examines the recalibrated model to determine if the desired accuracy exists between the calibrated model and an independent set of observed data. The calibrated model required inputs such as the pavement structure, traffic loading, and environmental data. The simulation model must predict results (e.g., rutting, fatigue cracking) that are reasonably close to those observed in the field. Separate and independent data sets should be used for calibration and validation. Assuming that the calibrated models are successfully validated, the models can then be recalibrated using the two combined data sets without the need for additional validation to provide a better estimate of the residual error." (*3*)

3.3 Calibration Process

The process of calibration generally consists of three steps:



The first step involves verification or evaluation of the existing global models to determine how well the model represents actual distresses and to evaluate the accuracy and bias. The second step is calibration of the model coefficients to improve the model and reduce bias, typically using the same dataset as used in the verification step. The third step is validation of the newly calibrated model using a separate dataset.

The AASHTO MEPDG manual of practice specifically states that the verification procedure does not need to utilize field data to assess if the model is reliable and consistent (*4*). It is suggested that this should be addressed in the calibration and validation steps; however, it becomes rather confusing when reporting two sets of results in the calibration procedure (i.e. results for the statistical comparison with measured data for performance predicted using the nationally calibrated model and those results for the performance predicted by the locally calibrated model). To distinguish between the various results reported for each calibration effort, the more commonly used terminology is utilized in this report. Verification refers to the application of the globally calibrated model for the available data used in design and compared with actual field performance data to assess bias and accuracy. Results reported under the calibration step are the results from the local calibration of the model coefficients and compared with the field performance data. Validation refers to the application of the newly calibrated model to a new dataset (and field performance data), separate from the dataset used to calibrate the model.

3.4 Local Calibration

The MEPDG developed under the National Cooperative Highway Research Program (NCHRP) 1-37 A and 1-40 projects was globally calibrated using representative database of pavement sites across North America. Most of these sites have been monitored through the LTPP program. However, real-world differences between these sites and a specific site can significantly affect the distress predictions. These differences include: construction and material specifications, materials characteristics, climatic conditions, and pavement preservation practices. To address these differences, local calibration of the coefficients associated with the distress transfer functions is needed. This process is shown in Figure 3.2.

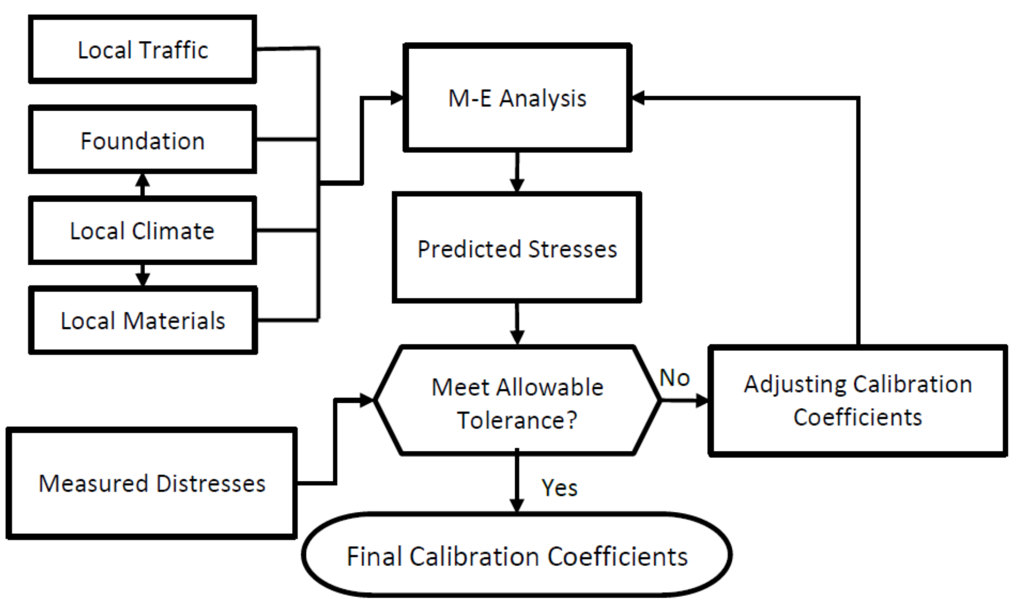


Figure 3.2: Local Calibration of Pavement ME Design (*2*)

It is worth noting that, prior to embarking on the local calibration process, agencies need to conduct a local verification at a minimum. The local verification is needed to determine if practices, policies, and conditions will significantly affect the prediction of the distresses using the MEPDG. In the local verification process, the distresses predicted by the AASHTOWare® Pavement M-E Design software using the globally calibrated coefficients are compared with the distresses measured in the field for selected pavement sections. If the difference between the predicted and measured distresses is not significant, the design can be adopted. Otherwise, the design should then be calibrated to local conditions.

A detailed step-by-step procedure for local calibration is described in the *AASHTO Guide for the Local Calibration of the MEPDG* (*2,4*). NCAT summarizes the steps from the AASHTO guide concisely. These steps are presented verbatim from NCAT as Steps 1 through 11 shown in the following (*2*):

1. ***Select hierarchical input level for each input parameter***. This is likely a policy-based decision that can be influenced by several factors, including the agency's field and laboratory testing capabilities, material and construction specifications, and traffic collection procedures and equipment. Agencies can refer to the MEPDG Manual of Practice (*4*) for recommendations on selecting the hierarchical input level for each input parameter.

2. ***Develop experimental design***. An experimental plan or matrix is set up in this step to help select pavement segments that represent the pavement distresses observed in the state and local factors that may affect the observed distresses, such as the agency's design and construction practices and materials, as well as traffic and climatic conditions.

3. ***Estimate sample size for assessing distress models***. This step is to estimate the number of pavement segments, including replicates, which should be included in the local calibration process to provide statistically meaningful results. The minimum number of pavement segments recommended for each distress model is as follows:
    - Total rutting: 20 roadway segments
    - Load-related cracking: 30 roadway segments
    - Non-Load related cracking: 26 roadway segments
    - Reflection cracking (asphalt surface only): 26 roadway segments

4. ***Select roadway segments***. Appropriate roadway segments and replicates are identified in this step to satisfy the experimental plan developed in Step 2. The pavement segments selected are recommended to have at least three condition surveys conducted in the past 10 years.

5. ***Extract and evaluate data***. The inputs available for each roadway segment are compiled and verified in this step. Data not compatible with the format required for the Pavement ME Design software will be converted accordingly. Missing data will be identified for further testing to be conducted in Step 6.

6. ***Conduct field and forensic investigations of test sections***. This step encompasses field sampling and testing of the selected pavement segments to obtain missing data as identified in Step 5. The level of testing should be selected appropriately so that the data generated are compatible with the hierarchical input level selected in Step 1. Forensic investigations are necessary to confirm assumptions in the MEDPG, at the discretion of the agency. Investigations suggested include test cores, and trenching to identify location, initiation, and propagation of distresses in the pavement structure.

7. ***Assess local bias***. The Pavement ME Design software with global calibration factors is conducted to design pavements using the inputs available from the selected pavement segments at 50% reliability. For each distress model, the predicted distresses are plotted and compared with the measured distresses for which linear regression is performed. Diagnostic statistics, bias, and the standard error of the estimate (S_e), are determined. Bias is determined by performing linear regression using the measured and MEPDG predicted distress and comparing it to the line of equality. Three hypotheses, listed below, are tested to determine if bias is present. If bias exists the prediction model should be recalibrated (see Step 8). If the difference is not significant, the standard error of the estimate is assessed (see Step 9).
   - Assess if the measured and predicted distress/IRI represents the same population of distress/IRI using a paired t-test.
   - Assess if the linear regression model developed has an intercept of zero.
   - Assess if the linear regression model has a slope of one.

8. ***Eliminate local bias***. If significant bias exists (as determined in Step 7), the cause should be determined. Inputs that may cause prediction bias include traffic, climate, and material characteristics (*5*). If possible, the bias should be removed by adjusting the calibration coefficients listed in Table 3.1. Figure 3.2 illustrates basic steps for determining local calibration coefficients. Then, the same analysis conducted in Step 7 is performed using the adjusted calibration factors.

Table 3.1: Coefficients to be Adjusted for Eliminating Bias and Reducing Standard Error (*2,4*)

Distress		Eliminate Bias	Reduce Standard Error
Total Rutting	Unbound Materials and HMA Layers	k_{r1}, β_{s1}, or β_{r1}	k_{r2}, k_{r3}, and β_{r2}, β_{r3}
Load-Related Cracking	Alligator Cracking	C_2 or k_{f1}	k_{f2}, k_{f3}, and C_1
	Longitudinal Cracking	C_2 or k_{f1}	k_{f2}, k_{f3}, and C_1
	Semi-Rigid Pavements	C_2 or β_{c1}	C_1, C_2, C_4
Non-Load-Related Cracking	Transverse Cracking	β_{t1}	β_{t1}
IRI		C_4	C_1, C_2, C_3

9. ***Assess standard error of the estimate***. In this step, the S_e values determined in Step 7 or 8 based on the predicted and measured distresses (local S_e) are compared with the S_e values of the globally calibrated distress models provided in the Pavement ME Design software (global S_e). Models whose local S_e values are greater than the global S_e values should be recalibrated in an attempt to lower the standard error (see Step 10). For the other models, the local S_e values can be used for pavement design. The S_e values found to be reasonable based on the global calibration process are provided in Table 3.2 for reference.

Table 3.2 Standard Error of the Estimate (*4,5*)

Performance Prediction Model	**Standard Error (S_e)**
Total Rutting (in)	0.10
Alligator Cracking (%lane area)	7
Longitudinal Cracking (ft/mi)	600
Transverse Cracking (ft/mi)	250
Reflection Cracking (ft/mi)	600
IRI (in/mi)	17

10. ***Reduce standard error of the estimate***. Table 3.1 lists the calibration coefficients that can be adjusted to reduce the standard error of the estimate for each distress model. If the S_e cannot be reduced, the agency can decide whether it should accept the higher local S_e or lower global S_e values for pavement design. This decision should consider the difference in sample size used in the global and local calibration processes.

11. ***Interpret the results and decide on the adequacy of calibration parameters***. The agency should review the results and check if the expected pavement design life is "reasonable" for the performance criteria and reliability levels used by the agency.

Finally, to perform verification or local calibration, input parameters are needed that represent the traffic and also the material characteristics of each pavement layer. The MEPDG introduced three hierarchical input levels (*4*) as outlined in the following:

- **Input Level 1**: Input parameter is measured directly; it is site or project specific. Level 1 is the most accurate but requires testing which could be costly to an agency.

- **Input Level 2**: Input parameter is estimated from correlations or regression equations. In other words, the input value is calculated from other site-specific data or parameters that are less costly to measure.

- **Input Level 3**: Input parameter is based on "best-estimate" or default values.

3.4 State Agency Experience with Local Calibration

The AASHTO publication *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* was published in 2010 (*3*) to provide guidelines for local calibration. However, the efforts of some agencies to perform the local calibration did not follow the AASHTO guide as their efforts were initiated prior to its publication or their efforts were ongoing when the guide became available. Additionally, many agencies did not use the latest version of software as the AASHTOWare® Pavement M-E Design software is constantly being updated to include the up-to-date mechanistic models associated with the asphalt pavement distresses. Therefore, this section will present the agencies calibration efforts regardless if they used the AASHTO guide or an older version of the software.

The section briefly summarizes state agency experience with local calibration. Specifically, the following key areas are presented: distresses calibrated, steps followed for the calibration, sample size and sites selection, existing data that was used, laboratory and field testing to generate the required inputs, traffic data, climatic data, problems encountered, and any reported benefits from the calibration. A report published by NCAT summarized, the local verification and calibration efforts of twelve agencies (*2*). Table 3.3 shows their summary.

Table 3.3 NCAT Summary of State Agency Local Verification & Calibration Efforts (*2*)

State	Agency	Verification (V) and Calibration (C) Efforts									
		Fatigue Cracking		Rutting		Transverse Cracking		IRI		Longitudinal Cracking	
		V	C	V	C	V	C	V	C	V	C
AZ	AZ DOT	✓	✓	✓	✓	✓	✓	✓	✓		
CO	CO DOT	✓	✓	✓	✓	✓	✓	✓	✓		
IA	IA DOT	✓		✓	✓	✓		✓		✓	✓
MO	MO DOT	✓		✓	✓	✓	✓	✓	✓		
NY	NY DOT	✓	✓	✓	✓	✓		✓	✓	✓	✓
NC	NC DOT	✓	✓	✓	✓						
OH	OH DOT			✓	✓	✓		✓	✓		
OR	OR DOT	✓	✓	✓	✓	✓	✓			✓	✓
TN	TN DOT			✓	✓			✓	✓		
UT	UT DOT	✓		✓	✓	✓		✓			
WA	WADOT	✓	✓	✓	✓	✓		✓		✓	✓
WI	WI DOT	✓		✓	✓	✓	✓	✓	✓		

V= Verification C = Calibration

3.4.1 Arizona *(6)*

In 2014, a study by Darter et al. (*6*) was prepared for the Arizona Department of Transportation (ADOT) to aid in the implementation of the former AASHTO DARWin-ME software (predecessor to the current design software). ADOT's desired applications for ME design included: flexible HMA pavements, composite pavements, rigid pavements, and HMA overlays of flexible pavements. Only flexible pavements will be covered in this literature review as they are the focus of this current

MassDOT research project. ADOT's efforts included both verification and local calibration. Conventional and Superpave mixtures with thicknesses above and below 8 inches were used. ADOT characterized its materials using different input levels (i.e.. Level 1, Level 2, or Level 3).

Flexible Distresses Calibrated
Local calibration was performed to assess the following distress models for flexible pavements: alligator cracking, transverse thermal cracking, rutting, and IRI.

Steps Utilized for Local ME Calibration
Arizona followed the 11-step roadmap for calibrating the MEPDG software to local conditions outlined in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*).

Sample Size & Site Selection
A minimum sample size for each distress/IRI was found using statistical analysis based on a chosen 90% confidence interval and a tolerable bias at 90% reliability. A minimum requirement of 18 flexible pavements were needed to perform local calibration. To encompass geographic/climatic variability of the state sites were selected from the northern, southern, and central regions that included both high and low elevations. 180 LTPP sections were chosen for the local calibration.

Existing Data Collection
Designs, materials, and inputs came from the LTPP database as well as ADOT files.

Laboratory & Field Testing
Little information is given in this study as to what field and laboratory tests were conducted. It is noted that survey videos and windshield surveys were used to measure alligator and transverse cracking on the roadways. Rutting was measured using a three-point laser equipment. This varies from the typical wire or straight-edge measurements used on projects from the LTPP database. This required ADOT rutting measurements to be corrected to be compatible with the M-E software. Forensic investigations were used for ADOT Pavement Management System (PMS) projects and were composed of the aforementioned windshield surveys, FWD testing, or a combination of the two. FWD testing and back-calculation was used for ADOT PMS sections with no foundation support data.

Traffic Data
Arizona used default vehicle class distributions, axle load distributions, and other default values as traffic inputs during the local calibration process. It was noted in the study that a detailed action plan is needed to obtain and compile necessary traffic data for use in the M-E design software in the future.

Climate Data
Climatic data for this study were obtained from the National Climatic Data Center (NCDC).

Problems Encountered
None noted.

Benefits to Calibration
Local calibration allowed pavements to be designed for desired reliability at the most optimum cost.

3.4.2 Colorado (*7*)

For the state of Colorado, a study by Mallela et al. in 2013 was performed in an attempt to facilitate local calibration of the AASHTO Pavement M-E Design models. A variety of new and overlay asphalt mixture sections were used. These sections had neat and modified asphalt binders. The asphalt mixture layer thicknesses varied, but most of them were less than 8 inches. The climatic zones ranged from hot to very cool locations. The asphalt materials properties were characterized at Levels 2 or 3 hierarchal inputs depending on the availability of data.

Flexible Distresses Calibrated
The flexible pavement distress models calibrated by Colorado DOT included: alligator cracking, rutting, transverse “thermal” cracking, and IRI. The national model under-predicted alligator cracking, thermal cracking, and IRI. It is also noted that the national rutting model displayed bias but the report did not state if the model was over- or under-predicting rutting.

Steps Utilized for Local ME Calibration
Colorado followed the 11-step roadmap for calibrating the MEPDG software to local conditions outlined in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*).

Sample Size & Site Selection
Colorado selected 126 pavement projects. Projects consisted of a mix between LTPP and Colorado PMS projects. Colorado’s sole criterion for inclusion into the local calibration database for LTPP projects was whether they represent a pavement type of interest. Of the 126 projects, 40 were identified for field testing. This consisted of 16 new HMA sites, 21 HMA over existing HMA sites, and 3 HMA over existing concrete sites.

Existing Data Collection
The two sources of data utilized by Colorado were the CDOT pavement management system and the LTPP database.

Laboratory & Field Testing
Field testing consisted of hot mix asphalt (HMA) coring and extraction of HMA/PCC cores and unbound aggregate base and subgrade samples. Cores were tested for basic volumetric, strength, thickness, and durability properties. Other tests included layer thickness measurements, trenching, distress surveys, and rut-depth measurements. All cores were tested for moisture damage and signs of stripping. Sieve analysis, Atterberg limits, and in-situ moisture content tests were also performed to extract AASHTO soil class and in-situ moisture content. Trenching was performed by sawing a full-depth 4 by 6-foot hole in the right or left wheel path and excavating the sample. Following the path of a straight edge placed along the length of the sample, measurements for rut-depth are taken every 3 inches along the face of the trench. Nondestructive testing was also performed in the fashion of Falling Weight Deflectometer (FWD) testing in a separate effort to obtain deflection data for back-calculating pavement layer moduli and the modulus of subgrade reaction for concrete and composite pavements. For HMA pavements this test was performed at 25-ft intervals along the length of the road. Deflection data were used to estimate the following: HMA layer modulus (damage in-situ modulus), base layer elastic modulus (for unbound and treated base materials), subgrade elastic modulus (at in-situ moisture) for HMA pavements and modulus of subgrade reaction (k-values) at in-situ moisture for concrete pavements. For HMA mixes the laboratory testing included: dynamic modulus test, indirect tensile strength and creep compliance test, repeated load deformation test, and rut testing using the Hamburg wheel tracking (HWT) test.

Traffic Data
Traffic data came from Colorado DOT’s Online Transportation Information System (OTIS) which included traffic data for 120 permanent automated traffic recorders (ATRs) and 13 continuous weigh-in-motion (WIM) sites.

Climate Data
Climatic data was obtained from the Colorado Climate Center, National Climatic Data Center (NCDC), and United States Department of Agriculture (USDA) National Resources Conservation Services (NRCS) Soil Survey Geographic (SSURGO) databases.

Problems Encountered
None noted.

Benefits to Calibration
None noted.

3.4.3 Louisiana (*8*)

This preliminary study by Wu and Yang was performed in 2011 to evaluate the current (at the time of the study) version of the MEPDG software. Performance of typical Louisiana flexible pavement types, materials, and structures was compared with LA-PMS pavement performance data to identify any possible areas for further calibration of the MEPDG in Louisiana.

Flexible Distresses Calibrated
The two distresses calibrated by Louisiana were the load-related fatigue cracking and rutting models as well as IRI. For AC over AC pavements the globally calibrated models adequately predicted load-related fatigue cracking, rutting, and IRI. For AC over soil cement base pavements the globally calibrated models under-predicted load-related fatigue cracking and over-predicted rutting. The performed sensitivity analysis indicated that out of all level-3 inputs for AC materials, binder type was the most influential parameter.

Steps Utilized for Local ME Calibration
Louisiana followed a 6-step process for local calibration that is as follows. Project selection, determine input strategy (traffic, climate, and materials), construct LA-MEPDG database, interpret LA-PMS data, validate MEPDG outputs using LA-PMS data, and model calibration.

Sample Size & Site Selection
40 projects were selected, spanning from 1997 to 2005.

Existing Data Collection
Louisiana used level 3 material inputs for the MEPDG software that were available from their mainframe/MATT database. Pavement distress data had previously been collected via windshield surveys and the use of the Automatic Road Analyzer (ARAN). Distress data previously collected included: rutting, IRI, alligator cracking, longitudinal cracking, transverse cracking, and block cracking. Network-level pavement condition surveys are conducted once every two years, and stored in the LA-PMS.

Laboratory & Field Testing
A series of FWD tests were conducted along with rutting and IRI measurements using a three-point laser between 2000 to 2003 and a 1280-point laser from 2004 to 2005. A secondary outcome of this study was the creation of a unified materials library for the state

Traffic Data
Louisiana used WIM station data for axle load spectra data and number of axles per truck inputs. For other traffic inputs in which no local information was available Louisiana used default MEPDG values.

Climate Data

Location data for climatic inputs (longitude, latitude, and elevation) came from LA-PMS and was determined at the mid-point of the project. Virtual weather stations were generated by interpolating climatic data from the nearest two or three adjacent weather stations to each project. For analysis Louisiana was divided into two sections at a latitude of 30.6°. Stations north of this line represent areas of higher elevation and have greater fluctuation in temperature. Areas to the south are considered coastal plains and typically have lower fluctuations in temperature.

Problems Encountered

None noted.

Benefits to Calibration

None noted.

3.4.4 Michigan (*9*)

This study by Haider et al. in 2014 was part three of a three-part investigation into the implementation and local calibration of the mechanistic-empirical pavement design guide for the state of Michigan. To perform local calibration for the state the project was split into three parts. Part one focused on materials testing of typical Michigan asphalt mixes. Part two included a sensitivity analysis of rehabilitation designs. Part three focused on the local calibration for Michigan conditions.

Flexible Distresses Calibrated

The distresses calibrated included: alligator cracking, longitudinal (top-down fatigue) cracking, rutting, and thermal cracking, and IRI.

Steps Utilized for Local ME Calibration

Michigan followed the 11-step roadmap for calibrating the MEPDG software to local conditions outlined in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*).

Sample Size & Site Selection

Local calibration was performed using 108 asphalt reconstruct projects and 41 of the rehabilitation projects from part two. Distresses predicted from the M-E software were compared to observed distresses from 40+ in-service rehabilitation projects.

Existing Data Collection

Cross-sectional pavement information, such as layer thickness and lane dimensions, was obtained from as-constructed or as-designed drawings provided by the Michigan Department of Transportation (MDOT).

Laboratory & Field Testing

Extensive laboratory testing was performed to characterize asphalt mixtures commonly used in Michigan for the complex (dynamic) modulus (|E*|), complex shear modulus (|G*|) of the binders, and Indirect Tension Strength (IDT) at low temperatures. A software called DYNAMOD was developed as a materials database for the material testing that was performed as part of this study. |E*| was tested by applying compressive haversine stresses to cylindrical samples and the resulting strain was measured using Linear Variable Differential Transformers (LVDT). This is a main input used in bottom-up, top-down fatigue cracking, and rutting models for the M-E software. The dynamic shear modulus (|G*|) was measured using Dynamic Shear Rheometer (DSR) testing at various loading frequencies. Creep compliance for this study was mathematically computed from the |E*| master curve. Tests were performed on 213 specimens consisting of 64 unique asphalt mixture types.

Traffic Data

Traffic data for local calibration came from weigh in motion (WIM) sites throughout the state.

Climate Data

Michigan used data from the 24 weather stations that are part of the Pavement ME design software, with the addition of 15 weather stations to bridge missing data for vacant areas throughout the state.

Problems Encountered
None noted.

Benefits to Calibration
None noted.

3.4.5 Missouri (*10,11*)

Missouri was an early adopter of the ME Pavement Design guide in 2009. A study was performed to recalibrate the distress models for new and rehabilitated flexible and rigid pavements (*10*). Specifically, the pavement sections used in the study included new or reconstructed HMA, HMA over HMA, and HMA over concrete with different thicknesses. Materials properties were characterized at different levels depending on the information available. The study used Level 2 hierarchal inputs for the dynamic modulus and Level 1 inputs for the volumetric properties. Due to an increased use of reclaimed materials (RAS & RAP) and a previous lack of historical data for MoDOT projects, a second study was performed by Titus-Glover et al. in 2020 (*11*). The following information is related to the earlier 2009 study.

Flexible Distresses Calibrated

The flexible pavement distresses that were calibrated as part of this study include: alligator (bottom-up fatigue) cracking, alligator reflection cracking, AC thermal cracking, transverse reflection cracking, total rutting, and IRI. Significant improvements were made for AC alligator cracking, reflection cracking, thermal cracking, and transverse reflection cracking models.

Steps Utilized for Local ME Calibration

For the process of local calibration, MoDOT followed the following five step process: selection of pavement design type of interest, project selection, development of pavement ME design database, local calibration of distress prediction models, and sensitivity analysis and case studies.

Sample Size & Site Selection

Missouri selected a total of 94 pavement sections, comprised of both MoDOT and LTPP samples (50 from MoDOT and 44 from LTPP). The process of random sampling was incorporated for the section, but the sampling needed to be stratified in order to represent a variety of different parameters in Missouri. These sections were selected to represent the different climate types in the state (north, south, and central), different base types (crushed stone or large stone), different asphalt layer thicknesses, and varying RAP/RAS content. Additionally, the sections represented the old and current protocols for pavement specifications in the state, and the assortment of different pavement construction projects (new AC projects, AC over AC, AC over concrete, new concrete, and concrete over concrete).

Existing Data Collection

Missouri attempted to maintain a Level 1 input accuracy as often as possible, but it varied based on available data. For traffic data, the truck volume data, vehicle class distribution, and monthly adjustment factors were set to Level 1. Axle load distributions were assigned to either Level 1 or 2 depending on the project information. The remainder of traffic data was set to Level 3. For the AC materials, the HMA dynamic modulus, creep compliance and indirect tensile strength had Level 1 inputs for the MoDOT PMS sections, while having Level 2 accuracy for the LTPP sections. The air voids for both sections remained at a Level 1 input accuracy. The binder information had a Level 1 input for the PMS sections and a Level 3 input for the LTPP sections. All other inputs were assigned to Level 3 default values. Concrete had Level 1 input accuracy for the strength data from the previous lab results for different MoDOT gradations, while all other CTE inputs had either Level 2 or 3 input levels. The resilient modulus, Atterberg limits and gradation for the base and subgrade had Level 1 inputs for the MoDOT PMS sections, while the LTPP sections had Level 3 inputs. Finally, the performance values of distress and smoothness were set to level 1 as the values were field measured.

Laboratory & Field Testing

MoDOT performed both field and laboratory tests in pursuit of their local calibration. Laboratory tests for the asphalt properties varied depending on desired parameter. The dynamic modulus was determined through the AASHTO T342 "Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures." The tests conducted to determine the asphalt binder G* and phase angle were the AASHTO T315, AASHTO T316, AASHTO T319 and AASHTO T164. For creep compliance and indirect tensile strength, AASHTO T322 was conducted. The in-place air voids followed the procedures set out by the AASHTO T166, AASHTO T209, and AASHTO 269 protocols. The in-place binder content was conducted in line with the AASHTO T308 test.

Traffic Data

Traffic information came from 18 WIM sites and represented between two and seven years of data.

Climate Data

Climatic data was generated via virtual weather stations using data interpolated from sites within a 20-mile radius of project locations, which could include weather stations from neighboring states.

Problems Encountered
None noted.

Benefits to Calibration
None noted.

3.4.6 Nevada (*12*)

This local calibration effort for the state of Nevada was performed as graduate research at the University of Nevada Reno by Nebhan in 2015 (*12*). The main tasks carried out in this study involve creating a database for material, traffic, and climatic inputs for the Pavement M-E software, collecting Nevada Department of Transportation (NDOT) Pavement Management System (PMS) data, conducting calibration of the MEPDG performance models, validating calibration factors, and conducting a sensitivity analysis of the calibrated models.

Flexible Distresses Calibrated

Local calibration of the fatigue bottom-up cracking and rutting models for the M-E design software was performed. For Nevada the nationally calibrated models over-predicted rutting and under-predicted fatigue bottom-up cracking for flexible pavements.

Steps Utilized for Local ME Calibration

To perform local calibration for the state of Nevada, NDOT followed the process of developing a database consisting of the Pavement M-E software inputs for Nevada, collecting relevant project data from NDOT's PMS, conducting the calibration for rutting and bottom-up fatigue cracking, validating the local calibration, and finally conducting a sensitivity analysis of the calibrated models.

Sample Size & Site Selection

All of the samples used for the local calibration were pulled from the NDOT PMS. A total of 54 sections were selected and were chose to represent the three districts of the NDOT that comprise of each county in Nevada. District 1 had 19 sections, district 2 had 25 sections and district 3 had 15 sections. These districts helped to represent the different climatic and traffic distributions throughout the state and the data was divided to ensure that new and old NDOT practices were represented by the samples.

Existing Data Collection

Data were collected from the NDOT PMS database and were converted to match the format of their respective MEPDG model requirements.

Laboratory & Field Testing

Field mixtures were sampled from 45 projects in efforts to develop a materials database and for materials testing. Nevada was prompted to perform local calibration for pavement materials due to the Pavement-ME software using unmodified binders for its nationally calibrated models. Asphalt binder viscosity was assessed for 17 different pavement binders using the Dynamic Shear Rheometer (DSR) test. This test was done in order to obtain values for complex shear modulus (G*) and phase angle (δ). For the dynamic modulus (|E*|) was tested under a variety of loading frequencies and temperatures. The Repeated Load Triaxial (RLT) test was used to evaluate asphalt mixture deformations under repeated loading conditions. The outputs from this test were used to experimentally procure k_{r1}, k_{r2}, and k_{r3} inputs for the Pavement-ME software. Flexural beam fatigue tests were run for eight of the asphalt samples to experimentally determine the regression coefficients k_{f1}, k_{f2}, and k_{f3}.

Traffic Data

Nevada traffic data came from the NDOT Traffic Records Information Access (TRINA). Traffic data were from both permanent and temporary weigh-in-motion sites throughout the state.

Climate Data

Climatic data for this study was generated via the creation of virtual weather stations in the Pavement M-E software. Weather stations within a radius of < 100 miles from the project's location were used for analysis.

Problems Encountered

None noted.

Benefits to Calibration

None noted.

3.4.7 South Carolina (*13*)

This University of South Carolina study by Gassman and Rahman in 2016 aimed to identify historical SCDOT data for use in local calibration for the MEPDG for South Carolina.

Flexible Distresses Calibrated

AC rutting, AC fatigue, and AC transverse cracking

Steps Utilized for Local ME Calibration

South Carolina followed the 11-step roadmap for calibrating the MEPDG software to local conditions outlined in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*).

Sample Size & Site Selection

Fourteen AC sections were chosen for this study. Sites were selected based on the following criteria: pavement sections are primary or interstate routes, sections of both flexible and rigid pavements, differing services times for different pavement types, and selected sections will not include overlays or rehabilitated pavements.

Existing Data Collection

Historical climatic, traffic, materials, and pavement performance data came from South Carolina Department of Transportation (SCDOT) files.

Laboratory & Field Testing

Field and laboratory tests were performed to study the subgrade modulus at three sites. Field data for this study included IRI values derived from wheel path profiles using non-contacting inertial profilers. The 14 selected AC sections rut data was collected in situ via an automated profiler tethered to a moving vehicle. Three sites were selected for further study to obtain new data for material inputs in: Orangeburg County, Georgetown County, and Pickens County. At each site FWD tests were performed, asphalt cores were collected, and soil samples (Shelby tube and bulk samples) were taken. It should be noted that for Phase II of this study more asphalt coring and trench studies are also planned. The resilient modulus (M_R) values of unbound materials from the three different regions of South Carolina were determined via laboratory testing using repeated load triaxial compression tests. Bulk soil samples were used for soil classification. Laboratory M_R was compared to its corresponding FWD modulus to determine M-E Pavement design model parameters K_1, K_2, and K_3.

Traffic Data

Traffic data used came from SCDOT via Automatic Traffic Recorders (ATRs) and Weigh-in-Motion (WIM) stations. SCDOT monitors more than 100 ATRs and 2 WIM stations.

Climate Data

Climatic data was taken directly from the 12 South Carolina weather stations included in the AASHTOWare program. For counties with no weather station present a virtual weather station was created by averaging station data from adjacent counties.

Problems Encountered

South Carolina encountered problems in the collection of material, traffic, and climatic data. Material data for dynamic modulus were collected for a single project not on a project-specific basis. This was also the case for material properties for unbound layers. Traffic data was primarily obtained through ATRs which do not provide axle load spectra. SCDOT plans to collect data using portable WIM stations for Phase II of this study. Climatic data from weather stations were not available for all testing locations and weather data for some counties needed to be extrapolated from adjacent weather stations.

Benefits to Calibration

A benefit to this research is to better allow SCDOT to allocate funding for more precise pavement designs than are currently possible.

3.4.8 Utah (*14*)

The Utah Department of Transportation (UDOT) sponsored a verification and local calibration study in 2009 using an early version of the MEPDG. The study was performed by Darter et al. (*14*). The pavement sections included new HMA and HMA over HMA with different thicknesses. Most layer thicknesses were between 4-8 inches. Most of the material properties were characterized as Level 3 with the exception of the subgrade that used level by back calculating the modulus using deflection data.

Flexible Distresses Calibrated

Local calibration was performed to assess the following distress models for flexible pavements: alligator cracking, transverse thermal cracking, rutting, and IRI. The findings of this study showed that the national model predicted alligator cracking relatively well for Utah conditions. It should be noted that a comparison could not be made relative to pavements experiencing significant amounts of alligator cracking due to a lack of projects experiencing this type of distress. For younger UDOT SuperPave binders the national model predicted transverse cracking well. For older conventional asphalt binders (AC-10 and AC-20) the national model was deemed very inadequate. The project team decided not to recalibrate due to UDOT's efforts to move away from Marshall mix design and towards SuperPave.

The national model adequately predicted rutting for older viscosity graded asphalt mixes but poorly predicted rutting in newer, more commonly used, SuperPave HMA mixes. Thus, a local calibration for that national model was needed. The national model also adequately predicted IRI. The study recommends continued monitoring of relatively newer (at the time of the study) Superpave HMA projects for a possible need to recalibrate the rutting model in the future.

Steps Utilized for Local ME Calibration

Utah followed the 11-step roadmap for calibrating the MEPDG software to local conditions outlined in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*).

Sample Size & Site Selection

A minimum requirement of 18 flexible pavements were needed to perform local calibration. A total of 60 LTPP and UDOT PMS projects were identified for analysis. These projects included: new HMA, HMA overlaid existing HMA, and new concrete.. A minimum sample size for each distress/IRI was found using statistical analysis based on a chosen 90% confidence interval and a tolerable bias at 90% reliability.

Existing Data Collection

Existing distress and IRI data of interest were obtained from the LTPP database for LTPP projects and UDOT PMS performance data files were used for UDOT PMS projects.

Laboratory & Field Testing

No field of forensic investigations were performed.

Traffic Data

Utah collected traffic input data from a mix of their 90 ATR and 15 WIM sites. Traffic data collected included historical and current truck traffic type and volume, axle load distribution, vehicle class distribution, axle spacing and dimension, and more.

Climate Data

Utah collects climatic data using automated Road Weather Information System stations. Unfortunately, the data collected are not properly formatted for the Pavement M-E software. For the local calibration process Utah opted to use climatic data from the National Oceanic and Atmospheric Administration (NOAA) NCDC archive. This included 25 weather stations throughout the state.

Problems Encountered
None noted.

Benefits to Calibration
None noted.

3.4.9 Virginia (*15*)

For the state of Virginia, a 2015 study by Smith and Nair (*15*) was performed in an attempt at local calibration of the M-E design software.

Flexible Distresses Calibrated

Local calibration offered improvement to the globally calibrated distress models. Previously the global rutting model over-predicted rutting and IRI while under-predicting bottom-up fatigue cracking. It is noted in this study that local calibration will allow VDOT to develop better estimates for future rehabilitation needs of pavement sections and for better estimates of pavement performance.

Steps Utilized for Local ME Calibration

Virginia followed the 11-step roadmap for calibrating the MEPDG software to local conditions outlined in the AASHTO *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*3*).

Sample Size & Site Selection

The Virginia Department of Transportation (VDOT) began test site selection prior to the publication of the AASHTO local calibration guide. VDOT had the foresight to create a large and varied sampling of projects and initially calibrated using five sites from each district of the state. Pavement samples were taken from sites at least 0.5 miles long with more than 8 inches of asphalt and constructed after 1999.

Existing Data Collection

Data was extracted from the VDOT Pavement Management System (PMS) for rut depth, fatigue cracking, and IRI. Virginia gathered materials inputs from multiple different sources. Asphalt pavement structure information was provided by VDOT materials personnel, subgrade information was obtained from records of resilient modulus testing of similar local materials. It is noted in this study that forensic investigations were not performed due to many of the sites consisting of either rehabilitated pavements or displaying a minimal amount of distress.

Laboratory & Field Testing

No laboratory or field testing was performed for this study.

Traffic Data

Traffic inputs were taken as averages from year of construction to present-day to obtain Average Daily Traffic (ADT). Average annual daily truck traffic (AADTT) was obtained using the percent truck traffic from the design year. Statewide average values were used for vehicle class distribution, axle load spectra, and axles per truck.

Climate Data

Climatic inputs for this study were obtained by selecting a single weather station near each project location. The distresses of primary interest for Virginia included total rutting and bottom-up fatigue cracking, with a secondary interest for IRI.

Problems Encountered

None noted.

Benefits to Calibration

It is noted that local calibration can begin to improve data available to Virginia in forecasting future pavement needs. Also, forensic pavement investigations may be performed with the locally calibrated models to obtain better estimates of pavement performance.

3.4.10 Wyoming (*16*)

For the state of Wyoming, Biplab et al. worked with the Applied Research Associates Inc. to create a set of local calibration parameters to be used for implementation in the Mechanistic Empirical Pavement Design Guide software in 2015.

Flexible Distresses Calibrated

Calibration of transfer function coefficients was performed for the following flexible pavement distresses: rutting, bottom-up fatigue cracking, thermal cracking, reflection cracking, and IRI. The globally calibrated models for predicting IRI were found to be unbiased for both flexible and rigid pavements.

Steps Utilized for Local ME Calibration

Wyoming utilized a four-step process for local calibration that is as follows: determine the inputs for the calibration pavement sections, verify the global calibration coefficients for each transfer function, modify or adjust coefficients to eliminate bias and reduce standard error, and verify the resulting calibration coefficients.

Sample Size & Site Selection

The team generated both LTTP test sections (9 flexible pavement sections, 13 semi-rigid sections and 1 rigid section) and non-LTPP sections (nine flexible sections and one semi rigid section). However, they felt that they should include more LTPP sections, so they included additional sections located on the borders of neighboring states. Non-Wyoming sites consisted of 68 flexible and 25 rigid pavements. All sites from neighboring states were LTPP sites. The non-LTPP sections were added as a way to better reflect the current practices performed by the Wyoming Department of Transportation (WYDOT).

Existing Data Collection

Climate, traffic, and materials data from were obtained from the LTPP database for test sections in Wyoming and the surrounding states.

Laboratory & Field Testing

For these sections, field investigations included site condition surveys to determine type and severity distresses. Wyoming also performed coring to confirm and measure layer thickness and obtain materials for laboratory testing.

Traffic Data

Portable weigh in-motion (WIM) station data were used for many of the LTPP sites in Wyoming.

Climate Data

Climatic inputs were generated using the closest weather station to each project site, typically including 96 to 116 months of climate data.

Problems Encountered

The number of LTPP sites located in Wyoming for rigid, semi-rigid, and flexible pavements were insufficient for determining calibration coefficients of transfer functions.

Benefits to Calibration

It is noted that locally calibrated transfer functions can be used to optimize new and rehabilitated pavement design strategies to better forecast maintenance, repair, rehabilitation, and reconstruction costs.

4.0 Current MassDOT Pavement Design State-of-Practice

In addition to the literature review, the research team was tasked with determining what pavement design methods MassDOT currently utilizes in an effort to capture the current state-of-practice. This section provides a brief history and concise description of the design method currently being utilized.

AASHTO developed a pavement design method in the early 1960s that was based on the results of the extensive American Association of State Highway Officials (AASHO) Road Test conducted in Ottawa Illinois in the late 1950s and early 1960s. The foundation of this design method was empirical performance equations derived from the road test results. It is significant to note that the empirical performance equations were developed under a very specific climatic setting with a specific set of pavement materials and subgrade soils. Because of these site-specific conditions, this design method has fundamental shortcomings since factors like climate, pavement materials, and subgrade conditions are not global and vary from one region to another.

A research study entitled *Layered Pavement Design Method for Massachusetts* (*17*) was completed in the mid 1960's by members of academia and the Massachusetts Department of Public Works. The study adapted the AASHTO design method for use in Massachusetts by modifying the data and analyses from the AASHO Road Test experiments. This modified design method closely mirrors the guidance outlined in the *AASHTO Interim Guide For Design of Pavement Structures* (*18*) published in 1972 and revised in 1981. MassDOT currently uses the 1972 AASHTO guide for their pavement designs with a slight modification. For structural resurfacing on Interstate and other controlled access highways, MassDOT uses the *AASHTO Guide for Design of Pavement Structures* (*19*) published in 1993 for designs.

The current MassDOT pavement design methods are summarized in Chapter 9 of the Project Development and Design Guide (*20*). These methods, as stated above, generally utilize the guidance presented in the 1972 AASHTO guide (*18*). These methods have the same shortcomings and limitations of the original AASHTO pavement design method introduced in the 1960s. It is based on AASHO Road Tests from one specific site with a specific set of pavement structure/materials tested. It does not relate pavement response to pavement design as it is empirically based. The traffic data used is represented by a repetition of an 18 kip load value known as an equivalent single axle load (ESAL). The use of a single value to represent the overall traffic spectrum is questionable, if not inaccurate. Traffic volume changes by time, day, week, and season. Furthermore, the impact of high traffic volume during the day versus low traffic during the night on pavement responses is significantly different and not accounted for in this method. Additionally, the trucks used during the AASHO Road Test to develop this design method were modest in comparison to the trucks utilized currently. Overall, the models developed and modified from the AASHO Road Test relate key pavement properties and traffic to performance but do not consider the range of other effects (climate, etc.) that can also contribute to pavement distress.

In the new generation of pavement design, M-E design, materials responses (stresses, strains, and deflections) are measured under local traffic and climatic (moisture and temperature) conditions. Responses are then related to target performance using different pavement structural designs (different thickness per each layer). Thus, unlike MassDOT's current methodology, this pavement design method does relate pavement response to pavement design. Moreover, the AASHTO M-E pavement design procedure incorporates mechanistic principles (calculations of pavement stress, strain and deformation responses) using site-specific climatic, material, and traffic characteristics. This pavement design method replaces the currently utilized subjective-based parameters (performance index and the present serviceability index) with objective distress models for various modes of pavement failure. More significantly, the AASHTO M-E pavement design procedure allows calibration of the distress models to allow the design method to be applicable and adaptable to each site/region's unique conditions.

As it can be seen, the AASHTO M-E pavement design is a significant advancement from the method currently utilized by MassDOT. It will help MassDOT build more durable pavements since the local traffic spectrum, local climate, and site specific characteristic of the materials in each layers are utilized in the design. This type of efficiency will optimize designs and minimize the chances of under-designing or over-designing a pavement. Under-designing a pavement typically results in premature appearance of distress and reduced longevity. Over-designing a pavement results in increased life cycle cost of the pavement.

5.0 Mixture Selection & Initial Testing

In order to accelerate the future phases of this project (particularly Phase 3), initial testing of plant-produced mixtures was conducted in Phase 1.

5.1 Mixture Selection

Prior to the initiation of this study, mixtures being placed in Massachusetts were already being collected by the research team as part of a different MassDOT study relating to development of a Balanced Mixture Design protocol. These plant-produced mixtures represented a wide variety of mixtures being designed and placed in Massachusetts. The mixtures tested in this study were those most produced on regular basis (based on tonnage) and not developed for a specialized application. The mixtures shown in Table 5.1 were selected for initial testing in Phase 1.

Table 5.1: Mixtures Selected for Initial Testing in Phase 1

Mixture ID	Type	Gyration Level	Binder	Contractor
#14	12.5mm SSC/SIC	100	PG64S-28	Northeast Paving
#16	12.5mm SSC/SIC	75	PG64S-28	Palmer Paving Easthampton
#18	12.5mm SSC/SIC	100	PG64E-28	JH Lynch Millbury
#19	12.5mm SSC/SIC	75	PG64S-28	Aggregate Industries Saugus
#25	12.5mm SSC	100	PG64E-28	PJ Keating Lunenburg
#28	12.5mm SSC	75	PG64S-28	Warner Bros LLC
#35	19.0mm SIC	100	PG64S-28	AI Wrentham

Selection was first based on quantity of mixture received as the team needed to make sure there was sufficient material to complete the testing required for the Balanced Mixture Design project and this study. Next, only mixtures with companion asphalt binder samples were considered as the binder must be tested as well for M-E analysis. Next, mixtures were narrowed down by type, gyration level, and binder type. The final mixture selections shown in Table 5.1 represent the typical surface course (12.5mm SSC) and intermediate course (19.0 mm) mixtures utilized in Massachusetts. The typical gyration levels (100 and 75) are represented as well as the typical binder types (PG64S-28 & PG64E-28). These mixtures and the companion binder samples were tested as outlined in the following sections.

5.2 Mixture Dynamic Modulus |E*|

For Level 1 hierarchal M-E analysis, laboratory mixture testing data is required, specifically dynamic modulus (|E*|) of the mixture. Each plant-produced mixture was reheated, split and then compacted in the Superpave Gyratory Compactor (SGC) to fabricate a cylindrical specimen 180 mm tall by 150 mm in diameter. This process was repeated using different weights of mixture until the compacted specimens had an air void content between 8-9%. Four replicate specimens were fabricated at this air void content for each mixture. Next, a 100 mm core was taken out of the middle of each specimen. The ends of this core were then cut to yield a 150 mm tall specimen. The air void content of these cored specimens was then determined with the target being between 6-8%. Specimens outside this range were rejected and re-fabricated. Three of the four specimens for each mixture were allocated for dynamic modulus testing and the remaining specimen was utilized to tune the Asphalt Mixture Performance Tester (AMPT) for each specific mixture.

Mixture dynamic modulus testing was conducted in accordance with AASHTO T378 “Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)” using three test temperatures (4°C, 20°C and 40°C) and at multiple frequencies per temperature (0.1, 0.5, 1, 5, 10, & 25 Hz).

The dynamic modulus data for the three replicate specimens of each mixture was then entered into an analysis software package called FlexMat™, developed by North Carolina State University. A mixture master curve was created and utilized to calculate the dynamic modulus at five temperatures (14.0°C, 39.2°C, 68.0°C, 104.0°C, 129.2°C) and six frequencies (0.1, 0.5, 1, 5, 10, & 25 Hz). The temperatures correspond to -10°C, 4°C, 20°C, 40°C and 54°C. By utilizing the master curve, the dynamic modulus data at low and high temperature was obtained which could not be directly measured experimentally at -10°C and 54°C due to machine and specimen limitations.

5.3 Binder Testing

Also required for Level 1 M-E analysis was the properties of the asphalt binder used in the mixture fabrication. Specifically, the binder shear modulus (G*) and phase angle at multiple temperatures was required.

First, each binder was short-term aged in the Rolling Thin Film Oven (RTFO) in accordance with AASHTO T240 “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test).” Then the aged binder residue was then tested in the Dynamic Shear Rheometer (DSR) in accordance with AASHTO T315 “Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)” at typical temperatures of 52°C, 58°C, 64°C, 70°C and 76°C (125.6°F, 136.4°F, 147.2°F, 158.0°F, and 168.8°F).

5.4 As-Built Properties

Finally, in addition to the mixture and binder properties, the as-built properties of the mixture were required, including: total unit weight of the mixture (pcf), mixture effective binder content by volume (%), and mixture air voids (%). These parameters were calculated from the production data supplied by MassDOT for each mixture.

5.5 Level 1 Hierarchal Input Data for Initial Mixtures

The final M-E analysis input data for each mixture tested is presented in Tables 5.2 through 5.8. The format is that of the input cells of the AASHTOWare® Pavement M-E Design software. Thus, the data can be directly cut and paste into the software.

Table 5.2: M-E Analysis Input Data for Mix #14

Mix ID #:	14
Contractor:	Northeast Paving
Mix:	12.5mm SSC/SIC
Binder:	PG64S-28
MassDOT ID:	19-04-05-08-15-33

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	2163245	2519257	2664169	2982179	3111744	3276709
39.2	903122	1271959	1440472	1834111	1999804	2212337
68.0	187458	324809	405897	652449	783499	976581
104.0	28930	51545	66454	119852	153943	212854
129.2	12054	19713	24880	43991	56643	79301

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	13600	69.1
136.4	7150	70.4
147.2	3585	72.4
158.0	1825	74.7
168.8	-	-

General: Properties As-Built	
Total Unit Weight (pcf)	160.1
Effective Binder Content by Volume (%)	10.7
Air Voids (%)	3.5

Table 5.3: M-E Analysis Input Data for Mix #16

Mix ID #:	16
Contractor:	Palmer Paving Corp
Mix:	12.5mm SSC/SIC
Binder:	PG64S-28
MassDOT ID:	18-02-16-10-31-03

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	1989839	2359588	2504987	2813496	2935533	3088550
39.2	825195	1213562	1393989	1812797	1985323	2201648
68.0	182341	323201	408629	675050	819118	1032394
104.0	32990	56742	72701	131049	168982	235400
129.2	16017	23663	28949	48976	62494	87042

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	12233	73.4
136.4	5670	75.8
147.2	2710	78.3
158.0	1327	80.7
168.8	679	82.8

General: Properties As-Built	
Total Unit Weight (pcf)	158.1
Effective Binder Content by Volume (%)	9.4
Air Voids (%)	4.3

Table 5.4: M-E Analysis Input Data for Mix #18

Mix ID #:	18
Contractor:	JH Lynch
Mix:	12.5mm SSC/SIC
Binder:	PG64E-28
MassDOT ID:	17-03-08-13-56-46

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	1805527	2067164	2176136	2420927	2523069	2655339
39.2	860750	1125889	1244780	1523010	1641617	1795857
68.0	241566	372134	442656	640151	738639	879083
104.0	48631	80509	99733	162024	198309	256911
129.2	20539	33979	42275	70100	86962	115204

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	26500	60.8
136.4	13967	61.1
147.2	7563	61.5
158.0	4243	62.4
168.8	2440	63.9
179.6	1430	65.9

General: Properties As-Built	
Total Unit Weight (pcf)	152.1
Effective Binder Content by Volume (%)	11.8
Air Voids (%)	2.9

Table 5.5: M-E Analysis Input Data for Mix #19

Mix ID #:	19
Contractor:	Aggregate Industries Saugus
Mix:	12.5mm SSC/SIC
Binder:	PG64S-28
MassDOT ID:	17-02-17-09-02-27

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	1715899	2042705	2174240	2459248	2574204	2720093
39.2	694750	1012046	1161517	1516521	1666687	1858556
68.0	153204	265123	332170	540341	653399	822518
104.0	27266	46351	58902	103822	132539	182321
129.2	12698	18955	23172	38739	49027	67441

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	13733	71.3
136.4	6653	73.2
147.2	3200	75.4
158.0	1597	77.6
168.8	824	79.7

General: Properties As-Built	
Total Unit Weight (pcf)	158.1
Effective Binder Content by Volume (%)	12.2
Air Voids (%)	3.5

Table 5.6: M-E Analysis Input Data for Mix #25

Mix ID #:	25
Contractor:	PK Keating Lunenburg
Mix:	12.5mm SSC/SIC
Binder:	PG64E-28
MassDOT ID:	PJKL-12.5-SSC-100G-15%-E

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	1715250	1983512	2085627	2295771	2376602	2476433
39.2	673499	975367	1116820	1447285	1583258	1752276
68.0	145751	246947	307464	496418	600047	756451
104.0	30876	50941	63856	109103	137542	186326
129.2	16584	25066	30615	50474	63259	85713

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	14767	57.4
136.4	8233	55.9
147.2	4850	55.6
158.0	3013	55.5
168.8	1883	55.9
179.6	1200	56.8

General: Properties As-Built	
Total Unit Weight (pcf)	150.5
Effective Binder Content by Volume (%)	10.6
Air Voids (%)	4.2

Table 5.7: M-E Analysis Input Data for Mix #28

Mix ID #:	28
Contractor:	Warner Bros LLC
Mix:	12.5mm SSC
Binder:	PG64S-28
MassDOT ID:	WB-12.5-SSC-75G-15%-S

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	1986813	2242596	2342385	2556151	2642254	2751982
39.2	893759	1244488	1396507	1729190	1859997	2020530
68.0	181514	318279	400032	649389	780739	970773
104.0	30885	52492	66970	119747	153965	213747
129.2	15657	22958	27985	46945	59696	82781

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	13567	71.9
136.4	6327	74.1
147.2	3023	76.3
158.0	1493	78.6
168.8	758	80.8

General: Properties As-Built	
Total Unit Weight (pcf)	154.8
Effective Binder Content by Volume (%)	12.3
Air Voids (%)	2.5

Table 5.8: M-E Analysis Input Data for Mix #35

Mix ID #:	35
Contractor:	Aggregate Industries Wrentham
Mix:	19.0mm SIC
Binder:	PG64S-28
MassDOT ID:	-

	|E*| Dynamic Modulus (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14.0	1831281	2170217	2306190	2600111	2718387	2868225
39.2	769108	1110180	1268797	1641251	1797357	1995914
68.0	172011	297675	372537	602814	726510	909822
104.0	28952	49683	63341	112290	143604	197884
129.2	12763	19138	23449	39416	50001	68990

Binder Data		
Temperature (°F)	**G* (Pa)**	**Delta (°)**
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158.0	1803	76.8
168.8	928	79.0

General: Properties As-Built	
Total Unit Weight (pcf)	151.0
Effective Binder Content by Volume (%)	9.2
Air Voids (%)	4.0

6.0 Discussion

This report outlines the work conducted in phase one of a four phase larger research project aimed at implementing the AASHTO MEPDG in Massachusetts. The goal of this study was to conduct a thorough literature review to determine the overall state-of-practice with regards to AASHTO MEPDG implementation with focus on local verification and calibration. MassDOT's current pavement design methods were researched to capture the current state-of-practice and to compare and contrast with the AASHTO M-E design method. Finally, initial testing was conducted on typical plant-produced mixtures sampled from across Massachusetts in an attempt to accelerate future phases of this research. The results were input into the AASHTOWare® software to conduct trial designs.

The AASHTO M-E design method is a sophisticated tool used to design and predict the performance of pavements. It requires rigorous input data relating to traffic, climate and materials properties. This is contrary to MassDOT's current pavement design method which relies heavily on empirical relationships.

The literature review of published works by other state agencies that are implementing the AASHTO M-E design method indicated that it is critical to calibrate the distress models using local inputs and available performance data. This is critical because the distress prediction models included in the AASHTO M-E design method were calibrated using a national database which likely does not represent local climatic conditions, traffic, and materials. For example, the state of Oregon reported that its locally calibrated models for rutting, alligator cracking, and longitudinal cracking provided better predictions with lower bias and standard error than the nationally calibrated models. Virginia reported that the local calibration values offered improved pavement performance predictions in terms of rutting, bottom-up fatigue, and IRI. Specifically, Virginia reported the rutting model local calibration coefficients removed an overprediction from the global model, whereas the global model for bottom-up fatigue cracking underpredicted the actual performance. The bottom-up fatigue cracking model and IRI model local calibration coefficients removed the underprediction from the global model. Tennessee reported that without local calibration, the nationally-calibrated performance models in the AASHTO M-E design method were not applicable to the local conditions of Tennessee. Tennessee's calibrated distress models showed improved design reliability relative to the nationally calibrated models. Mississippi determined that the dispersion between the predicted and measured transverse cracks in flexible pavements was large. The local calibration of the thermal cracking distress function decreased significantly the difference between the predicted and measured transverse cracking. Based on these, and many other agencies experiences, local calibration is a critical and significant step towards implementing the AASHTO MEPDG in Massachusetts. Local calibration will remove any underprediction and/or overprediction from the globally calibrated distresses models.

Finally, in an effort to accelerate future phases of this research, the research team started generating data for the database needed to conduct the local calibration. Seven plant-produced mixtures were sampled and tested. These mixtures represent the most produced (based on tonnage) surface and intermediate course mixtures placed in Massachusetts. From the testing, the necessary Level 1 hierarchal inputs for the asphalt layers were determined. The results were input into the AASHTOWare® Pavement M-E to perform trial designs. The outputs from the software for these designs are presented in Appendix A.

7.0 References

1. National Center for Asphalt Technology (NCAT), *"How Accurate Are Designs Using the New Pavement ME Program?"* In Asphalt Technology News, National Center for Asphalt Technology (NCAT), Auburn AL, Volume 26, Number 1, Spring 2014.

2. Robbins, M., C. Rodezno, N. Tran, and D. Timm. *Pavement ME Design – A Summary of Local Calibration Efforts for Flexible Pavements*. National Center for Asphalt Technology (NCAT), NCAT Report 17-07, August 2017.

3. American Association of State Highway and Transportation Officials (AASHTO). *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide*. AASHTO, Washington D.C., 2010.

4. American Association of State Highway and Transportation Officials (AASHTO). *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice*, AASHTO Washington D.C., 3rd Edition, 2020.

5. Pierce, L. M. and G. McGovern. *NCHRP Synthesis Report 457: Implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide and Software*. TRB, National Research Council, Washington, D.C., 2014, pp. 81.

6. Darter, M. I., L. Titus-Glover, H. Von Quintus, B.B. Bhattacharya, and J. Mallela. *Calibration and Implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide for Arizona*. SPR-606, Arizona Department of Transportation, 2014.

7. Mallela, J., L. Titus-Glover, S. Sadasivam, B. Bhattacharya, M. Darter, and H. Von Quintus. *Implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide for Colorado*. Report CDOT-2013-4, Colorado Department of Transportation, 2013.

8. Wu, Z. and X. Yang. *Evaluation of Current Louisiana Flexible Pavement Structures Using PMS Data and New Mechanistic-Empirical Pavement Design Guide*. Report FHWA/LA.11/482, Louisiana Department of Transportation and Development, 2012.

9. Haider, S. W., N. Buch, W. Brink, K. Chatti, and G. Baladi. *Preparation for Implementation of the Mechanistic-Empirical Pavement Design Guide in Michigan Part 3: Local Calibration and Validation of the Pavement-ME Performance Models.* Report RC-1595, Michigan State University, 2014.

10. Mallela, J., L. Titus-Glover, V.L Von Quintus, M. Darter, M. Stanley, C. Rao. *Implementing the AASHTO Mechanistic Empirical Pavement Design Guide in Missouri, Volume I: Study Findings, Conclusions, and Recommendations, and Volume II: MEPDG Model Validation and Calibration,* Report No. CM08.01 for Project RI04-002, Pavement Section Investigation Report, 2009.

11. Titus-Glover, L., C. Rao, and S. Sadasivam. *Local Calibration of the Pavement ME for Missouri.* Report cmr 20-007, Missouri Department of Transportation, 2020.

12. Nabhan, P.. *Calibration of the AASHTO MEPDG for Flexible Pavements to Fit Nevada's Conditions.* University of Nevada, Reno, 2015.

13. Gassman, S. L. and M .M. Rahman. *Calibration of the AASHTO Pavement Design Guide to South Carolina Conditions – Phase 1.* Report FHWA-SC-16-02, South Carolina Department of Transportation, 2016.

14. Darter, M.I., L. Titus-Glover, and H. L. Von Quintus. *Implementation of the Mechanistic-Empirical Pavement Design Guide in Utah: Validation, Calibration, and Development of the UDOT MEPDG User's Guide.* Report UT-09.11, Utah Department of Transportation, 2009.

15. Smith, B. and H. Nair. *Development of the Local Calibration Factors and Design Criteria Values for Mechanistic-Empirical Pavement Design.* Report FHWA/VCTIR 16-R1, Virginia Department of Transportation, 2015.

16. Bhattacharya, B.B., H. L. Von Quintus, and M. I. Darter. *Implementation and Local Calibration of the MEPDG Transfer Functions in Wyoming.* Report FHWA 16/02F, Wyoming Department of Transportation, 2015.

17. Tons, E., R. Chambers and M. Kamin. *Layered Pavement Design Method for Massachusetts.* Presented at the Transportation Research Board (TRB) 44th Annual Meeting, 1965. http://onlinepubs.trb.org/Onlinepubs/hrr/1965/71/71-010.pdf Last Accessed April 2021.

18. American Association of State Highway and Transportation Officials (AASHTO). *AASHTO Interim Guide For Design Of Pavement Structures*, AASHTO Washington D.C., 1972 & Revised 1981.

19. American Association of State Highway and Transportation Officials (AASHTO). *AASHTO Guide for Design of Pavement Structures*, AASHTO Washington D.C., 1993.

20. Massachusetts Highway Department. *Project Development & Design Guide*. 2006 Edition.

Appendix A: AASHTOWare® Pavement M-E Software Outputs for Trial Design

14 Northeast Paving 12.5mm SSC

File Name: S:\HSRC Restricted\Active Project Folders\MassDOT Mechanistic Emprical (ME) Phase 1 (2020)\AASHTOWare Output\14 Northeast Paving 12.5mm SSC.dgpx

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: May, 2022
Pavement construction: June, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42, -71.25

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	Default asphalt concrete	4.0
Flexible	Default asphalt concrete	10.0
Sandwich/Fractured	Sandwich Granular	10.0
NonStabilized	Crushed stone	10.0
Subgrade	A-3	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	10.7
Air voids (%)	7.0

Traffic

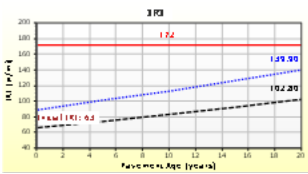
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	4,000
2033 (10 years)	7,876,620
2043 (20 years)	17,835,200

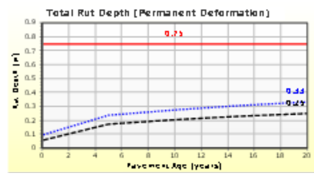
Design Outputs

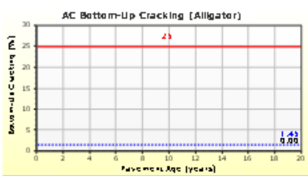
Distress Prediction Summary

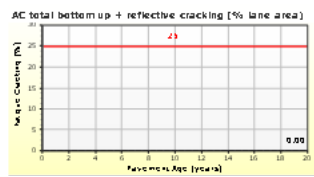
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	139.88	90.00	99.16	Pass
Permanent deformation - total pavement (in)	0.75	0.33	90.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	25.00	1.45	90.00	100.00	Pass
AC total fatigue cracking: bottom up + reflective (% lane area)	25.00	0.00	90.00	0.00	Pass
AC thermal cracking (ft/mile)	1000.00	216.32	90.00	100.00	Pass
AC top-down fatigue cracking (% lane area)	25.00	13.57	90.00	99.94	Pass
Permanent deformation - AC only (in)	0.25	0.20	90.00	98.61	Pass

Distress Charts





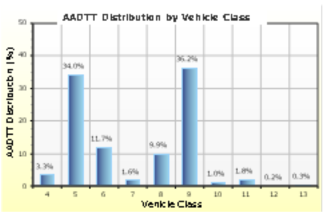


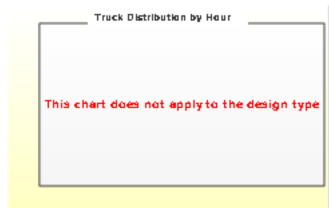


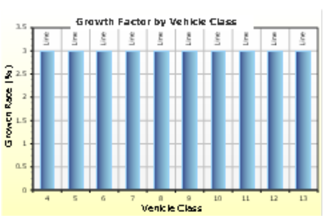
Traffic Inputs

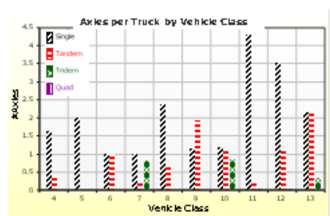
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	4,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	60.0

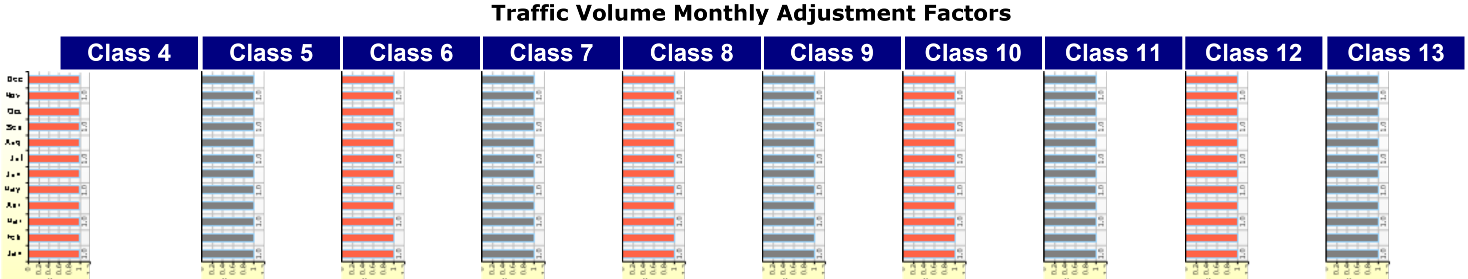








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	3.3%	3%	Linear
Class 5	34%	3%	Linear
Class 6	11.7%	3%	Linear
Class 7	1.6%	3%	Linear
Class 8	9.9%	3%	Linear
Class 9	36.2%	3%	Linear
Class 10	1%	3%	Linear
Class 11	1.8%	3%	Linear
Class 12	0.2%	3%	Linear
Class 13	0.3%	3%	Linear

Truck Distribution by Hour does not apply

Axle Configuration

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

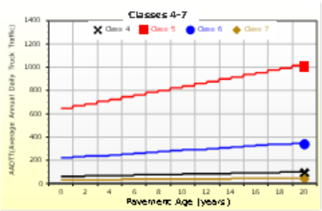
Wheelbase does not apply

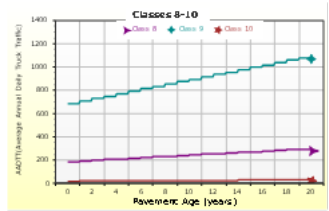
Number of Axles per Truck

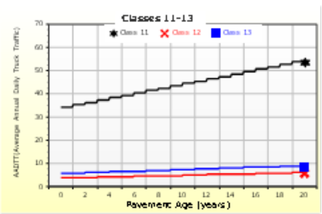
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

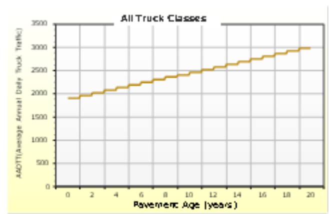
AADTT (Average Annual Daily Truck Traffic) Growth

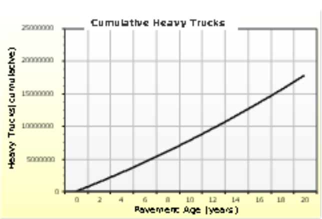
*** Traffic cap is not enforced**







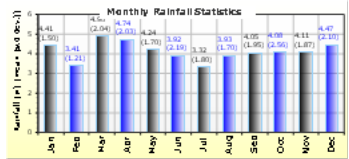




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
US, MA	42.00000 -71.25000 148

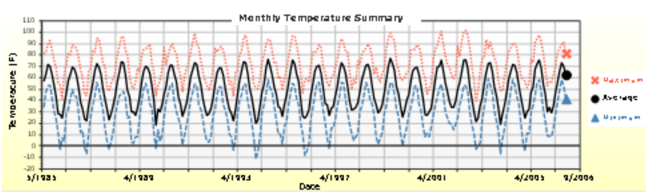


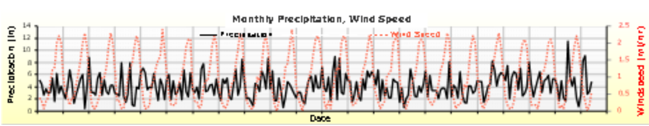
Annual Statistics:

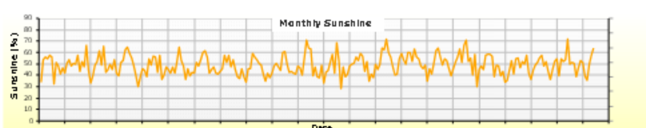
Mean annual air temperature (ºF)	49.50
Mean annual precipitation (in)	49.60
Freezing index (ºF - days)	528.51
Average annual number of freeze/thaw cycles:	85.91

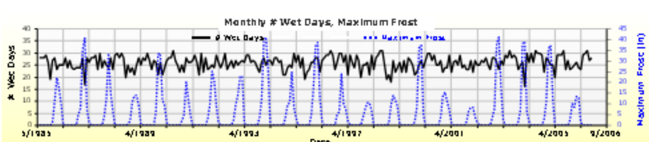
Water table depth (ft) 10.00

Monthly Climate Summary:



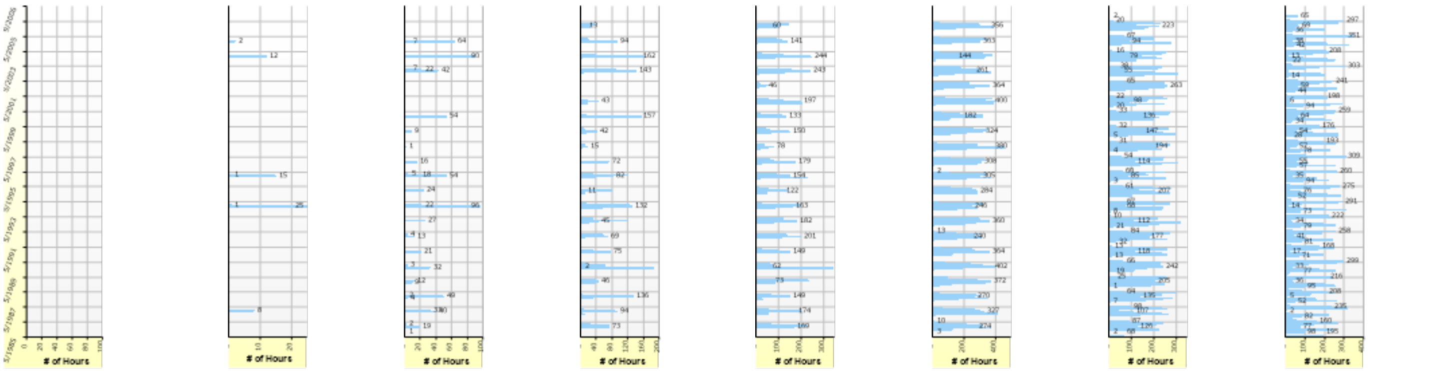




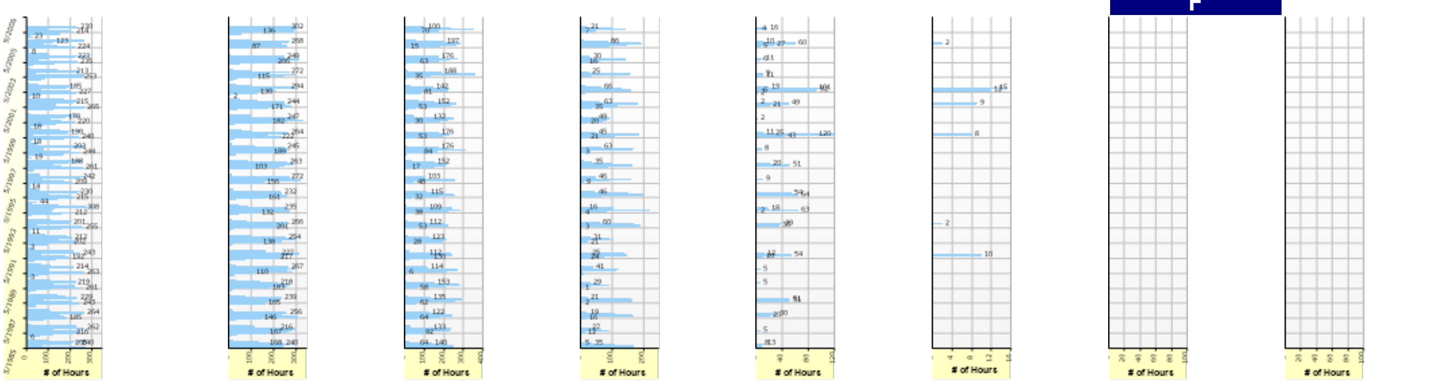


Hourly Air Temperature Distribution by Month:

< -13º F	-13º F to -4º F	-4º F to 5º F	5º F to 14º F	14º F to 23º F	23º F to 32º F	32º F to 41º F	41º F to 50º F



50º F to 59º F	59º F to 68º F	68º F to 77º F	77º F to 86º F	86º F to 95º F	95º F to 104º F	104º F to 113º F	> 113º F



Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

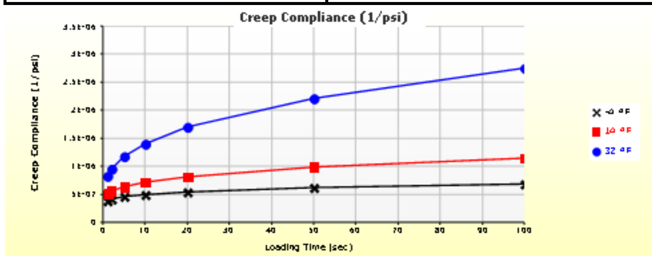
Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

Layer Name	Layer Type	Interface Friction
Layer 1 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 2 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 3 Sandwich/Fractured : Sandwich Granular	Sandwiched Granular (3)	1.00
Layer 4 Non-stabilized Base : Crushed stone	Non-stabilized Base (4)	1.00
Layer 5 Subgrade : A-3	Subgrade (5)	-

Thermal Cracking

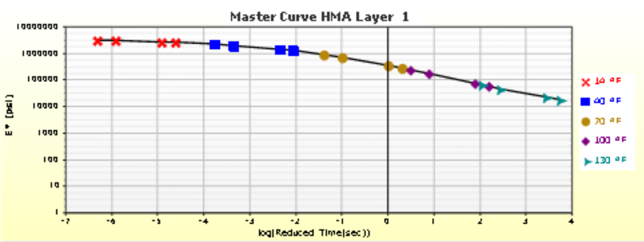
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	17.7

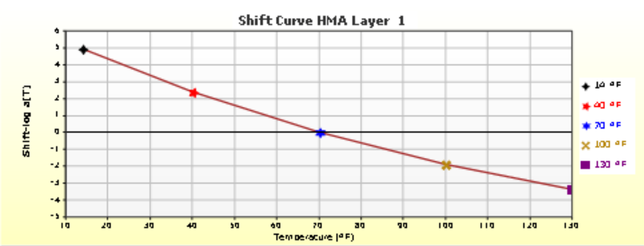
Indirect Tensile Strength (Input Level: 3)	
Test Temperature (ºF)	Indirect Tensilte Strength (psi)
14.0	458.78

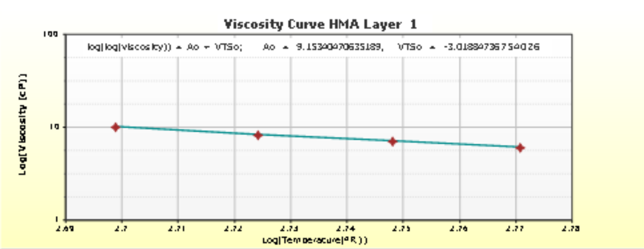


Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	-4 ºF	14 ºF	32 ºF
1	3.84e-007	5.16e-007	8.32e-007
2	4.19e-007	5.67e-007	9.60e-007
5	4.66e-007	6.51e-007	1.18e-006
10	5.02e-007	7.29e-007	1.41e-006
20	5.47e-007	8.25e-007	1.70e-006
50	6.23e-007	9.93e-007	2.23e-006
100	6.93e-007	1.16e-006	2.77e-006

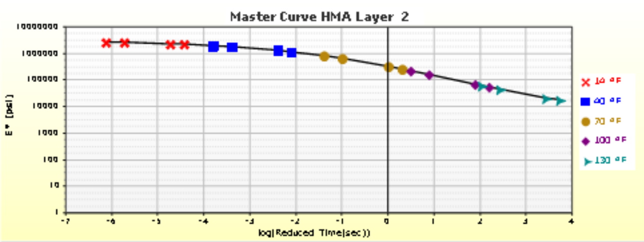
HMA Layer 1: Layer 1 Flexible : Default asphalt concrete

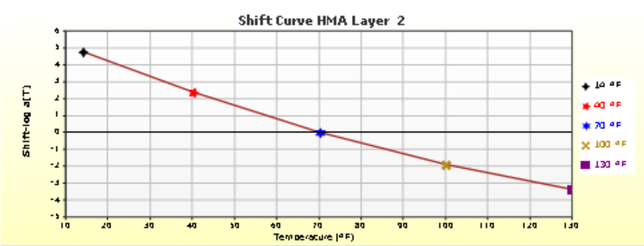


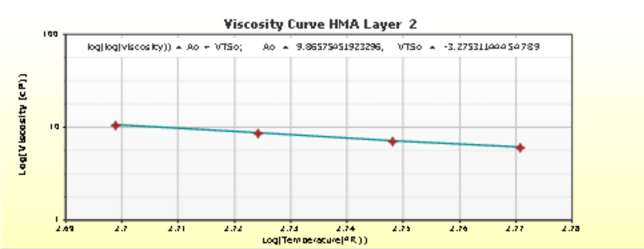




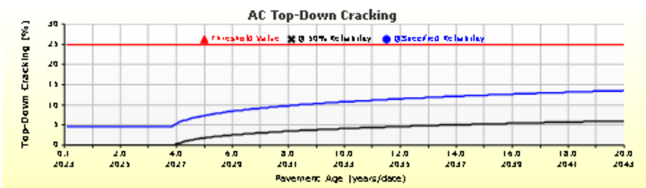
HMA Layer 2: Layer 2 Flexible : Default asphalt concrete

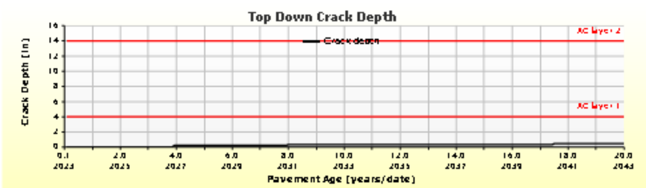


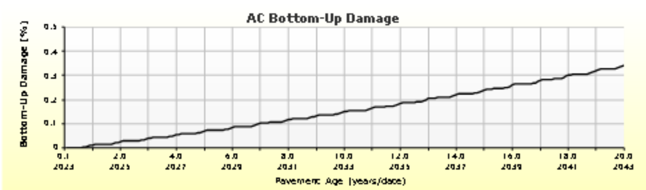


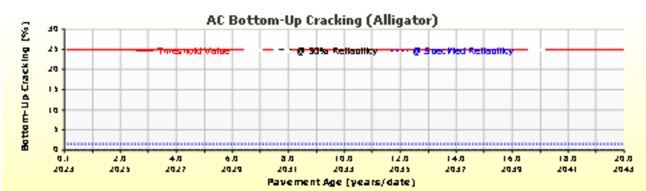


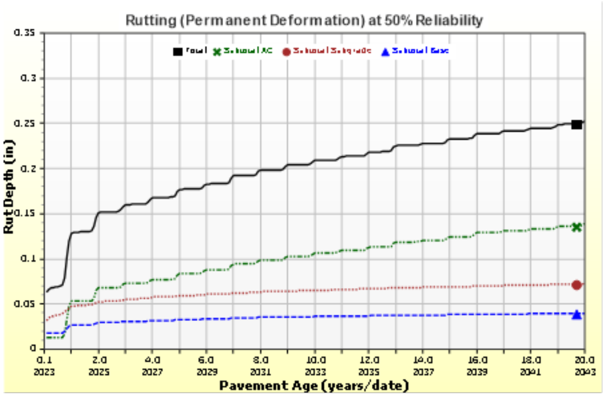
Analysis Output Charts

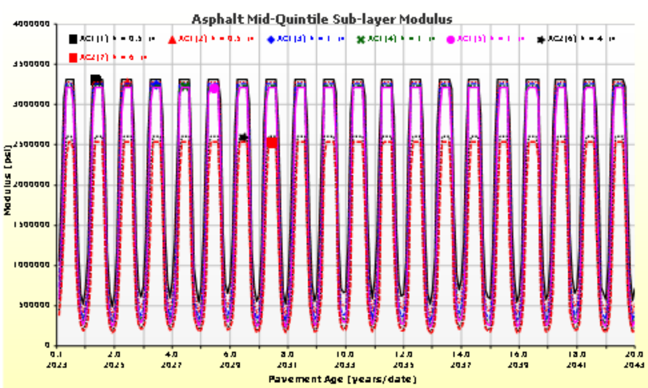

AC Top-Down Cracking
Top-Down Cracking (%)
Pavement Age (years/date)

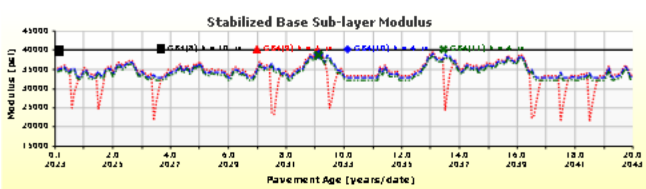

Top Down Crack Depth
Crack Depth (in)
Pavement Age (years/date)

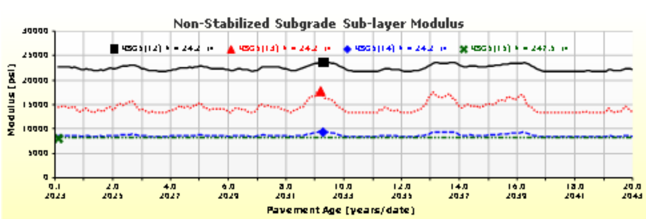

AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)


AC Bottom-Up Cracking (Alligator)
Bottom-Up Cracking (%)
Pavement Age (years/date)


Rutting (Permanent Deformation) at 50% Reliability
Rut Depth (in)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Pavement Age (years/date)
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Stabilized Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	4.0	
Unit weight (pcf)	160.1	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	28 Hz
14	2163245	2519257	2664169	2982179	3111744	3276709
40	903122	1271959	1440472	1834111	1999804	2212337
70	187458	324809	405897	652449	783499	976581
100	28930	51545	66454	119852	153943	212854
130	12054	19713	24880	43991	56643	79301

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	13600	69.1
136.4	7150	70.4
147.2	3585	72.4
158	1825	74.7

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	10.7
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.24
Aggregate parameter	0.4021

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	10.0	
Unit weight (pcf)	151.0	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1831281	2170217	2306190	2600111	2718387	2868225
40	769108	1110180	1268797	1641251	1797357	1995914
70	172011	297675	372537	602814	726510	909822
100	28952	49683	63341	112290	143604	197884
130	12763	19138	23449	39416	50001	68990

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158	1803	76.8
168.8	928	79

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Sandwich/Fractured : Sandwich Granular

Sandwiched Granular	
Layer thickness (in)	10
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	40000

Thermal	
Heat capacity (BTU/lb-ºF)	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	Sandwich Granular
Description of object	Default
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : Crushed stone

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
30000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Crushed stone
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Water Content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#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
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 5 Subgrade : A-3

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	A-3
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	11.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	120
Saturated hydraulic conductivity (ft/hr)	False	3.777e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	7.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	4.7572
bf	2.8814
cf	0.8694
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	5.2
#100	
#80	33.0
#60	
#50	
#40	76.8
#30	
#20	
#16	
#10	93.4
#8	
#4	95.3
3/8-in.	96.6
1/2-in.	97.1
3/4-in.	98.0
1-in.	98.6
1 1/2-in.	99.2
2-in.	99.7
2 1/2-in.	
3-in.	
3 1/2-in.	99.9

Calibration Coefficients

$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$	k1: 3.75
	k2: 2.87
$C = 10^M$	k3: 1.46
	Bf1: 0.001032
$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$	Bf2: 1.38
	Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_a^2 + 2.4868 * H_a - 17.342$$

$$C_2 = 0.0172 * H_a^2 - 1.7331 * H_a + 27.428$$

Where:

$H_{ac} = total\ AC\ thickness(in)$

$\varepsilon_p = plastic\ strain(in/in)$

$\varepsilon_r = resilient\ strain(in/in)$

$T = layer\ temperature(°F)$

$N = number\ of\ load\ repetitions$

acRuttingStandardDeviation	0.24 * Pow(RUT,0.8026) + 0.001	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36

Thermal Fracture

$$C_f = \beta_{t1} N \left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 1 Standard Deviation: 0.14 * THERMAL + 168
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

$N_f = number\ of\ repetitions\ to\ fatigue\ cracking$

$\sigma_s = Tensile\ stress(psi)$

$M_r = modulus\ of\ rupture(psi)$

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

k1: 0.965	Bs1: 1	k1: 0.965	Bs1: 1
Standard Deviation (BASERUT) 0.1477 * Pow(BASERUT,0.6711) + 0.001		Standard Deviation (BASERUT) 0.1235 * Pow(SUBRUT,0.5012) + 0.001	

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0/2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

c1: 2.5219	c2: 0.8069	c3: 1
kL1: 64271618	kL2: 0.2855	kL3: 0.011
kL4: 0.01488	kL5: 3.266	

0.3657 * TOP + 3.6563

$$FC = \left(\frac{6000}{1 + e^{(C_1 * C_1' + C_2 * C_2' \log_{10}(D * 100))}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 1.31	c2: 3.9666	c3: 6000

1.13 + 13/(1+exp(7.57-15.5*LOG10(BOTTOM+0.0001)))

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1: 0	C2: 75	C3: 2	C4: 2

csmCrackingStandardDeviation

CTB*1

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 40	C2: 0.4	C3: 0.008	C4: 0.015

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: May, 2022
Pavement construction: June, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42, -71.25

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	Default asphalt concrete	4.0
Flexible	Default asphalt concrete	10.0
Sandwich/Fractured	Sandwich Granular	10.0
NonStabilized	Crushed stone	10.0
Subgrade	A-3	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	9.4
Air voids (%)	7.0

Traffic

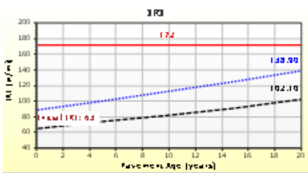
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	4,000
2033 (10 years)	7,876,620
2043 (20 years)	17,835,200

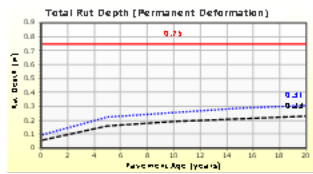
Design Outputs

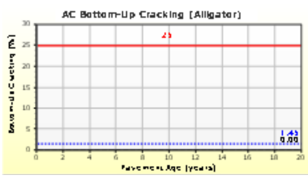
Distress Prediction Summary

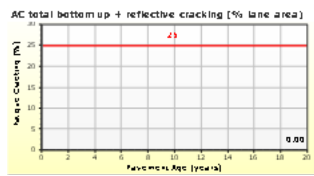
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	138.94	90.00	99.25	Pass
Permanent deformation - total pavement (in)	0.75	0.31	90.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	25.00	1.45	90.00	100.00	Pass
AC total fatigue cracking: bottom up + reflective (% lane area)	25.00	0.00	90.00	0.00	Pass
AC thermal cracking (ft/mile)	1000.00	216.30	90.00	100.00	Pass
AC top-down fatigue cracking (% lane area)	25.00	13.56	90.00	99.94	Pass
Permanent deformation - AC only (in)	0.25	0.18	90.00	99.77	Pass

Distress Charts





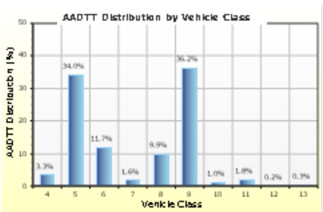


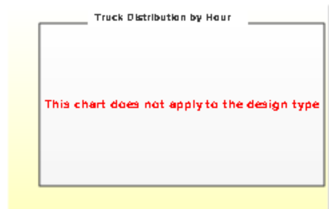


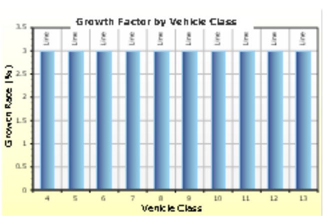
Traffic Inputs

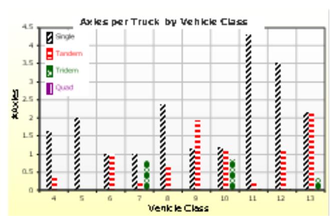
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	4,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	60.0

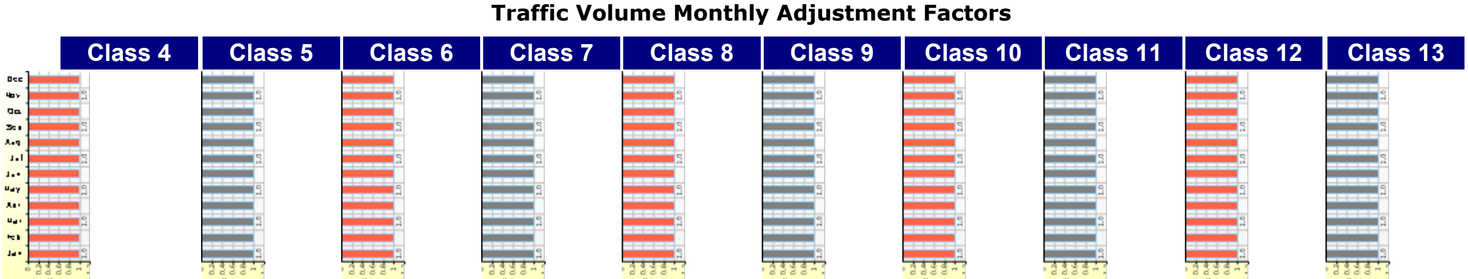








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	3.3%	3%	Linear
Class 5	34%	3%	Linear
Class 6	11.7%	3%	Linear
Class 7	1.6%	3%	Linear
Class 8	9.9%	3%	Linear
Class 9	36.2%	3%	Linear
Class 10	1%	3%	Linear
Class 11	1.8%	3%	Linear
Class 12	0.2%	3%	Linear
Class 13	0.3%	3%	Linear

Truck Distribution by Hour does not apply

Axle Configuration

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

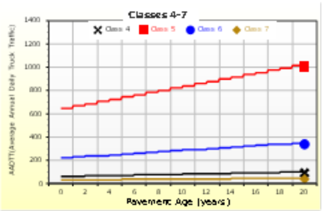
Wheelbase does not apply

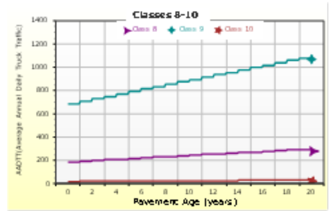
Number of Axles per Truck

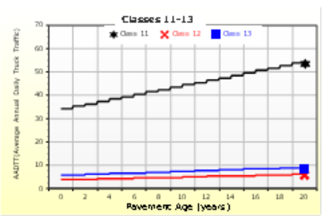
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

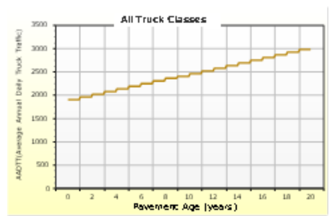
AADTT (Average Annual Daily Truck Traffic) Growth

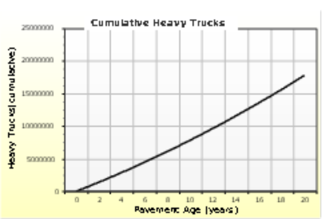
*** Traffic cap is not enforced**







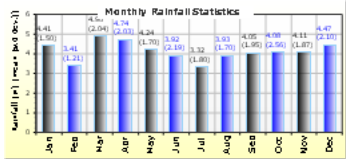




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
US, MA	42.00000 -71.25000 148

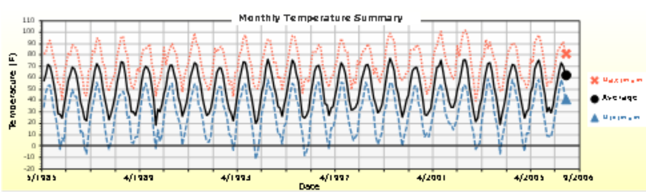


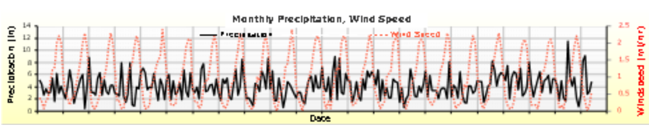
Annual Statistics:

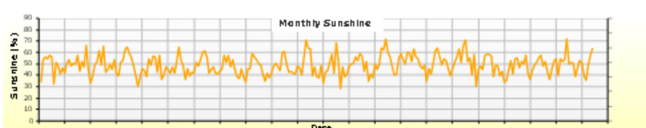
Mean annual air temperature (ºF)	49.50
Mean annual precipitation (in)	49.60
Freezing index (ºF - days)	528.51
Average annual number of freeze/thaw cycles:	85.91

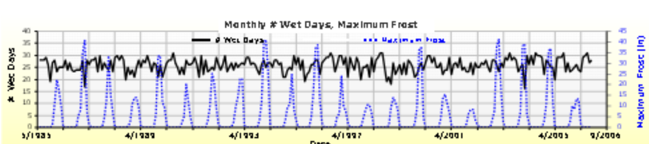
Water table depth (ft) 10.00

Monthly Climate Summary:



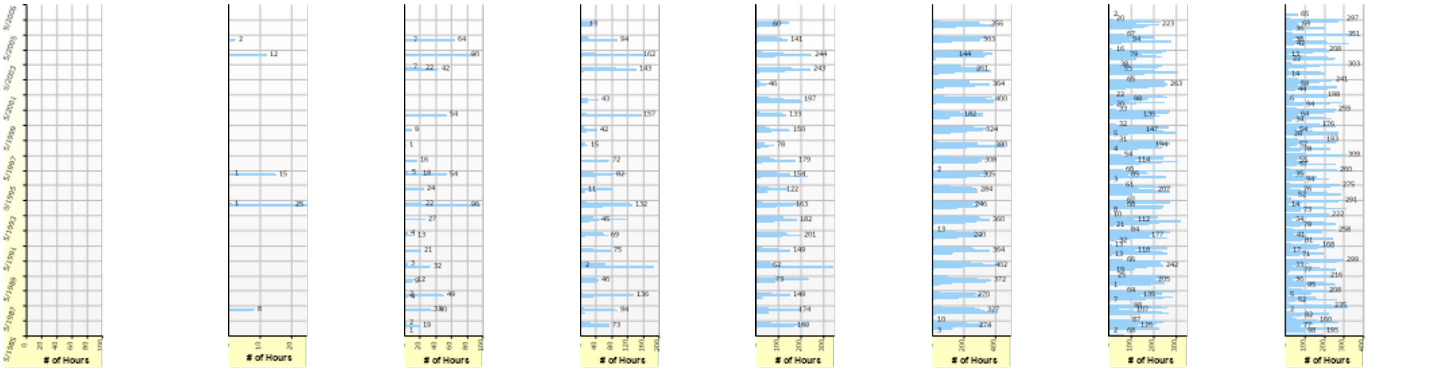




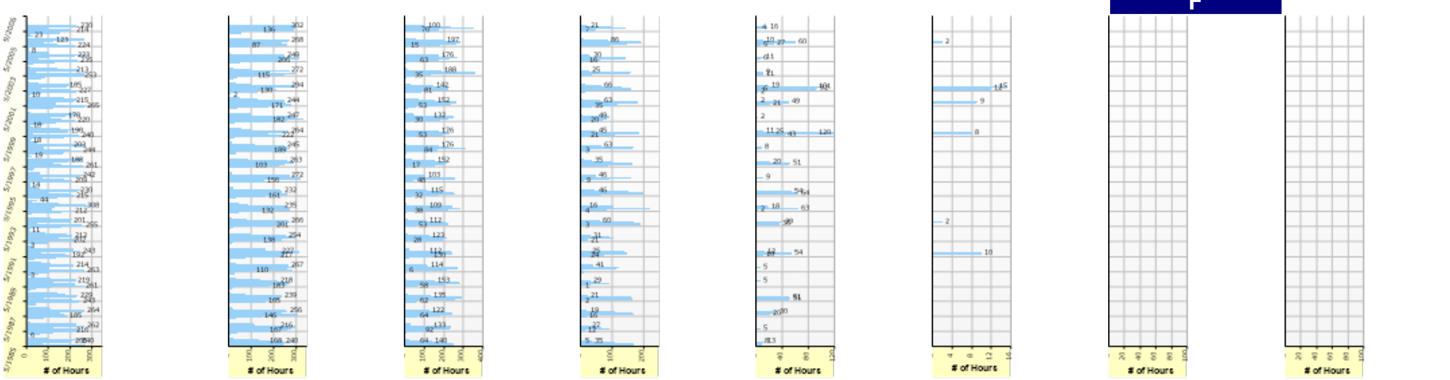


Hourly Air Temperature Distribution by Month:

< -13º F	-13º F to -4º F	-4º F to 5º F	5º F to 14º F	14º F to 23º F	23º F to 32º F	32º F to 41º F	41º F to 50º F



50º F to 59º F	59º F to 68º F	68º F to 77º F	77º F to 86º F	86º F to 95º F	95º F to 104º F	104º F to 113º F	> 113º F



Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

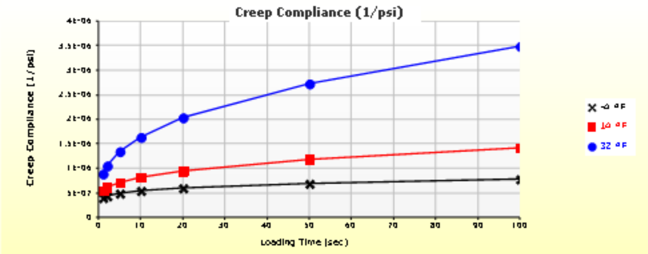
Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

Layer Name	Layer Type	Interface Friction
Layer 1 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 2 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 3 Sandwich/Fractured : Sandwich Granular	Sandwiched Granular (3)	1.00
Layer 4 Non-stabilized Base : Crushed stone	Non-stabilized Base (4)	1.00
Layer 5 Subgrade : A-3	Subgrade (5)	-

Thermal Cracking

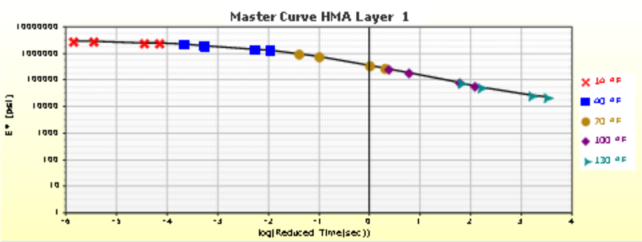
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	16.4

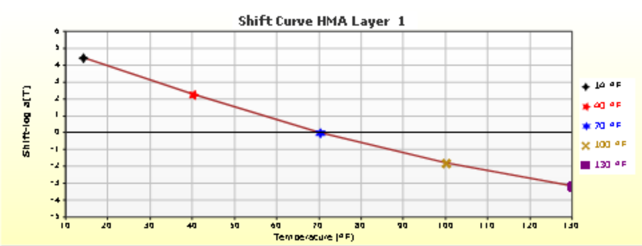
Indirect Tensile Strength (Input Level: 3)	
Test Temperature (ºF)	**Indirect Tensilte Strength (psi)**
14.0	539.81

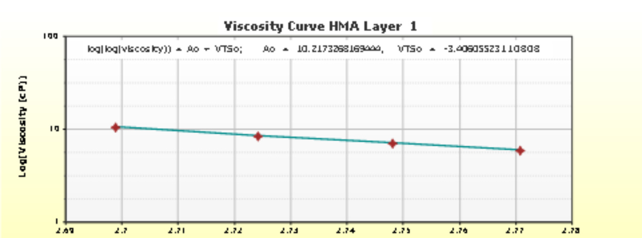


Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	**-4 ºF**	**14 ºF**	**32 ºF**
1	4.15e-007	5.56e-007	9.09e-007
2	4.49e-007	6.19e-007	1.07e-006
5	4.98e-007	7.24e-007	1.36e-006
10	5.46e-007	8.26e-007	1.65e-006
20	6.06e-007	9.58e-007	2.04e-006
50	7.04e-007	1.19e-006	2.74e-006
100	7.98e-007	1.44e-006	3.50e-006

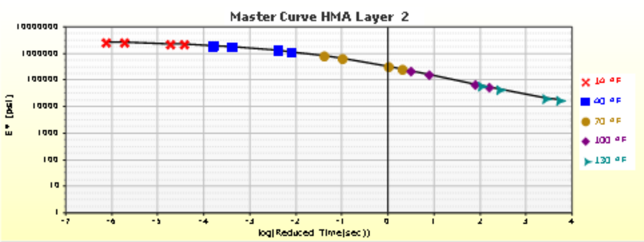
HMA Layer 1: Layer 1 Flexible : Default asphalt concrete

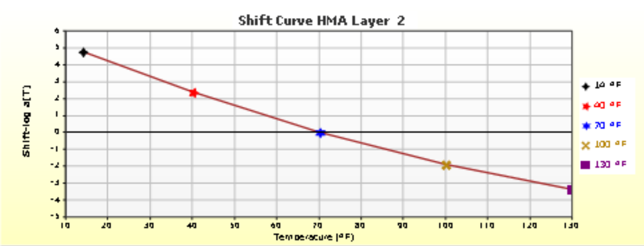


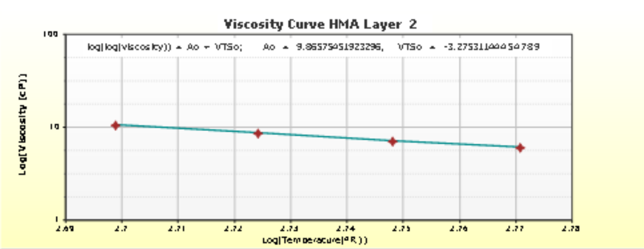




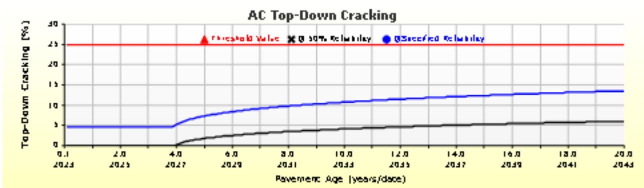
HMA Layer 2: Layer 2 Flexible : Default asphalt concrete

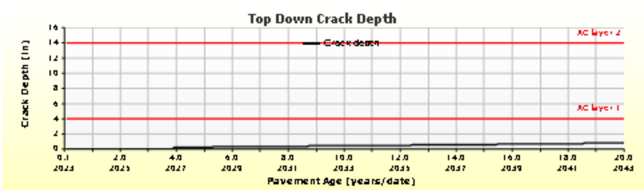


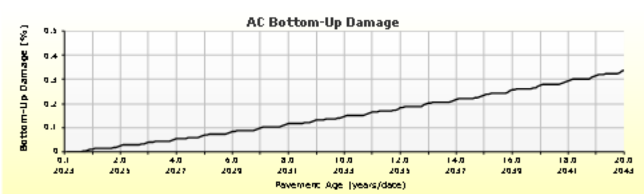


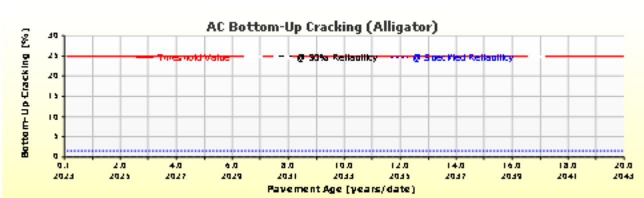


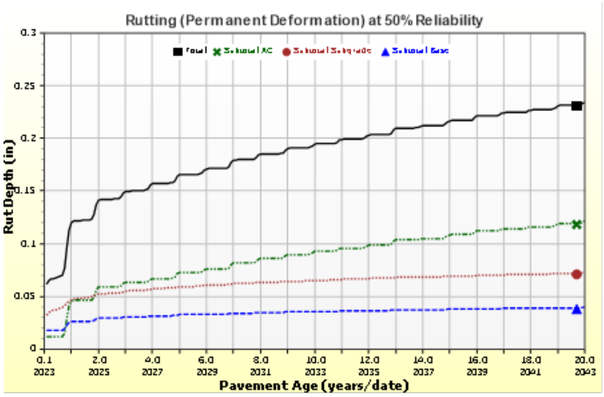
Analysis Output Charts

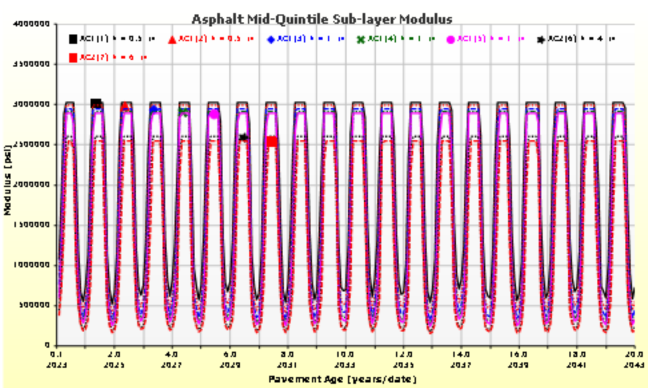

AC Top-Down Cracking
Top-Down Cracking (%)
Pavement Age (years/date)

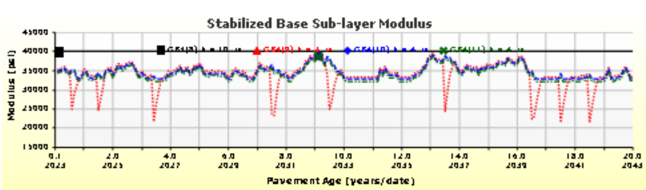

Top Down Crack Depth
Crack Depth (in)
Pavement Age (years/date)

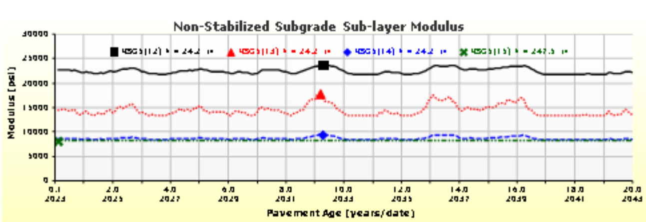

AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)


AC Bottom-Up Cracking (Alligator)
Bottom-Up Cracking (%)
Threshold Value
@ 50% Reliability
@ Specified Reliability
Pavement Age (years/date)


Rutting (Permanent Deformation) at 50% Reliability
Rut Depth (in)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Stabilized Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	4.0	
Unit weight (pcf)	158.1	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1989839	2359588	2504987	2813496	2935533	3088550
40	825195	1213562	1393989	1812797	1985323	2201648
70	182341	323201	408629	675050	819118	1032394
100	32990	56742	72701	131049	168982	235400
130	16017	23663	28949	48976	62494	87042

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	12233	73.4
136.4	5670	75.8
147.2	2710	78.3
158	1327	80.7
168.8	679	82.8

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.4
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	4.79
Aggregate parameter	0.4021

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	10.0	
Unit weight (pcf)	151.0	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1831281	2170217	2306190	2600111	2718387	2868225
40	769108	1110180	1268797	1641251	1797357	1995914
70	172011	297675	372537	602814	726510	909822
100	28952	49683	63341	112290	143604	197884
130	12763	19138	23449	39416	50001	68990

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158	1803	76.8
168.8	928	79

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Sandwich/Fractured : Sandwich Granular

Sandwiched Granular	
Layer thickness (in)	10
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	40000

Thermal	
Heat capacity (BTU/lb-ºF)	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	Sandwich Granular
Description of object	Default
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : Crushed stone

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
30000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Crushed stone
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Water Content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#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
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 5 Subgrade : A-3

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	A-3
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	11.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	120
Saturated hydraulic conductivity (ft/hr)	False	3.777e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	7.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	4.7572
bf	2.8814
cf	0.8694
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	5.2
#100	
#80	33.0
#60	
#50	
#40	76.8
#30	
#20	
#16	
#10	93.4
#8	
#4	95.3
3/8-in.	96.6
1/2-in.	97.1
3/4-in.	98.0
1-in.	98.6
1 1/2-in.	99.2
2-in.	99.7
2 1/2-in.	
3-in.	
3 1/2-in.	99.9

Calibration Coefficients

$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$	k1: 3.75
	k2: 2.87
$C = 10^M$	k3: 1.46
	Bf1: 0.001032
$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$	Bf2: 1.38
	Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_\alpha^2 + 2.4868 * H_\alpha - 17.342$$

$$C_2 = 0.0172 * H_\alpha^2 - 1.7331 * H_\alpha + 27.428$$

Where:

$H_{ac} = total\ AC\ thickness(in)$

$\varepsilon_p = plastic\ strain(in/in)$

$\varepsilon_r = resilient\ strain(in/in)$

$T = layer\ temperature(°F)$

$N = number\ of\ load\ repetitions$

acRuttingStandardDeviation	0.24 * Pow(RUT,0.8026) + 0.001	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36

Thermal Fracture

$$C_f = \beta_{t1} N\left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 1 Standard Deviation: 0.14 * THERMAL + 168
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

$N_f = number\ of\ repetitions\ to\ fatigue\ cracking$

$\sigma_s = Tensile\ stress(psi)$

$M_r = modulus\ of\ rupture(psi)$

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

k1: 0.965	Bs1: 1	k1: 0.965	Bs1: 1
Standard Deviation (BASERUT) 0.1477 * Pow(BASERUT,0.6711) + 0.001		Standard Deviation (BASERUT) 0.1235 * Pow(SUBRUT,0.5012) + 0.001	

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0/2A_0) + (k_{L3} \times \text{HT}) + (k_{L4} \times \text{LT}) + (k_{L5} \times \log_{10}\text{AADTT})}}$$

c1: 2.5219	c2: 0.8069	c3: 1
kL1: 64271618	kL2: 0.2855	kL3: 0.011
kL4: 0.01488	kL5: 3.266	
0.3657 * TOP + 3.6563		

$$FC = \left(\frac{6000}{1 + e^{\left(C_1 * C_1' + C_2 * C_2' \log_{10}(D*100)\right)}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 1.31	c2: 3.9666	c3: 6000
1.13 + 13/(1+exp(7.57-15.5*LOG10(BOTTOM+0.0001)))		

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1: 0	C2: 75	C3: 2	C4: 2
csmCrackingStandardDeviation			
CTB*1			

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 40	C2: 0.4	C3: 0.008	C4: 0.015

18 JH Lynch Millbury 12.5mm SSC

File Name: S:\HSRC Restricted\Active Project Folders\MassDOT Mechanistic Emprical (ME) Phase 1 (2020)\AASHTOWare Output\18 JH Lynch Millbury 12.5mm SSC.dgpx

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: May, 2022
Pavement construction: June, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42, -71.25

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	Default asphalt concrete	4.0
Flexible	Default asphalt concrete	10.0
Sandwich/Fractured	Sandwich Granular	10.0
NonStabilized	Crushed stone	10.0
Subgrade	A-3	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	11.8
Air voids (%)	7.0

Traffic

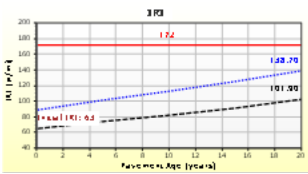
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	4,000
2033 (10 years)	7,876,620
2043 (20 years)	17,835,200

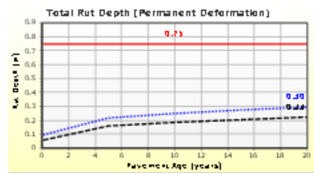
Design Outputs

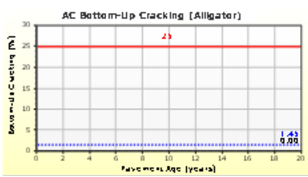
Distress Prediction Summary

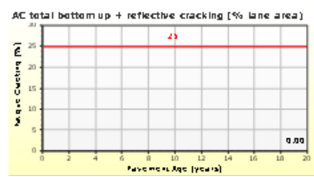
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	138.66	90.00	99.27	Pass
Permanent deformation - total pavement (in)	0.75	0.30	90.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	25.00	1.45	90.00	100.00	Pass
AC total fatigue cracking: bottom up + reflective (% lane area)	25.00	0.00	90.00	0.00	Pass
AC thermal cracking (ft/mile)	1000.00	216.49	90.00	100.00	Pass
AC top-down fatigue cracking (% lane area)	25.00	14.11	90.00	99.90	Pass
Permanent deformation - AC only (in)	0.25	0.17	90.00	99.94	Pass

Distress Charts







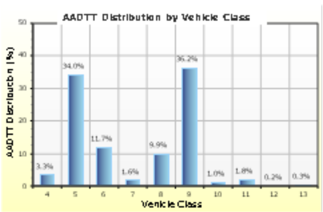


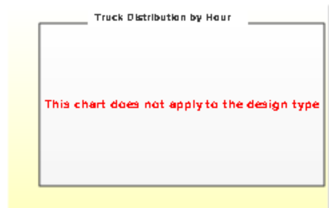
Threshold Value ····· @ Specified Reliability - - - @ 50% Reliability

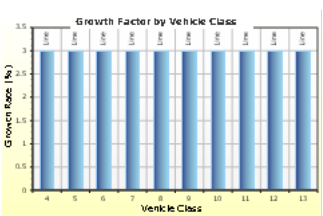
Traffic Inputs

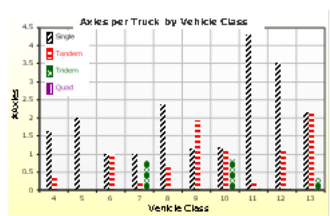
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	4,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	60.0

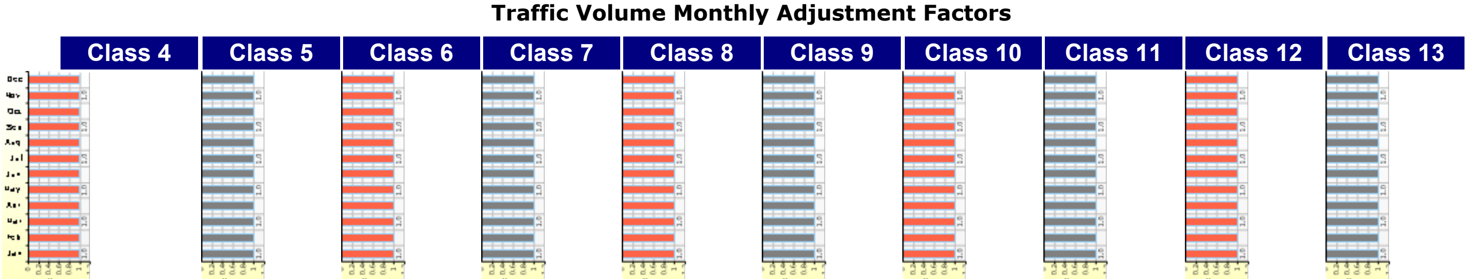








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	3.3%	3%	Linear
Class 5	34%	3%	Linear
Class 6	11.7%	3%	Linear
Class 7	1.6%	3%	Linear
Class 8	9.9%	3%	Linear
Class 9	36.2%	3%	Linear
Class 10	1%	3%	Linear
Class 11	1.8%	3%	Linear
Class 12	0.2%	3%	Linear
Class 13	0.3%	3%	Linear

Truck Distribution by Hour does not apply

Axle Configuration

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

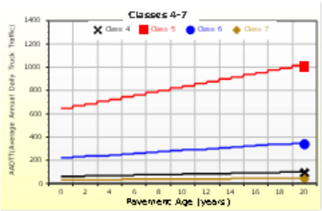
Wheelbase does not apply

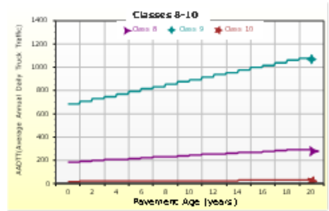
Number of Axles per Truck

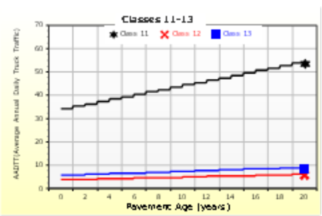
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

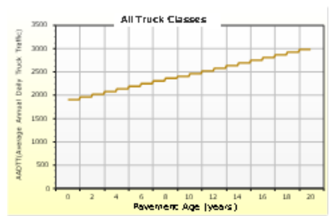
AADTT (Average Annual Daily Truck Traffic) Growth

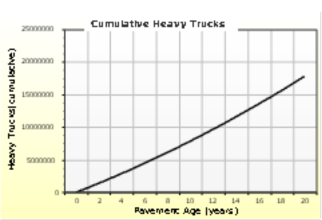
*** Traffic cap is not enforced**







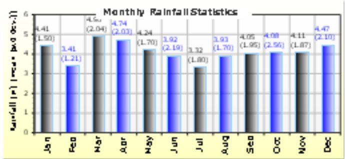




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
US, MA	42.00000 -71.25000 148

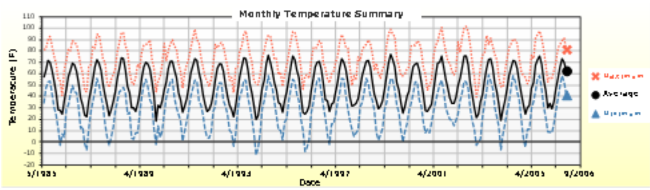


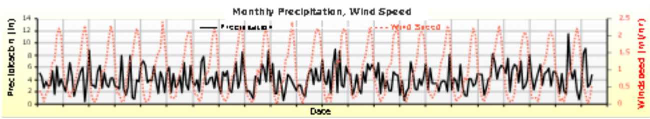
Annual Statistics:

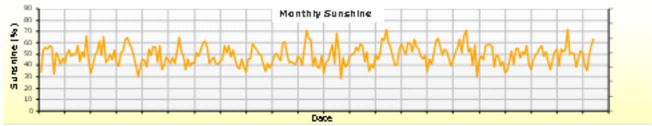
Mean annual air temperature (ºF)	49.50
Mean annual precipitation (in)	49.60
Freezing index (ºF - days)	528.51
Average annual number of freeze/thaw cycles:	85.90

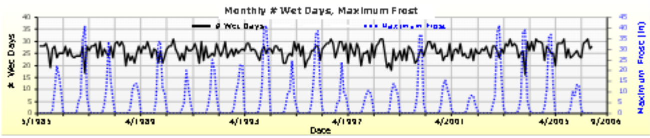
Water table depth (ft) 10.00

Monthly Climate Summary:



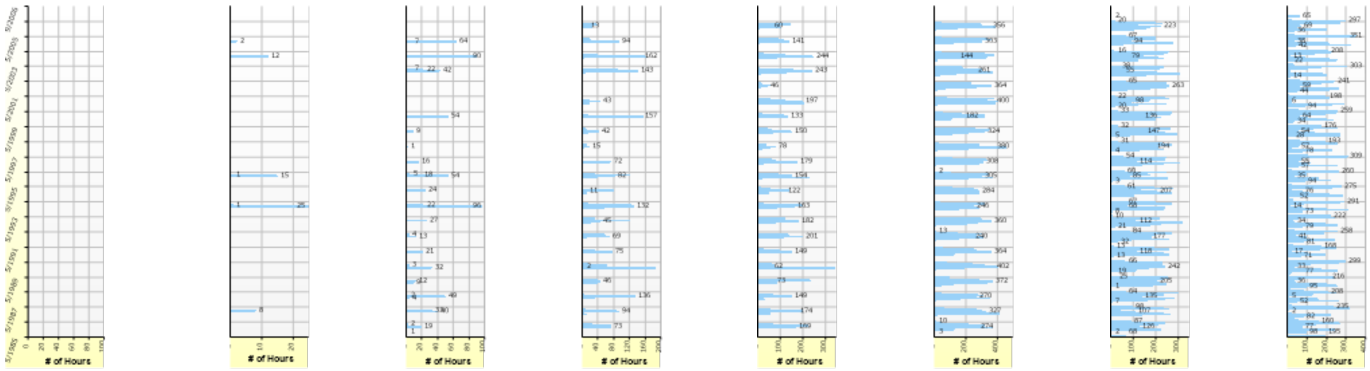




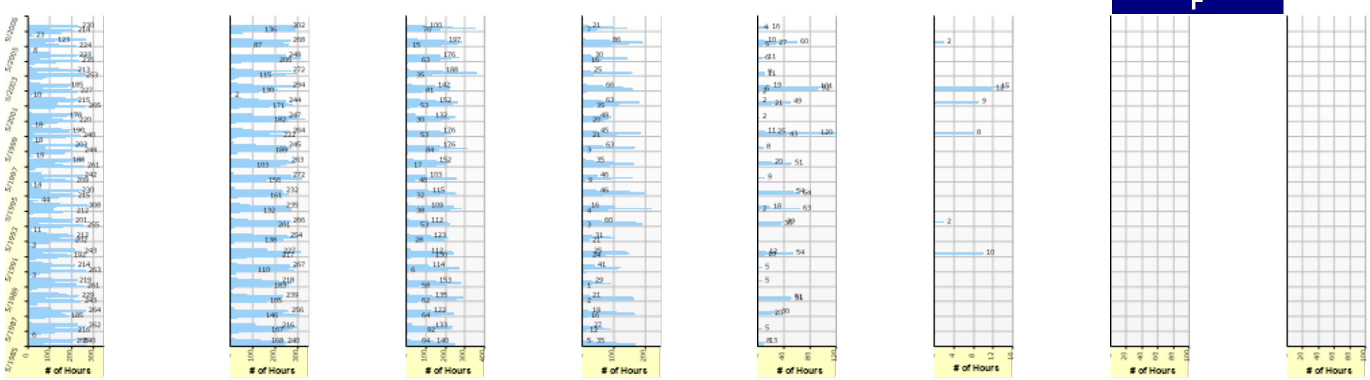


Hourly Air Temperature Distribution by Month:

< -13º F	-13º F to -4º F	-4º F to 5º F	5º F to 14º F	14º F to 23º F	23º F to 32º F	32º F to 41º F	41º F to 50º F



50º F to 59º F	59º F to 68º F	68º F to 77º F	77º F to 86º F	86º F to 95º F	95º F to 104º F	104º F to 113º F	> 113º F



Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

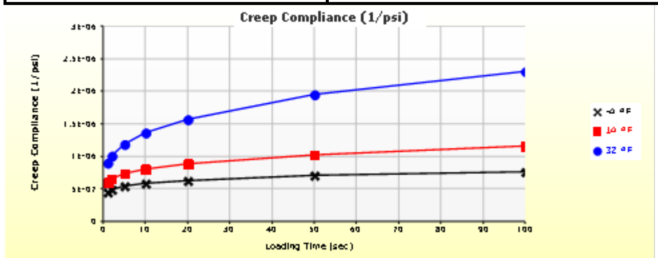
Layer Name	Layer Type	Interface Friction
Layer 1 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 2 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 3 Sandwich/Fractured : Sandwich Granular	Sandwiched Granular (3)	1.00
Layer 4 Non-stabilized Base : Crushed stone	Non-stabilized Base (4)	1.00
Layer 5 Subgrade : A-3	Subgrade (5)	-

Thermal Cracking

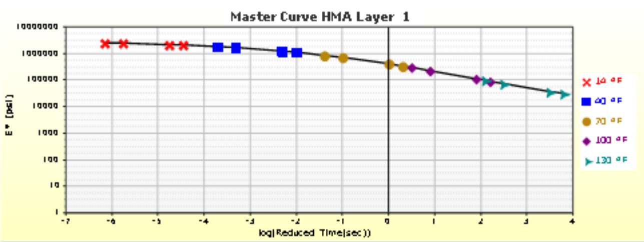
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	18.8

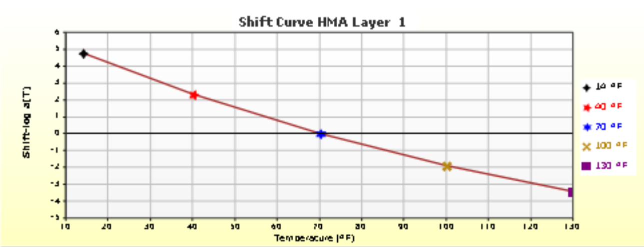
Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	-4 ºF	14 ºF	32 ºF
1	4.55e-007	6.09e-007	9.03e-007
2	4.95e-007	6.59e-007	1.01e-006
5	5.50e-007	7.38e-007	1.19e-006
10	5.92e-007	8.07e-007	1.36e-006
20	6.39e-007	8.91e-007	1.58e-006
50	7.10e-007	1.03e-006	1.95e-006
100	7.74e-007	1.16e-006	2.32e-006

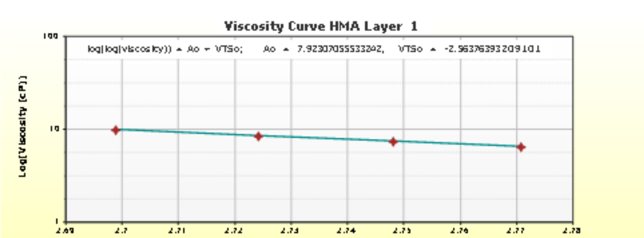
Indirect Tensile Strength (Input Level: 3)	
Test Temperature (ºF)	Indirect Tensilte Strength (psi)
14.0	539.75



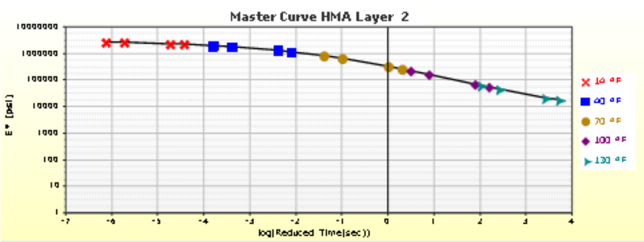
HMA Layer 1: Layer 1 Flexible : Default asphalt concrete

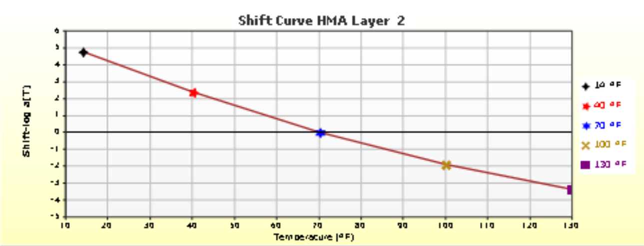


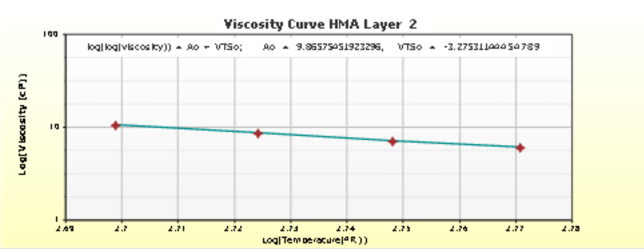




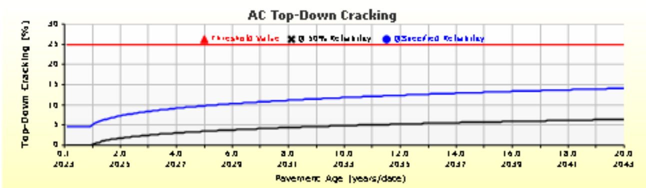
HMA Layer 2: Layer 2 Flexible : Default asphalt concrete

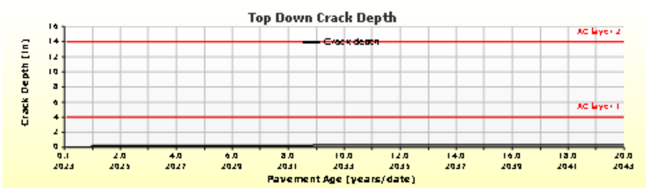


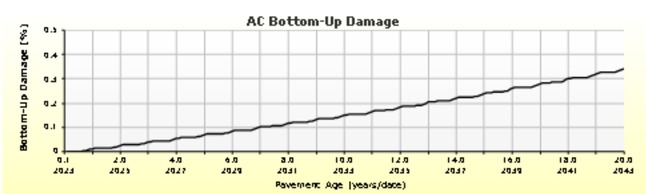


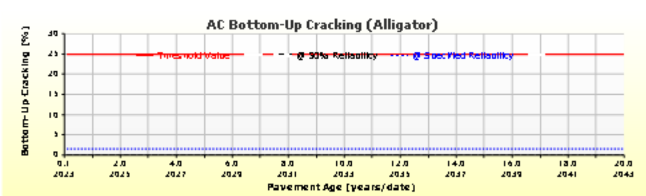


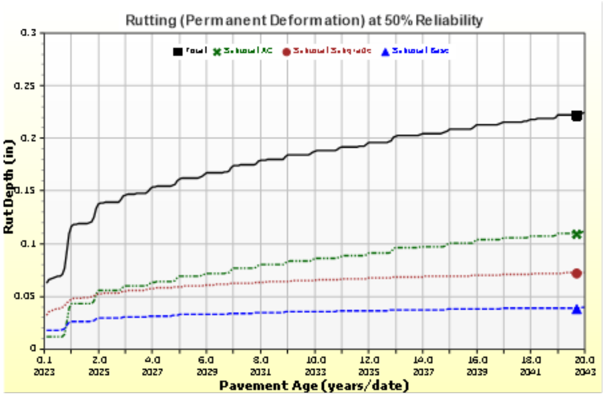
Analysis Output Charts

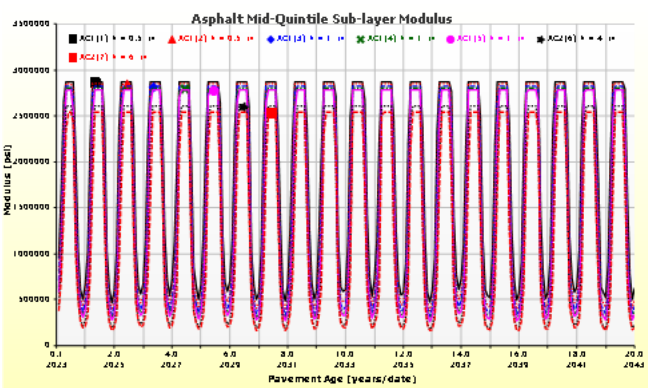

AC Top-Down Cracking
Top-Down Cracking (%)
Pavement Age (years/date)

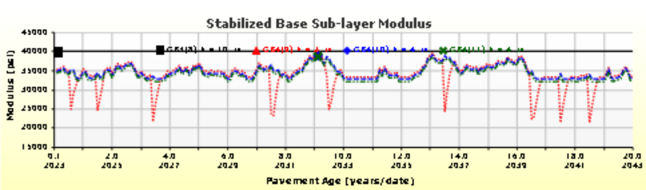

Top Down Crack Depth
Crack Depth (in)
Pavement Age (years/date)

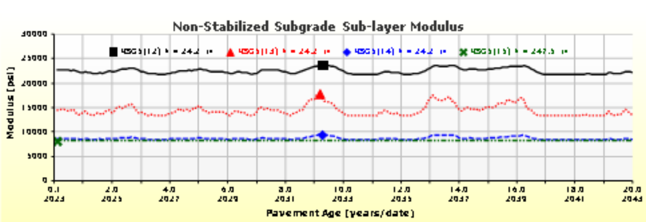

AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)


AC Bottom-Up Cracking (Alligator)
Bottom-Up Cracking (%)
Pavement Age (years/date)


Rutting (Permanent Deformation) at 50% Reliability
Rut Depth (in)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Stabilized Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	4.0	
Unit weight (pcf)	152.1	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	28 Hz
14	1805527	2067164	2176136	2420927	2523069	2655339
40	860750	1125889	1244780	1523010	1641617	1795857
70	241566	372134	442656	640151	738639	879083
100	48631	80509	99733	162024	198309	256911
130	20539	33979	42275	70100	86962	115204

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	26500	60.8
136.4	13967	61.1
147.2	7563	61.5
158	4243	62.4
168.8	2440	63.9
179.6	1430	65.9

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	11.8
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.39
Aggregate parameter	0.4021

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	10.0	
Unit weight (pcf)	151.0	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1831281	2170217	2306190	2600111	2718387	2868225
40	769108	1110180	1268797	1641251	1797357	1995914
70	172011	297675	372537	602814	726510	909822
100	28952	49683	63341	112290	143604	197884
130	12763	19138	23449	39416	50001	68990

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158	1803	76.8
168.8	928	79

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Sandwich/Fractured : Sandwich Granular

Sandwiched Granular	
Layer thickness (in)	10
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	40000

Thermal	
Heat capacity (BTU/lb-ºF)	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	Sandwich Granular
Description of object	Default
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : Crushed stone

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
30000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Crushed stone
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Water Content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#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
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 5 Subgrade : A-3

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	A-3
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	11.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	120
Saturated hydraulic conductivity (ft/hr)	False	3.777e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	7.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	4.7572
bf	2.8814
cf	0.8694
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	5.2
#100	
#80	33.0
#60	
#50	
#40	76.8
#30	
#20	
#16	
#10	93.4
#8	
#4	95.3
3/8-in.	96.6
1/2-in.	97.1
3/4-in.	98.0
1-in.	98.6
1 1/2-in.	99.2
2-in.	99.7
2 1/2-in.	
3-in.	
3 1/2-in.	99.9

Calibration Coefficients

$$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$$

k1: 3.75
k2: 2.87
k3: 1.46
Bf1: 0.001032
Bf2: 1.38
Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_a^2 + 2.4868 * H_a - 17.342$$

$$C_2 = 0.0172 * H_a^2 - 1.7331 * H_a + 27.428$$

Where:

H_{ac} = total AC thickness(in)

ε_p = plastic strain(in/in)

ε_r = resilient strain(in/in)

T = layer temperature(°F)

N = number of load repetitions

acRuttingStandardDeviation	0.24 * Pow(RUT,0.8026) + 0.001	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36

Thermal Fracture

$$C_f = \beta_{t1} N\left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 1 Standard Deviation: 0.14 * THERMAL + 168
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

N_f = number of repetitions to fatigue cracking
σ_s = Tensile stress(psi)
M_r = modulus of rupture(psi)

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

k1: 0.965	Bs1: 1	k1: 0.965	Bs1: 1
Standard Deviation (BASERUT) 0.1477 * Pow(BASERUT,0.6711) + 0.001		Standard Deviation (BASERUT) 0.1235 * Pow(SUBRUT,0.5012) + 0.001	

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0 / 2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

c1: 2.5219	c2: 0.8069	c3: 1
kL1: 64271618	kL2: 0.2855	kL3: 0.011
kL4: 0.01488	kL5: 3.266	

0.3657 * TOP + 3.6563

$$FC = \left(\frac{6000}{1 + e^{\left(C_1 * C_1' + C_2 * C_2' \log_{10}(D * 100)\right)}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 1.31	c2: 3.9666	c3: 6000

1.13 + 13/(1+exp(7.57-15.5*LOG10(BOTTOM+0.0001)))

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1: 0	C2: 75	C3: 2	C4: 2

csmCrackingStandardDeviation

CTB*1

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 40	C2: 0.4	C3: 0.008	C4: 0.015

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: May, 2022
Pavement construction: June, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42, -71.25

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	Default asphalt concrete	4.0
Flexible	Default asphalt concrete	10.0
Sandwich/Fractured	Sandwich Granular	10.0
NonStabilized	Crushed stone	10.0
Subgrade	A-3	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	12.2
Air voids (%)	7.0

Traffic

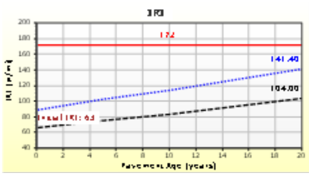
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	4,000
2033 (10 years)	7,876,620
2043 (20 years)	17,835,200

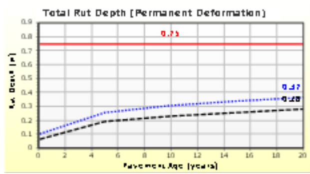
Design Outputs

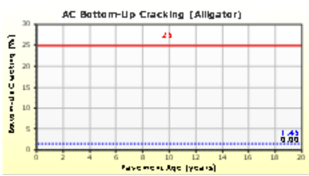
Distress Prediction Summary

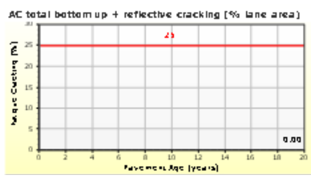
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	141.40	90.00	99.01	Pass
Permanent deformation - total pavement (in)	0.75	0.37	90.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	25.00	1.45	90.00	100.00	Pass
AC total fatigue cracking: bottom up + reflective (% lane area)	25.00	0.00	90.00	0.00	Pass
AC thermal cracking (ft/mile)	1000.00	216.31	90.00	100.00	Pass
AC top-down fatigue cracking (% lane area)	25.00	13.70	90.00	99.93	Pass
Permanent deformation - AC only (in)	0.25	0.24	90.00	92.83	Pass

Distress Charts







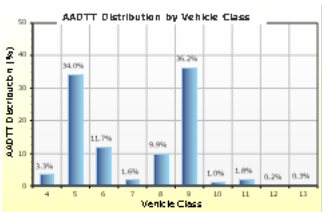


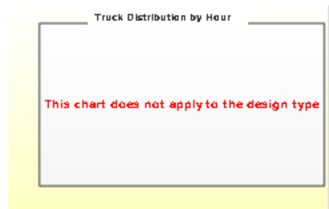
Threshold Value ····· @ Specified Reliability - - - @ 50% Reliability

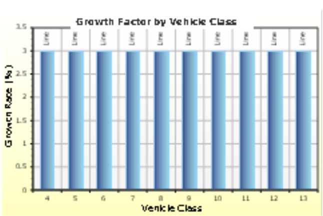
Traffic Inputs

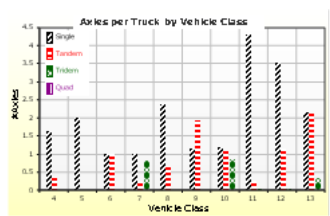
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	4,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	60.0



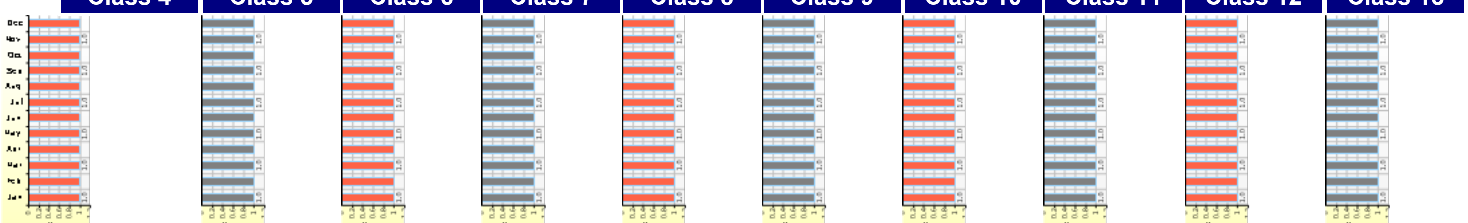






Traffic Volume Monthly Adjustment Factors

Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	3.3%	3%	Linear
Class 5	34%	3%	Linear
Class 6	11.7%	3%	Linear
Class 7	1.6%	3%	Linear
Class 8	9.9%	3%	Linear
Class 9	36.2%	3%	Linear
Class 10	1%	3%	Linear
Class 11	1.8%	3%	Linear
Class 12	0.2%	3%	Linear
Class 13	0.3%	3%	Linear

Truck Distribution by Hour does not apply

Axle Configuration

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

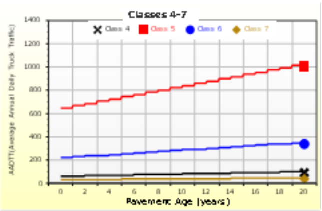
Wheelbase does not apply

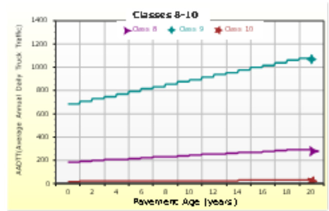
Number of Axles per Truck

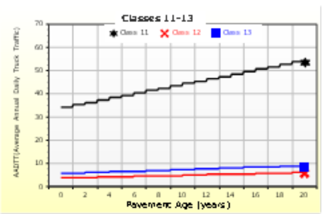
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

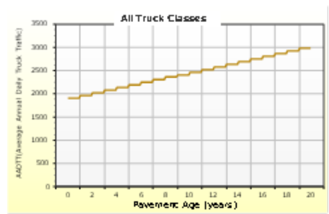
AADTT (Average Annual Daily Truck Traffic) Growth

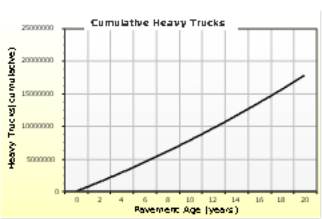
*** Traffic cap is not enforced**







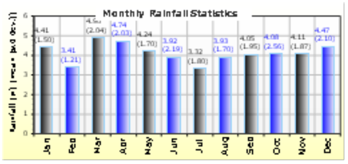




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
US, MA	42.00000 -71.25000 148

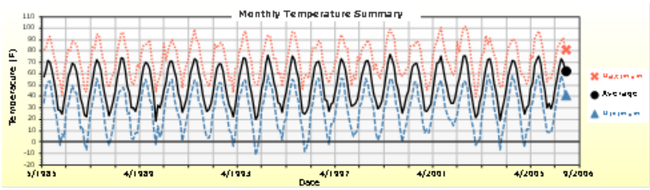


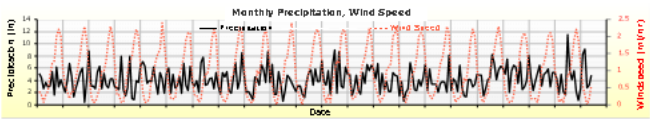
Annual Statistics:

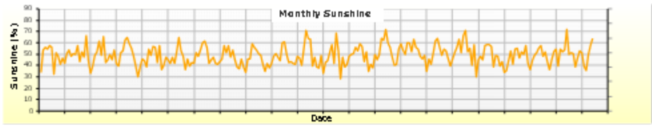
Mean annual air temperature (ºF)	49.50
Mean annual precipitation (in)	49.60
Freezing index (ºF - days)	528.51
Average annual number of freeze/thaw cycles:	85.91

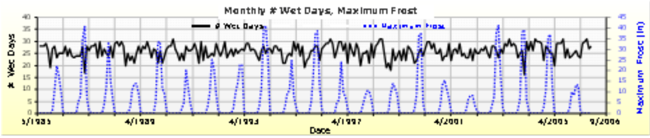
Water table depth (ft) 10.00

Monthly Climate Summary:

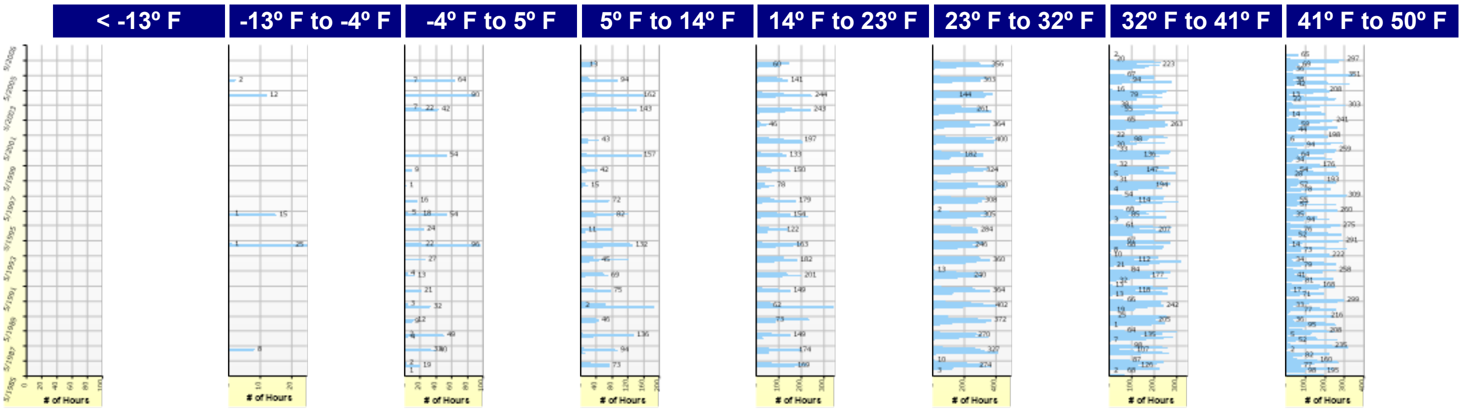


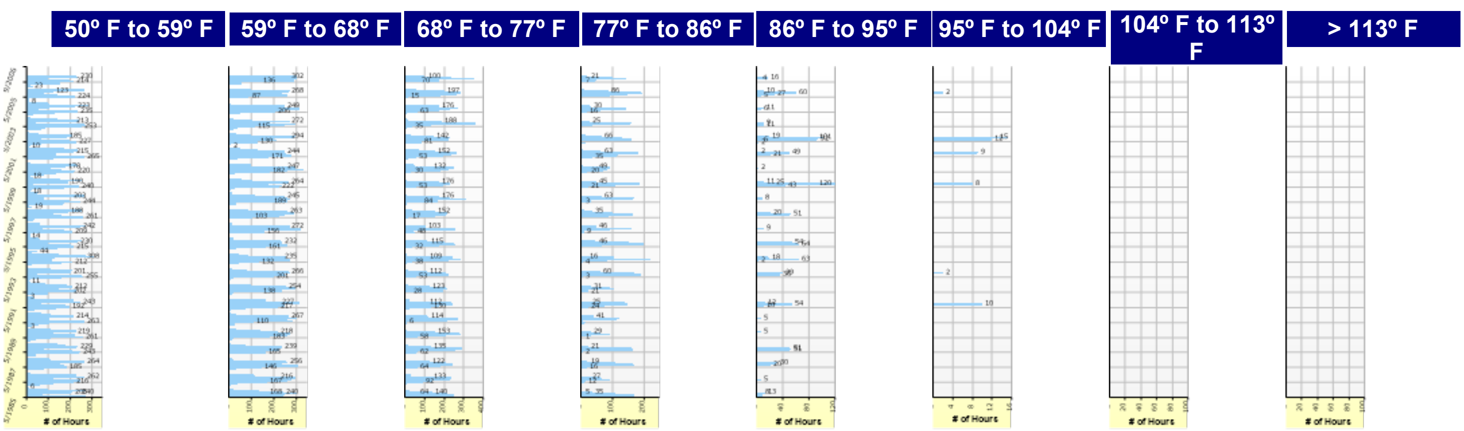






Hourly Air Temperature Distribution by Month:





Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

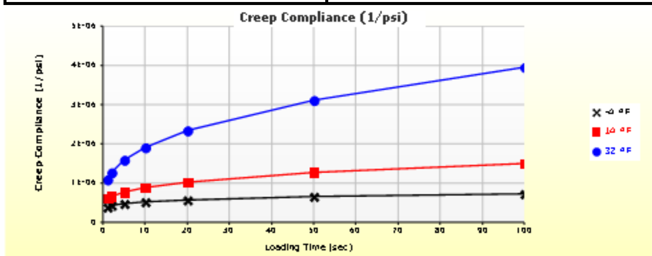
Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

Layer Name	**Layer Type**	**Interface Friction**
Layer 1 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 2 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 3 Sandwich/Fractured : Sandwich Granular	Sandwiched Granular (3)	1.00
Layer 4 Non-stabilized Base : Crushed stone	Non-stabilized Base (4)	1.00
Layer 5 Subgrade : A-3	Subgrade (5)	-

Thermal Cracking

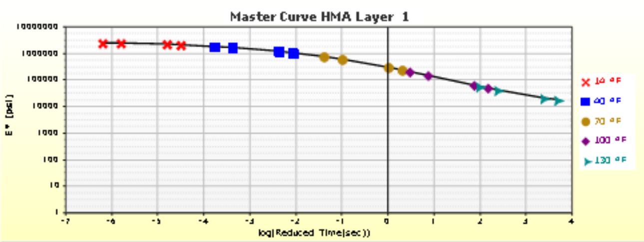
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	19.2

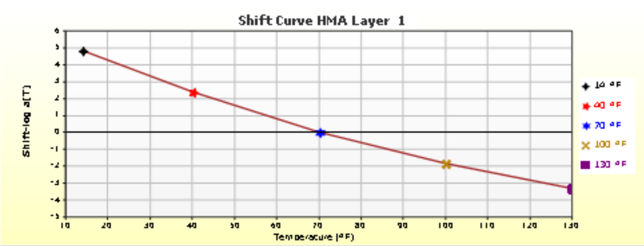
Indirect Tensile Strength (Input Level: 3)	
Test Temperature (ºF)	**Indirect Tensilte Strength (psi)**
14.0	535.05

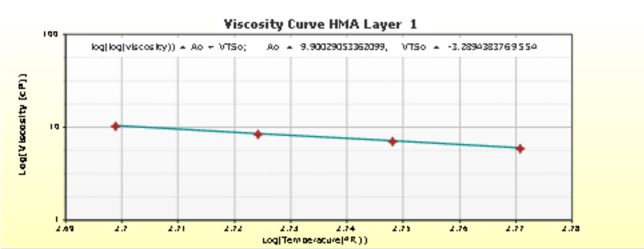


Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	**-4 ºF**	**14 ºF**	**32 ºF**
1	3.93e-007	6.14e-007	1.09e-006
2	4.36e-007	6.81e-007	1.28e-006
5	4.94e-007	7.95e-007	1.60e-006
10	5.38e-007	9.06e-007	1.93e-006
20	5.84e-007	1.04e-006	2.35e-006
50	6.62e-007	1.28e-006	3.13e-006
100	7.38e-007	1.51e-006	3.97e-006

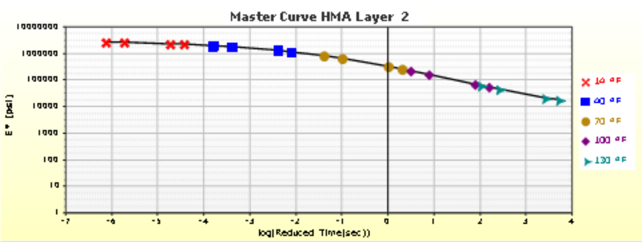
HMA Layer 1: Layer 1 Flexible : Default asphalt concrete

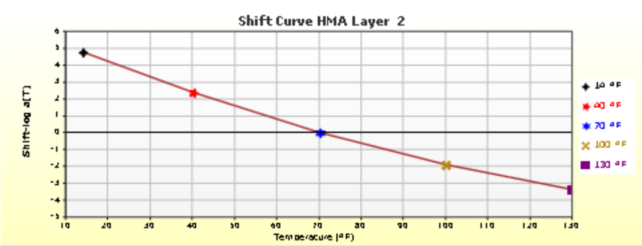


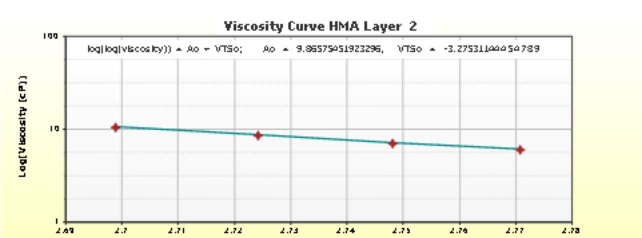




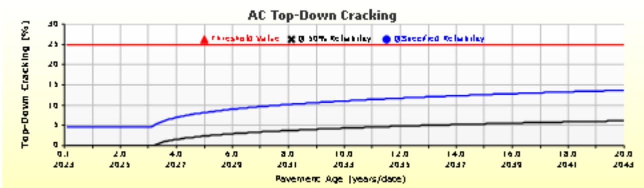
HMA Layer 2: Layer 2 Flexible : Default asphalt concrete

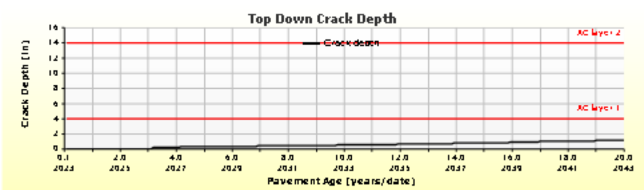


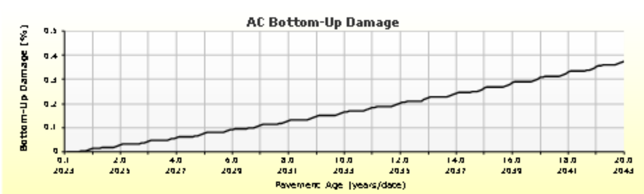


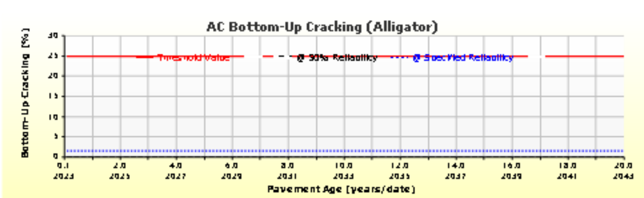


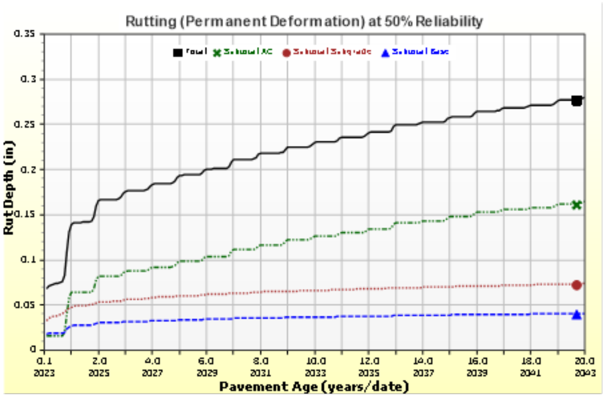
Analysis Output Charts

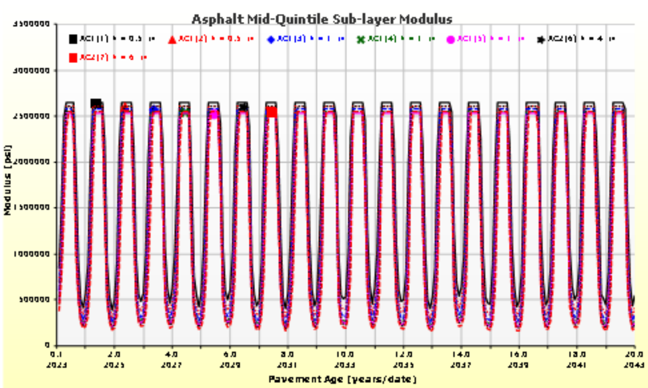

AC Top-Down Cracking
Threshold Value
@ 50% Reliability
@Specified Reliability
Top-Down Cracking (%)
Pavement Age (years/date)

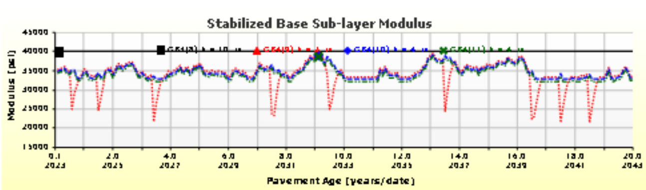

Top Down Crack Depth
Crack depth
AC layer 2
AC layer 1
Crack Depth (in)
Pavement Age (years/date)

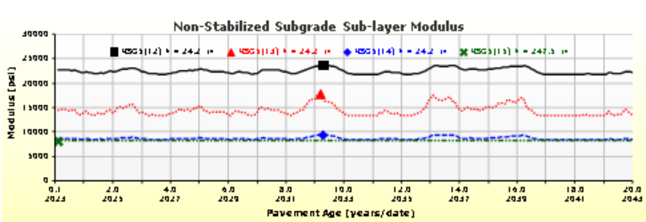

AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)


AC Bottom-Up Cracking (Alligator)
Threshold Value
@ 50% Reliability
@ Specified Reliability
Bottom-Up Cracking (%)
Pavement Age (years/date)


Rutting (Permanent Deformation) at 50% Reliability
Rut Depth (in)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Stabilized Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	4.0	
Unit weight (pcf)	158.1	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	28 Hz
14	1715899	2042705	2174240	2459248	2574204	2720093
40	694750	1012046	1161517	1516521	1666687	1858556
70	153204	265123	332170	540341	653399	822518
100	27266	46351	58902	103822	132539	182321
130	12698	18955	23172	38739	49027	67441

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	13733	71.3
136.4	6653	73.2
147.2	3200	75.4
158	1597	77.6
168.8	824	79.7

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	12.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.2
Aggregate parameter	0.4021

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	10.0	
Unit weight (pcf)	151.0	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1831281	2170217	2306190	2600111	2718387	2868225
40	769108	1110180	1268797	1641251	1797357	1995914
70	172011	297675	372537	602814	726510	909822
100	28952	49683	63341	112290	143604	197884
130	12763	19138	23449	39416	50001	68990

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158	1803	76.8
168.8	928	79

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Sandwich/Fractured : Sandwich Granular

Sandwiched Granular	
Layer thickness (in)	10
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	40000

Thermal	
Heat capacity (BTU/lb-ºF)	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	Sandwich Granular
Description of object	Default
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : Crushed stone

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
30000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Crushed stone
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Water Content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#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
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 5 Subgrade : A-3

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	A-3
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	11.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	120
Saturated hydraulic conductivity (ft/hr)	False	3.777e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	7.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	4.7572
bf	2.8814
cf	0.8694
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	5.2
#100	
#80	33.0
#60	
#50	
#40	76.8
#30	
#20	
#16	
#10	93.4
#8	
#4	95.3
3/8-in.	96.6
1/2-in.	97.1
3/4-in.	98.0
1-in.	98.6
1 1/2-in.	99.2
2-in.	99.7
2 1/2-in.	
3-in.	
3 1/2-in.	99.9

Calibration Coefficients

$$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{\text{E}}\right)^{k_3 \beta_{f3}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$$

	k1: 3.75
	k2: 2.87
	k3: 1.46
	Bf1: 0.001032
	Bf2: 1.38
	Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_\alpha^2 + 2.4868 * H_\alpha - 17.342$$

$$C_2 = 0.0172 * H_\alpha^2 - 1.7331 * H_\alpha + 27.428$$

Where:

$H_{ac} = total\ AC\ thickness(in)$

$\varepsilon_p = plastic\ strain({}^{in}/_{in})$

$\varepsilon_r = resilient\ strain({}^{in}/_{in})$

$T = layer\ temperature({}^\circ F)$

$N = number\ of\ load\ repetitions$

acRuttingStandardDeviation	0.24 * Pow(RUT,0.8026) + 0.001	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36

Thermal Fracture

$$C_f = \beta_{t1} N \left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 1 Standard Deviation: 0.14 * THERMAL + 168
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

$N_f = number\ of\ repetitions\ to\ fatigue\ cracking$

$\sigma_s = Tensile\ stress(psi)$

$M_r = modulus\ of\ rupture(psi)$

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

k1: 0.965	Bs1: 1	k1: 0.965	Bs1: 1
Standard Deviation (BASERUT) 0.1477 * Pow(BASERUT,0.6711) + 0.001		Standard Deviation (BASERUT) 0.1235 * Pow(SUBRUT,0.5012) + 0.001	

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0/2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

c1: 2.5219	c2: 0.8069	c3: 1
kL1: 64271618	kL2: 0.2855	kL3: 0.011
kL4: 0.01488	kL5: 3.266	
0.3657 * TOP + 3.6563		

$$FC = \left(\frac{6000}{1 + e^{\left(C_1 * C_1' + C_2 * C_2' \log_{10}(D*100)\right)}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 1.31	c2: 3.9666	c3: 6000
1.13 + 13/(1+exp(7.57-15.5*LOG10(BOTTOM+0.0001)))		

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1: 0	C2: 75	C3: 2	C4: 2
csmCrackingStandardDeviation			
CTB*1			

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 40	C2: 0.4	C3: 0.008	C4: 0.015

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: May, 2022
Pavement construction: June, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42, -71.25

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	Default asphalt concrete	4.0
Flexible	Default asphalt concrete	10.0
Sandwich/Fractured	Sandwich Granular	10.0
NonStabilized	Crushed stone	10.0
Subgrade	A-3	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	10.6
Air voids (%)	7.0

Traffic

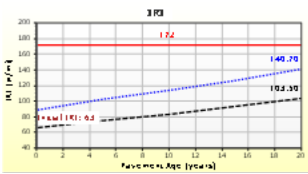
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	4,000
2033 (10 years)	7,876,620
2043 (20 years)	17,835,200

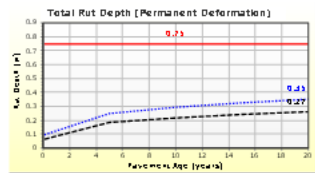
Design Outputs

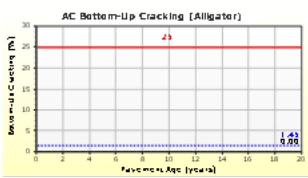
Distress Prediction Summary

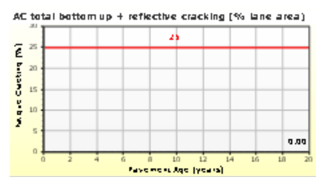
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	140.74	90.00	99.08	Pass
Permanent deformation - total pavement (in)	0.75	0.35	90.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	25.00	1.45	90.00	100.00	Pass
AC total fatigue cracking: bottom up + reflective (% lane area)	25.00	0.00	90.00	0.00	Pass
AC thermal cracking (ft/mile)	1000.00	216.30	90.00	100.00	Pass
AC top-down fatigue cracking (% lane area)	25.00	13.92	90.00	99.92	Pass
Permanent deformation - AC only (in)	0.25	0.22	90.00	96.33	Pass

Distress Charts





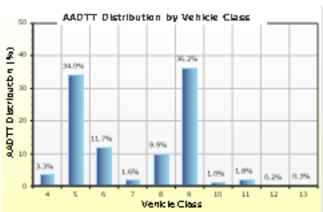


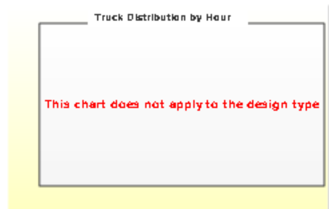


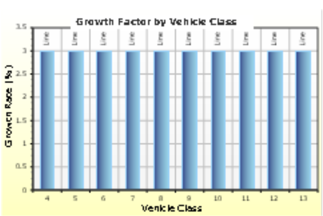
Traffic Inputs

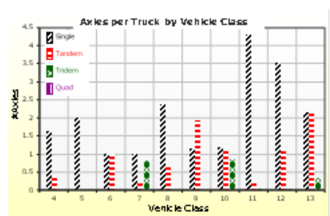
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	4,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	60.0

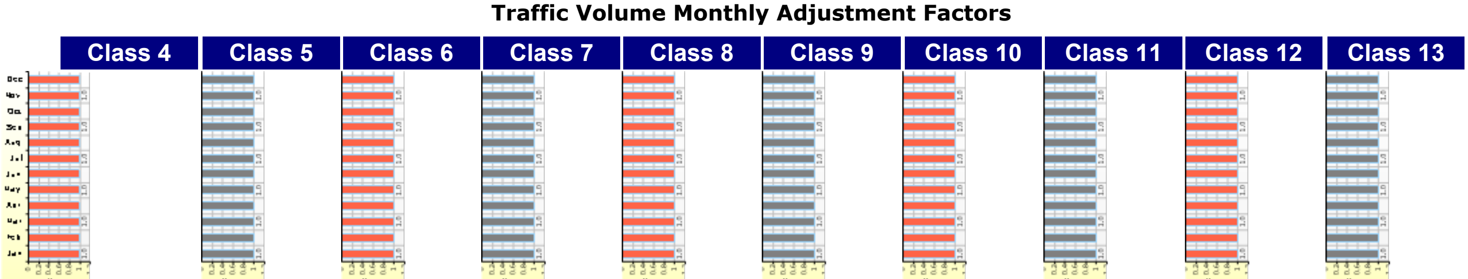








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	3.3%	3%	Linear
Class 5	34%	3%	Linear
Class 6	11.7%	3%	Linear
Class 7	1.6%	3%	Linear
Class 8	9.9%	3%	Linear
Class 9	36.2%	3%	Linear
Class 10	1%	3%	Linear
Class 11	1.8%	3%	Linear
Class 12	0.2%	3%	Linear
Class 13	0.3%	3%	Linear

Truck Distribution by Hour does not apply

Axle Configuration

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

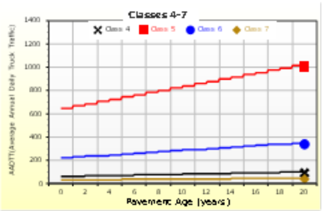
Wheelbase does not apply

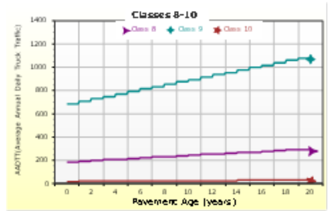
Number of Axles per Truck

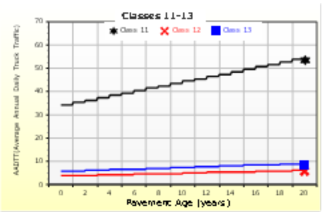
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

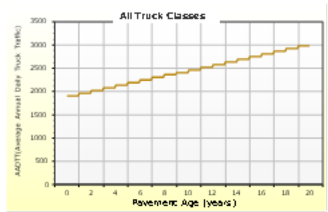
AADTT (Average Annual Daily Truck Traffic) Growth

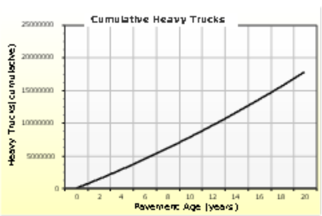
*** Traffic cap is not enforced**







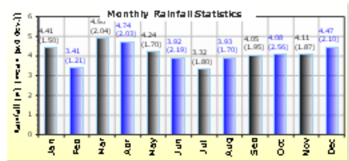




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
US, MA	42.00000 -71.25000 148

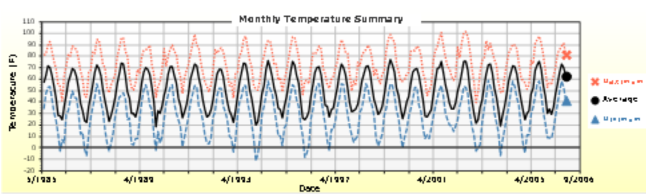


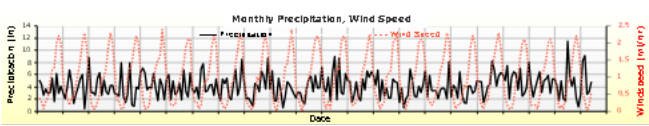
Annual Statistics:

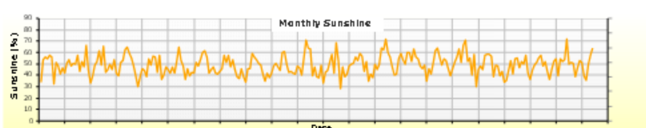
Mean annual air temperature (ºF)	49.50
Mean annual precipitation (in)	49.60
Freezing index (ºF - days)	528.51
Average annual number of freeze/thaw cycles:	85.91

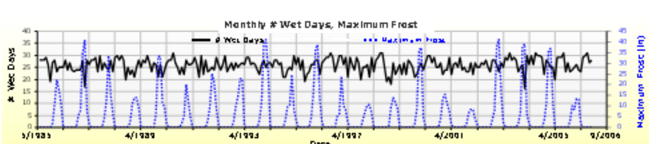
Water table depth (ft) 10.00

Monthly Climate Summary:



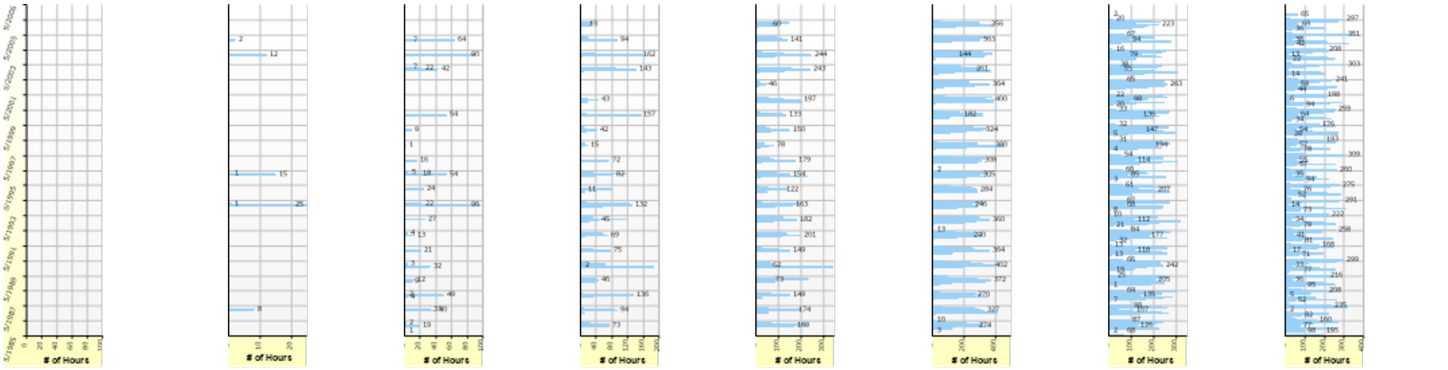




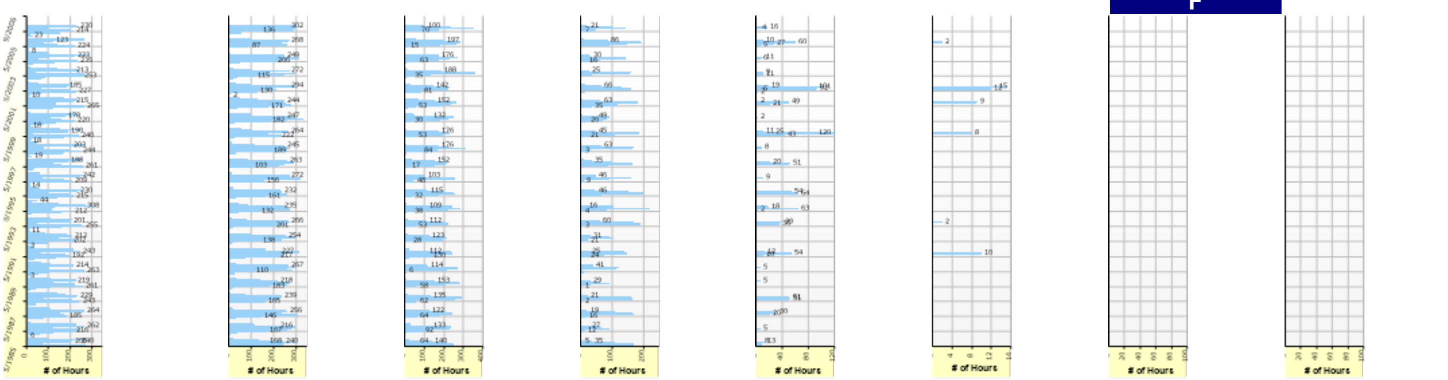


Hourly Air Temperature Distribution by Month:

< -13º F | -13º F to -4º F | -4º F to 5º F | 5º F to 14º F | 14º F to 23º F | 23º F to 32º F | 32º F to 41º F | 41º F to 50º F



50º F to 59º F | 59º F to 68º F | 68º F to 77º F | 77º F to 86º F | 86º F to 95º F | 95º F to 104º F | 104º F to 113º F | > 113º F



Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

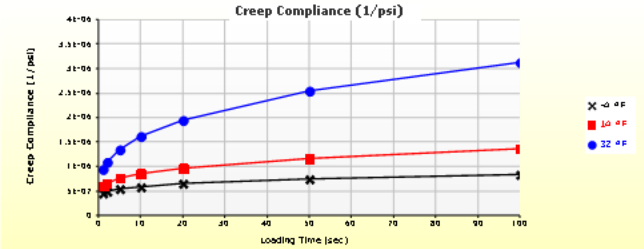
Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

Layer Name	Layer Type	Interface Friction
Layer 1 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 2 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 3 Sandwich/Fractured : Sandwich Granular	Sandwiched Granular (3)	1.00
Layer 4 Non-stabilized Base : Crushed stone	Non-stabilized Base (4)	1.00
Layer 5 Subgrade : A-3	Subgrade (5)	-

Thermal Cracking

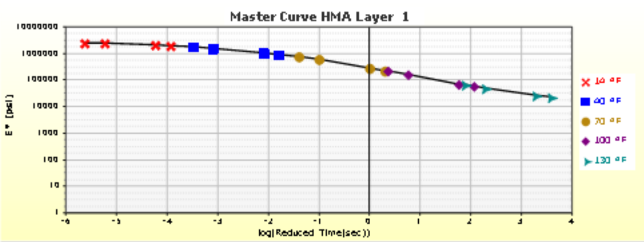
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	17.6

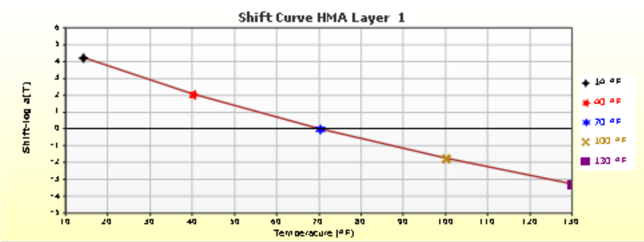
Indirect Tensile Strength (Input Level: 3)	
Test Temperature (ºF)	**Indirect Tensilte Strength (psi)**
14.0	535.05

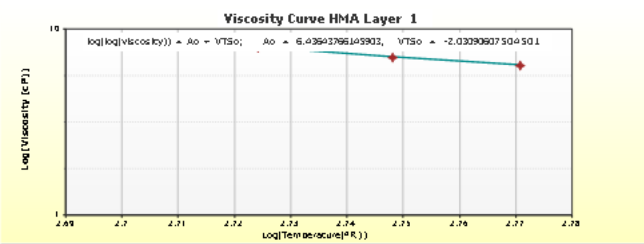


Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	**-4 ºF**	**14 ºF**	**32 ºF**
1	4.56e-007	6.03e-007	9.62e-007
2	4.93e-007	6.66e-007	1.11e-006
5	5.47e-007	7.67e-007	1.36e-006
10	5.96e-007	8.62e-007	1.62e-006
20	6.56e-007	9.78e-007	1.96e-006
50	7.52e-007	1.18e-006	2.55e-006
100	8.41e-007	1.38e-006	3.14e-006

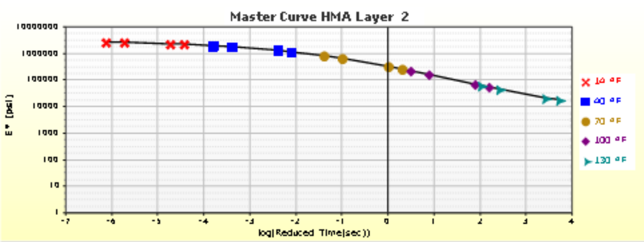
HMA Layer 1: Layer 1 Flexible : Default asphalt concrete

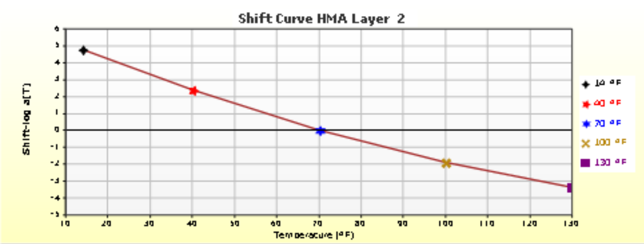


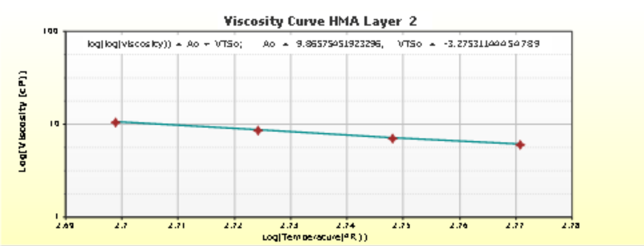




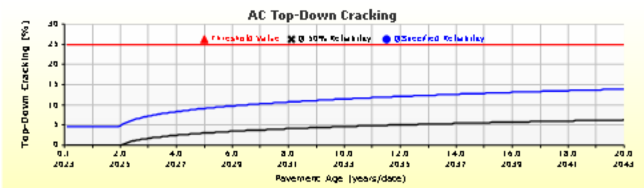
HMA Layer 2: Layer 2 Flexible : Default asphalt concrete

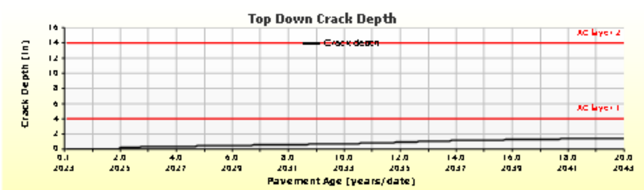


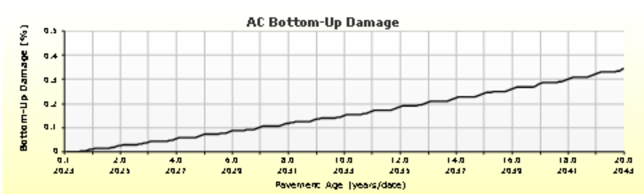


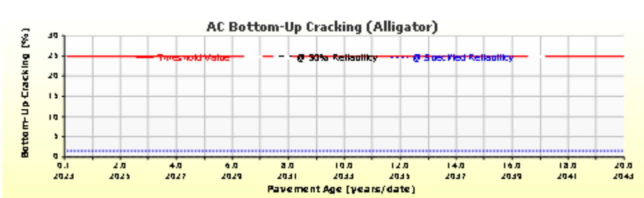


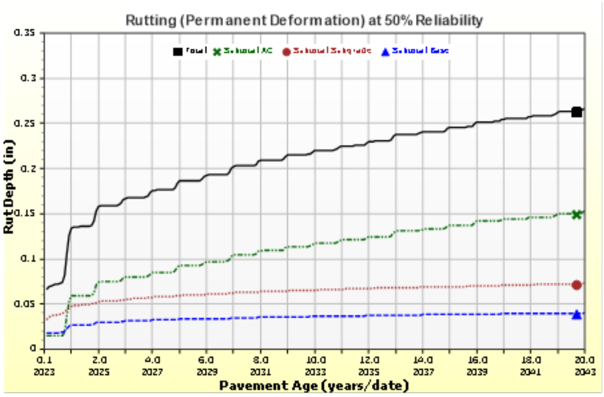
Analysis Output Charts

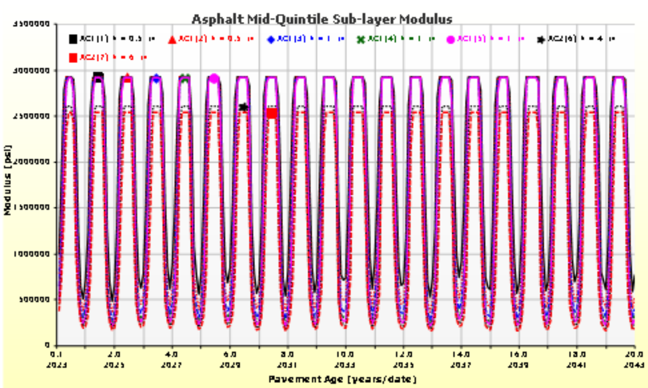

AC Top-Down Cracking
Top-Down Cracking (%)
Pavement Age (years/date)

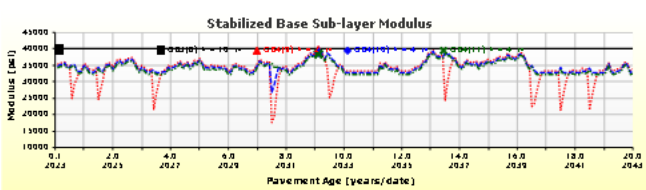

Top Down Crack Depth
Crack Depth (in)
Pavement Age (years/date)

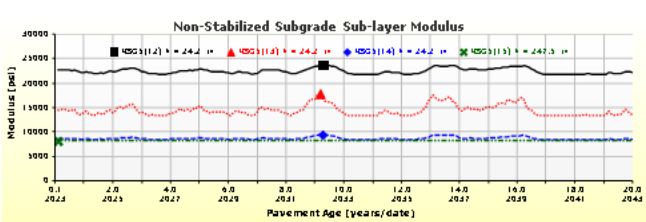

AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)


AC Bottom-Up Cracking (Alligator)
Bottom-Up Cracking (%)
Pavement Age (years/date)


Rutting (Permanent Deformation) at 50% Reliability
Rut Depth (in)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Stabilized Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	4.0	
Unit weight (pcf)	150.5	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	28 Hz
14	1715250	1983512	2085627	2295771	2376602	2476433
40	673499	975367	1116820	1447285	1583258	1752276
70	145751	246947	307464	496418	600047	756451
100	30876	50941	63856	109103	137542	186326
130	16584	25066	30615	50474	63259	85713

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	14767	57.4
136.4	8233	55.9
147.2	4850	55.6
158	3013	55.5
168.8	1883	55.9
179.6	1200	56.8

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	10.6
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.15
Aggregate parameter	0.4021

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	10.0	
Unit weight (pcf)	151.0	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1831281	2170217	2306190	2600111	2718387	2868225
40	769108	1110180	1268797	1641251	1797357	1995914
70	172011	297675	372537	602814	726510	909822
100	28952	49683	63341	112290	143604	197884
130	12763	19138	23449	39416	50001	68990

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158	1803	76.8
168.8	928	79

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Sandwich/Fractured : Sandwich Granular

Sandwiched Granular	
Layer thickness (in)	10
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	40000

Thermal	
Heat capacity (BTU/lb-ºF)	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	Sandwich Granular
Description of object	Default
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : Crushed stone

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
30000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Crushed stone
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Water Content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#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
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 5 Subgrade : A-3

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	A-3
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	11.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	120
Saturated hydraulic conductivity (ft/hr)	False	3.777e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	7.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	4.7572
bf	2.8814
cf	0.8694
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	5.2
#100	
#80	33.0
#60	
#50	
#40	76.8
#30	
#20	
#16	
#10	93.4
#8	
#4	95.3
3/8-in.	96.6
1/2-in.	97.1
3/4-in.	98.0
1-in.	98.6
1 1/2-in.	99.2
2-in.	99.7
2 1/2-in.	
3-in.	
3 1/2-in.	99.9

Calibration Coefficients

$$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$$

	k1: 3.75
	k2: 2.87
	k3: 1.46
	Bf1: 0.001032
	Bf2: 1.38
	Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$

$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * H_\alpha^2 + 2.4868 * H_\alpha - 17.342$$

$$C_2 = 0.0172 * H_\alpha^2 - 1.7331 * H_\alpha + 27.428$$

Where:

H_{ac} = total AC thickness(in)

ε_p = plastic strain(in/in)

ε_r = resilient strain(in/in)

T = layer temperature(°F)

N = number of load repetitions

acRuttingStandardDeviation	0.24 * Pow(RUT,0.8026) + 0.001	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36

Thermal Fracture

$$C_f = \beta_{t1} N\left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 1 Standard Deviation: 0.14 * THERMAL + 168
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

N_f = number of repetitions to fatigue cracking

σ_s = Tensile stress(psi)

M_r = modulus of rupture(psi)

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

k1: 0.965	Bs1: 1	k1: 0.965	Bs1: 1
Standard Deviation (BASERUT) 0.1477 * Pow(BASERUT,0.6711) + 0.001		Standard Deviation (BASERUT) 0.1235 * Pow(SUBRUT,0.5012) + 0.001	

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_0}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0/2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

$$FC = \left(\frac{6000}{1 + e^{\left(C_1 * C_1' + C_2 * C_2' \log_{10}(D * 100)\right)}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 2.5219	c2: 0.8069	c3: 1	c1: 1.31	c2: 3.9666	c3: 6000
kL1: 64271618	kL2: 0.2855	kL3: 0.011			
kL4: 0.01488	kL5: 3.266		1.13 + 13/(1+exp(7.57-15.5*LOG10(BOTTOM+0.0001)))		
0.3657 * TOP + 3.6563					

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 0	C2: 75	C3: 2	C4: 2	C1: 40	C2: 0.4	C3: 0.008	C4: 0.015
csmCrackingStandardDeviation							
CTB*1							

Design Inputs

Design Life: 20 years
Design Type: FLEXIBLE

Base construction: May, 2022
Pavement construction: June, 2023
Traffic opening: September, 2023

Climate Data Sources (Lat/Lon): 42, -71.25

Design Structure

Layer type	Material Type	Thickness (in)
Flexible	Default asphalt concrete	4.0
Flexible	Default asphalt concrete	10.0
Sandwich/Fractured	Sandwich Granular	10.0
NonStabilized	Crushed stone	10.0
Subgrade	A-3	Semi-infinite

Volumetric at Construction:	
Effective binder content (%)	12.3
Air voids (%)	7.0

Traffic

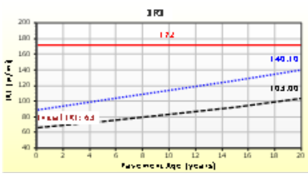
Age (year)	Heavy Trucks (cumulative)
2023 (initial)	4,000
2033 (10 years)	7,876,620
2043 (20 years)	17,835,200

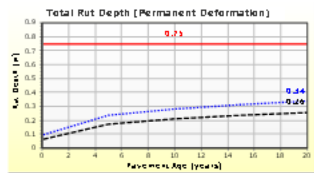
Design Outputs

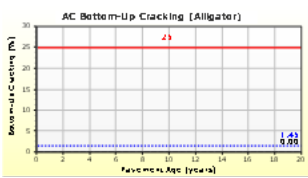
Distress Prediction Summary

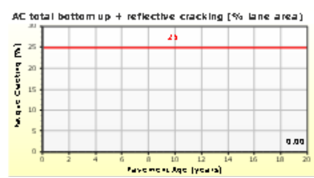
Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	172.00	140.11	90.00	99.14	Pass
Permanent deformation - total pavement (in)	0.75	0.34	90.00	100.00	Pass
AC bottom-up fatigue cracking (% lane area)	25.00	1.45	90.00	100.00	Pass
AC total fatigue cracking: bottom up + reflective (% lane area)	25.00	0.00	90.00	0.00	Pass
AC thermal cracking (ft/mile)	1000.00	216.30	90.00	100.00	Pass
AC top-down fatigue cracking (% lane area)	25.00	13.70	90.00	99.93	Pass
Permanent deformation - AC only (in)	0.25	0.21	90.00	98.25	Pass

Distress Charts





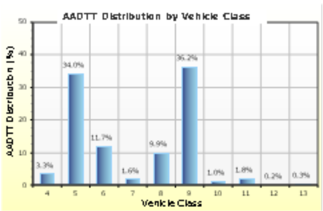


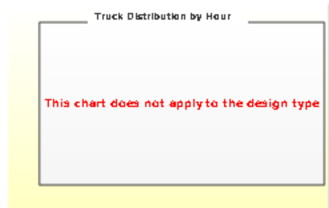


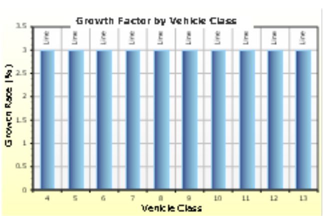
Traffic Inputs

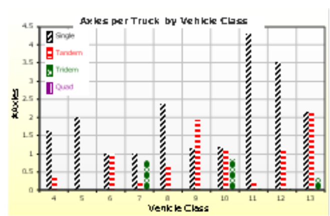
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	4,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	60.0

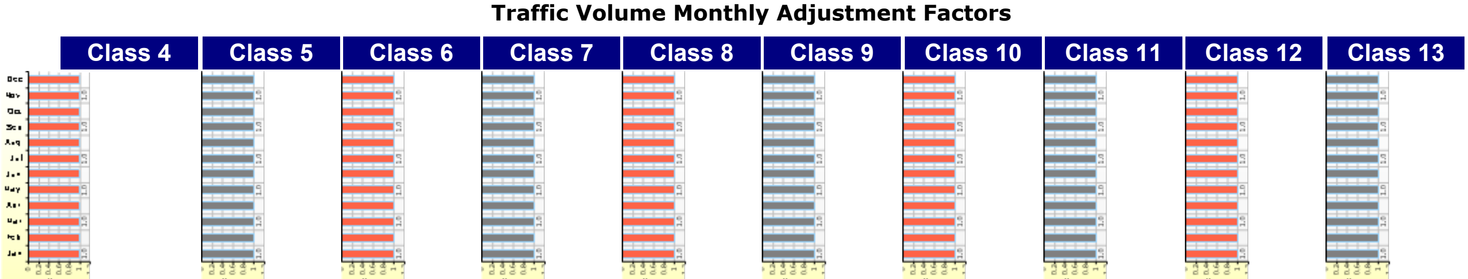








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	3.3%	3%	Linear
Class 5	34%	3%	Linear
Class 6	11.7%	3%	Linear
Class 7	1.6%	3%	Linear
Class 8	9.9%	3%	Linear
Class 9	36.2%	3%	Linear
Class 10	1%	3%	Linear
Class 11	1.8%	3%	Linear
Class 12	0.2%	3%	Linear
Class 13	0.3%	3%	Linear

Truck Distribution by Hour does not apply

Axle Configuration

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

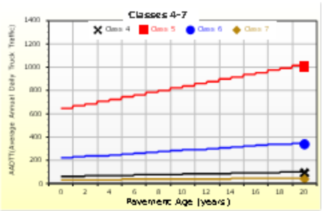
Wheelbase does not apply

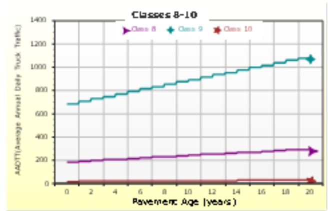
Number of Axles per Truck

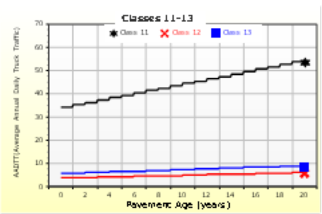
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

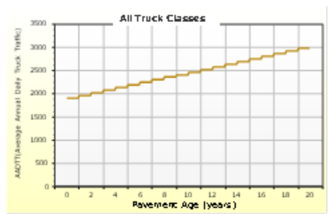
AADTT (Average Annual Daily Truck Traffic) Growth

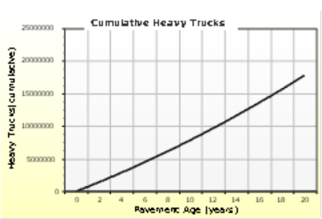
*** Traffic cap is not enforced**







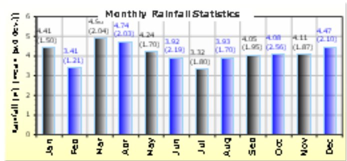




Climate Inputs

Climate Data Sources:

Climate Station Cities:	Location (lat lon elevation(ft))
US, MA	42.00000 -71.25000 148

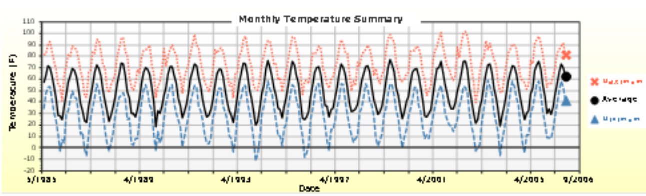


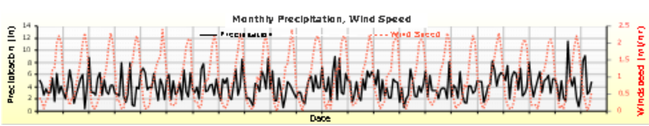
Annual Statistics:

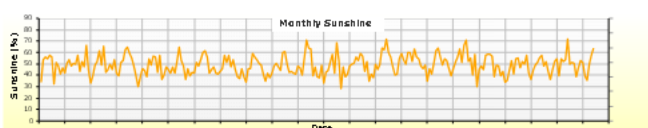
Mean annual air temperature (ºF)	49.50
Mean annual precipitation (in)	49.60
Freezing index (ºF - days)	528.51
Average annual number of freeze/thaw cycles:	85.91

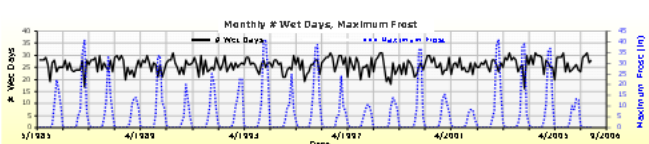
Water table depth (ft) 10.00

Monthly Climate Summary:

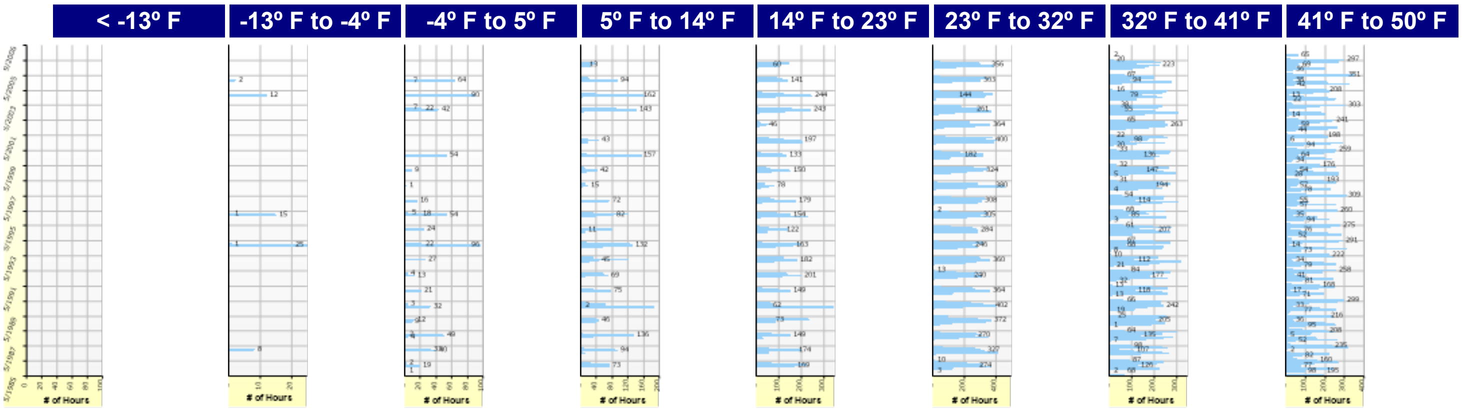


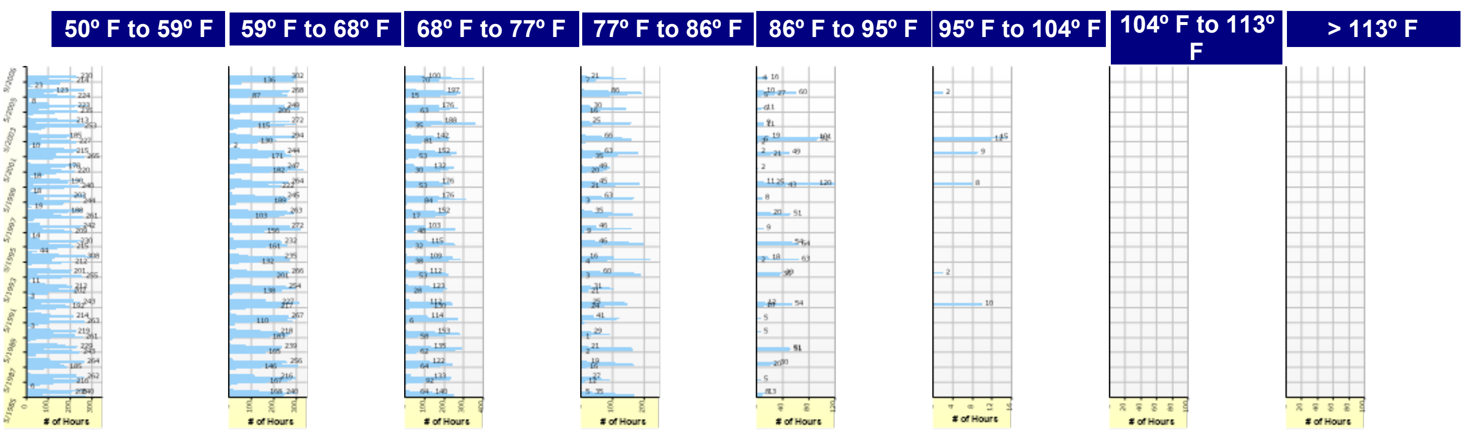






Hourly Air Temperature Distribution by Month:





Design Properties

HMA Design Properties

Use Multilayer Rutting Model	False
Using G* based model (not nationally calibrated)	False
Is NCHRP 1-37A HMA Rutting Model Coefficients	True
Endurance Limit	-
Use Reflective Cracking	True

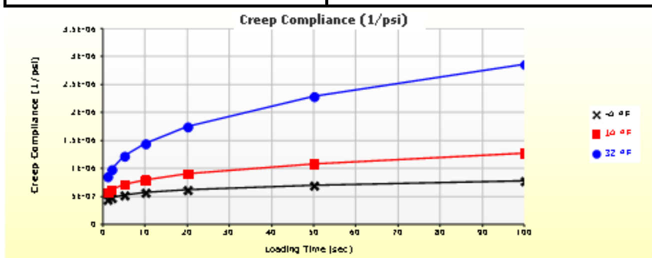
Structure - ICM Properties	
AC surface shortwave absorptivity	0.85

Layer Name	Layer Type	Interface Friction
Layer 1 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 2 Flexible : Default asphalt concrete	Flexible (1)	1.00
Layer 3 Sandwich/Fractured : Sandwich Granular	Sandwiched Granular (3)	1.00
Layer 4 Non-stabilized Base : Crushed stone	Non-stabilized Base (4)	1.00
Layer 5 Subgrade : A-3	Subgrade (5)	-

Thermal Cracking

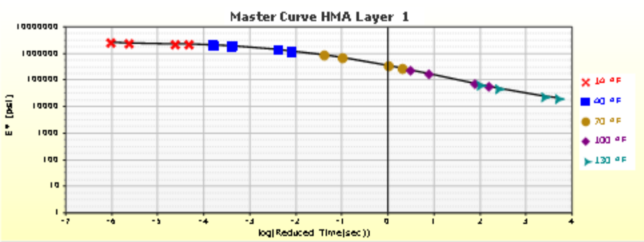
Thermal Contraction	
Is thermal contraction calculated?	True
Mix coefficient of thermal contraction (in/in/ºF)	-
Aggregate coefficient of thermal contraction (in/in/ºF)	5.0e-006
Voids in Mineral Aggregate (%)	19.3

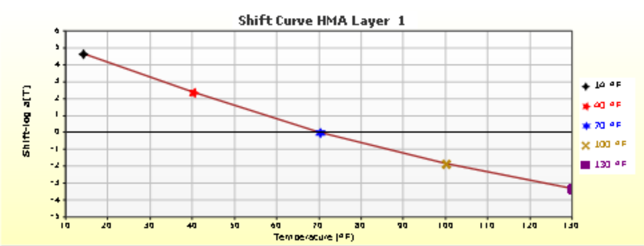
Indirect Tensile Strength (Input Level: 3)	
Test Temperature (ºF)	**Indirect Tensilte Strength (psi)**
14.0	535.05

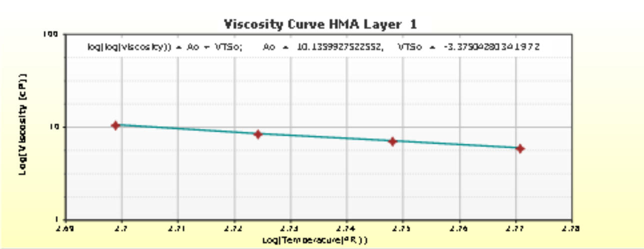


Creep Compliance (1/psi) (Input Level: 1)			
Loading time (sec)	**-4 ºF**	**14 ºF**	**32 ºF**
1	4.59e-007	5.78e-007	8.73e-007
2	4.91e-007	6.33e-007	1.00e-006
5	5.37e-007	7.20e-007	1.23e-006
10	5.79e-007	8.03e-007	1.46e-006
20	6.31e-007	9.07e-007	1.76e-006
50	7.15e-007	1.09e-006	2.31e-006
100	7.94e-007	1.27e-006	2.88e-006

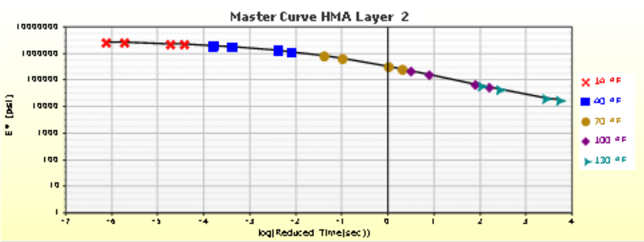
HMA Layer 1: Layer 1 Flexible : Default asphalt concrete

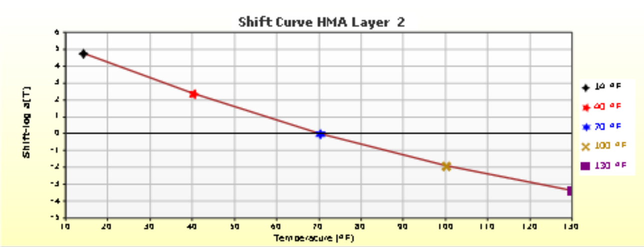


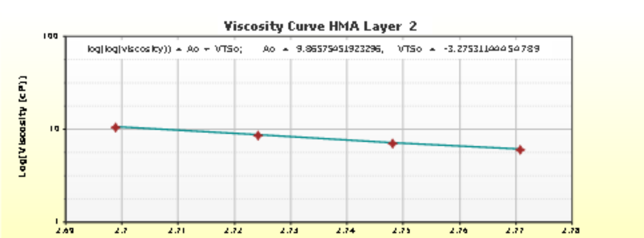




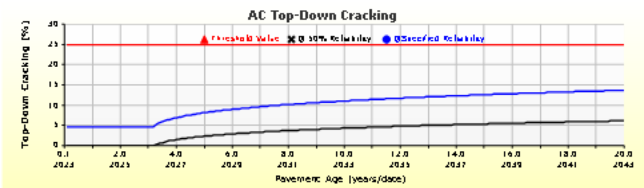
HMA Layer 2: Layer 2 Flexible : Default asphalt concrete



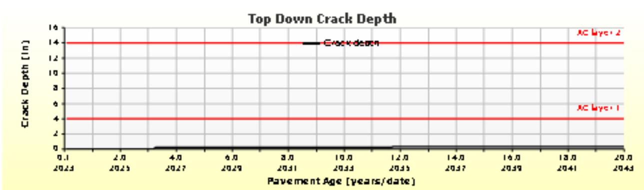




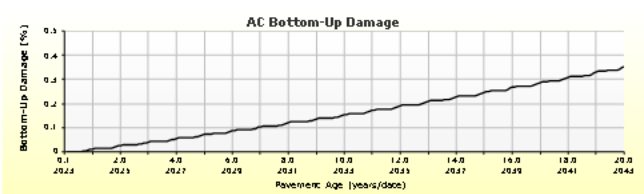
Analysis Output Charts



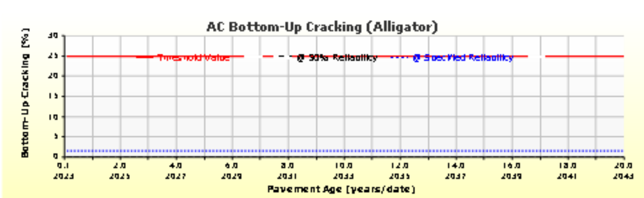
AC Top-Down Cracking
Top-Down Cracking (%)
Pavement Age (years/date)



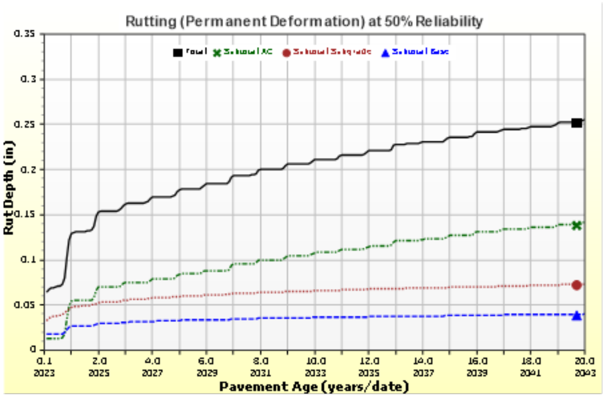
Top Down Crack Depth
Crack Depth (in)
Pavement Age (years/date)



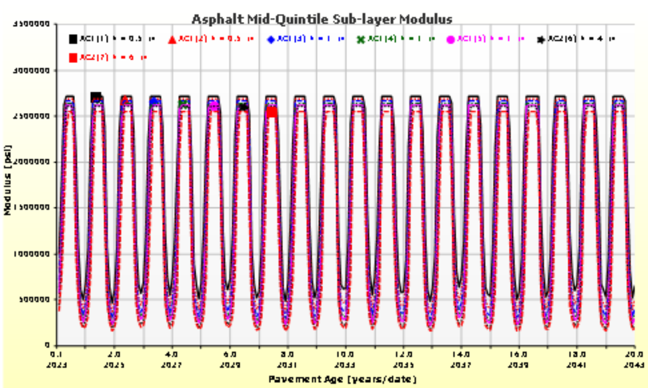
AC Bottom-Up Damage
Bottom-Up Damage (%)
Pavement Age (years/date)

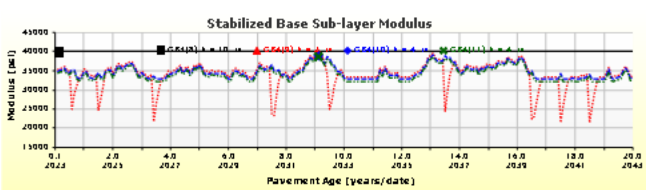


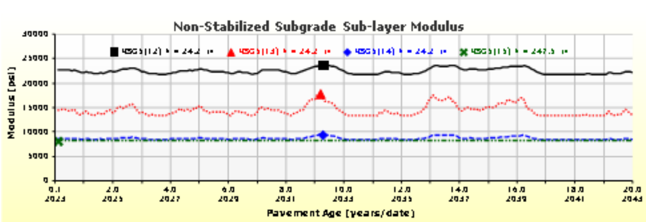
AC Bottom-Up Cracking (Alligator)
Bottom-Up Cracking (%)
Pavement Age (years/date)



Rutting (Permanent Deformation) at 50% Reliability
Rut Depth (in)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1 2023
2.0 2025
4.0 2027
6.0 2029
8.0 2031
10.0 2033
12.0 2035
14.0 2037
16.0 2039
18.0 2041
20.0 2043
Pavement Age (years/date)


Asphalt Mid-Quintile Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Stabilized Base Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)


Non-Stabilized Subgrade Sub-layer Modulus
Modulus (psi)
Pavement Age (years/date)

Layer Information

Layer 1 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	4.0	
Unit weight (pcf)	154.8	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	28 Hz
14	1986813	2242596	2342385	2556151	2642254	2751982
40	893759	1244488	1396507	1729190	1859997	2020530
70	181514	318279	400032	649389	780739	970773
100	30885	52492	66970	119747	153965	213747
130	15657	22958	27985	46945	59696	82781

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	13567	71.9
136.4	6327	74.1
147.2	3023	76.3
158	1493	78.6
168.8	758	80.8

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	12.3
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	5.6
Aggregate parameter	0.4021

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Flexible : Default asphalt concrete

Asphalt		
Thickness (in)	10.0	
Unit weight (pcf)	151.0	
Poisson's ratio	Is Calculated?	False
	Ratio	0.35
	Parameter A	-
	Parameter B	-

Asphalt Dynamic Modulus (Input Level: 1)

T (ºF)	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	1831281	2170217	2306190	2600111	2718387	2868225
40	769108	1110180	1268797	1641251	1797357	1995914
70	172011	297675	372537	602814	726510	909822
100	28952	49683	63341	112290	143604	197884
130	12763	19138	23449	39416	50001	68990

Asphalt Binder

Temperature (ºF)	Binder Gstar (Pa)	Phase angle (deg)
125.6	15433	70.1
136.4	7447	72.1
147.2	3630	74.4
158	1803	76.8
168.8	928	79

General Info

Name	Value
Reference temperature (ºF)	70
Effective binder content (%)	9.2
Air voids (%)	7
Thermal conductivity (BTU/hr-ft-ºF)	0.67
Heat capacity (BTU/lb-ºF)	0.23
Asphalt content by weight (%)	-
Aggregate parameter	-

Identifiers

Field	Value
Display name/identifier	Default asphalt concrete
Description of object	
Author	
Date Created	10/30/2010 1:00:00 AM
Approver	
Date approved	10/30/2010 1:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Sandwich/Fractured : Sandwich Granular

Sandwiched Granular	
Layer thickness (in)	10
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	40000

Thermal	
Heat capacity (BTU/lb-ºF)	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	Sandwich Granular
Description of object	Default
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 4 Non-stabilized Base : Crushed stone

Unbound	
Layer thickness (in)	10.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
30000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	Crushed stone
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Water Content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#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
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 5 Subgrade : A-3

Unbound	
Layer thickness (in)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	A-3
Description of object	Default material
Author	AASHTO
Date Created	1/1/2011 12:00:00 AM
Approver	
Date approved	1/1/2011 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 1	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	11.0
Plasticity Index	0.0
Is layer compacted?	True

	Is User Defined?	Value
Maximum dry unit weight (pcf)	True	120
Saturated hydraulic conductivity (ft/hr)	False	3.777e-03
Specific gravity of solids	False	2.7
Water Content (%)	False	7.3

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	4.7572
bf	2.8814
cf	0.8694
hr	100.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	5.2
#100	
#80	33.0
#60	
#50	
#40	76.8
#30	
#20	
#16	
#10	93.4
#8	
#4	95.3
3/8-in.	96.6
1/2-in.	97.1
3/4-in.	98.0
1-in.	98.6
1 1/2-in.	99.2
2-in.	99.7
2 1/2-in.	
3-in.	
3 1/2-in.	99.9

Calibration Coefficients

$N_f = 0.00432 * C * \beta_{f1} k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 \beta_{f2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f3}}$ $C = 10^M$ $M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$	k1: 3.75
	k2: 2.87
	k3: 1.46
	Bf1: 0.001032
	Bf2: 1.38
	Bf3: 0.88

AC Rutting

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}}$$
$$k_z = (C_1 + C_2 * depth) * 0.328196^{depth}$$
$$C_1 = -0.1039 * H_\alpha^2 + 2.4868 * H_\alpha - 17.342$$
$$C_2 = 0.0172 * H_\alpha^2 - 1.7331 * H_\alpha + 27.428$$

Where:

H_{ac} = total AC thickness(in)

ε_p = plastic strain(in/in)
ε_r = resilient strain(in/in)
T = layer temperature(°F)
N = number of load repetitions

acRuttingStandardDeviation	0.24 * Pow(RUT,0.8026) + 0.001	
AC Layer 1	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36
AC Layer 2	K1:-2.45 K2:3.01 K3:0.22	Br1:0.4 Br2:0.52 Br3:1.36

Thermal Fracture

$$C_f = \beta_{t1} N\left[\frac{1}{\sigma_d} log\left(\frac{C}{h_{AC}}\right)\right]$$

$$\Delta C = A(\Delta K)^n$$

$$A = k_t \beta_t 10^{[4.389 - 2.52 \log(E_{HMA} \sigma_m n)]}$$

Cf = Observed amount of thermal cracking, ft. / 500ft.
β_{t1} = Regression coefficient determined through global calibration (400)
N[z] = Standard normal distribution evaluated at [z]
σ_d = Standard deviation of the logarithm of crack depth in the pavement (0.769), in.
C = Crack depth, in.
h_{AC} = Thickness of asphalt layer, in.
ΔC = Change in the crack depth due to a cooling cycle
ΔK = Change in the stress intensity factor due to a cooling cycle
A, n = Fracture parameters for the asphalt mixture
E = Asphalt mixture stiffness, MPa
σ_m = Undamaged mixture tensile strength, MPa
k_t = Regression coefficient determined through field calibration
β_t = Calibration parameter

Level 1 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 1 Standard Deviation: 0.14 * THERMAL + 168
Level 2 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 2 Standard Deviation: 0.20 * THERMAL + 168
Level 3 K: ((3 * Pow(10,-7)) * Pow(MAAT,4.0319)) * 1 + 0	Level 3 Standard Deviation: 0.289 * THERMAL + 168

CSM Fatigue

$$N_f = 10^{\left(\frac{k_1 \beta_{c1}\left(\frac{\sigma_s}{M_r}\right)}{k_2 \beta_{c2}}\right)}$$

N_f = number of repetitions to fatigue cracking
σ_s = Tensile stress(psi)
M_r = modulus of rupture(psi)

k1: 0.972	k2: 0.0825	Bc1: 1	Bc2:1

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \left| e^{-\left(\frac{\rho}{N}\right)^{\beta}} \right|$$

δ_a = permanent deformation for the layer
N = number of repetitions
ε_v = average veritcal strain(in/in)
$\varepsilon_0, \beta, \rho$ = material properties
ε_r = resilient strain(in/in)

k1: 0.965	Bs1: 1	k1: 0.965	Bs1: 1
Standard Deviation (BASERUT) 0.1477 * Pow(BASERUT,0.6711) + 0.001		Standard Deviation (BASERUT) 0.1235 * Pow(SUBRUT,0.5012) + 0.001	

$$L(t) = L_{Max} e^{-\left(\frac{C_1 \rho}{t - C_3 t_o}\right)^{C_2 \beta}}$$

$$t_0(\text{Days}) = \frac{k_{L1}}{1 + e^{(k_{L2} \times 100 \times a_0 / 2A_0) + (k_{L3} \times HT) + (k_{L4} \times LT) + (k_{L5} \times \log_{10} AADTT)}}$$

$$FC = \left(\frac{6000}{1 + e^{\left(C_1 * C_1' + C_2 * C_2' \log_{10}(D * 100)\right)}}\right) * \left(\frac{1}{60}\right)$$

$$C_2' = -2.40874 - 39.748 * (1 + h_{ac})^{-2.856}$$

$$C_1' = -2 * C_2'$$

c1: 2.5219	c2: 0.8069	c3: 1	c1: 1.31	c2: 3.9666	c3: 6000
kL1: 64271618	kL2: 0.2855	kL3: 0.011			
kL4: 0.01488	kL5: 3.266		1.13 + 13/(1+exp(7.57-15.5*LOG10(BOTTOM+0.0001)))		

0.3657 * TOP + 3.6563

$$FC_{ctb} = C_1 + \frac{C_2}{1 + e^{C_3 - C_4 * \log_{10}(Damage)}}$$

C1 - Rutting
C2 - Fatigue Crack
C3 - Transverse Crack
C4 - Site Factors

C1: 0	C2: 75	C3: 2	C4: 2	C1: 40	C2: 0.4	C3: 0.008	C4: 0.015

csmCrackingStandardDeviation
CTB*1