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Sensitivity Analyses of Flexible Pavement Performance in VT, NY and MA using the Mechanistic-Empirical Pavement Design Guide

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Sensitivity Analyses of Flexible Pavement Performance in VT, NY and MA using the Mechanistic-Empirical Pavement Design Guide

BY

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THESIS

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ABSTRACT

Many state highway agencies are in the process of transitioning pavement design procedures from the empirical AASHTO design to the new M-E PDG. The New England states and the State of New York initiated NETC Project 06-1 "New England Verification of NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide with Level 2&3 Inputs" to gather more information about the new design and to make the implementation process smoother. The objective of this project was to evaluate which of the Level 2 and 3 input variables require state specific information, which of the national default values are acceptable for the M-E PDG in New England and New York, which variables are available and collected by the state agencies, and for which variables regional or local calibration will be necessary. This study identified critical state specific factors affecting predicted flexible pavement distresses and roughness as well as to what degree. This thesis presents data, analysis, state specific recommendations, and general conclusions for the states of Vermont, Massachusetts and New York.

Acknowledgements

I would like to thank Dr. Jo S. Daniel for her guidance and mentoring through my research work and graduate career. I am especially thankful to her for her motivational support and providing me the opportunity to explore, understand and integrate different sources of information for successfully conducting my research. I would also like to thank Dr. David L. Gress and Dr. Jeff Melton for serving as members on my thesis committee. I would especially like to thank my wife Marzanna and my son Michael Alexander for their help and support throughout my graduate career at the University of New Hampshire.

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Chapter 1: Introduction

Most of the State Highway Agencies (80%) are still using pavement design methods based on empirical equations derived from the American Association of State Highway Officials (AASHO) Road Test that was conducted in the late 1950s. The test was conducted with modest traffic levels compared to current traffic levels, with limited structural sections, and the test was based on the study of only one location in Ottawa, Illinois. The results from the AASHO Road Test have limited application relative to current pavement design criteria in use today. To address this, in the mid-1990s, the National Cooperative Highway Research Program began work on a design guide based on a mechanistic-empirical approach. Representatives from state DOT's, HMA and PCC paving industries, academia and FHWA worked together to deliver a novel pavement design software called the Mechanistic-Empirical Pavement Design Guide (M-E PDG). This user friendly M-E PDG software predicts the pavement condition over time taking into consideration of many different factors including traffic, climate and pavement structure.

The Mechanistic-Empirical Pavement Design Guide (M-E PDG) was developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A for design of flexible and rigid pavement structures. The mechanistic-empirical approach of the M-E PDG methodology represents a fundamental shift for pavement design. It considers the input parameters that influence pavement performance – including traffic, climate, pavement, unbound material structure and layer thickness – and applies the principles of engineering mechanics to predict critical pavement responses. The responses of the pavement defined in terms of stresses, strains and as well as other parameters are analyzed using rigorous theories of mechanics, and subsequently the critical response quantities are empirically related to pavement performance.

The M-E PDG changes the design process, required inputs and the way engineers develop and implement efficient and effective pavement design (2) (3). The M-E PDG does not provide the user with a design thickness of the pavement (like the AASHTO design does), but rather provides the user with projected pavement distresses and smoothness (IRI) over the design period. The design process is completed after user's acceptance of the projected level of distresses.

In 2006 the New England Transportation Consortium (NETC) introduced Project NETC 06-1 "New England Verification of NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide with Level 2&3 Inputs". The main purpose of this project was to help New England states and the State of New York to gather more information about this new pavement design, to realize advantages over the existing AASHTO methods, as well as to provide recommendations of steps that need to be taken before the decision to implement the M-E PDG.

1.1 Objective

The main objective of the research was to identify critical state specific factors affecting predicted pavement performance for level 2 and 3 M-E PDG input values, in Vermont, New York and Massachusetts. The research focused only on the mechanistic-empirical design of new flexible pavements with a 20 year design life. The research also provides the state highway agencies with the option of using default inputs for low volume roads, addresses some issues and concerns that arose during the design process, identifies the necessity for a local calibration or field and laboratory data evaluations, and specifies the guidelines for future implementation strategy in terms of data collection techniques and existence of required specifications for the M-E PDG design. This research is a part of the New England Transportation Consortium (NETC) Project 06-1: "New England Verification of NCHRP 1-37A Mechanistic – Empirical Pavement Design Guide with Level 2 and 3 Inputs" and is presented in this thesis.

For all research sensitivity analyses the M-E PDG version 1.1 was used. Version 1.1 outputs were compared, during the first phase of the research, to results from the previous analyses, which used the 1.0 version software with different states (RI, CT, ME and NH) (4).

1.2 Research Significance

The mechanistic-empirical pavement design guide (M-E PDG) procedure requires defining a large number of traffic, climate and material related inputs by the pavement designer before conducting an analysis. Therefore, before conducting any runs, the designer must determine which variables are to remain fixed and at what level, which inputs need to be investigated and which input value ranges are to be used for the sensitivity analysis to represent specific conditions. It is known that not all inputs in the performance models have an equal impact on the predicted distresses. Therefore, it is very important to try to determine which variables have the largest impact for the typical pavement design. The sensitivity analysis can determine the impact on pavement performance caused by individual changes in the previously selected significant design inputs.

The sensitivity analyses were conducted only for new flexible pavements throughout three states (VT, NY and MA) with inputs variables based on the relevant state's Department of Transportation (DOT) specifications, LTPP database, climatic stations data, selected project locations, and other findings obtained from both the internet and from published literature, e.g., research papers.

The research significance was to determine the critical state specific factors as well as to provide an analysis of their influence on the M-E PDG prediction data.

1.3 Research Tasks

The following identify the steps which were used to perform the Sensitivity analysis process:

1. Identification of the LTPP road sections.
2. Collection of all necessary input values. Analysis data and values were based on an existing pavement structure, material properties, tolerances, specifications, monitored performance or literature review.

3. Evaluation of the accuracy and adequacy of data collection.
4. Identification of critical inputs which could affect the M-E PDG pavement distress predictions.
5. Selection of the control input file, which was used as a baseline for the sensitivity analysis.
6. Variation of one input value over its typical range while holding other inputs constant and analysis using the M-E PDG software.
7. Repetition of the same process for all critical inputs for the design, including climatic, traffic inputs, material properties and structural design parameters.
8. Identification of the state specific critical input variables based on the M-E PDG runs and comparison to nationally calibrated data.
9. Presention of sensitivity analysis in graphical form and summarization of the pavement performance results.

1.4 Organization of Thesis

Chapter 2 presents a literature review of the M-E PDG. It presents the history and background of the M-E PDG, the existing AASHTO methodology, differences between these two designing methods, critical input parameters for the M-E PDG, and findings from completed research activities in Indiana, Ohio, and South Dakota.

Chapter 3 presents a research methodology used for this study. It contains data collection methods, tolerances used by the respective states, and input values required for M-E PDG.

Chapter 4 presents data analysis, results and discussion for the states of VT, NY and MA.

Chapter 5 presents state specific recommendations, general conclusions, and recommendations for future work.

Chapter 2: Literature Review

Results of the literature review are summarized in the following section. The significant findings from the literature review were applied to this research.

2.1 Background of Flexible Pavement Design

2.1.1 Existing AASHTO Methodology

Starting in the 1920s the State Highway Agencies and the Bureau of Public Roads started a series of road tests to determine the relationship between axle loading and pavement structure on pavement performance (2). This knowledge was needed to assist in the design of pavements to establish maximum load limits, and to provide a basis for the allocation of highway user taxation. The AASHO Road Test (1958-1960) was the last of the series. It was conducted with limited structural sections at one location in Ottawa, Illinois. The test studied the performance of known thickness pavement structures under moving loads of known magnitude and frequency. These tests were conducted for both pavement types: asphaltic concrete and portland cement concrete. The test facilities had six loops of 7 mile two-lane pavements (Figure 2), which contained 836 test sections with a wide range of surface, base and subbase thicknesses. Test traffic was inaugurated on October 15, 1958 and ended November 30, 1960 (Figure 1).

Five of the loops were exposed to traffic loading shown in Figure 3, and one was used to test environmental effects.

Figure 1: Test Vehicles during the 1950s AASHO Road Test (Ref: AASHTO Design Guide, 1972).

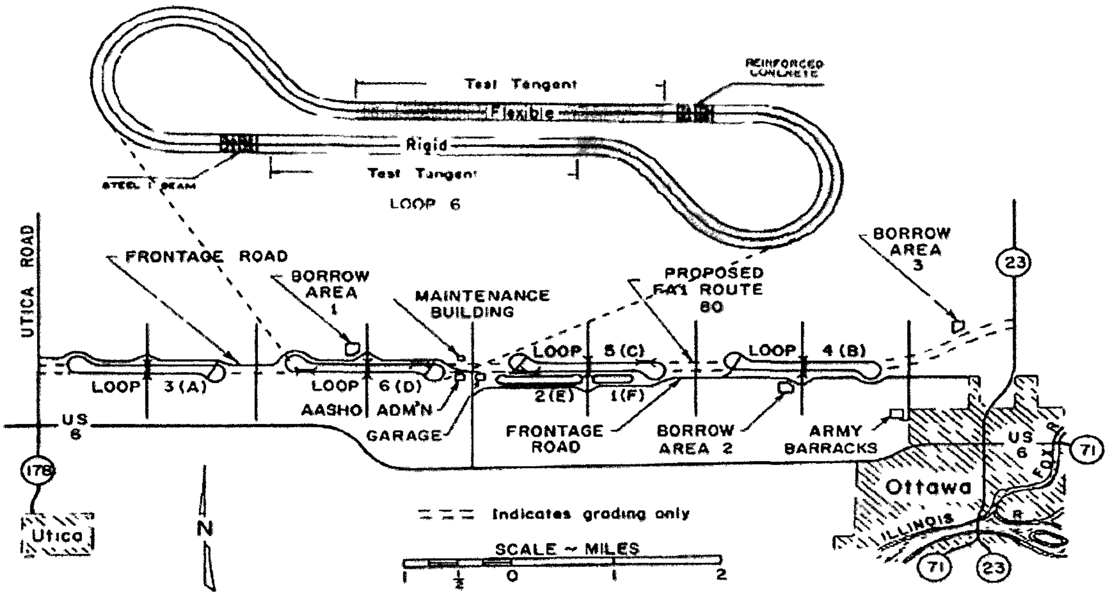


Figure 2: AASHO Road Test Layout (Ref. Smith and Skok, Transportation Research Circular, July 2007).

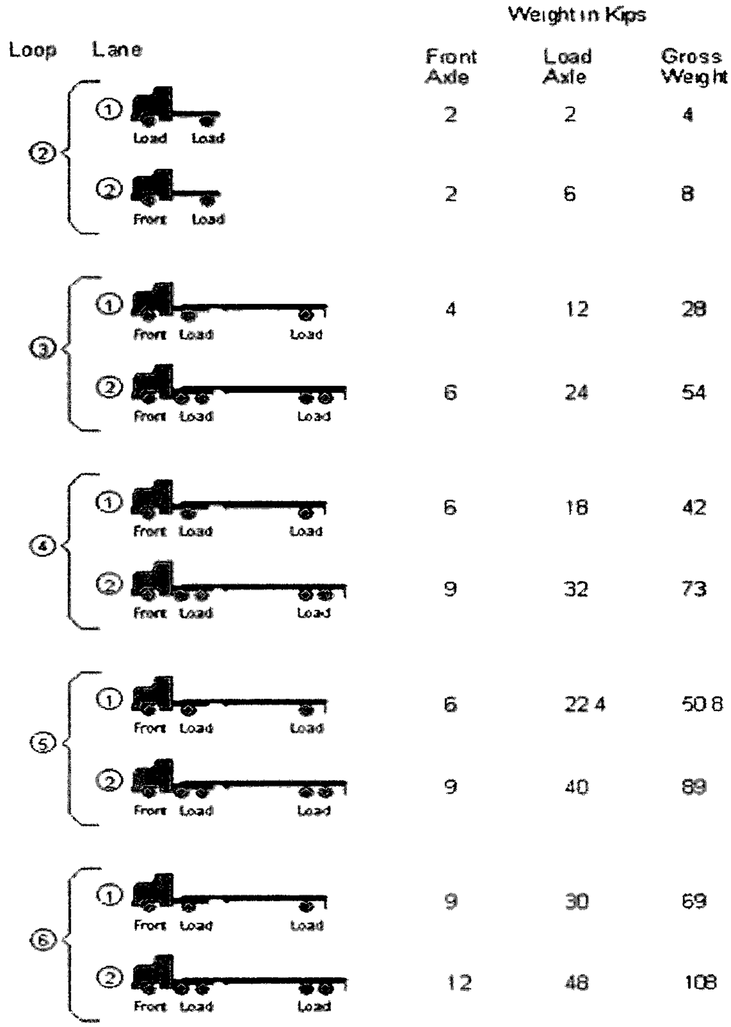


Figure 3: Axle Weights and Distributions Used on Various Loops of the AASHO Road Test
(Ref:http://training.ce.washington.edu/wsdot/Modules/06_structural_design/aasho_road_test.htm).

The test data established the relationships for pavement structural designs based on expected loadings over the life of a pavement. Figure 4 shows the construction of the flexible pavement section for the AASHO Road Test.

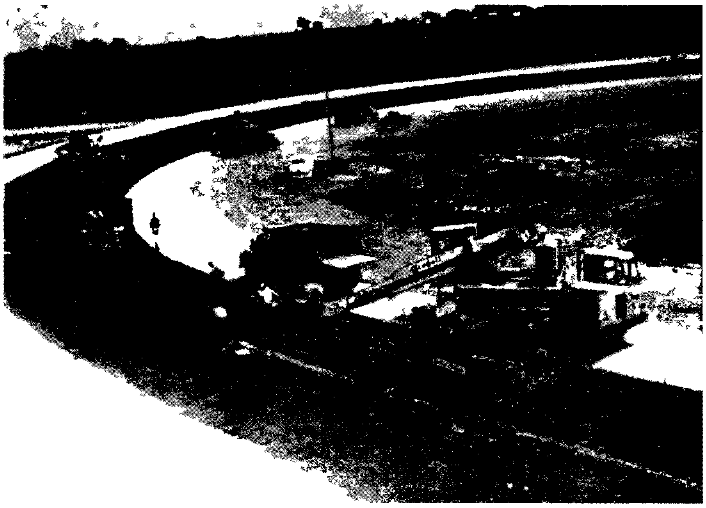


Figure 4: Bituminous Concrete Construction for AASHO Road Test
(Ref. CH. Wagner, FHWA – Resource Center, February 2007).

Following completion of the Road Test, in May 1962 the AASHO Design Committee reported the development of the AASHO Interim Design Guides (1st – Flexible, and 2nd – Rigid Pavement Structures). All the pavement design procedures within these Interim Design Guides were based on the results from the AASHO Road Test and were supported by existing design procedures and available theory. Although the AASHO Road Test represented the most comprehensive development of the relationship between traffic loadings, material characteristics, structural thicknesses and performance, the results were limited by the scope of the test and conditions under which it was conducted. The performance equations from the AASHO Road Test were developed based on: (2)

- Specific set of paving materials
- One subgrade material type
- A single environment
- An accelerated procedure for accumulating traffic

- Accumulation of traffic on each test section by operating vehicles with identical loads and axle configuration, rather than by mixed traffic.

To develop a new design procedure for a different location it was necessary to make certain assumptions, which adjusted the different traffic conditions, specific climate and material types.

The assumptions and limitations associated with each design procedure were enumerated in the guides, and each emphasized that:

"The Guide is interim in nature and it is subject to adjustment based on experience and additional research" (2).

The 1962 Interim Guide was first revised in 1972 (2). The design methods and procedures contained in 1962 version of the guide were not changed in the 1972 revision, but both the flexible and rigid design guides were incorporated into one document.

A more significant revision to the Interim Guide was made in 1986, however the procedures were still based on the performance equations developed in the 1960s (5). At this revision several important items were considered:

- Resilient modulus for roadbed soils was recommended for characterizing soil support
- Design reliability for adding safety to the pavement structure
- The resilient modulus test (AASHTO Test T-247) was recommended for determining layer coefficient in flexible pavement design
- Subsurface drainage
- Environmental factors such as frost heave, thaw weakening and swelling soils

- Rehabilitation of pavements
- Discussion on the mechanistic-empirical design.

The 1986 Guide for Design of Pavement Structures was, for the first time, not labeled as interim.

The most recent revision of the Guide for Design of Pavement Structures, which guide included the consideration of the flexible pavements was introduced in 1993 (3).

2.1.2 M-E PDG Methodology

In December 1996, the National Cooperative Program (NCHRP) started Project 01-37A: "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures," which was the initial step for developing a new pavement design process. The design procedure developed under this project was a large leap forward from existing practice. Project 1-37A was completed in 2004 and has entered the implementation process. As of December, 2010 forty states in the US (Figure 5) are planning to adopt this design procedure (a few states are already using it), now known as the Mechanistic-Empirical Pavement Design Guide (M-E PDG).

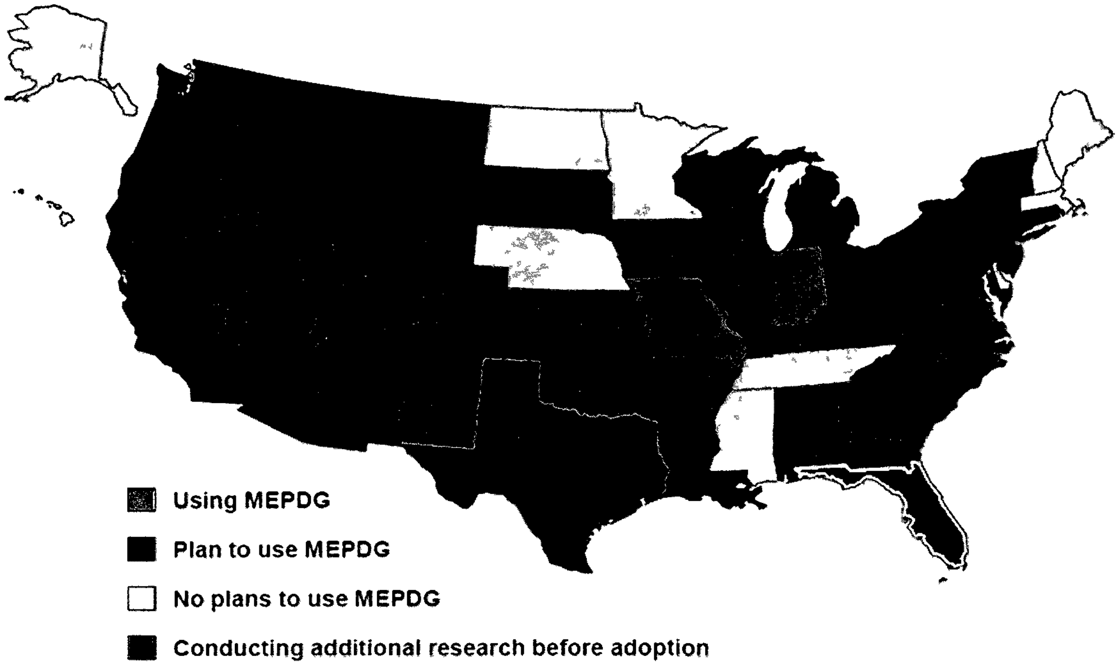


Figure 5: M-E PDG Implementation Status as of December, 2010 (Ref: Federal Highway Administration Office of Pavement Technology, December 2010).

The M-E PDG design incorporates a hierarchical approach to design inputs for subgrade, materials, environment, and traffic information. Three levels of hierarchy are provided for within the design inputs:

- **Level 1** – the highest level of prediction. This level would be used for designing heavily trafficked pavements. Material inputs would require field or laboratory evaluation.
- **Level 2** – an intermediate level of prediction. This level could be used when resources or testing equipment are not available. Inputs would be estimated via correlations or experience.

- **Level 3** – the lowest level of prediction. This level might be used for designing low volume roads, in which there are minimal consequences of early failure. Inputs are based on global or regional values.

The engineers select the inputs and determine the types and quantities of data needed for a reliable design. This process requires a thorough evaluation of all of design parameters and a detailed analysis of how the input values will affect the predicted performance. The M-E PDG design process therefore demands a huge amount of information from the engineers concerning pavement inputs and pavement performance.

Figure 6 provides a flow chart for the mechanistic-empirical design approach as implemented in the M-E PDG procedures (6).

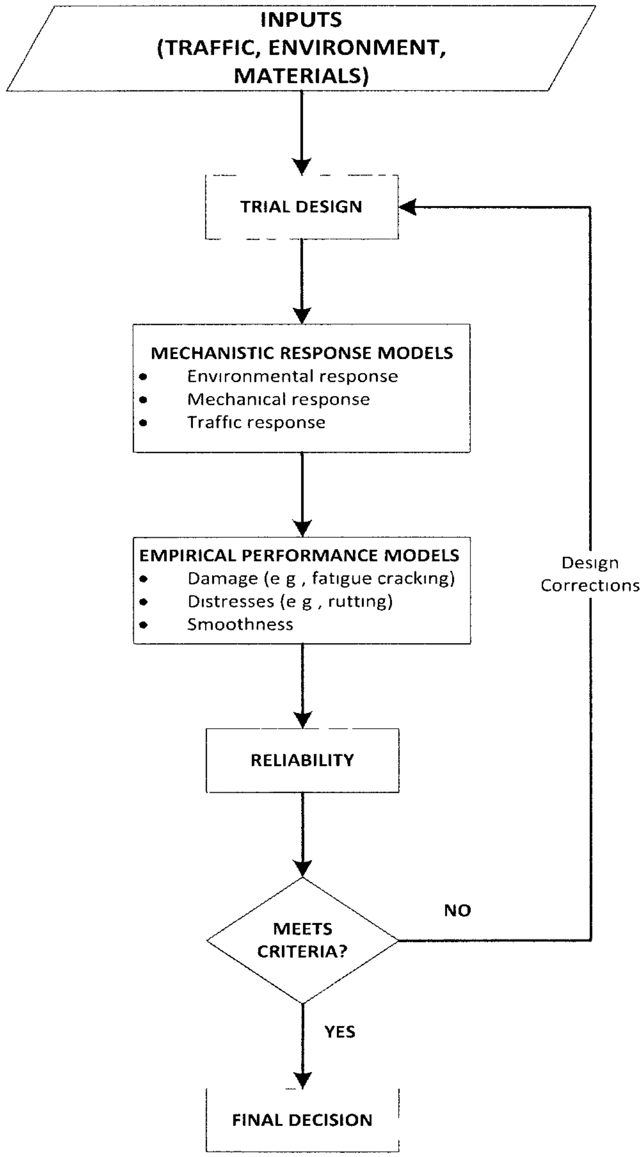


Figure 6: Flow Chart for Mechanistic-Empirical Design Methodology (6).

The following lists the major steps in this design methodology for a new flexible pavement:

1. Specify and define the required inputs including traffic, environmental, materials, etc.
2. Select a trial pavement section for analysis.

3. Define the properties of materials in the various pavement layers.
4. Analyze the pavement response due to traffic loading and environmental influences.
5. Empirically relate critical pavement responses to damage and distress for the pavement distresses of interest.
6. Adjust the predicted distresses for the specified design reliability.
7. Compare the predicted distresses at the end of pavement design life against design limits.
8. If necessary, adjust the trial pavement section and repeat steps 3-7 until all predicted distresses are within design limits.

To implement the above mechanistic-empirical methodology, the following corresponding major components are needed:

- Inputs – traffic, materials, climate and other general values (e.g. design life, latitude, longitude and elevation)
- Pavement response model
- Environmental response model
- Material characterization model
- Performance prediction model
- Design reliability – to increase the safety of the design
- Software – to implement the mechanistic-empirical models and calculation in a usable form.

The M-E PDG "system" has been designed in a modular fashion. This approach recognizes that pavement response is a function of three primary influences: environmental (climate), traffic, and pavement (materials and thicknesses). The mechanistic-empirical process is outlined in Figure 7 (7).

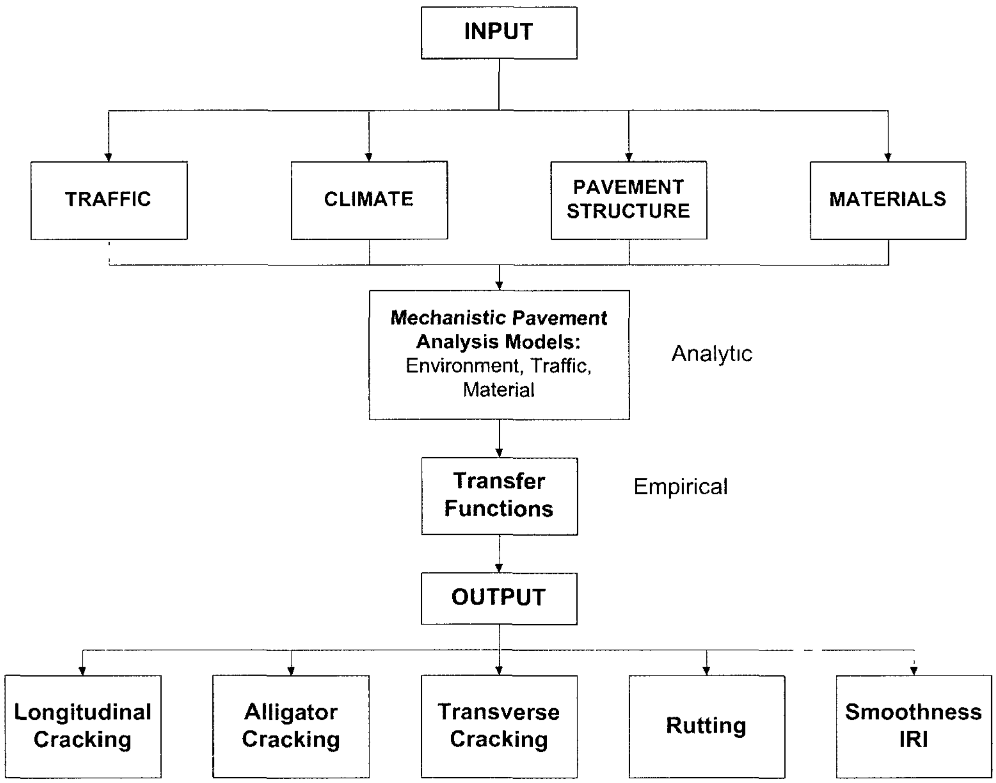


Figure 7: M-E PDG Outline Process (7).

The environmental model plays a significant role in the performance of pavement. The M-E PDG software provides environmental data sets for specific locations from over 800 weather stations throughout the U.S., as well as historical records for up to 10 years. This model recognizes not only external factors such as temperature, precipitation, freeze-thaw cycles and depth to water table, but also internal factors such as the susceptibility of the pavements materials to moisture and frost heaving, drainage ability of the paving layers and potential infiltration of the pavements. Temperature and moisture variations within the pavement structures and subgrade over the design life of pavement are simulated by the Enhanced Integrated Climatic Model (EICM).

The traffic model inputs are also significant for the analysis and design of pavement structures. The mechanistic response model in the M-E PDG requires the magnitudes and frequencies of the actual wheel load that the pavement is expected to experience over its design life. Typically, state highway agencies collect two categories of traffic data: weight-in-motion (WIM) and Automatic Vehicle Classification (AVC). WIM data provides information about truck axle weights and gross vehicle weights as they drive over a sensor. AVC data provides information about the number and types of vehicles that use a given roadway over some period of time.

The material characterization model is used in the M-E PDG to calculate the stresses, strains and deflections in the pavement. Pavement performance is evaluated in the M-E PDG by individual empirical distress models, also termed as transfer functions.

"The transfer function is the empirical part of the distress prediction model that relates the critical pavement response parameter, either directly or through the damage concept, to pavement distress" (8).

Empirical models are incorporated in the M-E PDG for the major structural distresses and smoothness estimation in flexible pavements.

Distress prediction equations and transfer functions for flexible pavements and HMA overlays are listed in Table 1 (9) (4).

Table 1: Distress Prediction Equations and Transfer Functions (9) (4).

Distress Type	Equations	Terms
Fatigue Cracking	$N_f = 0.00432 \times k_1 C \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \left(\frac{1}{E}\right)^{1.281}$	N_F=Number of repetitions to fatigue cracking k_1=correction for asphalt layer thickness E=stiffness of material ε_t=tensile strain at critical location C=laboratory to field adjustment factor
Alligator Cracking (Bottom-Up)	$FC_{Bottom} = \left(\frac{1}{60}\right)\left(\frac{C_4}{1 + e^{\left(C_1 C_1' + C_2 C_2' Log(DI_{Bottom})\right)}}\right)$	FC_{Bottom}=Bottom-Up Cracking (%) C_1, C_1',C_2, C_2',C_4=calibration functions; C_4=6000 DI_{Bottom}=Cumulative damage index at the bottom of the HMA layers
Transverse Cracking	$TC = \beta_1 N\left[\frac{1}{\delta_d} Log\left(\frac{C_d}{H_{HMA}}\right)\right]$	TC=thermal cracking, ft/mi β_1=Regression coefficient determined through global calibration N[z]=standard normal distribution evaluated at [z] δ_d=Standard deviation of log of the depth of cracks in the pavement (0.7690, in C_d=Crack depth, in H_{HMA}=Thickness of HMA layers, in
Longitudinal (Top-Down Fatigue) cracking	$FC_{Top} = \left(\frac{1000}{1 + e^{(7.0 - 3.5x \times (D \times 100))}}\right)$	FC_{Top}=top-down cracking, ft/mi D=top-down fatigue damage coefficient

Rutting in Unbound Materials	$\delta_a(N) = \beta_1 \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \varepsilon_v \times h$	$\delta_a(N)$=Permanent deformation of layer, in N=Number of traffic repetitions β_1=Local calibration factor ε_0,β,ρ=material properties ε_r=Resilient strain imposed in laboratory test to obtain above properties ε_v=Average resilient strain from primary response model h=Thickness of layer/sublayer
Rutting in Asphalt Layer	$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \times 10^{-3.4488} T^{1.5606} N^{0.479244}$	ε_p=Accumulated plastic strain at N load repetitions ε_r=Resilient strain of asphalt as a function of mix properties, temperature and loading time k_1=correction for asphalt layer thickness T=Temperature, ^oF N=Number of load repetitions
Smoothness (IRI)	$IRI = IRI_o + 0.0150(SF) + 0.400(FC_{Total}) + 0.0080(TC) + 40.0(RD)$ $SF = FROSTH + SWELL \times AGE^{1.5}$ $FROSTH = LN([PRECIP + 1] \times FINES \times [FI + 1])$ $SWELL = LN([PRECIP + 1] \times CLAY \times [PI + 1])$ $FINES = FSAND + SILT$	IRI=Smoothness, in/mi IRI_o=Initial IRI after construction, in/mi FC_{Total}=Area of fatigue cracking TC=Length of transverse cracking, ft/mi RD=Average rut depth, in SF=Site Factor AGE= Pavement age, years PRECIP=Mean annual precipitation, in PI=Subgrade plasticity index FI=Mean annual freezing index

Smoothness (IRI) (Continued)		CLAY=Amount of clay particles in subgrade FSAND=Amount of fine sand particles in subgrade SILT=Amount of particles in subgrade

2.1.3 AASHTO vs. M-E PDG Design Guide

Table 2 shows some major differences between the old AASHTO pavement design guides and the M-E PDG design.

Table 2: AASHTO versus M-E PDG Design.

AASHTO Design	M-E PDG Design
Predicts AC thickness	Predicts pavement performance
Northern Illinois (wet-freeze climate) based	Uses more than 800 weather stations
One subgrade type (A-6 silty sand)	Project specific subgrade type
Uses equivalent single axle load (ESAL)	Individual Axle type and actual loading per axle
Uses Structural Number (SN) for flexible pavements	HMA specific characteristics
AASHO Road Test database	LTPP and NCDC databases

2.2 Critical Input Parameters

The M-E PDG is used to calculate all the pavement responses and to predict the resulting distresses but the program requires a large number of design inputs. Many of these inputs are more sophisticated than those currently being collected by the state highway agencies

(SHA). Some design inputs are more critical for the prediction of pavement distresses than others. Knowing the critical inputs necessary for the design process will definitely reduce SHA's overall cost and minimize the required resources.

This section provides an example of critical input parameters based on research conducted by different states highway agencies, with the focus on flexible pavements (3).

Traffic Inputs

The M-E PDG uses axle load spectra data, which includes collecting following traffic-related inputs:

a) Initial two-way Annual Average Daily Truck Traffic (AADTT)

b) Number of lanes in design direction (%)

c) Percent of trucks in design line (%)

d) Operational speed (mph)

Traffic volume adjustments:

a) Monthly adjustment by vehicle class specification

b) Vehicle class distribution

c) Hourly distribution

d) Traffic growth factor

Axle load distribution factor:

a) Level 1: site specific

b) Level 2: regional (not used in the M-E PDG version 1.1)

c) Level 3: default

General Traffic Inputs:

a) Mean wheel location
b) Traffic wander standard deviation
c) Design lane width (ft)
d) Number of axles per truck, axle configuration and wheelbase

Climatic Inputs

Within the M-E PDG, the Enhanced Integrated Climatic Model (EICM) handles the input, collection, characterization and analysis of environmental and material properties which determine the stiffness or modulus of unbound materials (10). This stiffness significantly influences the pavement distresses predicted by M-E PDG. The following are climatic-related inputs:

General Information:

a) Base/subgrade construction completion dates
b) Existing pavement construction date (required for overlay design)
c) Pavement construction date (required for new and overlay design)
d) Date when the pavement will be opened to traffic

Weather-related information:

a) Hourly values for past air temperatures, precipitation, wind speed, percentage sunshine, relative humidity, etc. This information is available from over 800 weather stations throughout the U.S.

Ground water table depth:

a) At level 1 could be determined from borings.

b) At the level 2 and 3 could be determined from local wells or county soil reports.

Drainage and surface properties:

a) Water infiltration potential of the drainage path length, pavement slope, etc.

Pavement Structure Materials:

a) Layer thicknesses.

b) Material properties such as surface shortwave absorptivity, thermal conductivity (K), and heat or thermal capacity (Q).

Material Inputs

Materials are divided into two groups: asphalt concrete inputs and unbound materials. Figure 8 describes M-E PDG pavement layer structure.

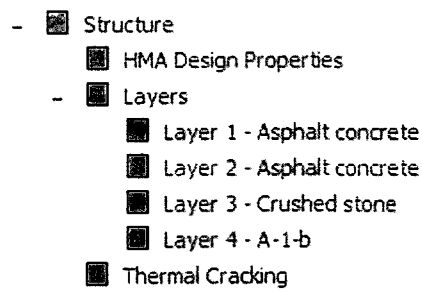


Figure 8: M-E PDG Pavement Layer Structure.

Asphalt concrete inputs Level 3:

a) Asphalt mix parameters – layer thickness, aggregate gradation

b) AC binder parameters – binder grade

c) Asphalt general parameters – reference temperature (70 ^{o}F), Poisson's ratio, volumetric properties (air voids %, effective binder content %, total unit weight – pcf), thermal properties).

Asphalt concrete inputs Level 2:

a) Asphalt mix – same as Level 3 inputs

b) Asphalt binder – requires the complex shear modulus (G*), and the phase angle (δ) values and testing temperatures

Unbound material inputs:

a) Layer type – typical resilient modulus (M_R) value for Level 3 obtained from national averages, and Level 2 from laboratory test or a state specific value (AASHTO or Unified Classifications). Level 1 - when active, will incorporate k_1, k_2, k_3 values from universal model.

b) Layer thickness

c) Poisson's ratio

d) Material properties – level 2 options: resilient modulus, CBR value, R-value, layer coefficient, penetration (DCP) or based upon plasticity index and grading.

2.3 Findings from Completed Research Activities on M-E PDG Implementation

This section presents some activities, conclusions and results on the M-E PDG topics conducted by researchers in other states: Indiana (10), Ohio (11), and South Dakota (12).

2.3.1 Implementing the M-E PDG for Cost Savings in Indiana

The implementation of the new pavement design methodology is a huge task for the state Departments of Transportation (DOT). Indiana DOT's experience is a good example of how to handle this difficult and time consuming task (11). Implementation of the M-E PDG design process demands knowledge about pavement design inputs and pavement performance. This task was completed by interactions among the highway agency personnel who work in traffic, material, geotechnical areas and pavement structures to identify the proper parameters for the design (11). To ensure successful outcome of the analysis and design process, the team of engineers had sufficient knowledge in pavement engineering. The implementation process was coordinated with other agencies such as Federal Highway of Administration (FHWA), state pavement associations and contractor associations. FHWA must approve all projects supported by government funds and the contractor association members actually build the pavements.

The full M-E PDG implementation in Indiana began on January 1, 2009, although initial implementation efforts started seven years earlier, in 2002. Indiana DOT coordinates all implementation activities with agency pavement design engineers, FHWA, pavement association and contractor associations. There were regular monthly meetings, where implementation issues were discussed and approved for the next steps in the process. Training sessions were initiated throughout the entire implementation process for all involved parties.

In 2009, Indiana DOT's engineers and consultants designed over 100 pavement sections using the M-E PDG procedure. All the new M-E PDG design pavement thicknesses were documented and compared to the thicknesses estimated according to the 1993 AASHTO design. They provided profit calculations based on the material, labor cost and time savings. Savings resulted from more efficient M-E PDG design which also reduced thickness of the pavement; most pavements were reduced by 2 inches. Significant savings of material, labor cost and time were realized.

Summarizing Indiana DOT's experience, the implementation of the M-E PDG results in more efficient pavement designs, that can be built at a lower cost as shown in Table 3 (11).

Table 3: Cost Savings Attributed to the M-E PDG Implementation in Indiana.

Road	AASHTO 1993 HMA Thickness	M-E PDG HMA Thickness	Estimated Contract Saving	Actual Contract Saving
SR 14	15"	13.5"	\$333,000	\$155,440
US 231	15.5"	13"	\$557,000	\$673,796
SR 62	16"	13"	\$403,000	\$420,548

2.3.2 M-E PDG Sensitivity Analysis Results for New HMA in Ohio

In Ohio, M-E PDG research mainly focused on the characterization of paving materials utilized in that state. In this study (12), the basic HMA properties such as air voids %, effective binder content and total unit weight were obtained from job mix formulas (JMF) for level 3 design. A very limited amount of effort has been expended on traffic related studies under Ohio Department of Transportation's (ODOT) research program. ODOT typically collects three categories of traffic data: weight-in-motion (WIM), automatic vehicle classification (AVC) and traffic volume, however most of this information has not been analyzed for M-E PDG purposes. The following observations were obtained from the research and from sensitivity analysis:

- Longitudinal cracking was mostly affected by thickness of the HMA layer alone, and was caused mostly by poor construction methods. The subgrade and base stiffness did not influence the longitudinal cracking.
- Transverse (thermal) cracking was highly affected by climate, volumetric binder content and base type. HMA thickness had a moderate influence with thicker asphalt pavements showing lower thermal cracking predictions.
- Alligator cracking was significantly affected by HMA thickness and asphalt binder content. Higher thicknesses and higher asphalt contents lead to lower predicted alligator cracking. Also the base type had a major impact on the alligator cracking. Percentage of heavy trucks (class 9 or greater), subgrade type and climate affected alligator cracking moderately.
- Total rutting (includes HMA layers, base and subgrade) as expected, was affected mostly by the percentage of heavy trucks. Other significant factors affecting total

rutting were HMA thicknesses (the higher the pavement thickness, lower the rutting), binder content (the higher the content, higher the rutting), and base type (asphalt treated based showing lesser rutting). Moderate impacts on the predicted rutting were observed with the air voids content (higher air voids leading to increasing rutting), climate and subgrade type.

- Smoothness IRI (Ride Quality) was mostly affected by pavement thickness (thicker pavements exhibited lower IRI). Base and subgrade stiffnesses had a moderate effect on IRI (sections with stiffer layers having more beneficial IRI).

2.3.3 M-E PDG Sensitivity Analysis Results in South Dakota

The pavement performance for the sensitivity analysis in South Dakota (13) was expressed using the following performance indicators:

- Top-down fatigue (longitudinal) cracking,
- Bottom-up fatigue (alligator) cracking,
- AC rutting,
- Total rutting,
- Smoothness (IRI).

The transverse cracking performance predictions were omitted due to the M-E PDG version 1.1 software having specific shortcomings (transverse cracking values equal to "0").

Before conducting any runs for M-E PDG sensitivity analysis the South Dakota DOT Technical Panel (13) needed to determine:

- Fixed variables and their levels,
- Determine which inputs needed to be investigated,
- Input value ranges were to represent typical South Dakota conditions.

The newly designed rural AC pavement was evaluated based on 56 M-E PDG software simulations. The parameters in Table 4 are placed in decreasing order of their significance for each investigated performance indicator.

Table 4: Summary of Significance for New AC (Rural Design).

Pavement Type	Distress Type	Critical input Variables
New HMA	Top-down (longitudinal cracking)	• AC layer thickness • Initial 2-way AADTT • Base resilient modulus • AC binder grade
	Bottom-up fatigue (alligator cracking)	• Initial 2-way AADTT • AC binder grade • AC layer thickness • Base resilient modulus
	AC rutting	• Initial 2-way AADTT • AC layer thickness • AC binder grade • Location (climate)
	Total rutting	• Initial 2-way AADTT • AC layer thickness • Subgrade resilient modulus • Depth of water table • AC binder grade • Base resilient modulus
	Smoothness (IRI)	• Bottom-up fatigue (alligator) cracking • Total permanent deformation (rutting)

In the overall ranking, it was observed that the initial 2-way AADTT variable had the largest performance affect on all of the pavement distress types for the new HMA design, follow by: AC layer thickness, AC binder grade, base resilient modulus, and subgrade resilient modulus.

The smoothness indicator (IRI) was predicted as a function of the initial (as-constructed) IRI and the predicted longitudinal cracking, alligator cracking and total rutting. Based on these correlations the bottom-up fatigue cracking has the largest affect on the pavement smoothness in South Dakota.

Chapter 3: Research Methodology

This section describes in detail the tasks performed in order to accomplish the objectives of this research, namely, to identify required inputs for Level 3 and Level 2 and conduct sensitivity analyses with M-E PDG software for Vermont, New York and Massachusetts. The state-specific inputs were varied for typical ranges used in New England or were ranges obtained from the LTPP database. The sensitivity analysis was performed using state-specific input parameters chosen in accordance to state pavement design procedures, theoretical knowledge of flexible pavements, and engineering experience. The research methodology consists of three parts:

1. Data collection
2. M-E PDG sensitivity analysis
3. Predicted distresses data compilation

3.1 Data Collection

Input values for all M-E PDG runs were collected from the LTPP road sections (14). Vermont has two LTPP sections, one located in Addison County and the second in Grand Isle County. For sensitivity analysis, the first section was selected based on higher traffic values, thinner structural layers and central location. New York has only one LTPP road section located in the central part of the state in Onondaga County. The road layer structure was obtained from the LTPP section. No other sources of information were available and the research was completed based on current findings. Massachusetts has three LTPP road section locations: in the western part of the state (Hampden County), in the central part of the state (Norfolk County), and in the south eastern part of the state (Bristol County). Bristol County was selected for the M-E PDG sensitivity analysis based on traffic, road structure and available data.

The following information was collected for each state:

- General information such as construction dates for pavement, base, subbase and subgrade based on the state's seasonal paving periods.
- Climatic information and ground water table depths based on the closest weather station and local well records.
- Asphalt mix design specifications – based on currently adopted procedures and specifications.
- Unbound material (base, subbase) characteristics – state specifications or the State Soil Survey Geographic database (STATSGO2) for subgrade information (15).

Figure 9 shows typical road structures (layer thickness and material type) used for the M-E PDG sensitivity analysis in selected states.

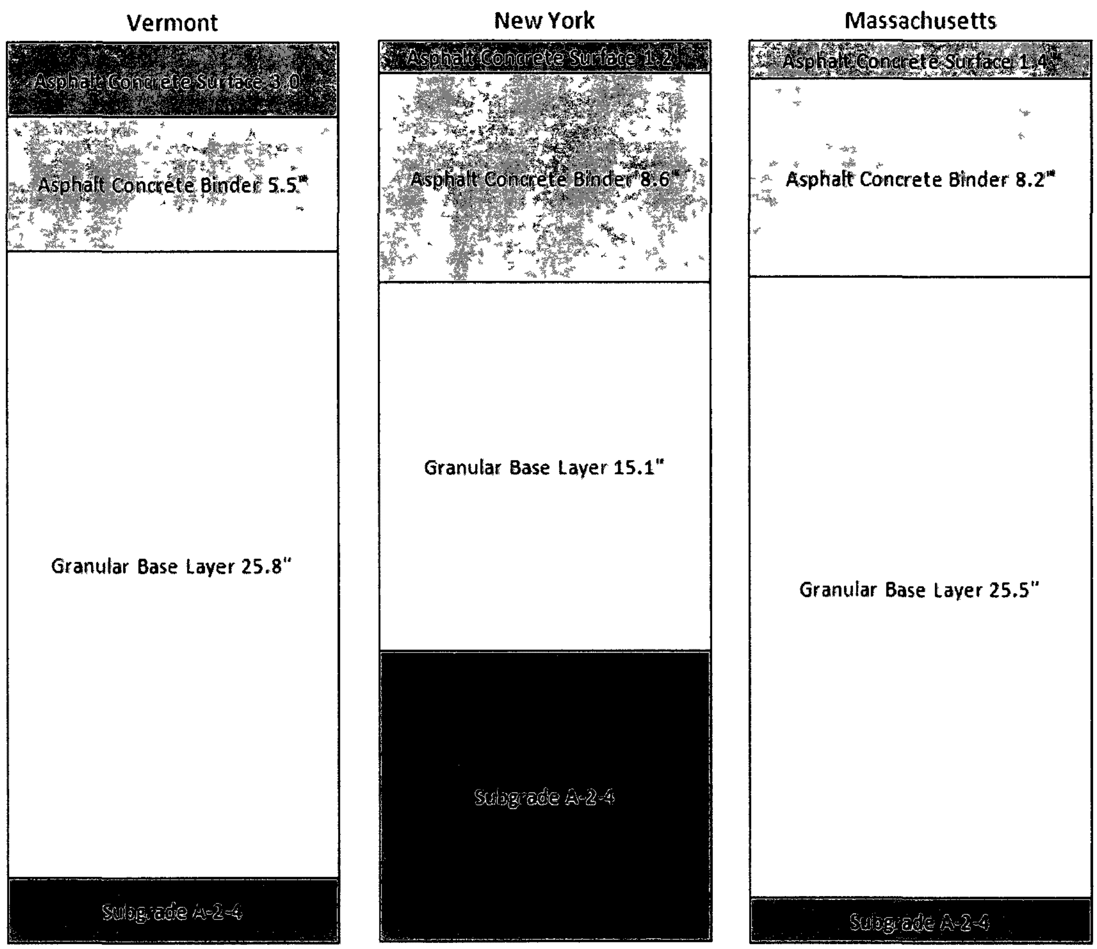


Figure 9: Pavement Structures Used for Sensitivity Analysis.

3.2 Tolerances and Determination of Material Properties

The research objectives for this project only require level 3 and level 2 approaches for determining design inputs. Level 3 requires the designers to estimate the most appropriate design value of the material property based on experience and with little or no testing. For level 3 analysis, the M-E PDG software contains major material types and their default values based on national calibration. In contrast, level 2 inputs are estimated through correlations with other material properties that are commonly measured in the field or laboratory.

All three states selected for this research are using the Superpave specification for asphalt binder and asphalt mixture grading requirements (16) (17). The tolerances for unbound materials were selected from the state agency specifications available online. Table 5 presents the HMA mix grading ranges and Table 6 presents the tolerances from target grading of percentage by weight of material retained on sieves in accordance with Superpave specification.

Table 5: Range of Values of HMA Mix Grading – Superpave Specification.

NMAS* of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
¾" sieve	0	0-10	10 – NR	NR	NR
3/8" sieve	0 – 10	10 – NR	NR	NR	NR
# 4 sieve	10 – NR	NR	NR	NR	NR
#200 sieve	2 – 10	2 – 10	2 – 8	1 – 7	0 – 6

* - Nominal Maximum Aggregate Size

NR - No Restriction on the value

Table 6: Tolerance for HMA Mix Grading – Superpave Specification.

NMAS of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
Cum. % Ret 3/4" sieve		± 4%	± 5%	± 7%	
Cum. % Ret 3/8" sieve		± 4%	± 5%	± 7%	
Cum. % Ret # 4 sieve	± 4%	± 3%	± 4%	± 4%	± 6%
#200 sieve	± 0.8%	± 0.8%	± 0.8%	± 0.8%	± 0.8%

The percentage of air voids for the analysis is 4% with a tolerance of ± 1%. For new HMA mixtures, the mid-range value or value from previous construction records for a particular type of HMA mixture needs to be used. For existing HMA layers, the air voids value can be obtained from pavement cores. Other asphalt properties, such as effective asphalt content, voids in mineral aggregate (VMA) or voids filled with asphalt (VFA) if unavailable, could also be obtained from pavement cores (9).

Base and subgrade resilient modulus values could also be characterized using the hierarchical approach. Appendix D contains typical resilient modulus (M_R) values for level 3 designs, which are national averages for a given type of soil or base material. Level 2 designs would require the user to choose resilient modulus values based on laboratory material testing. The strength of the unbound materials for level 2 inputs could be also be selected based on other parameters such as California Bearing Ratio (CBR), R-value, layer coefficient, dynamic cone penetration (DCP) or calculated from plasticity index or grading. Table 7 presents sieve size characteristics of unbound materials used for bases and subbases in accordance with the ASTM D 2940 specification.

Table 7: ASTM D 2940 Grading for Dense-Graded Bases and Subbases.

Sieve Size	Percent Passing
2 in. (50 mm)	100
1½ in. (37.5 mm)	95 – 100
3/4 in. (19.0 mm)	70 – 92
½ in. (9.5 mm)	50 – 70
No. 4 (4.75 mm)	35 – 55
No. 30 (0.600 mm)	12 – 25
No. 200 (0.075 mm)	0 – 8

Performance binder grade selections were specified based on state specifications, information obtained from the agency, or current Hot Mix Asphalt (HMA) suppliers. Level 2 design requires the complex shear modulus (G*) and the phase angle (δ) values from laboratory asphalt testing. Table 8 provides the example of binder selections for Vermont based on design ESAL's and average traffic speed values (18).

Table 8: Performance Graded Binder Selection Table (Ref: Vermont Agency of Transportation Flexible Pavement Design Procedures; March 1, 2002).

Design ESALs (million)	Adjusted PG Binder Grade		
	Average Traffic Speed		
	<20 km/h (12 mph)	20 to 70 km/h (12 to 44 mph)	>70 km/h (44 mph)
<0.3	PG 58-XX	PG 58-XX	PG 58-XX
0.3 to <3	PG 64-XX	PG 58-XX	PG 58-XX
3 to <10	PG 70-28	PG 64-XX	PG 58-XX
10 to <30	PG 70-28	PG 64-XX	PG 64-XX
>30	PG 70-28	PG 64-XX	PG 64-XX

Five binder grades for New York have been chosen based on the state DOT website and the NYS DOT Comprehensive Pavement Design Manual and Revision for the selected locations (Ref: NY Report, Appendix F and G). Massachusetts binder selections were obtained from the state HMA suppliers.

3.3 Input Values for M-E PDG

The M-E PDG software predicts the performance of the pavement during its service life based on a large amount of input values which need to be specified by the designer. Before choosing input values for the project, the designer should first decide on the "trial design", which is a reference file for a future sensitivity analysis. Data for the "trial design" may be selected based on existing pavement structure, material properties, monitored performance, a design catalog, or may be created solely by the design engineer. The "trial design" pavement predictions are then examined by the designer to achieve satisfactory results. Unacceptable design outputs are revised and re-run until all performance criteria are met. The following subsections provide characteristics of design inputs used for this research, and Figures 10, 11 and 12 present the input summaries for each state.

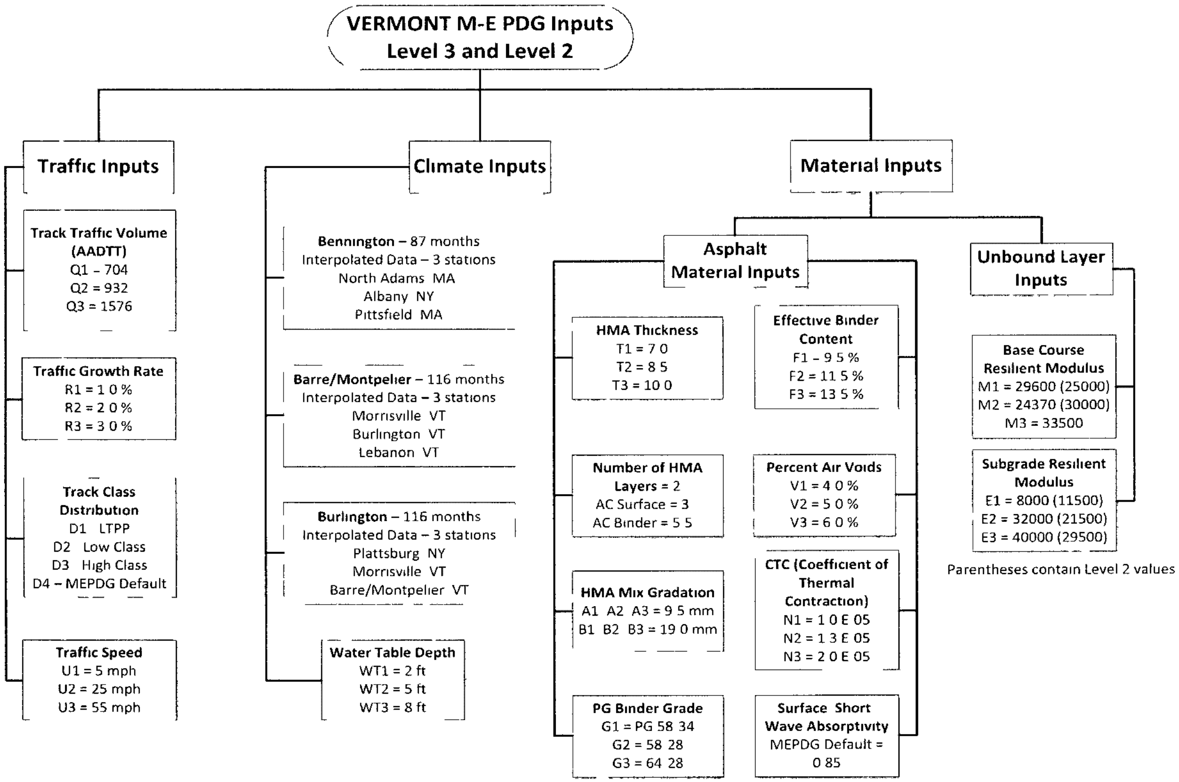


Figure 10: Vermont M-E PDG Inputs Level 3 and Level 2.

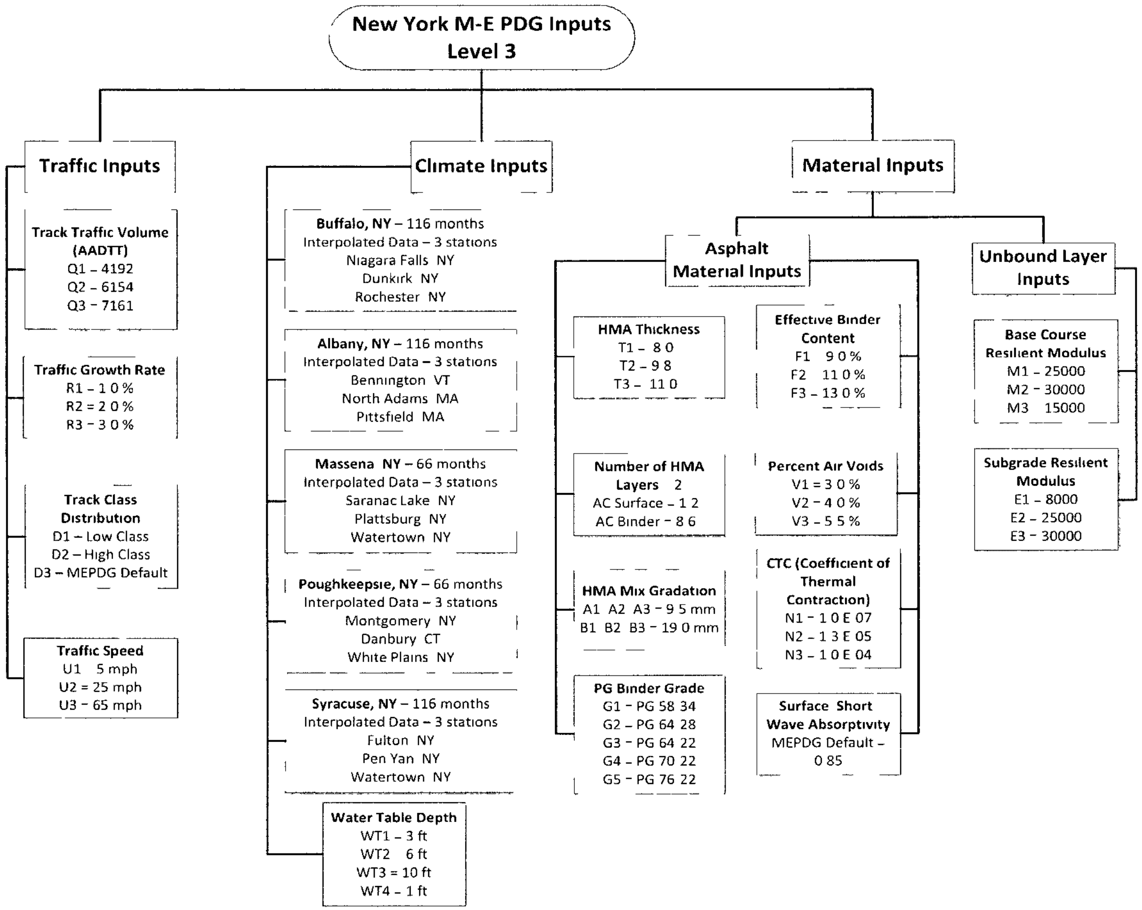


Figure 11: New York M-E PDG Inputs Level 3.

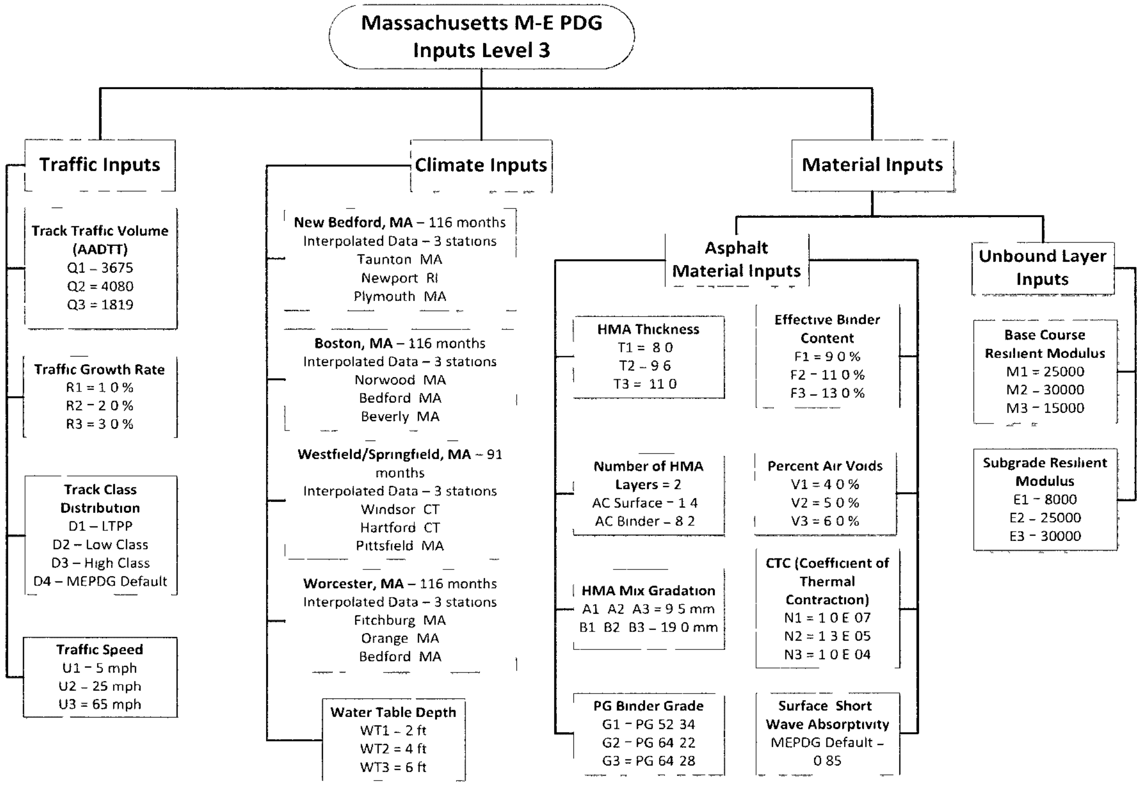


Figure 12: Massachusetts M-E PDG Inputs Level 3.

3.3.1 General Inputs

The M-E PDG software requires that the designer specify certain general project information such as pavement design life, base, subgrade and pavement construction dates, and the traffic opening date. The software will calculate predicted pavement distresses according to a reliability value which is selected by the user depending on the importance of the project and road functional classification. The reliability is the probability that the pavement will not achieve specific performance criteria over the design period.

The default reliability value used for the M-E PDG sensitivity analysis was 90%. Recommended reliability values for different roadway functional classifications are presented in Table 9 (8).

Table 9: Levels of Reliability for Different Functional Classifications of the Roadway (Ref: MEPDG; A Manual of Practice; July, 2008).

Functional Classification	Urban	Rural
Interstate/Freeways	95	92
Principal Arterials	90	85
Collectors	80	75
Local	70	60

Table 10 presents the default failure limits for performance criteria which have been used to perform this research.

Table 10: Performance Criteria for Flexible Pavements – Failure Limits.

Performance Criteria	Failure Limit
Terminal IRI (inches/mile)	172
AC Surface Down (Longitudinal) Cracking (feet/mile)	2000
AC Bottom-Up (Fatigue) Cracking (% area of lane)	25
AC Thermal Fracture – Crack Length (feet/mi)	1000
Permanent Deformation – Total Pavement (inches)	0.75
Permanent Deformation – AC Only (inches)	0.25

3.3.2 Traffic Inputs

The M-E PDG requires the initial 2-way average annual daily track traffic (AADTT) value. This value can be calculated by using the software calculator and providing the average annual daily traffic (AADT) and the percentage of heavy trucks (class 4 or higher – FHWA/AASHTO Vehicle Classification). These two values can be estimated from the specific DOT traffic count websites or from the LTPP road sections.

Truck Class Distribution values were obtained from the LTPP monitored traffic stations, state WIM stations, default M-E PDG values and from Iowa DOT research studies with similar road classifications (19). Track class selections (class 4 to 13) were specified based on the FHWA vehicle classification and the M-E PDG requirement.

Table 11 presents four cases of track class distribution investigated for the Massachusetts sensitivity analysis.

Table 11: Massachusetts Truck Class Distribution Summary.

TRUCK CLASS	CODE			
	D1 (LTPP-Control)	D2 (low class)*	D3 (high class)*	D4 (Level 3)
4	3.5	5.2	0.1	1.8
5	47.2	38.9	0.6	24.6
6	9.7	35.8	0.8	7.6
7	0.5	10.2	0.6	0.5
8	8.8	5.6	6.8	5.0
9	29.8	3.5	9.2	31.3
10	0.4	0.2	25.8	9.8
11	0.1	0.3	36.4	0.8
12	0.0	0.2	16.5	3.3
13	0.0	0.1	3.2	15.3

*Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

Tables 12 and 13 present track class distribution summaries for Vermont and New York.

Table 12: Vermont Truck Class Distribution Summary.

TRUCK CLASS	CODE			
	D1(from LTPP)	D2 (low class)*	D3 (high class)*	D4 (Control)
4	5.5	5.2	0.1	1.8
5	43.0	38.9	0.6	24.6
6	10.8	35.8	0.8	7.6
7	3.4	10.2	0.6	0.5
8	7.6	5.6	6.8	5.0
9	25.9	3.5	9.2	31.3
10	3.2	0.2	25.8	9.8

Table 12 Continued

11	0.0	0.3	36.4	0.8
12	0.4	0.2	16.5	3.3
13	0.2	0.1	3.2	15.3

*Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

Table 13: New York Truck Class Distribution Summary.

TRUCK CLASS	**CODE**			
	D (from LTPP)*	**D1 (low class)****	**D2 (high class)****	**D3 (Control)**
4	N/A	5.2	0.1	1.8
5	N/A	38.9	0.6	24.6
6	N/A	35.8	0.8	7.6
7	N/A	10.2	0.6	0.5
8	N/A	5.6	6.8	5.0
9	N/A	3.5	9.2	31.3
10	N/A	0.2	25.8	9.8
11	N/A	0.3	36.4	0.8
12	N/A	0.2	16.5	3.3
13	N/A	0.1	3.2	15.3

* - no LTPP Truck Class Distribution data

**- Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

Traffic operational speed depends on the road functional classification and varies from 55 mph in Vermont's Rt. 7 (Functional Class 2), to 65 mph in Massachusetts' I-195 (Functional Class 11). Traffic operational speed for this research was analyzed in conjunction with different binder grades to observe the effects of slow and fast moving traffic. Three operational speeds were selected for the analysis: 5 mph, 25 mph and 65 mph (with the exception of Vermont at 55 mph).

Level 3 and 2 sensitivity analysis allows the use of many default values for traffic inputs such as the monthly adjustment factors, hourly distribution, and axle load distribution factors.

3.3.3 Climatic Inputs

Climate inputs needed by the M-E PDG are available from over 800 weather stations embedded in this software. Multiple weather stations were selected for each state to provide climatic information for pavement design locations. The user may select only one weather station to obtain the data if the project is located less than 50 miles from the station. If it is located more than 50 miles, the user should select and interpolate climatic data from 2 to 6 surrounding weather stations. The weather stations selected to create the virtual weather station should have similar elevations (8). Multiple weather stations are recommended because of the possibility of missing data and errors in the database for a single station. The state specific project locations and selected weather stations are presented in details in the attached Appendixes A, B and C. As an example, Table 14 presents the virtual weather station interpolation results for a New Bedford, MA project.

Table 14: Virtual Weather Station Interpolation Table for New Bedford, MA.

STATION	Nearest 3 Stations	Latitude	Longitude	Distance	#Months of data
New Bedford Lat. 41.41 Lon. -70.58 Elev. 78 ft	Taunton, MA	41.53	-71.01	14.0	99
	Newport, RI	41.32	-71.17	19.4	116
	Plymouth, MA	41.55	-70.44	20.1	116

The water table depth is another climate input parameter that needs to be specified by the user. This input value affects pavement distresses such as fatigue cracking, total rutting and roughness of the pavement (IRI). Water table depths greater than 10 feet below the planned surface elevation have minimal affect on the pavement distress predictions. The current data for water table depths were obtained from the USGS website (20).

3.3.4 Asphalt Material Inputs

The asphalt layer thicknesses and grading were obtained from the LTPP database and the DOT's websites. The HMA mix grading was selected within the Superpave specification limits. Table 15 presents the HMA mix grading input values for the surface (9.5 mm) and the binder (19.0 mm) for all states.

Table 15: HMA Mix Grading Input Values.

% of Aggregate	9.5 mm (3/8")			19.0 mm (3/4")		
	mean	coarse	fine	mean	coarse	fine
Retained on 3/4" sieve	0	0	0	14.0	18.6	12.0
Retained on 3/8" sieve	5.0	8.2	3.6	24.0	32.4	19.8
Retained on #4 sieve	35.0	48.3	22.1	42.0	52.0	34.5
Passing #200 sieve	6.0	2.8	8.5	5.0	2.8	7.2

The mean aggregate mix values are used as the inputs for a control file in the M-E PDG sensitivity analysis.

The specific binder grade varies between states and they are listed in Table 16.

Table 16: Binder Grade Selections in VT, NT and MA.

State	Binder Grades
Vermont	PG 58-34, PG 58-28, PG 64-28
New York	PG 58-34, PG 64-28, PG 64-22, PG 70-22, PG 76-22
Massachusetts	PG 52-34, PG 64-22, PG 64-28

The mix coefficient of thermal contraction (CTC) default value of 1.3 E-05 (in/in/°F) was used for Level 3 and Level 2 sensitivity analysis in all states. This is the coefficient of thermal contraction of the AC mix, and is expressed as the change in length per unit length for unit decrease in temperature. The typical values range from 2.2 to 3.4 /°C.

3.3.5 Base and Subgrade Material Inputs

The unbound materials used in this research were based on the findings from another research project conducted for the New England states (21), as well as on the State Soil Geographic database (15). As an example, Table 17 presents the selected subgrade material types and resilient modulus values for level 2 and 3 sensitivity analysis in Vermont.

Table 17: Subgrade Types and Resilient Modulus Values for Vermont Level 2 & 3.

CODE	SUBGRADE TYPE	Material Classification	RESILIENT MODULUS (psi)	
			Level 2	Level 3
E1	Clayey soils	A-7-6	11500	8000
E2	Fine sand, some silt	A-2-4	21500	32000
E3	Coarse to fine gravelly, coarse to medium sand, some fine sand	A-1-a	29500	40000

The base layer material characteristics for the analysis were obtained from the DOT web sites, or when unavailable, the M-E PDG default values were selected. The State Final Reports (Appendix A, B and C) contain base layer input values for VT, NY and MA. The subgrade type resilient modulus range for level 2 is much smaller than level's 3 sensitivity analysis, giving more conservative approach for this research. Usually level 3 inputs should be lower than level's 2, as this level is less certain.

Chapter 4: Data Analysis, Results and Discussion

The results of the M-E PDG software runs for the evaluated input parameters provided numerous charts and tables. The results of all software runs are presented in separate state reports (Appendix A, B, and C). This chapter presents the general conclusions and discussion for all data.

4.1 Normalization of Distresses

Normalization of the distresses was done to compare the effects of each input parameter on predicted distresses. This method of normalization is based on the variability of distresses about the control. The normalized value describes how the specific distress varies about the control value. For a significant variable the normalized value is higher than for an insignificant value.

The normalized distress levels are calculated as the ratio of the difference between the maximum and minimum predicted distresses for each input variable to the distress levels corresponding to the control set of input values. The normalized values in this research were used to determine the significance of the input variables on the predicted pavement distress. Equation 1 presents the calculation method.

Equation 1: Normalized Value Parameter

$$N = \frac{Maximum\ Distress - Minimum\ Distress}{Distress\ for\ control\ input\ set}$$

N = normalized value

As an example, two variables were observed to determine the normalized values for fatigue (top-down) cracking, one with a significant influence on the predicted pavement distress, and the other one with a minimal impact. Tables 18 and 19 present the predicted pavement distress values for HMA thickness, and HMA effective binder content variables in Massachusetts. Equations 2 and 3 present the calculations and results.

Table 18: Predicted Pavement Distresses for HMA Thicknesses in MA.

HMA Thickness, in	Bottom-Up Cracking, % area of lane	Top-Down Cracking, ft/mi	AC Rutting, in	Total Rutting, in	IRI, in/mi
8.0	1.63	1367.91	0.204	0.489	168.2
9.6 (Control)	1.51	696.46	0.196	0.426	164.99
11.0	1.47	347.56	0.174	0.378	162.54

Equation 2: Normalized Value Calculation for Top-Down Cracking and HMA Thickness.

$$N = \frac{1367.91 - 347.56}{696.46} = 1.465$$

Table 19: Predicted Pavement Distresses for HMA Effective Binder Contents in MA.

HMA Effective Binder Content, %	Bottom-Up Cracking, % area of lane	Top-Down Cracking, ft/mi	AC Rutting, in	Total Rutting, in	IRI, in/mi
10.0	1.52	735.86	0.189	0.417	164.52
11.0 (Control)	1.51	696.46	0.196	0.426	164.99
12.0	1.50	663.95	0.203	0.435	165.41

Equation 3: Normalized Value Calculation for Top-Down Cracking and HMA Effective Binder Content.

$$N = \frac{735.86 - 663.95}{696.46} = 0.103$$

4.2 M-E PDG Sensitivity Analysis Results by State

The tables and graphs presented below are results of sensitivity analysis studies prepared for VT, NY and MA. This research investigated the effect of selected input variables (15 variables) on five predicted pavement distresses:

1. Longitudinal (top-down) cracking, ft/mi
2. Alligator (bottom-up) cracking, % area of lane
3. Asphalt concrete (AC) rutting, in
4. Total rutting, in
5. Smoothness IRI, in/mi.

The transverse cracking pavement distresses were not investigated in this research due to a M-E PDG software shortcoming that predicted no cracking (transverse cracking values equal to "0"). Individual state analyses are discussed in the next three sections, followed by the general discussion on the impact of various inputs.

4.2.1 Vermont sensitivity analysis results

The M-E PDG analysis in Vermont was performed for two hierarchical levels: Level 3 and 2.

Data presented in Tables 20 – 24 and Figures 13 – 22 show sensitivity analysis results for Vermont Level 3 and 2.

VT Level 3 results

Table 20 presents normalized value results for the Vermont Level 3 sensitivity analysis. Based on their ranks, Table 21 shows the six most significant input variables in decreasing order of significance for the Vermont Level 3 sensitivity analysis. Figures 13 to 17 present significance of effect of each variable on the predicted pavement distress based on the normalized value.

Table 20: Normalized Values and Ranks for Vermont Level 3.

VERMONT LEVEL 3										
Input Value	**Bottom-Up Cracking**		**Top-Down Cracking**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA thickness	0.079	1	0.997	1	0.145	8	0.218	4	0.027	4
HMA mix gradation	0.013	6	0.258	9	0.395	3	0.198	5	0.025	6
HMA air voids	0.053	2	0.546	3	0.125	9	0.069	12	0.009	11
HMA effective binder content	0.033	5	0.28	8	0.151	7	0.085	10	0.007	12
HMA binder grade	0.013	6	0.242	10	0.296	5	0.157	7	0.019	8
Base type/modulus	0.013	6	0.302	7	0.039	13	0.061	13	0.007	12
Subgrade type/modulus	0.013	6	0.768	2	0.046	12	0.303	2	0.1	2
Ground water table	0.007	7	0.203	11	0.066	11	0.102	9	0.012	10
WT with weakest subgrade	0.013	6	0.018	14	0.033	14	0.074	11	0.009	11
Climate	0.007	7	0.083	12	0.263	6	0.118	8	0.013	9
AADTT value	0.053	2	0.423	5	0.474	2	0.259	3	0.032	5
Operational speed	0.046	3	0.433	4	0.98	1	0.488	1	0.059	3
Traffic growth rate	0.007	7	0.076	13	0.079	10	0.044	14	0.007	12
Traffic distribution	0.04	4	0.409	6	0.309	4	0.171	6	0.022	7
HMA CTC	0	8	0	15	0	15	0	15	0.005	13
Initial IRI	0	8	0	15	0	15	0	15	0.615	1

Table 21: Ranking of Input Variable Significance for VT Level 3 Sensitivity Analysis.

	Bottom-Up Cracking	Top-Down Cracking	AC Rutting	Total Rutting	IRI
Most Significant Variable	HMA Thickness	HMA Thickness	Operational Speed	Operational Speed	Initial IRI
↓	HMA Air Voids	Subgrade Type/ Modulus	AADTT	Subgrade Type/ Modulus	Subgrade Type/ Modulus
	AADTT	HMA Air Voids	HMA Mix Gradation	AADTT	Operational Speed
	Operational Speed	Operational Speed	Traffic Distribution	HMA Thickness	HMA Thickness
	Traffic Distribution	AADTT	HMA Binder Grade	HMA Mix Gradation	AADTT
Least Significant Variable	HMA Effective Binder Content	Traffic Distribution	Climate	Traffic Distribution	HMA Mix Gradation

The "zero" value on the graph indicates, there is no impact of an input on a predicted pavement distress. Figures 13 through 16 show the initial IRI input which has no impact on the predicted pavement distresses such as bottom-up cracking, top-down cracking, AC rutting and total rutting.

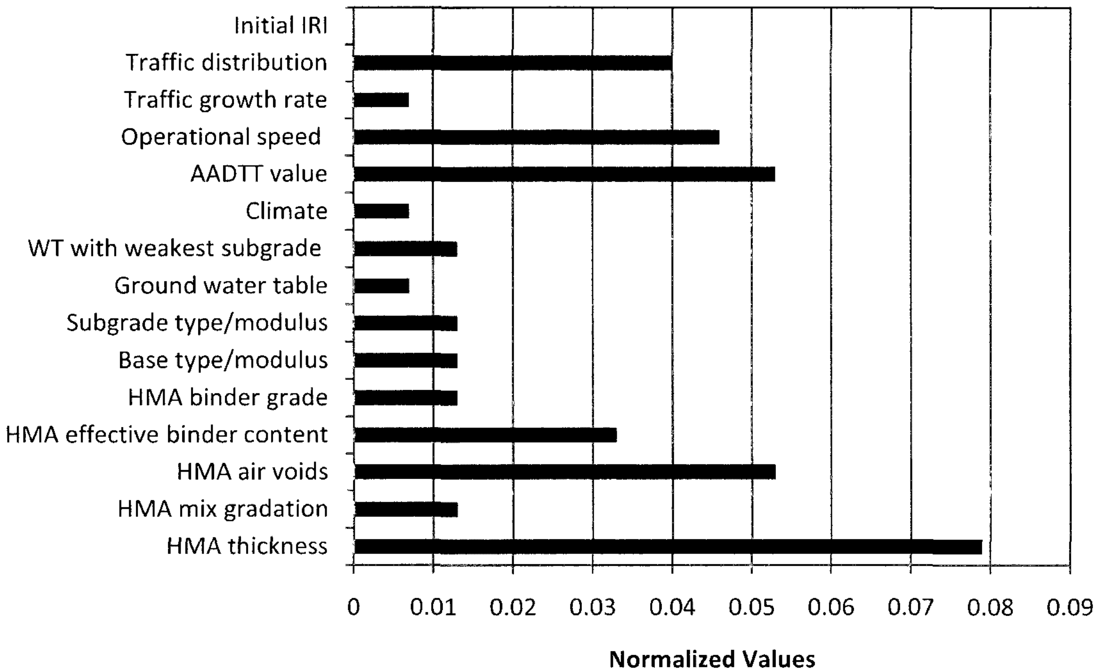


Figure 13: VT Level 3 Significance of Effect of Input Variables on Bottom-Up Cracking.

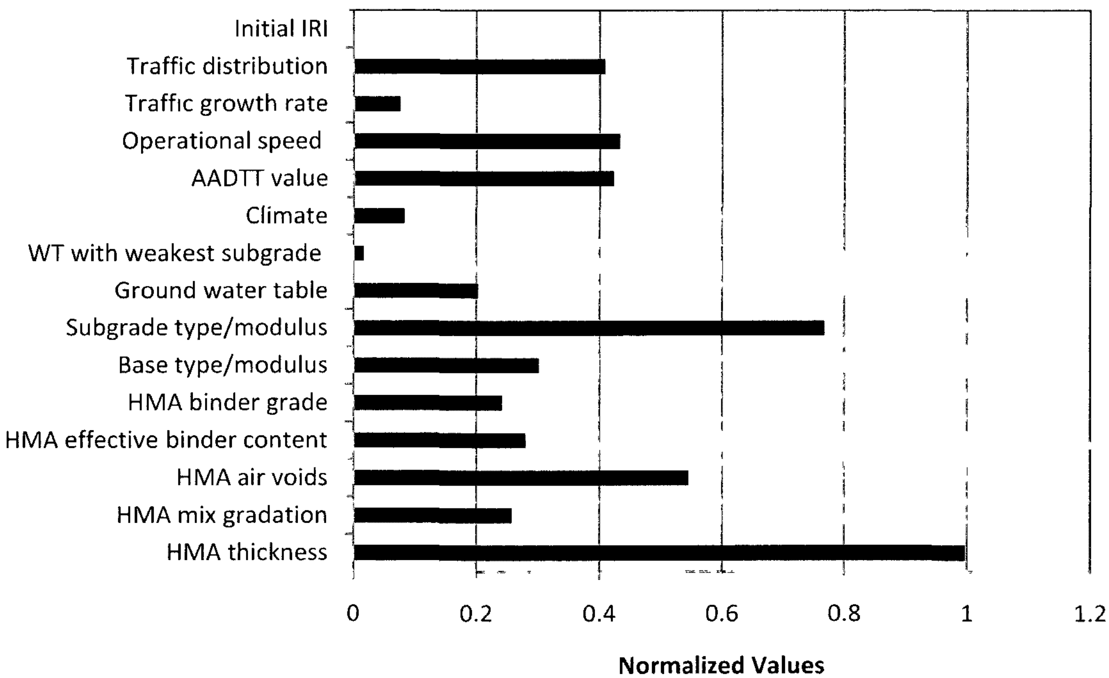


Figure 14: VT Level 3 Significance of Effect of Input Variables on Top-Down Cracking.

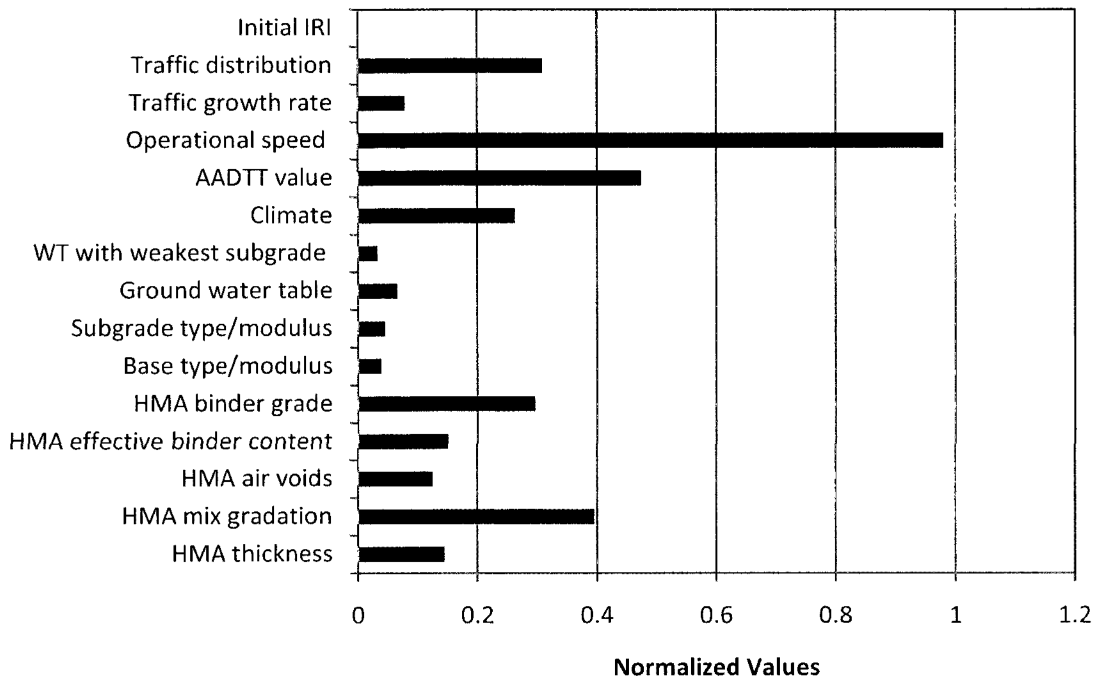


Figure 15: VT Level 3 Significance of Effect of Input Variables on AC Rutting.

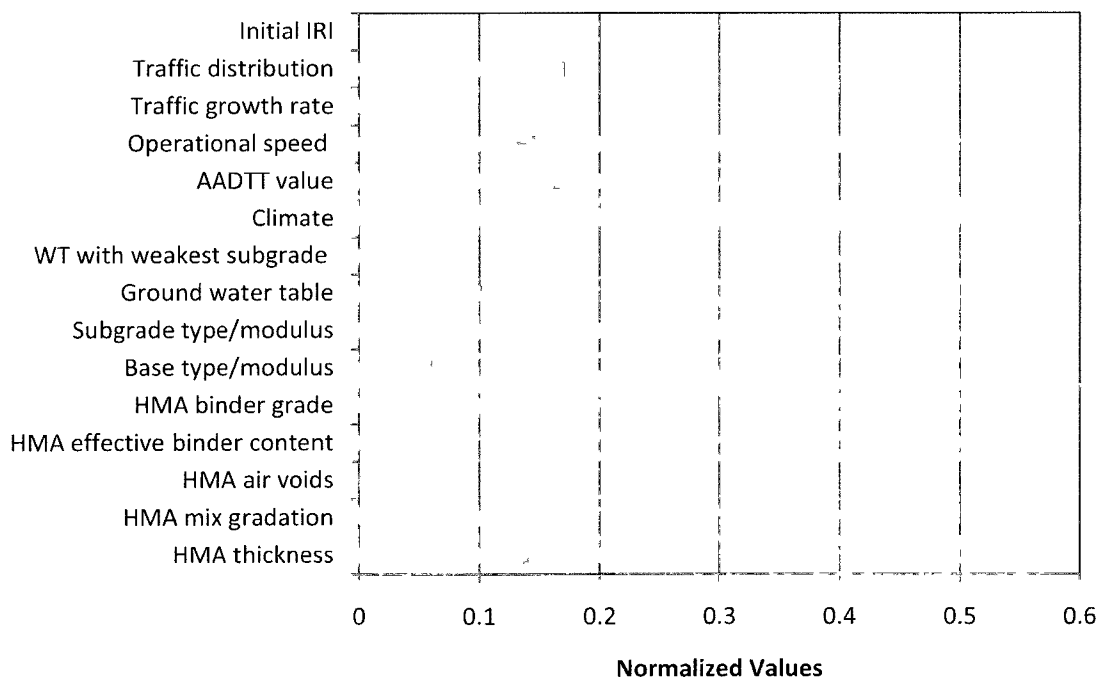


Figure 16: VT Level 3 Significance of Effect of Input Variables on Total Rutting.

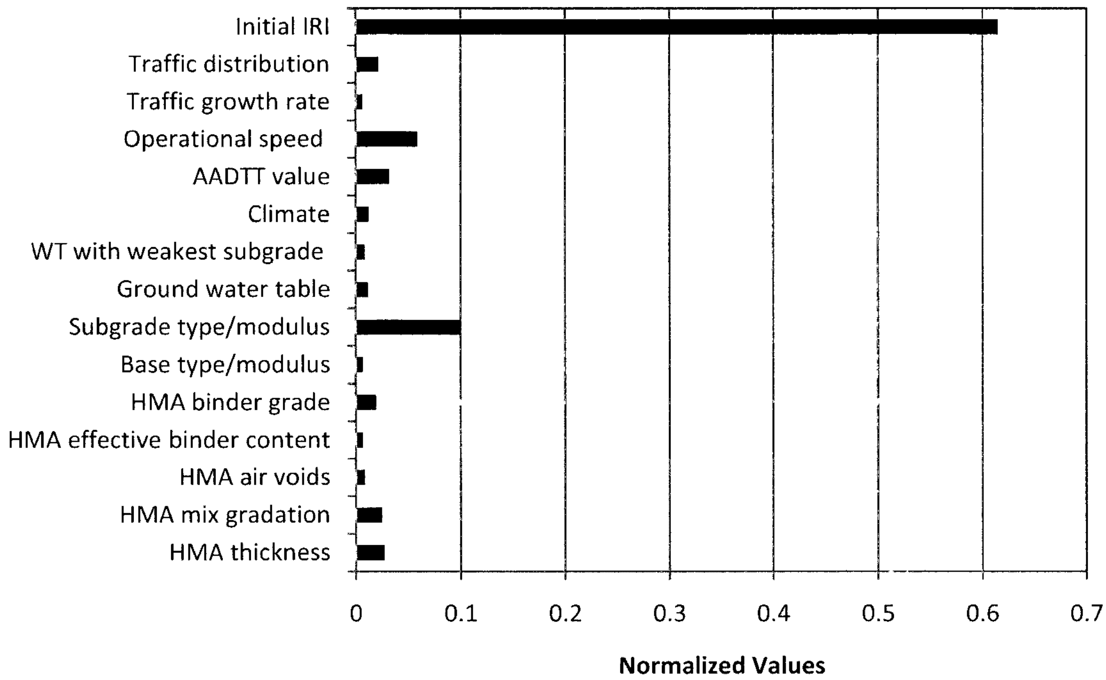


Figure 17: VT Level 3 Significance of Effect of Input Variables on IRI.

HMA thickness had a significant effect on both fatigue cracking distresses (bottom-up and top-down). Both of these distresses increased with the decrease of HMA thickness layer. Longitudinal (top-down) cracking was greatly affected, when the HMA layer thickness was reduced to 7.0". In this example, the failure in pavement compared to the design limit, which occurred after 18 years of service life (Appendix A, Figure 51A). The trends observed were reasonable for total rutting and IRI, with the highest distress/IRI for the thinner HMA (Appendix A, Figures 53A and 54A) (Table 21).

Traffic composition (i.e., operational speed, AADTT, and vehicle class distribution) are expected to influence the extent of pavement condition deterioration. Based on the literature review, pavement deterioration is significantly increased as the traffic composition is dominated by heavier trucks and axle loads. In Vermont, the AADTT value for the selected LTPP road section has a moderate rate of 10.35%. With the operational speed of 55 mph and the LTPP track distribution, the traffic composition impact was greatest on AC rutting and total rutting (Figures 15 and 16), and a moderate effect on fatigue (bottom-up) alligator cracking (Figure 13). Operational speed had a significant effect on both rutting pavement distresses, with the highest distresses for the lower speed value (Appendix A, Figures 70A to 84A).

The effect of subgrade type on pavement performance was determined by comparing distress and IRI over time with subgrade types (Appendix D – AASHTO Classification). Three soil types were chosen (A-1-a, A-2-4, and A-7-6) along with typical default inputs recommended for use in the M-E PDG and shown in Appendix A, Table 32A. Figures 90A, 93A, and 94A (Appendix A) present the effect of subgrade soil type on predicted distresses and roughness. In general, the lower the subgrade type/modulus the higher alligator fatigue cracking, rutting and IRI.

Changes in HMA parameters such as air voids or effective binder content were expected to have an effect on pavement distresses. Based on this research, an increase of air void content in the HMA layer results in a large increase in fatigue alligator and longitudinal cracking (Appendix A Figures 45A and 46A). There were no observed effects on the remaining pavement distresses and IRI with changes in air voids (Appendix A Figures 47A through 49A). The moderate effect of change in the effective binder content was only observed for fatigue alligator (bottom-up) cracking and longitudinal (top-down) cracking (Appendix A Figure 40A through 44A). In general, the increase of binder content reduces alligator and longitudinal cracking and increases rutting (AC and total).

There is no impact of change in the effective binder content to the pavement roughness IRI.

The effect of climate on the predicted distress and IRI was determined by selecting three representative weather stations for Vermont and three ground water table depths (2 ft , 5 ft, and 8 ft), and using the representative data to simulate climate condition across the state Appendix A Figures 30A through 39A). Table 21 presents the moderate effect of climate change only for AC rutting. In general, higher pavement distresses were observed in the southern part of the state due to warmer temperatures (Appendix A Figures 30A through 33A). The effect of ground water table level change was insignificant for all of the predicted pavement distresses. The ground water table effect is not reasonable to the current pavement design knowledge, and it needs to be reevaluated with the new M-E PDG version.

The moderate effect of HMA mix grading was observed mostly for AC rutting and total rutting (Table 21). In general, the coarse aggregates used for the production of HMA pavements, exhibited a higher level of all pavement distresses and IRI (Appendix A Figures 65A through 69A).

The effect of a binder grade selection was observed on AC rutting pavement distress. The binder grade selection is presented in Appendix A Table 26A, and the effects on the predicted pavement performance in Figures 70A through 84A (Appendix A). It was observed, that the lower HMA binder grades (PG 58) exhibited a higher level of all distresses and IRI, when compared to the higher binder grades (PG 64).

Table 22 presents Vermont's overall ranking summary of the significance of each input parameter on the performance of flexible pavement. This ranking method finds the most significant variables which impact the predictions of pavement distresses in the state. This method is very subjective and depends on the variables chosen by the researcher. In this example, based on the total ranking points (smaller numbers affected more), the following variables have a significant impact on pavement distress prediction in Vermont:

1. Operational speed
2. AADTT value
3. HMA thickness
4. Subgrade type/modulus
5. Traffic distribution
6. HMA mix grading
7. HMA binder grade.

In the above overall order of significance ranking, the high position of vehicle operational speed is surprising. This research did not investigate how realistic the ranking of vehicle speed is as a variable for pavement performance predictions. It is up to the state agency to decide if a change of vehicle speed and its range could really affect the pavement performance.

Table 22: VT Ranking Summary of Significance of Each Input Parameter on the Performance of Flexible Pavement

VERMONT LEVEL 3							
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**	**Total Ranking Points**	**Overall Order of Significance**
	Rank	**Rank**	**Rank**	**Rank**	**Rank**		
HMA thickness	1	1	8	4	4	**18**	**3**
HMA mix gradation	6	9	3	5	6	**29**	**6**
HMA air voids	2	3	9	12	11	**37**	**8**
HMA effective binder content	5	8	7	10	12	**42**	**9**
HMA binder grade	6	10	5	7	8	**36**	**7**
Base type/modulus	6	7	13	13	12	**51**	**11**
Subgrade type/modulus	6	2	12	2	2	**24**	**4**
Ground water table	7	11	11	9	10	**48**	**10**
WT with weakest subgrade	6	14	14	11	11	**56**	**13**
Climate	7	12	6	8	9	**42**	**9**
AADTT value	2	5	2	3	5	**17**	**2**
Operational speed	3	4	1	1	3	**12**	**1**
Traffic growth rate	7	13	10	14	12	**56**	**13**
Traffic distribution	4	6	4	6	7	**27**	**5**
HMA CTC	8	15	15	15	13	**66**	**14**
Initial IRI	8	15	15	15	1	**54**	**12**

VT Level 2 results

For VT Level 2 sensitivity analysis, only 10 input variables were selected. As a new variable, mix coefficient of thermal contraction (CTC) was added to the level 2 sensitivity analysis.

Table 23 presents normalized values and their ranks for Level 2 sensitivity analysis in VT.

Table 24 presents top five significant ranks of input variables for VT Level 2 sensitivity analysis. Variables are presented in decreasing order for each investigated performance indicator. Figures 18 to 22 present significance of effect of each variable on the predicted pavement distress based on the normalized value ranks from Table 23.

Table 23: Normalized Values and Ranks for Vermont Level 2.

VERMONT LEVEL 2										
Input Variable	**Bottom-Up Cracking**		**Top-Down Cracking**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA air voids	0.065	3	0.551	3	0.126	5	0.066	6	0.009	8
HMA effective binder content	0.033	5	0.297	6	0.153	3	0.080	5	0.011	7
HMA CTC	0.000	8	0.000	9	0.000	8	0.000	9	0.098	2
Base type/modulus	0.013	7	0.185	7	0.022	7	0.032	8	0.005	10
Subgrade type/modulus	0.020	6	0.672	2	0.033	6	0.096	4	0.075	3
WT with weakest subgrade	0.020	6	0.022	8	0.033	6	0.055	7	0.008	9
AADTT value	0.072	2	0.436	4	0.470	1	0.261	1	0.037	4
Traffic distribution	0.039	4	0.307	5	0.333	2	0.172	3	0.024	6
Initial IRI	0.000	8	0.000	9	0.000	8	0.000	9	0.600	1
HMA thickness	0.131	1	1.153	1	0.148	4	0.222	2	0.032	5

Table 24: Ranking of Input Variable Significance for VT Level 2 Sensitivity Analysis.

	Bottom-Up Cracking	Top-Down Cracking	AC Rutting	Total Rutting	IRI
Most Significant Variable	HMA Thickness	HMA Thickness	AADTT	AADTT	Initial IRI
↓	AADTT	Subgrade Type/ Modulus	Traffic Distribution	HMA Thickness	HMA CTC
↓	HMA Air Voids	HMA Air Voids	HMA Effective Binder Content	Traffic Distribution	Subgrade Type/ Modulus
↓	Traffic Distribution	AADTT	HMA Thickness	Subgrade Type/ Modulus	AADTT
Least Significant Variable	HMA Effective Binder Content	Traffic Distribution	HMA Air Voids	HMA Effective Binder Content	HMA Thickness

The "zero" value on the graph indicates, there is no impact of an input on a predicted pavement distress. As an example, Figures 18 through 21 present the initial IRI and the HMA CTC inputs which have no impact on the predicted pavement distresses such as: bottom-up cracking, top-down cracking, AC rutting and total rutting.

The predicted distresses and trends were observed to be similar with Level 3 sensitivity analysis, with slightly higher values predicted for Level 2 (Figure 13 through 22).

The effect of a new variable (mix coefficient of thermal contraction CTC) in this level of sensitivity analysis was insignificant for all of pavement distresses (zero value in Figures 18 through 21), and had only small effect on the roughness IRI prediction (Figure 22).

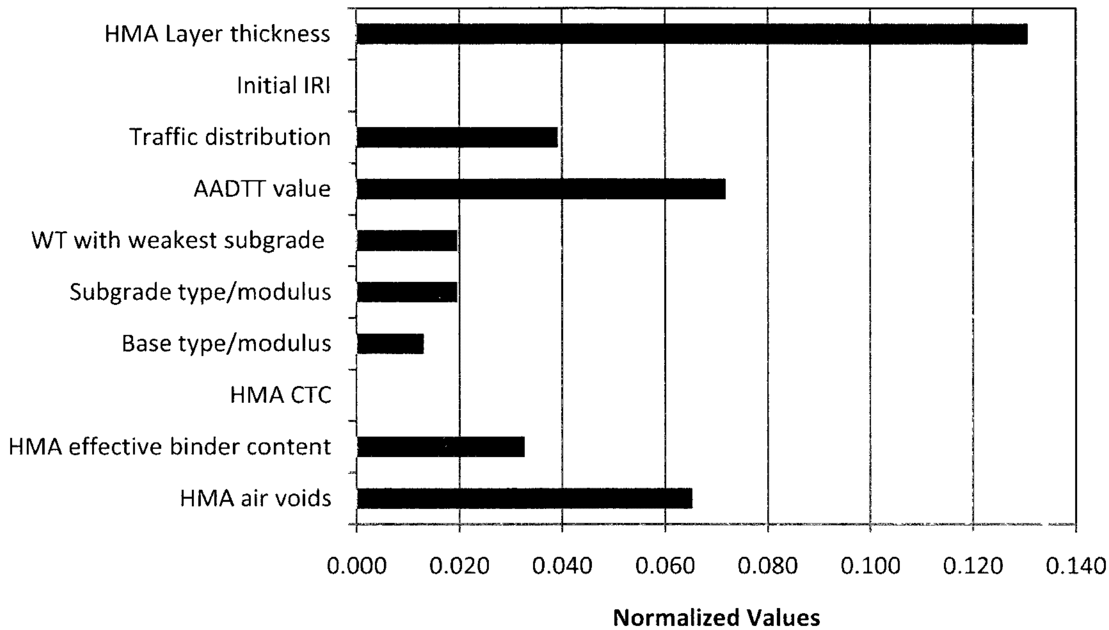


Figure 18: VT Level 2 Significance of Effect of Input Variables on Bottom-Up Cracking.

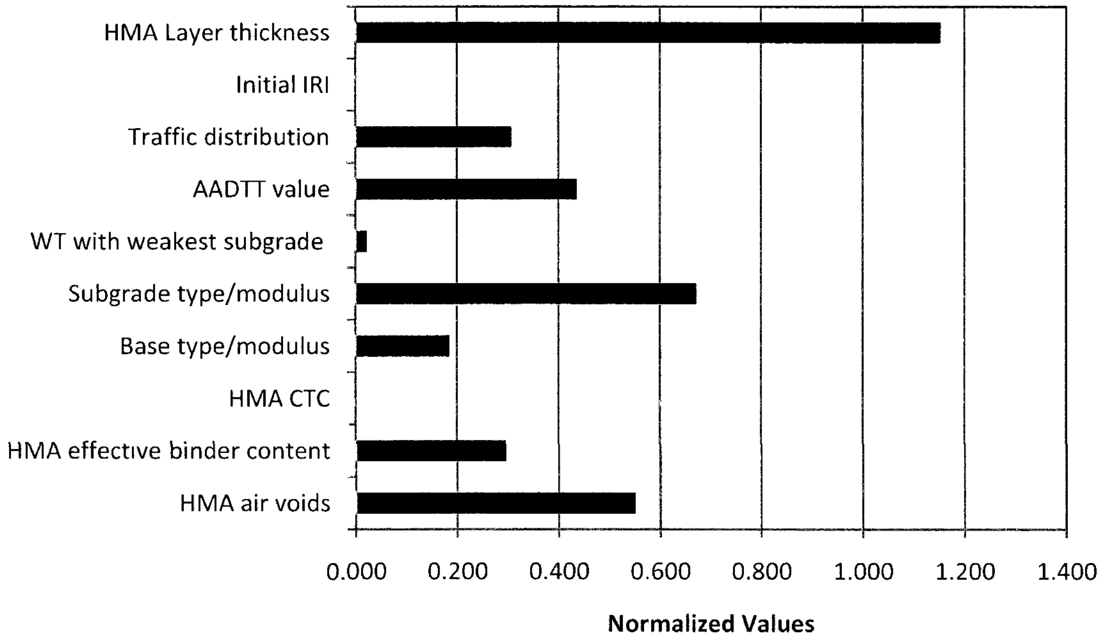


Figure 19: VT Level 2 Significance of Effect of Input Variables on Top-Down Cracking.

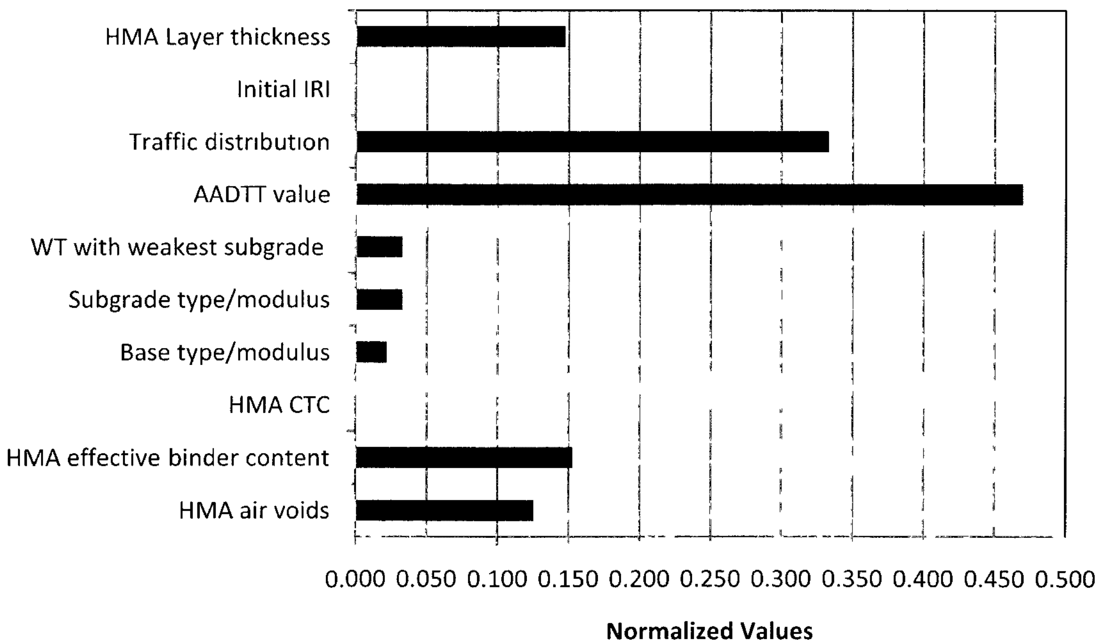


Figure 20: VT Level 2 Significance of Effect of Input Variables on AC Rutting.

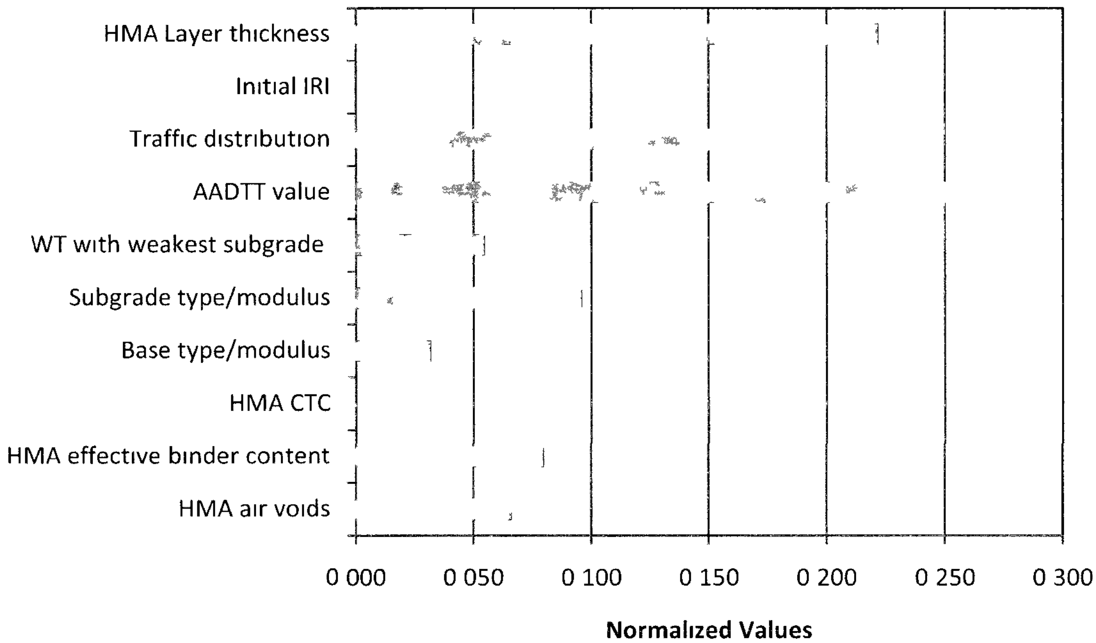


Figure 21: VT Level 2 Significance of Effect of Input Variables on Total Rutting.

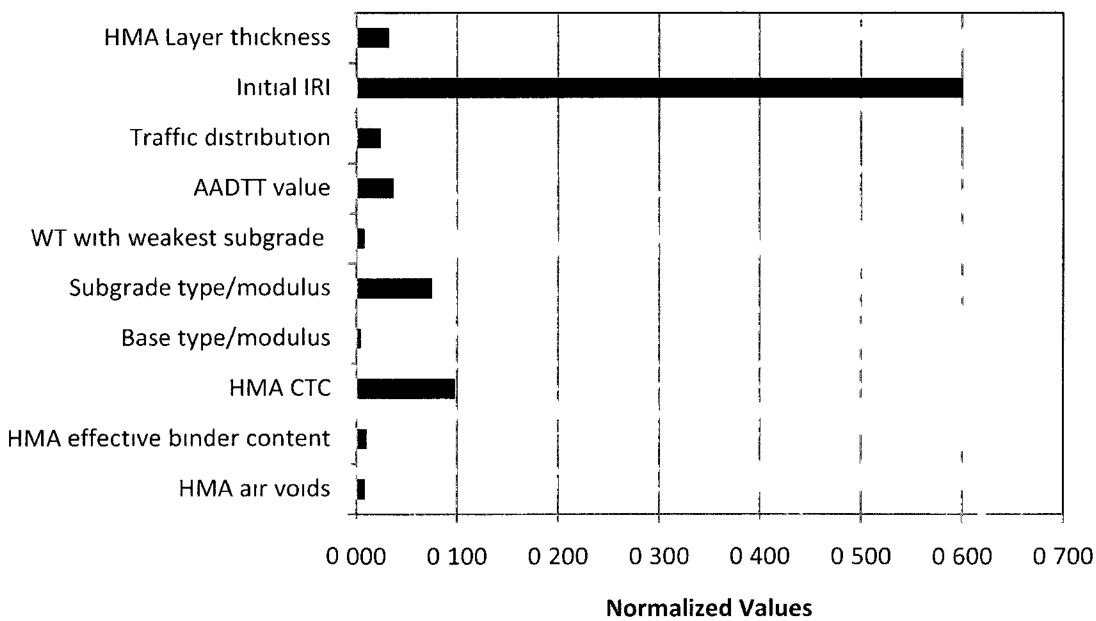


Figure 22: VT Level 2 Significance of Effect of Input Variables on IRI.

4.2.2 New York sensitivity analysis results

The M-E PDG sensitivity analysis in New York State was performed only for Level 3 because the NY DOT was not interested in participating in the research in order to provide Level 2 input values. Table 26 presents the six most significant input variables from the NY State Level 3 sensitivity analysis. The input variables in the table are presented in decreasing order of their significance for each investigated performance indicator. Figures 23 to 27 present significance of effect of each variable on the predicted pavement distress based on the normalized value. The normalized values for New York State are presented in Table 25.

Data presented in Tables 25 – 27 and Figures 23 – 27 showing sensitivity analysis results for New York Level 3.

Table 25: Normalized Values and Ranks for New York Level 3.

NEW YORK LEVEL 3										
Input Variable	**Bottom-Up**		**Top-Down**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA thickness	0.175	1	2.550	1	0.155	9	0.208	5	0.024	7
HMA mix gradation	0.019	11	0.417	8	0.244	6	0.134	8	0.015	10
HMA air voids	0.130	2	1.047	5	0.113	11	0.063	11	0.002	14
HMA effective binder content	0.026	10	0.141	12	0.167	8	0.089	9	0.020	8
HMA binder grade	0.065	5	1.409	3	0.768	3	0.411	2	0.046	6
Base type/modulus	0.032	9	0.295	10	0.065	13	0.066	10	0.008	12
Subgrade type/modulus	0.078	4	1.206	4	0.173	7	0.395	3	0.102	4
Ground water table	0.058	6	0.436	7	0.137	10	0.134	8	0.008	12
WT with weakest subgrade	0.078	4	0.010	14	0.077	12	0.061	12	0.009	11
Climate	0.045	8	0.881	6	0.786	2	0.392	4	0.149	2
AADTT value	0.045	8	0.326	9	0.292	5	0.161	7	0.019	9
Operational speed	0.091	3	1.633	2	1.024	1	0.529	1	0.061	5
Traffic growth rate	0.013	12	0.082	13	0.137	10	0.045	13	0.005	13
Traffic distribution	0.052	7	0.224	11	0.327	4	0.166	6	0.019	9
HMA CTC	0.000	13	0.000	15	0.000	14	0.000	14	0.115	3
Initial IRI	0.000	13	0.000	15	0.000	14	0.000	14	0.577	1

Table 26: Ranking of Input Variable Significance for NY Level 3 Sensitivity Analysis.

	Bottom-Up Cracking	Top-Down Cracking	AC Rutting	Total Rutting	IRI
Most Significant Variable	HMA thickness	HMA thickness	Operational speed	Operational speed	Initial IRI
↓	HMA air voids	Operational speed	Climate	HMA binder grade	Climate
↓	Operational speed	HMA binder grade	HMA binder grade	Subgrade type/modulus	HMA CTC
↓	Subgrade type/modulus	Subgrade type/modulus	Traffic distribution	Climate	Subgrade type/modulus
↓	WT with weakest subgrade	HMA air voids	AADTT value	HMA thickness	Operational speed
Least Significant Variable	HMA binder grade	Climate	HMA mix gradation	Traffic distribution	HMA binder grade

The "zero" value on the graph indicates, that there is no impact of an input on a predicted pavement distress. As an example, Figures 23 through 26 present the initial IRI and the HMA CTC inputs which have no impact on the predicted pavement distresses such as: bottom-up cracking, top-down cracking, AC rutting and total rutting.

In New York, HMA thickness had a significant effect on bottom-up and top down fatigue cracking distresses. Both of these increased with the decrease of HMA thickness

(Appendix B Figures 57B and 58B). The most significant effect of fatigue top-down cracking was especially visible when the HMA layer thickness was reduced to 8.0" (Appendix B Figure 58B). In general, all pavement distresses and roughness IRI were increased with the decrease of the total HMA thickness (Appendix B Figures 57B through 62B).

Traffic variables such as operational speed, AADTT, and vehicle class distribution had an expected influence on the predicted pavement distresses and roughness IRI (Figures 23 through 27). Operational speed was the most significant variable with a large impact on AC rutting and total rutting (Appendix B Figures 26B through 30B). In general, for all pavement distresses and roughness IRI, values increased with the decrease of the operational speed. For the AADTT and the vehicle class distribution (axle loads) as was expected, with the increase of these two variables the predicted pavement distresses and IRI increased as well. This study had confirmed this prediction as well (Appendix B Figures 31B – 35B, and Figures 16B – 20B).

The effect of binder grade selection was observed in New York State for all types of predicted pavement distresses and roughness IRI. The selected binder grades were analyzed in conjunction with three different operational speeds. The selected binder grades are listed in Table 22B (Appendix B). The significant effect of a selected binder grade was observed on fatigue top-down cracking, and both rutting distresses (AC and total). The small effect was visible on the fatigue (bottom-up) cracking distress and roughness IRI. In both examples, the lower selected pavement grade exhibited a higher distress level and a higher roughness IRI value (Appendix B Figures 77B through 91B).

The New York climate had a significant effect on fatigue top-down cracking and AC rutting, and moderate effects on total rutting and roughness IRI. The influence of climate in NY is very important due to the size of the state, geographic characteristics and local temperature variations. In general, higher predicted pavement distresses in southern state locations were observed (Appendix B Figures 36B through 39B). The opposite effects of binder grades on roughness and thermal cracking were observed in Figures 40B and 41B (Appendix B). In those two examples, the state's northern location exhibited a higher thermal cracking distress and a higher roughness IRI value.

Changes in HMA parameters such as air voids (%) or effective binder content (%) were expected to have an influence on pavement distresses. This expectation was only confirmed for the air voids content and its influence on fatigue bottom-up and top-down cracking. Increased HMA air voids content caused a large increase of fatigue alligator and longitudinal cracking distresses (Appendix B Figures 52B and 53B). The effective binder content variations within the state tolerances did not influence any of the predicted pavement distresses or roughness IRI.

The effect of subgrade type (AASHTO Classification) on performance was determined by comparing distress and IRI prediction over time with selected subgrade types (Appendix B Figures 97B to 101B). Figure 98B and 99B (Appendix B) showed unexpected results for the weaker subgrade type (A-7-6), where there was no influence on fatigue (top-down) cracking, and an opposite than expected effect on subtotal rutting. In general, the lower the subgrade type/modulus, there could be expected higher pavement distresses and IRI.

The effect of the mix coefficient of thermal contraction CTC in this level of sensitivity analysis was insignificant for all of pavement distresses (zero value in Figures 23 through 26), and the mix coefficient had only moderate effect on the roughness IRI prediction (Figure 27). The increase of the CTC value affected the increase in roughness IRI (Appendix B Figure 111B).

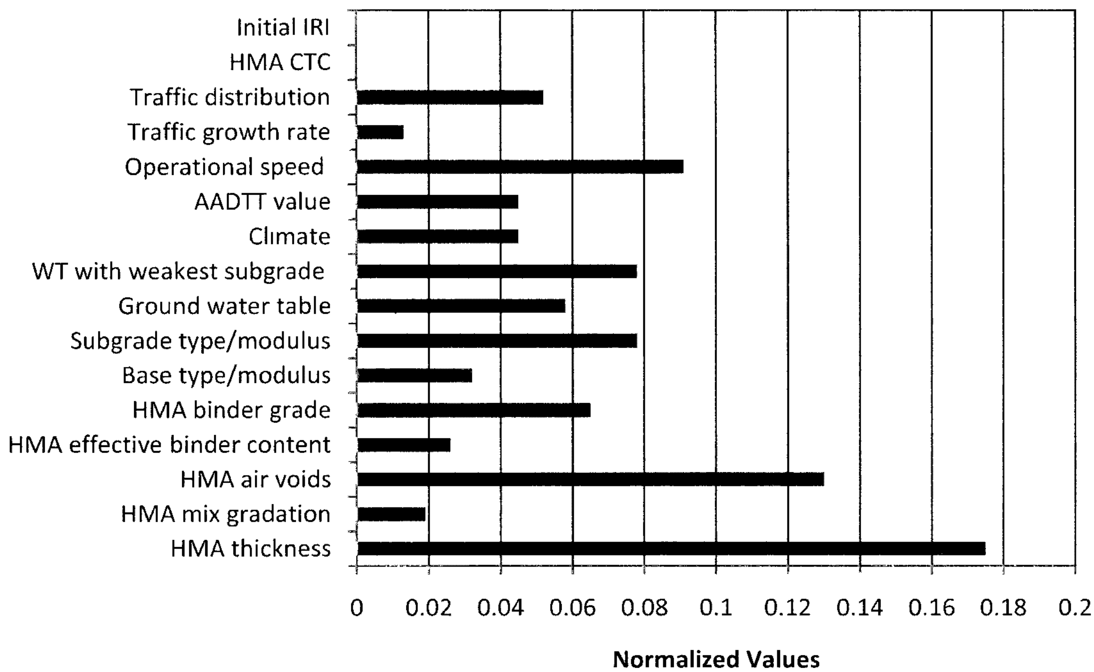


Figure 23: NY Level 3 Significance of Effect of Input Variables on Bottom-Up Cracking.

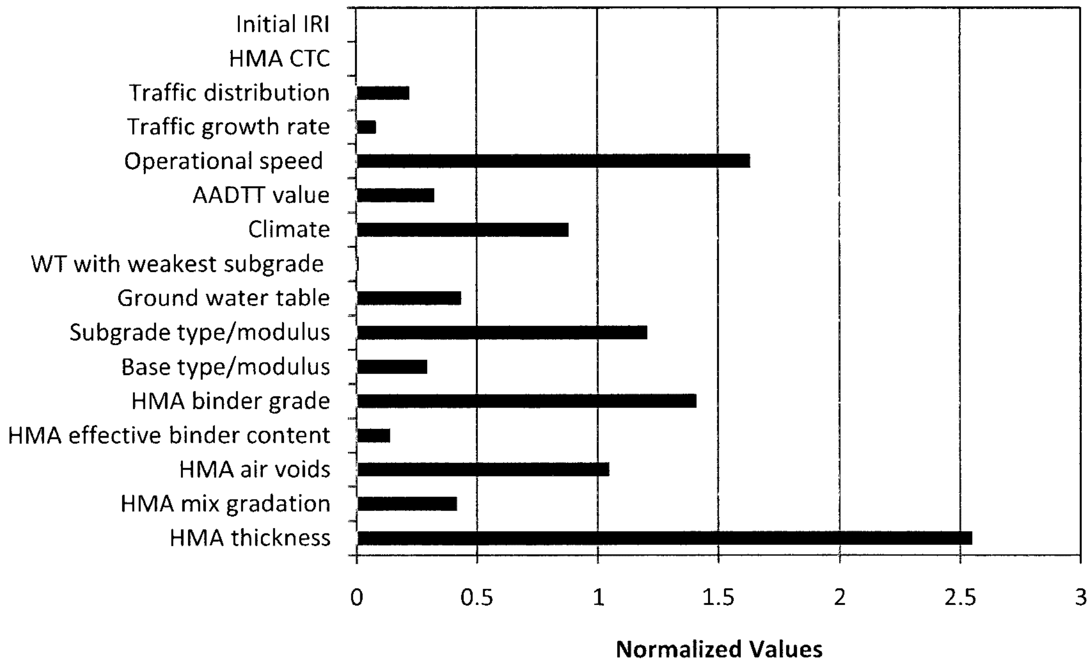


Figure 24: NY Level 3 Significance of Effect of Input Variables on Top-Down Cracking.

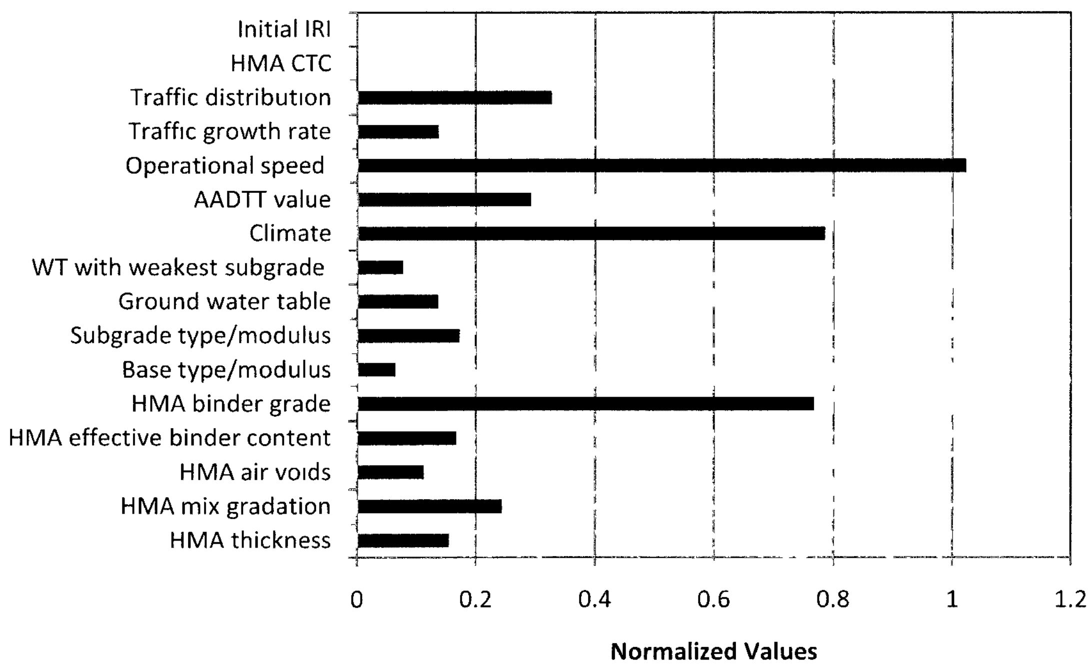


Figure 25: NY Level 3 Significance of Effect of Input Variables on AC Rutting.

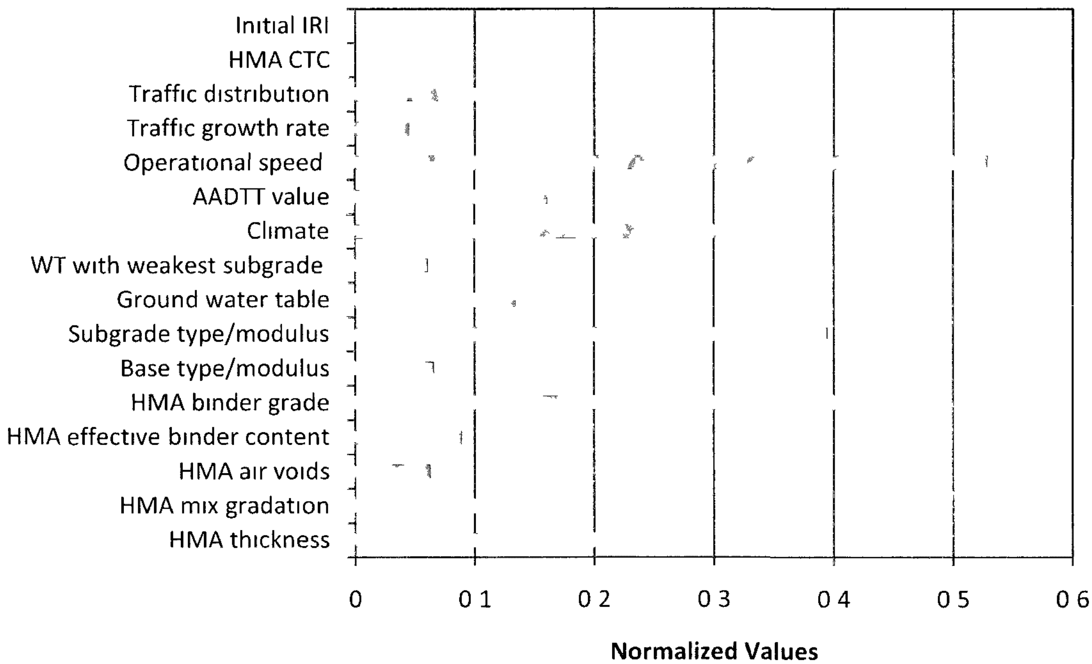


Figure 26: NY Level 3 Significance of Effect of Input Variables on Total Rutting.

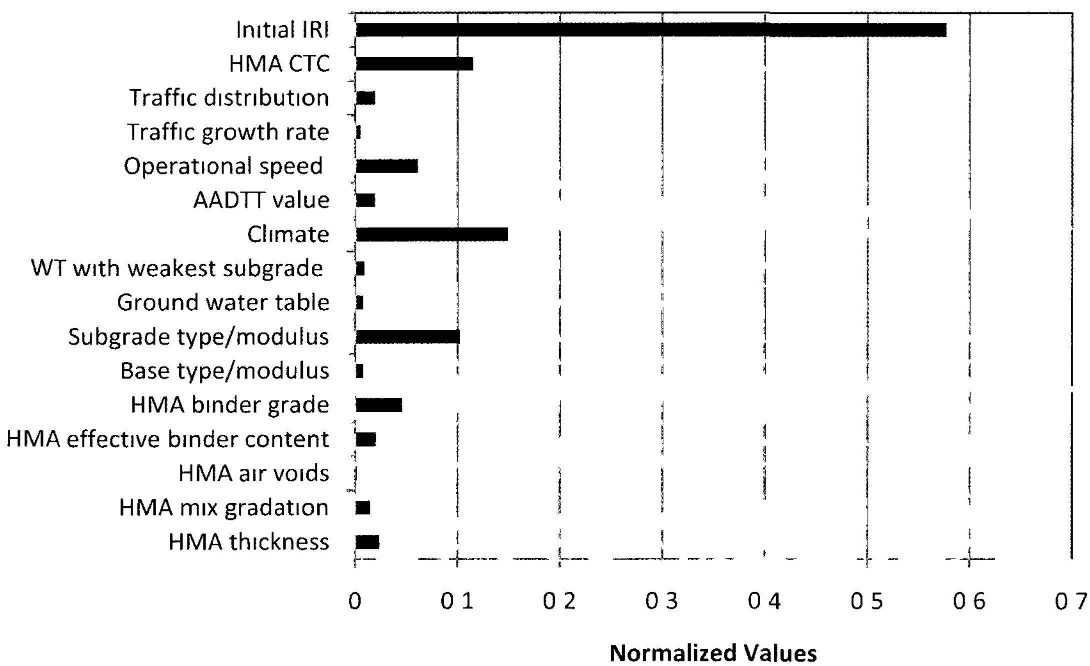


Figure 27: NY Level 3 Significance of Effect of Input Variables on IRI.

Table 27 presents the New York overall ranking summary of significance of each input parameter on the performance of flexible pavement. This ranking method finds the most significant variables which impact the predictions of pavement distresses in the state. This method is very subjective and depends on the variables chosen by the researcher. In this example, based on the total ranking points (smaller numbers had a higher effect), the following variables have a significant impact on the pavement distress prediction in New York:

1. Operational speed
2. HMA binder grade
3. Climate and subgrade type/modulus
4. HMA thickness
5. Traffic distribution
6. AADTT

In the above overall order of significance ranking the high position of the operational speed was surprising. This research did not investigate how realistic ranking of vehicle speed is as a variable for pavement performance predictions. It is up to the state agency to decide if the change of vehicle speed and its range could really affect the pavement performance.

Table 27: NY Overall Ranking Summary of Significance of Each Input Parameter on the Performance of Flexible Pavement.

NEW YORK LEVEL 3							
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**	**Total Ranking Points**	**Overall Order of Significance**
	Rank	Rank	Rank	Rank	Rank		
HMA thickness	1	1	9	5	7	**23**	**4**
HMA mix gradation	11	8	6	8	10	**43**	**7**
HMA air voids	2	5	11	11	14	**43**	**7**
HMA effective binder content	10	12	8	9	8	**47**	**8**
HMA binder grade	5	3	3	2	6	**19**	**2**
Base type/modulus	9	10	13	10	12	**54**	**10**
Subgrade type/modulus	4	4	7	3	4	**22**	**3**
Ground water table	6	7	10	8	12	**43**	**7**
WT with weakest subgrade	4	14	12	12	11	**53**	**9**
Climate	8	6	2	4	2	**22**	**3**
AADTT value	8	9	5	7	9	**38**	**6**
Operational speed	3	2	1	1	5	**12**	**1**
Traffic growth rate	12	13	10	13	13	**61**	**13**
Traffic distribution	7	11	4	6	9	**37**	**5**
HMA CTC	13	15	14	14	3	**59**	**12**
Initial IRI	13	15	14	14	1	**57**	**11**

4.2.3 Massachusetts sensitivity analysis results

In Massachusetts, only Level 3 sensitivity analysis was performed due to lack of Level 2 input data. In spite of many requests, the MA DOT did not provide any inputs for this level. Table 28 shows all input variables used for the study, as well as their ranks based on the normalized values from the final analysis. Table 29 presents the six most significant input variables for the Massachusetts Level 3 sensitivity analysis. The input variables in the table are presented in decreasing order of significance for each investigated performance indicator. Figures 28 to 32 present the significance of effect of each variable on the predicted pavement distress based on the normalized value (Table 26).

Data presented in Tables 28 – 30 and Figures 28 – 32 showing sensitivity analysis results for Massachusetts Level 3.

Table 28: Normalized Values and Ranks for Massachusetts Level 3.

MASSACHUSETTS LEVEL 3										
Input Variable	**Bottom-Up**		**Top-Down**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA thickness	0.106	1	1.465	1	0.153	7	0.261	4	0.034	8
HMA mix gradation	0.013	7	0.289	11	0.235	6	0.134	8	0.018	10
HMA air voids	0.086	2	0.942	3	0.133	8	0.075	11	0.010	13
HMA effective binder content	0.013	7	0.103	12	0.071	10	0.042	13	0.005	15
HMA binder grade	0.033	4	0.902	5	0.755	2	0.406	2	0.053	5
Base type/modulus	0.026	5	0.360	9	0.087	9	0.101	9	0.013	11
Subgrade type/modulus	0.013	7	0.623	6	0.046	13	0.202	7	0.084	3
Ground water table	0.013	7	0.349	10	0.061	12	0.096	10	0.012	12
WT with weakest subgrade	0.020	6	0.015	14	0.046	13	0.063	12	0.008	14
Climate	0.026	5	0.506	7	0.469	3	0.235	5	0.039	7
AADTT value	0.026	5	0.411	8	0.332	5	0.207	6	0.027	9
Operational speed	0.046	3	1.096	2	1.051	1	0.556	1	0.072	4
Traffic growth rate	0.007	8	0.069	13	0.066	11	0.040	14	0.005	15
Traffic distribution	0.086	2	0.908	4	0.429	4	0.289	3	0.044	6
HMA CTC	0.000	9	0.000	15	0.000	14	0.000	15	0.087	2
Initial IRI	0.000	9	0.000	15	0.000	14	0.000	15	0.588	1

Table 29: Ranking of Input Variable Significance for MA Level 3 Sensitivity Analysis.

	Bottom-Up Cracking	Top-Down Cracking	AC Rutting	Total Rutting	IRI
Most Significant Variable	HMA thickness	HMA thickness	Operational speed	Operational speed	Initial IRI
↓	HMA air voids	Operational speed	HMA binder grade	HMA binder grade	HMA CTC
	Traffic distribution	HMA air voids	Climate	Traffic distribution	Subgrade type/modulus
	Operational speed	Traffic distribution	Traffic distribution	HMA thickness	Operational speed
	HMA binder grade	HMA binder grade	AADTT value	Climate	HMA binder grade
Least Significant Variable	AADTT value	Subgrade type/modulus	HMA mix gradation	AADTT value	Traffic distribution

The "zero" value on the graph indicates that there is no impact of an input on a predicted pavement distress. As an example, Figures 28 through 31 present the initial IRI and the HMA CTC inputs which have no impact on the predicted pavement distresses such as: bottom-up cracking, top-down cracking, AC rutting and total rutting.

HMA thickness had a significant effect on both fatigue cracking distresses (bottom-up and top-down). Both of these pavement predicted distresses increased with the decrease of HMA thickness (Appendix C Figures 59C – 60C). The moderate effect of HMA thickness was observed for total rutting, and a small effect was observed for AC rutting in

Figures 62C and 61C (Appendix C). As was expected for the thinner HMA layers, higher pavement distresses and IRI were observed.

Traffic variables such as operational speed, AADTT, and vehicle class distribution had an expected influence on the predicted pavement distresses and roughness IRI (Figures 28 through 32). Operational speed was the most significant variable with the greatest impact on AC rutting and total rutting (Appendix C Figures 29C through 33C). In general, for all pavement distresses and roughness IRI, the decrease of the operational speed increased distresses and IRI values. For the AADTT and the vehicle class distribution (axle loads), as was expected, with the increase of the track traffic and axle load values, the predicted pavement distresses and IRI increased as well. This study had confirmed this prediction as well (Appendix C Figures 34C – 38C and Figures 19C – 23C).

The effect of binder grade selection was observed in Massachusetts for all types of predicted pavement distresses and roughness IRI. The selected binder grades were analyzed in the conjunction with three different operational speeds (5, 25 and 65 mph). The selected binder grades are listed in Table 23C (Appendix C). The significant effect of a selected binder grade was observed on fatigue top-down cracking, and both of rutting distresses (AC and total). The small effect was visible on the fatigue (bottom-up) cracking distress and roughness IRI. In both examples, the lower selected pavement grade exhibited a higher distress level and a higher roughness IRI value (Appendix C Figures 79C through 93C).

Changes in HMA parameters such as air voids (%) or effective binder content (%) were expected to have an influence on predicted pavement distresses in Massachusetts. This expectation was only confirmed for the air voids content and its influence on fatigue bottom-up and top-down cracking distresses. Increased HMA air voids content caused a large increase of fatigue alligator and longitudinal cracking pavement distresses (Appendix C Figures 54C and 55C). The effective binder content variations within the MA DOT tolerance limits did not influence any of the predicted pavement distresses or roughness IRI.

The Massachusetts climate effects were observed in Figures 39C through 43C (Appendix C). Four climatic weather stations and three ground water table levels were selected. The influence on a predicted pavement performance was only observed for the weather station variables, with moderate effects on AC and total rutting, and on fatigue top-down cracking distress. In general, the southern state locations had a higher predicted distress level, with the exception of roughness IRI value prediction, whereas the northern parts of the state exhibited higher values. The ground water table level variable was insignificant for all of the predictions (Table 26). The ground water table effect is not consistent to current pavement design knowledge, and it needs to be reevaluated with the new M-E PDG version.

The effect of subgrade type (AASHTO Classification) on performance was determined by comparing distress and IRI prediction over time with selected subgrade types (Appendix C Figures 99C to 103C). Figure 100C and 101C (Appendix C) showed unexpected results for the weaker subgrade type (A-7-6), where there was almost no influence on fatigue (top-down) cracking, and an opposite then expected effect on AC rutting (a weaker subgrade type effected pavement distress less than a stronger subgrade).

In general, the lower the subgrade type/modulus the higher the pavement distresses and IRI would be expected.

The effect of mix coefficient of thermal contraction CTC in this level of sensitivity analysis was insignificant for all of pavement distresses (zero value in Figures 28 through 31), and had only small effect on the roughness IRI prediction (Figure 32).

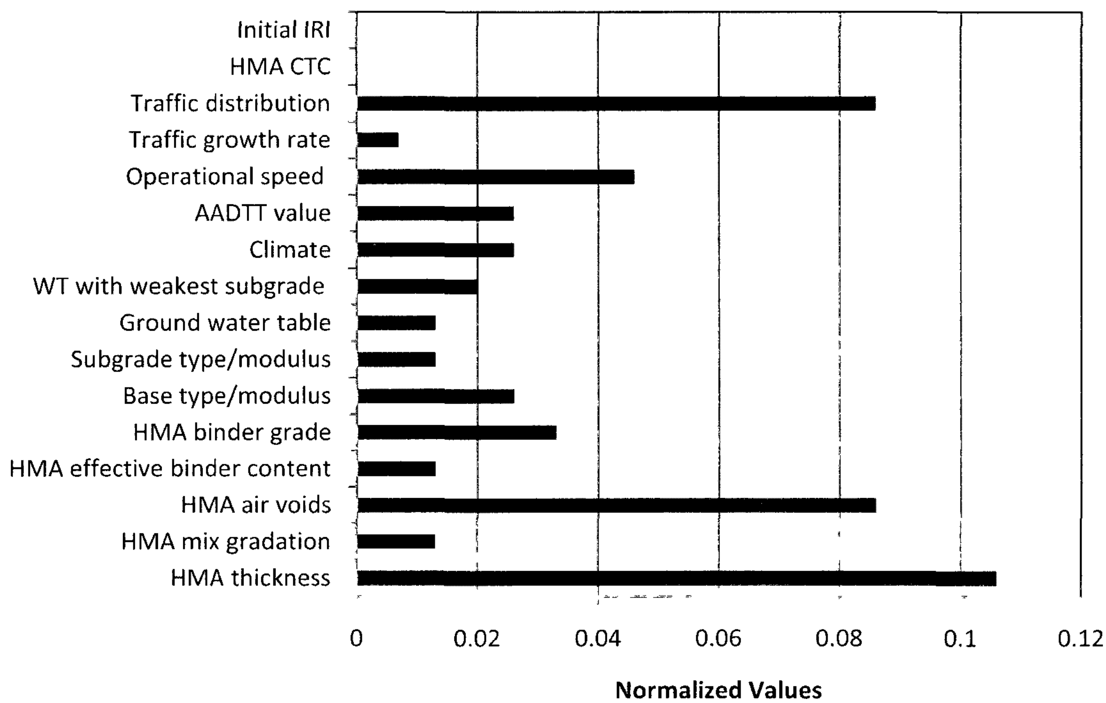


Figure 28: MA Level 3 Significance of Effect of Input Variables on Bottom-Up Cracking.

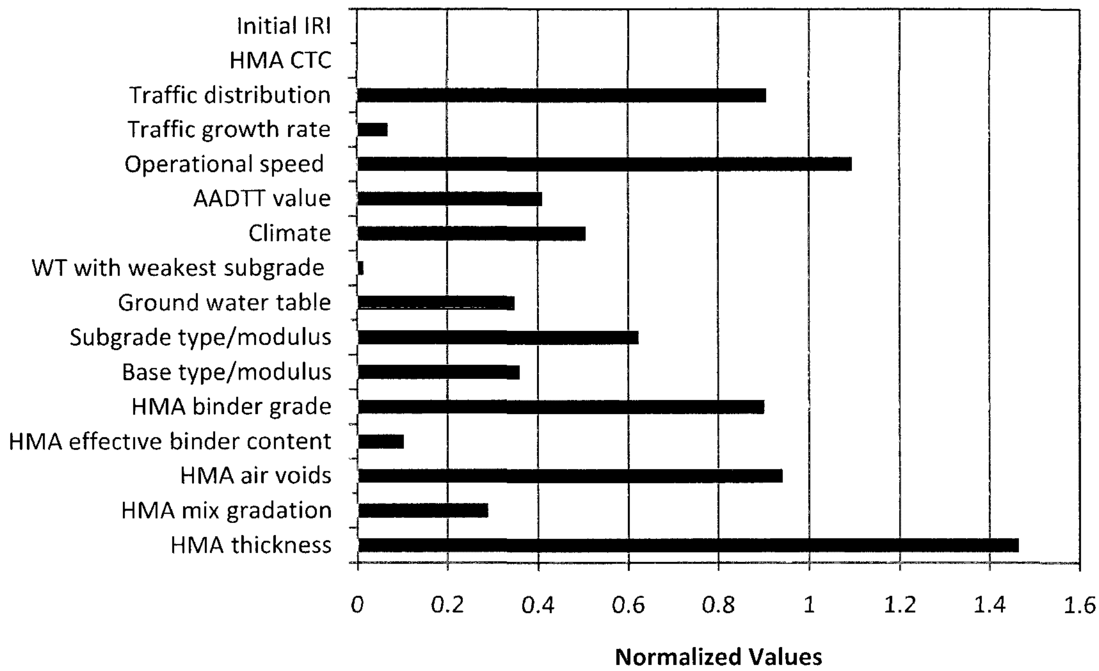


Figure 29: MA Level 3 Significance of Effect of Input Variables on Top-Down Cracking.

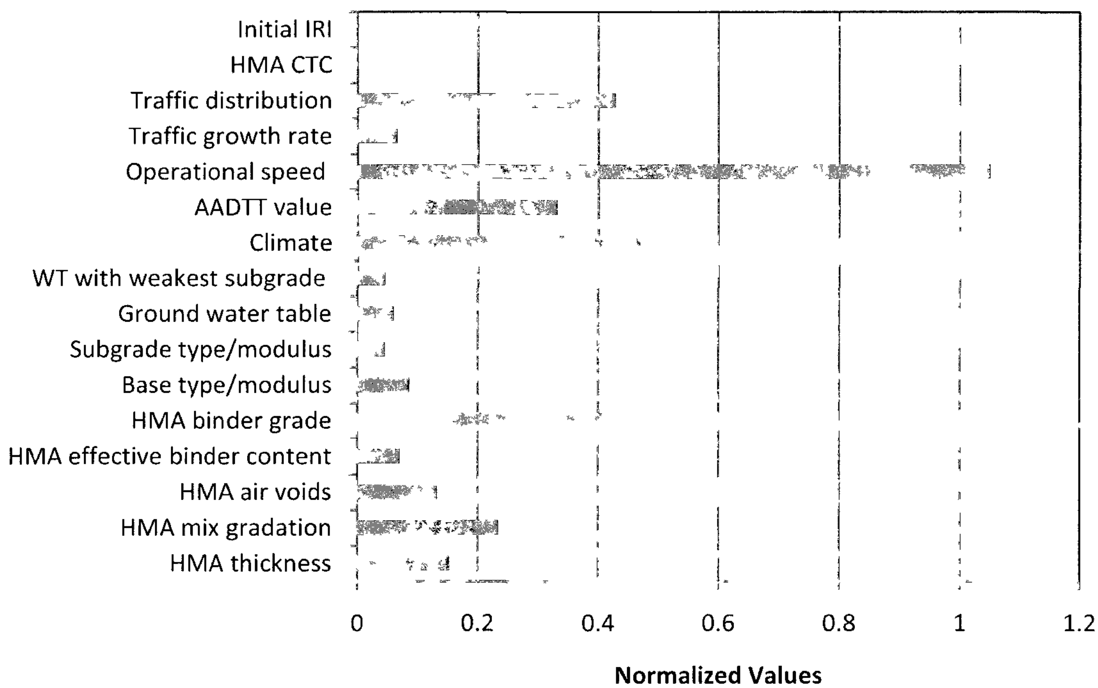


Figure 30: MA Level 3 Significance of Effect of Input Variables on AC Rutting.

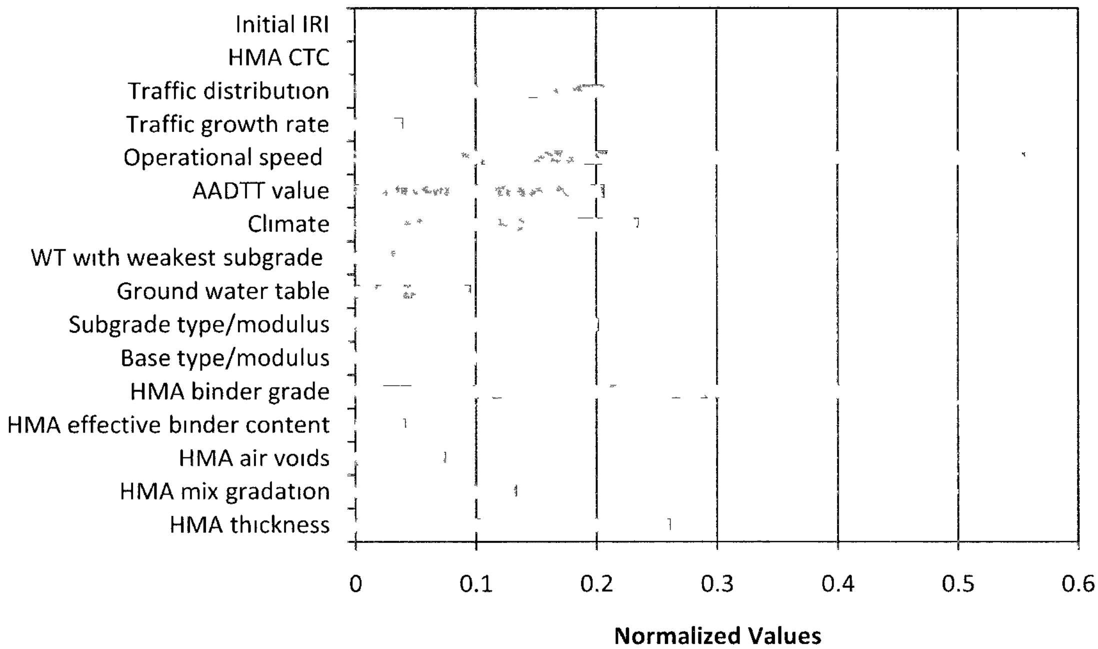


Figure 31: MA Level 3 Significance of Effect of Input Variables on Total Rutting.

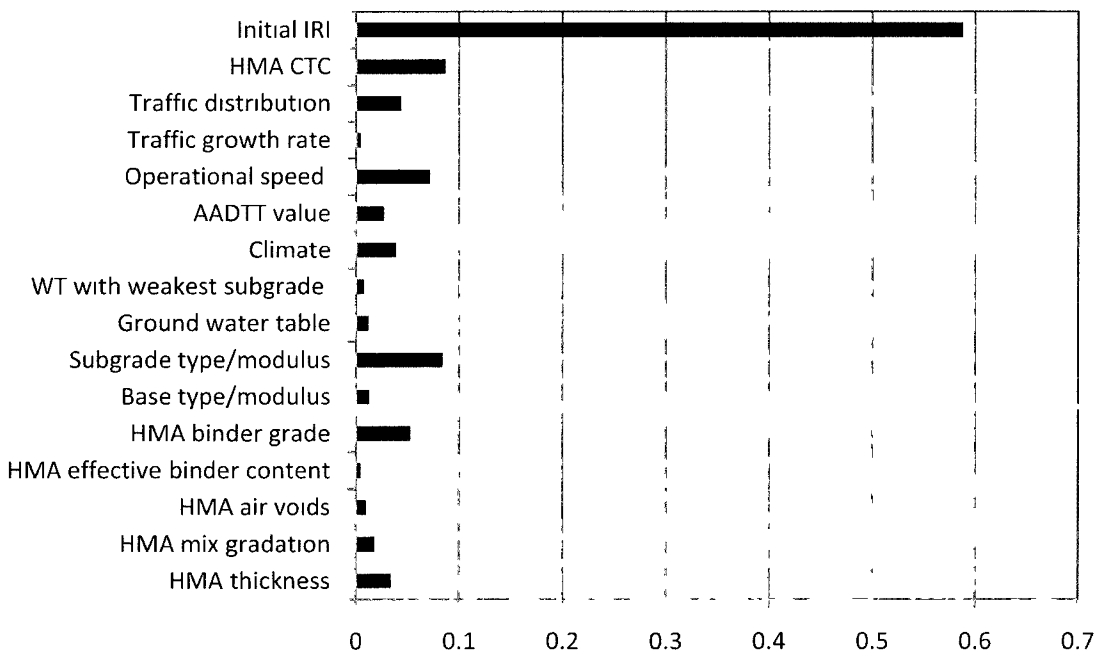


Figure 32: MA Level 3 Significance of Effect of Input Variables on IRI.

Table 30 presents the Massachusetts overall ranking summary of significance of each input parameter on the performance of flexible pavement. This ranking method identifies the most significant variables which impact the predictions of pavement distresses in the state. This method is very subjective and depends on the variables chosen by the researcher. In this example, based on the total ranking points (smaller numbers indicate a greater effect), the following variables have a significant impact on the pavement distress prediction in Massachusetts:

1. Operational speed
2. HMA binder grade
3. Traffic distribution
4. HMA thickness
5. Climate
6. AADTT
7. Subgrade type/modulus.

In the above overall order of significance ranking the high position of the operational speed was surprising. This research did not investigate how realistic ranking of vehicle speed is as a variable for pavement performance predictions. It is up to the state agency to decide if the change of vehicle speed and its range could really affect the pavement performance.

Table 30: MA Overall Ranking Summary of Significance of Each Input Parameter on the Performance of Flexible Pavement.

MASSACHUSETTS LEVEL 3							
Input Variable	**Bottom-Up Rank**	**Top-Down Rank**	**AC Rutting Rank**	**Total Rutting Rank**	**IRI Rank**	**Total Ranking Points**	**Overall Order of Significance**
HMA thickness	1	1	7	4	8	**21**	**4**
HMA mix gradation	7	11	6	8	10	**42**	**9**
HMA air voids	2	3	8	11	13	**37**	**8**
HMA effective binder content	7	12	10	13	15	**57**	**14**
HMA binder grade	4	5	2	2	5	**18**	**2**
Base type/modulus	5	9	9	9	11	**43**	**10**
Subgrade type/modulus	7	6	13	7	3	**36**	**7**
Ground water table	7	10	12	10	12	**51**	**11**
WT with weakest subgrade	6	14	13	12	14	**59**	**15**
Climate	5	7	3	5	7	**27**	**5**
AADTT value	5	8	5	6	9	**33**	**6**
Operational speed	3	2	1	1	4	**11**	**1**
Traffic growth rate	8	13	11	14	15	**61**	**16**
Traffic distribution	2	4	4	3	6	**19**	**3**
HMA CTC	9	15	14	15	2	**55**	**13**
Initial IRI	9	15	14	15	1	**54**	**12**

4.3 Impact of Traffic Inputs on M-E PDG predictions

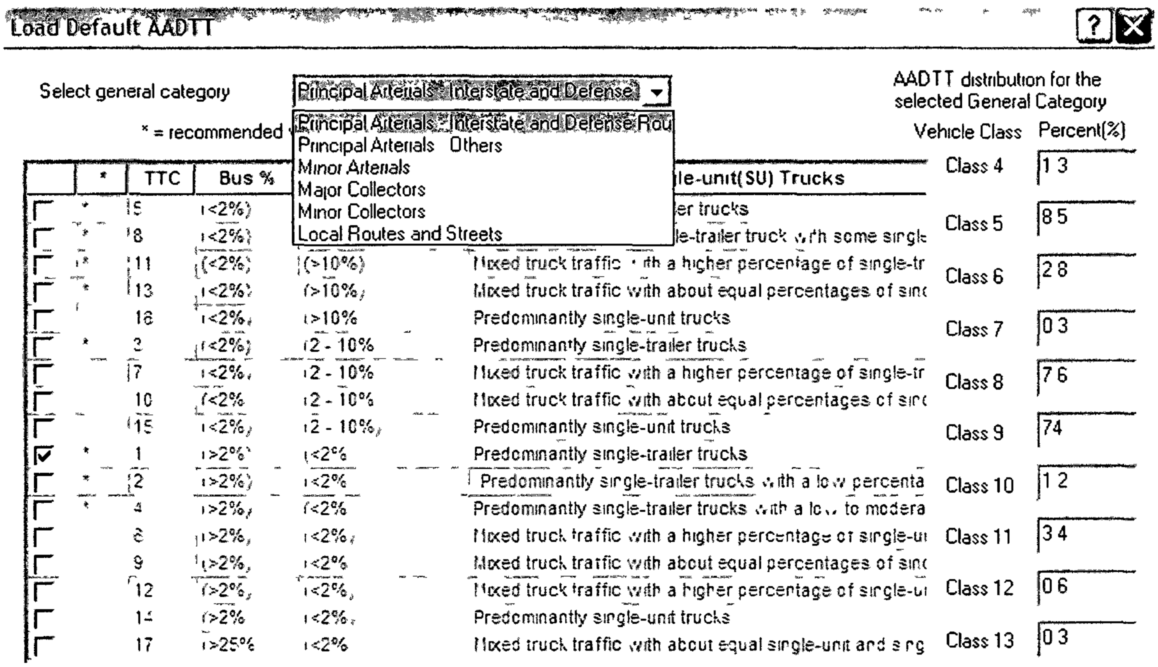
Level 3 and 2 M-E PDG sensitivity analysis required a large number of traffic inputs. The M-E PDG uses the full axle-load spectrum data for flexible new pavements. The axle-load spectra are obtained from processing weighting-in-motion (WIM) data. The M-E PDG defaults values were determined from an analysis of nearly 200 WIM stations from the Long Term Pavement Performance (LTPP) program. The results from this study show which traffic inputs are significant for the pavement predictions.

Operational speed was the most significant variable of the traffic inputs. The sensitivity analysis results are especially visible in the AC rutting and total rutting predictions.

Annual Average Daily Truck Traffic (AADTT) value in all three investigated states also had a significant effect on the predicted pavement performance distresses. This value could be obtained from the historic traffic data sites, either from the DOT or LTPP database. AADTT value affects both rutting predictions (AC and total), as well as fatigue bottom-up and top-down cracking.

The effect of traffic distribution was observed in Massachusetts for all the predicted pavement performance indicators. In Vermont and New York, a significant effect was only visible for AC and total rutting predicted distresses. The M-E PDG default AADTT option allows the designer to choose between different truck distributions depending on the road functional classification. Table 31 presents the options for selecting AADTT defaults based on the road functional classification and heavy truck traffic characteristics (vehicle class 4 to 13).

Table 31: AADTT Default Options.



The traffic growth factor was found to have an insignificant effect on the prediction of pavement distresses

The monthly adjustment and hourly distribution factors were found to be insignificant to the prediction of pavement distresses.

4.4 Impact of Climate Inputs on M-E PDG predictions

All of the climate data necessary for the M-E PDG sensitivity analysis is available from over 800 weather stations located across the U.S The designer must specify the project location (longitude and latitude) to obtain the six closest weather stations. At least three weather stations must be chosen for each project location to create a virtual weather station. The purpose of choosing more water stations was to avoid the possibility of missing data and of obtaining errors from a single weather station. The climate variable was found to have a significant effect on the AC and total rutting predictions.

The literature review shows that the climatic data have a significant affect on the thermal cracking predictions. The occurrence was only observed in New York State, where the thermal cracking model worked well, except for the Buffalo, NY location, where the thermal crack length values decreased with the increase of time. In the other states the task could not be completed due to the M-E PDG software shortcoming (transverse cracking values equal to “0”). The example of the climate effect on the thermal cracking distress is seen in Figure 33.

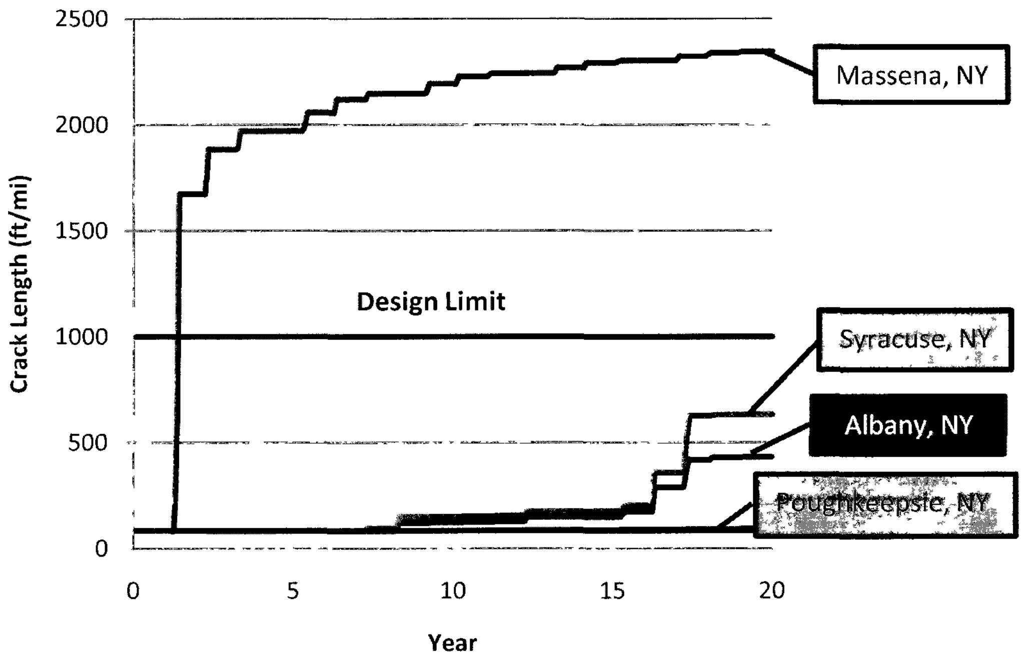


Figure 33: Effect of Climate on Thermal Cracking in NY State.

The water table depth was another climate input parameter selected for this study. This variable was found to have an insignificant effect on the most of the predicted pavement distresses, with only small effect on total rutting and fatigue (bottom-up) cracking. This finding does not seem to be reasonable, and it needs to be reevaluated in a future research using a new M-E PDG software version.

4.5 Impact of Pavement Layer Inputs on M-E PDG predictions

The research study considered pavement layer inputs variables such as: thicknesses and types of all layers in the pavement structure. The typical pavement structure consists of four layers: two asphalt layers (surface and binder), base layer and subgrade. The designer needs to specify thicknesses of asphalt and base layers, and material types of all of the layers. For the sensitivity analysis the asphalt layer thicknesses were varied within specific SHA limits and material types were selected based on local soil characteristics.

It was found during the research that changes in asphalt layer thickness were most significant for predicting fatigue bottom-up and top-down cracking. The asphalt layer thickness did not affect rutting or smoothness (IRI) predictions of the pavement.

Base type material was found to have an insignificant effect on predicted pavement distresses if used within the specification limits.

Subgrade type had a significant effect on fatigue top-down cracking (in VT), moderate effect on total rutting (in VT and NY) pavement prediction distresses and, a small effect on smoothness (IRI) in all three states.

4.6 Impact of Material Inputs – Asphalt on M-E PDG predictions

Asphalt material inputs required for M-E PDG Level 2 and Level 3 sensitivity analysis are specified by following variables:

- Asphalt layer thickness,
- Asphalt concrete mix aggregate gradation,
- Asphalt binder grade (Superpave, Viscosity or Penetration grades),
- Air void content,
- Effective binder content.

Asphalt layer thickness is most significant for predicting fatigue bottom-up and top-down cracking, and it does not exhibit have any influence on rutting or smoothness (IRI) of the pavement.

Asphalt mix aggregate grading was not found to be significant for any of the distress predictor indicators if used within the SHA tolerances.

Based on the literature review, the asphalt binder grade selection is dependent on traffic value level, operational speed and climate (16) (17). This study only investigated the interactions between the selected asphalt binder grades and traffic operational speed. It is also known that the asphalt binder grade selection has a large impact on the prediction of thermal cracking in pavements. Since this topic was omitted in this research, it is highly recommended to review it again.

This study shows the significant effect of asphalt binder grade in the conjunction with the traffic operational speed in two of the investigated states: NY and MA, and that the asphalt binder grade had only a moderate effect in Vermont.

HMA air voids content highly affected fatigue bottom-up cracking, and moderately affected top-down pavement distresses in all states. No significance effect of HMA air voids content was found on other pavement distresses.

HMA effective binder content was found to be insignificant for all investigated pavement performance distresses within tolerances examined.

4.7 Impact of Material Properties – Unbound Materials on M-E PDG predictions

The unbound material inputs for M-E PDG sensitivity analysis Level 3 and 2 are characterized by the following variables:

- Material type,
- Resilient modulus value,
- Base layer thickness (not investigated),

- Other methods to characterize material properties in Level 2 such as: CBR value, R-value, penetration DCP value, AASHTO layer coefficient – a_1, or plasticity index and grading.

In this research, the unbound material properties were only characterized by the material types and resilient modulus (measured in psi) values obtained from the state specifications or the LTPP database. It was found that base layer input variables based only on those two values have an insignificant effect on pavement distresses.

Base layer thickness variable was omitted in this study, but it can impact the M-E PDG pavement distress predictions as well. Therefore, it is highly recommended to review this topic in the next project.

Subgrade type had a significant effect on fatigue top-down cracking (in VT), a moderate effect on total rutting (in VT and NY) pavement prediction distresses but only a small effect on smoothness (IRI) in all three states.

Chapter 5: Conclusions

Based on the results of the sensitivity analyses conducted for flexible pavement systems in VT, NY and MA, the following observations were made and the following conclusions drawn:

The various inputs that affect predicted performance of the pavement in VT, NY and MA are:

- **Fatigue longitudinal (top-down) cracking** predictions were mostly affected by: HMA thickness, subgrade type/modulus, HMA air voids and operational speed.
- **Fatigue alligator (bottom-up) cracking** predictions were mostly affected by: HMA thickness, HMA air voids %, AADTT value, operational speed and traffic distribution.
- **Asphalt surface rutting** predictions were mostly affected by: operational speed, HMA binder grade, climate, AADTT value and HMA mix gradation.
- **Total rutting** predictions were mostly affected by: operational speed, HMA binder grade, subgrade type/modulus, HMA thickness, traffic distribution and AADTT.
- **Smoothness IRI** was not sensitive to most input parameters. Based on the literature review fatigue alligator cracking and thermal cracking are the primary contributors to the IRI value (19).
- Based on the above findings only a few parameters used in this study affected all predicted performance measures. However, asphalt volumetric properties, AADTT,

operational speed, and subgrade type generally influenced most of the predicted performance measures.

- **Transverse cracking** distresses were only predicted by the M-E PDG software in New York State (Appendix B). The model did not work in the Vermont and Massachusetts analysis (transverse cracking values equal to "0").

5.1 State Specific Recommendations

Feasibility of the nationally calibrated M-E PDG models in VT, NY and MA were investigated based on limited number of resources such as LTPP sections and state web sites. These resources are inadequate to finally specify the M-E PDG application feasibility in those states. However, this research and results presented herein can help with the transition process from the current AASHTO design practices to the M-E PDG, by evaluating the adequacy of Level 3 and 2 inputs for flexible pavement design.

5.1.1 Vermont Recommendations

According to this study, the most significant M-E PDG input variables on performance for new flexible pavements in Vermont are:

- Traffic values such as AADTT, operational speed and traffic distribution
- Asphalt thickness
- Asphalt properties such as air voids content and HMA mix gradation
- Subgrade type/modulus value

It is also recommended that Vermont carefully attend to the selection of the asphalt binder grade due to climate variations within the state. The use of the higher binder grades is recommended due to the smaller predicted pavement distresses. Based on an initial meeting with the Vermont AOT, it could be stated that they are the most advanced in the implementation process within the New England States. The Vermont AOT holds meetings with the involved departments on the regular basis, provides M-E PDG training to the personnel, discusses the M-E PDG implementation issues, makes future plans, collects the data necessary for future use with the new software, and validates the predicted pavement distress values with their road tests data and recent findings.

5.1.2 New York Recommendations

This recommendation is based only on the default input values, which were obtained for this state from one LTPP road section and from information available on the NY State DOT web site. According to this study, the most significant M-E PDG input variables on the performance for new flexible pavements in New York are:

- Traffic values such as operational speed and traffic distribution
- Asphalt thickness
- Other asphalt properties such as air void content and binder grade selection
- Subgrade type/modulus value
- Climate

Climate is a very important variable for this state due to its area. It was found that climate highly affected all predicted pavement distresses with the exception of bottom-up fatigue cracking.

5.1.3 Massachusetts Recommendations

This recommendation is based only on the default input values, which were obtained for this state from three LTPP road sections and from information from the MA DOT web site. According to this study, the most significant M-E PDG input variables on the performance for new flexible pavements in Massachusetts are:

- Traffic values such as operational speed, traffic distribution and AADTT value
- Asphalt thickness
- Other asphalt properties such as air voids content and binder grade selection
- Climate.

The climate variation is especially important with the AC and total rutting predictions for new flexible pavements.

5.2 General observations for the M-E PDG implementation

Implementation of the M-E PDG requires:

a) Time and agency resources (staffing, training, testing facilities and equipment).

b) Establishment of performance criteria against which the design evaluation can be measured.

c) Validation of the M-E PDG nationally calibrated pavement distress and smoothness prediction models with current state conditions.

d) Local calibration as may needed.

An example of an implementation plan which can be use by state highway agencies:

1. Form an Implementation Team and develop a communication plan
2. Establish a set of performance criteria against which design evaluations can be measured. These criteria may be stratified to reflect different levels of traffic, different levels of functional class, etc.
3. Set recommend M-E PDG input levels, required resources, and obtain necessary testing equipment
4. Conduct sensitivity analysis of M-E PDG inputs
5. Develop and populate a central database with required M-E PDG input values.
6. Conduct staff training
7. Develop a formal state specific M-E PDG-related documentation
8. Resolve differences between the M-E PDG predicted distresses and distresses collected in the field

9. Calibrate and validate M-E PDG performance prediction models to local conditions
10. Define long-term plan for adopting the M-E PDG design procedure
11. Develop a design catalog.

The benefits of implementing M-E PDG are:

a) Achieving the more cost effective and reliable pavements designs
b) Lower initial and life cycle cost to the agency
c) Reduced highway user impact due to less lane closures for maintenance and rehabilitation of pavements

5.3 Recommendations for future work

- Transverse cracking model and its performance predictions for flexible pavements needs to be analyzing with the new version of the M-E PDG.
- Improve interactions and data sharing between state highway agencies and researchers, (i.e., academia) to benefit future studies (knowledge of states specific issues, implementation plans, founding's, local calibrations, etc.,)
- The M-E PDG predicted pavement distresses should be validated against the recorded measurements by each of the state highway agencies covered by this research.
- Reevaluate the ground water table affect on pavement performance predictions, due to suspect findings in this research.
- Investigate the interaction between asphalt binder grades and traffic level.

- Investigate the interactions between asphalt binder grades and climate.
- Investigate unbound layer thickness effect on predicted pavement distresses for base and subbase.
- Compare summary resilient modulus values to average resilient modulus values for unbound layers.
- Compare affect of base and subbase on pavement distress predictions (as an example: rock base/sand subbase).
- Investigate how the M-E PDG ground water table values relate to unbound M_r values.
- Investigate how realistic is ranking of vehicle speed as a variable for pavement performance predictions.
- Perform the M-E PDG Level 1 sensitivity analysis for the New England States and New York.

References:

1. **Transportation Research Circular E-C155.** *Sensitivity Analyses for Flexible Pavement Design with the Mechanistic–Empirical Pavement Design Guide.* Washington, D.C. : TRB, July, 2011. ISSN 0097-8515.

2. **AASHO.** *AASHO Interim Guide For Design Of Pavement Structures 1972.* Washington, D.C. : The American Association Of State Highway Officials, 1972.

3. **AASHTO.** *AASHO Guide for Design of Pavement Structures 1993.* Washington, D.C. : AASHTO, 1993.

4. **Ayyala, Dinesh.** *Sensitivity Analysis of Pavement Performance Predicted Using the M-E PDG.* Philadelphia, PA : The Pensilvania State Un iversity, May, 2009.

5. **AASHTO.** *AASHO Guide for Design of Pavement Structures 1986.* Washington, D.C. : AASHTO, 1986.

6. **Schwartz, Charles W.** *Implementation of the NCHRP 1-37A Design Guide.* College Park, MD : Department of Civil and Environmental Engineering, February, 2007.

7. **Coree, Brian, Ceylan, Halil and Harrington, Dale.** *Implementing the MEPDG: Technical Report.* s.l. : CTRE, May, 2005.

8. **AASHTO.** *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice.* Washington, D.C. : AASHTO, July, 2008.

9. —. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice.* Washington, D.C. : s.n., July, 2008.

10. *A National Database of Subgrade soil-water characterictic curves and selected soil properties for use with the MEPDG.* **NCHRP.** 347, Washington, D.C. : NCHRP, August, 2010.

11. *Implementing the Mechanistic -Empirical Pavement Design Guide for Cost Saving in Indiana.* **Nantung, Tommy E.** Washington, D.C. : Transportation Research Board, 2010. 271.

12. **Mallela, Jagannath, et al.** *Guidelines for Implementing NCHRP 1-37A M-E PDG Design Procedures in Ohio.* Champaign, IL : Applied Research Associates, Inc., November, 2009.

13. **SD DOT.** *M-E PDG implementation Plan; StudySD2005-01.* Urbana, IL : Applied Pavement Technology, Inc., October, 2007.

14. **LTPP.** LTPP Data Pave Online. *http://www.ltpp-products.com/DataPave/visualization/Map.aspx.* [Online] LTPP. [Cited: 02 10, 2010.]

15. **Staff Soil Survey.** U.S. General Soil Map (STATSGO2). *http://soildatamart.nrsc.usda.gov.* [Online] [Cited: 04 15, 2010.]

16. **Asphalt Institute.** *Performance Graded Asphalt, Binder Specification and Tasting; SP-1.* Lexington, KY : Asphalt Institute, 2003.

17. —. *Superpave Mix Design; SP-2.* Lexington, KY : Asphalt Institute, 1996.

18. **Vermont AOT .** *Vermont Agency of Transportation Flexible Pavement Design Procedures.* s.l. : VT AOT, March, 2002.

19. **Kim, Sunghwan, Ceylan, Halil and Heitzman, Michael.** *Sensitivity Study of Design Input Parameters for Two Flexible Pavement Systems Using the M-E PDG.* Ames, Iowa : Iowa State University, August, 2005.

20. **USGS.** *http://groundwaterwatch.usgs.gov/.* [Online] USGS, 2011. [Cited: 09 15, 2010.]

21. **Malla, B. Ramesh and Joshi, Shraddha.** *Establish Subgrade Support values for Typical Soils in New England States.* s.l. : NETCR 57, April, 2006. Report 02-3.

22. **Highway Research Board.** *The AASHO Road Test: History and Description of the Project: Report 61A.* 1961.

23. **National Research Council.** *AASHO Road Test: History and Description of Project. Publication 816.* Washington, D.C. : National Academy of Sciences, 1961.

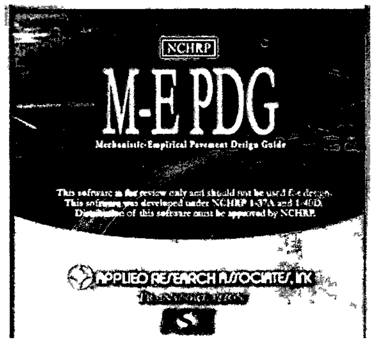
24. **Thompson et al.** *Research Results Digest 307.* s.l. : NCHRP, September, 2006.

25. **Daniel, Jo Sias, Chehab, Ghassan R. and Ayyala, Dinesh.** *Sensitivity of M-E PDG Level 2 and 3 Inputs using Statistical Analysis Techniques for New England States.* August, 2009.

Appendix A: Vermont M-E PDG Level 2 and Level 3 Report

VERMONT

RANGE OF VALUES FOR CRITICAL INPUT PARAMETERS



INPUT VALUE SELECTION FOR VERMONT FOR M-E PDG RUNS

1. General Inputs

1.1 Design Life

- 20 years for a new pavement is recommended

1.2 Construction & Traffic Opening Dates

- Base/subgrade construction month – July, 2010
- Pavement construction month - August, 2010
- Traffic opening date – October, 2010

1.3 Type of Pavement

- This analysis is performed for a new flexible pavement.

1.4 Site/Project Identification

The site is located in New Haven, VT on Rt. 7 (LTPP section # 50-1002-1)

- County: Addison
- Latitude, deg. 44.12
- Longitude, deg. -73.18
- Elevation, (ft) 283
- Org. Construction Date: 08/01/1984
- Functional Class: 2

1.5 Pavement Layer Structure

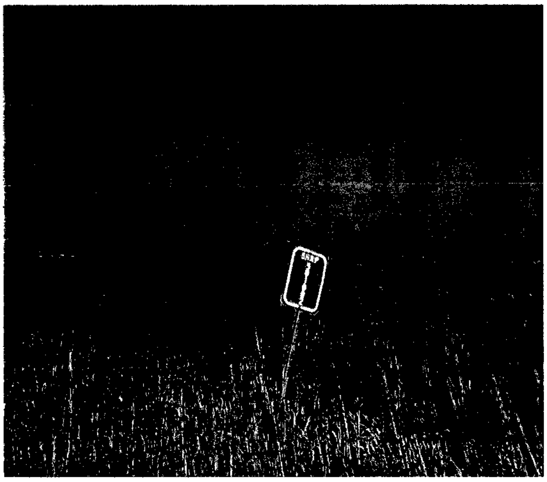


Figure 1A: New Haven, VT – Rt. 7

Table 1A: Pavement Layers Used for Rt. 7 in Vermont M-E PDG Analysis

Layer Type	**Layer Thickness (in)**
Original Surface Layer (layer Type: AC)	3.0"
AC Layer Below Surface (Binder Course)	5.5"
Base Layer (Layer Type: GB)	25 8"
Subgrade (Layer Type: SS)	Semi-infinite

The pavement layer structure used for VT M-E PDG analysis is similar to the LTPP section 50-1002-1 on Rt. 7 in New Haven, VT.

Table 2A: Pavement Layers at Rt. 2 in Vermont M-E PDG

Layer Type	**Layer Thickness (in)**
Original Surface Layer (layer Type: AC)	3.0"
AC Layer Below Surface (Binder Course)	5.0"
Base Layer (Layer Type: GB)	24.3"
Subbase Layer (Layer Type: GS)	22.8"
Subgrade (Layer Type: SS	Semi-infinite

The pavement layer structure LTPP section # 50-1004-1 at Rt. 2 in South Hero, VT.

2. Performance Criteria Inputs (Analysis Parameters)

Table 3A: Suggested Performance Criteria for Use in Pavement Design.*

Pavement Type	**Performance Criteria**	**Max. Value at End of Design Life at Design Reliability**
HMA pavement & overlays	HMA bottom up fatigue cracking (alligator cracking)	Interstate: 10 percent lane area Primary: 20 percent lane area Secondary: 45 percent lane area
	HMA longitudinal fatigue cracking (top down)	Interstate: 2,000-ft/mile Primary: 2,500-ft/mile Secondary: 3,000-ft/mile
	Permanent deformation (total mean rutting of both wheel paths)	Interstate: 0.40-in mean Primary: 0.50-in mean Others <40 mph: 0.75-in mean
	Thermal fracture (transverse cracks)	Interstate: Crack spacing > 70-ft (Crack length < 905-ft/mile) Primary/Secondary: Crack spacing > 50-ft (Crack length < 1267-ft/mile)
	IRI	Interstate/Primary: 169 in/mile maximum Secondary: 223 in/mile maximum

*Report No. UT-09.11a "Draft User's Guide for UDOT MEPDG"; October 2009

Table 4A: Analysis Parameters Used in VT

Analysis parameter	Maximum criteria at 90% Reliability
Initial IRI (in./mi)	75
Terminal IRI (in./mi)	172
AC Surface Down Cracking (ft/mi)	2000
AC Bottom Up Cracking (%)	25
AC Thermal Fracture (ft/mi)	1000
Permanent Deformation – Total Pavement (in)	0.75
Permanent Deformation – AC only (in)	0.25

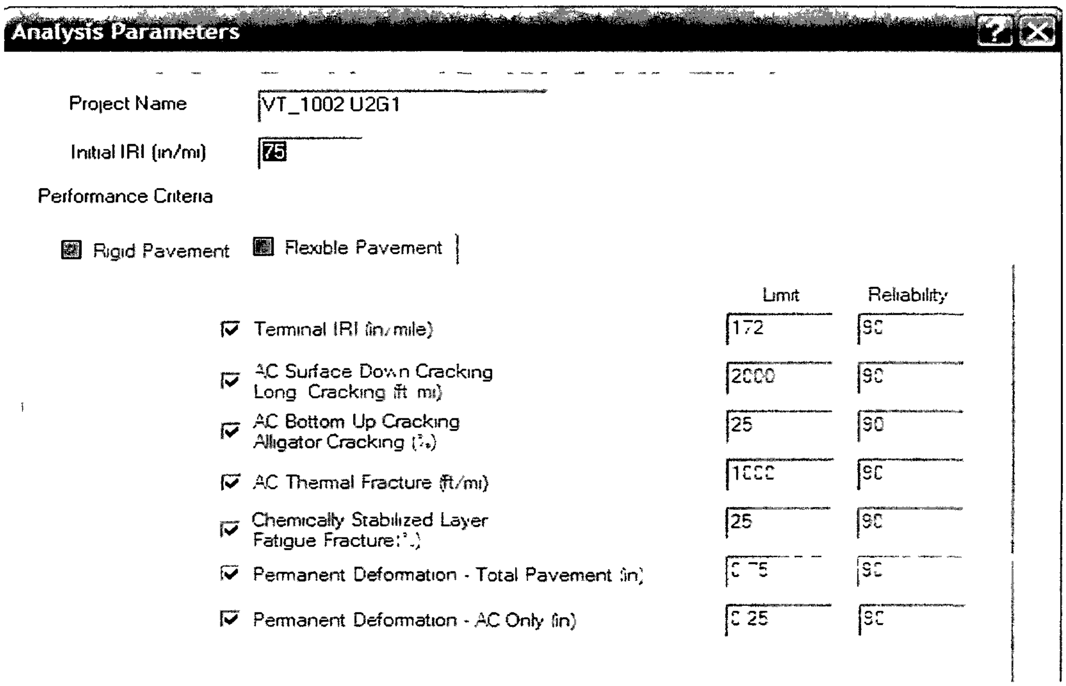


Figure 2A: Analysis Parameters Used in VT

3. Design Reliability Input

Table 5A: Tentative Recommended Level of Reliability

Functional Classification	Urban	Rural
Interstate/Freeways	95	92
Principal Arterials	90	85
Collectors	80	75
Locals	70	60

A design reliability of 90 percent is selected for this analysis. A higher level of design reliability is not recommended, because of the significant cost increase.

4. Traffic Inputs

Table 6A: Recommended Traffic Value Inputs

Traffic Input	**Recommended Value**
Initial two way AADTT (class 4 and above)	Projected traffic for opening month from measured historical data.
Number of lanes in design direction	Actual or from design plans.
Percent of trucks in design direction (%)	50%, unless higher truck volume is measured in design direction
Percent of trucks in design lane (%)	Actual measured in design lane over 24-hours, otherwise use the following: • 100% for 1 lane in design direction • 95% for 2 lanes in design direction For unusual truck traffic situations (mountainous terrain or urban usage complexity), conduct on site truck lane usage counts over 24-hour period.
Operational Speed (mph)	Posted or Design Speed

4.1 Annual Average Daily Truck Traffic (AADTT)

Truck Traffic (AADTT) is calculated by taking 10.35% of AADT as given in 2009 Automatic Vehicle Classification Report. AADT for Rt. 7 in New Haven, VT (Addison County) was 6800.

Control AADTT for this study is taken as 704.

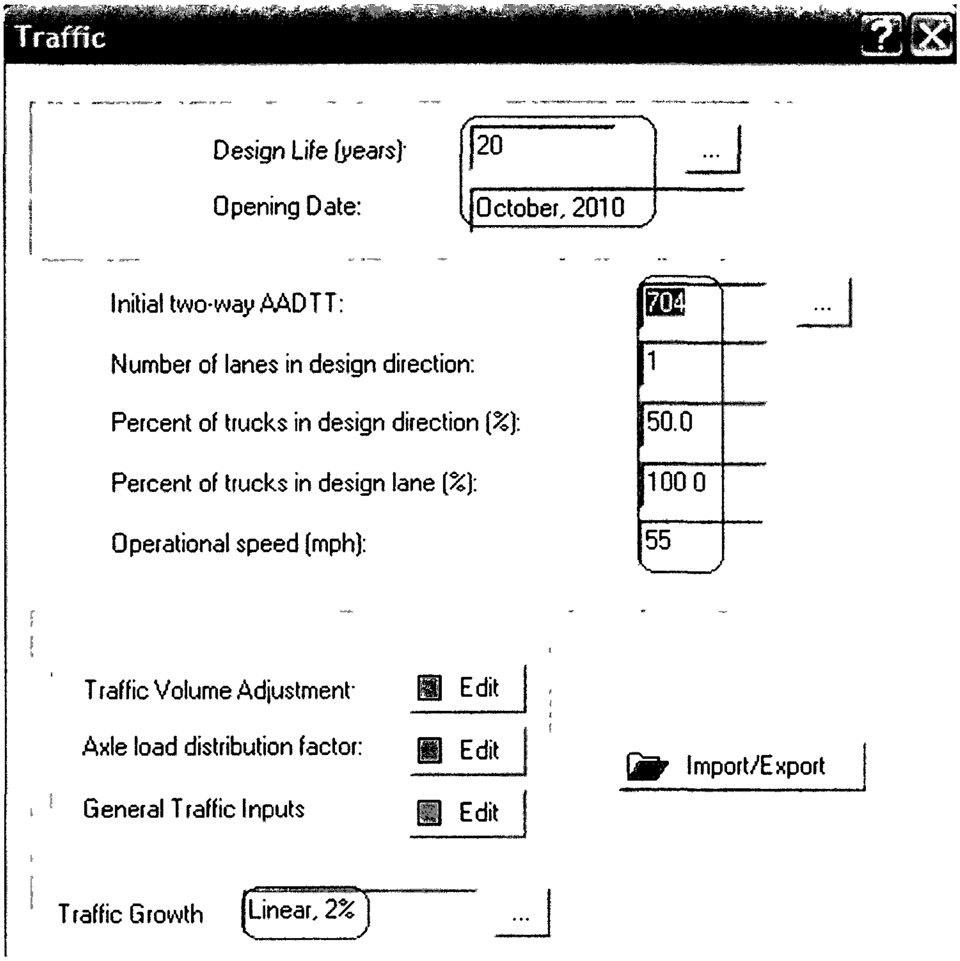


Figure 3A: Traffic Inputs for New Haven, VT

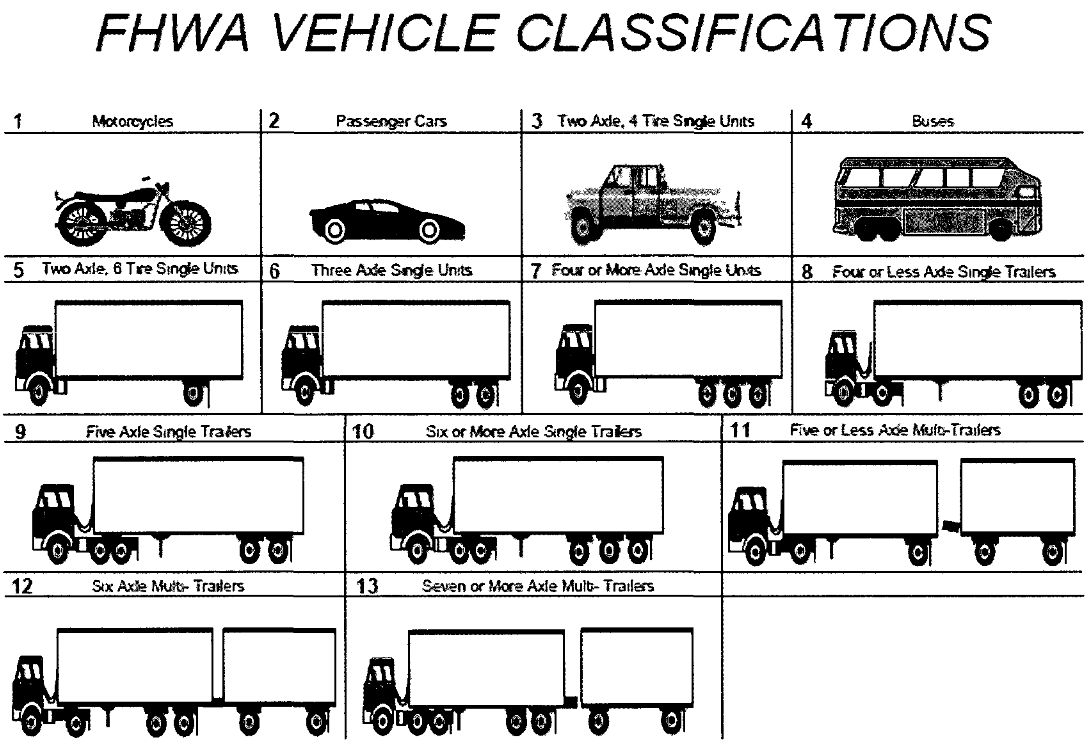


Figure 4A: Illustration of FHWA/AASHTO Vehicle Class Type Description

4.2 Truck Class Distribution selections

Table 7A: LTPP Truck Class Distribution

TRF_MEPDG_VEH_CLASS_DIST						
STATE_ CODE	**SHRP_ ID**	**YEAR**	**VEHICLE_ CLASS**	**TRF_DATA _TYPE**	**RECORD_STA TUS**	**PERCENT_OF _TRUCKS**
50	1002	2008	4	0	E	5.57
50	1002	2008	5	0	E	42.95
50	1002	2008	6	0	E	10.79
50	1002	2008	7	0	E	3.36
50	1002	2008	8	0	E	7.61
50	1002	2008	9	0	E	25.89
50	1002	2008	10	0	E	3.22
50	1002	2008	11	0	E	0.02
50	1002	2008	12	0	E	0.42
50	1002	2008	13	0	E	0.17

*based on LTPP data base, 2008

Table 8A: Track Class Distribution Level 3 (Control)

VEHICLE_CLASS	PERCENT_OF_TRUCKS
4	1.8
5	24.6
6	7.6
7	0.5
8	5.0
9	31.3
10	9.8
11	0.8
12	3.3
13	15.3

*based on level 3 M-E PDG, 2009

Table 9A: Low-Class Concentrated Distribution

VEHICLE_CLASS	PERCENT_OF_TRUCKS
4	5.2
5	38.9
6	35.8
7	10.2
8	5.6
9	3.5
10	0.2
11	0.3
12	0.2
13	0.1

*Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

Table 10A: High-Class Concentrated Distribution

VEHICLE_CLASS	PERCENT_OF_TRUCKS
4	0.1
5	0.6
6	0.8
7	0.6
8	6.8
9	9.2
10	25.8
11	36.4
12	16.5
13	3.2

*Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

Table 11A: Truck Class Distribution Summary

TRUCK CLASS	CODE			
	D1(from LTPP)	D2 (low class)	D3 (high class)	D4 (Level 3-Control)
4	5.5	5.2	0.1	1.8
5	43.0	38.9	0.6	24.6
6	10.8	35.8	0.8	7.6
7	3.4	10.2	0.6	0.5
8	7.6	5.6	6.8	5.0
9	25.9	3.5	9.2	31.3
10	3.2	0.2	25.8	9.8
11	0.0	0.3	36.4	0.8
12	0.4	0.2	16.5	3.3
13	0.2	0.1	3.2	15.3

4.3 Rate of Traffic Growth

Table 12A: Selected Traffic Growth Rates for Vermont

Code	Traffic Growth Rate
R1	1.0 % linear
R2 (Control)	2.0 % linear
R3	3.0 % linear

4.4 Traffic Operational Speed

Table 13A: Selected Traffic Operational Speeds

Code	Traffic Operational Speed (mph)	Binder Grades
U1	5	G1, G2, G3
U2	25	G1, G2, G3
U3 (Control)	55	G1, G2, G3

4.5 Annual Average Daily Truck Traffic (AADTT)

Table 14A: Calculated AADTT Values

Code	Station ID	Traffic Volume (AADTT)
Q1 (Control)	S6A041 - New Haven, VT (Rt.7)	704
Q2	S6A107 – Salisbury, VT (Rt. 7)	932
Q3	S6A014 – Ferrisburg, VT (Rt. 7)	1576

4.6 The Monthly Traffic Adjustment Factors

Table 15A: Monthly Adjustment Factors (MAF) for Pavement Design in New Haven

Location	Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
	Jan.	0.71	0.71	0.71	0.71	0.80	0.80	0.80	0.80	0.80	0.80
	Feb.	0.64	0.64	0.64	0.64	0.91	0.91	0.91	0.91	0.91	0.91
	Mar.	0.87	0.87	0.87	0.87	0.98	0.98	0.98	0.98	0.98	0.98
	Apr.	1.01	1.01	1.01	1.01	0.88	0.88	0.88	0.88	0.88	0.88
	May	1.21	1.21	1.21	1.21	1.00	1.00	1.00	1.00	1.00	1.00
New Haven	Jun.	1.35	1.35	1.35	1.35	1.11	1.11	1.11	1.11	1.11	1.11
	Jul.	1.20	1.20	1.20	1.20	0.90	0.90	0.90	0.90	0.90	0.90
	Aug.	1.21	1.21	1.21	1.21	1.12	1.12	1.12	1.12	1.12	1.12
	Scp.	0.94	0.94	0.94	0.94	1.05	1.05	1.05	1.05	1.05	1.05
	Oct.	1.13	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14
	Nov.	0.94	0.94	0.94	0.94	1.11	1.11	1.11	1.11	1.11	1.11
	Dec.	0.78	0.78	0.78	0.78	0.99	0.99	0.99	0.99	0.99	0.99

*-n/c – not collected

Table 16A: Monthly Adjustment Factors (MAF) for Pavement Design in Salisbury and Ferrisburg

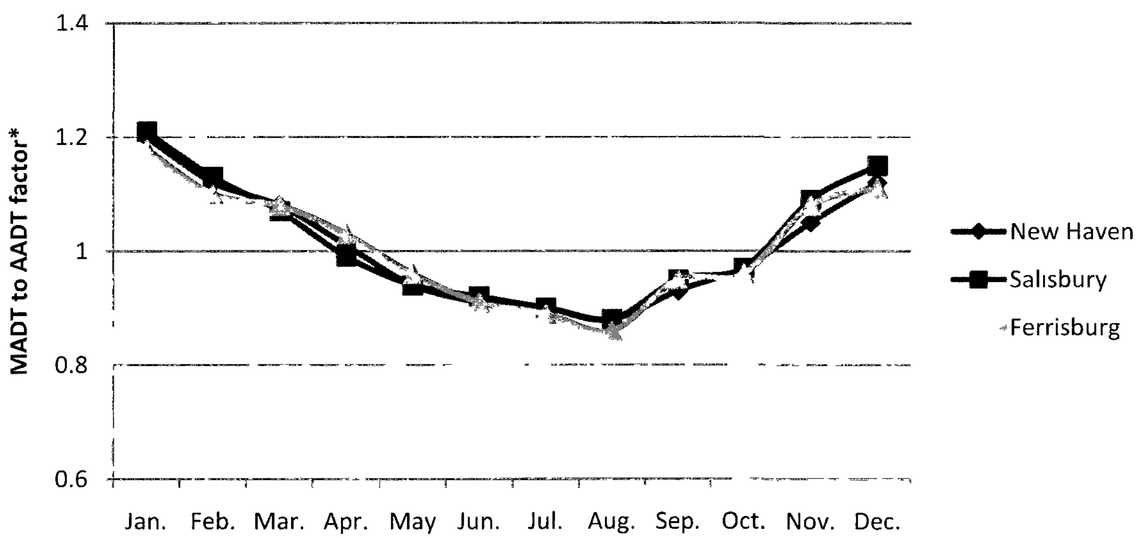
Location	Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
	Jan.	0.71	0.71	0.71	0.71	0.80	0.80	0.80	0.80	0.80	0.80
	Feb.	0.64	0.64	0.64	0.64	0.91	0.91	0.91	0.91	0.91	0.91
	Mar.	0.87	0.87	0.87	0.87	0.98	0.98	0.98	0.98	0.98	0.98
	Apr.	1.01	1.01	1.01	1.01	0.88	0.88	0.88	0.88	0.88	0.88
	May	1.21	1.21	1.21	1.21	1.00	1.00	1.00	1.00	1.00	1.00
Salisbury	Jun.	1.35	1.35	1.35	1.35	1.11	1.11	1.11	1.11	1.11	1.11
	Jul.	1.20	1.20	1.20	1.20	0.90	0.90	0.90	0.90	0.90	0.90
	Aug.	1.21	1.21	1.21	1.21	1.12	1.12	1.12	1.12	1.12	1.12
	Sep.	0.94	0.94	0.94	0.94	1.05	1.05	1.05	1.05	1.05	1.05
	Oct.	1.13	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14
	Nov.	0.94	0.94	0.94	0.94	1.11	1.11	1.11	1.11	1.11	1.11
	Dec.	0.78	0.78	0.78	0.78	0.99	0.99	0.99	0.99	0.99	0.99
	Jan.	0.71	0.71	0.71	0.71	0.80	0.80	0.80	0.80	0.80	0.80
	Feb.	0.64	0.64	0.64	0.64	0.91	0.91	0.91	0.91	0.91	0.91
	Mar.	0.87	0.87	0.87	0.87	0.98	0.98	0.98	0.98	0.98	0.98
	Apr.	1.01	1.01	1.01	1.01	0.88	0.88	0.88	0.88	0.88	0.88
	May	1.21	1.21	1.21	1.21	1.00	1.00	1.00	1.00	1.00	1.00
Ferrisburg	Jun.	1.35	1.35	1.35	1.35	1.11	1.11	1.11	1.11	1.11	1.11
	Jul.	1.20	1.20	1.20	1.20	0.90	0.90	0.90	0.90	0.90	0.90
	Aug.	1.21	1.21	1.21	1.21	1.12	1.12	1.12	1.12	1.12	1.12
	Sep.	0.94	0.94	0.94	0.94	1.05	1.05	1.05	1.05	1.05	1.05
	Oct.	1.13	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14
	Nov.	0.94	0.94	0.94	0.94	1.11	1.11	1.11	1.11	1.11	1.11
	Dec.	0.78	0.78	0.78	0.78	0.99	0.99	0.99	0.99	0.99	0.99

4.7 The MADT to AADT factor

Table 17A: Collected MADT's for Selected Locations

	MADT* TO AADT FACTOR		
Month	**New Haven**	**Salisbury**	**Ferrisburg**
Jan.	1.20	1.21	1.18
Feb.	1.12	1.13	1.10
Mar.	1.08	1.07	1.08
Apr.	1.01	0.99	1.03
May	0.94	0.94	0.96
Jun.	0.91	0.92	0.91
Jul.	0.90	0.90	0.89
Aug.	0.88	0.88	0.86
Sep.	0.93	0.95	0.95
Oct.	0.97	0.97	0.96
Nov.	1.05	1.09	1.08
Dec.	1.12	1.15	1.11

*- MADT – monthly average daily traffic



*MADT – Monthly Average Daily Traffic
*AADT – Annual Average Daily Traffic

Figure 5A: MADT to AADT Factor for Three Selected Location (Vehicle Classifications 1 to 13)

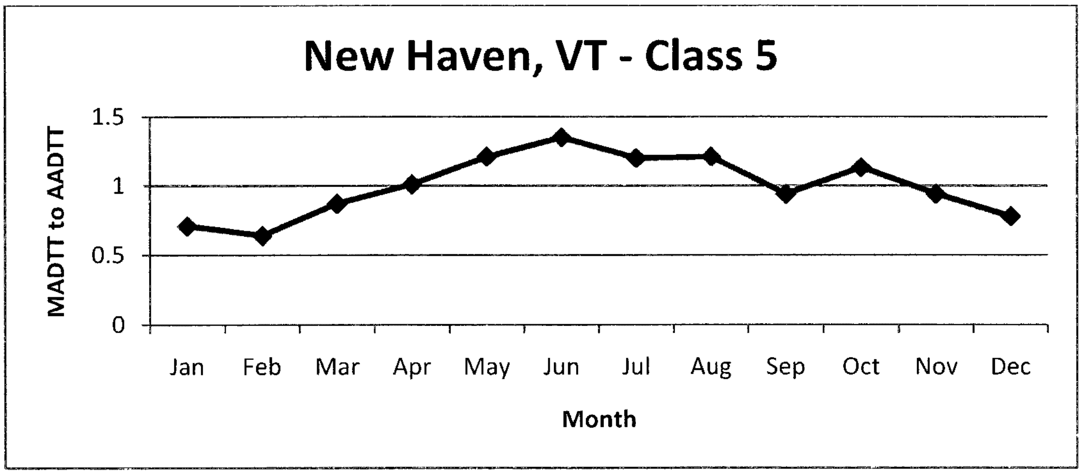


Figure 6A: MADTT to AADTT Factor for Class 5 in New Haven, VT

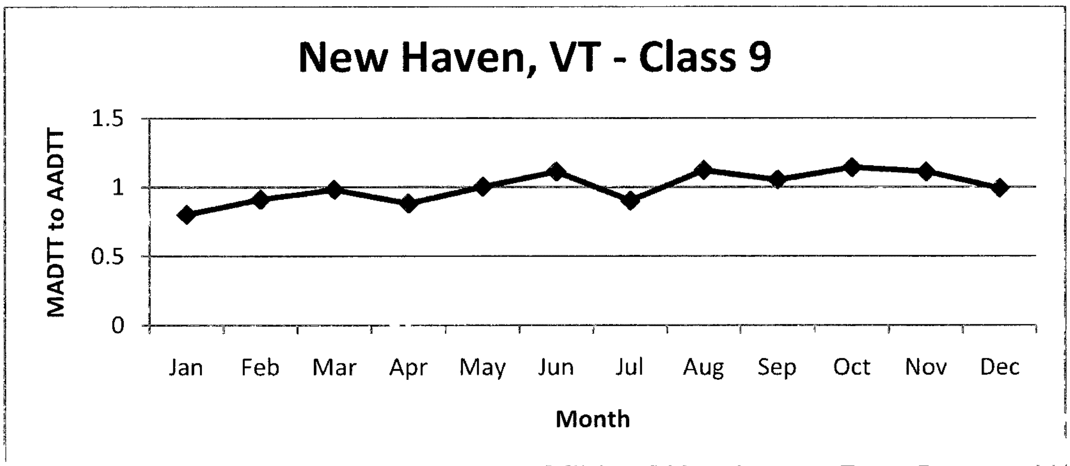


Figure 7A: MADTT to AADTT Factor for Class 9 in New Haven, VT

5. Climate Inputs

Three climate stations are selected from the five stations for which climate data is available in the M-E PDG. The three stations: Bennington, Barre -Montpelier and Burlington are chosen as they are more geographically dispersed.

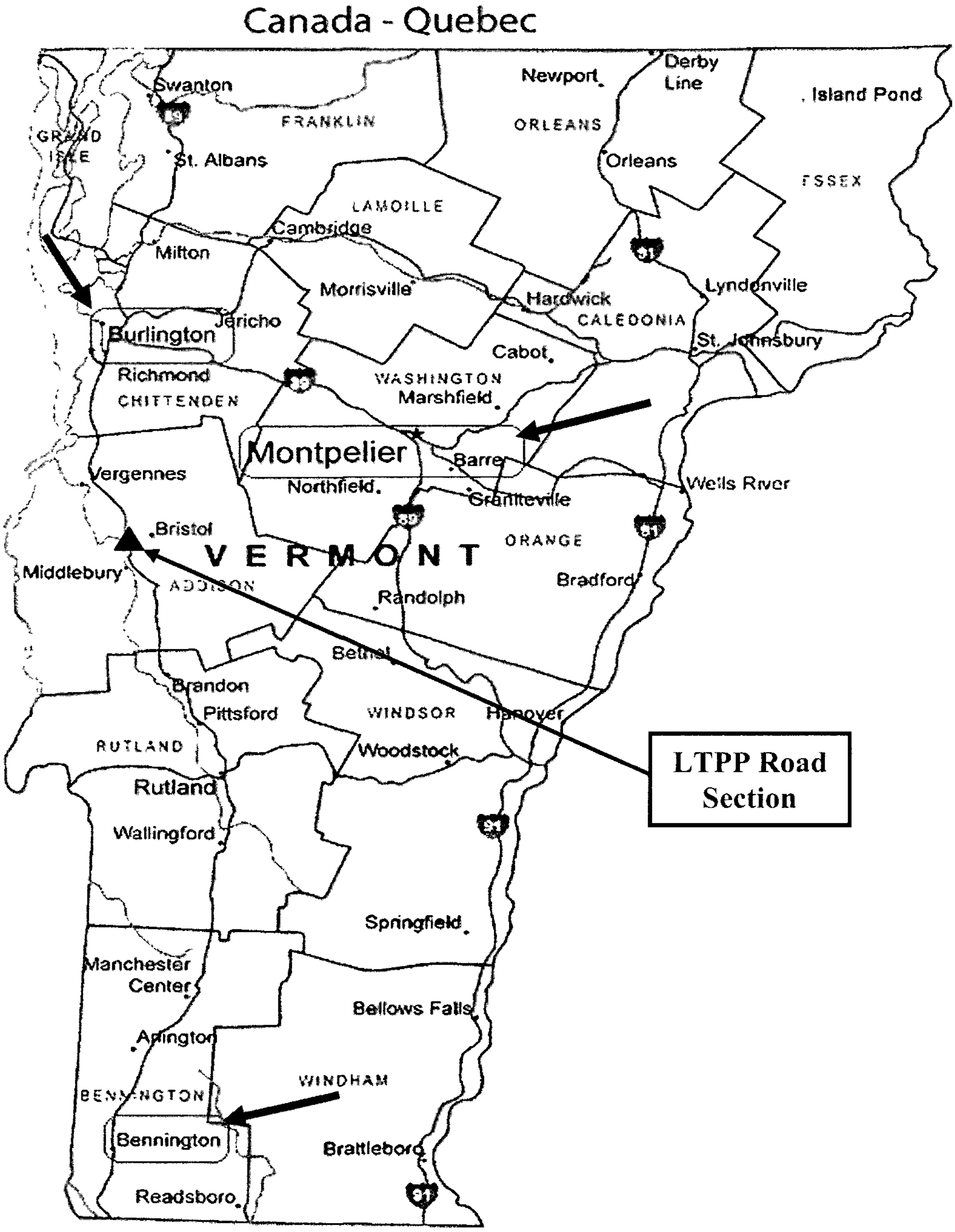


Figure 8A: Vermont Climate Station Locations

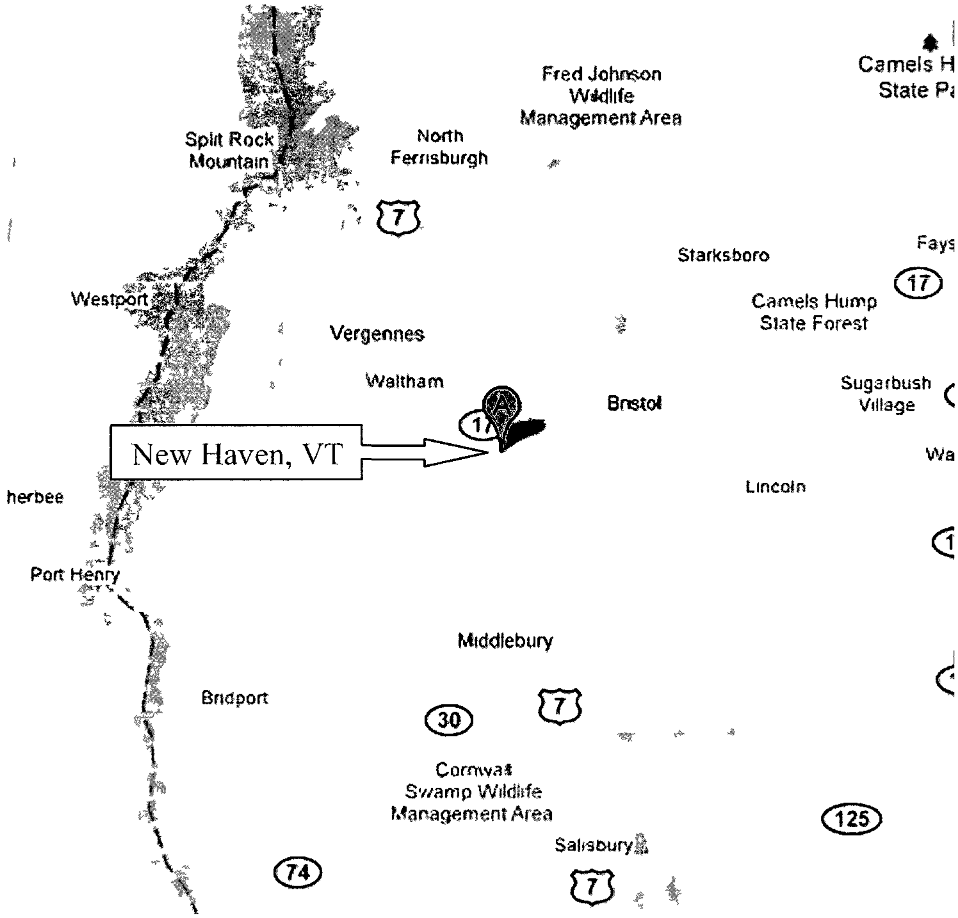


Figure 9A: New Haven, VT Location

5.1 Sensitivity to Climate Data Interpolation

Table 18A: Selected Locations Climate Data

STATION	Nearest 3 Stations	Latitude	Longitude	Distance	#Months of data
Bennington Lat. 42.53 Lon. -73.15 (803 ft)	North Adams, MA	42.42	-73.1	13.3 mi	116
	Albany, NY	42.45	-73.48	29.3	116
	Pittsfield, MA	42.26	-73.17	31.1	85
Barre/ Montpelier Lat. 44.12 Lon. -72.35 (1172 ft)	Morrisville, VT	44.32	-72.37	23.1	116
	Burlington, VT	44.28	-73.09	33.5	116
	Lebanon, NH	43.38	-72.18	41.6	94
Burlington Lat. 44.28 Lon. -73.09 (348 ft)	Plattsburg, NY	44.41	-73.31	23.4	92
	Morrisville, VT	44.32	-72.37	26.7	116
	Barre/Montpelier	44.12	-72.35	33.5	116

5.2 Water Table Depth Variation

Table 19A: Selected WT Depth for New Haven, VT

CODE	Depth of Water Table	Combination with A-2-4 and A-7-6 Subgrades
WT1	2 ft	WT1 E2, WT1 E1,
WT2 (Control)	5 ft	WT2 E2, WT2 E1
WT3	8 ft	WT3 E2, WT3 E1

The water table depth was selected based on average values from the Addison County well.

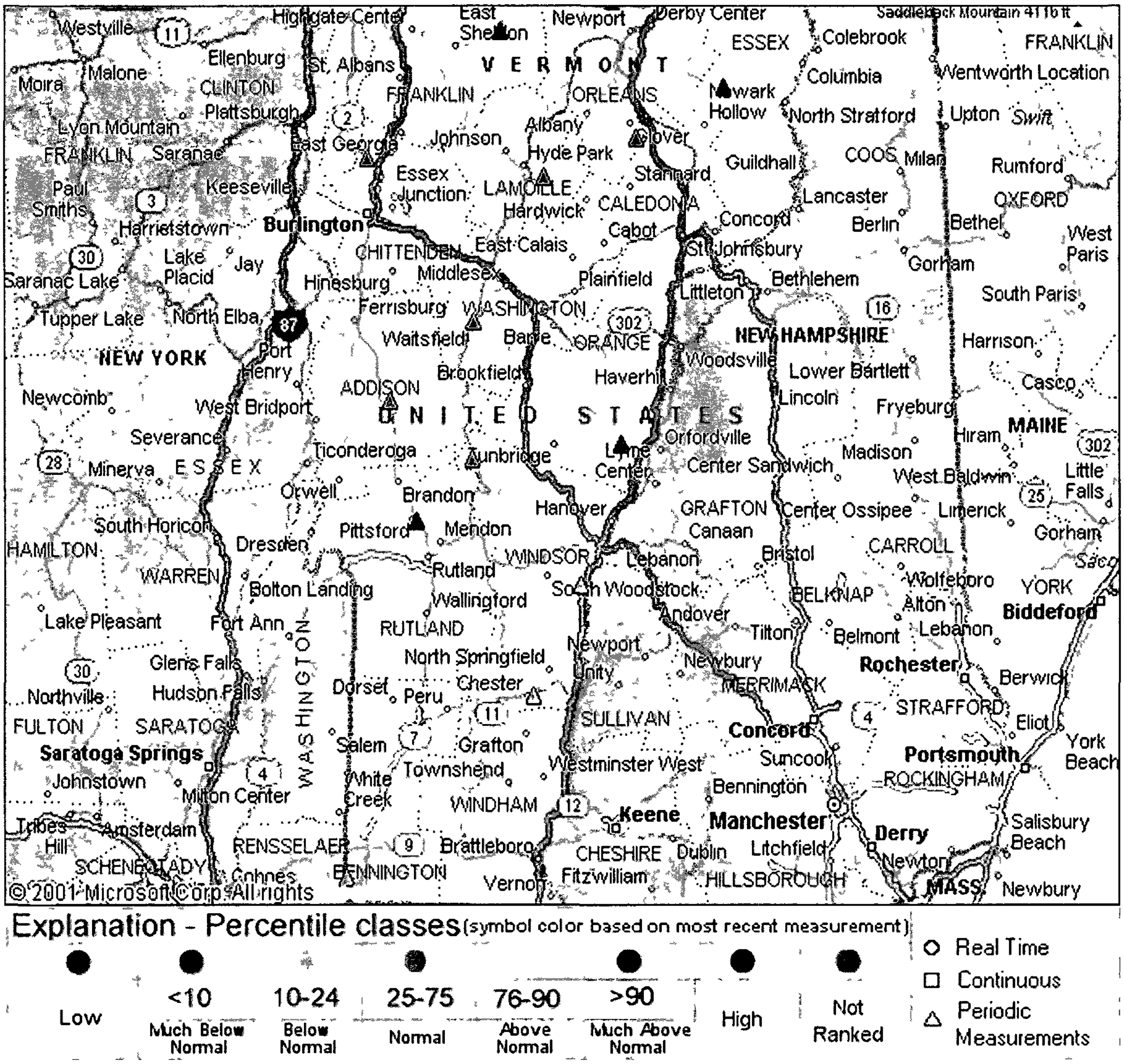


Figure 10A: Vermont Active Wells

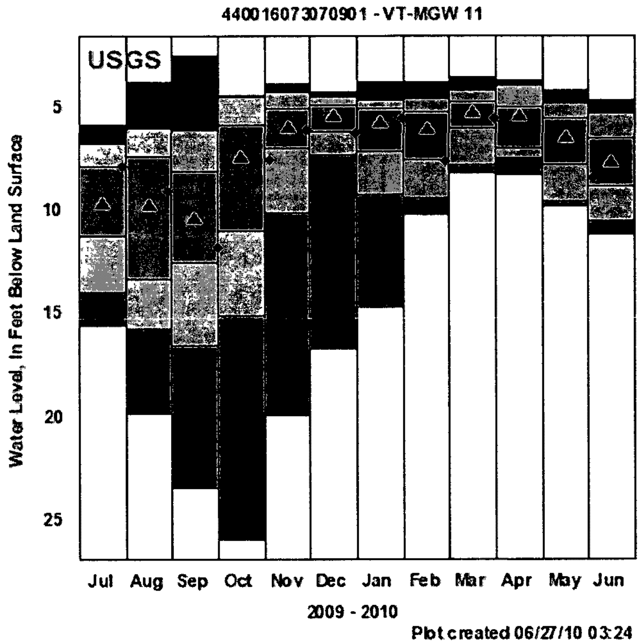


Figure 11A: Most recent data value: 6.30 on 6/28/2010 Period of Record Monthly Statistics for 440016073070901 Depth to Water Level, Feet below Land Surface.

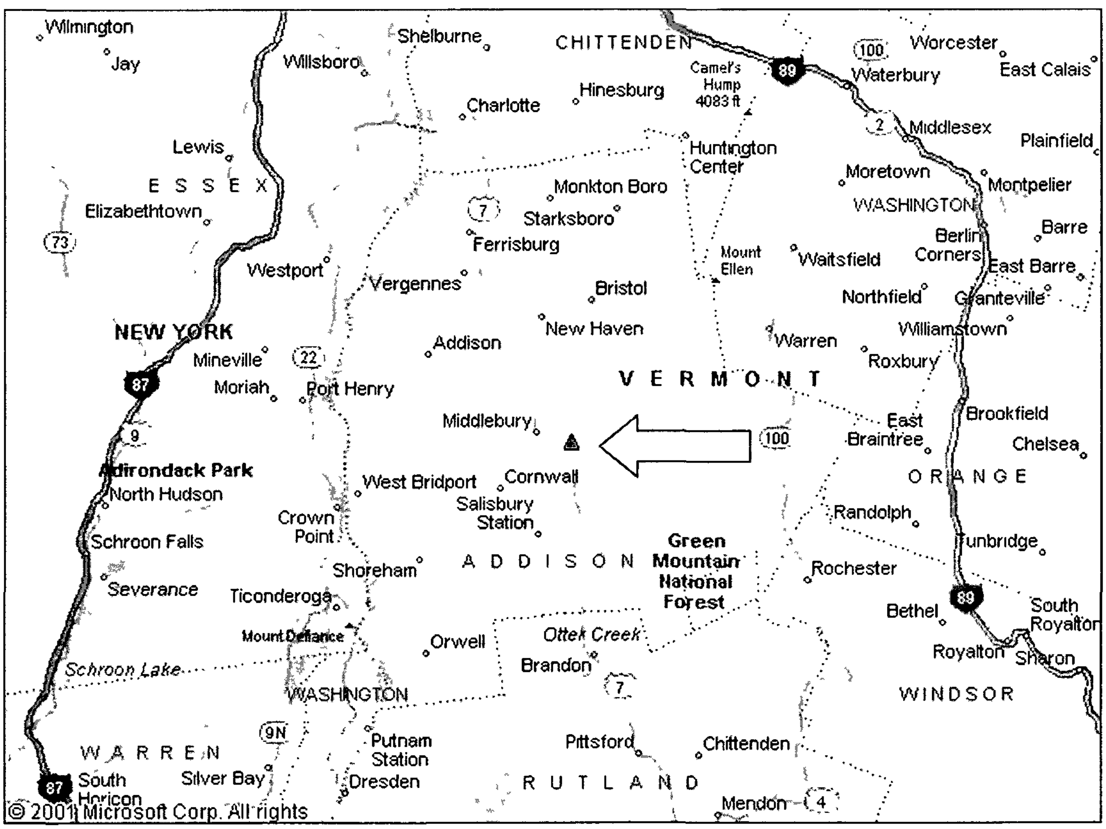


Figure 12A: Addison County Well (Site Number: 440016073070901 - VT-MGW 11)

Table 20A: Water Level Measurement Records at Addison Well

Highest WL	Date of Highest WL	Lowest WL	Date of Lowest WL
2.58	09/22/81	25.92	10/26/01

Table 21A: Most Recent Data for Water Levels at Addison Well

Month	Lowest Median	10th %ile	25th %ile	50th %ile	75th %ile	90th %ile	Highest Median	Number of Years
Jan	14.76	9.28	7.18	5.84	5.14	4.70	3.84	29
Feb	10.25	9.40	7.56	6.19	5.29	4.64	3.80	26
Mar	8.20	7.82	6.05	5.33	4.78	4.21	3.62	28
Apr	8.32	7.50	7.04	5.48	5.06	3.96	3.72	25
May	9.86	9.58	7.85	6.59	5.62	4.84	4.25	26
Jun	11.22	10.59	**8.85**	**7.77**	6.52	5.32	4.73	28
Jul	15.58	14.01	11.28	9.74	7.92	6.82	5.95	26
Aug	19.86	15.80	13.33	9.87	7.46	6.06	3.81	28
Sep	23.51	16.60	12.59	10.50	8.14	6.19	2.58	29
Oct	25.92	15.15	11.01	7.49	5.94	4.57	4.46	25
Nov	19.92	10.15	7.02	6.06	5.12	4.31	3.87	26
Dec	16.75	7.39	6.27	5.53	4.95	4.52	4.30	28

Note: Bold values in the table indicate closest statistic to the most recent data value.

6. Material Inputs

6.1 HMA Thickness

An HMA thickness for the control file is 8.5". To see the effect of HMA thickness on predicting distresses values two more HMA thicknesses has been selected:

Table 22A: Selected HMA Layer Thickness

CODE	Total HMA Thickness (in)
T1	7.0
T2 (Control)	8.5
T3	10.0

The two HMA layers (surface and binder) will be treated as one layer with 19.0 mm asphalt mix gradation (mean).

6.2 Number of HMA Layers

Two HMA layers are going to be used for the M-E PDG analysis:

- AC original surface – 3" (w/ 9.5 mm mix gradation)
- AC binder course – 5.5" (w/ 19.0 mm mix gradation)

6.3 HMA Mix Gradation

HMA mix gradation for Vermont conforms to Superpave specifications.

Table 23A: Range of Values of HMA Mix Gradation – Superpave Specification

NMAS of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
3/4" sieve	0	0 – 10	10 – NR*	NR	NR
3/8" sieve	0 – 10	10 – NR	NR	NR	NR
# 4 sieve	10 – NR	NR	NR	NR	NR
#200 sieve	2 – 10	2 – 10	2 – 8	1 – 7	0 – 6

* NR – No restriction on the value

Table 24A: Tolerance for HMA Mix Gradation

NMAS of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
Cum. % Ret 3/4" sieve		± 4%	± 5%	± 7%	
Cum. % Ret 3/8" sieve		± 4%	± 5%	± 7%	
Cum. % Ret # 4 sieve	± 4%	± 3%	± 4%	± 4%	± 6%
#200 sieve	± 0.8%	± 0.8%	± 0.8%	± 0.8%	± 0.8%

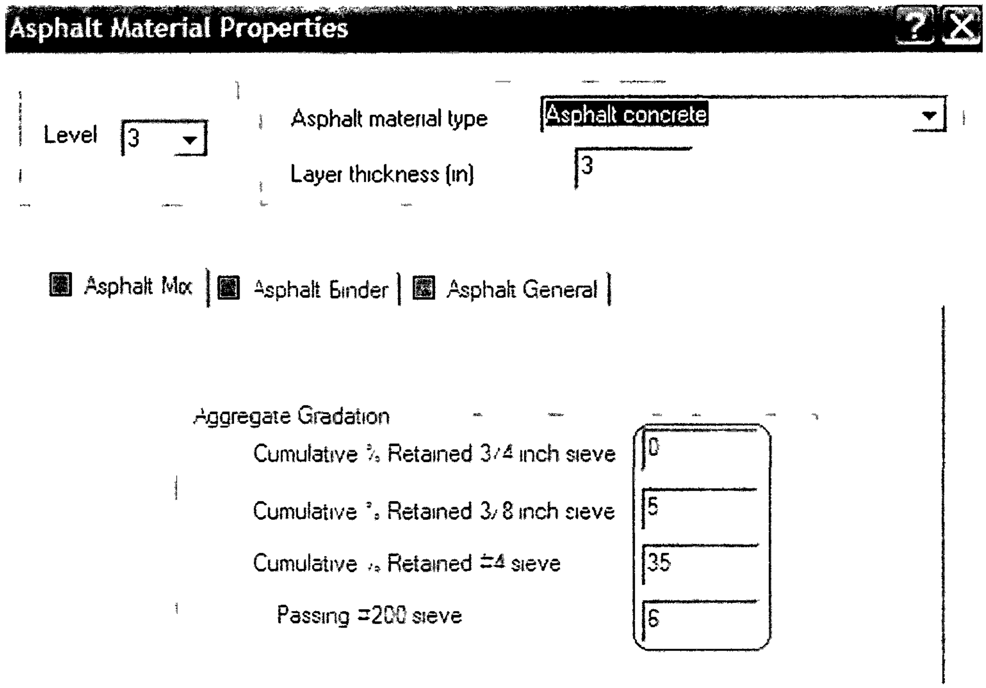


Figure 13A: 3/8” (9.5 mm) Asphalt Mix Aggregate Gradation

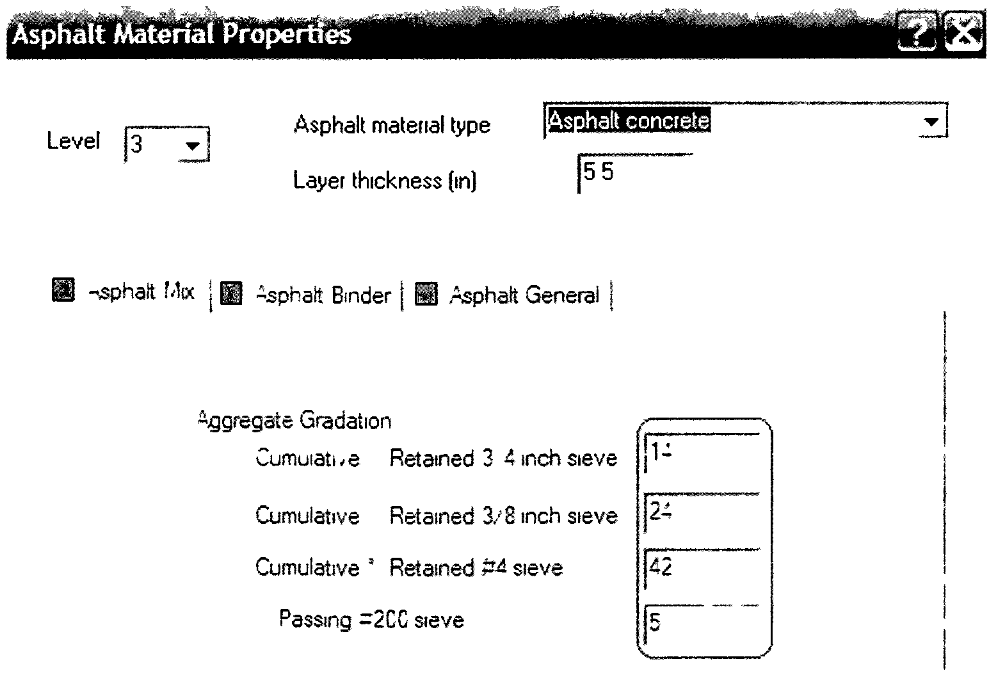


Figure 14A: ¾” (19.0 mm) Asphalt Mix Aggregate Gradation

Table 25A: Recommended Typical Vermont HMA Mix Gradations Input

Gradation Mix Designation	Percent Retained				Percent Passing
	¾-in Sieve	½-in Sieve	3/8-in Sieve	#4-in Sieve	#200 Sieve
1-in (25.0 mm)	15	30	48	62	4
¾-in (19.0 mm)	5	20	40	58	5
½-in (12.5 mm)	0	5	25	52	6
⅜-in (9.5 mm)	0	0	5	45	6

6.4 PG Binder Grade

Three different binder grades are chosen from among the PG binders that are suitable for use in the state of Vermont. PG 58-28 is used as the binder grade for the control case. The binder grade is tested in conjunction with operational speed of vehicle.

Table 26A: Vermont PG binder Grades

CODE	PG BINDER GRADE
G1	PG 58-34
G2 (Control)	PG 58-28
G3	PG 64-28

Table 27A: Level 2 asphalt binder values at Angular Frequency = 10 rad/sec (1.59 Hz)

PG Grades	Temperature (°F)	G * (Pa)	Delta (°)
PG 58-28	40	17950000	46.7
	68	1336381.7	64.3
	113	9478.4	78.4
PG 64-28	40	29540000	41.7
	68	2297155.4	58.3
	113	35275.56	72.3
PG 58-34	40	n/c*	n/c*
	68	n/c*	n/c*
	113	n/c*	n/c*

*n/c – not collected

6.5 Unbound Layer Inputs

ASTM D 2940, Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports. The gradation for base material from this standard is given below.

Table 28A: ASTM D 2940 Gradation for Dense-Graded Bases and Subbases

Sieve Size	Percent Passing
2 in. (50 mm)	100
1½ in. (37.5 mm)	95 – 100
3/4 in. (19.0 mm)	70 – 92
½ in. (9.5 mm)	50 – 70
No. 4 (4.75 mm)	35 – 55
No. 30 (0.600 mm)	12 – 25
No. 200 (0.075 mm)	0 – 8

6.6 Base Course Resilient Modulus

Table 29A: Base Course Aggregate Gradations (Level 3)

CODE	M1	M2	M3
Type of course	Crushed Gravel	Crushed Stone (Fine)	Crushed Stone (Coarse)
Sieve Size	Percent Passing by Weight		
3 ½ in (90mm)	-	-	100
3 in (75mm)	100	-	92.5
2 in (50mm)	97.5	100	-
1 ½ in (37.5mm)	-	92.5	75.0
1 in (25mm)	70.0	-	-
¾ in (19mm)	-	60.0	55.0

Table 29A Continued

#4 (4.75mm) #200 (0.075mm)	39.5 6.0	27.5 2.5	27.5 2.5
Resilient Modulus Level 3	**29600**	**24370**	**33500**

* M-E PDG accepts values only between 20000 psi and 30000 psi

Table 30A: Base Course Aggregate Gradations (Level 2)

CODE	M1L2	M2L2
Type of course	**Crushed Gravel**	**Crushed Stone**
Sieve Size	**Percent Passing by Weight**	
3 ½ in (90mm)	97.6	97.6
3 in (75mm)	-	-
2 in (50mm)	91.6	91.6
1 ½ in (37.5mm)	85.8	85.8
1 in (25mm)	78.8	78.8
¾ in (19mm)	72.7	72.7
½ in (12.5mm)	63.1	63.1
3/8 in (9.5mm)	57.2	57.2
#4 (4.75mm)	44.7	44.7
#10 (2.0 mm)	33.8	33.8
#40 (0.425 mm)	20.0	20.0
#80 (0.18 mm)	12.9	12.9
#200 (0.075mm)	8.7	8.7
Resilient Modulus Level 2	**25000**	**30000**

Table 31A: Untreated Base Course Gradation Limits

Gradation Limits		
Sieve Size	**Job Mix Gradation Target Band**	**Job Mix Gradation Tolerance**
$1^1/_2$ inch	100	
1 inch	90 – 100	±9.0
$^3/_4$ inch	70 – 85	±9.0
$^1/_2$ inch	65 – 80	±9.0
$^3/_8$ inch	55 – 75	±9.0
No. 4	40 – 65	±7.0
No. 16	25 – 40	±5.0
No. 200	7 – 11	±3.0

6.7 Subgrade Resilient Modulus M_R

Table 32A: Subgrade Types and Subgrade Resilient Modulus

CODE	SUBGRADE TYPE	Material Classification	RESILIENT MODULUS (psi)	
			Level 2	Level 3
E1	Clayey soils	A-7-6	11500	8000
E2 (Control)	Fine sand, some silt	A-2-4	21500	32000
E3	Coarse to fine gravelly, coarse to medium sand, some fine sand	A-1-a	29500	40000

6.8 Effective Binder Content V_{be}, % (AASHTO T308)

From table 490.03 B – Design Criteria the VT AOT specifies VFA % from 65% to 75% for Traffic Level (ESALs) >3,000,000

V_a = Air voids (%)

V_{beff} = Effective binder content, %

VFA = Void filled with asphalt (%)

$$VFA = [V_{beff} / (V_{beff} + V_a)] \times 100$$

Table 33A: V_{beff} Calculated from VFA and V_a Values

VFA (%)	65			70			75		
V_a (%)	4	5	6	4	5	6	4	5	6
V_{beff} (%)	7.4	9.3	11.1	9.3	11.7	14	12	15	18

Table 34A: Recommended Typical Mix VMA and Binder Content

Gradation Mix Designation	**In-situ VMA, percent**	**In-situ Effective Binder Content, percent by volume**
1-in	16.5	10.0
¾-in	18.0	11.5
½-in	19.5	13.0
⅜-in	21.0	14.5

Table 35A: Effective Binder Content

CODE	EFFECTIVE BINDER CONTENT
F1	9.5
F2 (Control)	11.5
F3	13.5

Table 36A: HMA Mix Gradation Input Values

% of Aggregate	9.5 mm (3/8")			19.0 mm (3/4")		
	A1	A2	A3	B1	B2	B3
Retained on 3/4" sieve	0	0	0	14.0	18.6	12.0
Retained on 3/8" sieve	5.0	8.2	3.6	24.0	32.4	19.8
Retained on #4 sieve	35.0	48.3	22.1	42.0	52.0	34.5
Passing #200 sieve	6.0	2.8	8.5	5.0	2.8	7.2

1 – Mean values of the allowable range of values

2 – Coarse mix gradation

3 – Fine mix gradation

6.9 Air Voids Content, %

Table 37A: Air Voids Percentage (Mixture design)

CODE	AIR VOIDS PERCENT
V1	4.0
V2 (Control)	5.0
V3	6.0

Non mixture design Air Voids (in-situ air voids at construction site) will be based on percent compaction in specification:

- Range 3.5 to 9.5 (90.5 to 96.5)
- Target 6.5 (93.5) – recommended

6.10 Mix Coefficient of Thermal Contraction (CTC)

Table 38A: Mix Coefficient of Thermal Contraction Level 2

CODE	COEFFICIENT OF THERMAL CONTRACTION
N1	1.0 E-05
N2 (Control)	1.3 E-05
N3	2.0 E-05

The Mix CTC default value of 1.3 E-05 is used for Level 3 sensitivity analysis. Level 2 CTC are listed above.

6.11 Aggregate Coefficient of Thermal Contraction

The MEPDG default value is $5.0*10^{-6}/^{o}F$.

6.12 Initial IRI Values for New Pavement Design

Table 39A: Suggested Initial IRI Values for New Pavement Design.

PAVEMENT TYPE	IRI, IN/MI		
	MINIMUM	AVERAGE	MAXIMUM
NEW HMA AND HMA/HMA*	32	70	106

*- Initial IRI for HMA pavements shall be set within the range of 70 to 85 in/mi.

Table 40A: Initial IRI Values Used for Analysis.

CODE	Initial IRI (in/mi)
S1	32
S2 (Control)	75
S3	106

7. Vermont Level 3 Sensitivity Analysis

7.1 Effect of Traffic Inputs on Pavement Distresses

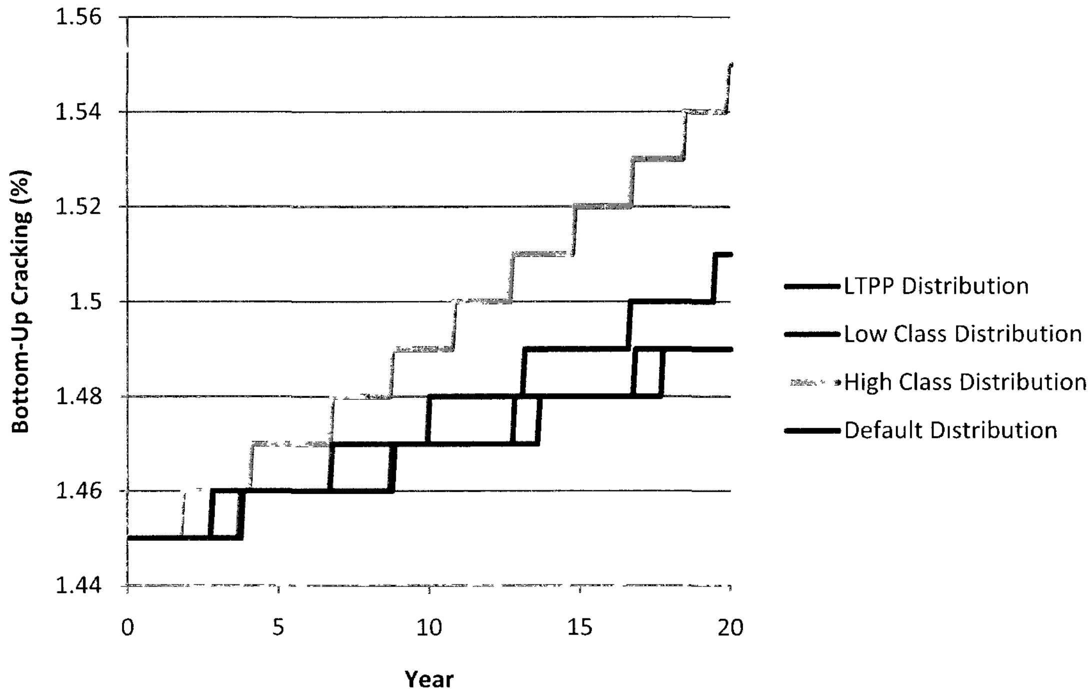


Figure 15A: Effect of Truck Class Distribution on Bottom-Up Cracking

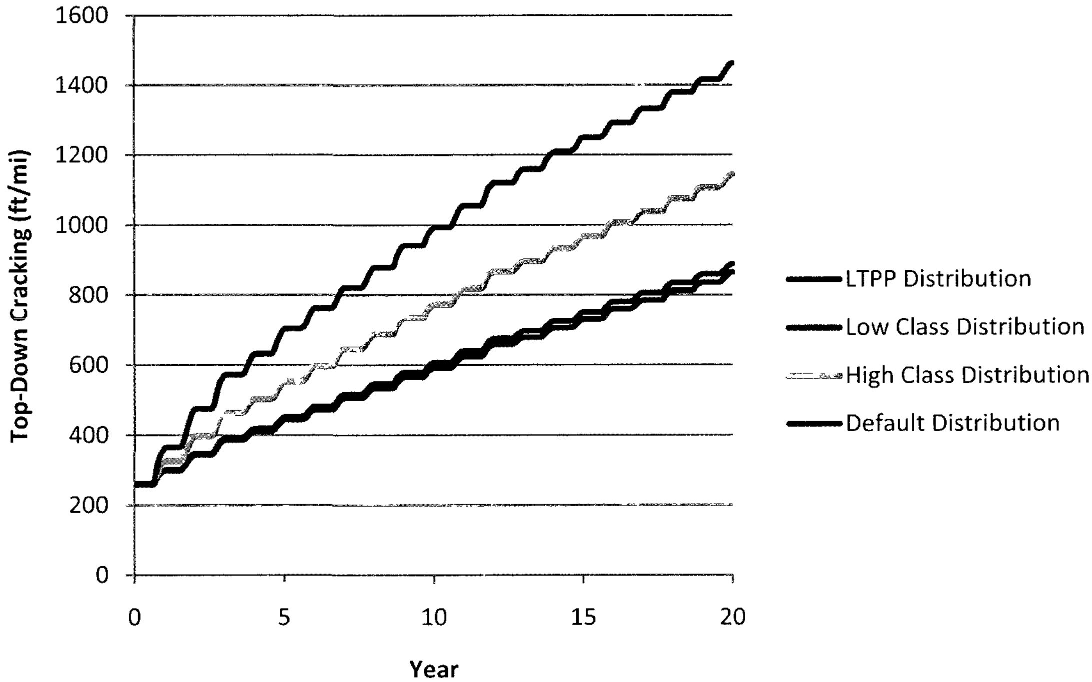


Figure 16A: Effect of Truck Class Distribution on Top-Down Cracking

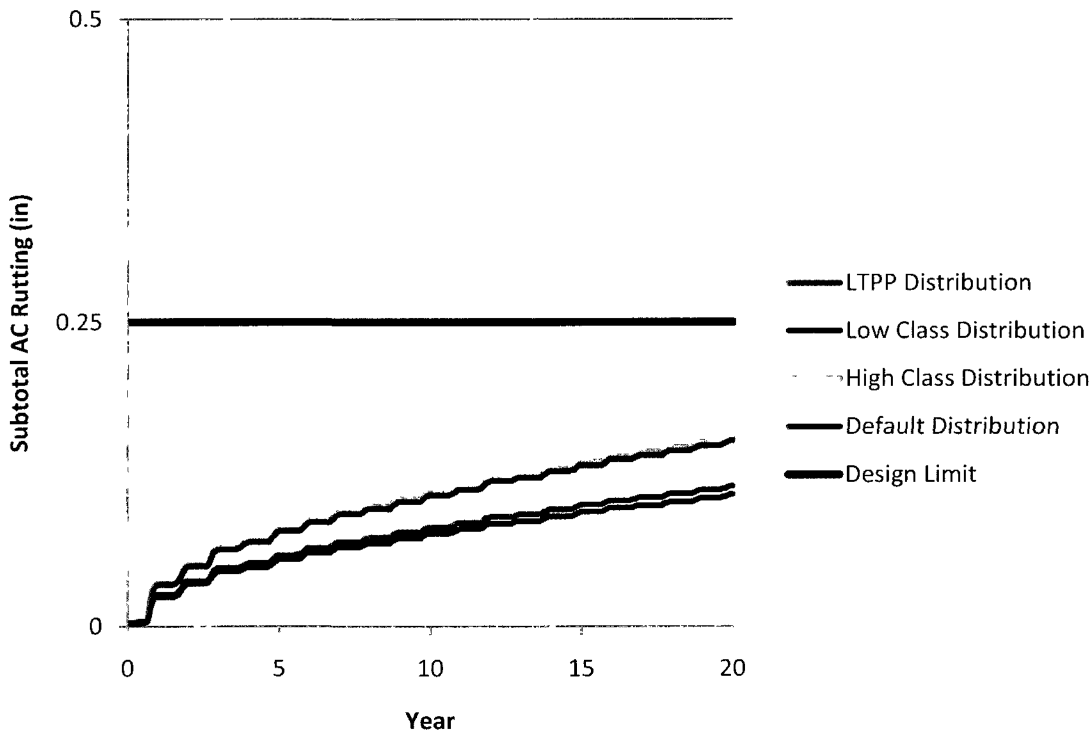


Figure 17A: Effect of Truck Class Distribution on Subtotal AC Rutting

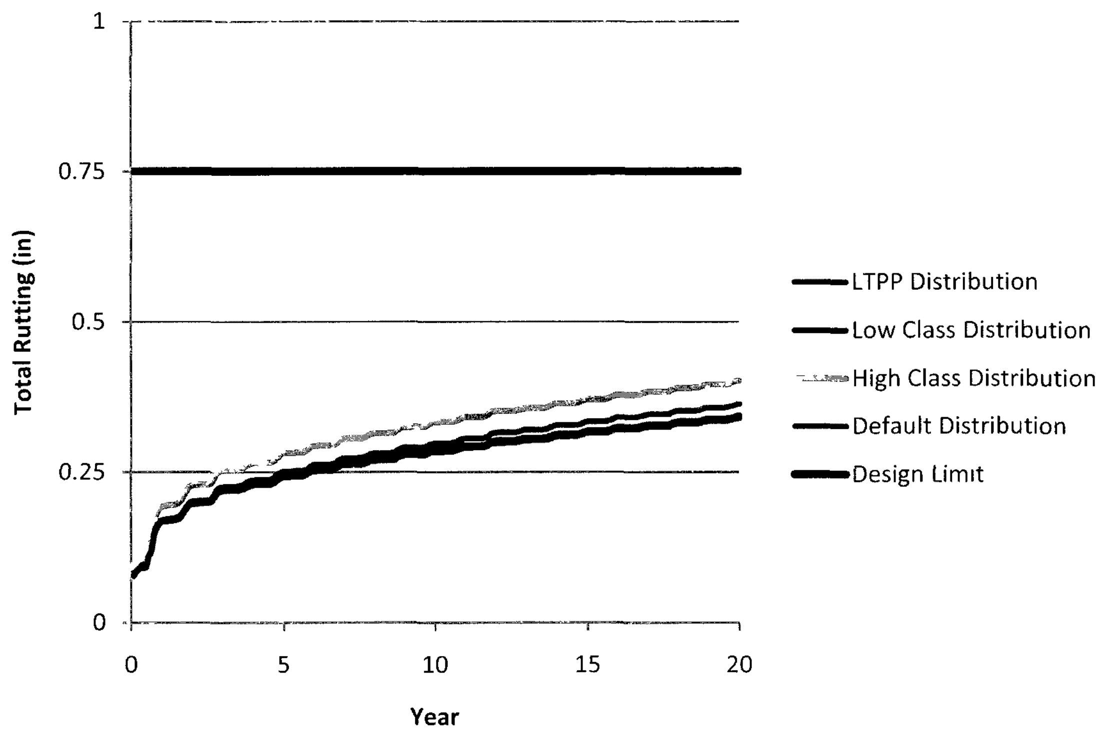


Figure 18A: Effect of Truck Class Distribution on Total Rutting

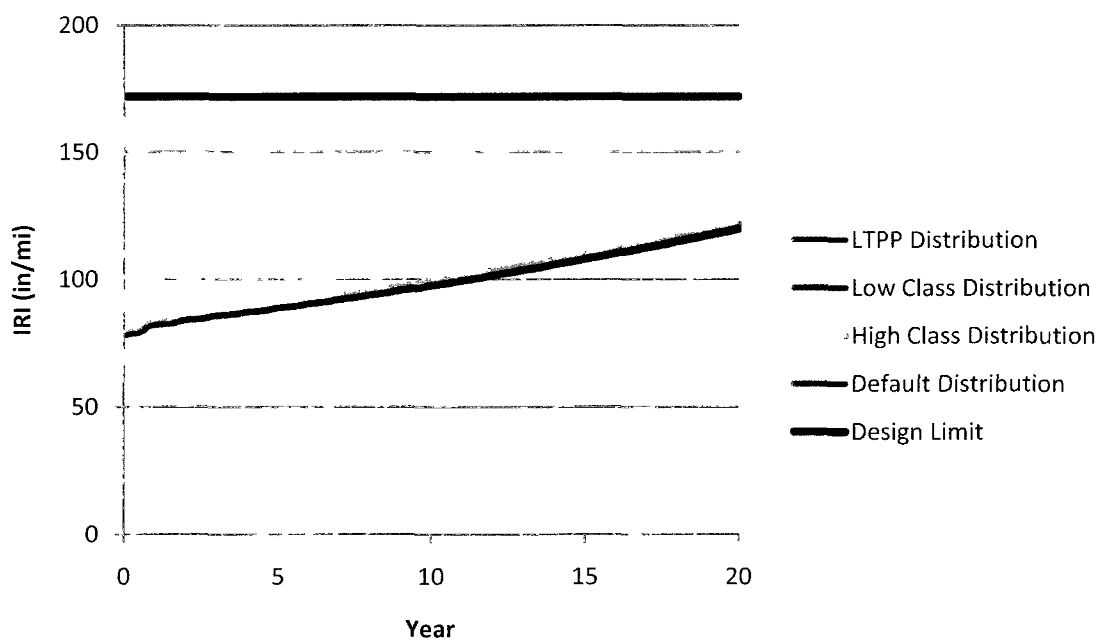


Figure 19A: Effect of Truck Class Distribution on IRI

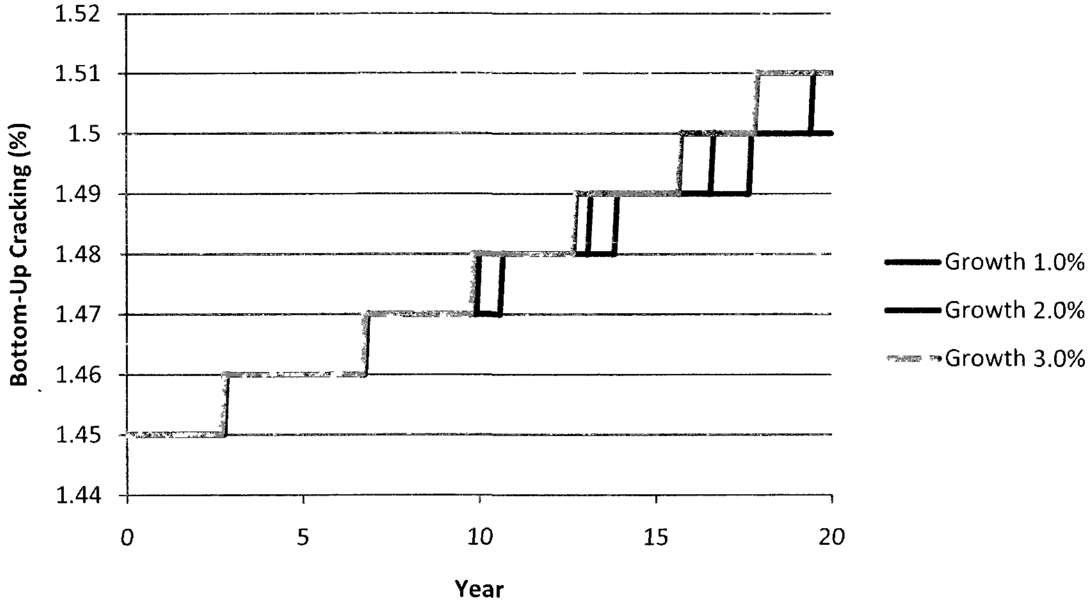


Figure 20A: Effect of Traffic Growth Rate at Bottom-Up Cracking

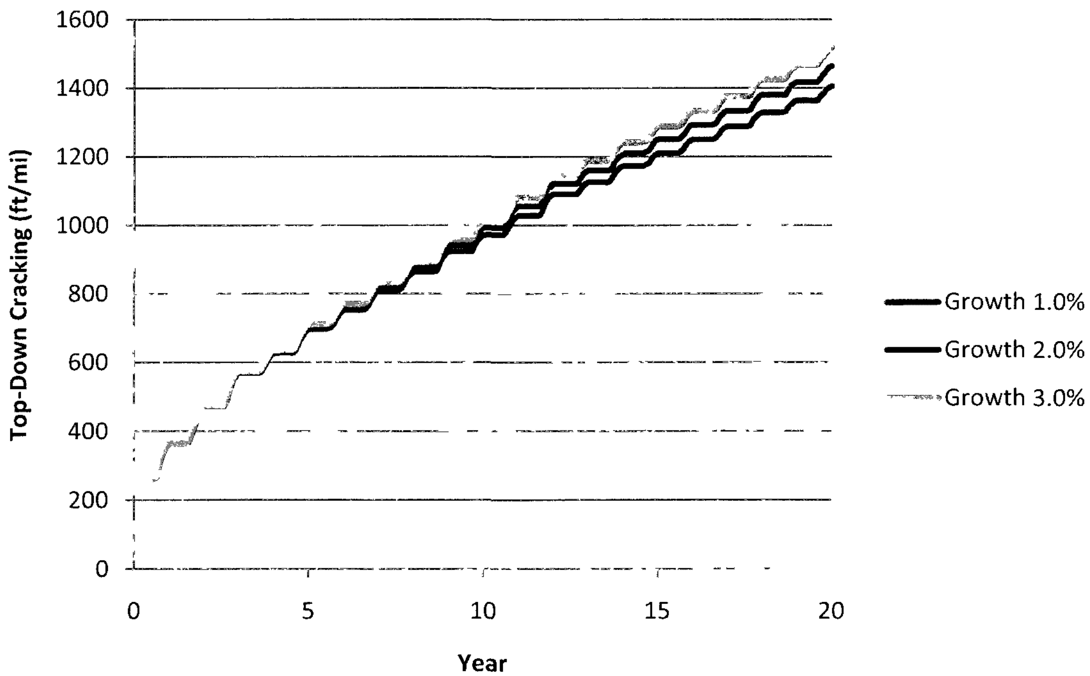


Figure 21A: Effect of Traffic Growth Rate on Top-Down Cracking

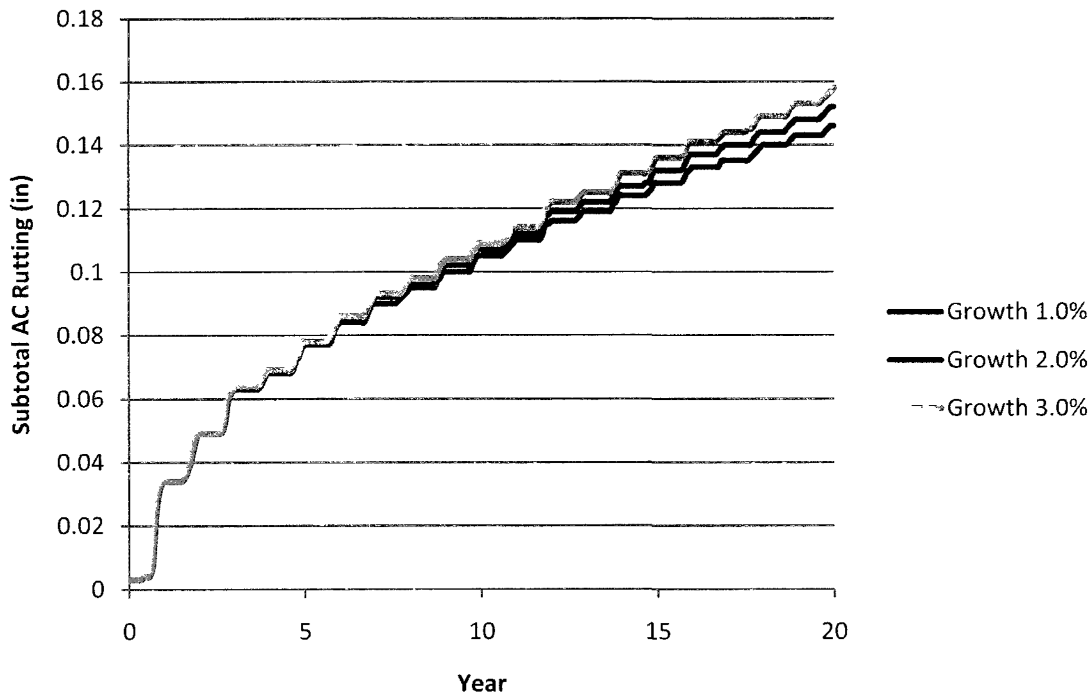


Figure 22A: Effect of Traffic Growth on Subtotal AC Rutting

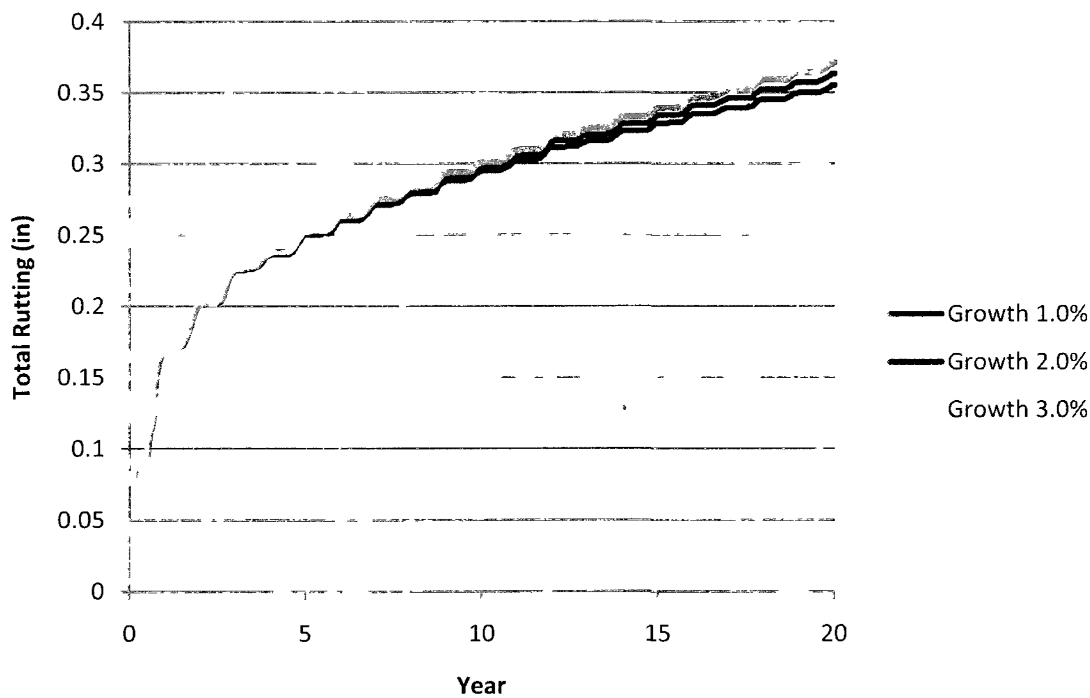


Figure 23A: Effect of Traffic Growth Rate on Total Rutting

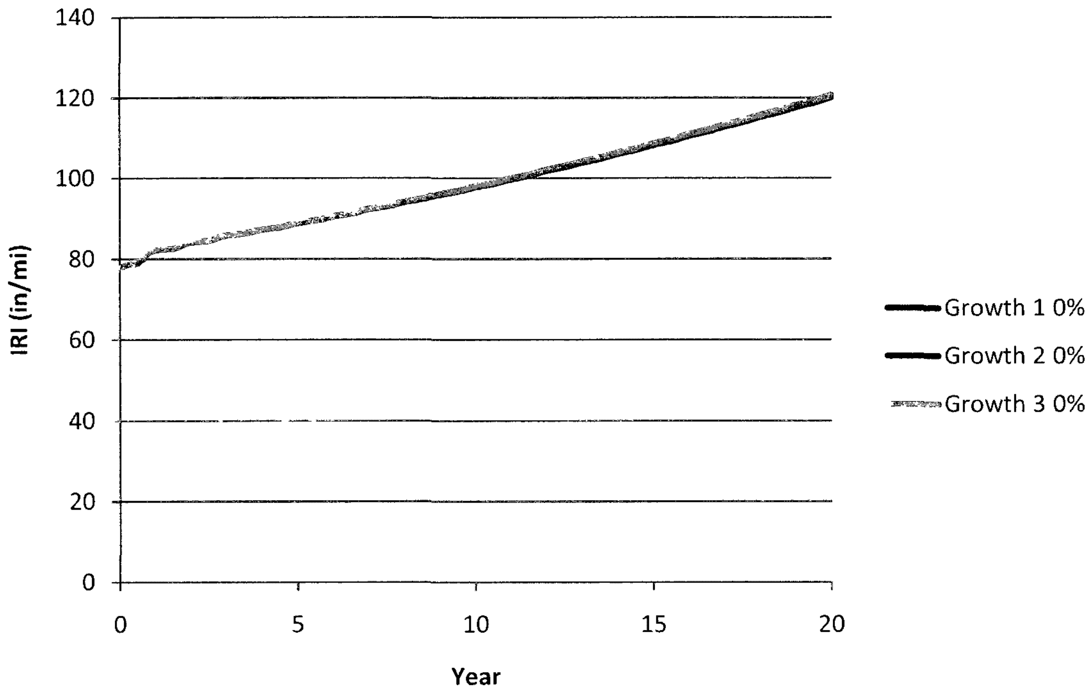


Figure 24A: Effect of Traffic Growth Rate on IRI

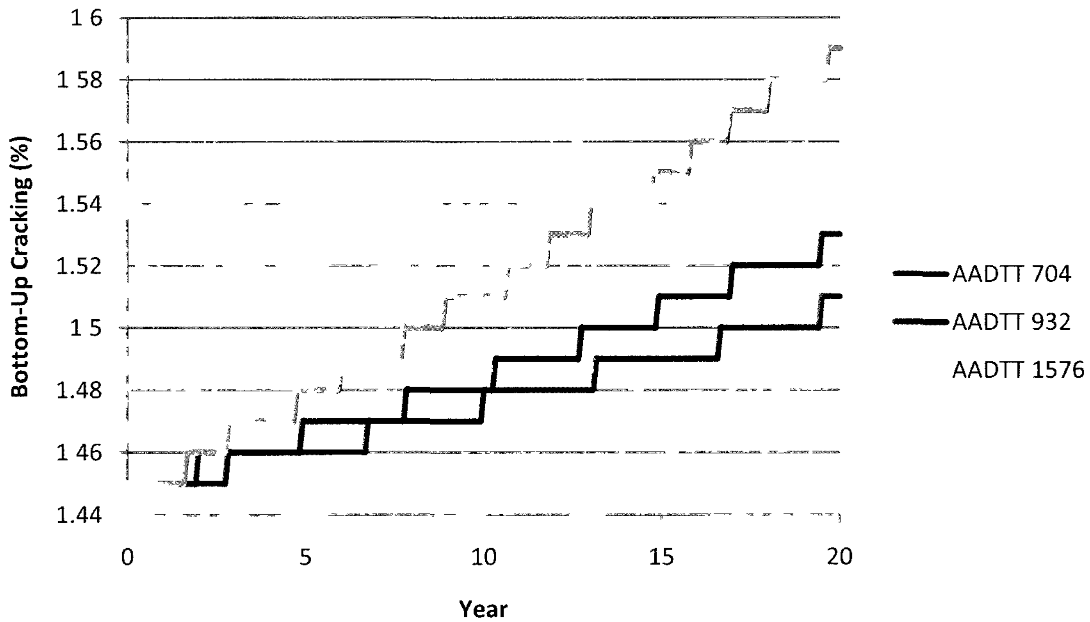


Figure 25A: Effect of AADTT on Bottom-Up Cracking

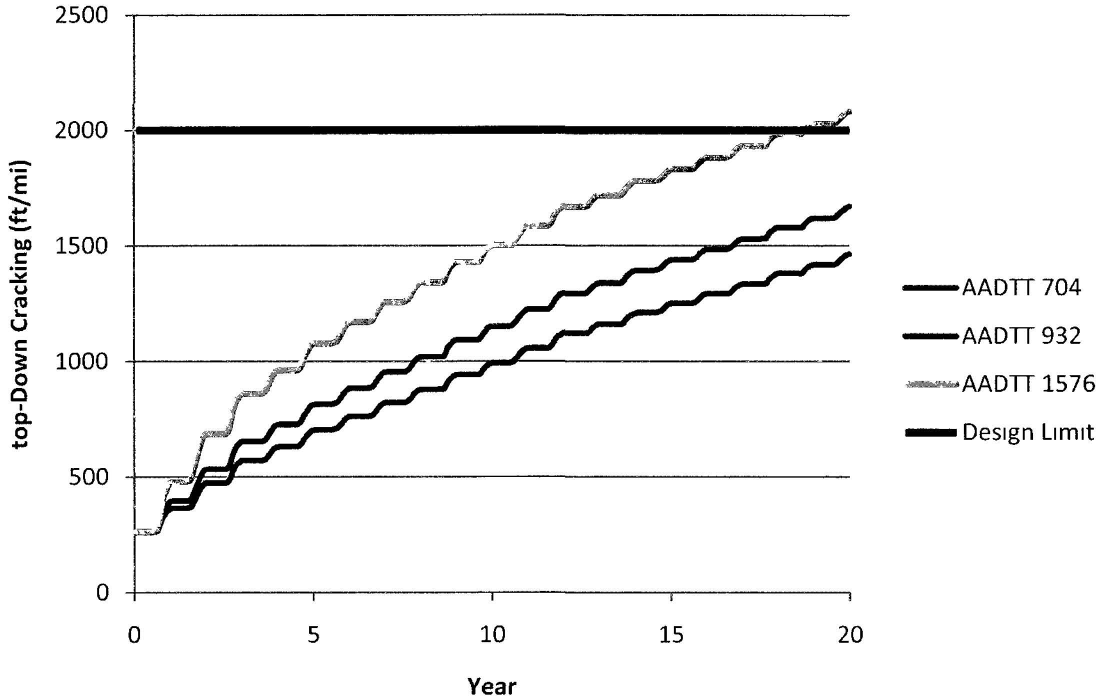


Figure 26A: Effect of AADTT on Top-Down Cracking

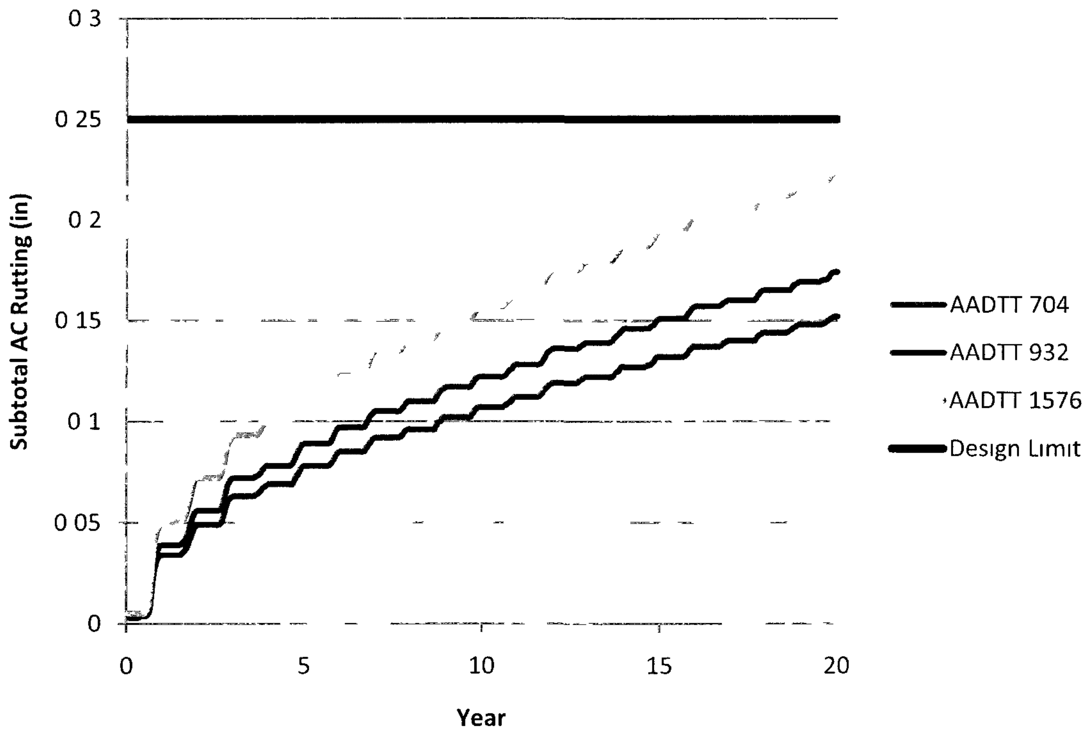


Figure 27A: Effect of AADTT on Subtotal AC Rutting

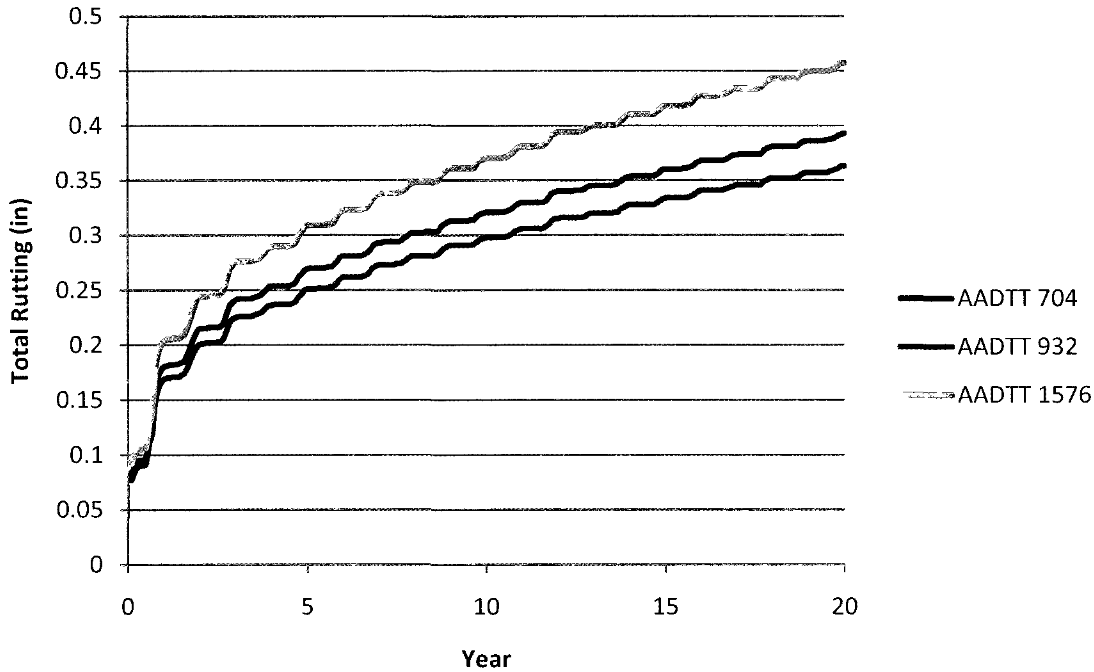


Figure 28A: Effect of AADTT on Total Rutting

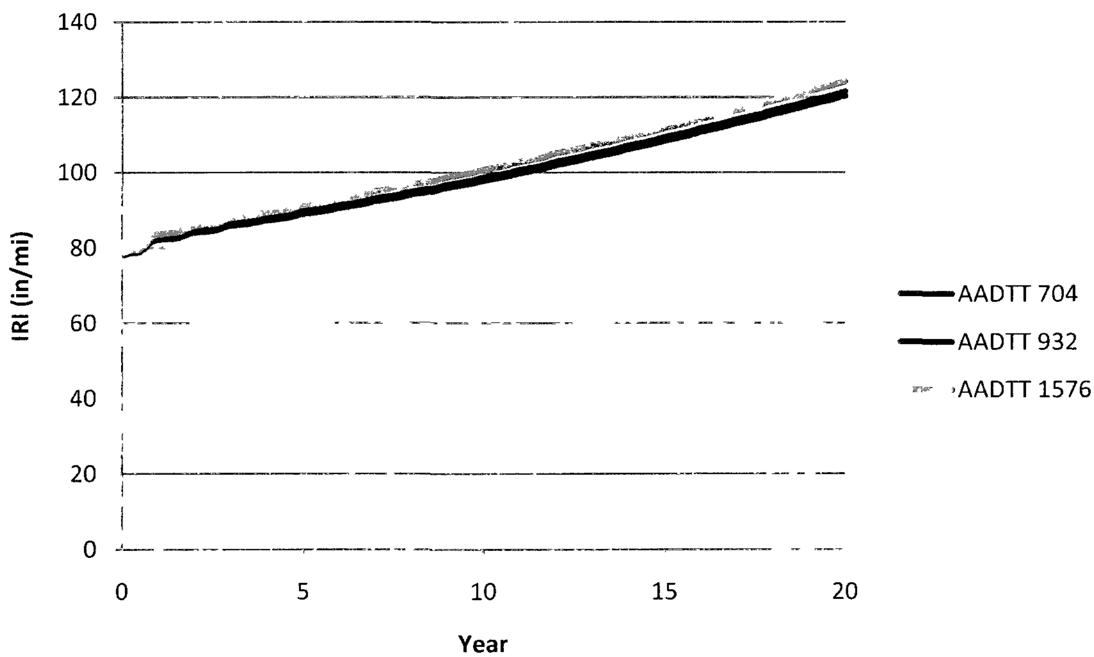


Figure 29A: Effect of AADTT on IRI

7.2 Effect of Climate Inputs on Pavement Distresses

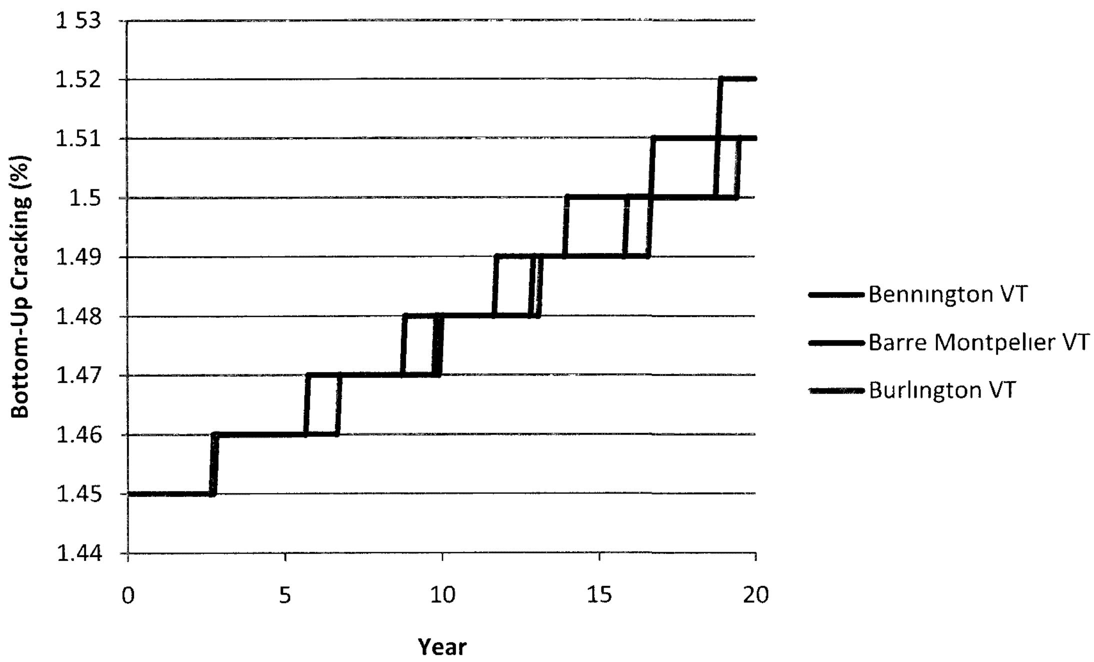


Figure 30A: Effect of Climate on Bottom-Up Cracking

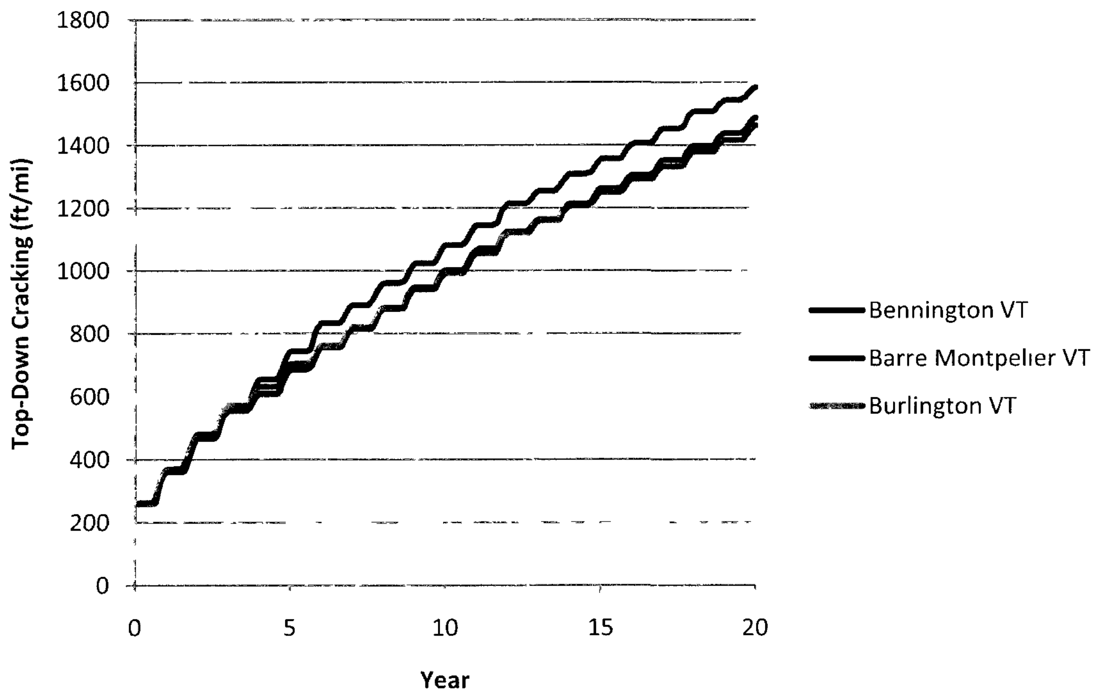


Figure 31A: Effect of Climate on Top-Down Cracking

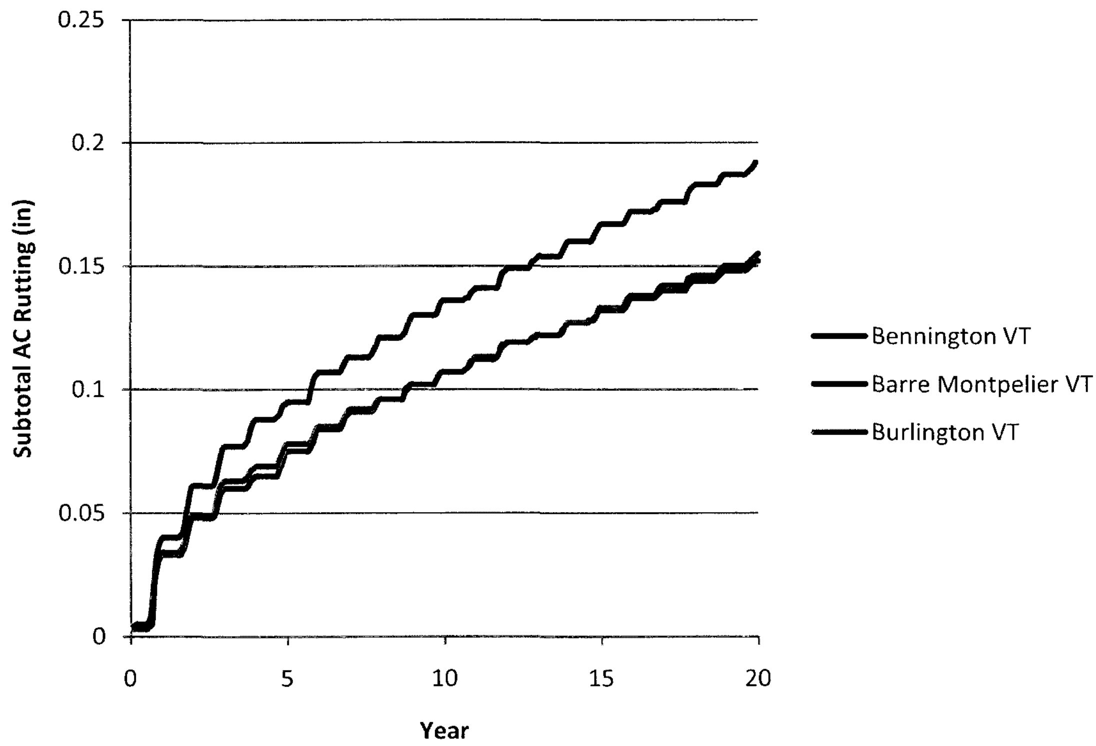


Figure 32A: Effect of Climate on Subtotal AC Rutting

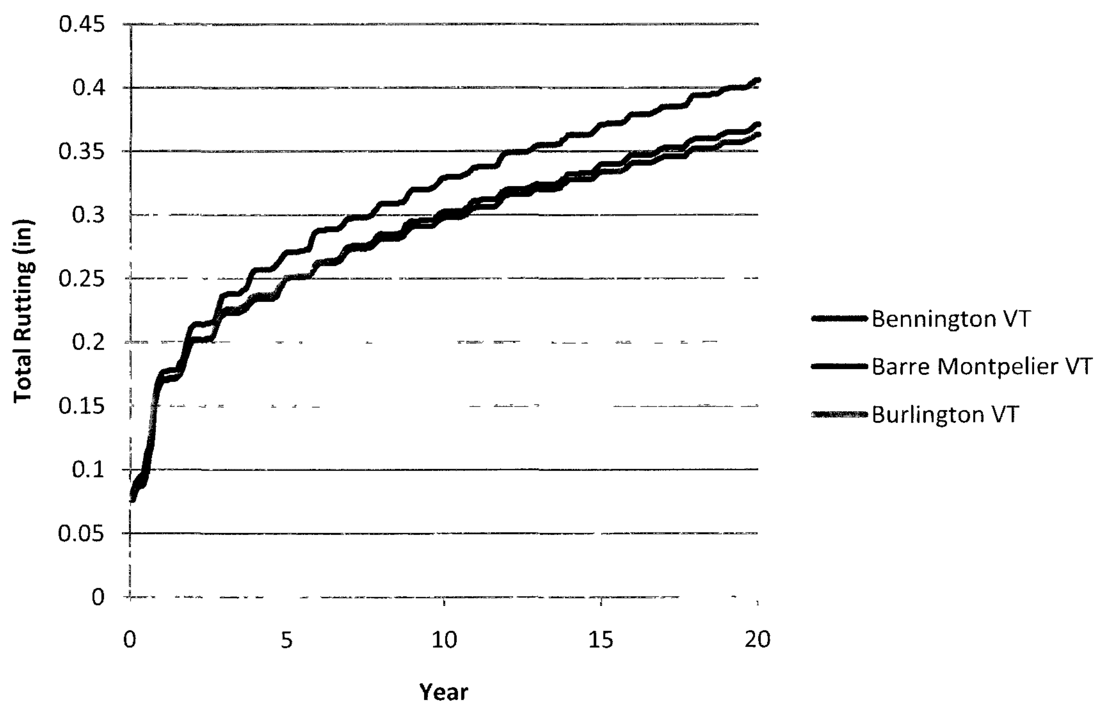


Figure 33A: Effect of Climate on Total Rutting

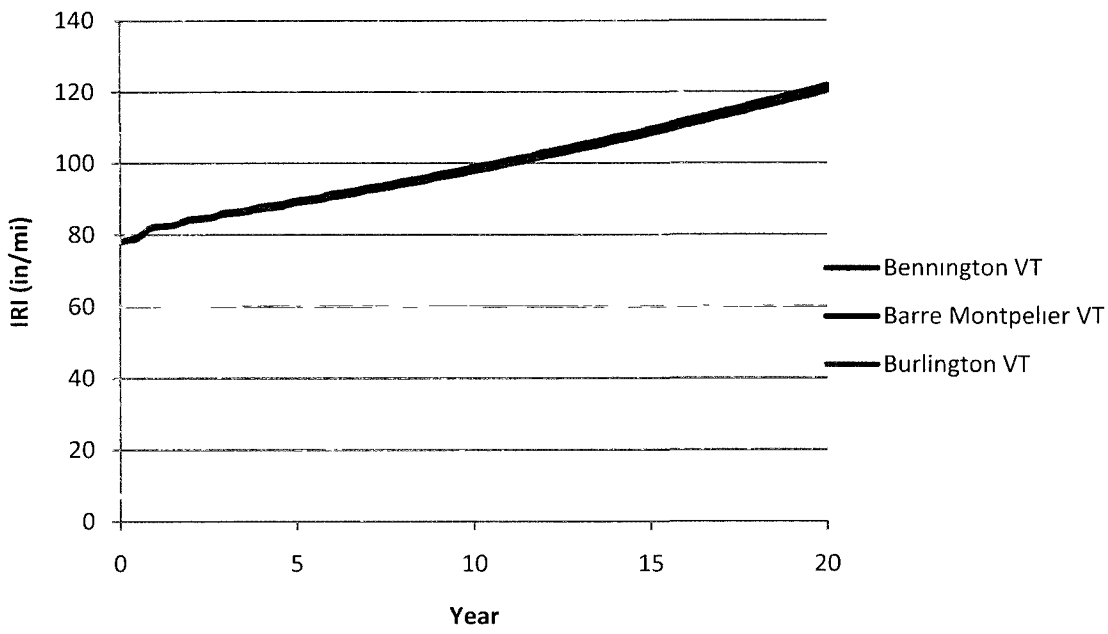


Figure 34A: Effect of Climate on IRI

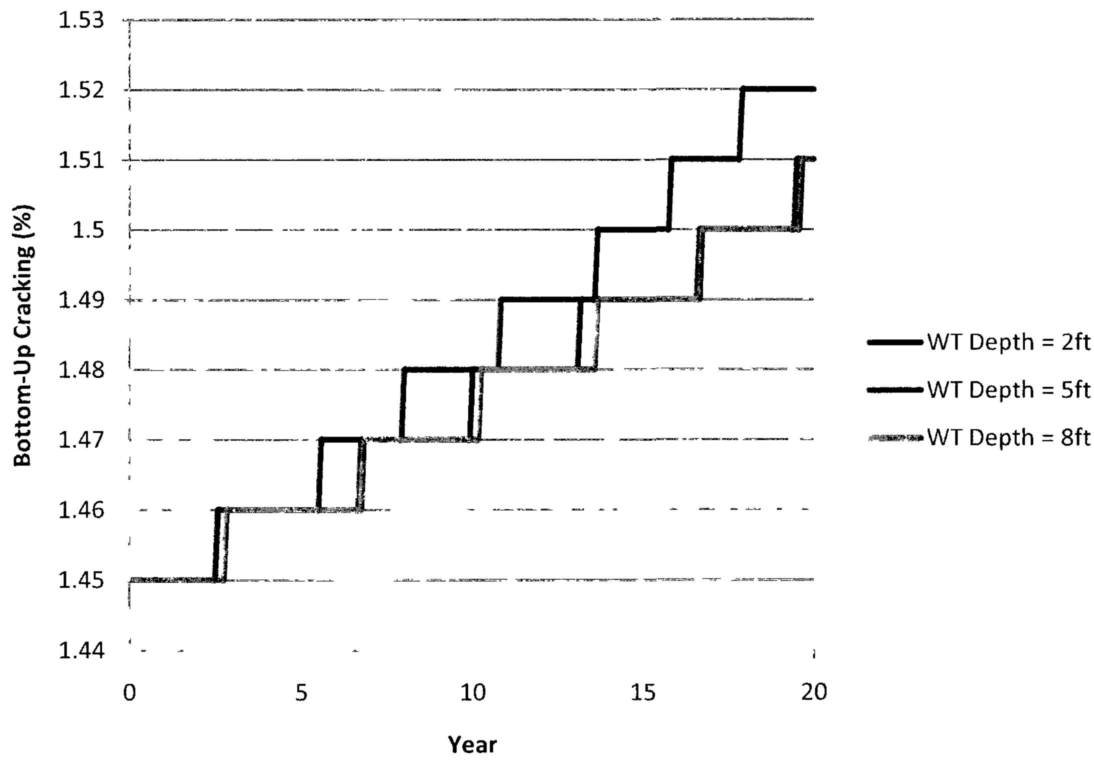


Figure 35A: Effect of Water Table Depth on Bottom-Up Cracking

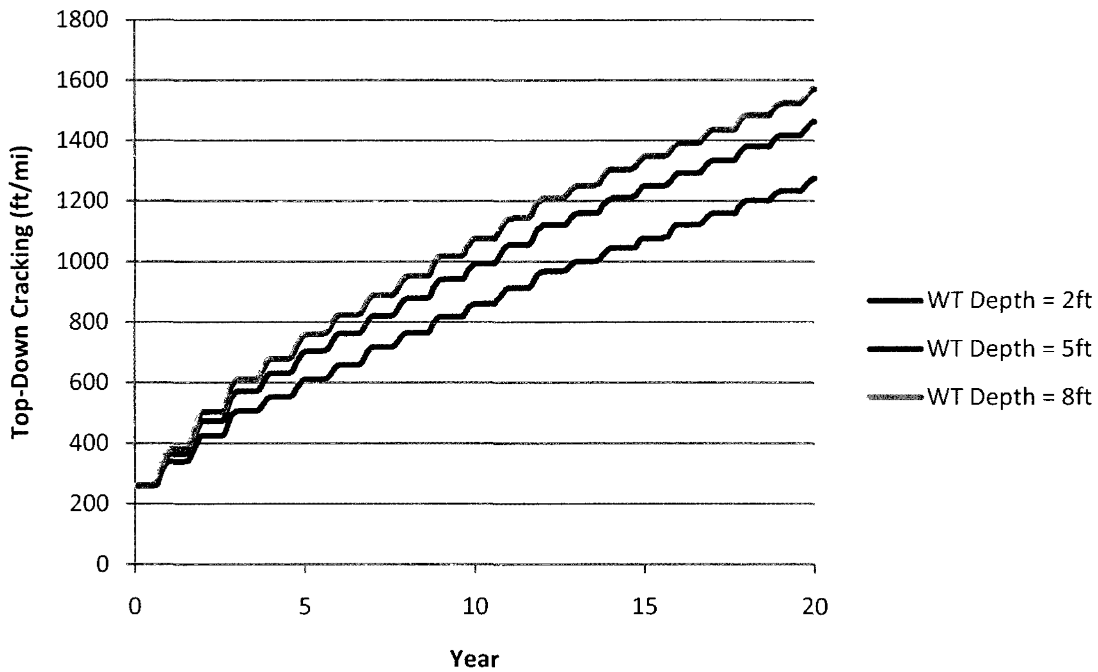


Figure 36A: Effect of Water Table Depth on Top-Down Cracking

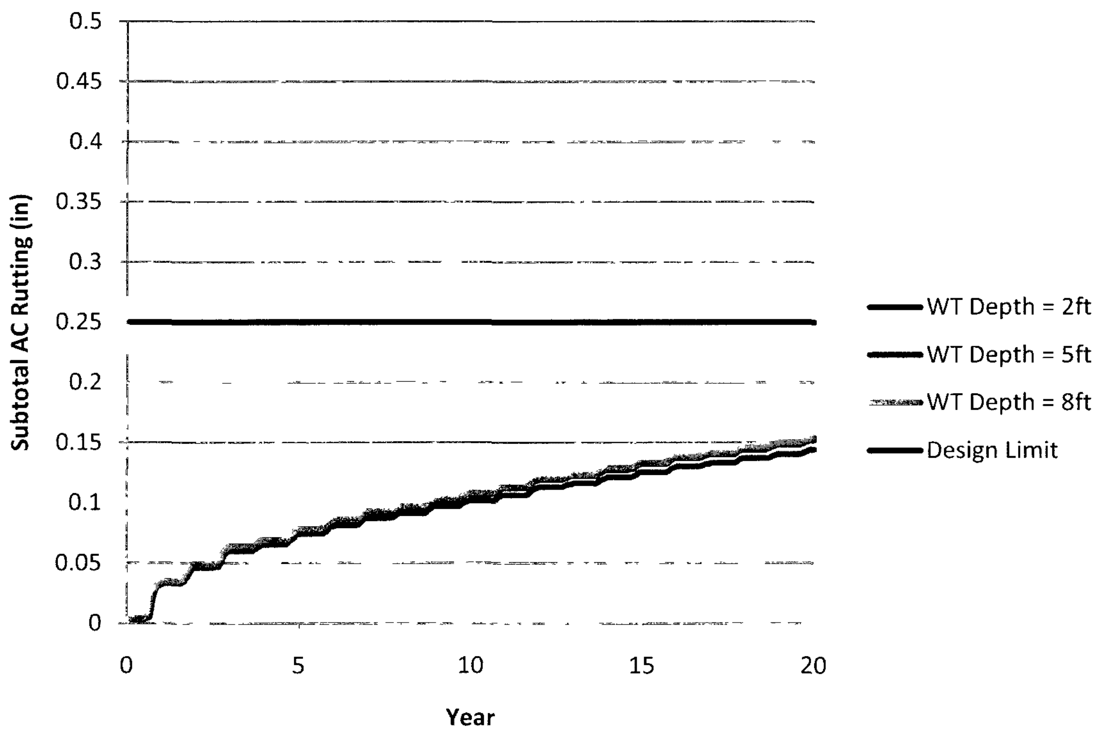


Figure 37A: Effect of Water Table Depth on Subtotal AC Rutting

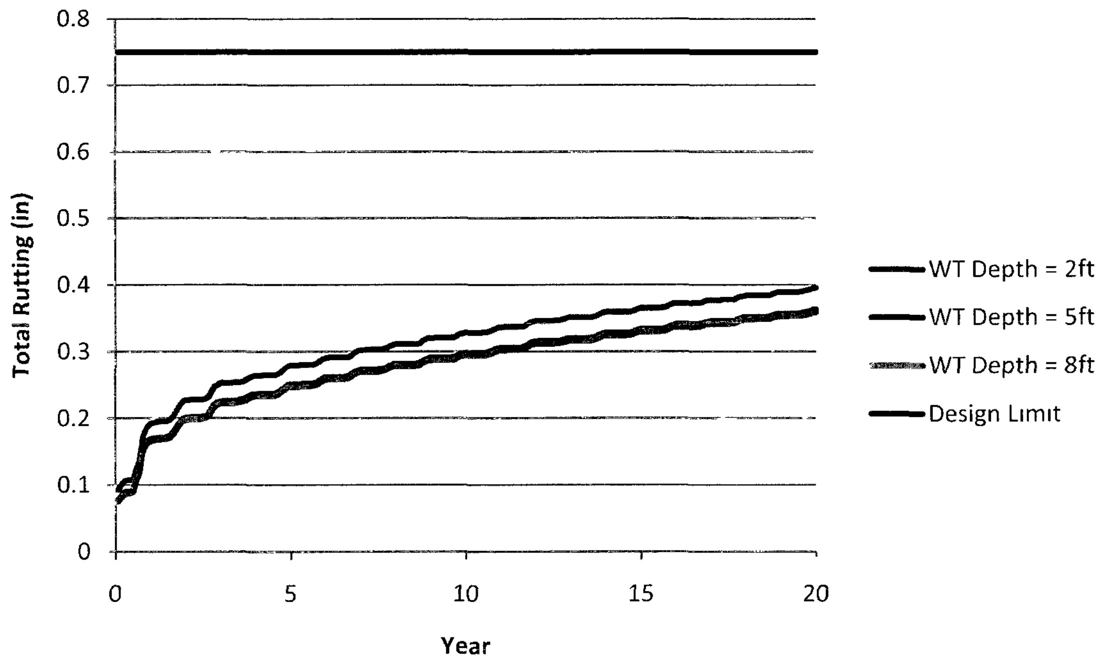


Figure 38A: Effect of Water Table Depth on Total Rutting

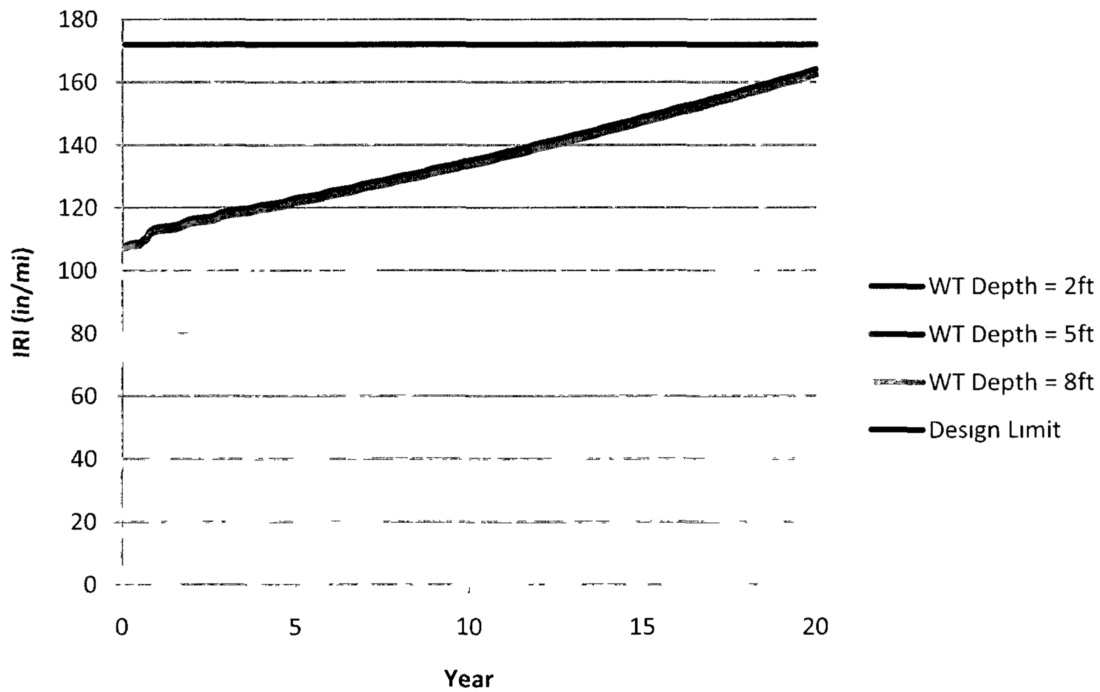


Figure 39A: Effect of Water Table Depth on IRI

7.3 Effect of Material Inputs on Pavement Distresses

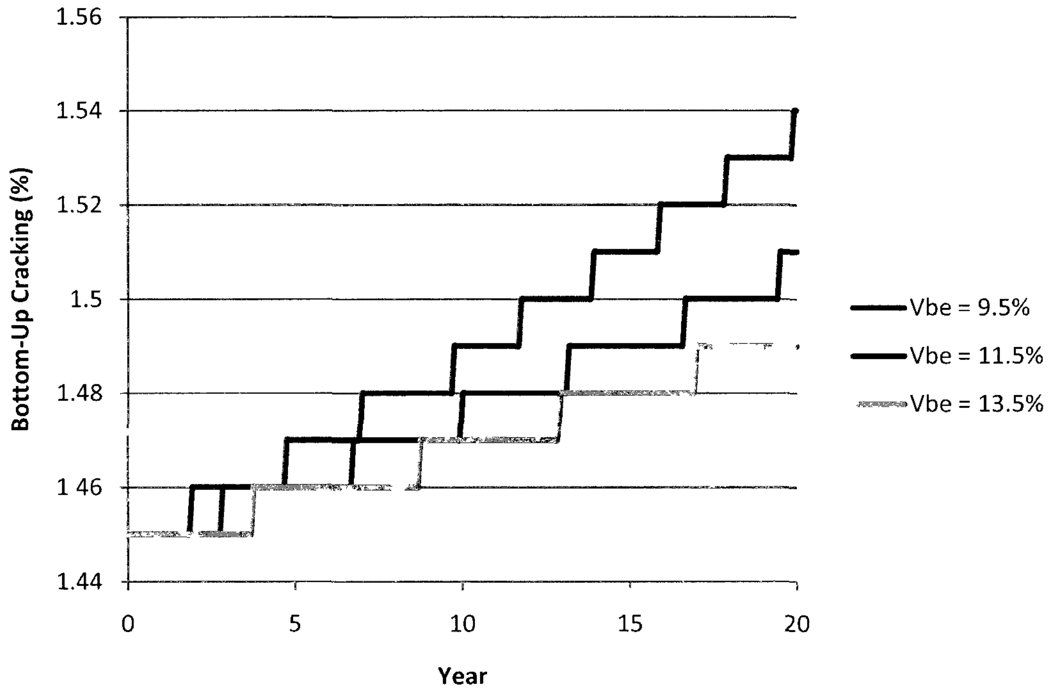


Figure 40A: Effect of Effective Binder Content on Bottom-Up Cracking

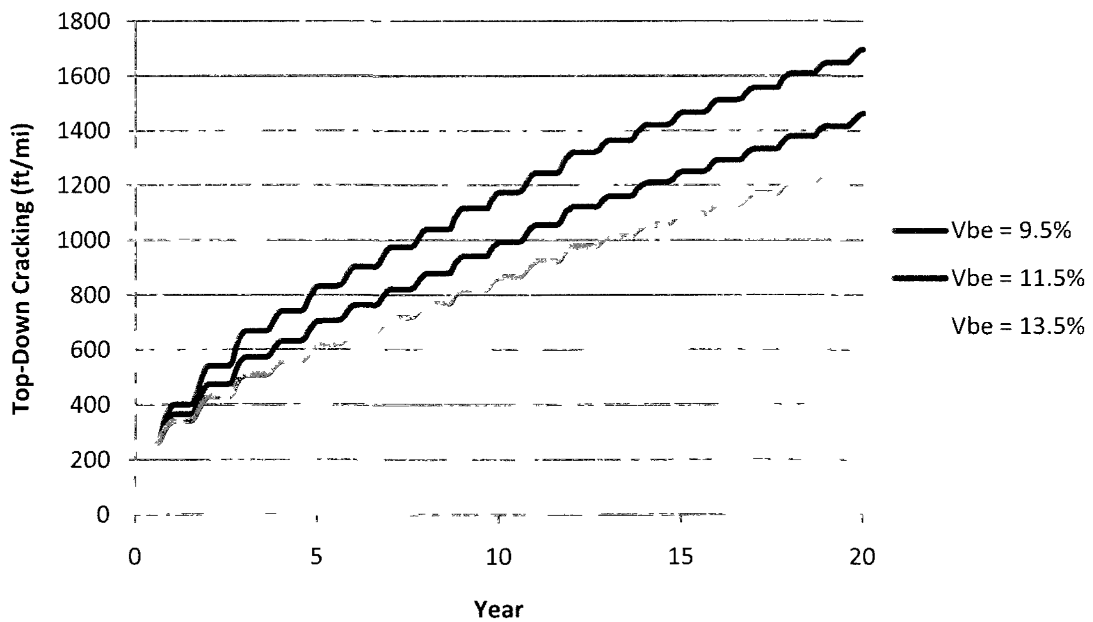


Figure 41A: Effect of Effective Binder Content on Top-Down Cracking

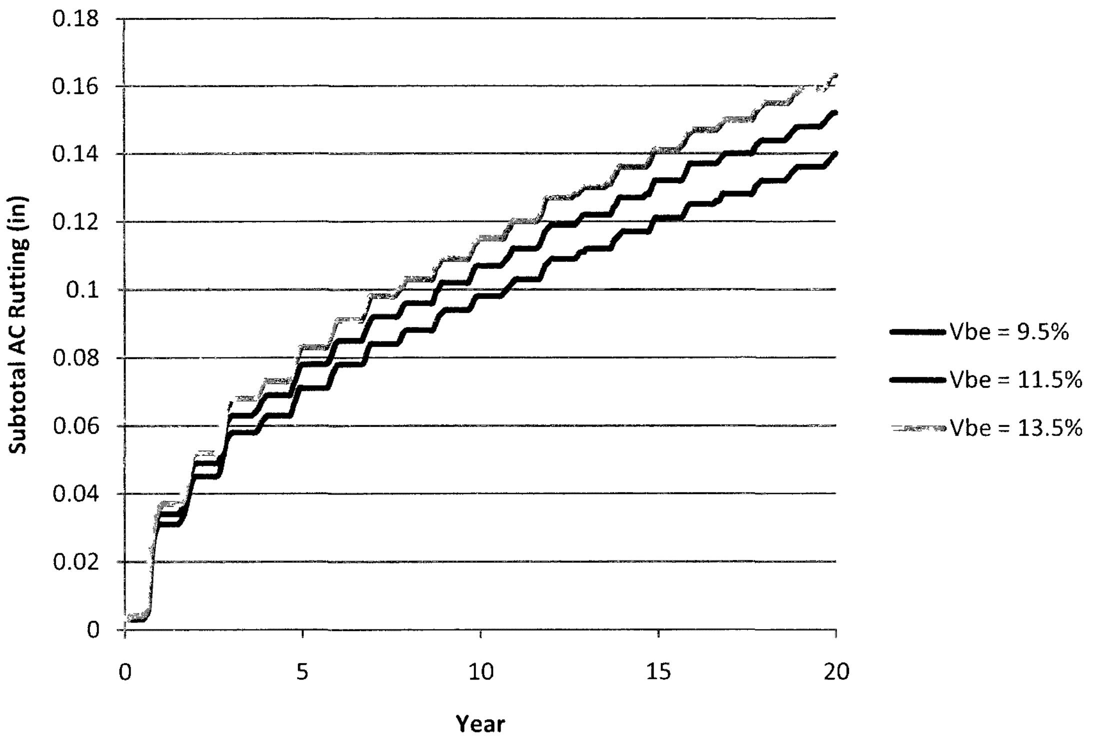


Figure 42A: Effect of Effective Binder Content on Subtotal AC Rutting

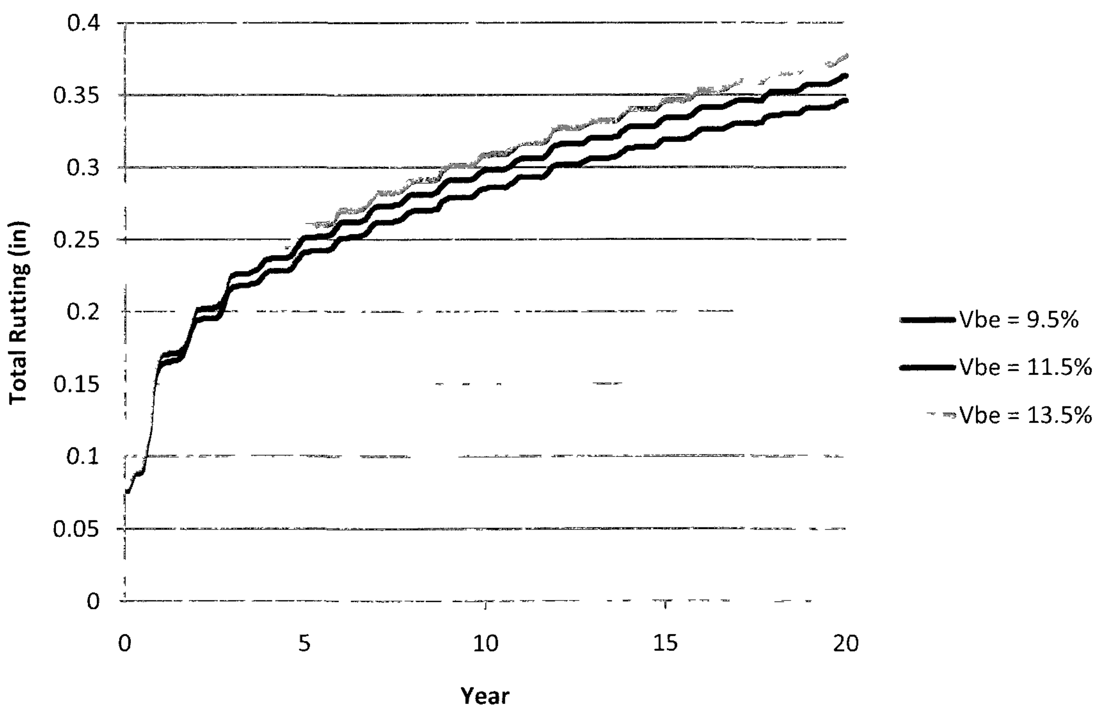


Figure 43A: Effective of Effective Binder Content on Total Rutting

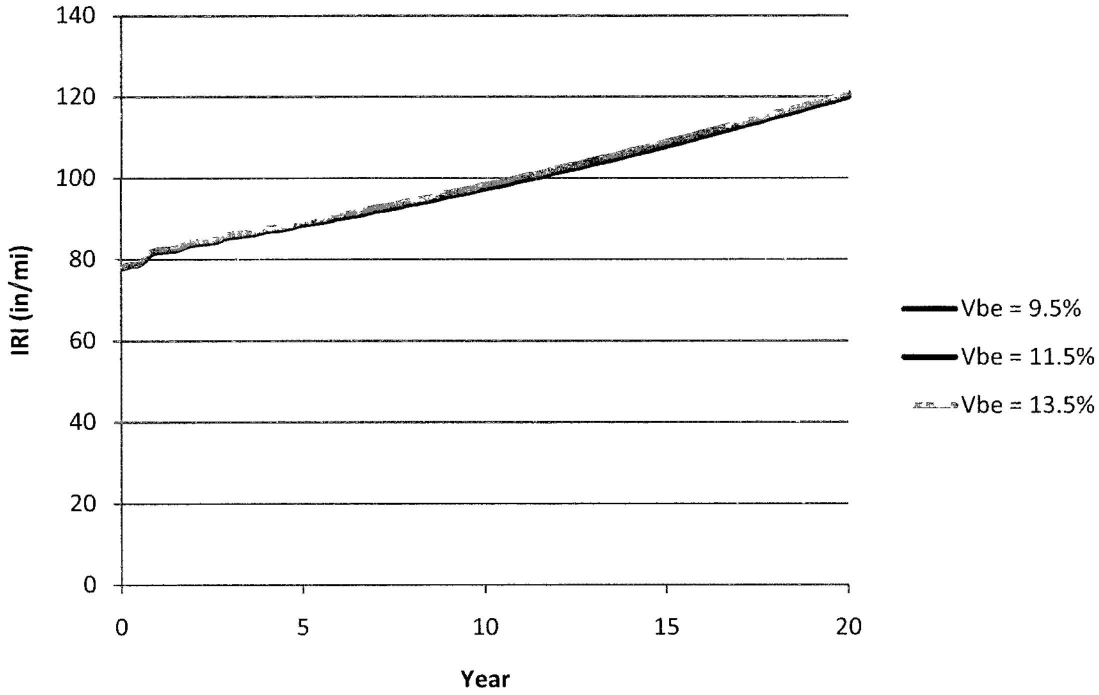


Figure 44A: Effect of Effective Binder Content on IRI

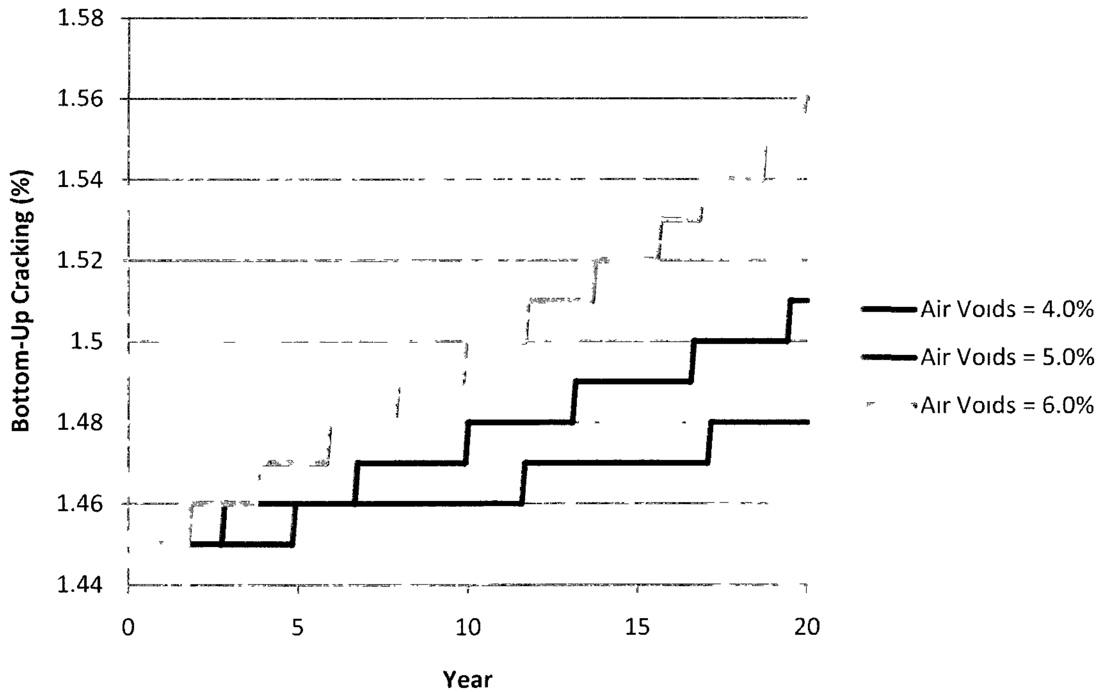


Figure 45A: Effect of Percent Air Voids on Bottom-Up Cracking

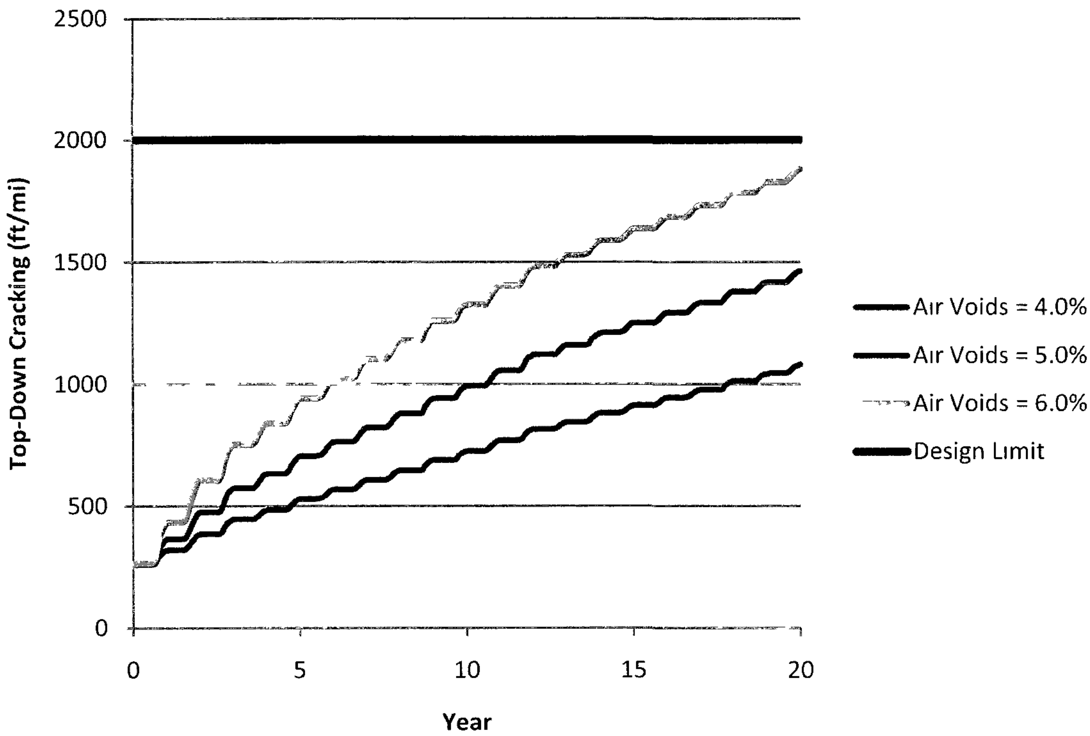


Figure 46A: Effect of Percent Air Voids on Top-Down Cracking

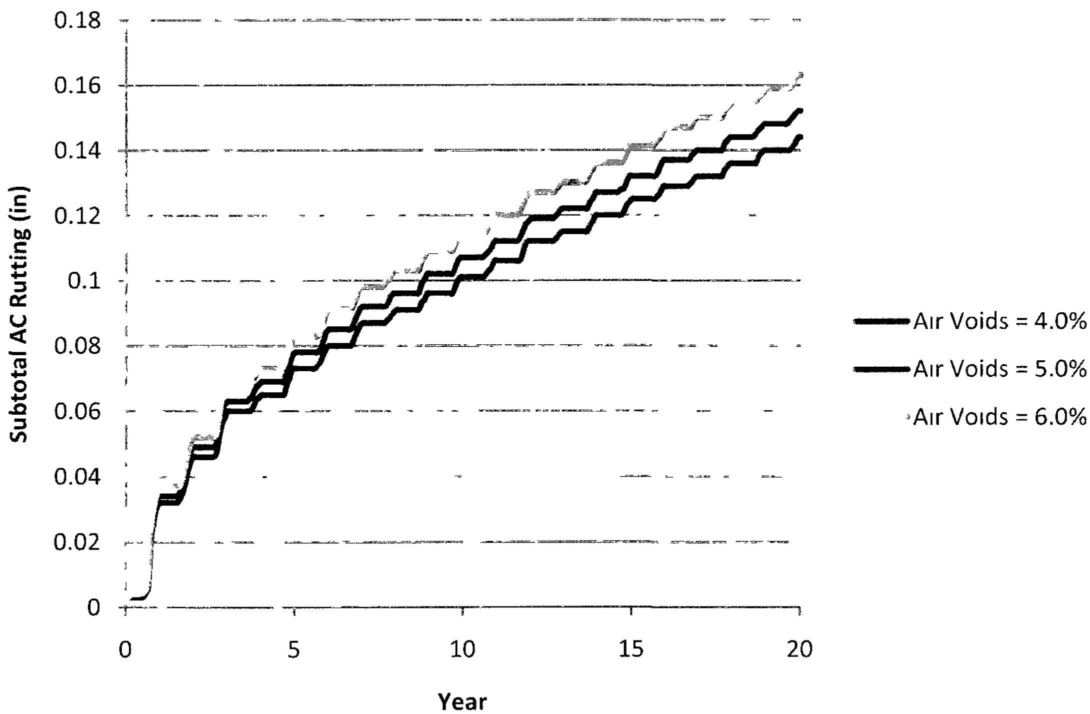


Figure 47A: Effect of Percent Air Voids on Subtotal AC Rutting

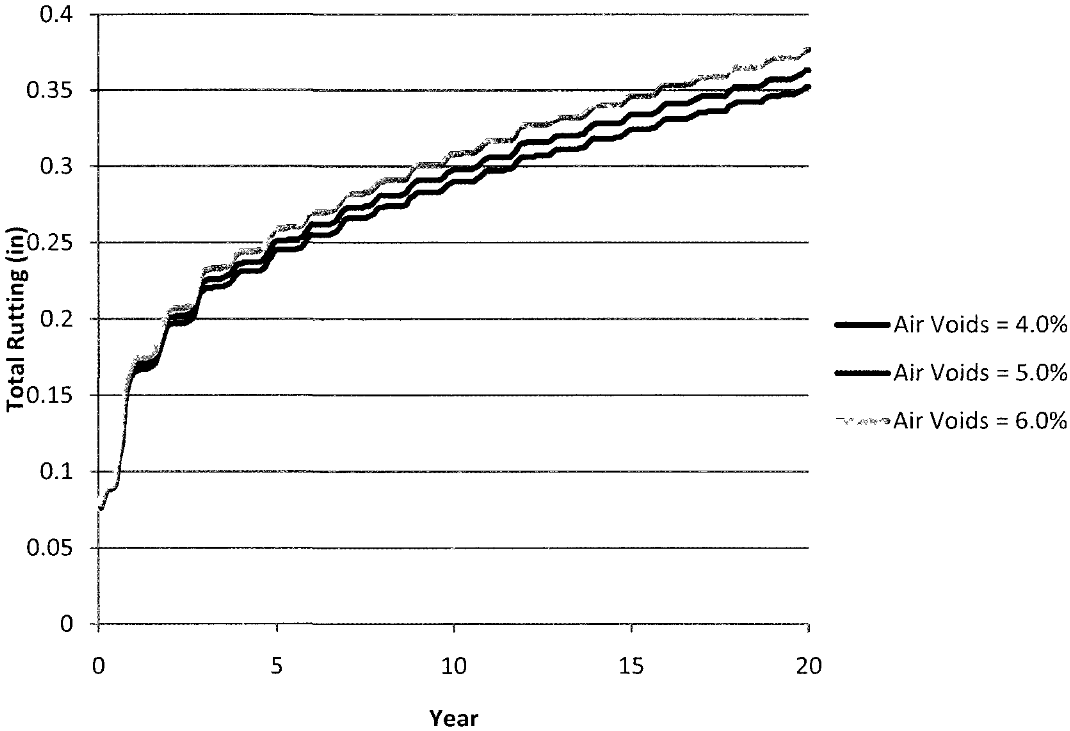


Figure 48A: Effect of Percent Air Voids on Total Rutting

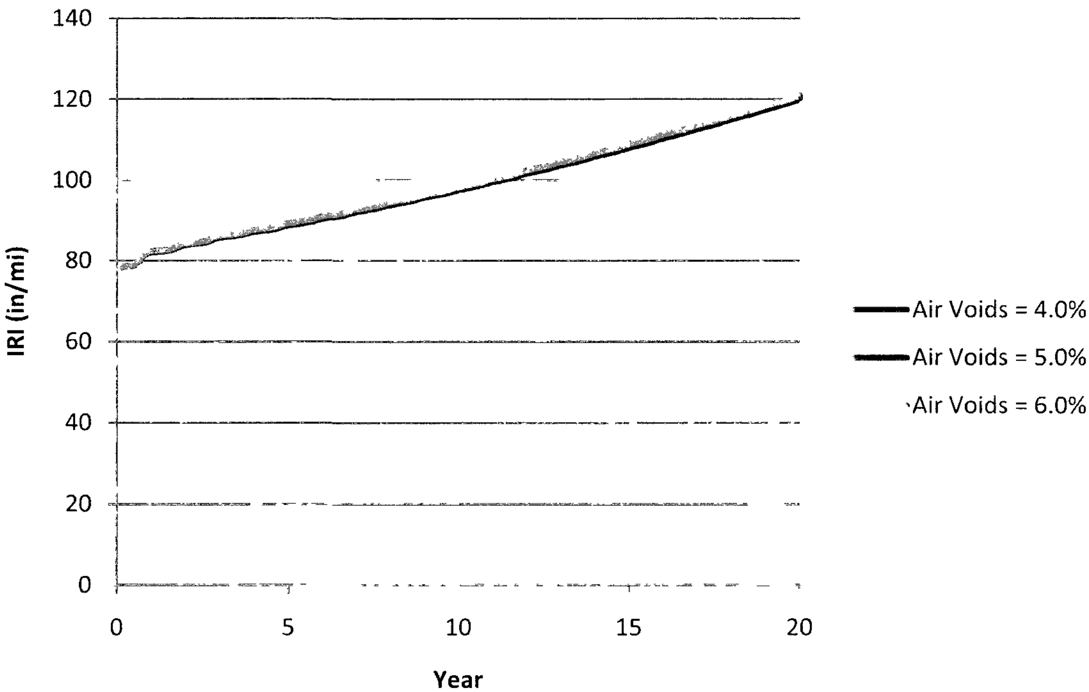


Figure 49A: Effect of Percent Air Voids on IRI

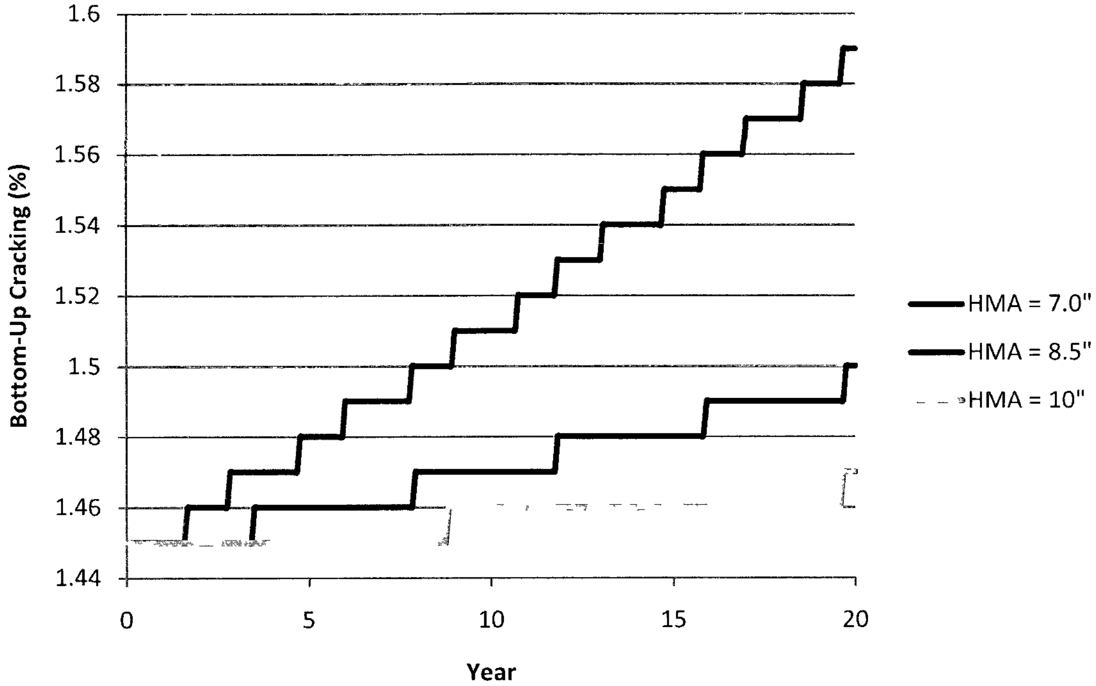


Figure 50A: Effect of AC Layer Thickness on Bottom-Up Cracking

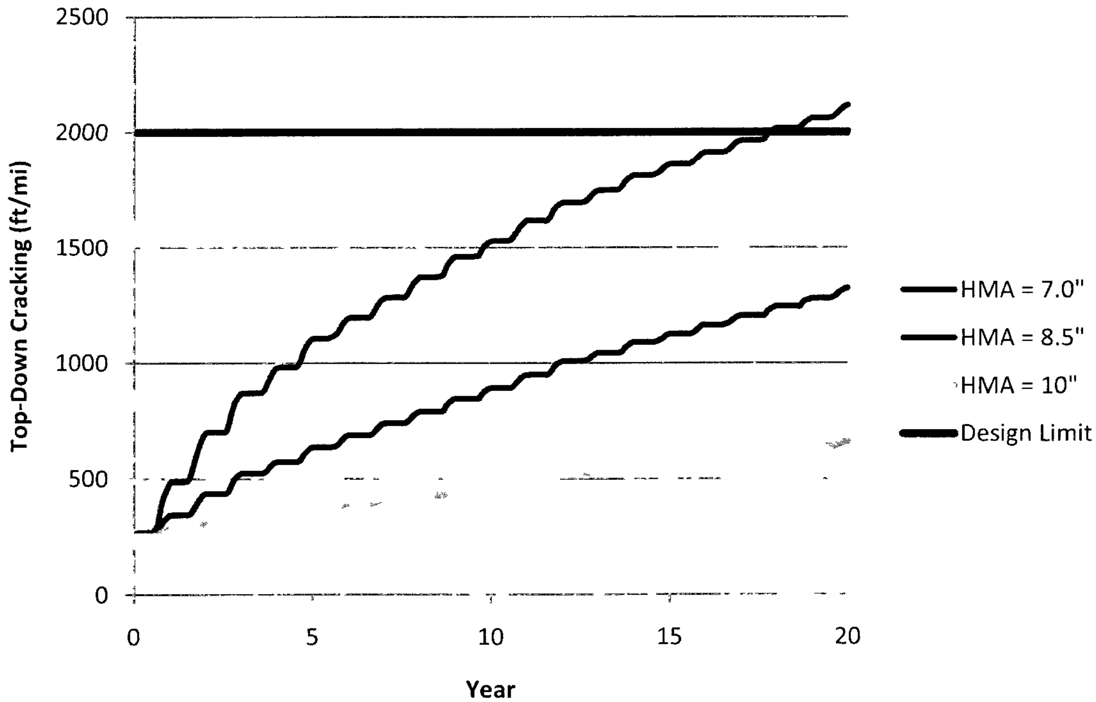


Figure 51A: Effect of AC Layer Thickness on Top-Down Cracking

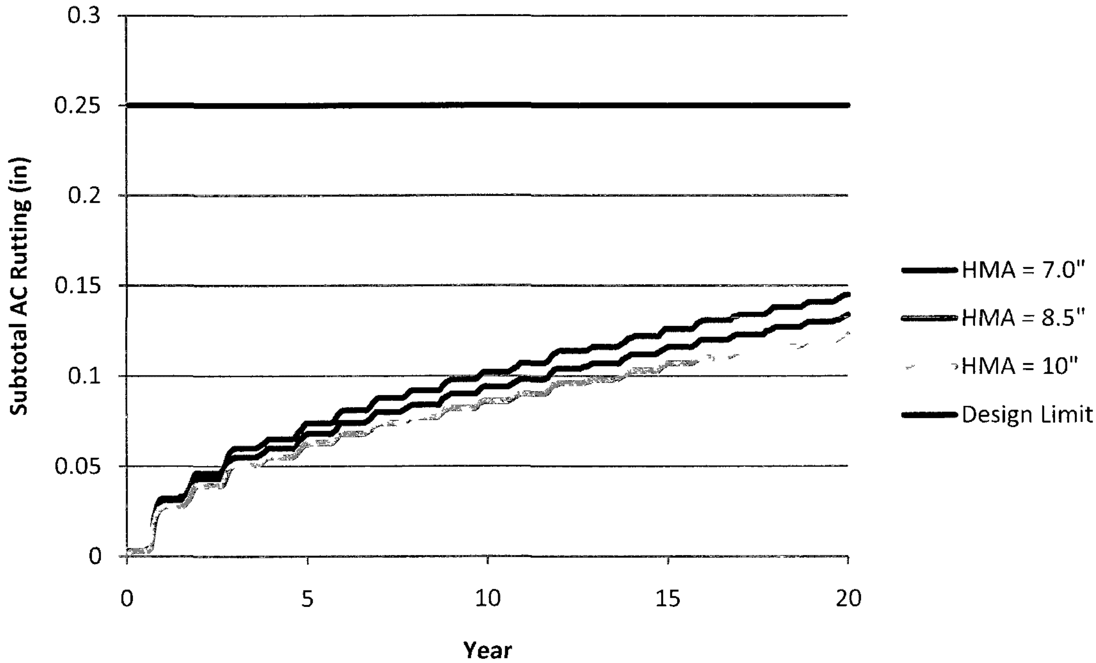


Figure 52A: Effect of AC Layer Thickness on Subtotal AC Rutting

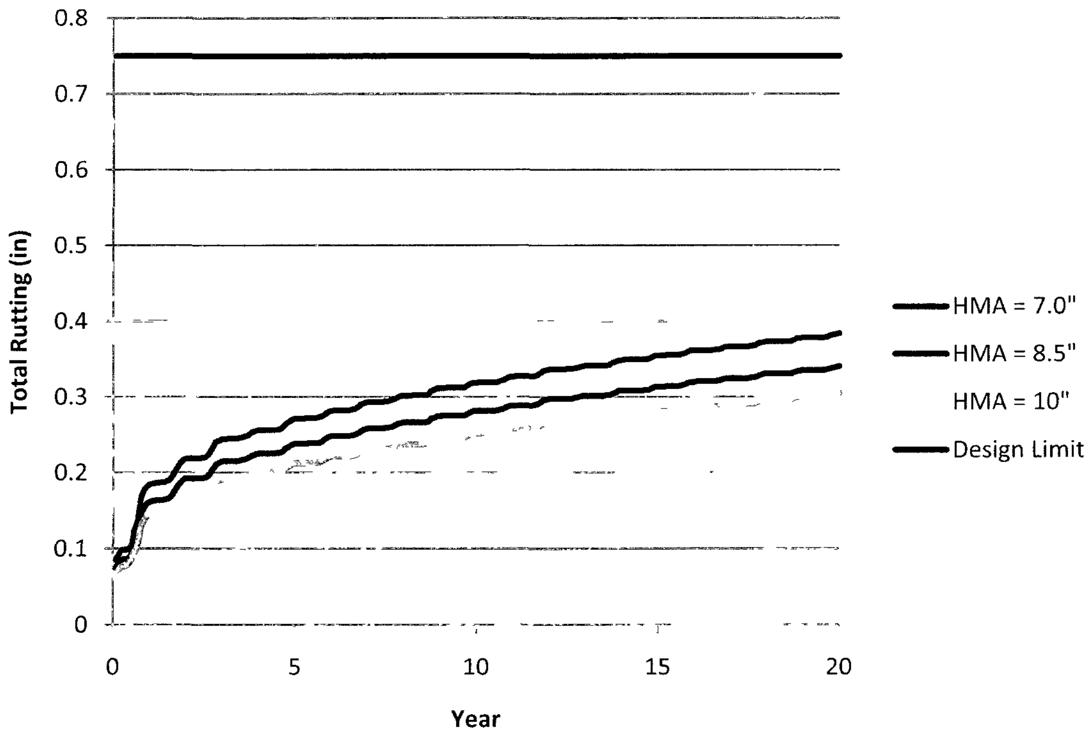


Figure 53A: Effect of AC Layer Thickness on Total Rutting

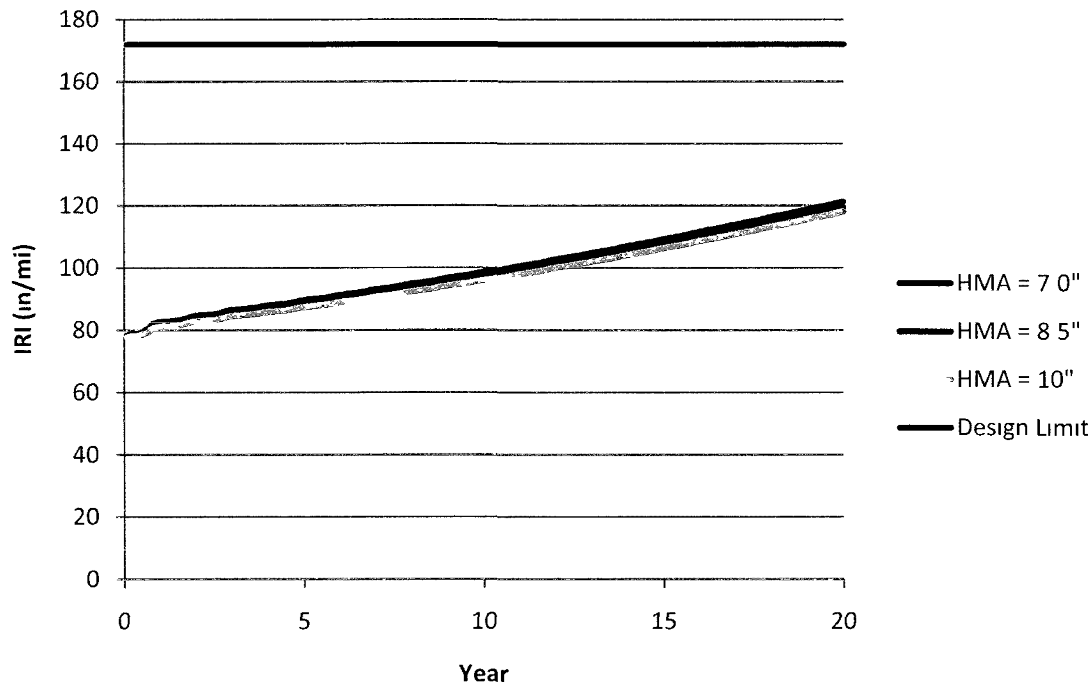


Figure 54A: Effect of AC Layer Thickness on IRI

7.4 Effect of Asphalt Concrete Mix Gradation

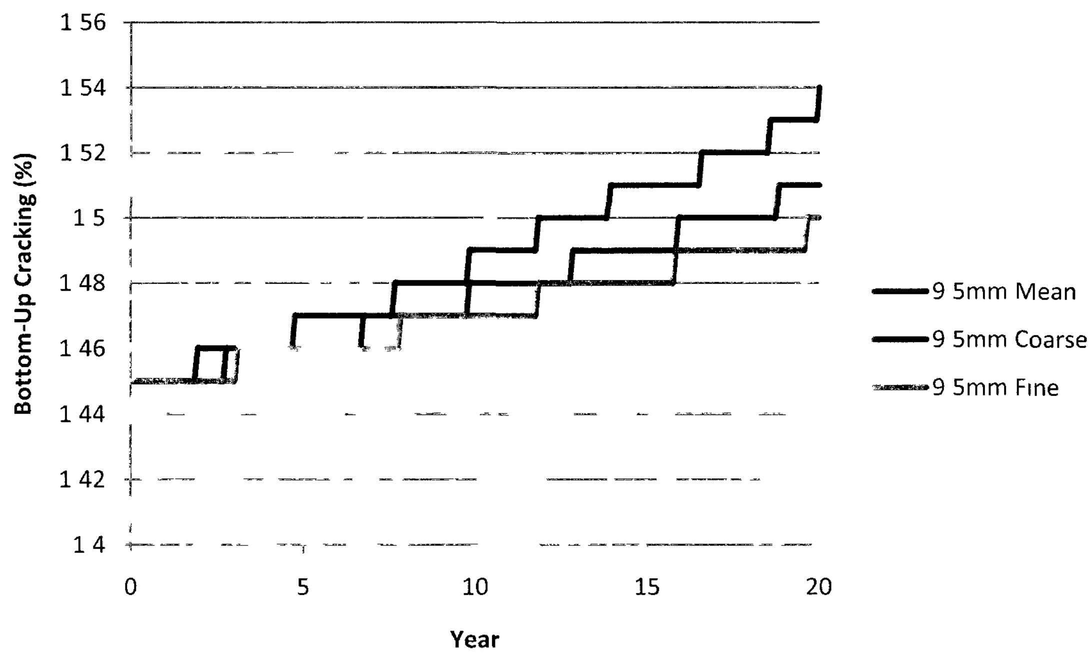


Figure 55A: Effect of Aggregate Gradation of 9.5 mm AC mix on Bottom-Up Cracking

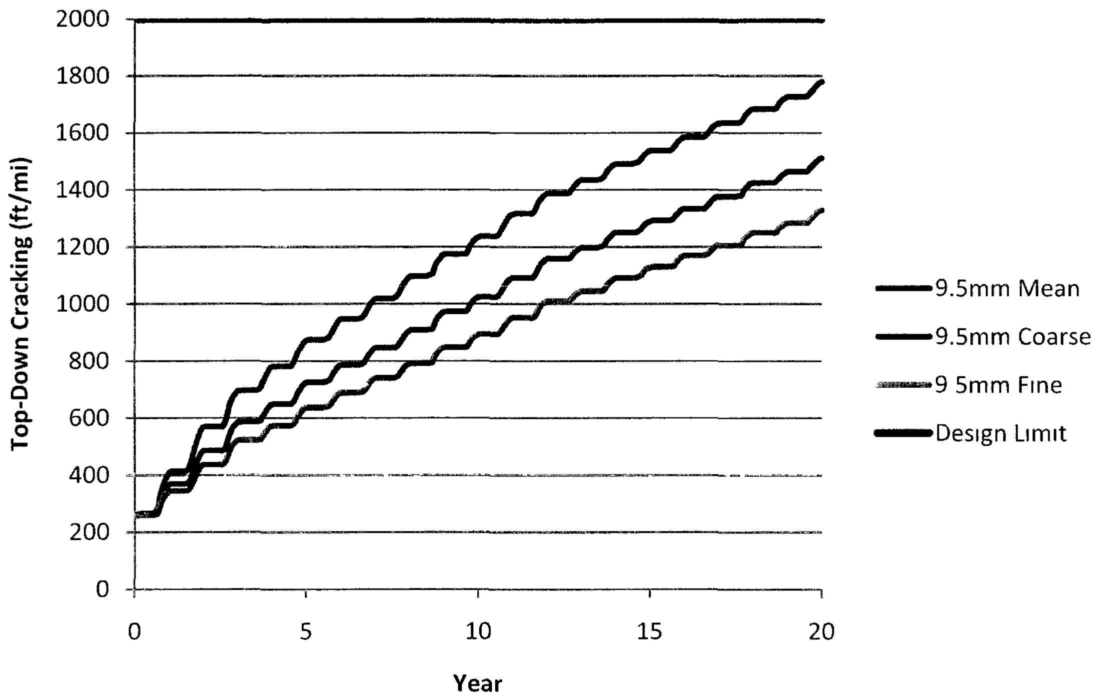


Figure 56A: Effect of Aggregate Gradation of 9.5 mm AC mix on Top-Down Cracking

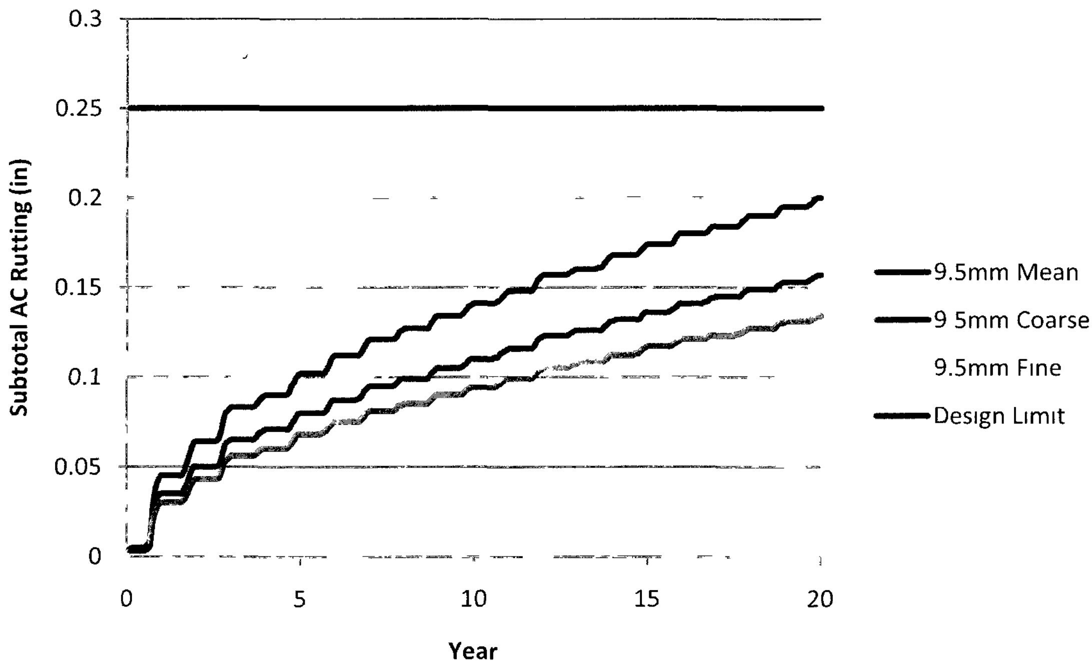


Figure 57A: Effect of Aggregate Gradation of 9.5 mm AC mix on Subtotal AC Rutting

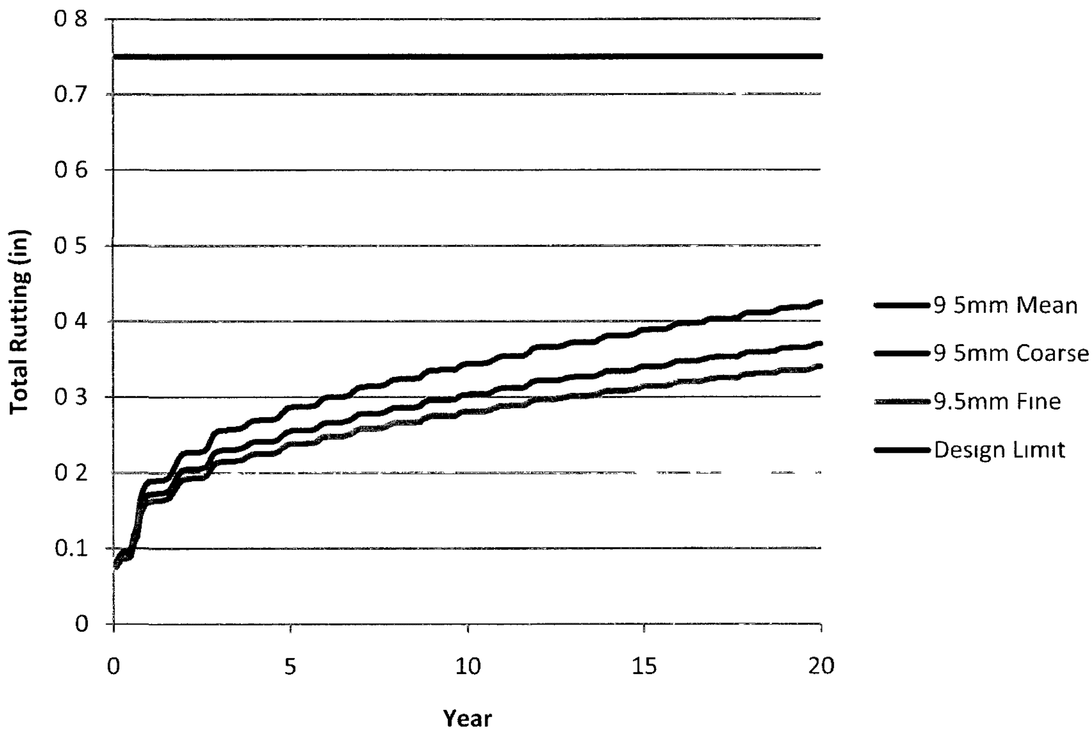


Figure 58A: Effect of Aggregate Gradation of 9.5 mm AC mix on Total Rutting

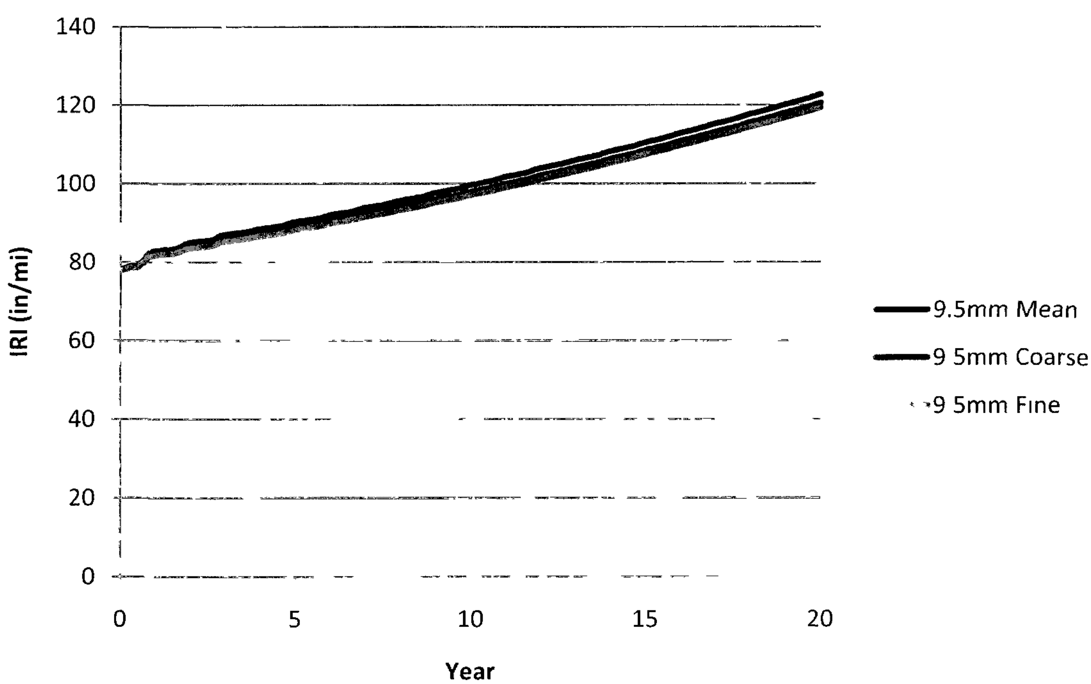


Figure 59A: Effect of Aggregate Gradation of 9.5 mm AC mix on IRI

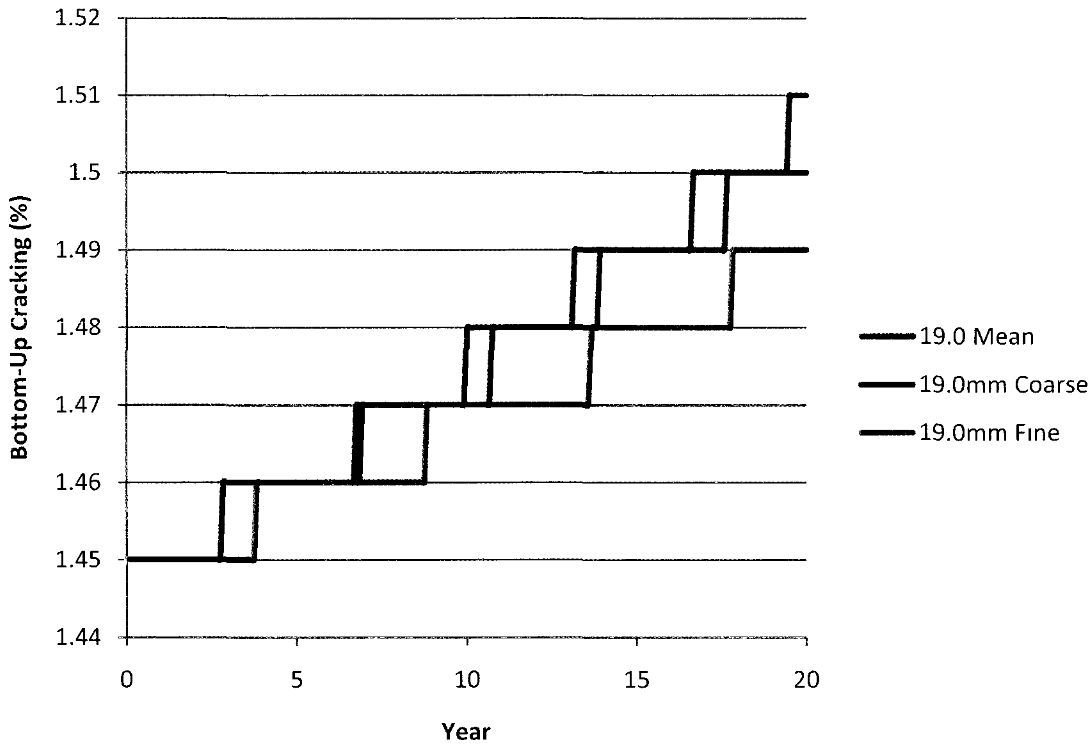


Figure 60A: Effect of Aggregate Gradation of 19.0 mm mix on Bottom-Up Cracking

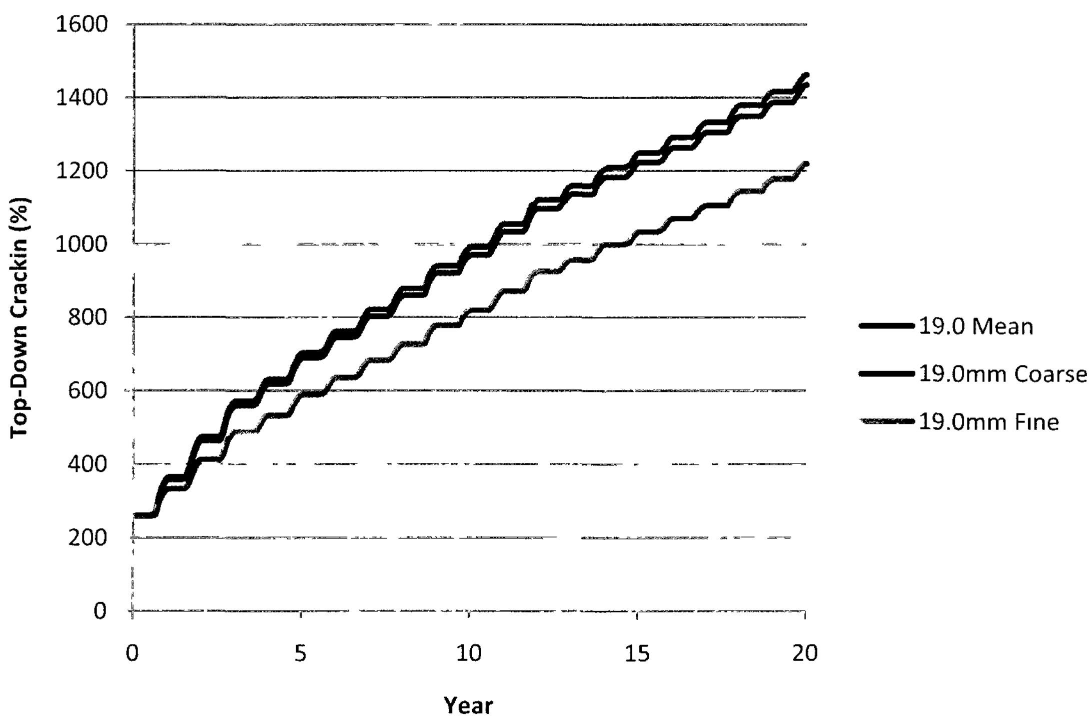


Figure 61A: Effect of Aggregate Gradation of 19.0 mm mix on Top-Down Cracking

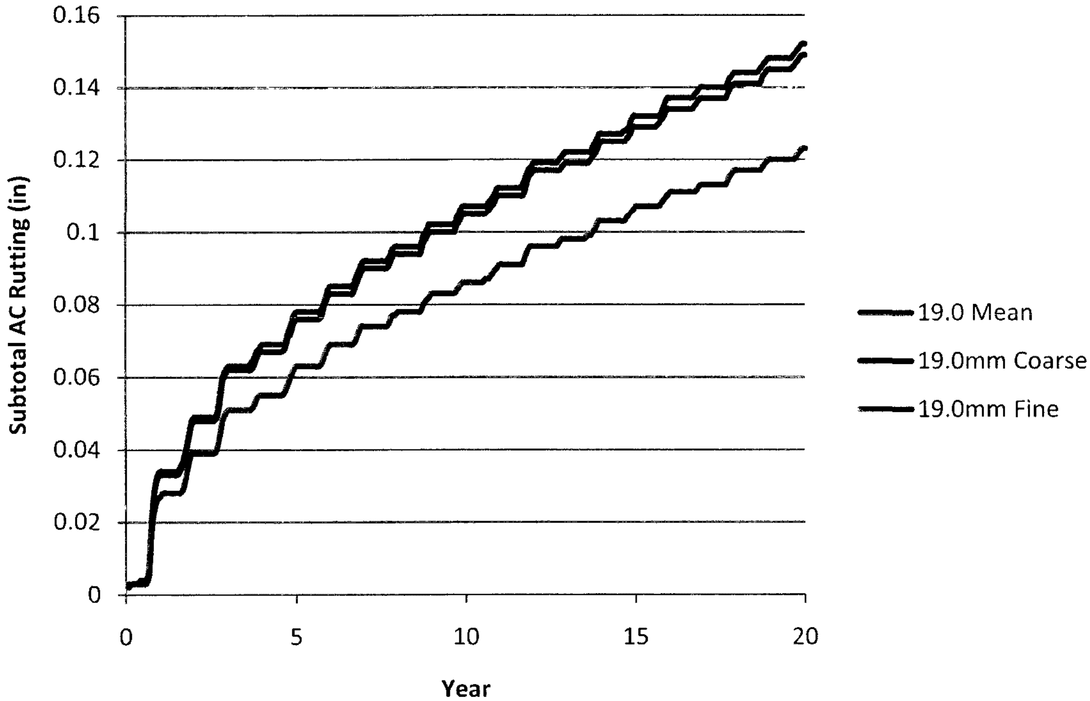


Figure 62A: Effect of Aggregate Gradation of 19.0 mm mix on Subtotal AC Rutting

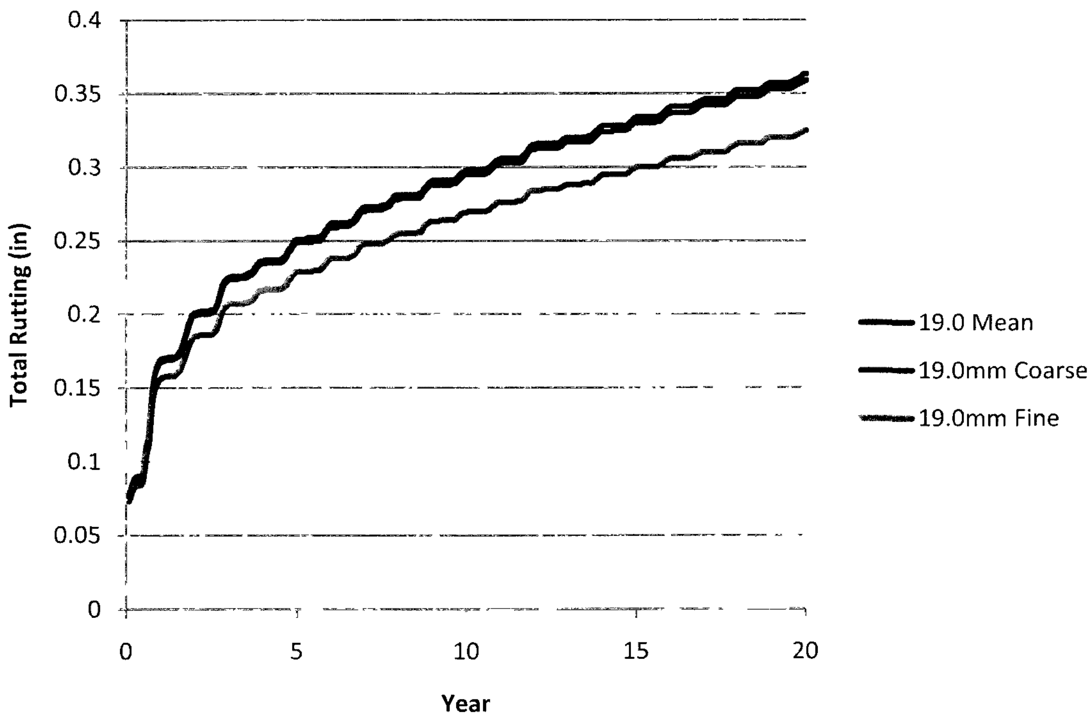


Figure 63A: Effect of Aggregate Gradation of 19.0 mm mix on Total Rutting

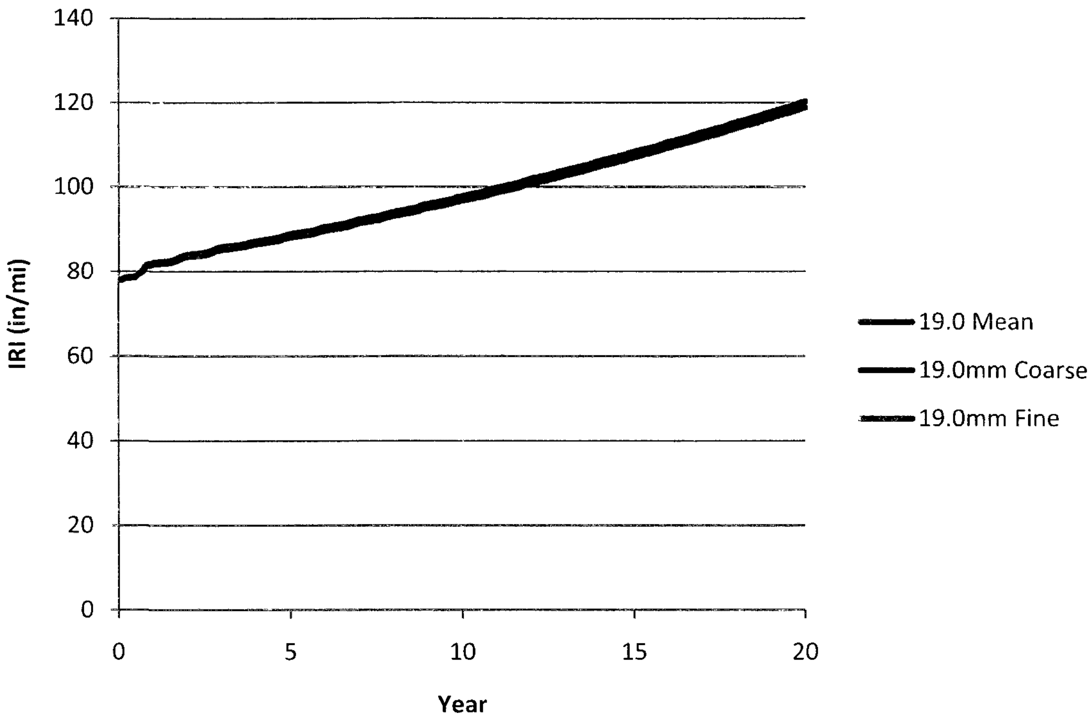


Figure 64A: Effect of Aggregate Gradation of 19.0 mm mix on IRI

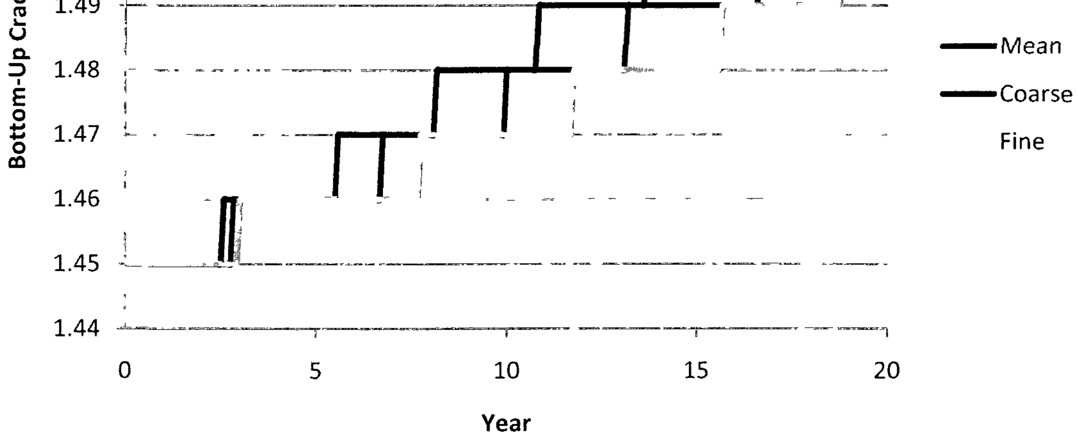


Figure 65A: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Bottom-Up Cracking

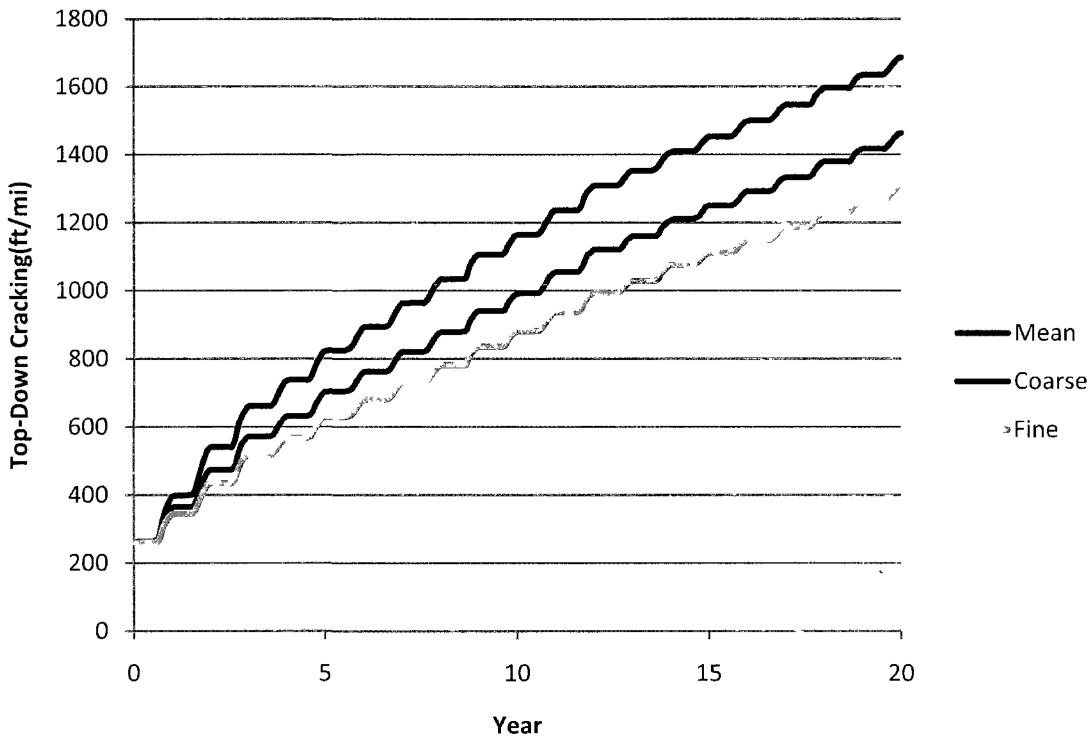


Figure 66A: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Top-Down Cracking

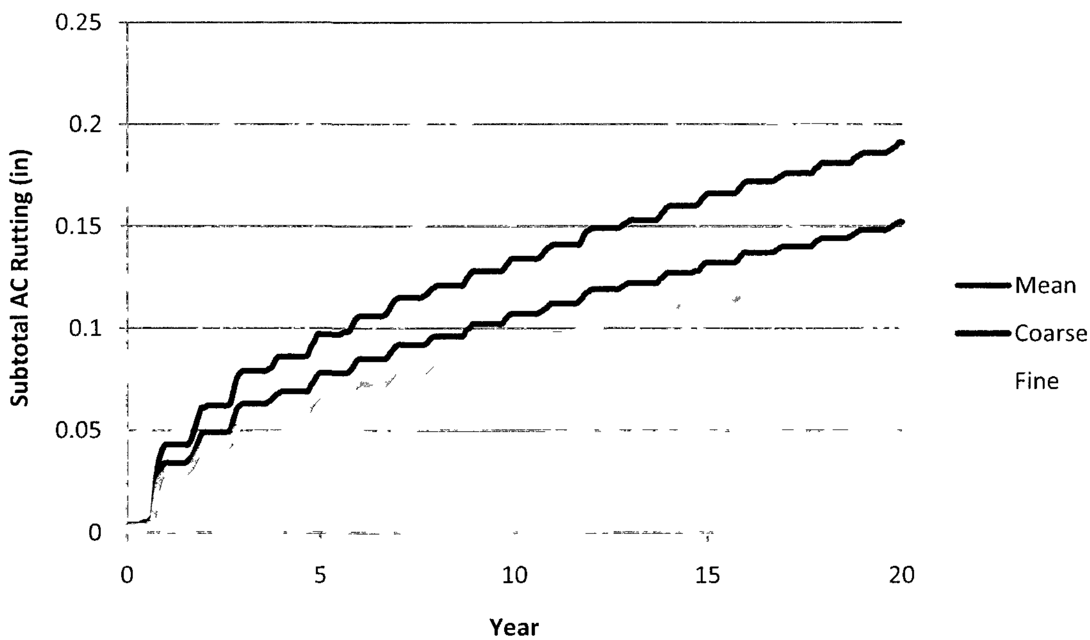


Figure 67A: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Subtotal AC Rutting

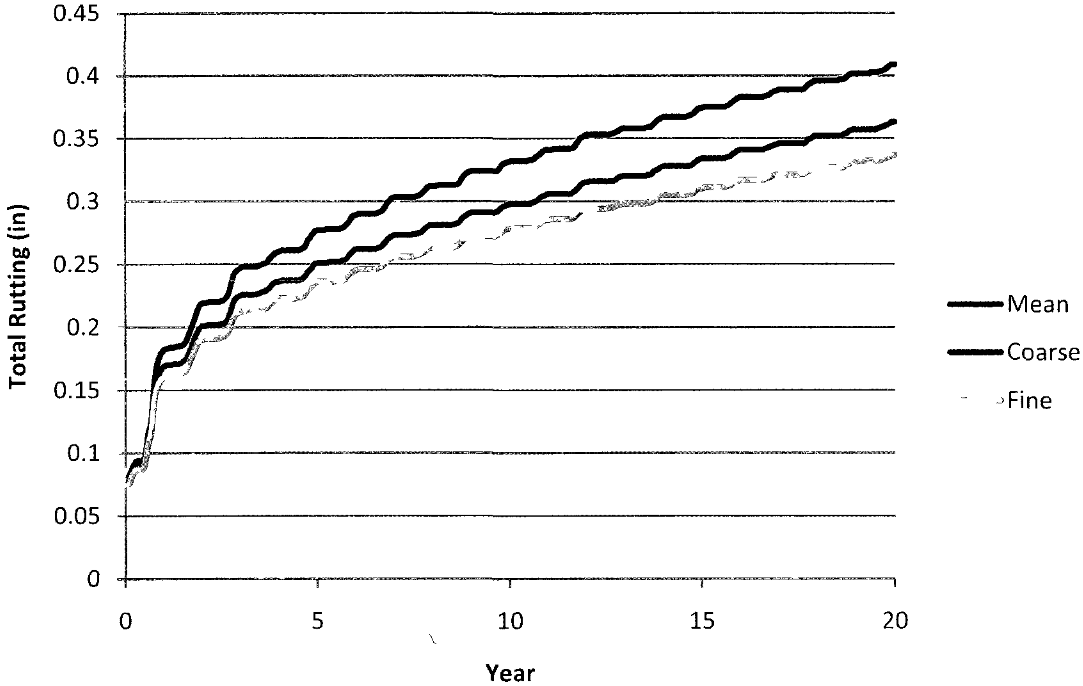


Figure 68A: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Total Rutting

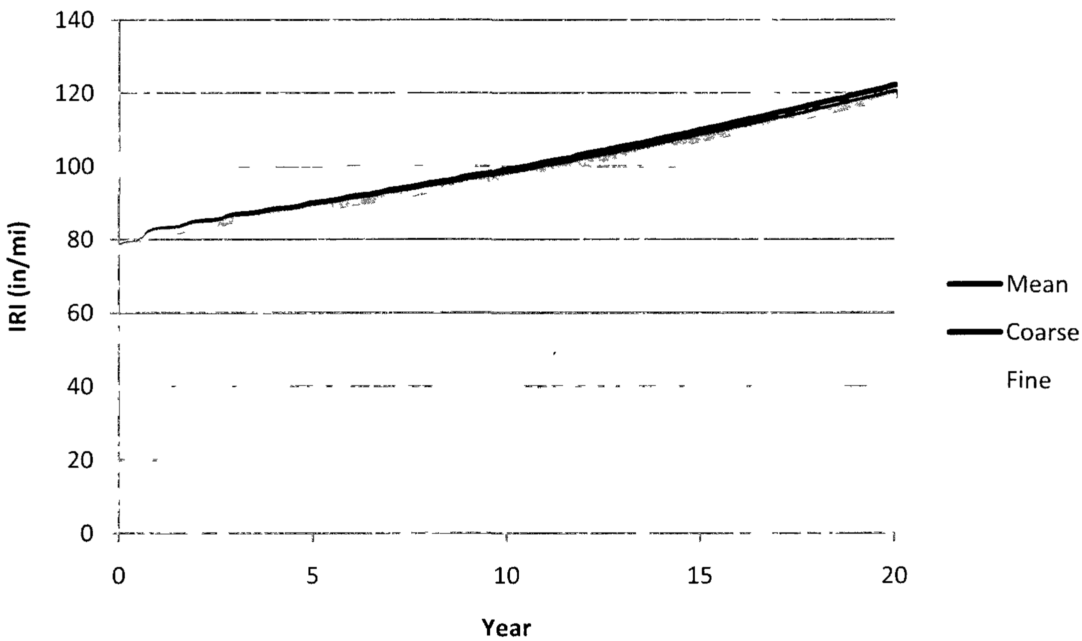


Figure 69A: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on IRI

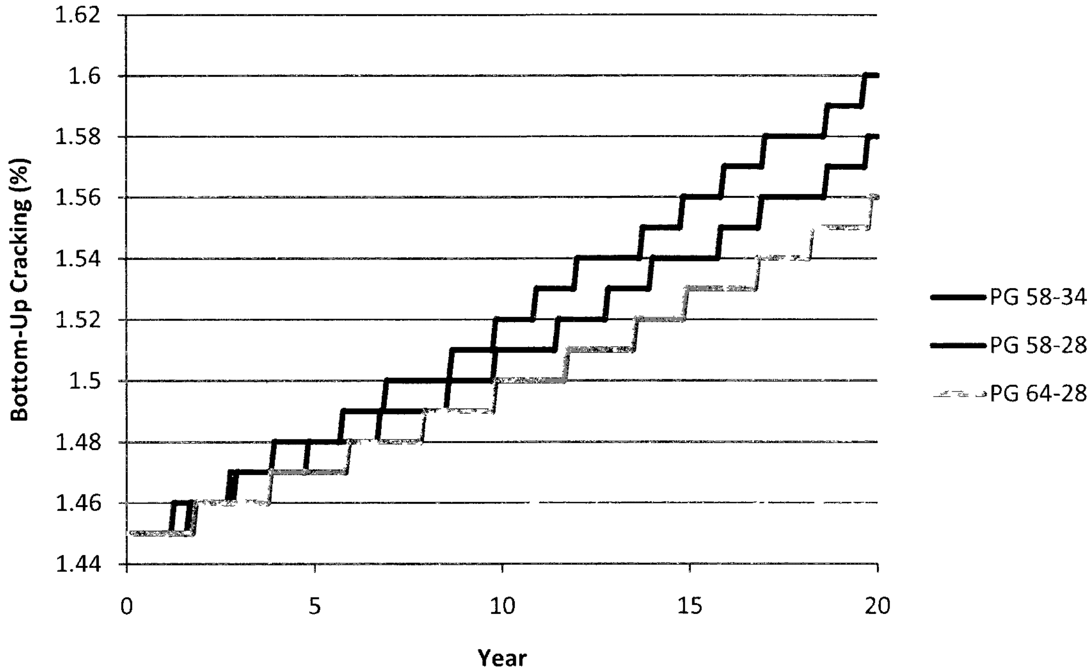


Figure 70A: Effect of Binder Grade on Bottom-Up Cracking at Speed 5 mph

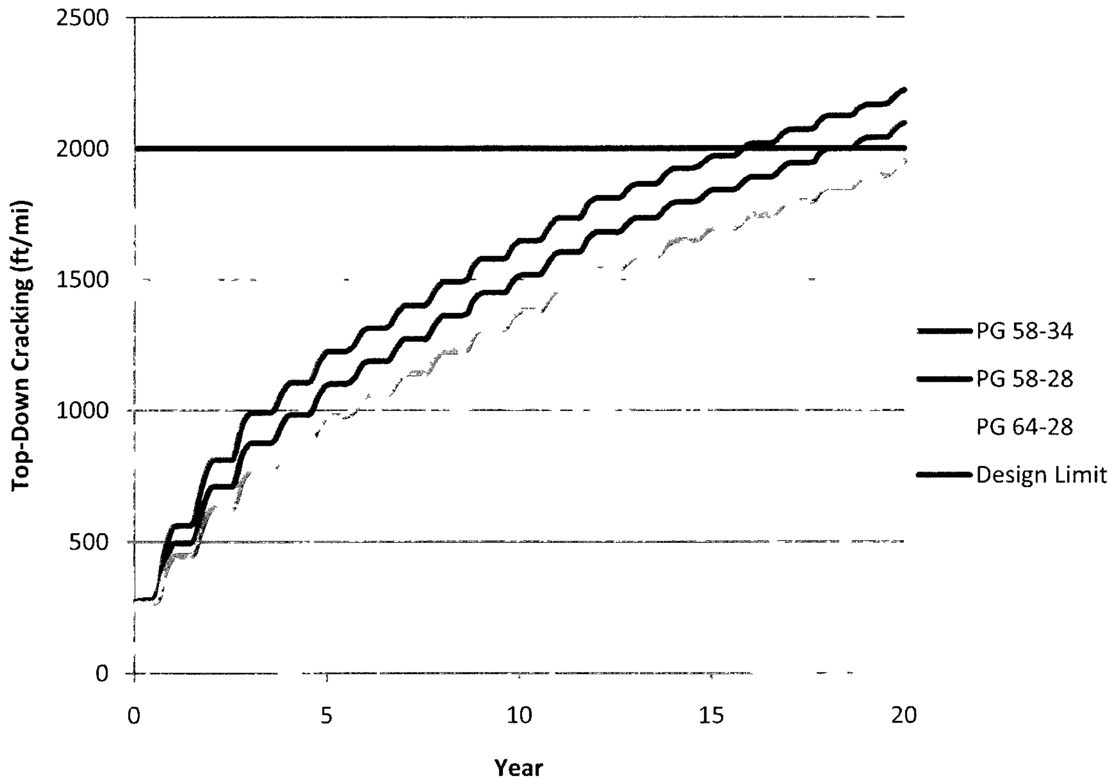


Figure 71A: Effect of Binder Grade on Top-Down Cracking at Speed 5 mph

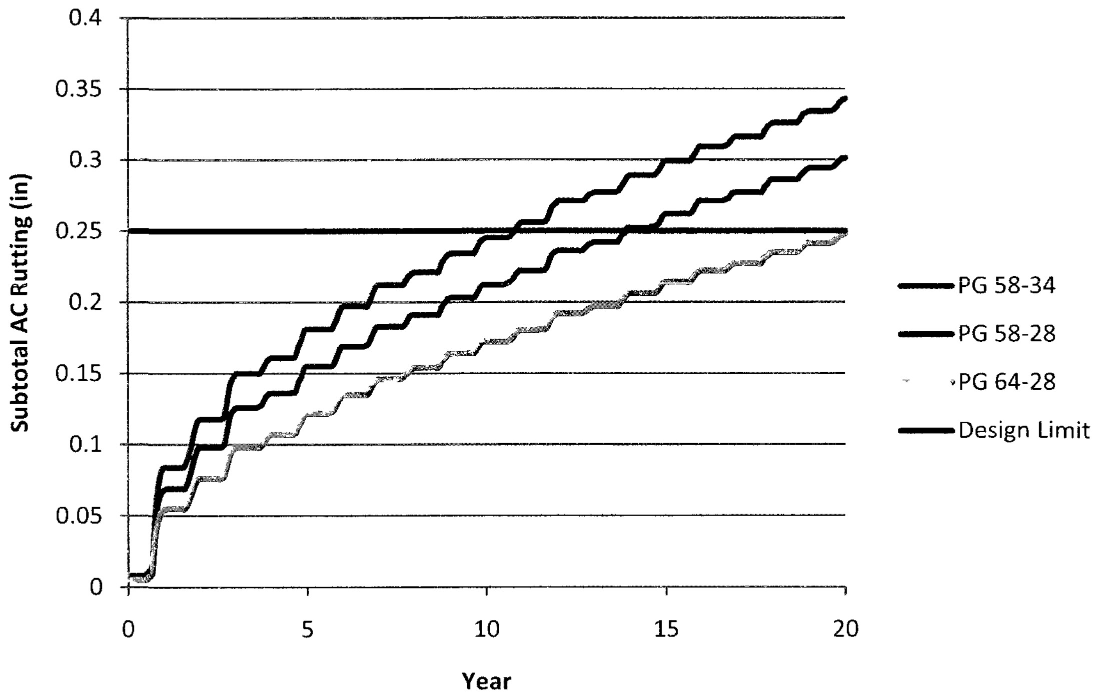


Figure 72A: Effect of Binder Grade on Subtotal AC Rutting at Speed 5 mph

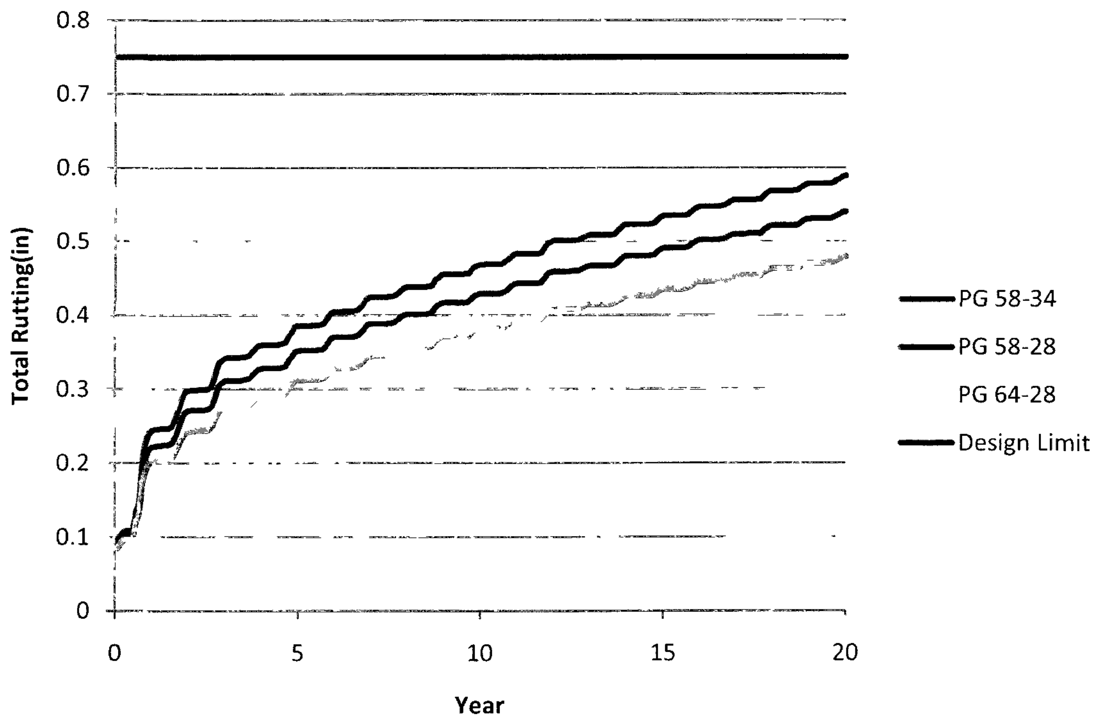


Figure 73A: Effect of Binder Grade on Total Rutting at Speed 5 mph

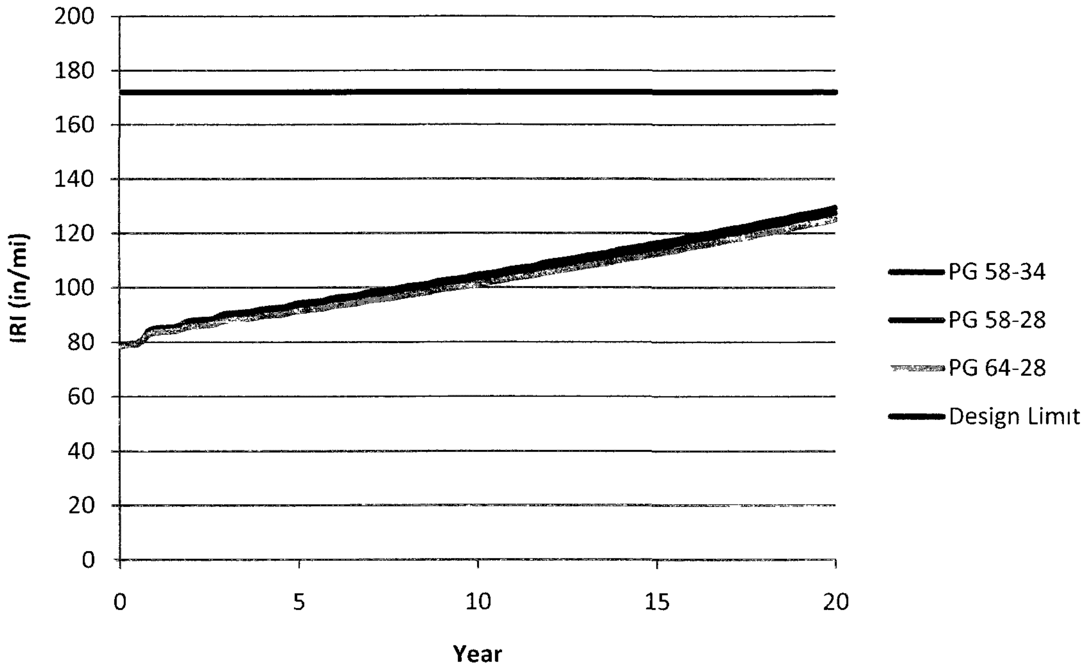


Figure 74A: Effect of Binder Grade on IRI at Speed 5 mph

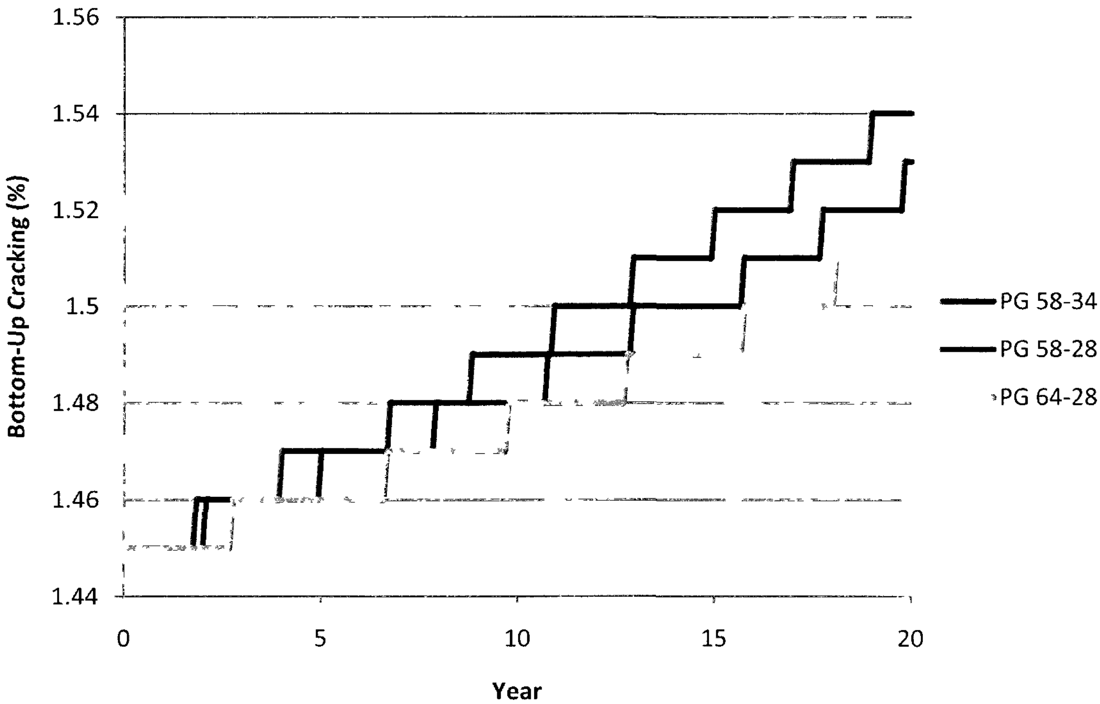


Figure 75A: Effect of Binder Grade on Bottom-Up Cracking at Speed 25 mph

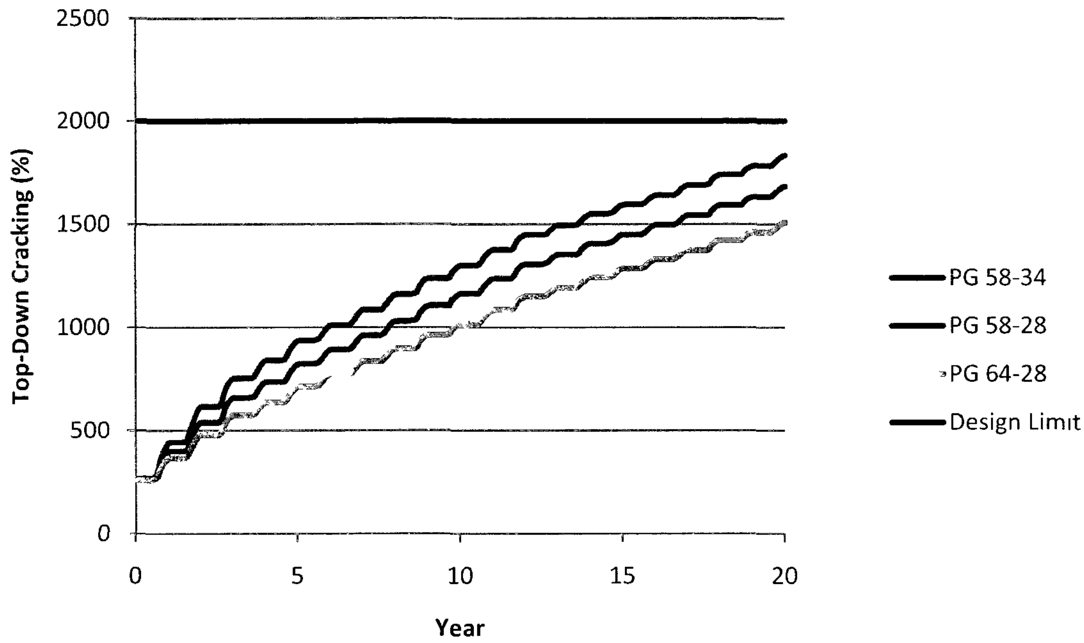


Figure 76A: Effect of Binder Grade on Top-Down Cracking at Speed 25 mph

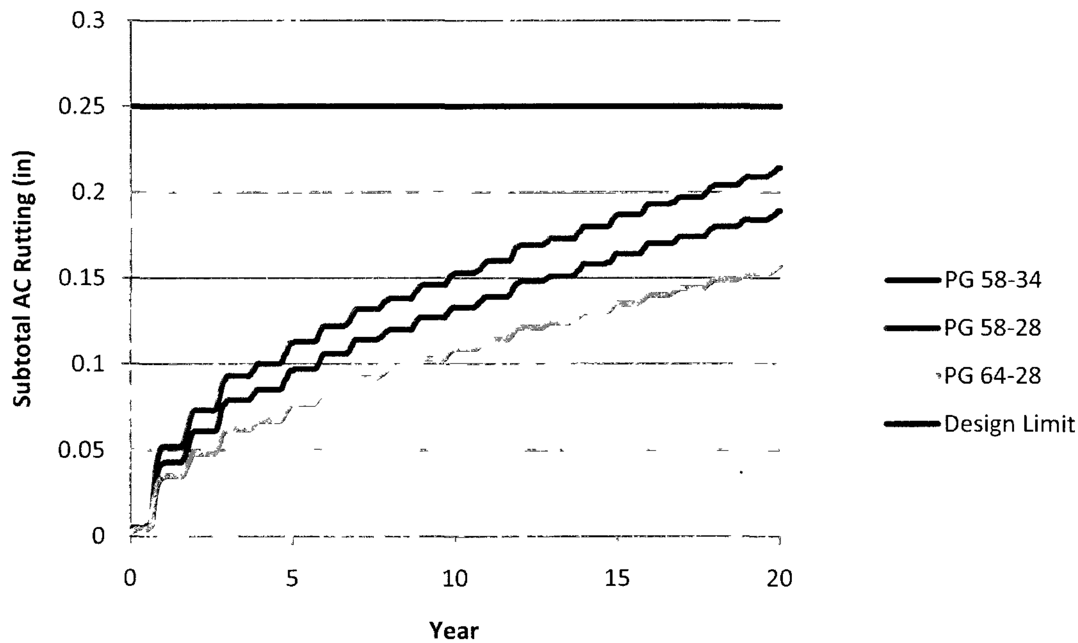


Figure 77A: Effect of Binder Grade on Subtotal AC Rutting at Speed 25 mph

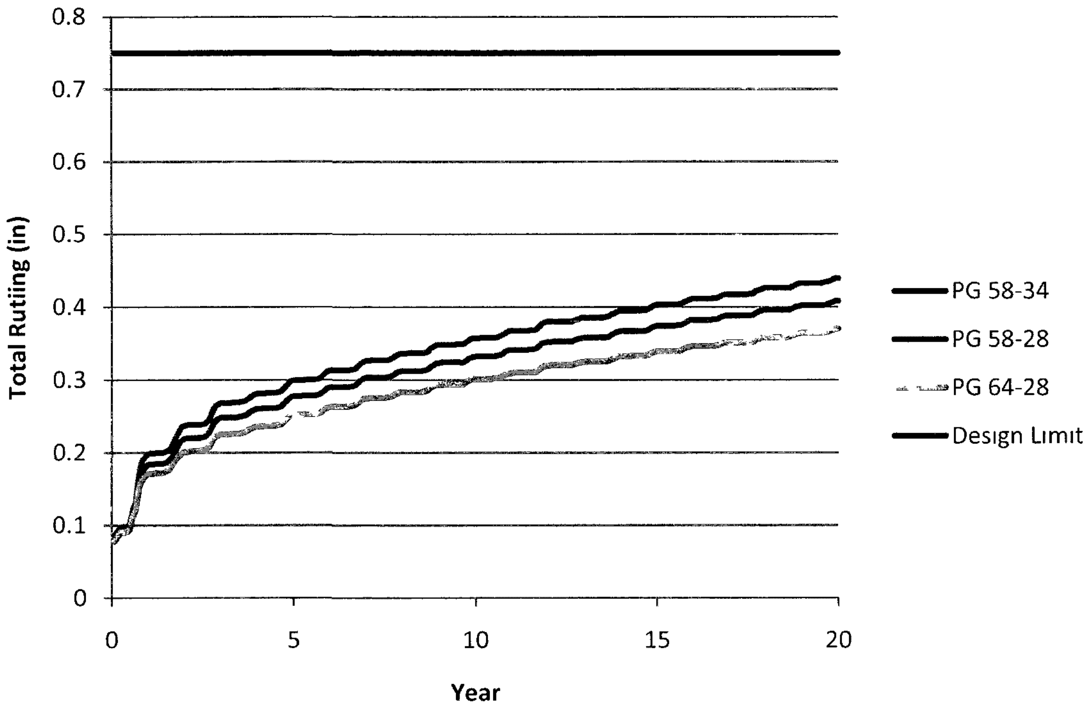


Figure 78A: Effect of Binder Grade on Total Rutting at Speed 25 mph

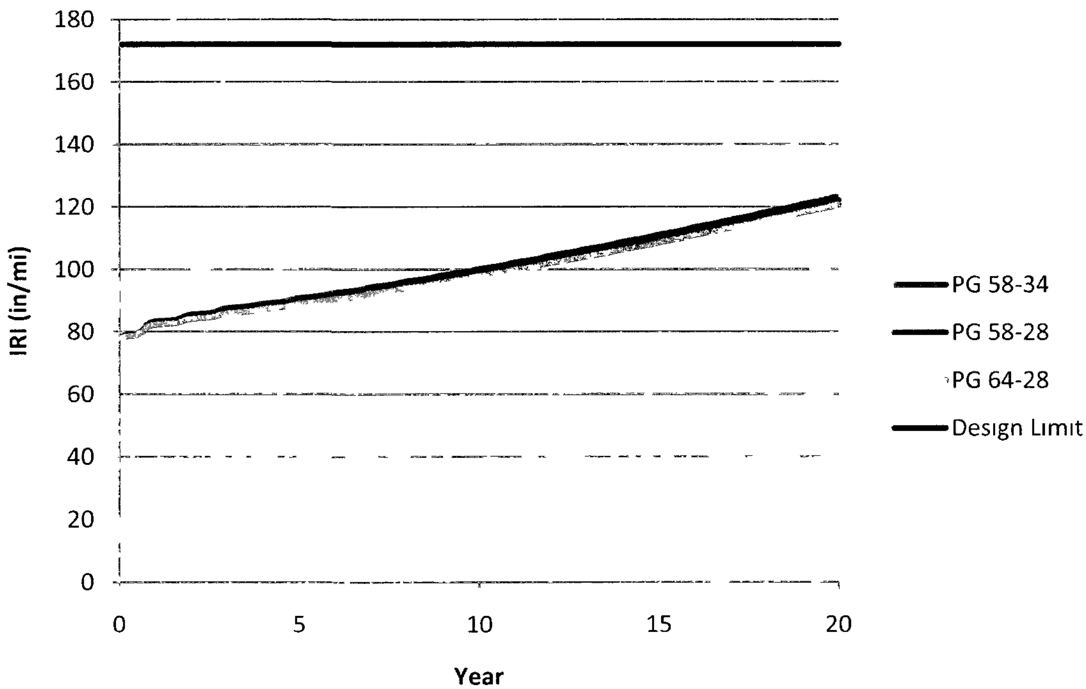


Figure 79A: Effect of Binder Grade on IRI at Speed 25 mph

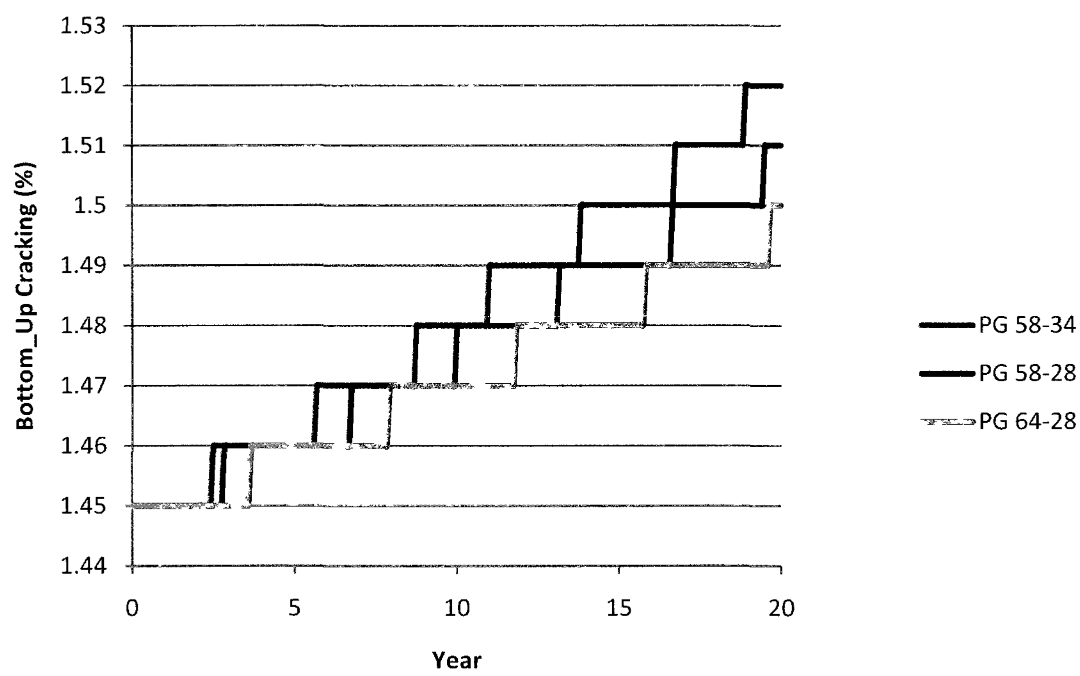


Figure 80A: Effect of Binder Grade on Bottom-Up Cracking at Speed 55 mph

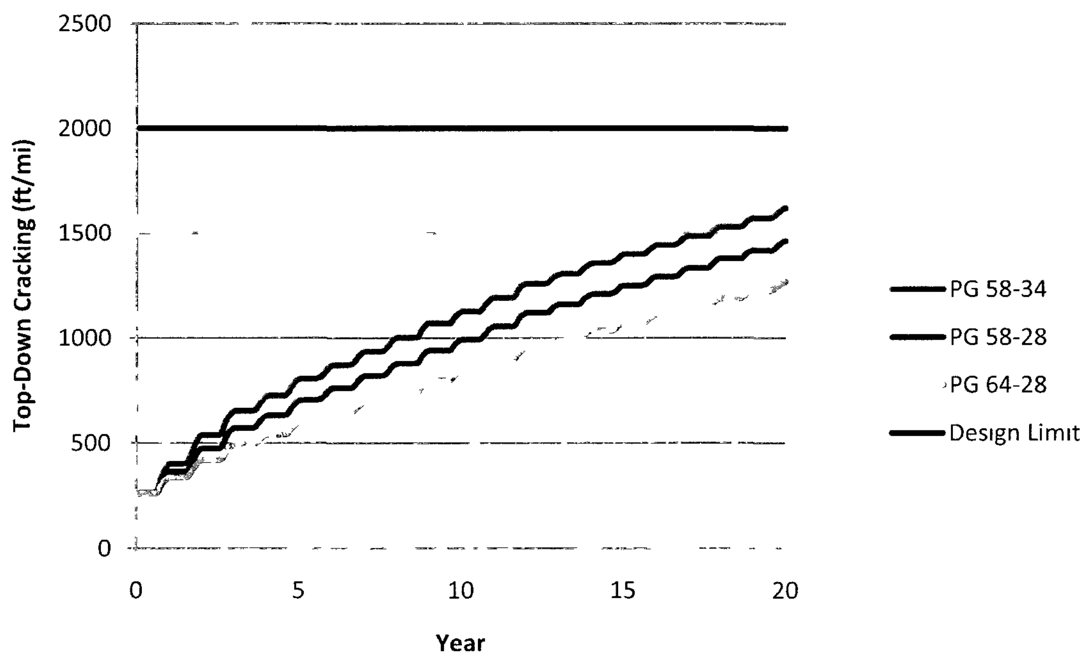


Figure 81A: Effect of Binder Grade on Top-Down Cracking at Speed 55 mph

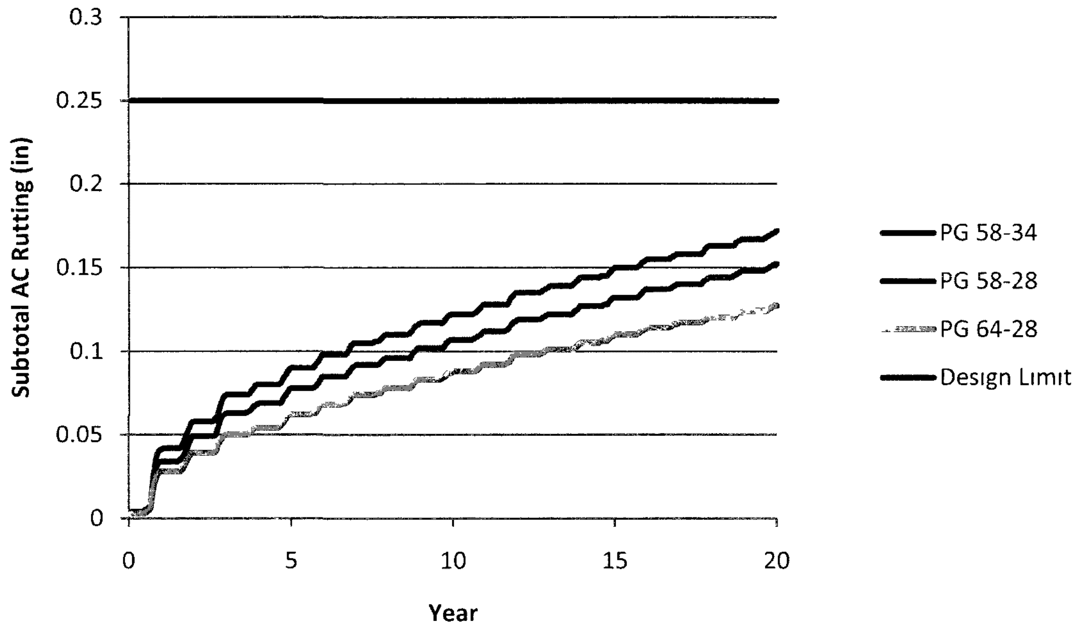


Figure 82A: Effect of Binder Grade on Subtotal AC Rutting at Speed 55 mph

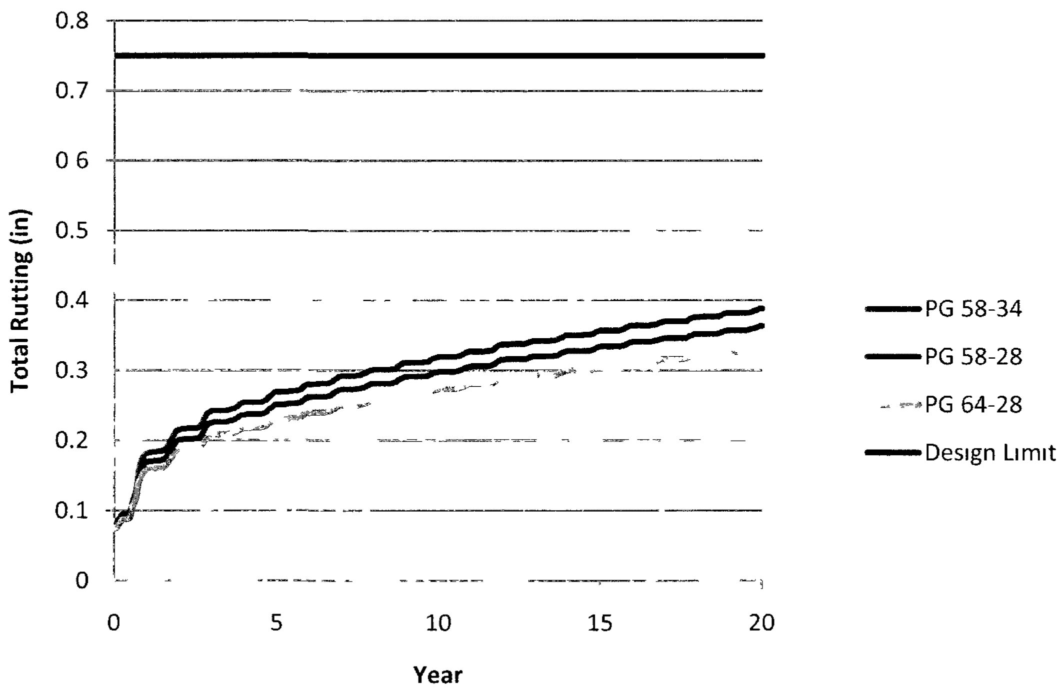


Figure 83A: Effect of Binder Grade on Total Rutting at Speed 55 mph

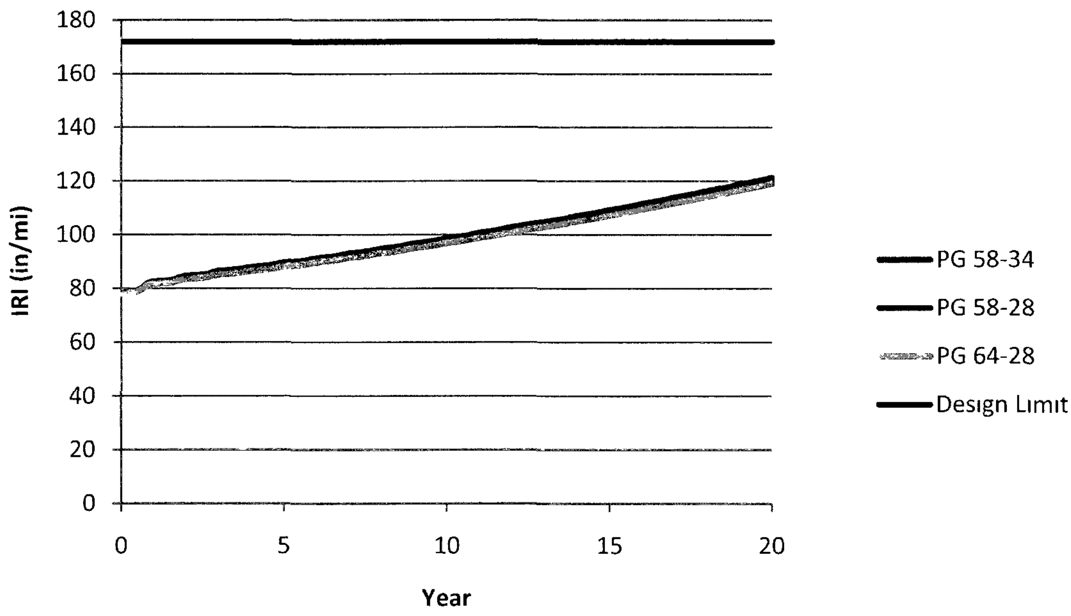


Figure 84A: Effect of Binder Grade on IRI at Speed 55 mph

7.5 Effect of Base/Subbase Inputs on Pavement Distresses

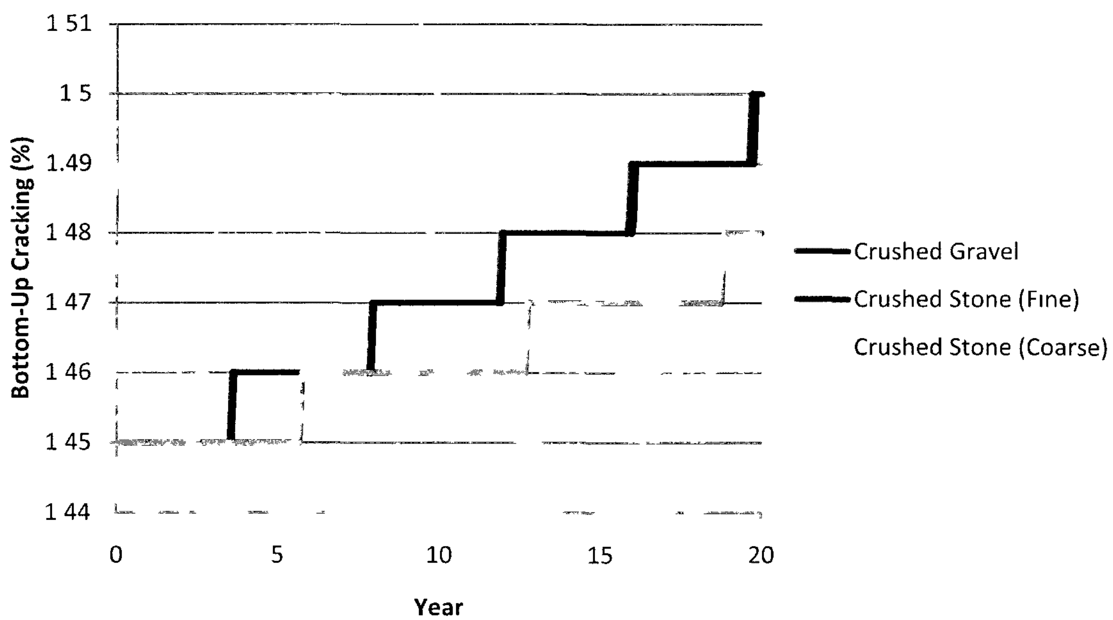


Figure 85A: Effect of Base Course Material on Bottom-Up Cracking

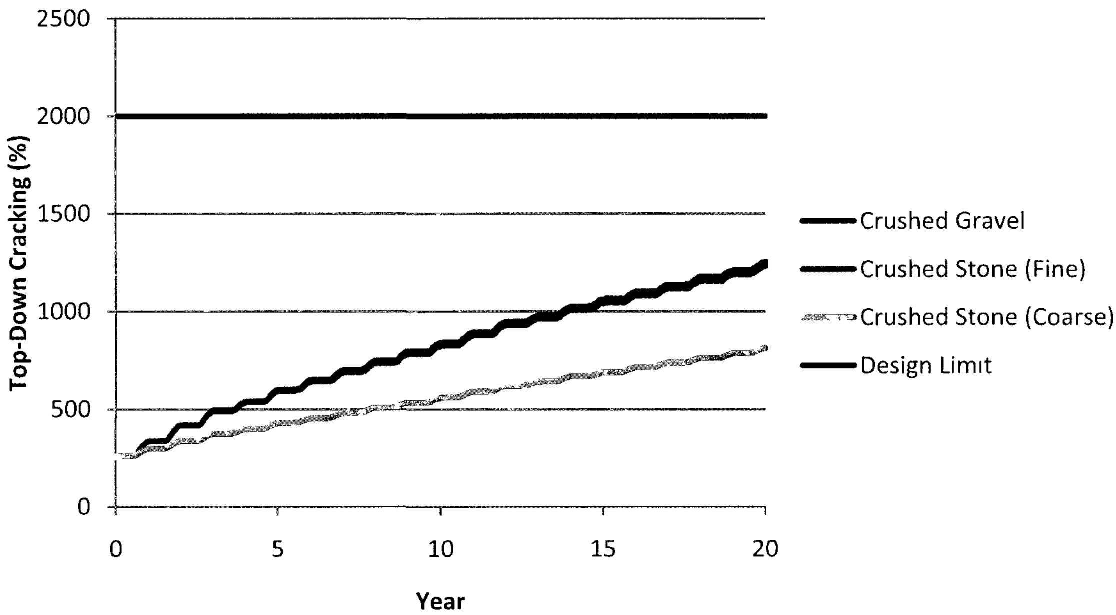


Figure 86A: Effect of Base Course Material on Top-Down Cracking

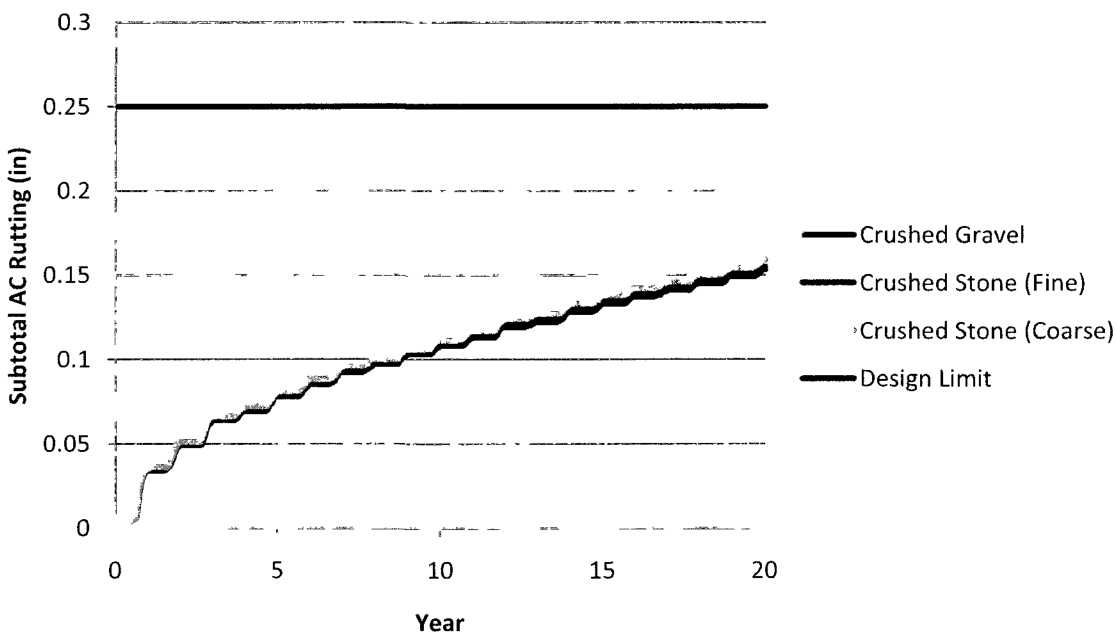


Figure 87A: Effect of Base Course Material on Subtotal AC Rutting

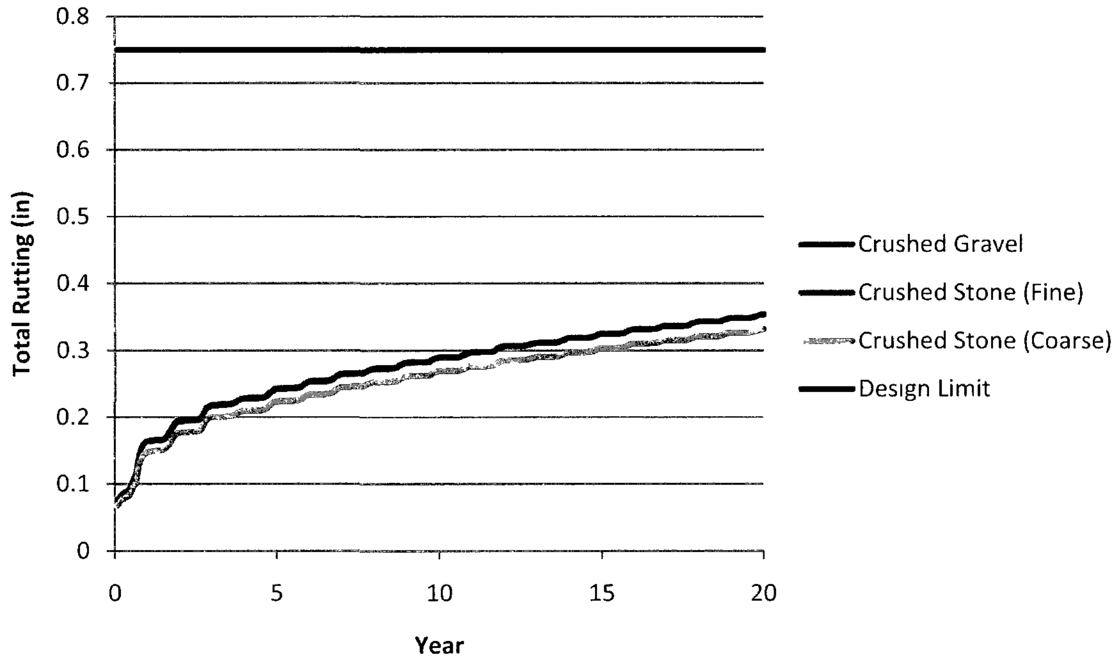


Figure 88A: Effect of Base Course Material on Total Rutting

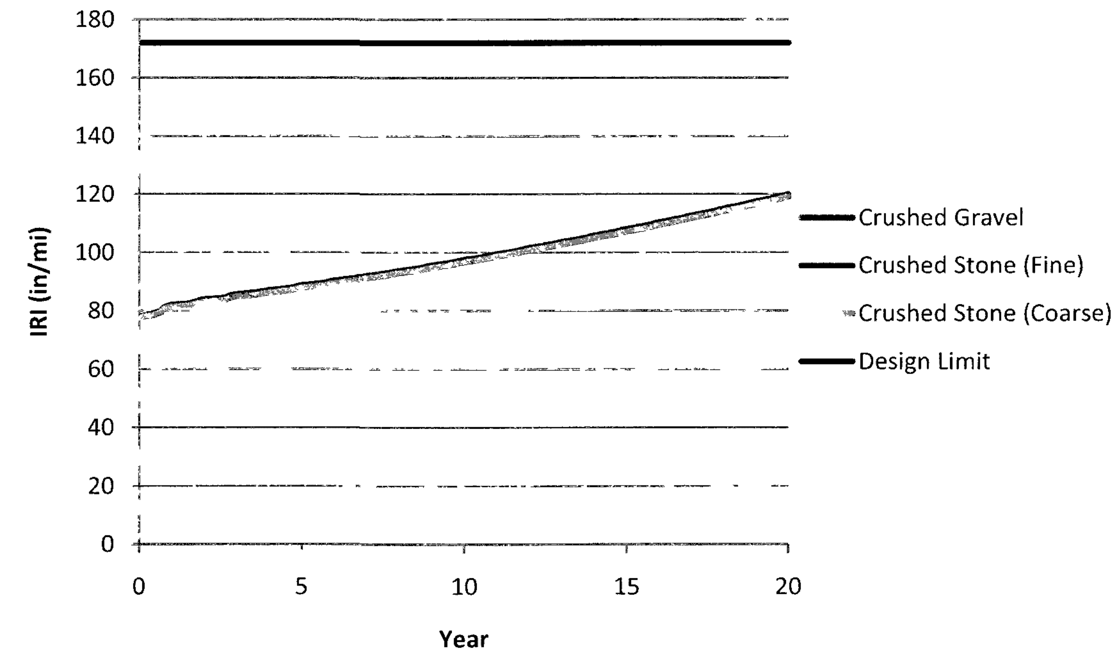


Figure 89A: Effect of Base Course Material on IRI

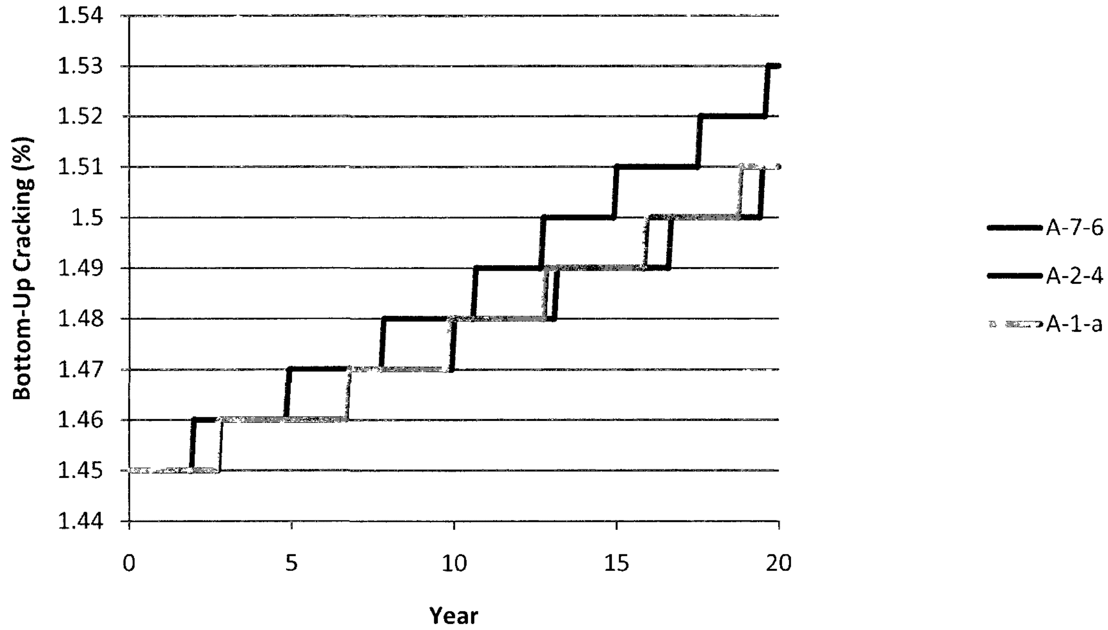


Figure 90A: Effect of Subgrade Type on Bottom-Up Cracking

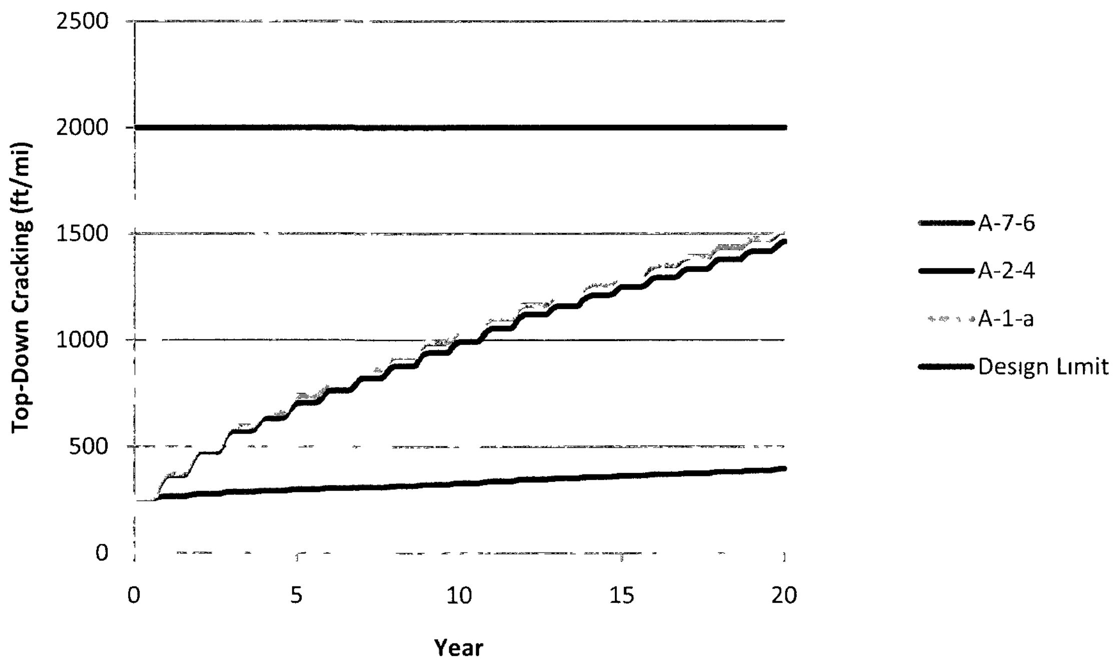


Figure 91A: Effect of Subgrade Type on Top-Down Cracking

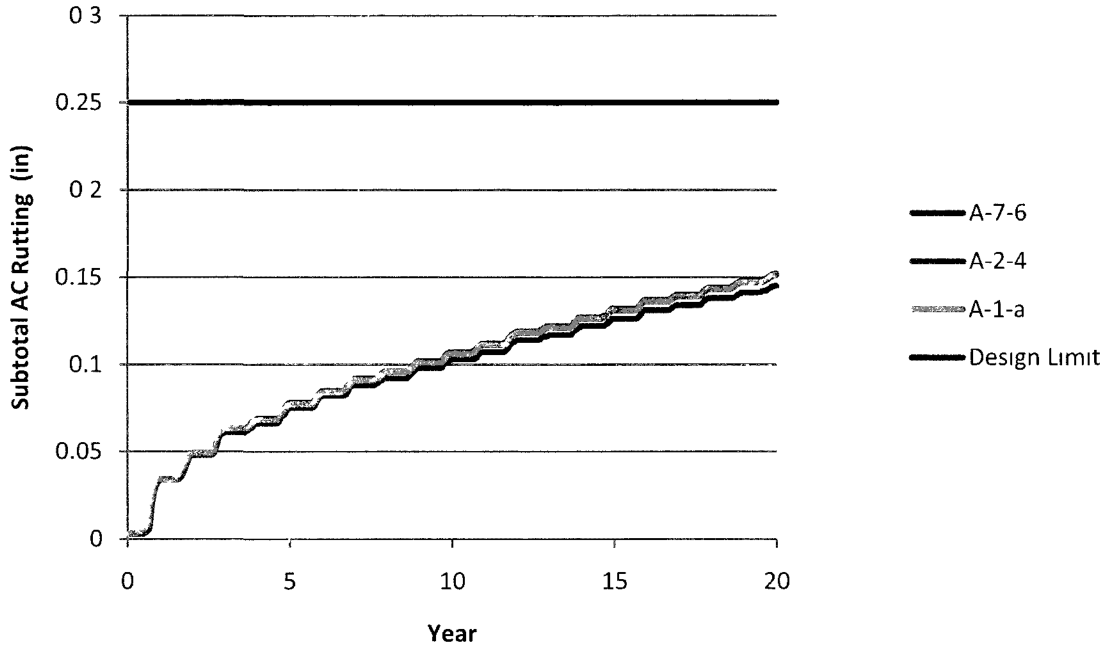


Figure 92A: Effect of Subgrade Type on Subtotal AC Rutting

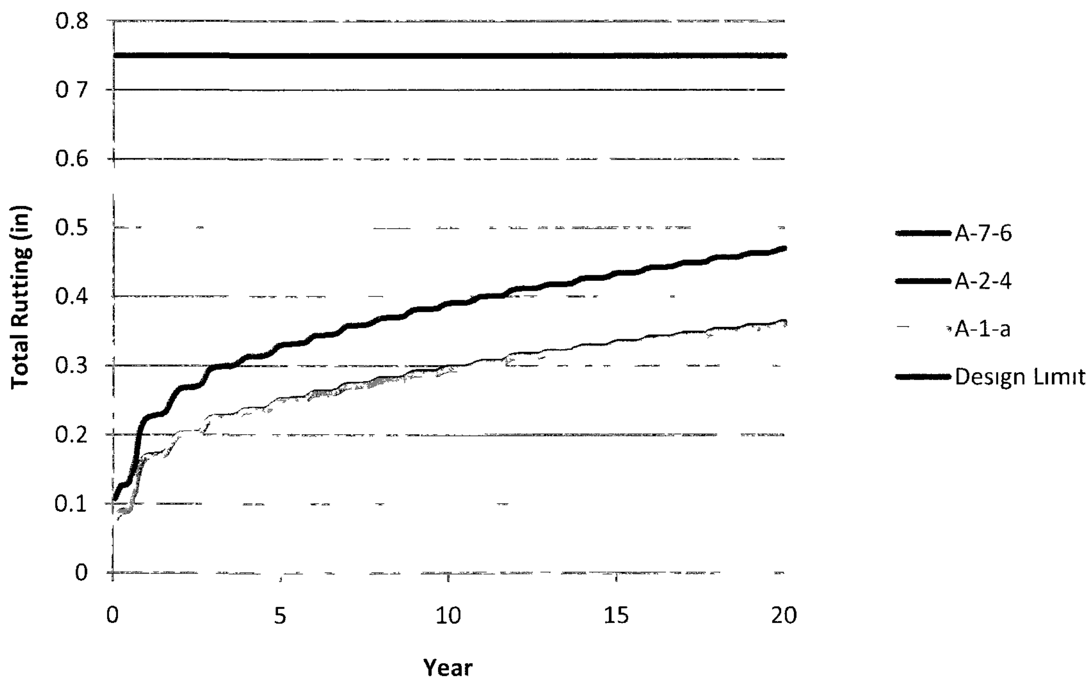


Figure 93A: Effect of Subgrade Type on Total Rutting

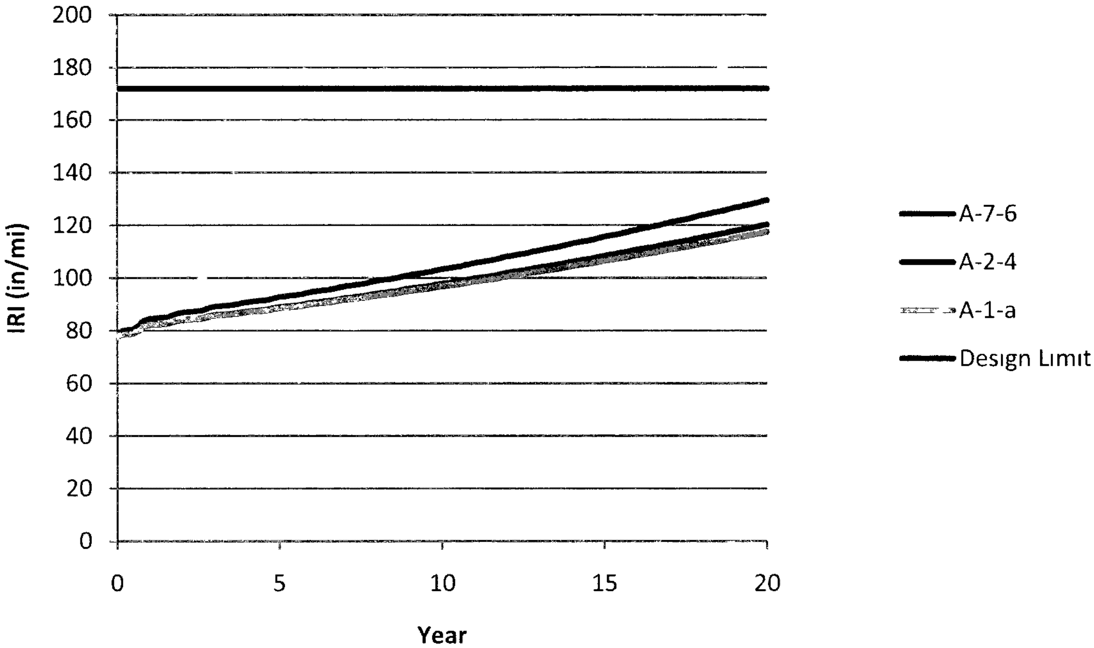


Figure 94A: Effect of Subgrade Type on IRI

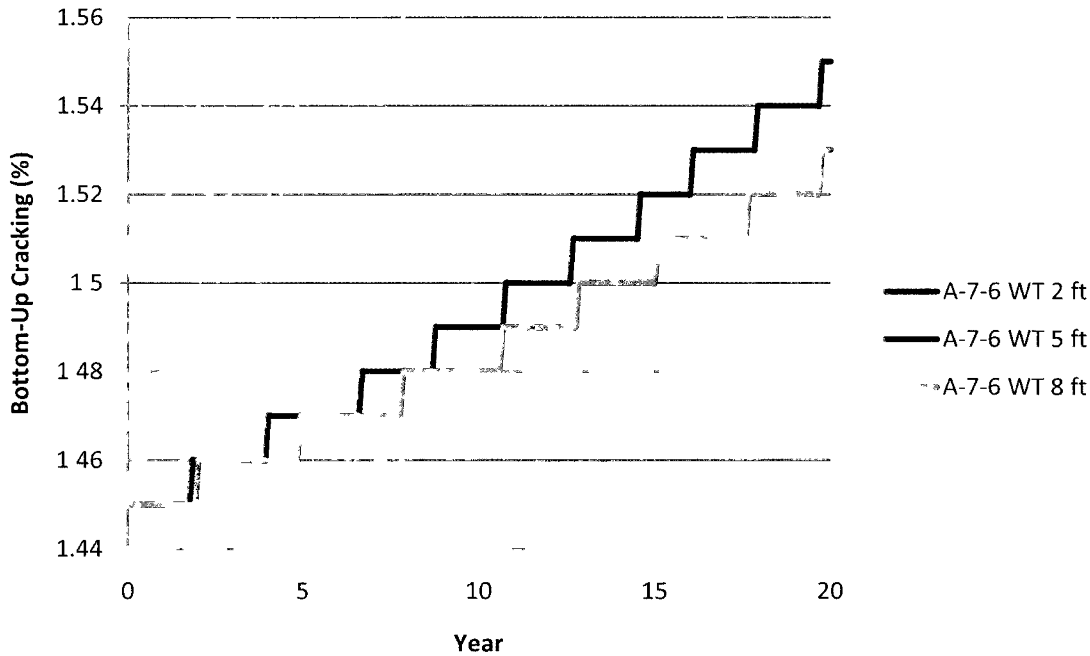


Figure 95A: Effect of Water Table on Bottom-Up Cracking with Weakest Subgrade

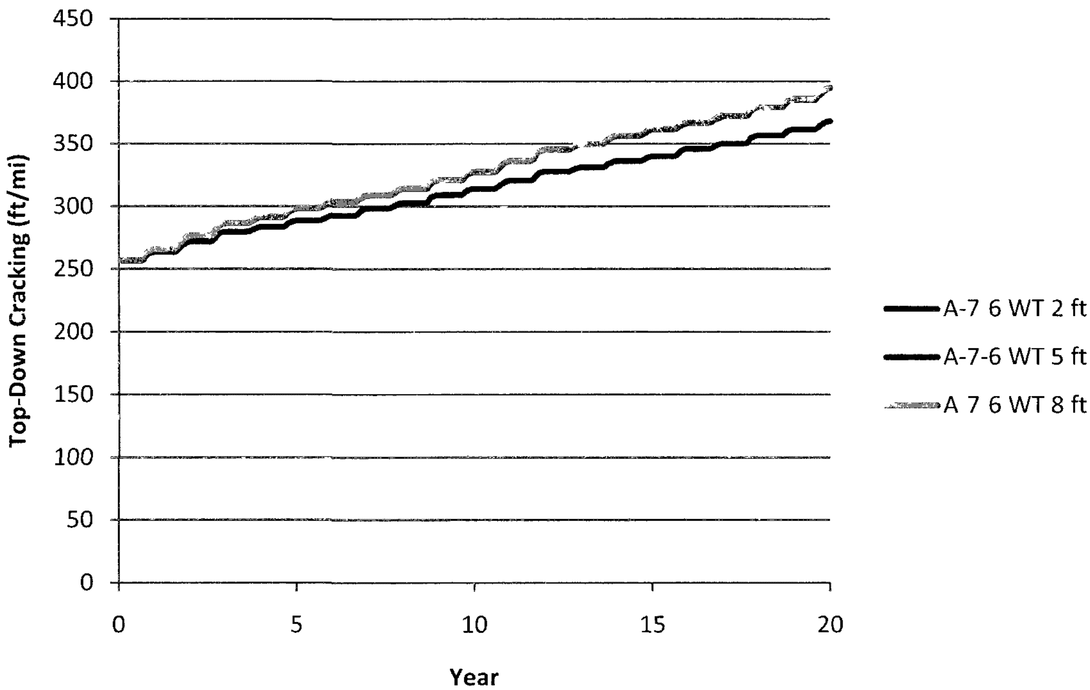


Figure 96A: Effect of Water Table on Top-Down Cracking with Weakest Subgrade

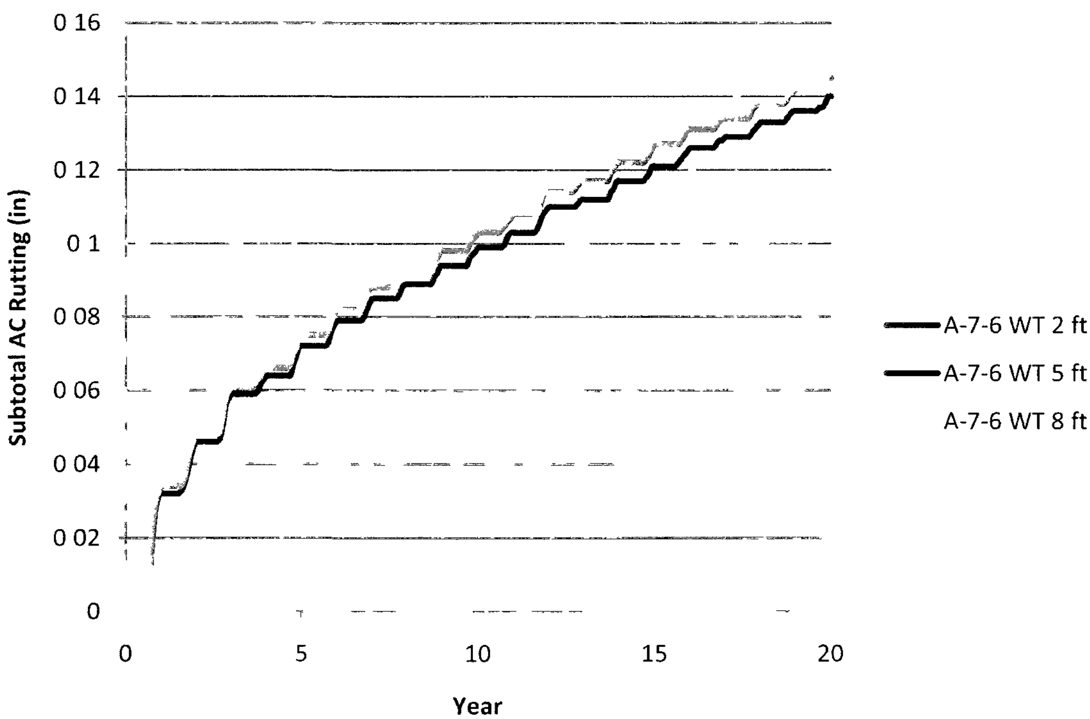


Figure 97A: Effect of Water Table on Subtotal AC Rutting with Weakest Subgrade

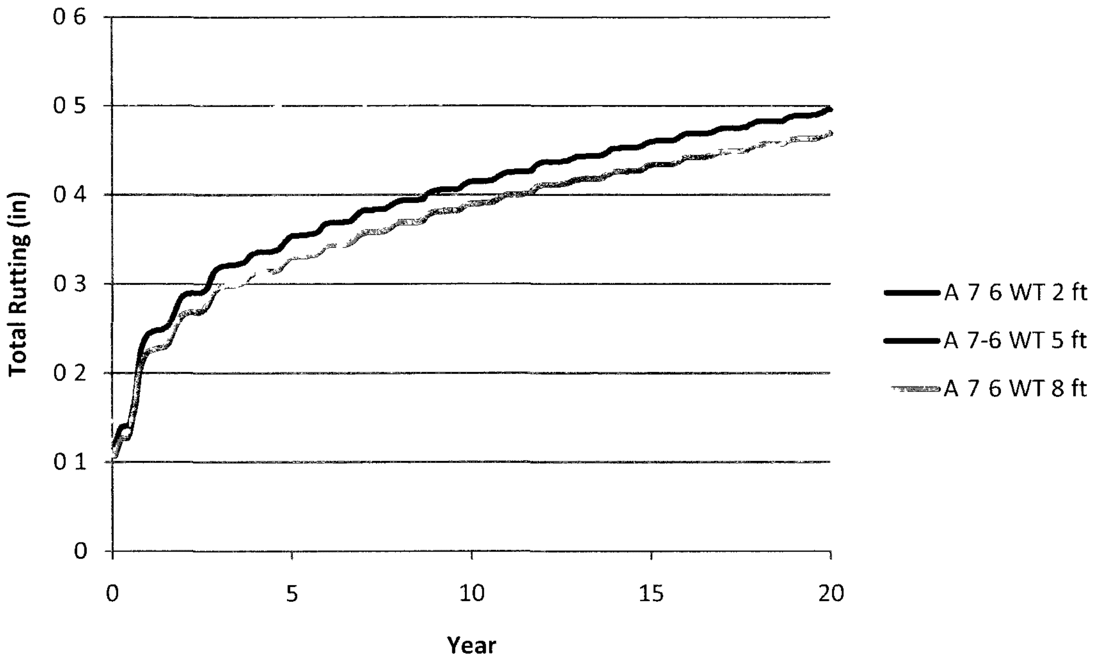


Figure 98A: Effect of Water Table on Total Rutting with Weakest Subgrade

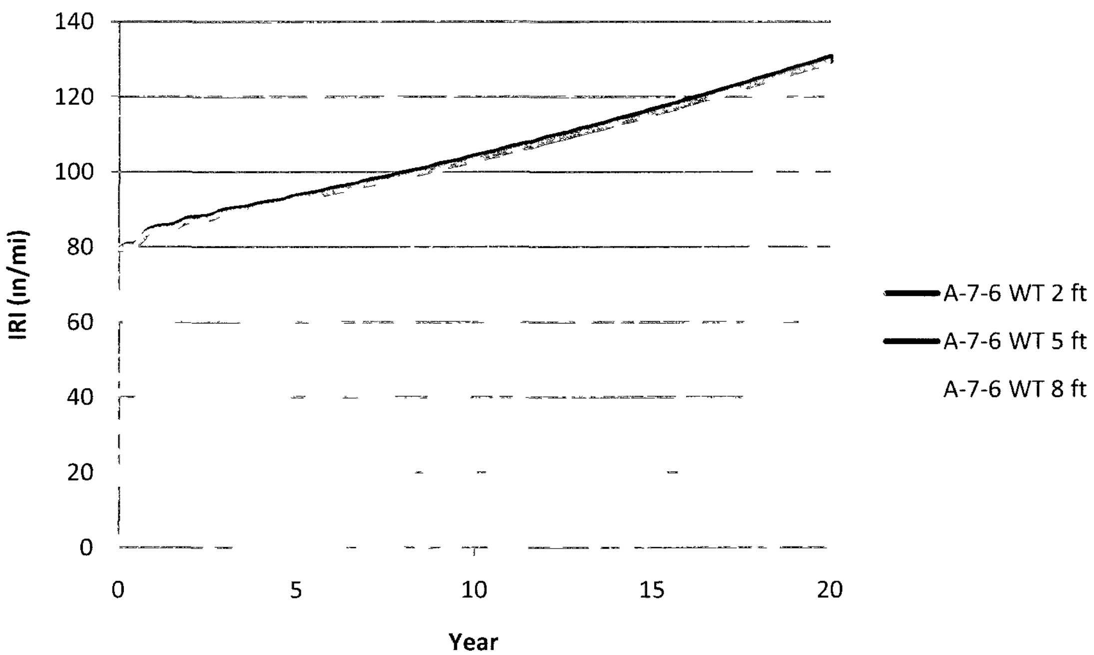


Figure 99A: Effect of Water Table on IRI with Weakest Subgrade

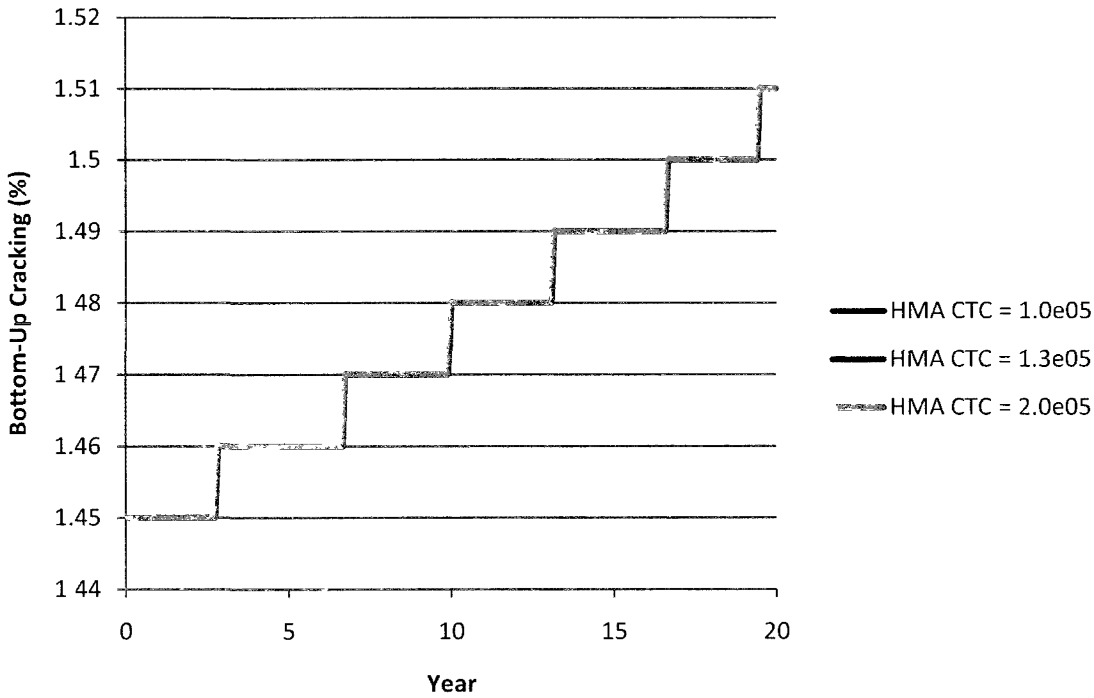


Figure 100A: Effect of HMA CTC on Bottom-Up Cracking

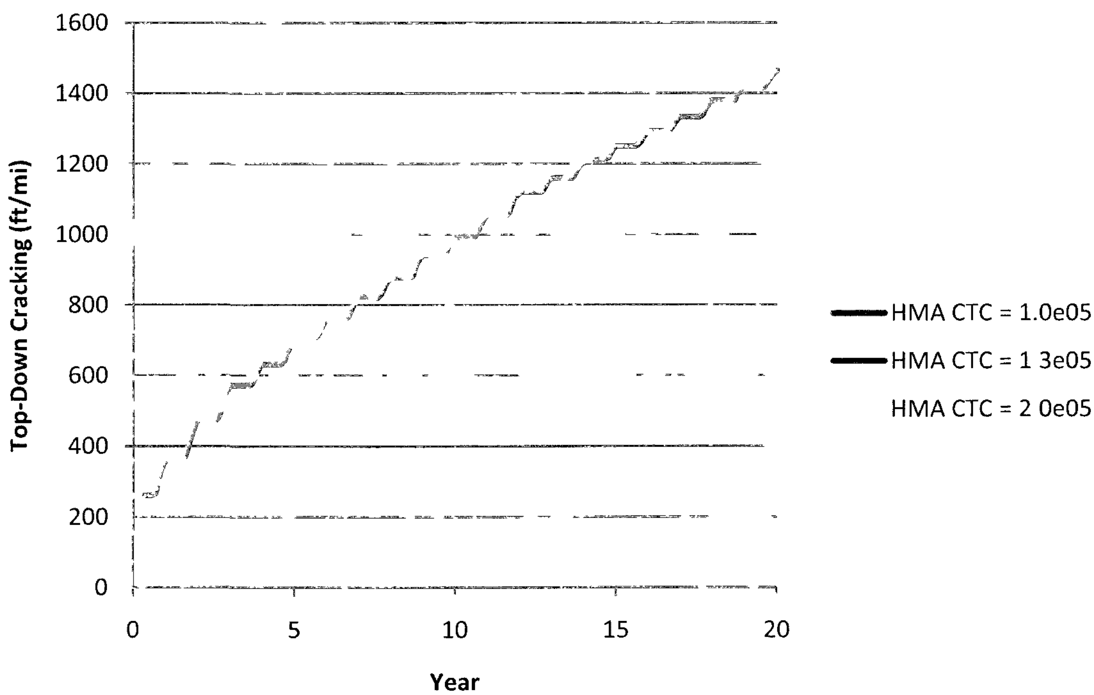


Figure 101A: Effect of HMA CTC on Top-Down Cracking

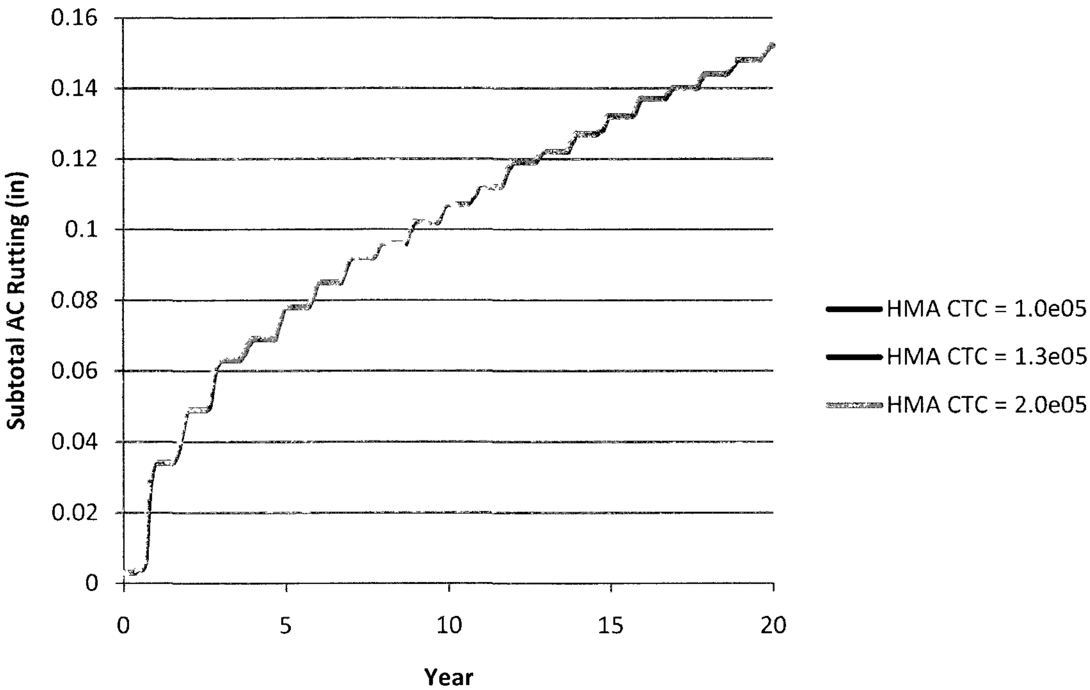


Figure 102A: Effect of HMA CTC on Subtotal AC Rutting

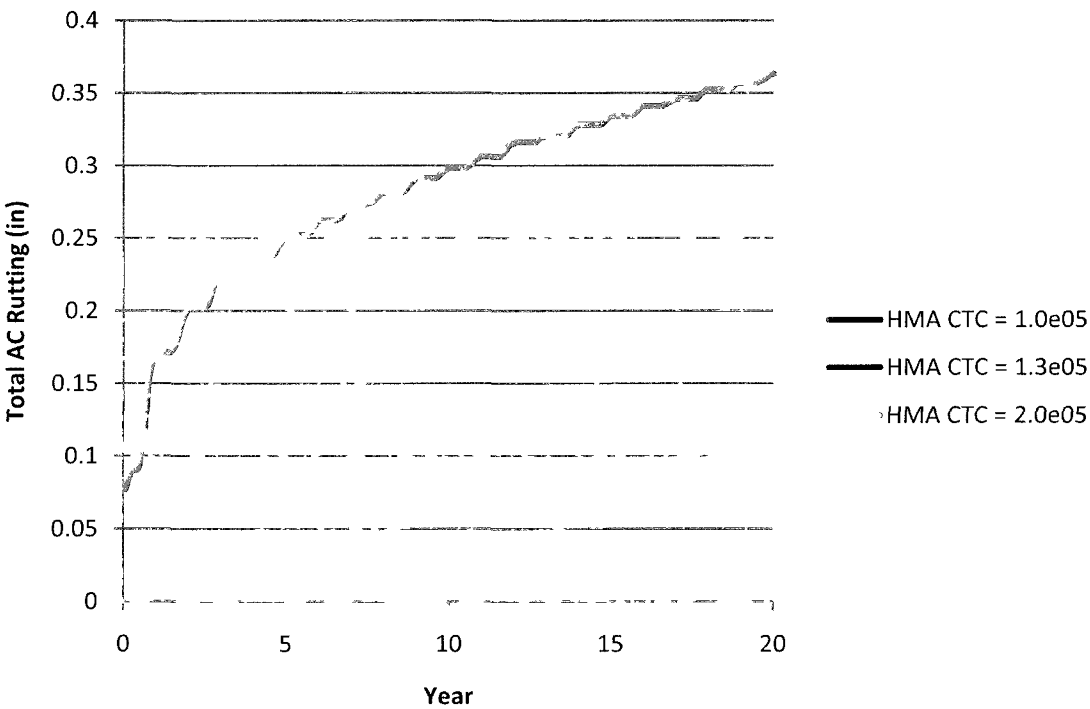


Figure 103A: Effect of HMA CTC on Total AC Rutting

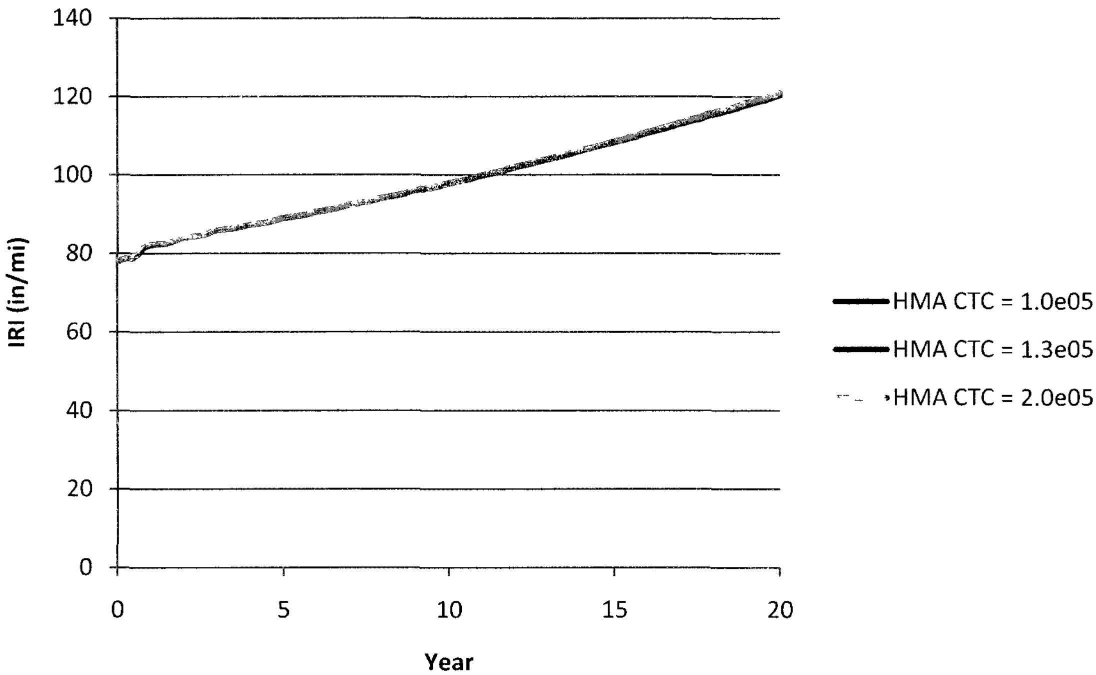


Figure 104A: Effect of HMA CTC on IRI

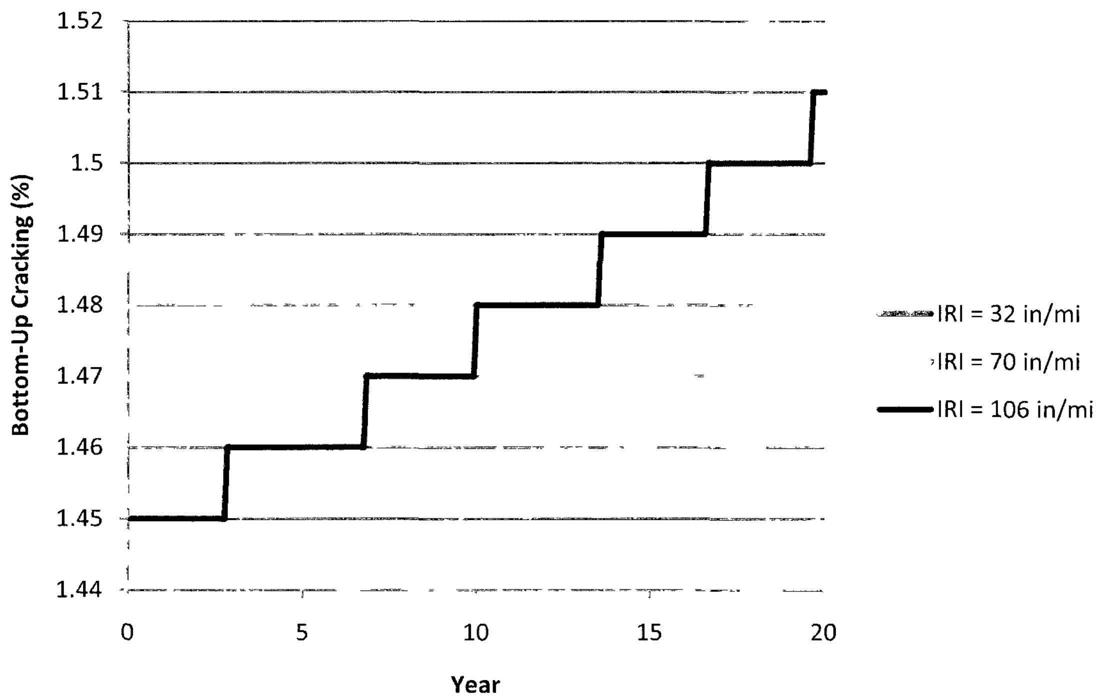


Figure 105A: Effect of Initial IRI on Bottom-Up Cracking

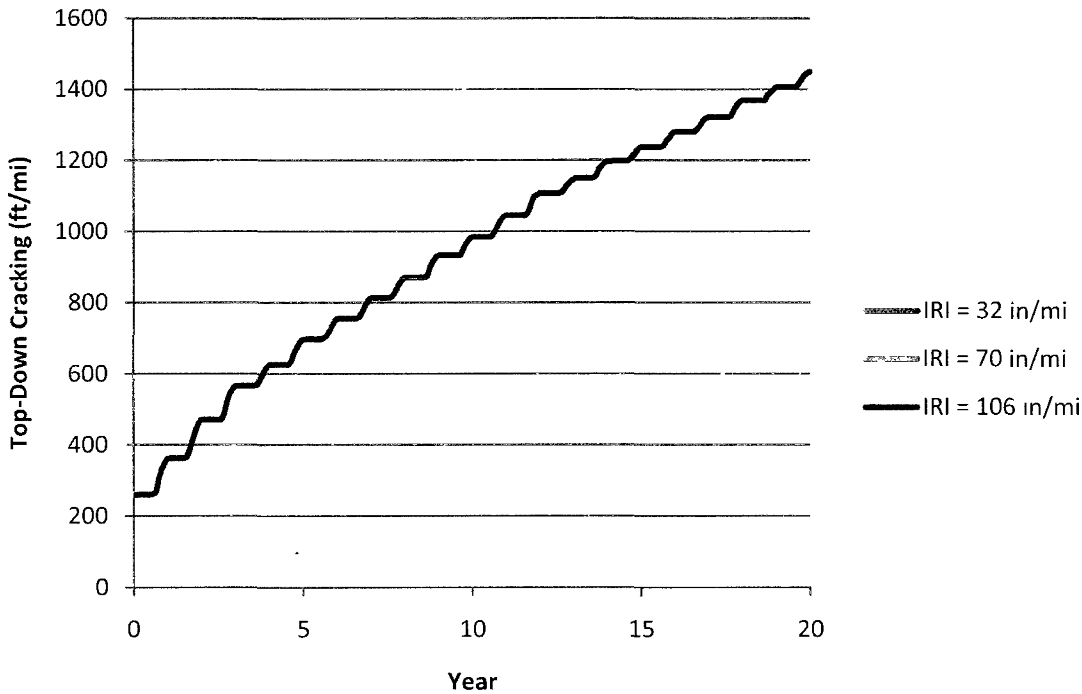


Figure 106A: Effect of Initial IRI on Top-Down Cracking

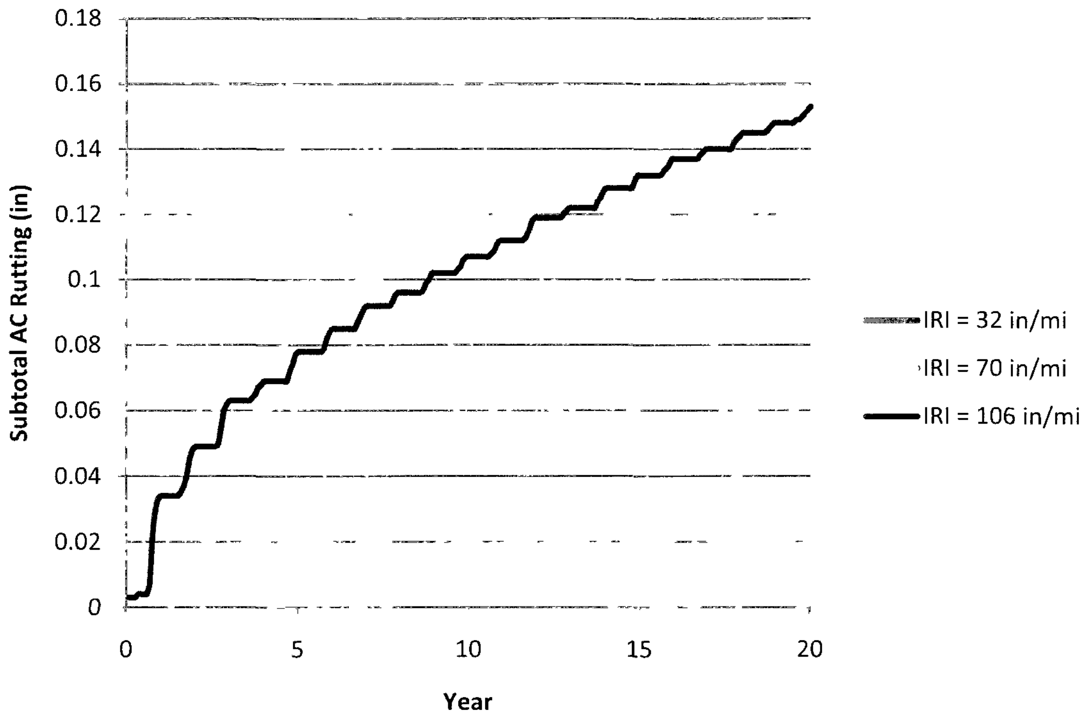


Figure 107A: Effect of Initial IRI on Subtotal AC Rutting

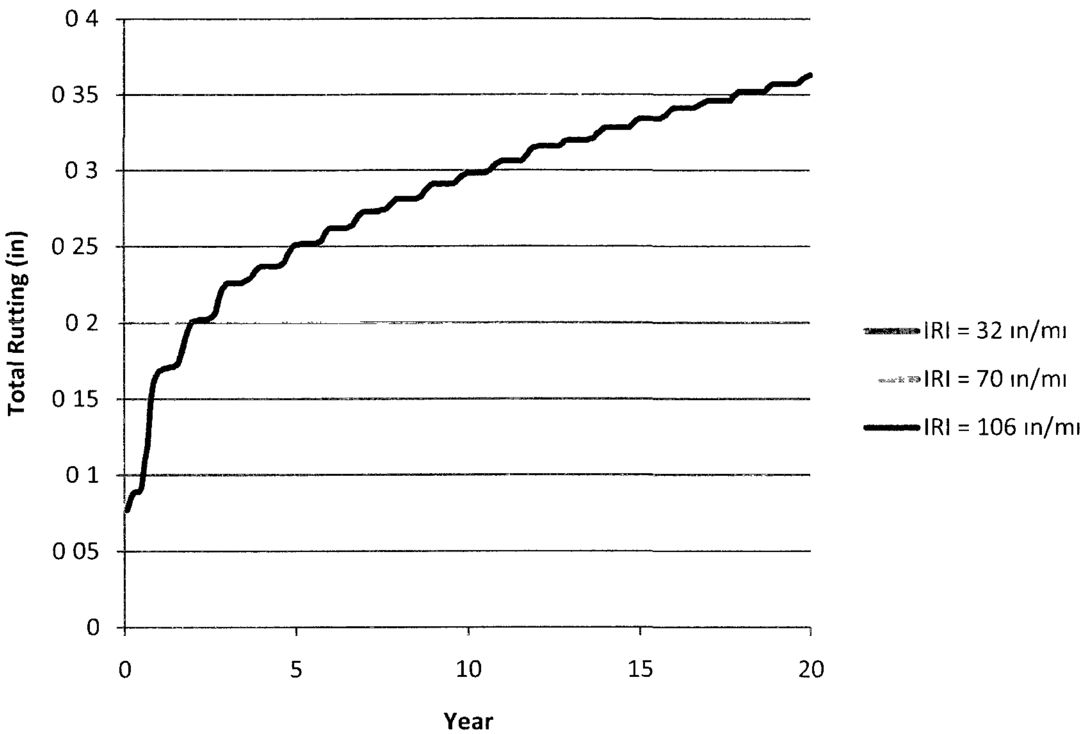


Figure 108A: Effect of Initial IRI on Total Rutting

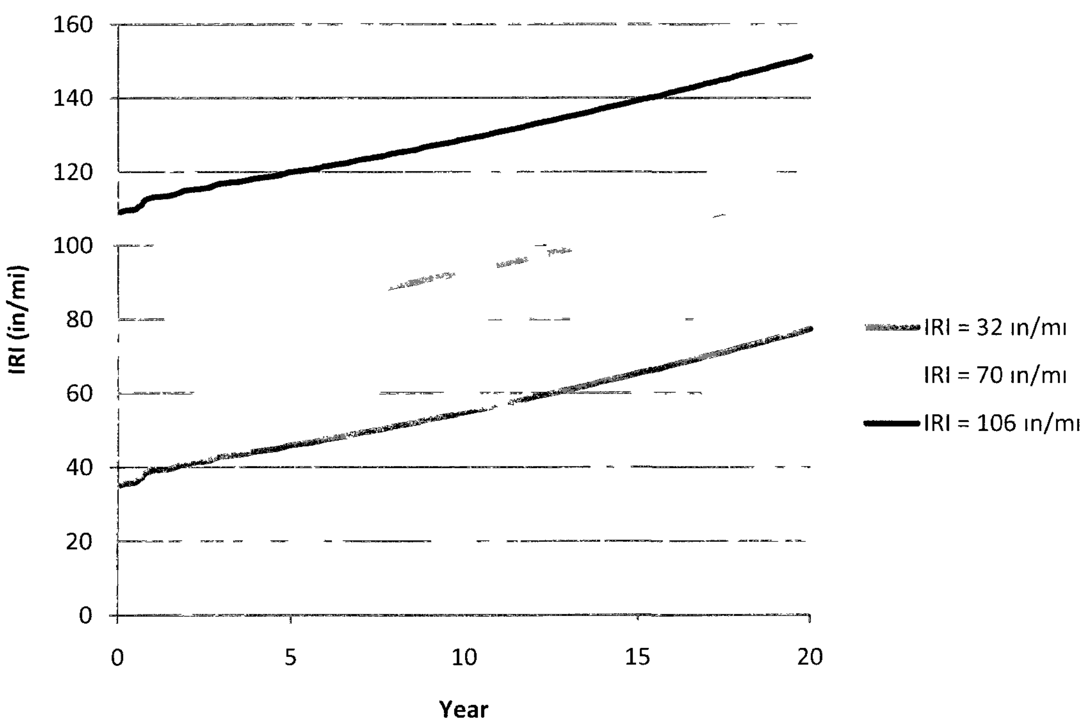


Figure 109A: Effect of Initial IRI on IRI

8. Sensitivity Analysis Summary Level 3

Normalization of the distresses was done to compare the effects of each input parameter on predicted distresses.

The normalized distress levels are calculated as the ratio of the difference between the maximum and minimum predicted distresses for each input variable to the distress levels corresponding to the control set of input values.

$$N = \frac{\textbf{Maximum Distress} - \textbf{Minimum Distress}}{\textbf{Distress for control input set}}$$

N - Normalized Value

Table 41A: Difference between Maximum and Minimum Distress Level – Level 3

VERMONT LEVEL 3					
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**
HMA thickness	0.12	1458.07	0.022	0.079	3.2
HMA mix gradation	0.02	377.43	0.06	0.072	3.0
HMA air voids	0.08	798.56	0.019	0.025	1.1
HMA effective binder content	0.05	409.08	0.023	0.031	0.9
HMA binder grade	0.02	353.41	0.045	0.057	2.3
Base type/modulus	0.02	442.11	0.006	0.022	0.9
Subgrade type/modulus	0.02	1123.56	0.007	0.11	12.0
Ground water table	0.01	296.48	0.01	0.037	1.5
WT with weakest subgrade	0.02	26.87	0.005	0.027	1.1
Climate	0.01	121.11	0.04	0.043	1.6
AADTT value	0.08	618.19	0.072	0.094	3.8
Operational speed	0.07	634.17	0.149	0.177	7.1
Traffic growth rate	0.01	111.66	0.012	0.016	0.79
Traffic distribution	0.06	598.17	0.047	0.062	2.6
HMA CTC	0	0	0	0	0.6
Initial IRI	0	0	0	0	74

Table 42A: Normalized Values for Vermont Level 3 and Ranks

VERMONT LEVEL 3										
Input Variable	**Bottom-Up**		**Top-Down**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA thickness	0.079	1	0.997	1	0.145	8	0.218	4	0.027	4
HMA mix gradation	0.013	6	0.258	9	0.395	3	0.198	5	0.025	6
HMA air voids	0.053	2	0.546	3	0.125	9	0.069	12	0.009	11
HMA effective binder content	0.033	5	0.280	8	0.151	7	0.085	10	0.007	12
HMA binder grade	0.013	6	0.242	10	0.296	5	0.157	7	0.019	8
Base type/modulus	0.013	6	0.302	7	0.039	13	0.061	13	0.007	12
Subgrade type/modulus	0.013	6	0.768	2	0.046	12	0.303	2	0.100	2
Ground water table	0.007	7	0.203	11	0.066	11	0.102	9	0.012	10
WT with weakest subgrade	0.013	6	0.018	14	0.033	14	0.074	11	0.009	11
Climate	0.007	7	0.083	12	0.263	6	0.118	8	0.013	9
AADTT value	0.053	2	0.423	5	0.474	2	0.259	3	0.032	5
Operational speed	0.046	3	0.433	4	0.980	1	0.488	1	0.059	3
Traffic growth rate	0.007	7	0.076	13	0.079	10	0.044	14	0.007	12
Traffic distribution	0.040	4	0.409	6	0.309	4	0.171	6	0.022	7
HMA CTC	0.000	8	0.000	15	0.000	15	0.000	15	0.005	13
Initial IRI	0.000	8	0.000	15	0.000	15	0.000	15	0.615	1

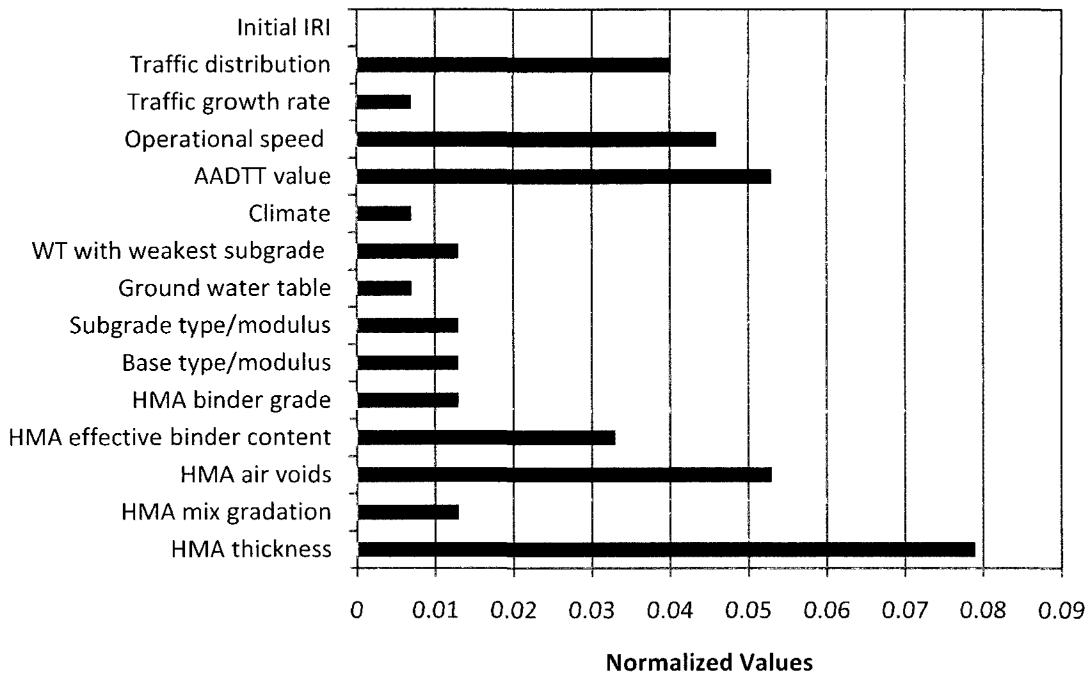


Figure 110A: Significance of Effect of Input Variables on Bottom-Up Cracking

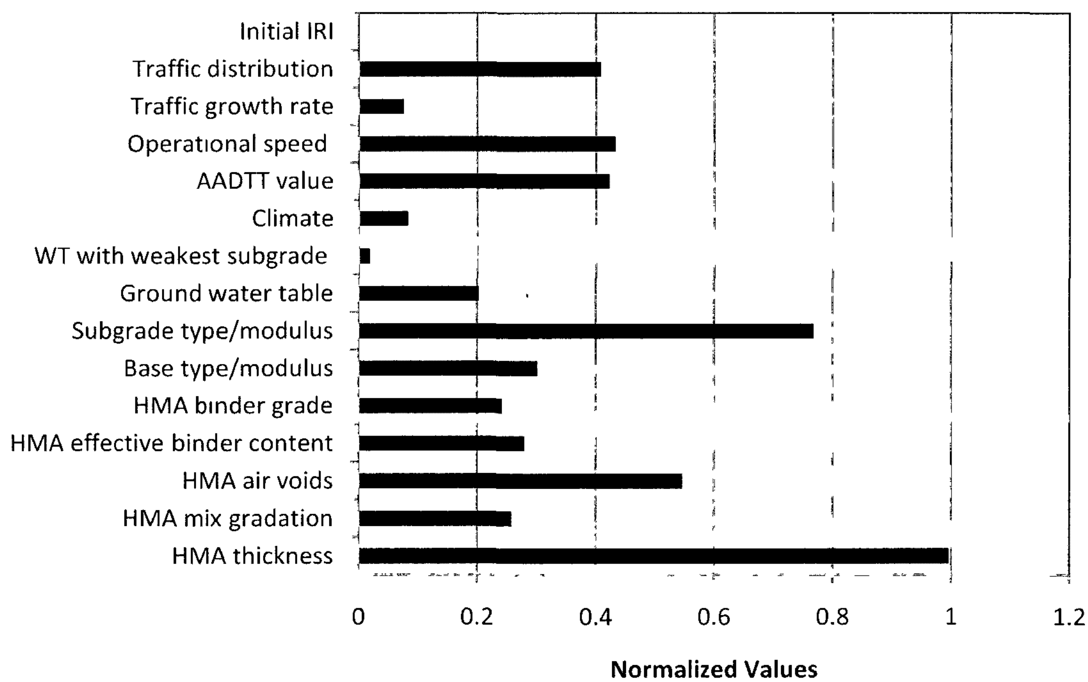


Figure 111A: Significance of Effect of Input Variables on Top-Down Cracking

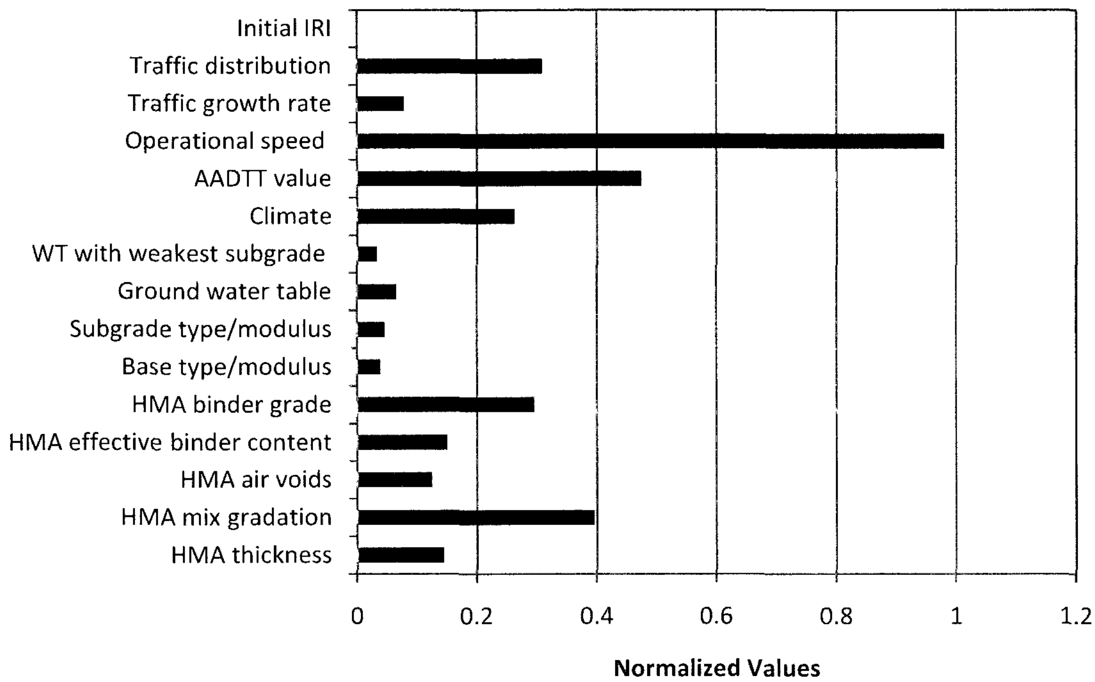


Figure 112A: Significance of Effect of Input Variables on AC Rutting

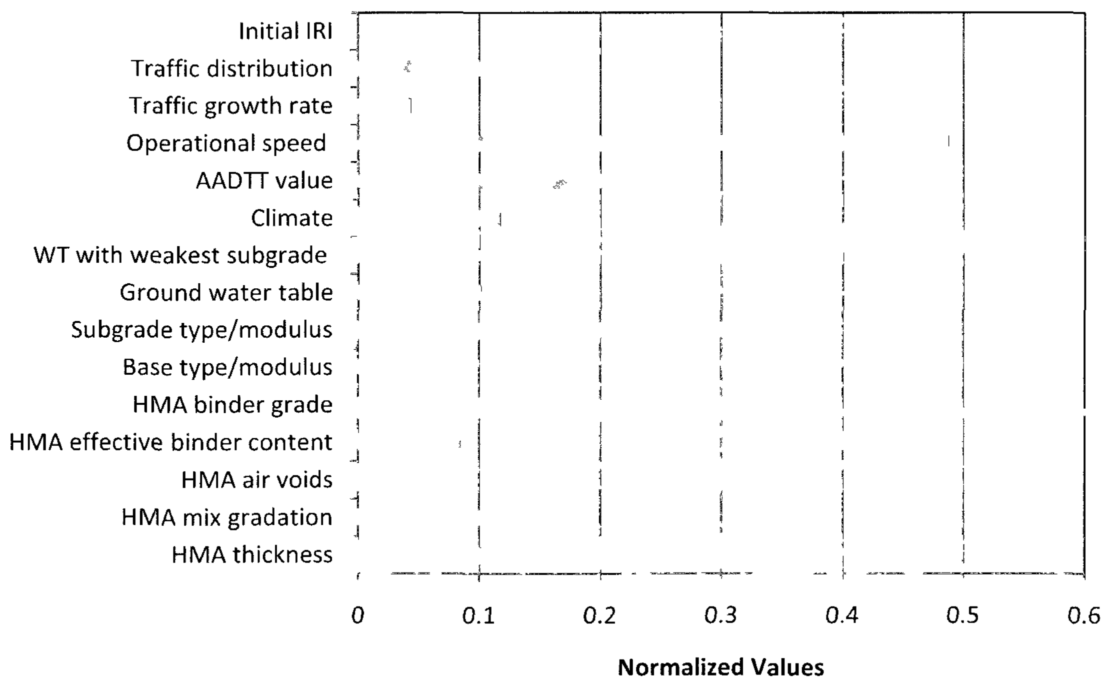


Figure 113A: Significance of Effect of Input Variables on Total Rutting

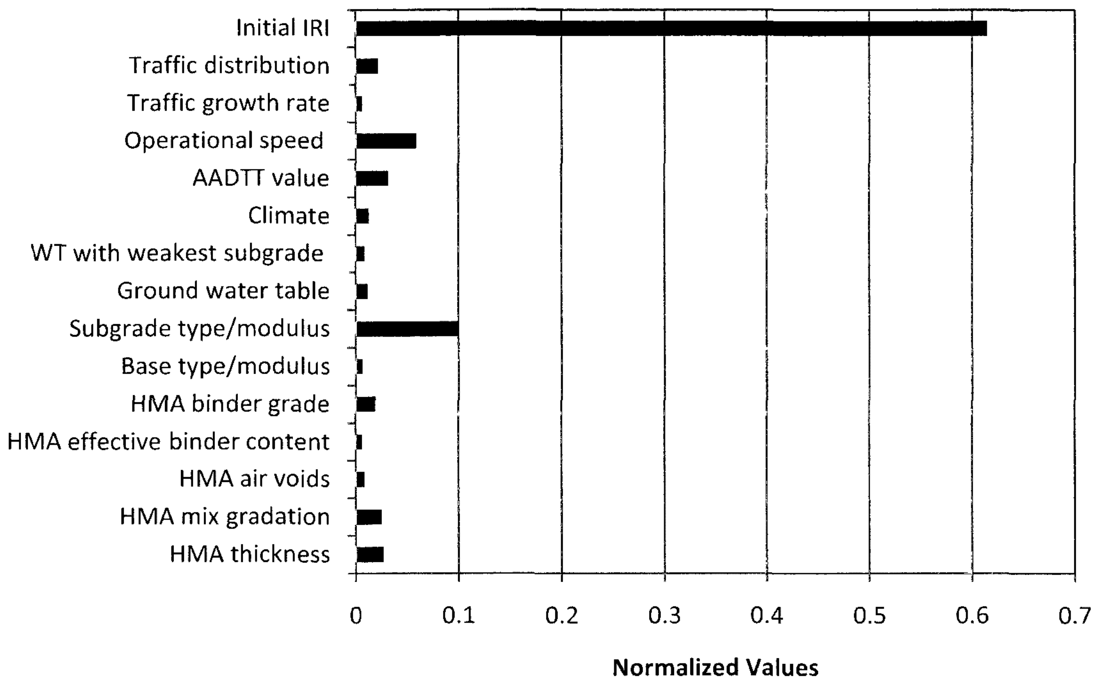


Figure 114A: Significance of Effect of Input Variables on IRI

Table 43A: Sensitivity Analysis Results Level 3

Bottom-Up	Top-Down	AC Rutting	Total Rutting	IRI
HMA Thickness	HMA Thickness	Operational Speed	Operational Speed	Initial IRI
HMA Air Voids	Subgrade Type/ Modulus	AADTT	Subgrade Type/ Modulus	Subgrade Type/ Modulus
AADTT	HMA Air Voids	HMA Mix Gradation	AADTT	Operational Speed
Operational Speed	Operational Speed	Traffic Distribution	HMA Thickness	HMA Thickness
Traffic Distribution	AADTT	HMA Binder Grade	HMA Mix Gradation	AADTT
HMA Effective Binder Content	Traffic Distribution	Climate	Traffic Distribution	HMA Mix Gradation

Table 44A: Sensitivity Analysis Summary Level 3

Design/ Material Variable	Distress/Smoothness				
	Bottom-Up Cracking (%)	**Top-Down Cracking (ft/mi)**	**AC Rutting (in)**	**Total Rutting (in)**	**IRI (in/mi)**
HMA thickness	XXX	XXX	X	X	
HMA mix gradation	XX	XX	XX	X	
HMA air voids	XXX	XXX	X		
HMA effective binder content	XX	XX	X		
HMA binder grade	X	XX	XX	X	
Base type/modulus	X	XX			
Subgrade type/modulus	X	XXX		XX	X
Ground water table	X	XX	X	X	
WT with weakest subgrade	X	X	X	X	
Climate	X		XX	X	
AADTT value	XXX	XX	XXX	XX	
Operational speed	XX	XX	XXX	XX	X
Traffic growth rate	X	X	X		
Traffic distribution	XX	XX	XX	X	
HMA CTC					
Initial IRI					XXX

Note: **X – Small effect**
XX – moderate effect
XXX – large effect

Table 45A: VT Ranking Summary of Significance of Each Input Parameter on the Performance of Flexible Pavement

VERMONT LEVEL 3							
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**	**Total Ranking Points**	**Overall Order of Significance**
	Rank	Rank	Rank	Rank	Rank		
HMA thickness	1	1	8	4	4	**18**	**3**
HMA mix gradation	6	9	3	5	6	**29**	**6**
HMA air voids	2	3	9	12	11	**37**	**8**
HMA effective binder content	5	8	7	10	12	**42**	**9**
HMA binder grade	6	10	5	7	8	**36**	**7**
Base type/modulus	6	7	13	13	12	**51**	**11**
Subgrade type/modulus	6	2	12	2	2	**24**	**4**
Ground water table	7	11	11	9	10	**48**	**10**
WT with weakest subgrade	6	14	14	11	11	**56**	**13**
Climate	7	12	6	8	9	**42**	**9**
AADTT value	2	5	2	3	5	**17**	**2**
Operational speed	3	4	1	1	3	**12**	**1**
Traffic growth rate	7	13	10	14	12	**56**	**13**
Traffic distribution	4	6	4	6	7	**27**	**5**
HMA CTC	8	15	15	15	13	**66**	**14**
Initial IRI	8	15	15	15	1	**54**	**12**

9. Vermont Level 2 Sensitivity Analysis

9.1 Effect of Traffic Inputs on Level 2 Predicted Pavement Distresses

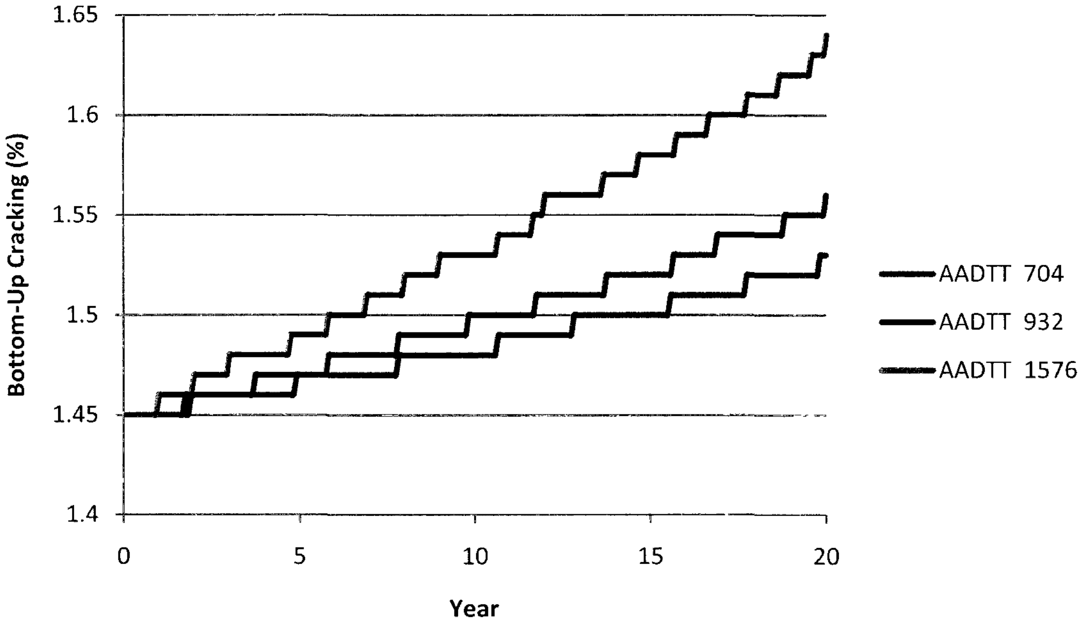


Figure 115A: Effect of AADTT on Bottom-Up Cracking

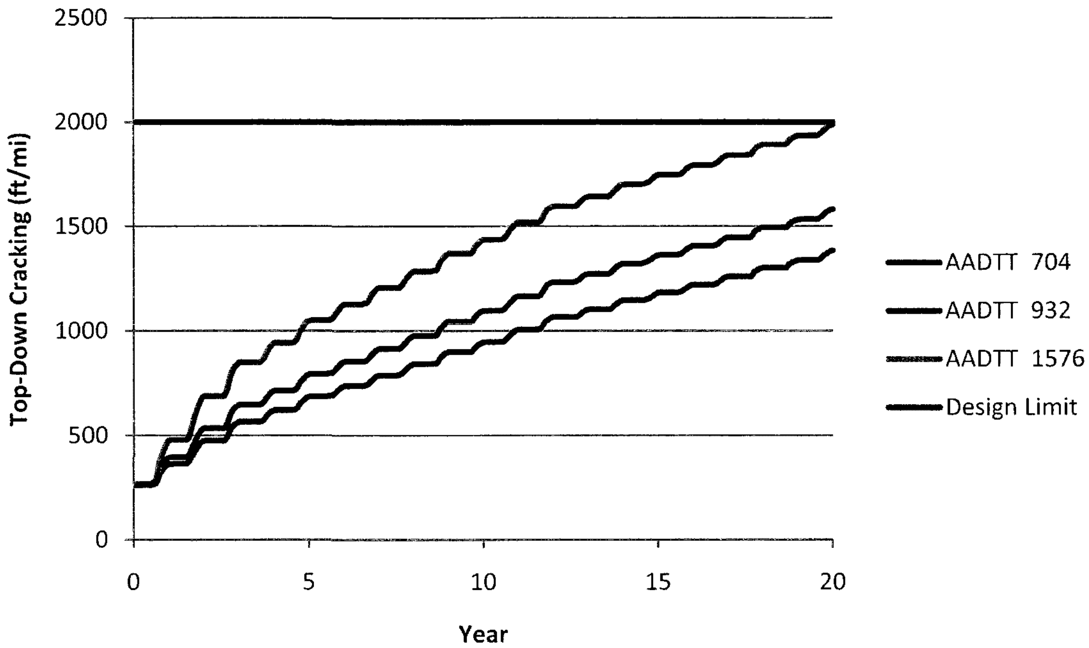


Figure 116A: Effect of AADTT on Top-Down Cracking

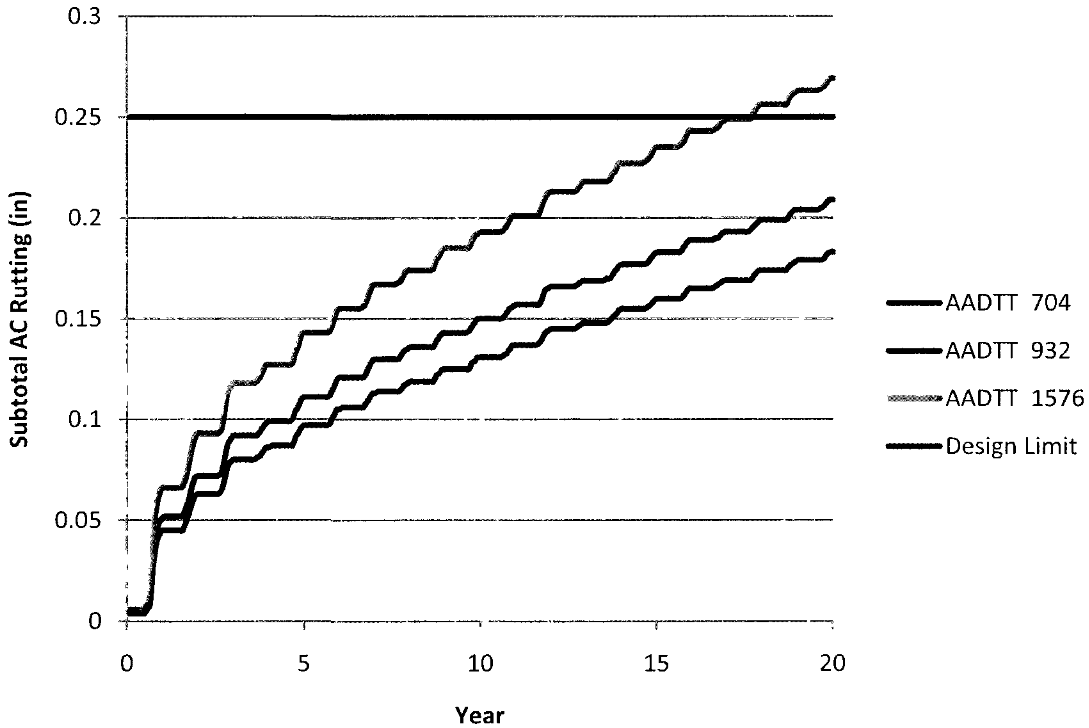


Figure 117A: Effect of AADTT on Subtotal AC Rutting

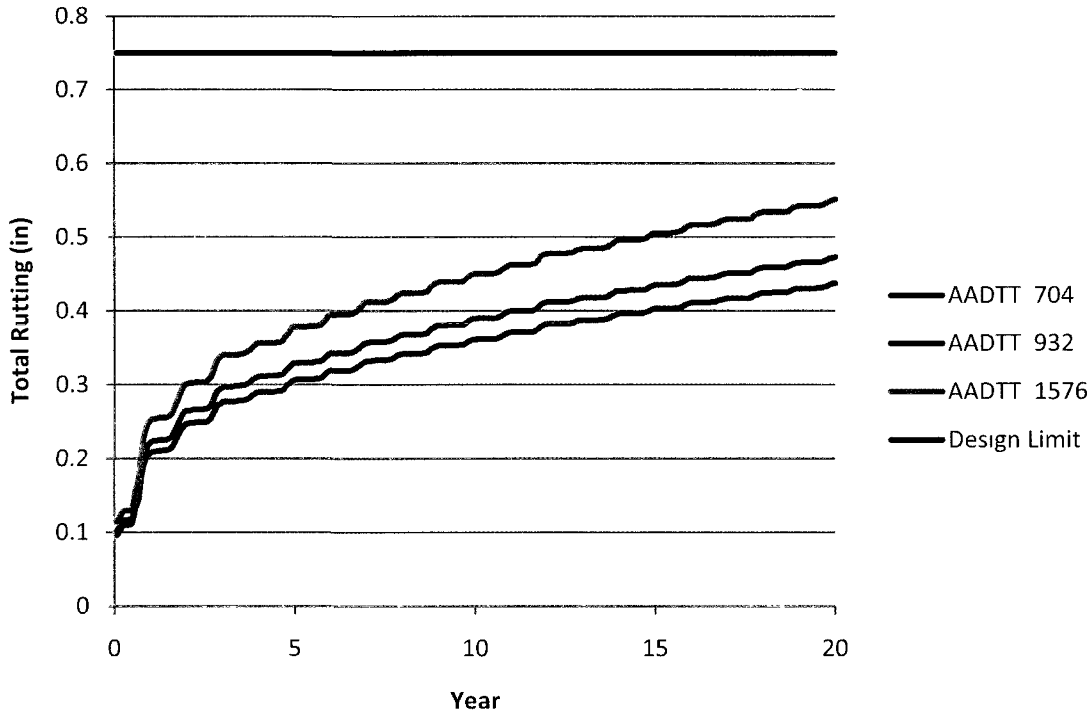


Figure 118A: Effect of AADTT on Total Rutting

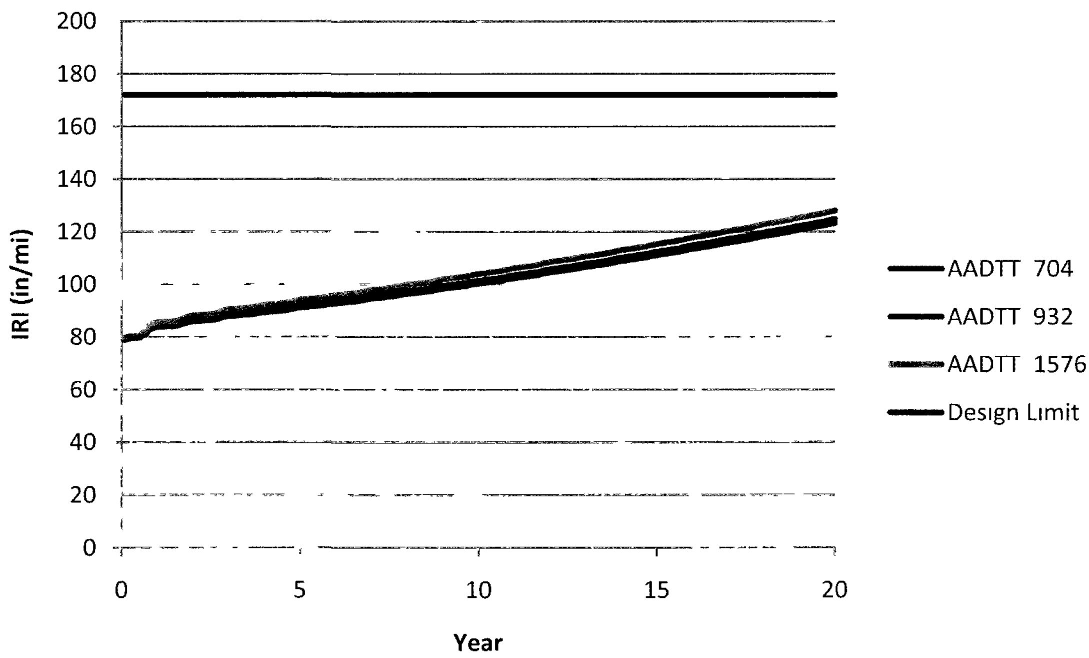


Figure 119A: Effect of AADTT on IRI

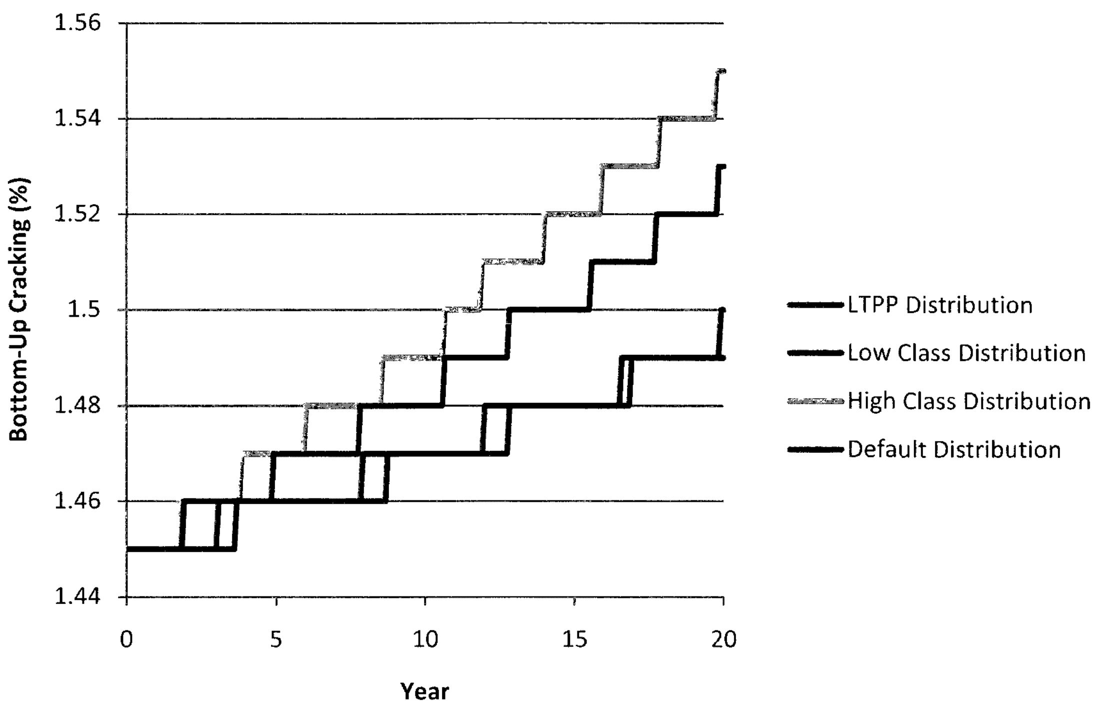


Figure 120A: Effect of Truck Class Distribution on Bottom-Up Cracking

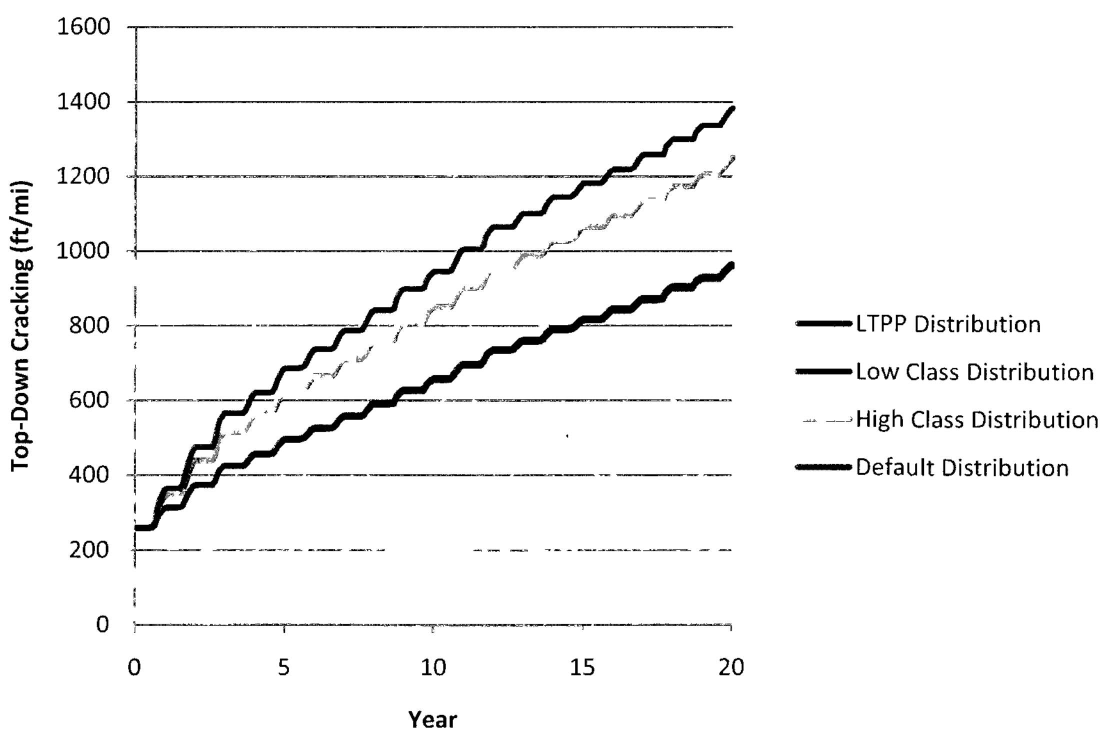


Figure 121A: Effect of Truck Class Distribution on Top-Down Cracking

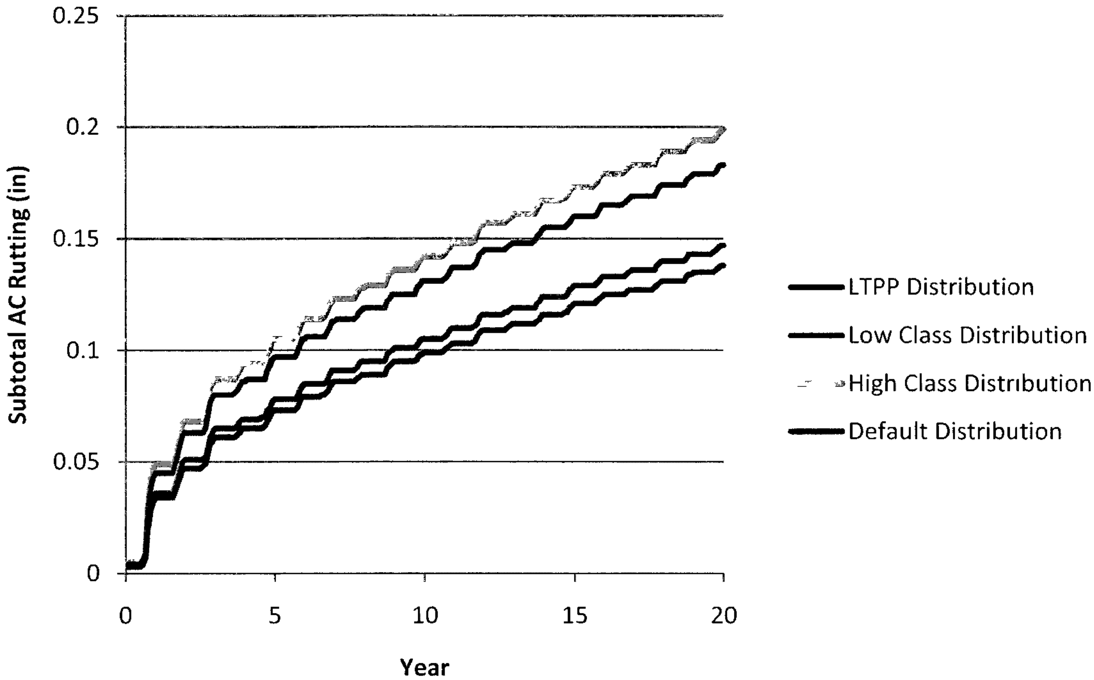


Figure 122A: Effect of Truck Class Distribution on Subtotal AC Rutting

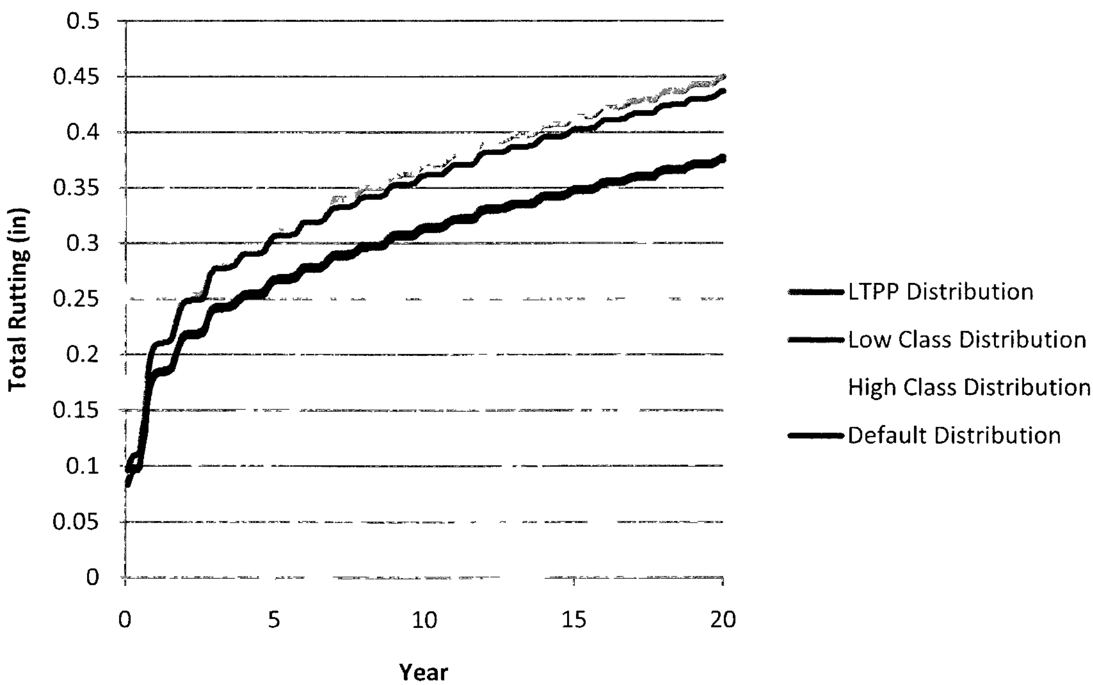


Figure 123A: Effect of Truck Class Distribution on Total Rutting

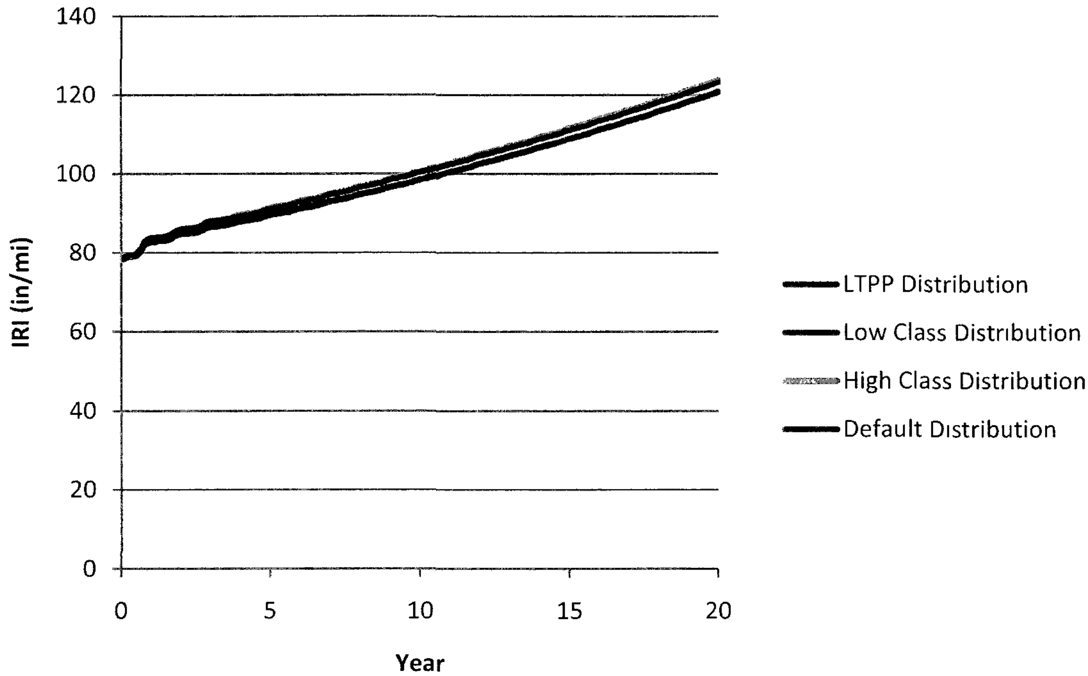


Figure 124A: Effect of Truck Class Distribution on IRI

9.2 Effect of Material Inputs on Level 2 predicted Pavement Distresses

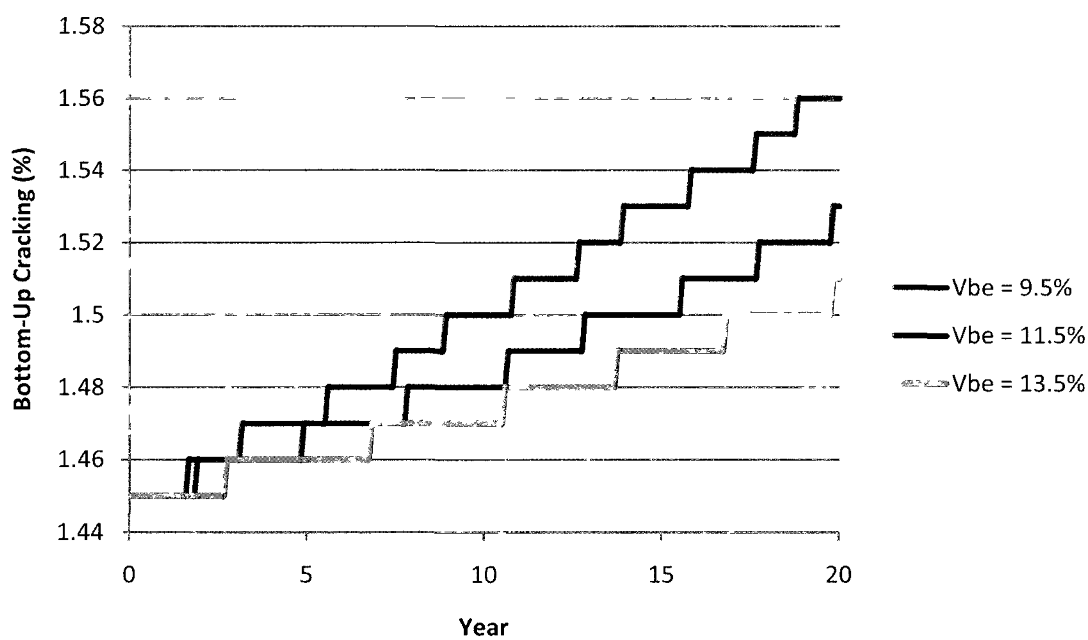


Figure 125A: Effect of Effective Binder Content on Bottom-Up Cracking

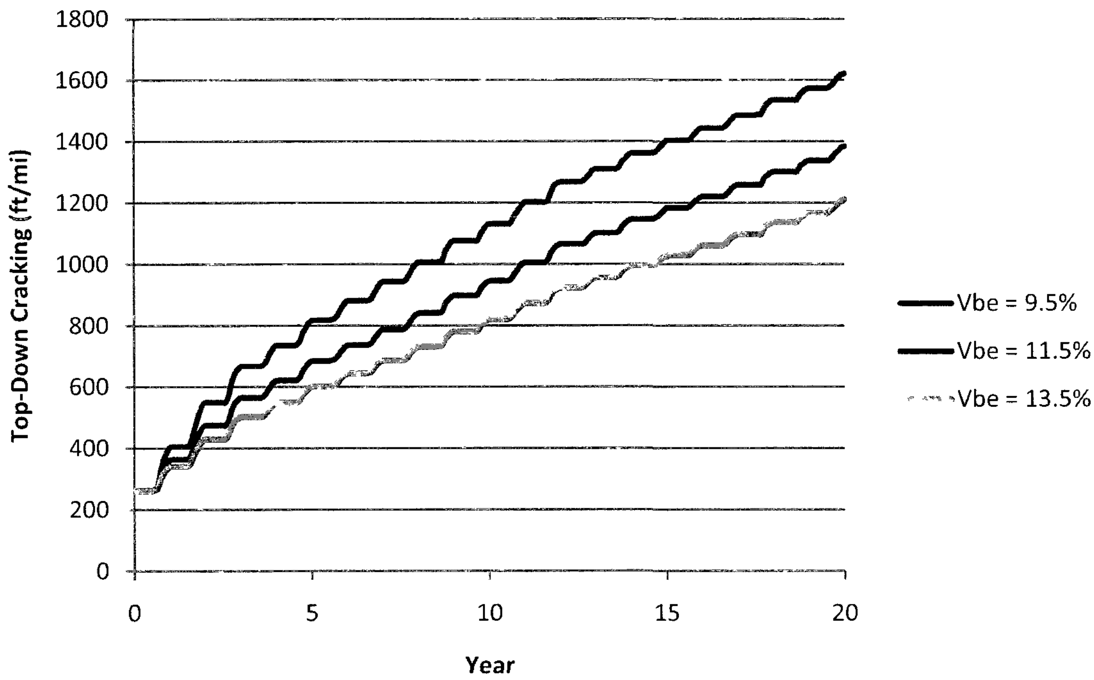


Figure 126A: Effect of Effective Binder Content on Top-Down Cracking

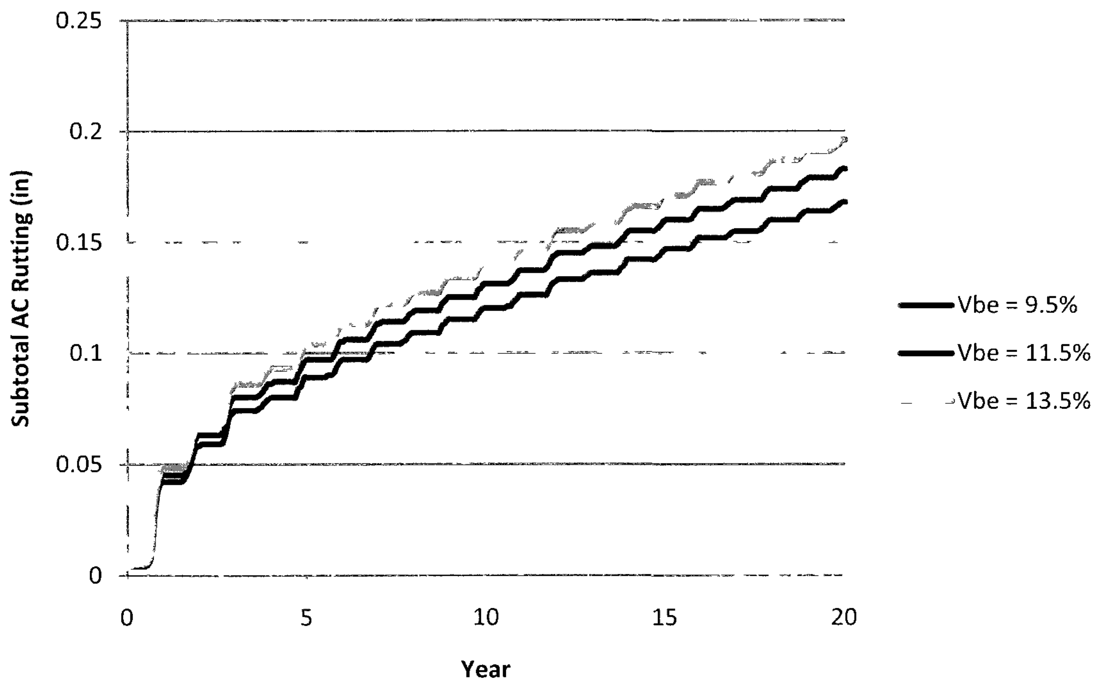


Figure 127A: Effect of Effective Binder Content on Subtotal AC Rutting

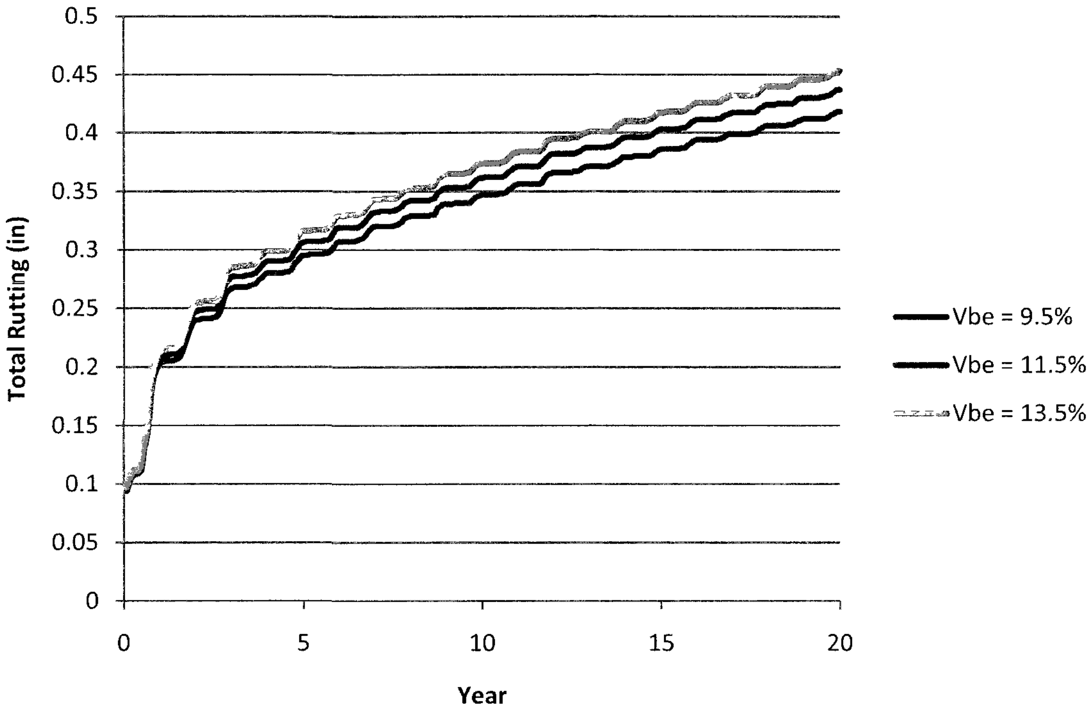


Figure 128A: Effect of Effective Binder Content on Total Rutting

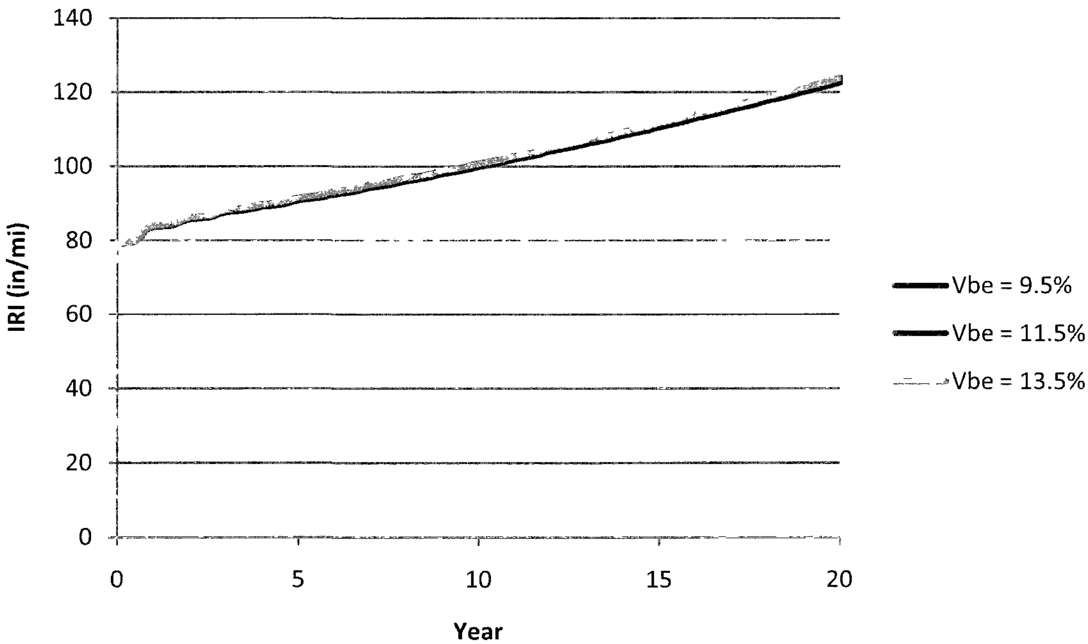


Figure 129A: Effect of Effective Binder Content on IRI

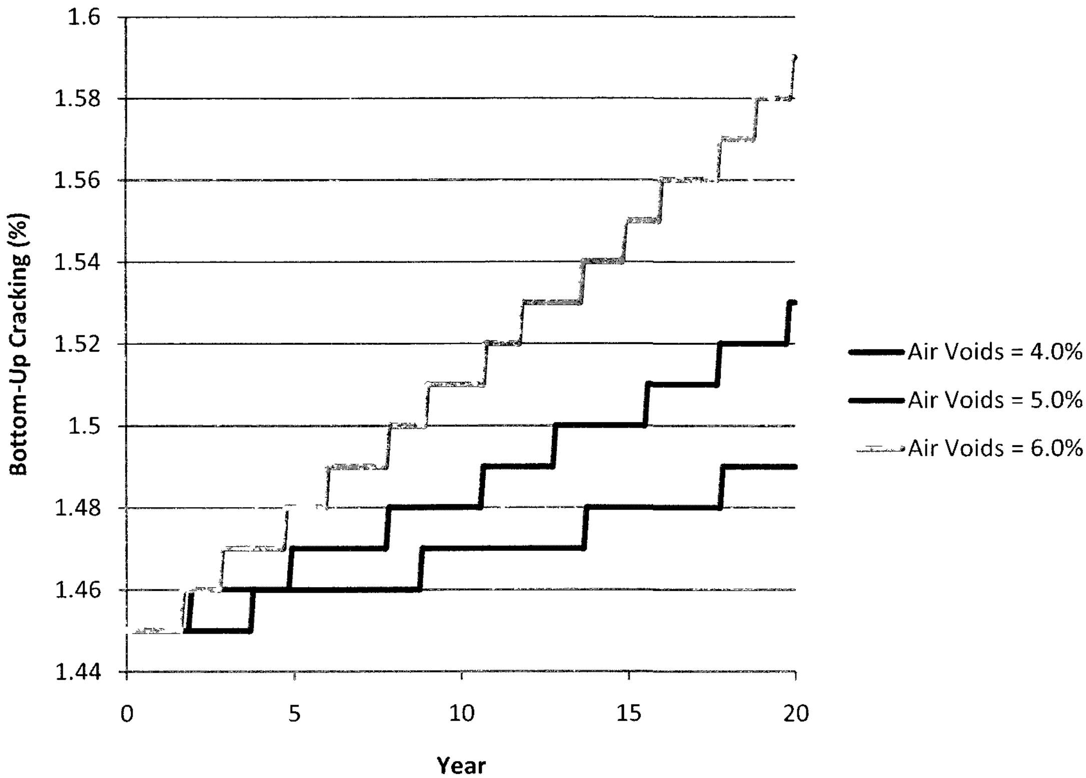


Figure 130A: Effect of Air Void Content on Bottom-Up Cracking

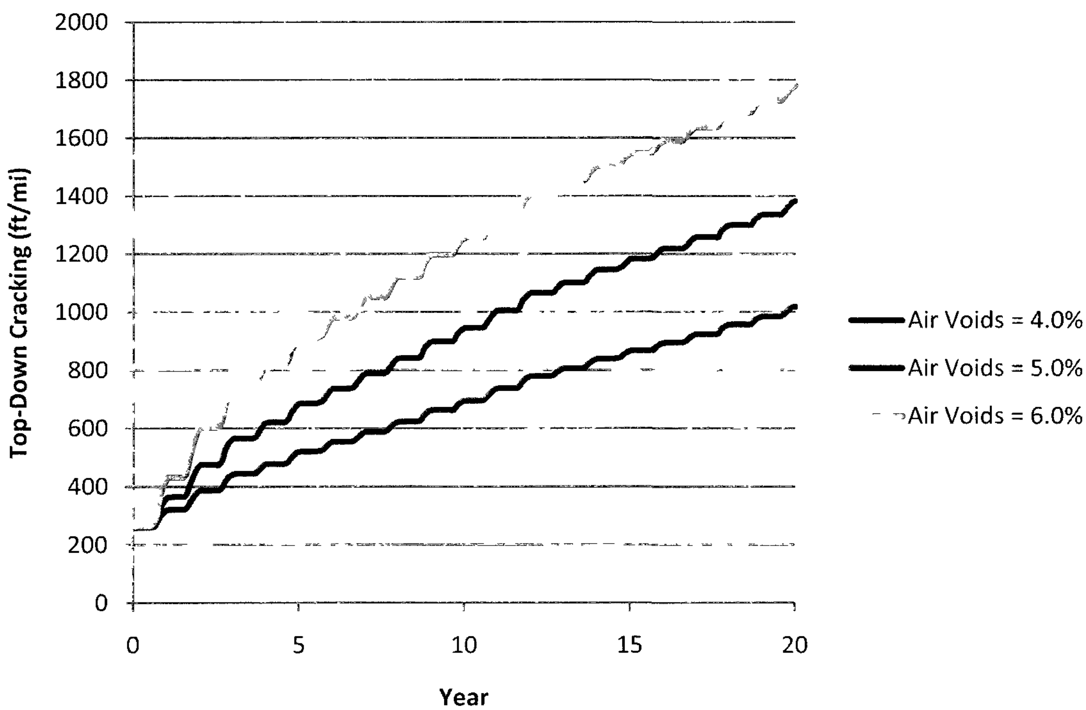


Figure 131A: Effect of Air Void Content on Top-Down Cracking

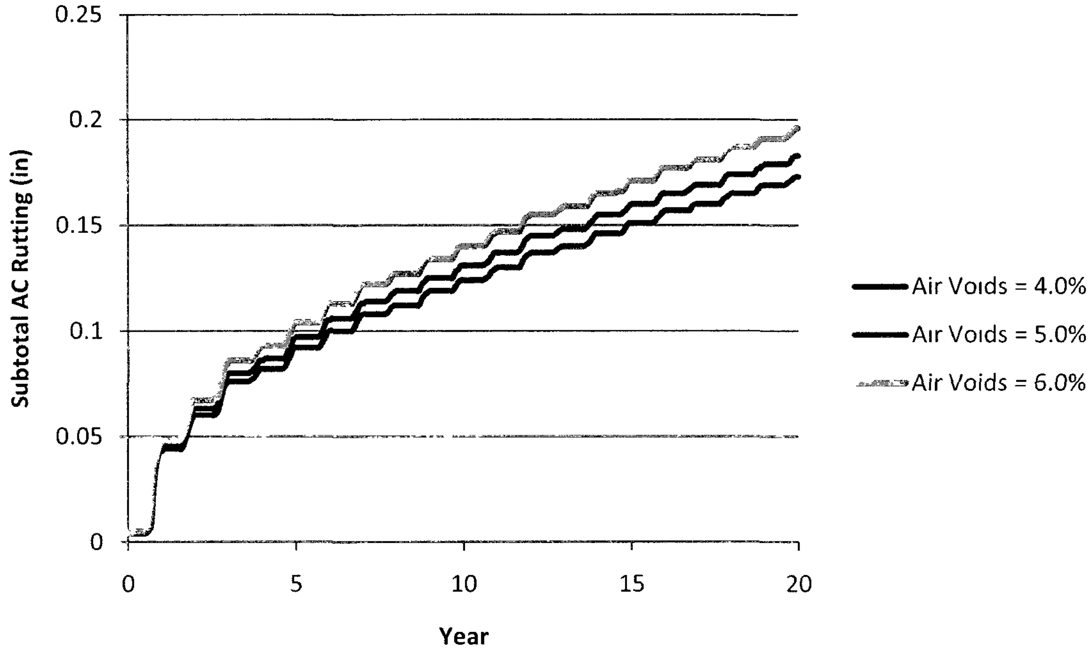


Figure 132A: Effect of Air Void Content on Subtotal AC Rutting

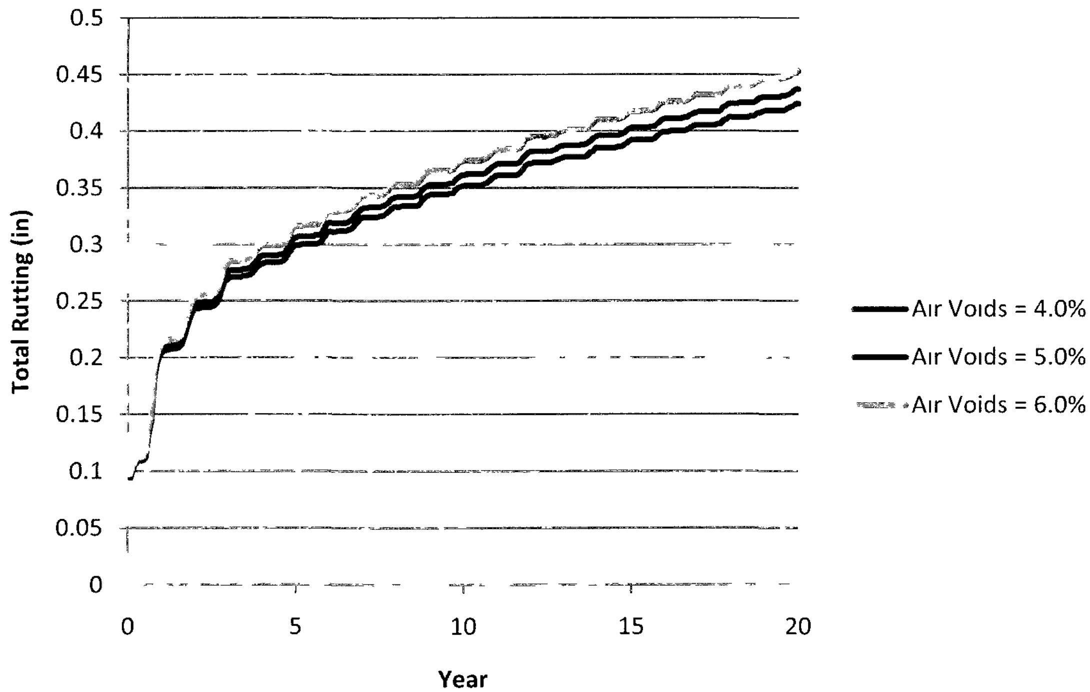


Figure 133A: Effect of Air Void Content on Total Rutting

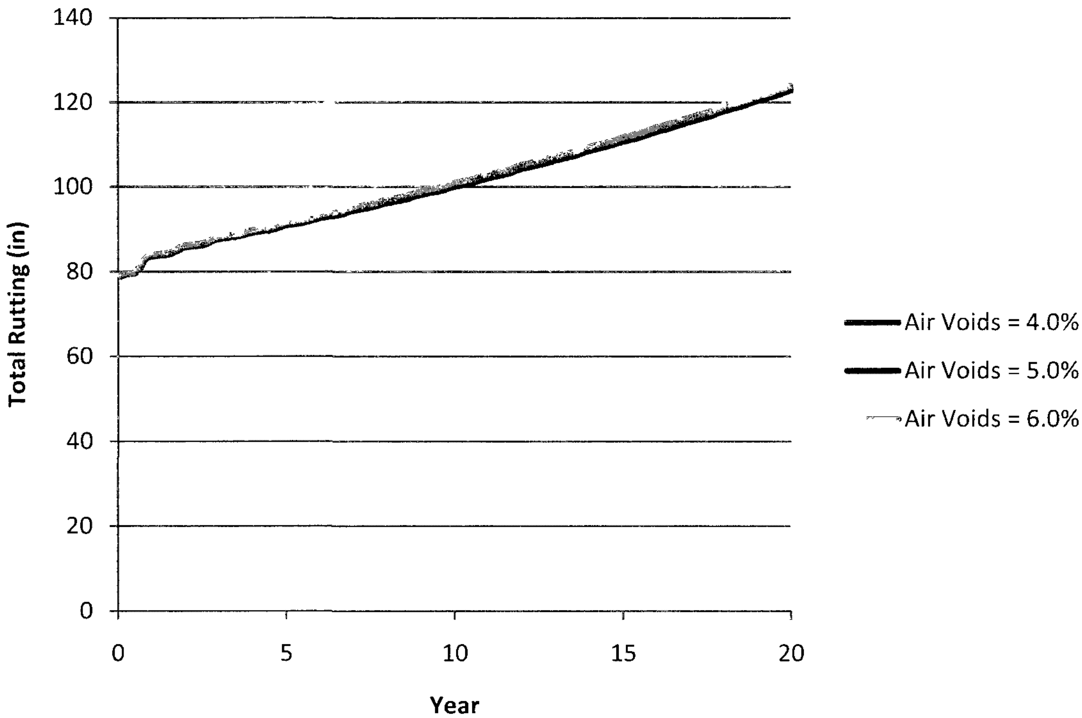


Figure 134A: Effect of Air Void Content on IRI

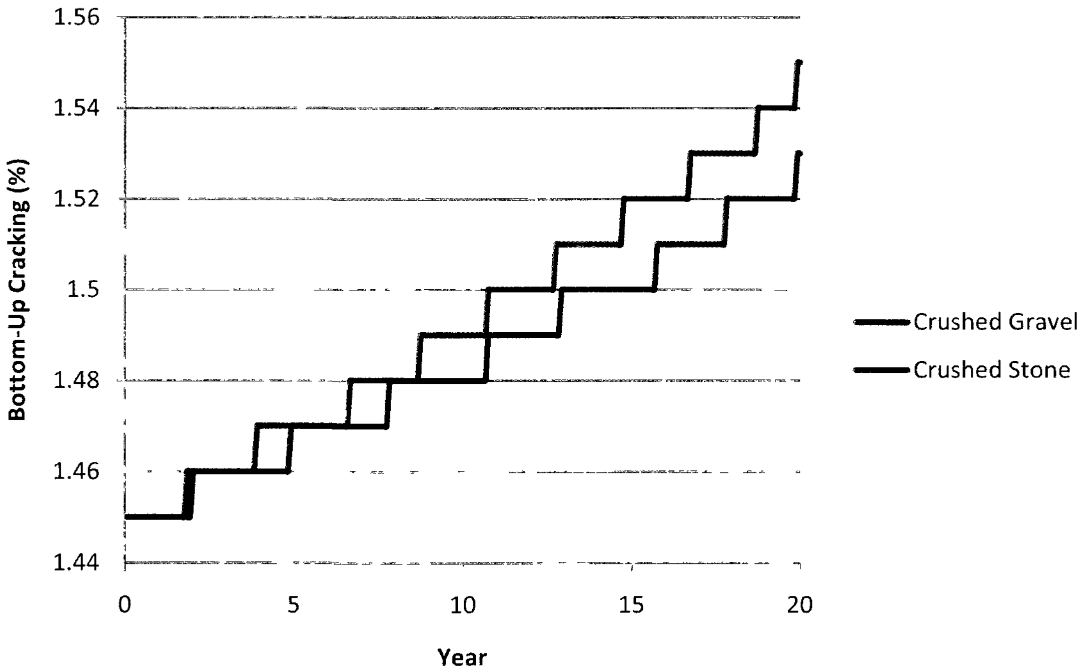


Figure 135A: Effect of Base Course Material on Bottom-Up Cracking

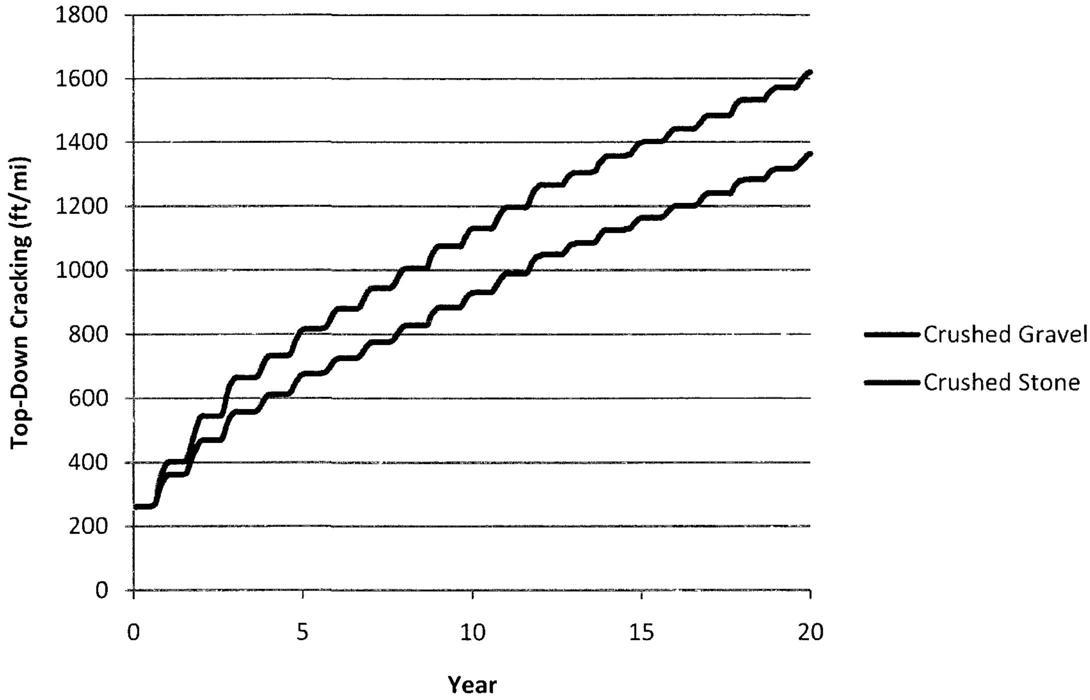


Figure 136A: Effect of Base Course Material on Top-Down Cracking

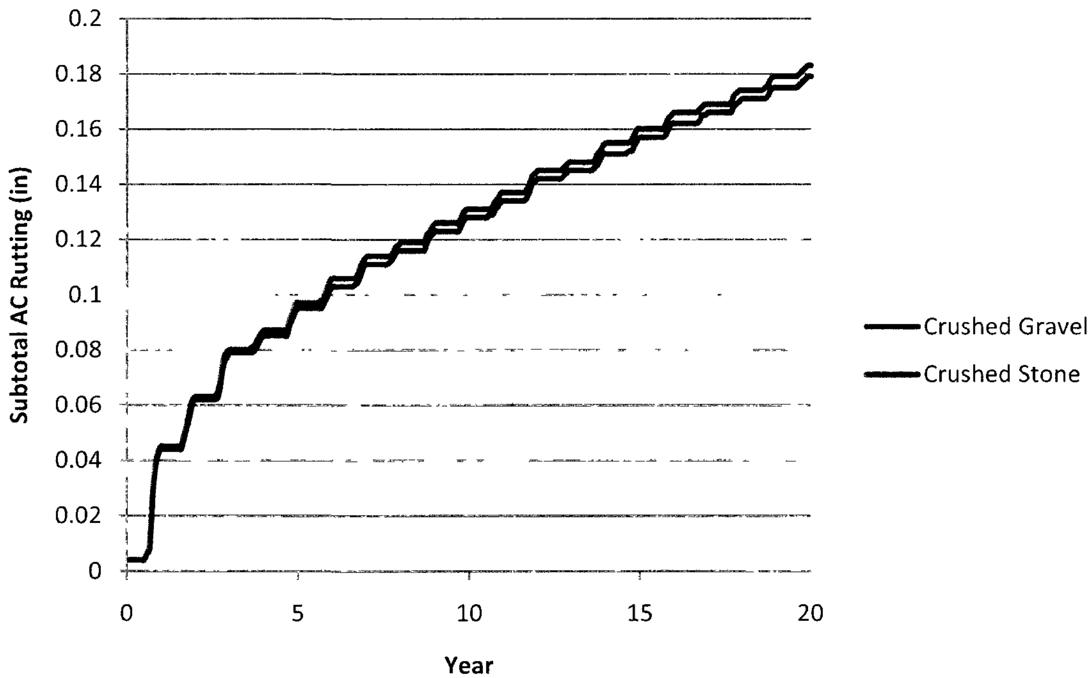


Figure 137A: Effect of Base Course Material on Subtotal AC Rutting

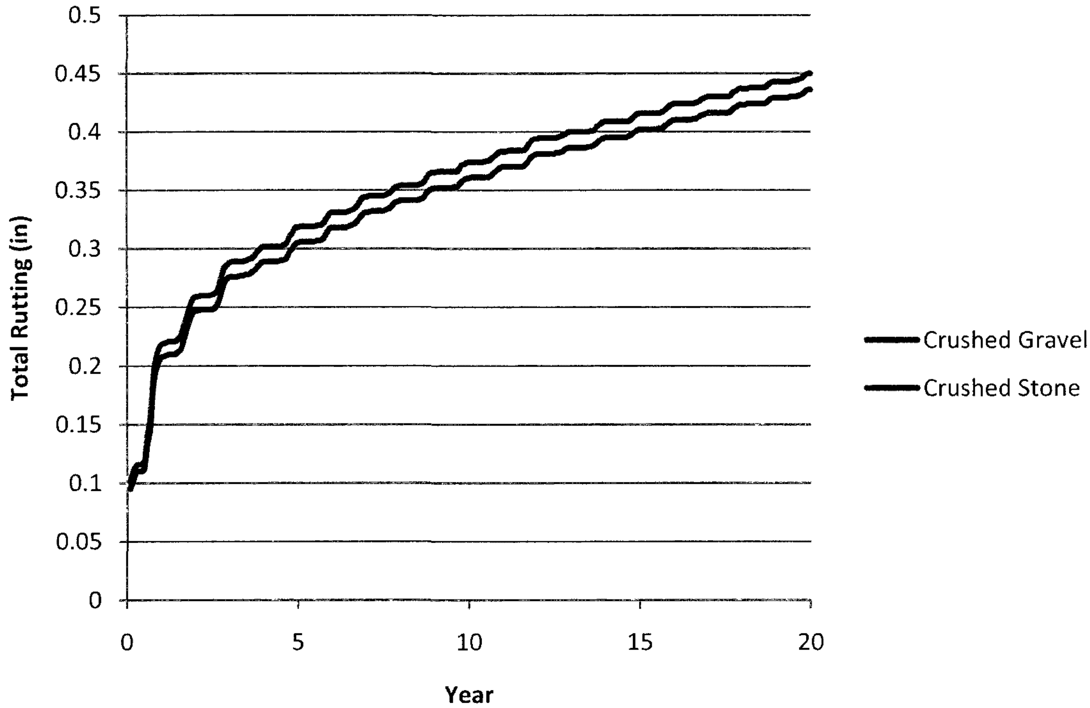


Figure 138A: Effect of Base Course Material on Total Rutting

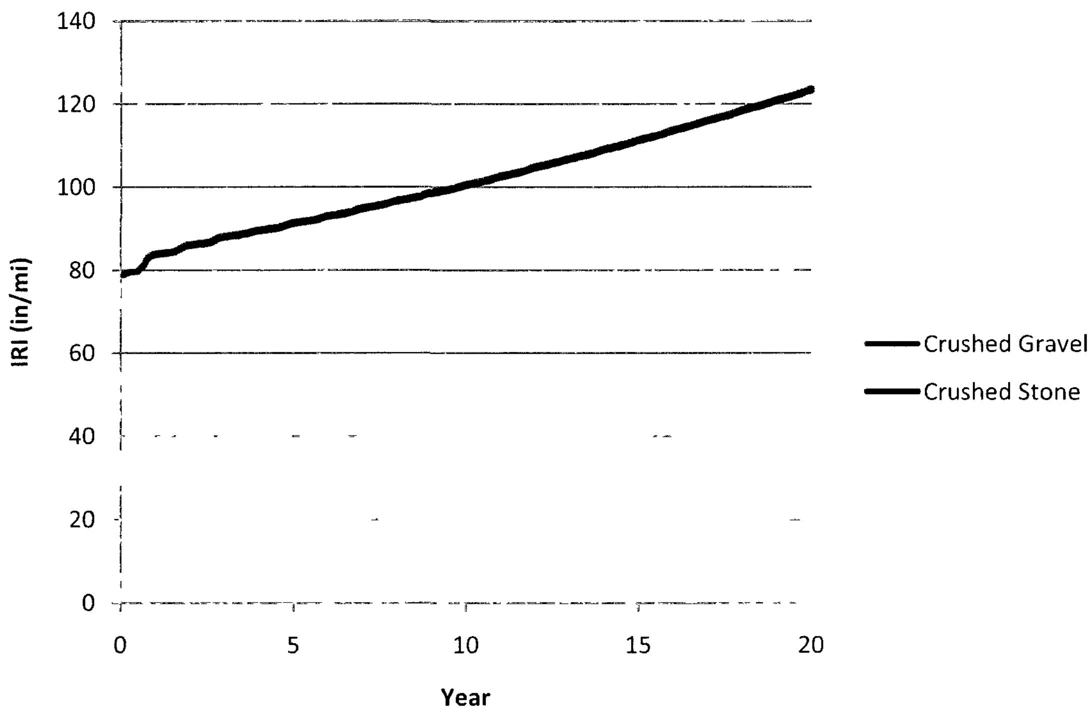


Figure 139A: Effect of Base Course Material on IRI

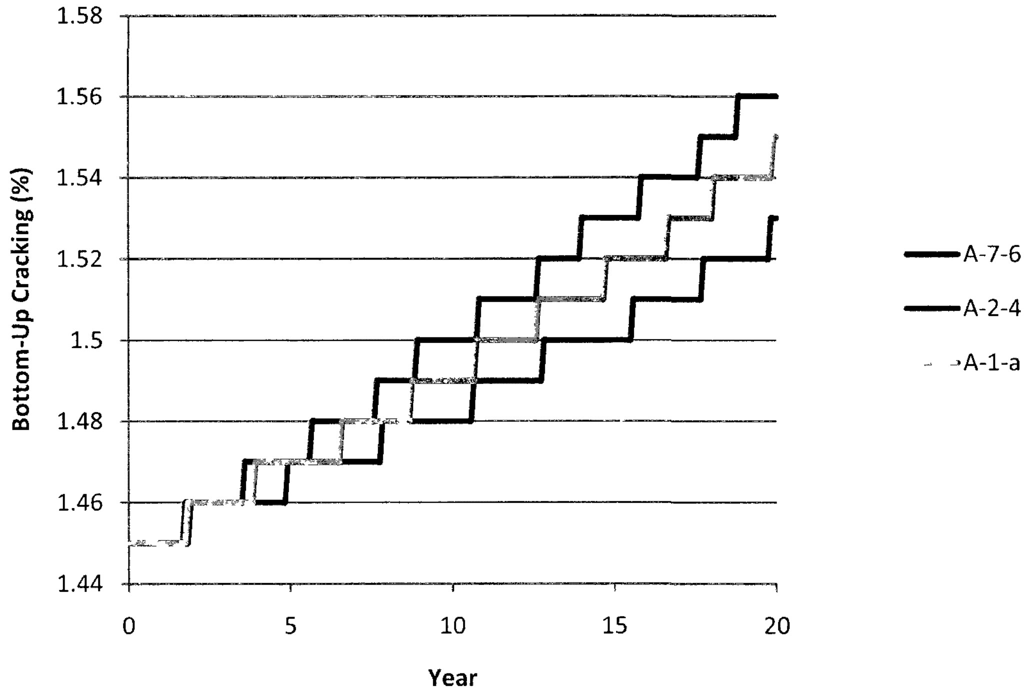


Figure 140A: Effect of Subgrade Type on Bottom-Up Cracking

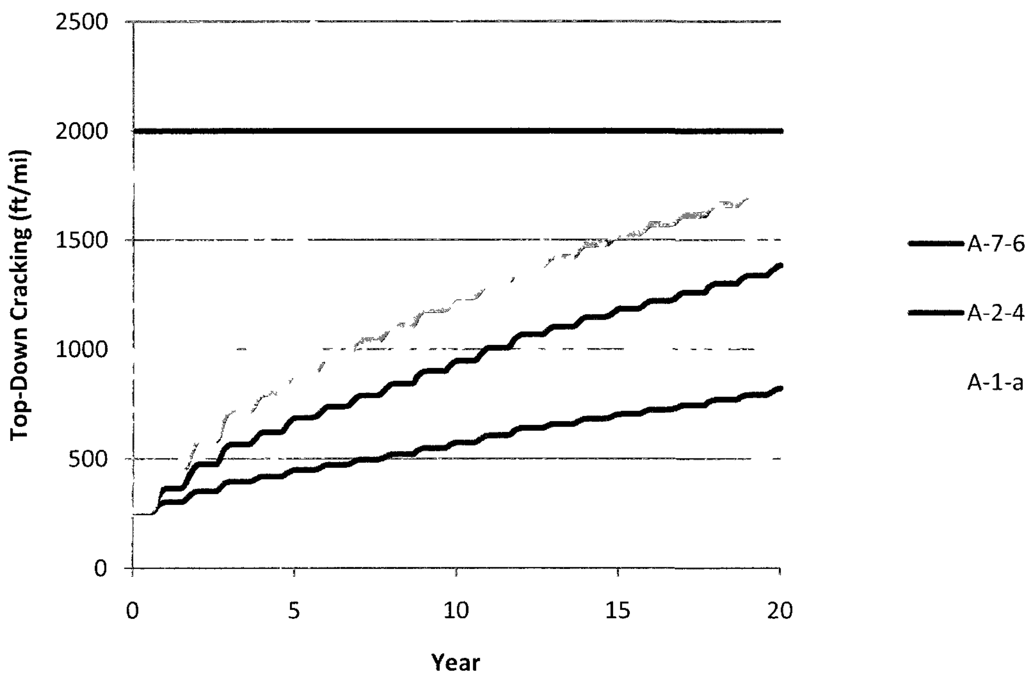


Figure 141A: Effect of Subgrade Type on Top-Down Cracking

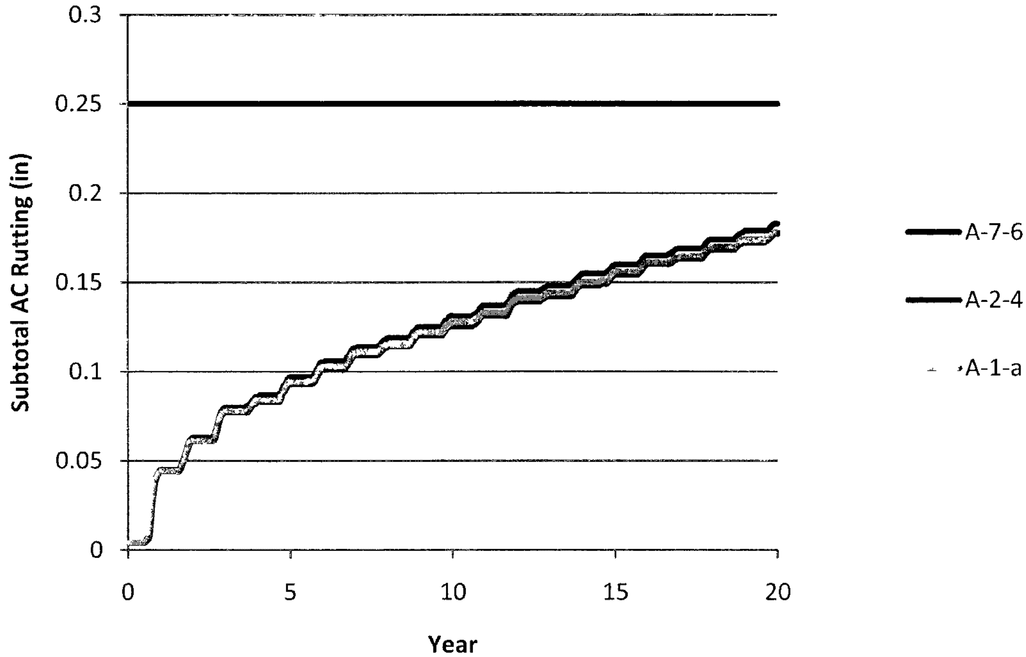


Figure 142A: Effect of Subgrade Type on Subtotal AC Rutting

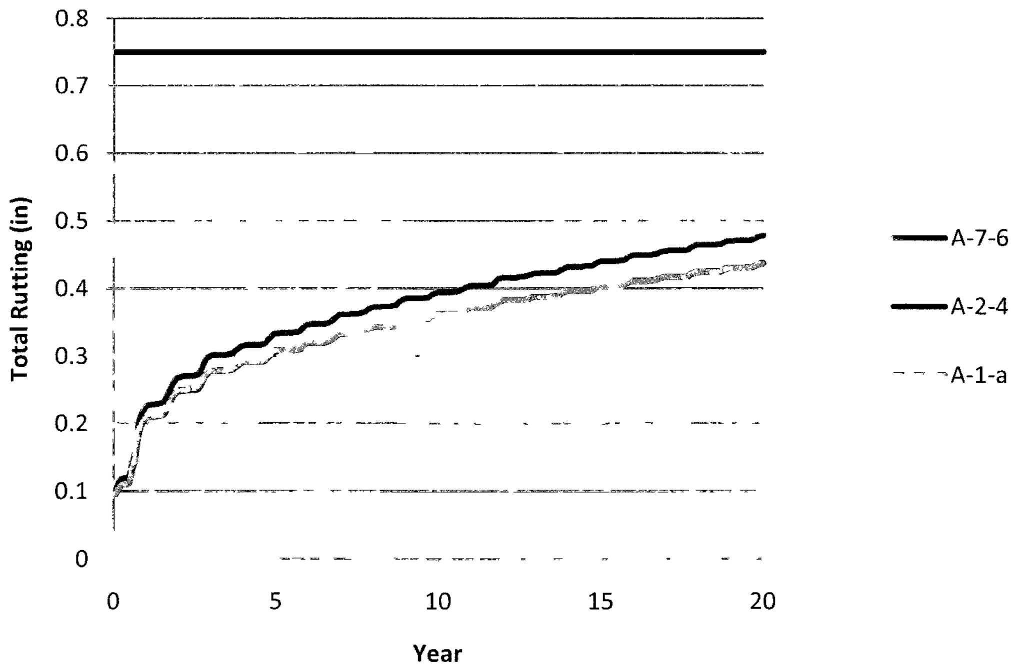


Figure 143A: Effect of Subgrade Type on Total Rutting

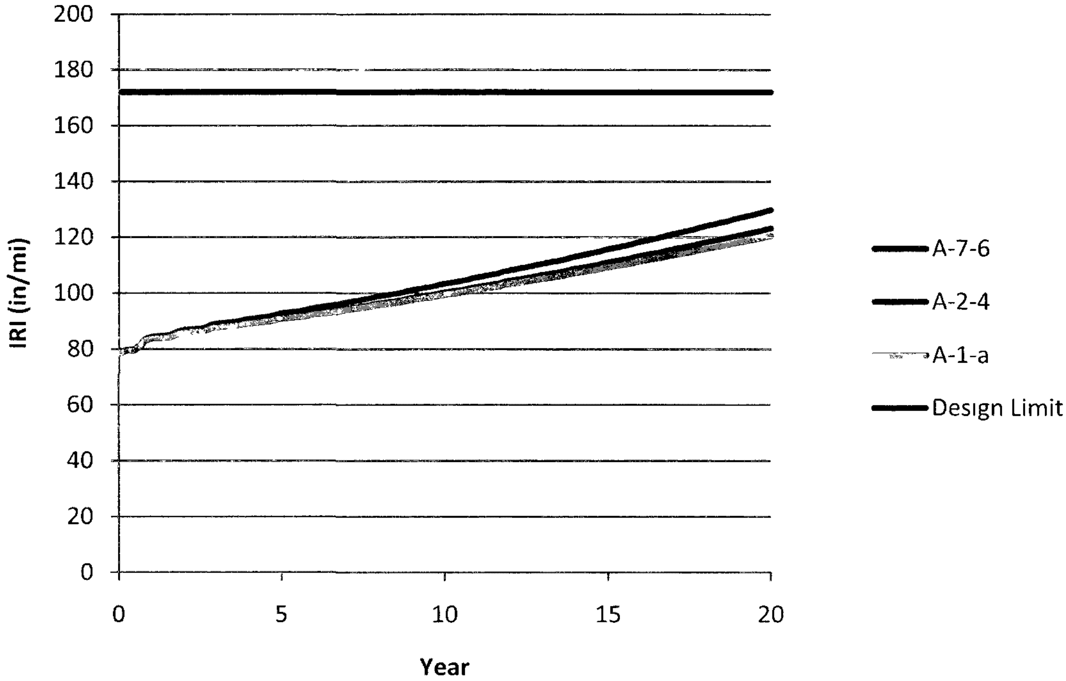


Figure 144A: Effect of Subgrade Type on IRI

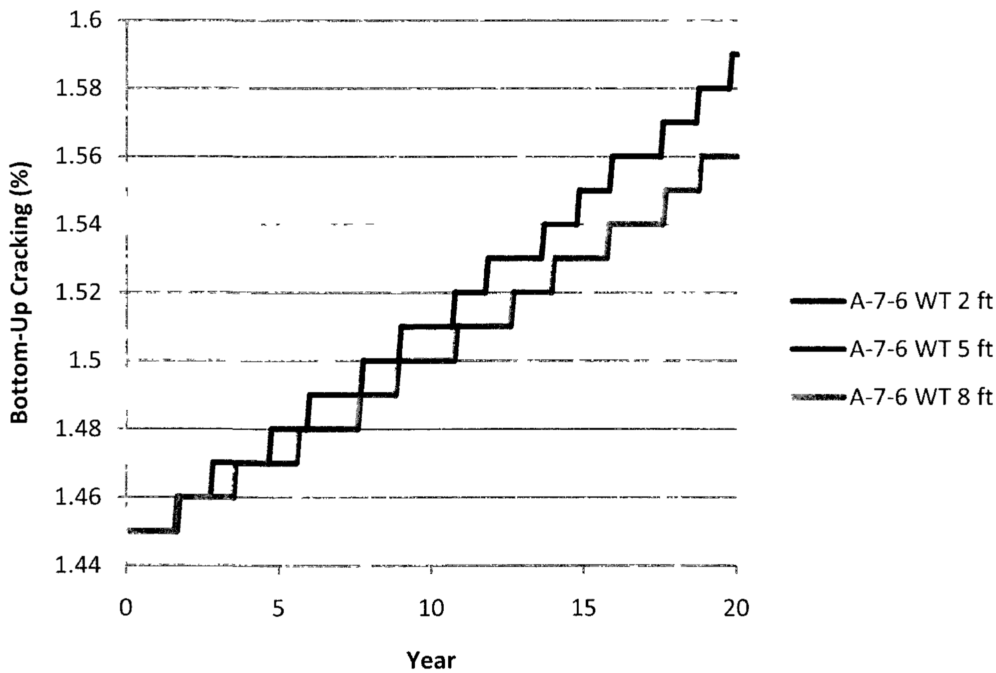


Figure 145A: Effect of Water Table on Bottom-Up Cracking with Weakest Subgrade

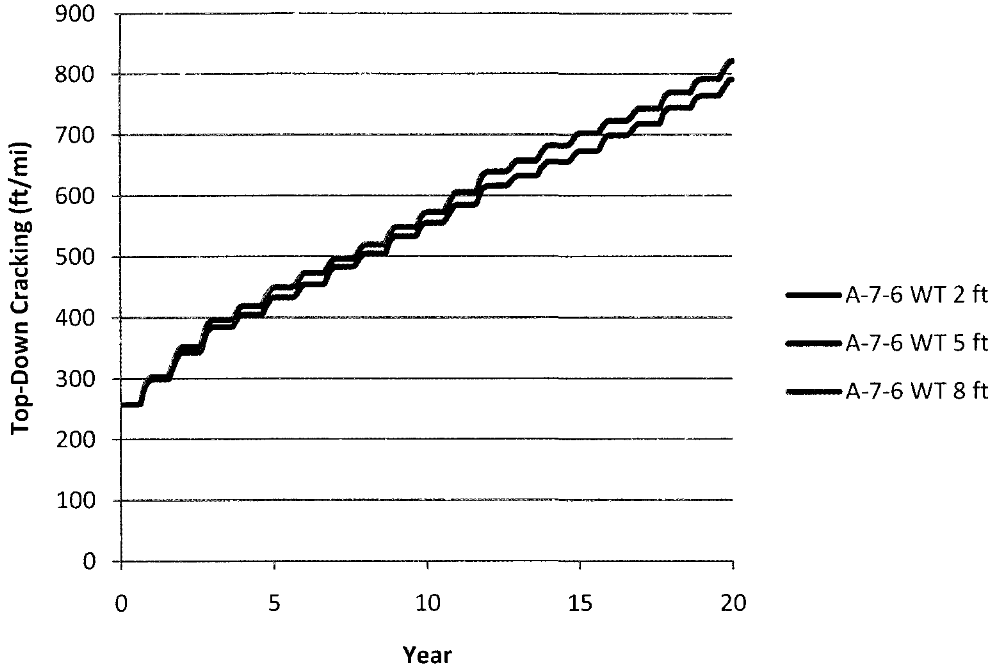


Figure 146A: Effect of Water Table on Top-Down Cracking with Weakest Subgrade

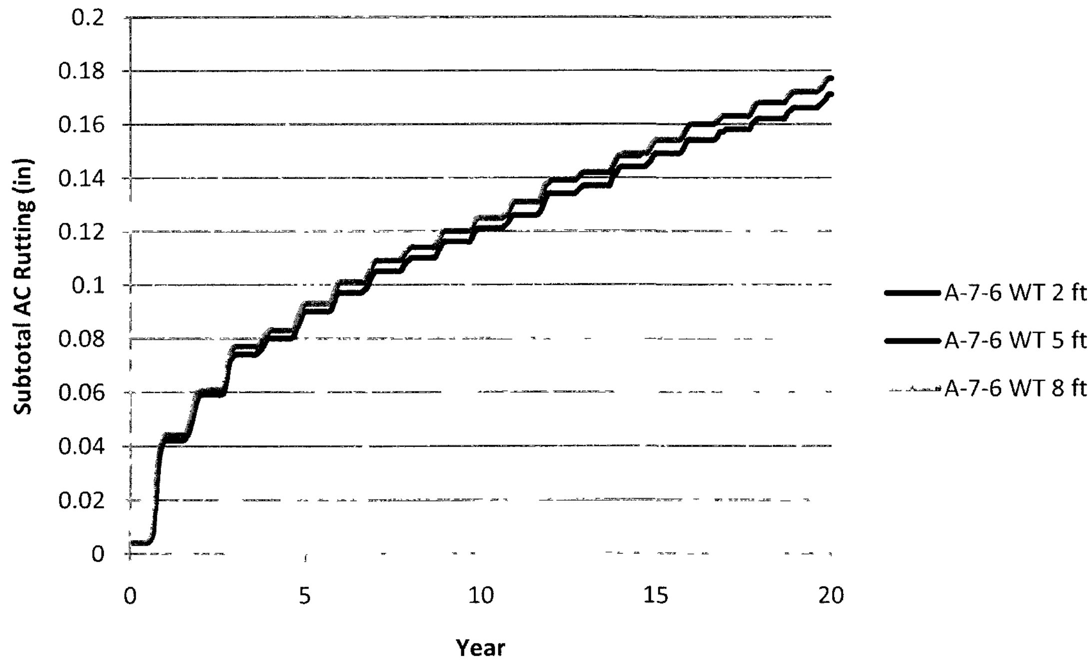


Figure 147A: Effect of Water Table on Subtotal AC Rutting with Weakest Subgrade

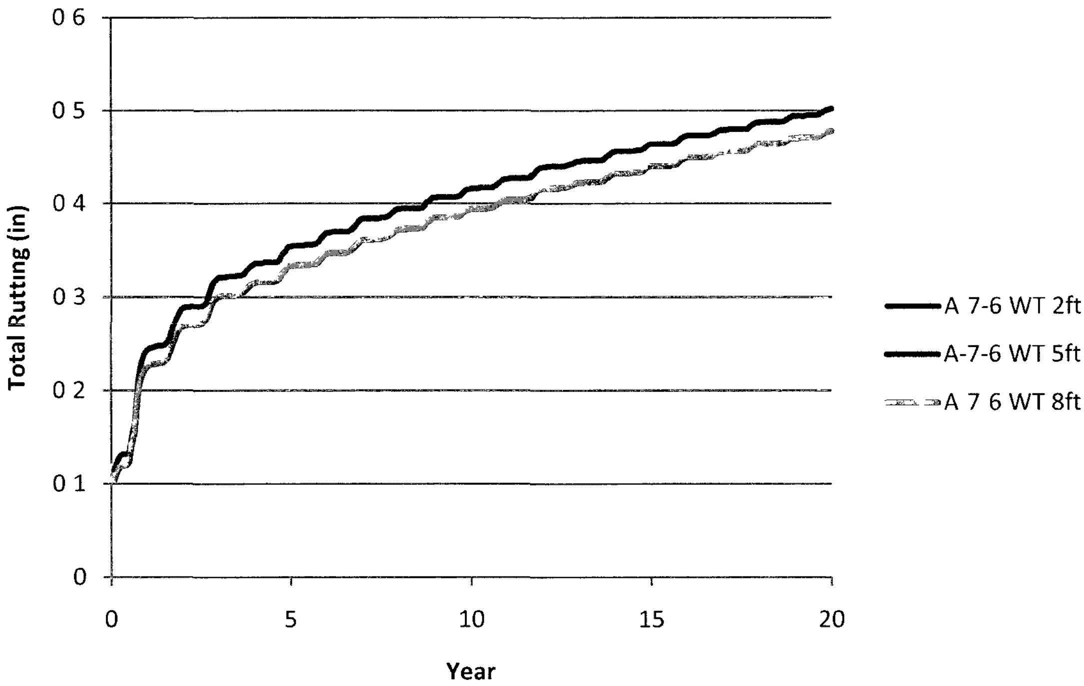


Figure 148A: Effect of Water Table on Total Rutting with Weakest Subgrade

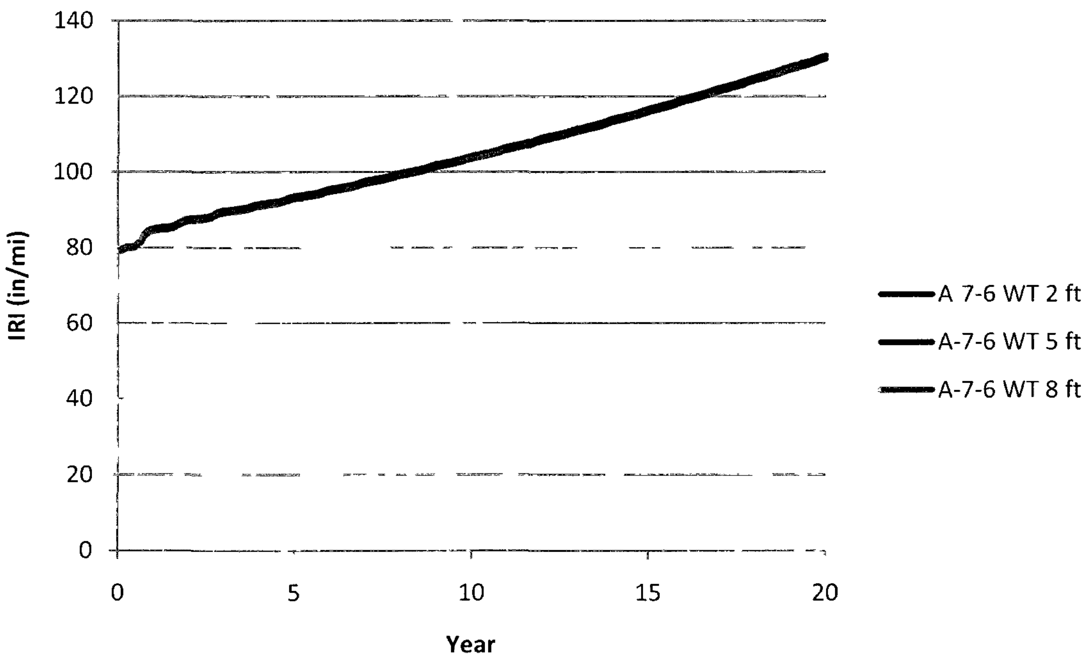


Figure 149A: Effect of Water Table on IRI with Weakest Subgrade

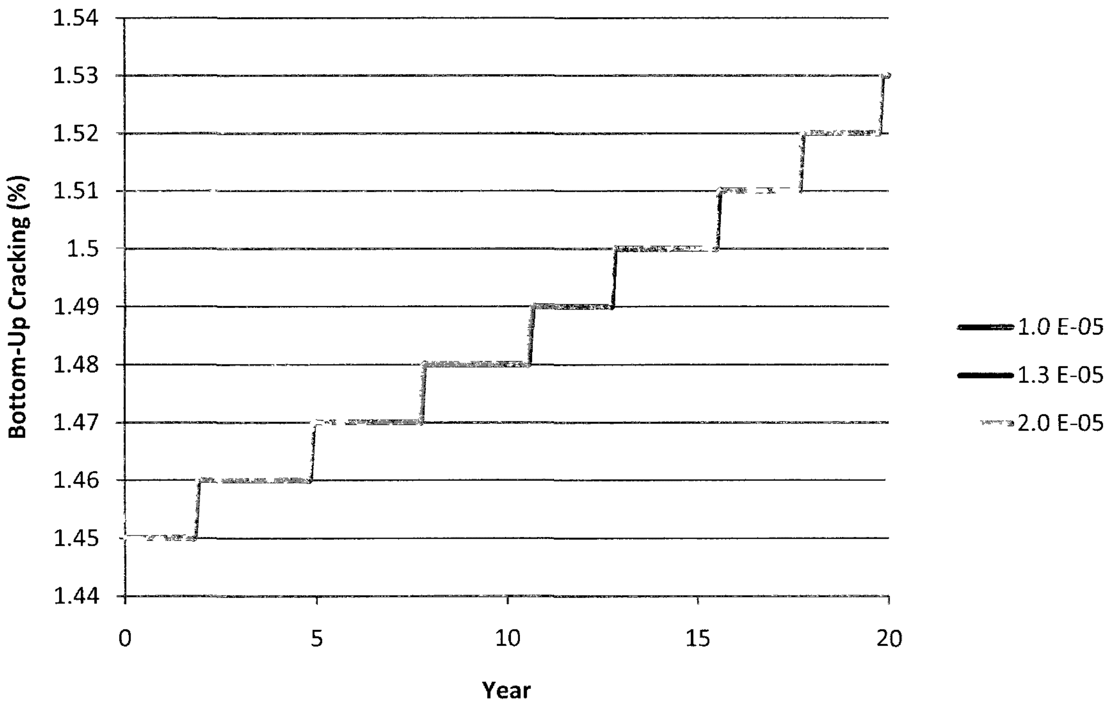


Figure 150A: Effect of HMA CTC on Bottom-Up Cracking

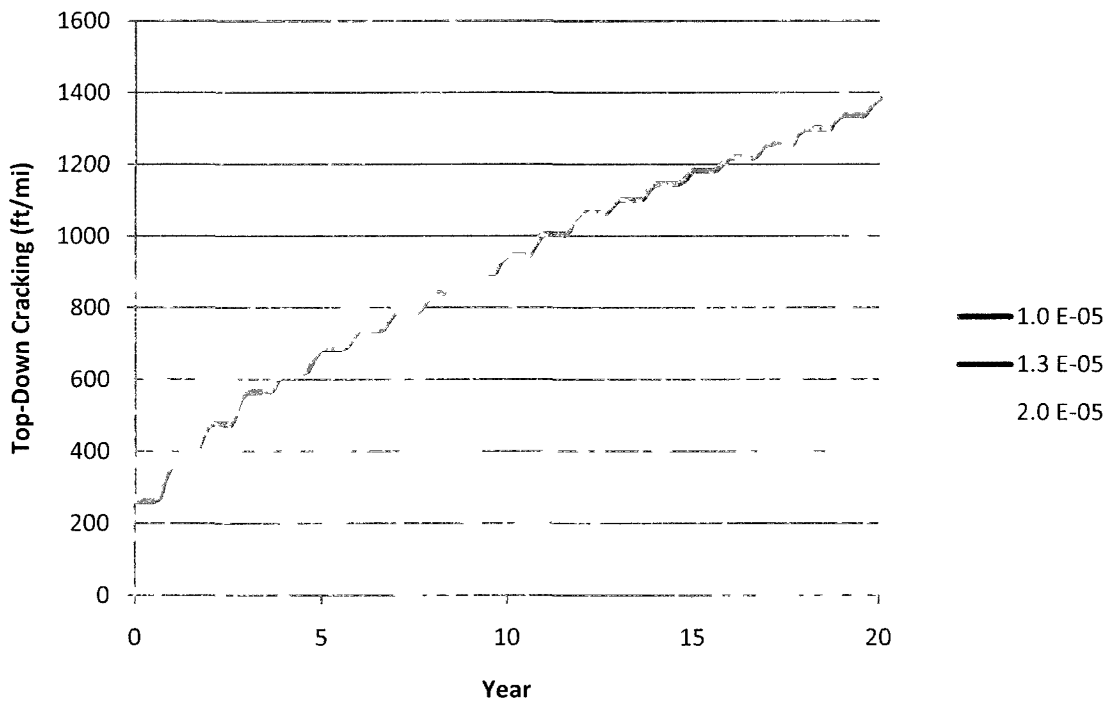


Figure 151A: Effect of HMA CTC on Top-Down Cracking

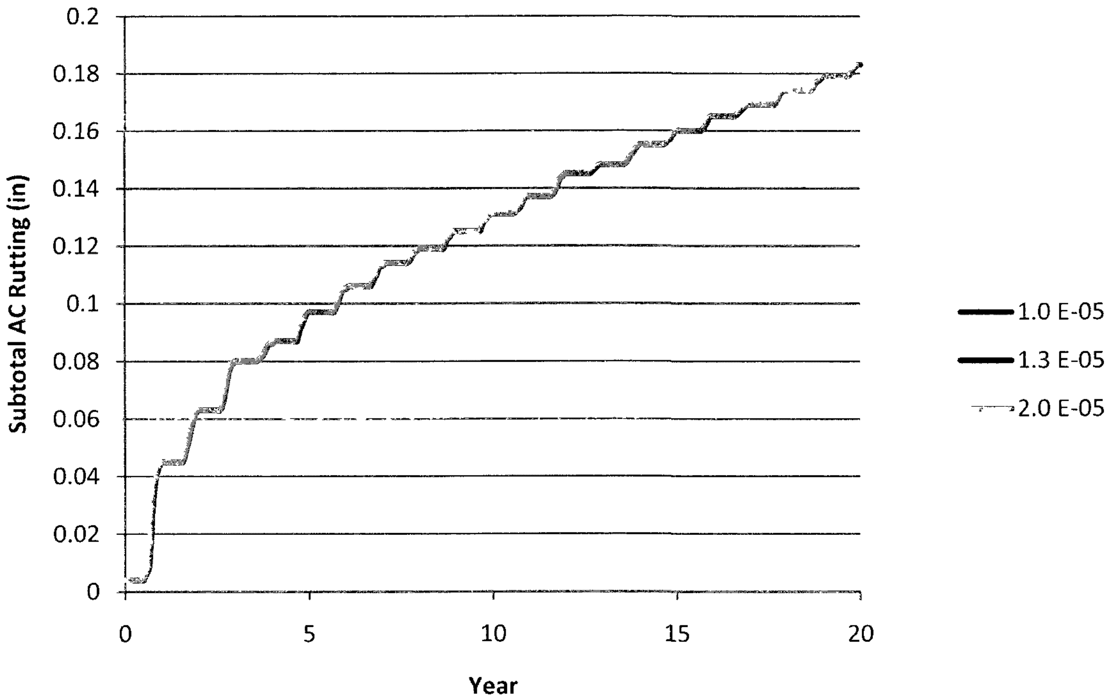


Figure 152A: Effect of HMA CTC on Subtotal AC Rutting

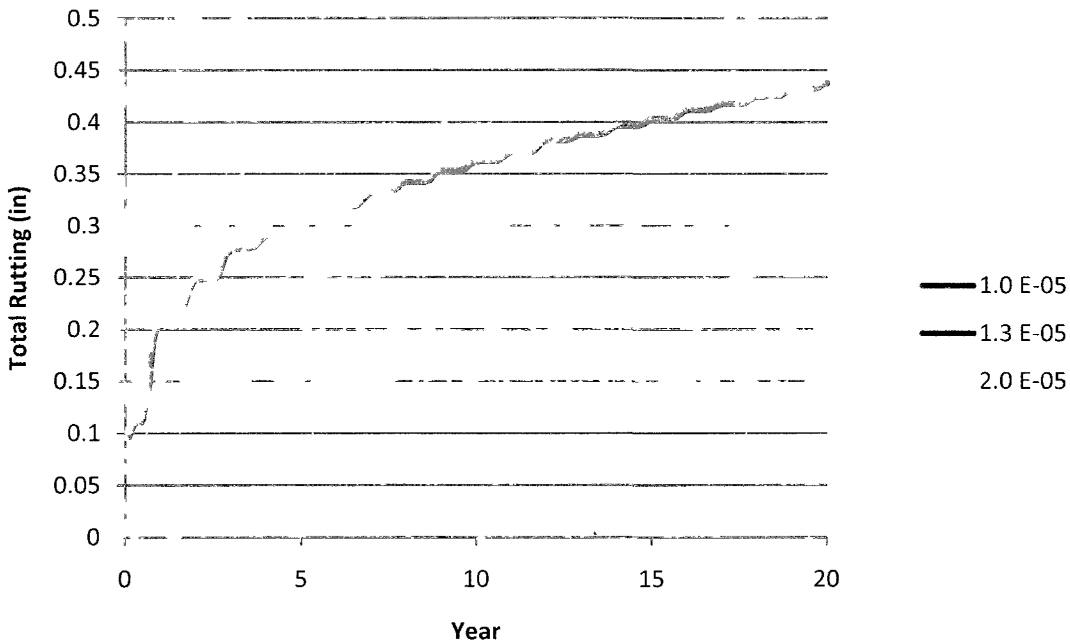


Figure 153A: Effect of HMA CTC on Total Rutting

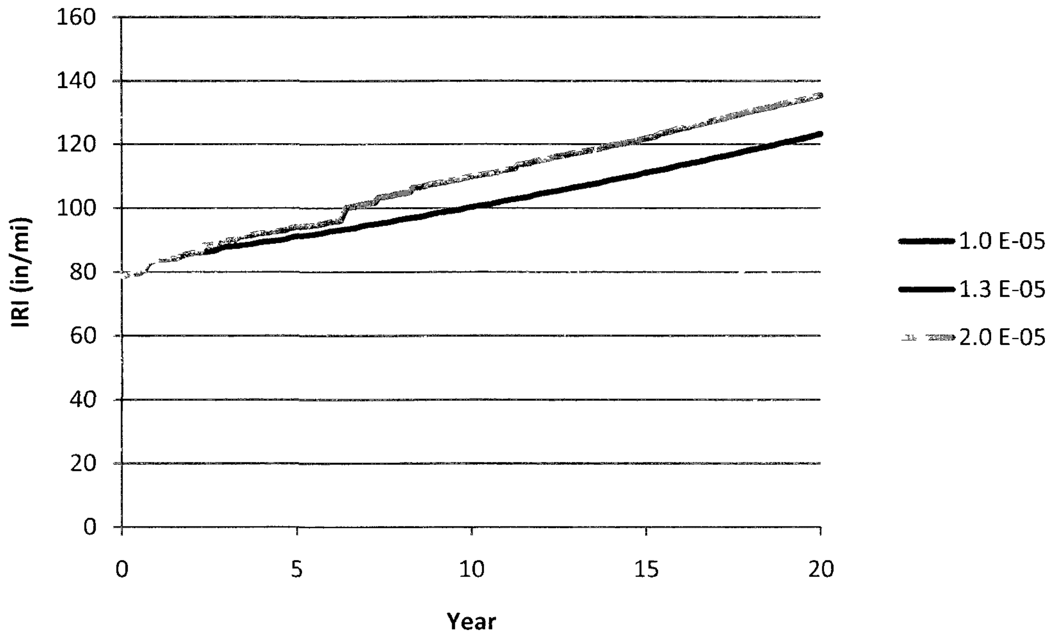


Figure 154A: Effect of HMA CTC on IRI

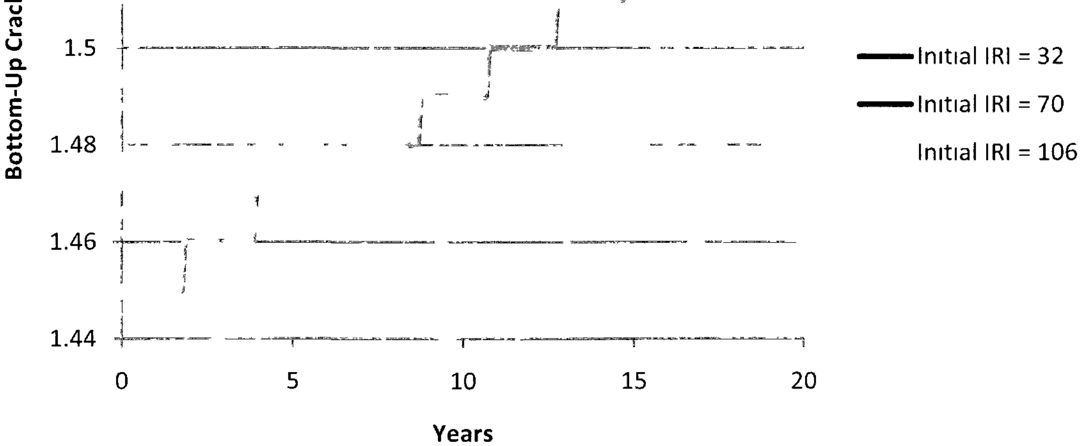


Figure 155A: Effect of Initial IRI on Bottom-Up Cracking

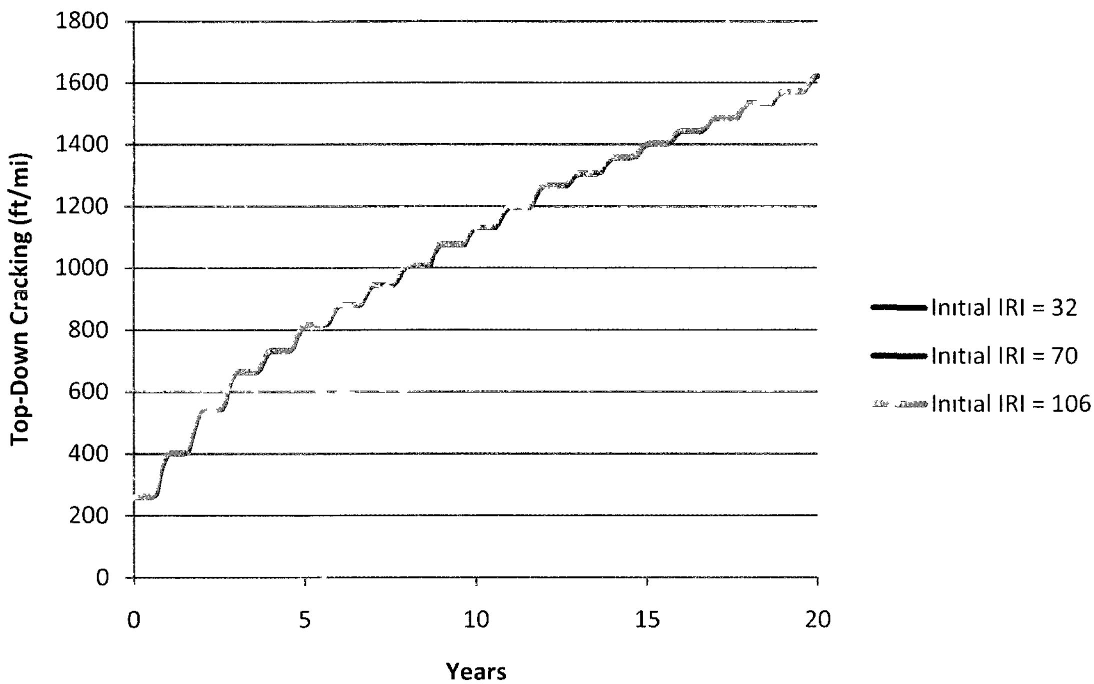


Figure 156A; Effect of Initial IRI on Top-Down Cracking

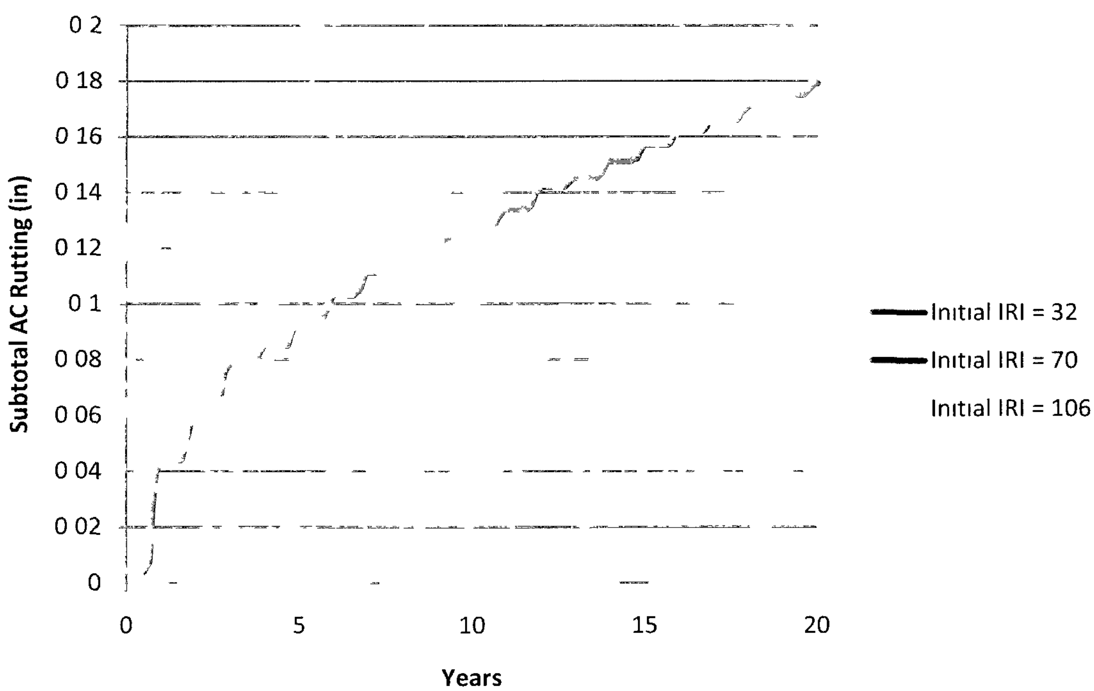


Figure 157A: Effect of Initial IRI on Subtotal AC Rutting

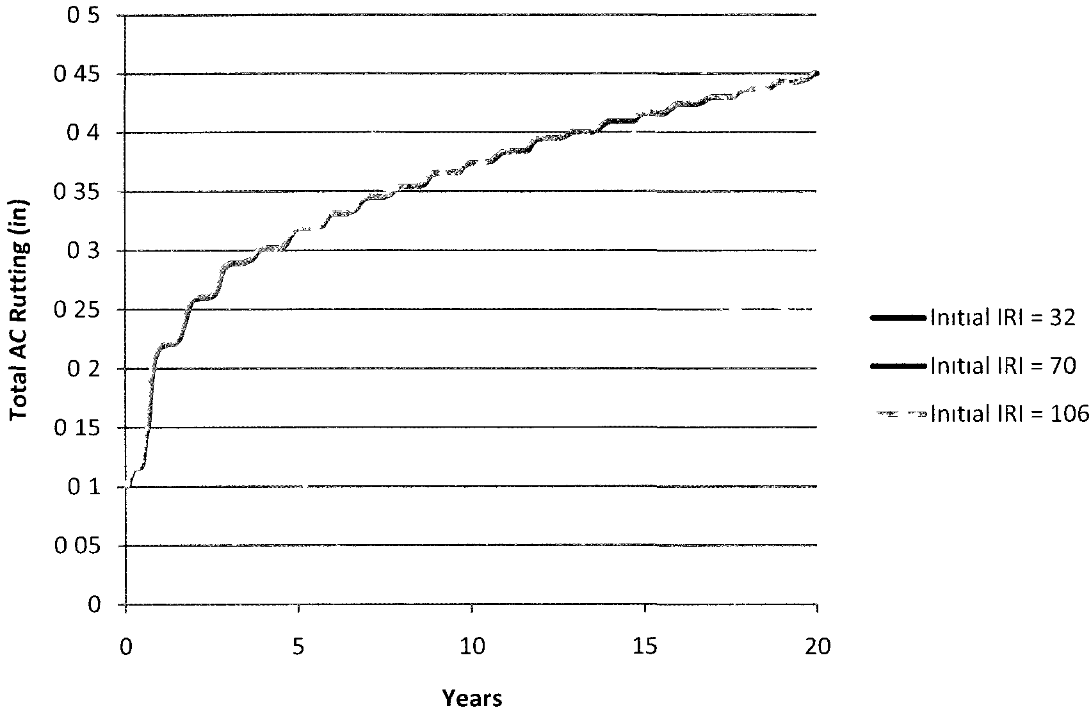


Figure 158A: Effect of Initial IRI on Total AC Rutting

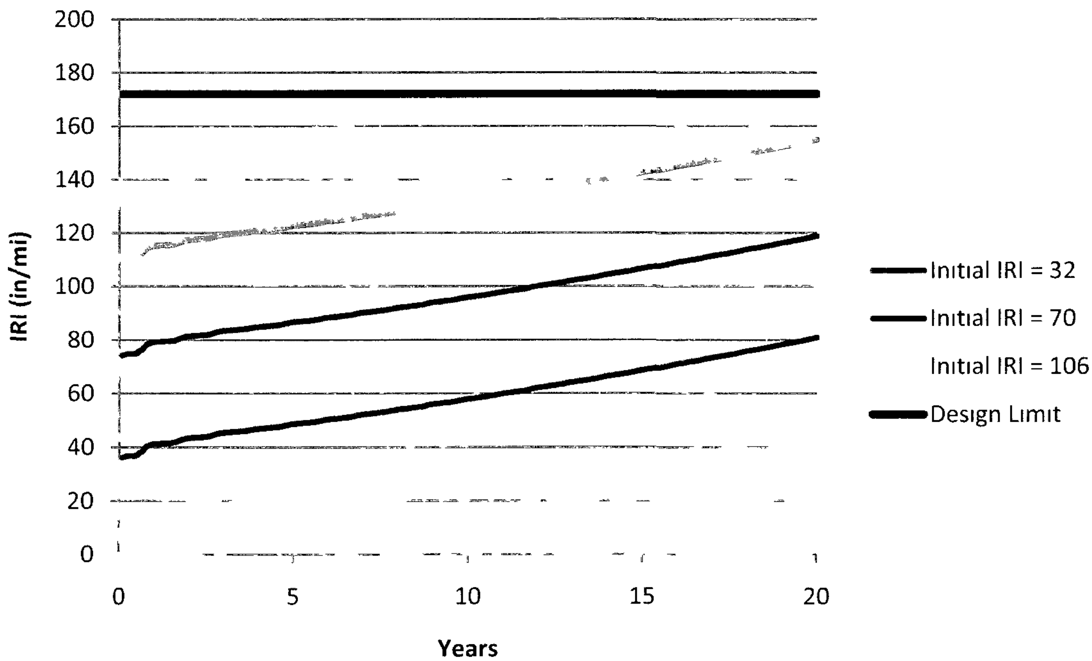


Figure 159A: Effect of Initial IRI on IRI

10. Sensitivity Analysis Summary Level 2

Normalization of the distresses was done to compare the effects of each input parameter on predicted distresses.

The normalized distress levels are calculated as the ratio of the difference between the maximum and minimum predicted distresses for each input variable to the distress levels corresponding to the control set of input values.

$$N = \frac{\textbf{Maximum Distress} - \textbf{Minimum Distress}}{\textbf{Distress for control input set}}$$

N - Normalized Value

Table 46A: Difference between Maximum and Minimum Distress Level – Level 2

VERMONT LEVEL 2					
Input Variable	**Bottom-Up Cracking**	**Top-Down Cracking**	**AC Rutting**	**Total Rutting**	**IRI**
HMA air voids	0.1	762.4	0.023	0.029	1.1
HMA effective binder content	0.05	410.48	0.028	0.035	1.3
HMA CTC	0	0	0	0	12.1
Base type/modulus	0.02	256.33	0.004	0.014	0.6
Subgrade type/modulus	0.03	928.81	0.006	0.042	9.3
WT with weakest subgrade	0.03	30.98	0.006	0.024	1.0
AADTT value	0.11	603.71	0.086	0.114	4.6
Traffic distribution	0.06	424.95	0.061	0.075	3.0
Initial IRI	0	0	0	0	74.0
HMA Layer thickness	0.2	1595.26	0.027	0.097	4.0

Table 47A: Normalized Values for Vermont Level 2 and Ranks

VERMONT LEVEL 2										
Input Variable	**Bottom-Up Cracking**		**Top-Down Cracking**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA air voids	0.065	3	0.551	3	0.126	5	0.066	6	0.009	8
HMA effective binder content	0.033	5	0.297	6	0.153	3	0.080	5	0.011	7
HMA CTC	0.000	8	0.000	9	0.000	8	0.000	9	0.098	2
Base type/modulus	0.013	7	0.185	7	0.022	7	0.032	8	0.005	10
Subgrade type/modulus	0.020	6	0.672	2	0.033	6	0.096	4	0.075	3
WT with weakest subgrade	0.020	6	0.022	8	0.033	6	0.055	7	0.008	9
AADTT value	0.072	2	0.436	4	0.470	1	0.261	1	0.037	4
Traffic distribution	0.039	4	0.307	5	0.333	2	0.172	3	0.024	6
Initial IRI	0.000	8	0.000	9	0.000	8	0.000	9	0.600	1
HMA thickness	0.131	1	1.153	1	0.148	4	0.222	2	0.032	5

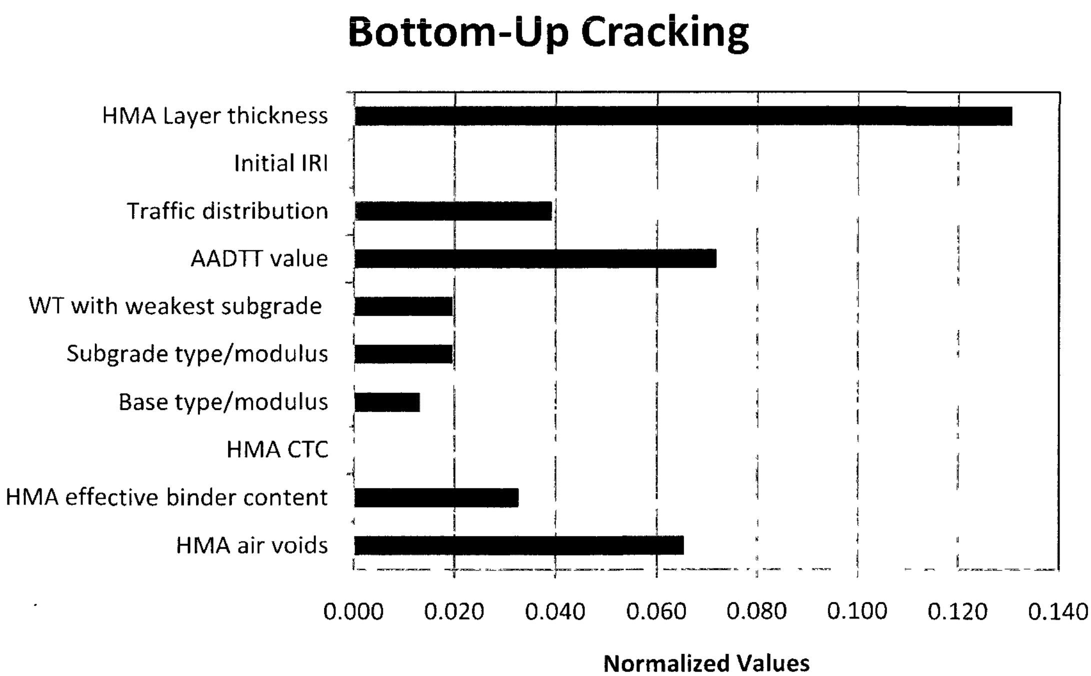


Figure 160A: Significance of Effect of Input Variables on Bottom-Up Cracking

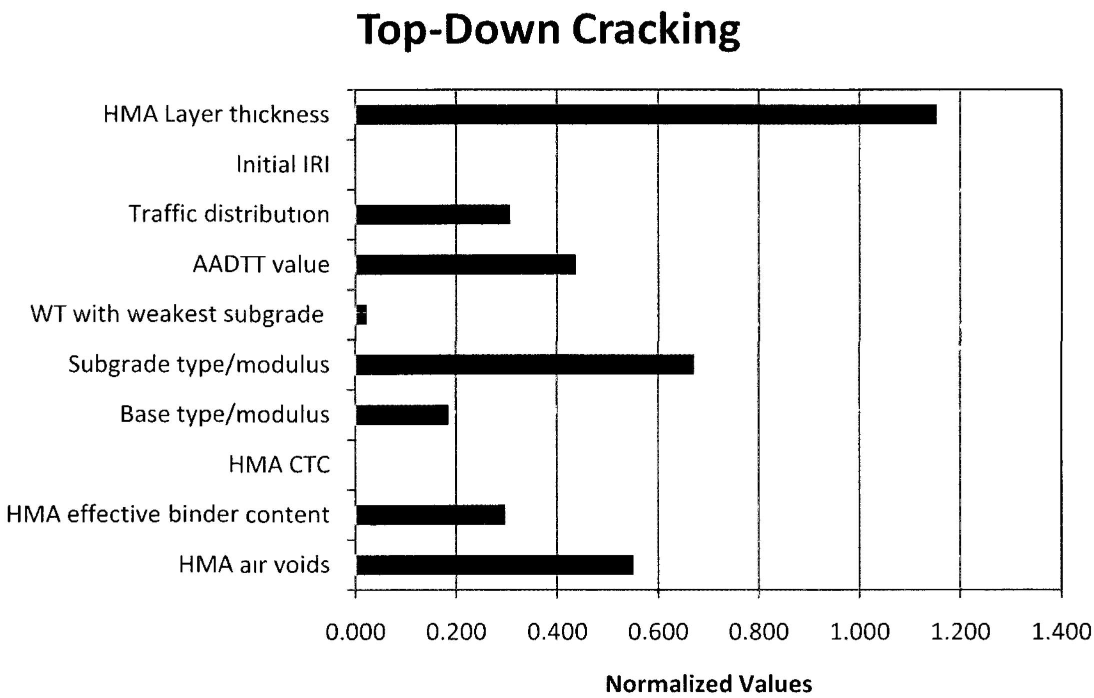


Figure 161A: Significance of Effect of Input Variables on Top-Down Cracking

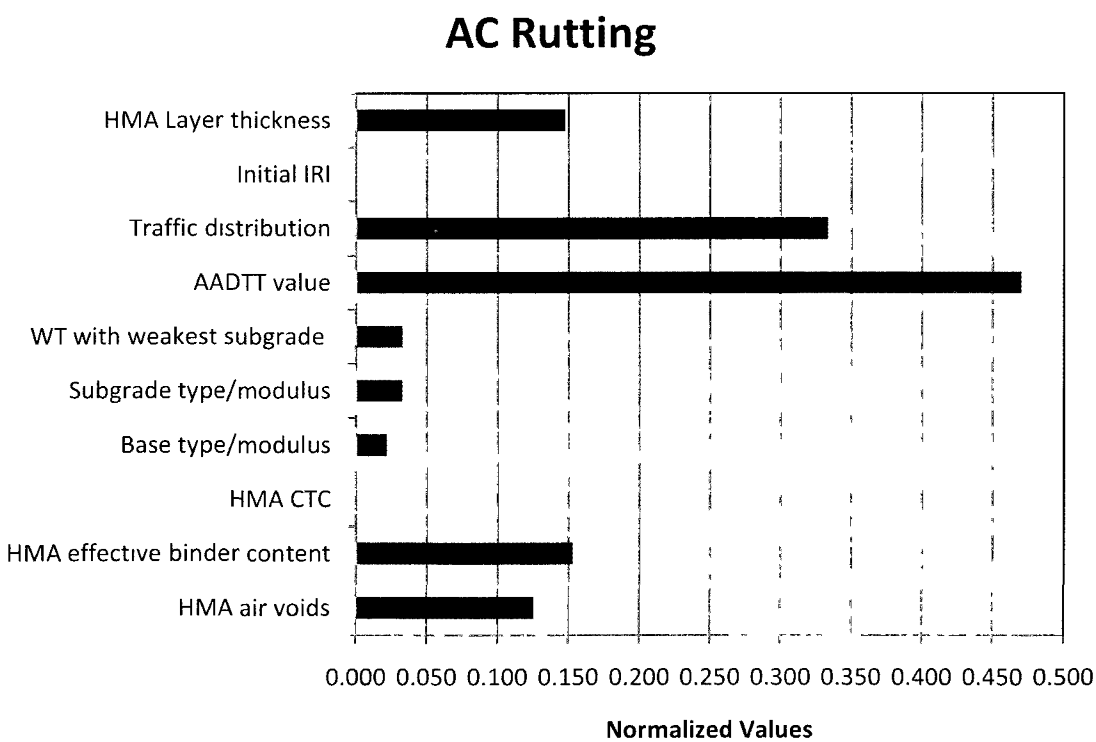


Figure 162A: Significance of Effect of Input Variables on AC Rutting

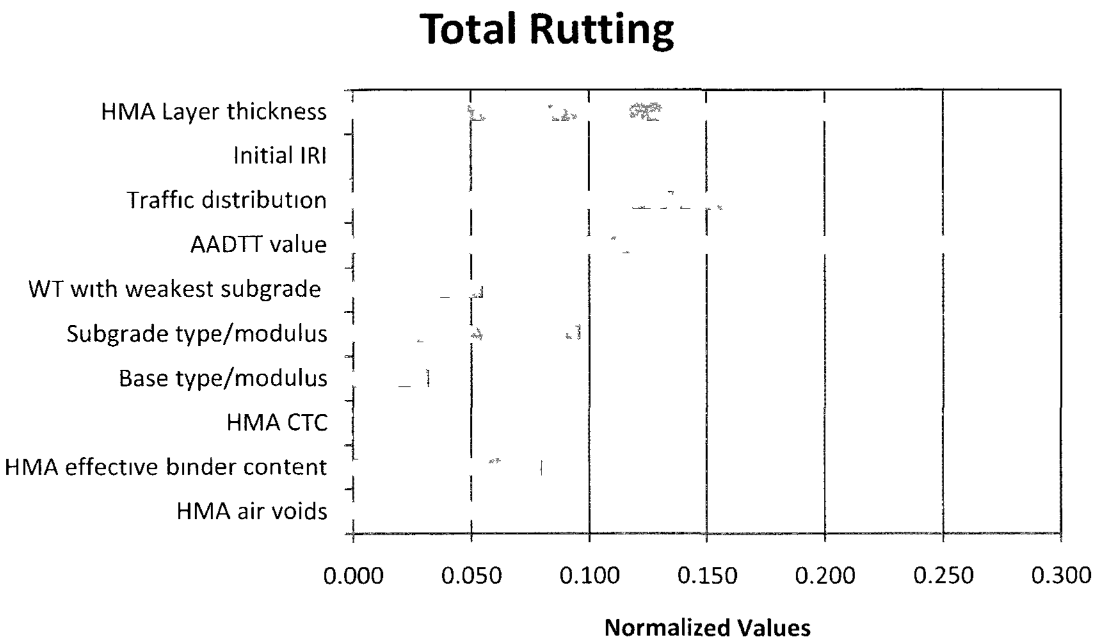


Figure 163A: Significance of Effect of Input Variables on Total Rutting

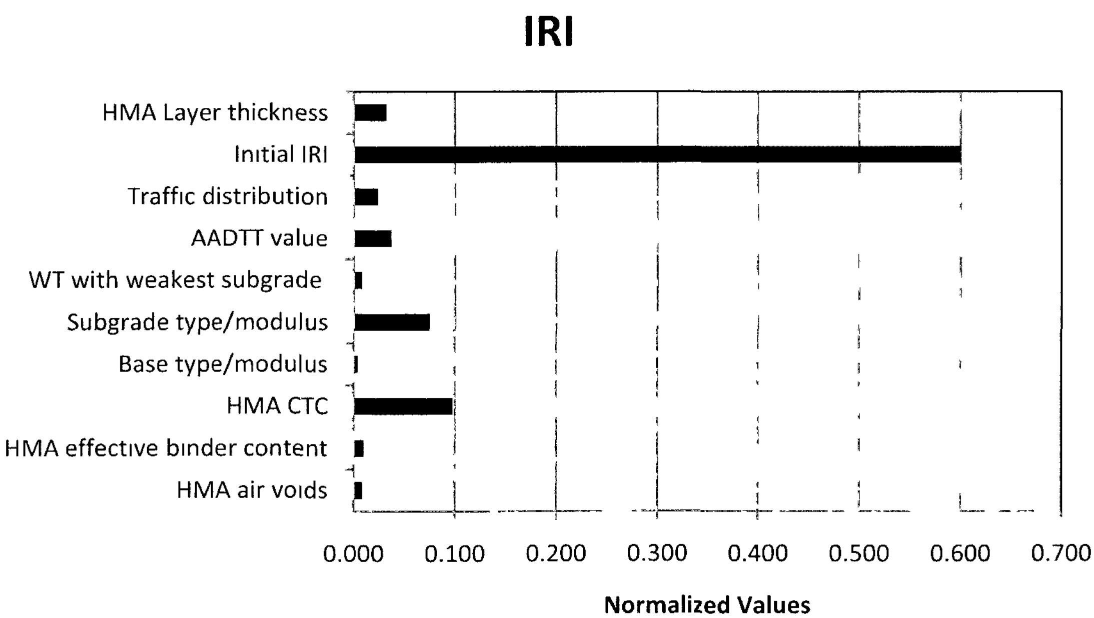


Figure 164A: Significance of Effect of Input Variables on IRI

Table 48A: Sensitivity Analysis Results Level 2*

Bottom-Up	Top-Down	AC Rutting	Total Rutting	IRI
HMA Thickness	HMA Thickness	AADTT	AADTT	Initial IRI
AADTT	Subgrade Type/ Modulus	Traffic Distribution	HMA Thickness	HMA CTC
HMA Air Voids	HMA Air Voids	HMA Effective Binder Content	Traffic Distribution	Subgrade Type/ Modulus
Traffic Distribution	AADTT	HMA Thickness	Subgrade Type/ Modulus	AADTT
HMA Effective Binder Content	Traffic Distribution	HMA Air Voids	HMA Effective Binder Content	HMA Thickness

*** Values from highest to lowest**

Table 49A: Sensitivity Analysis Summary Level 2

Design/ Material Variable	Distress/Smoothness				
	Bottom-Up Cracking	Top-Down Cracking	AC Rutting	Total Rutting	IRI
HMA air voids	XXX	XXX	X	X	
HMA effective binder content	XX	XX	XX	X	
HMA CTC					X
Base type/modulus	X	X	X	X	
Subgrade type/modulus	X	XXX	X	X	X
WT with weakest subgrade	X	X	X	X	
AADTT value	XXX	XXX	XXX	XXX	
Traffic distribution	XX	XX	XX	XX	
HMA Thickness	XXX	XXX	XX	XX	
Initial IRI					XXX

Note: **X – Small effect**
XX – moderate effect
XXX – large effect

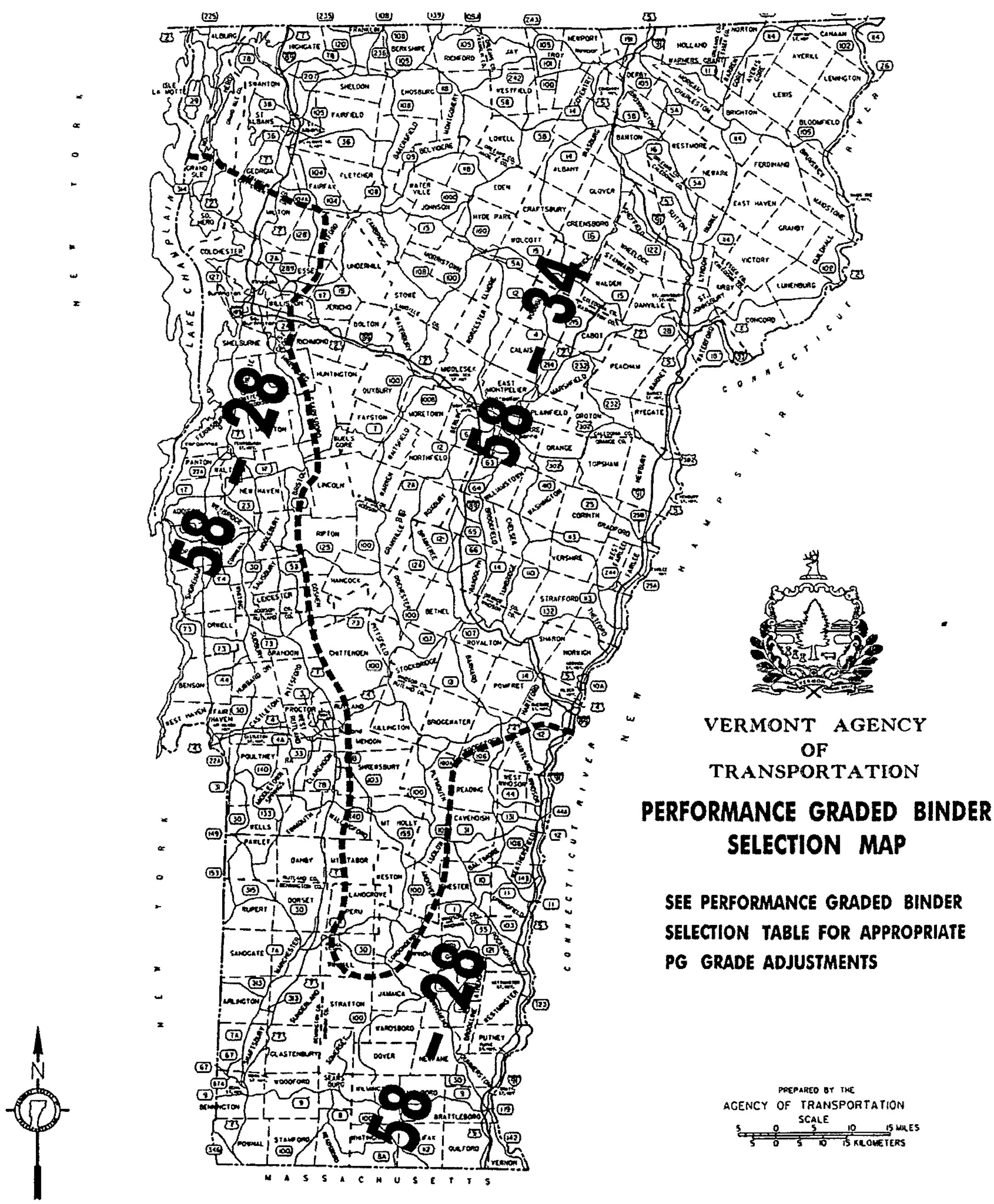
References (Vermont)

1. http://groundwaterwatch.usgs.gov/AWLSites.asp?S=440016073070901&ncd=
2. http://www.ltpp-products.com/DataPave/index.asp
3. Sensitivity Study of Design Input Parameters for Two Flexible Pavement Systems Using the MEPDG; Sunghwan Kim, Iowa State University, August 2005.
4. Vermont Agency of Transportation Flexible Pavement Design Procedures for use with the 1993 AASHTO Guide for Design of Pavement Structures; March 1, 2002.
5. Sensitivity Analysis of Pavement Performance Predicted Using the MEPDG; Dinesh Ayyala, May 2009.
6. Superpave Series No. 1 (SP-1, 2003) and No. 2 (SP-2, 1996)
7. Report No. UT-09.11a Draft User's Guide for UDOT MEPDG; October 2009.
8. ASTM Standards Volume 04.03, 2008
9. ASTM Standards Volume 04.08, 2009

Appendix A: Code Descriptions (Vermont)

CODE	DESCRIPTIONS
A1, A2, A3	3/8" (9.5 mm) HMA mix gradation
B1, B2, B3	3/4" (19 mm) HMA mix gradation
A1B1, A2B2, A3B3	Mean, coarse, fine HMA mix gradation
D1, D2, D3, D4	Truck class distribution
E1, E2, E3	Subgrade type
F1, F2, F3	Effective binder content
G1, G2, G3	AC Binder grade
M1, M2, M3	Base course aggregate gradation level 3
M1L2, M2 L2	Base course aggregate gradation level 2
N1, N2, N3	Coefficient of Thermal Contraction
Q1, Q2, Q3	AADTT value
R1, R2, R3	Traffic growth rate
S1, S2, S3	Initial IRI
T1, T2, T3	HMA layer thickness
U1, U2, U3	Traffic operational speed
V1, V2, V3	Binder air content
WT1, WT2, WT3	Ground water table level

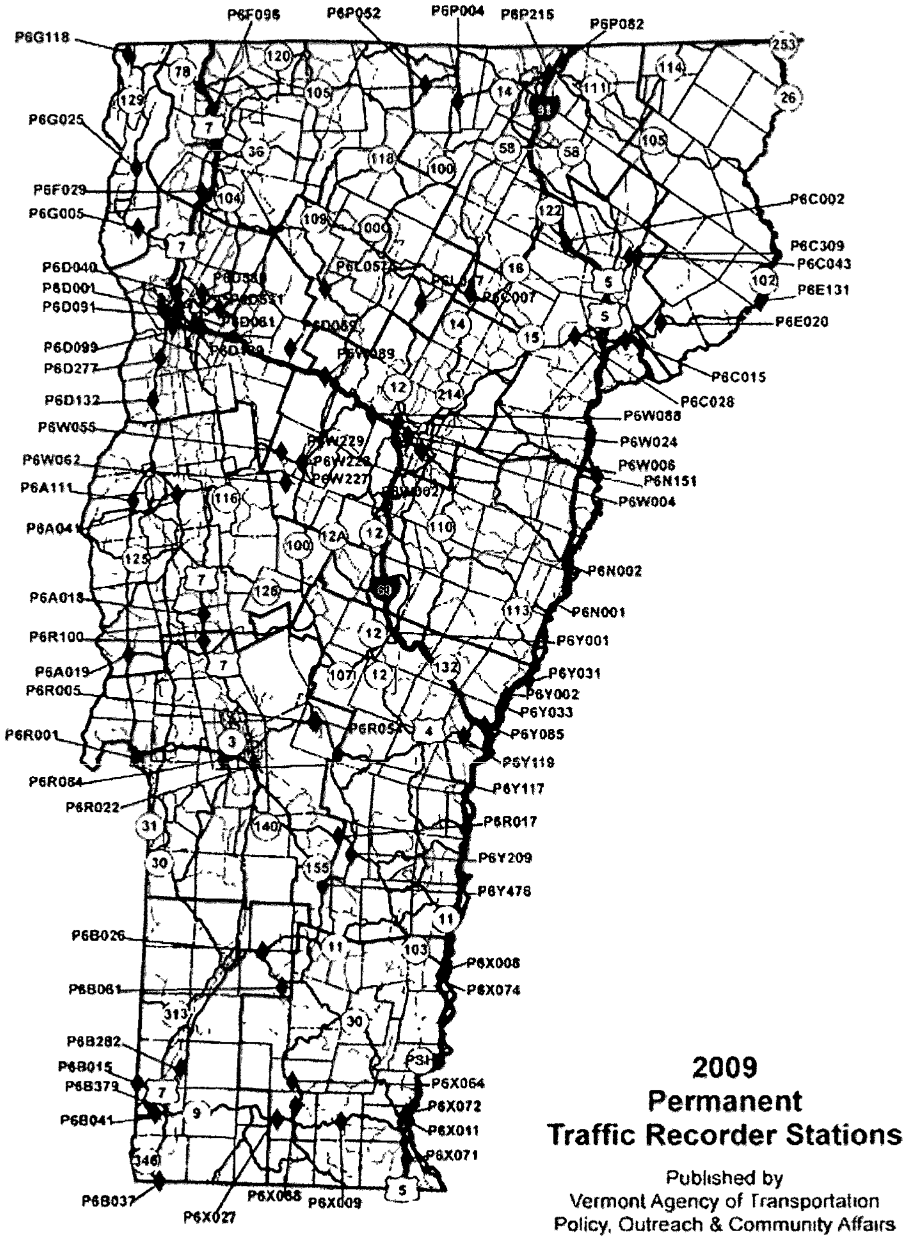
Appendix B: Vermont Performance Graded Binder Selection Map (Vermont)



Appendix C: Material Classification (Vermont)

Material Classification	M_r Range	Typical M_r
A-1-a	38,500 – 42,000	40,000
A-1-b	35,500 – 40,000	38,000
A-2-4	28,000 – 37,500	32,000
A-2-5	24,000 – 33,000	28,000
A-2-6	21,500 – 31,000	26,000
A-2-7	21,500 – 28,000	24,000
A-3	24,500 – 35,500	29,000
A-4	21,500 – 29,000	24,000
A-5	17,000 – 25,500	20,000
A-6	13,500 – 24,000	17,000
A-7-5	8,000 – 17,500	12,000
A-7-6	5,000 – 13,500	8,000
CH	5,000 – 13,500	8,000
MH	8,000 – 17,500	11,500
CL	13,500 – 24,000	17,000
ML	17,000 – 25,500	20,000
SW	28,000 – 37,500	32,000
SP	24,000 – 33,000	28,000
SW-SC	21,500 – 31,000	25,500
SW-SM	24,000 – 33,000	28,000
SP-SC	21,500 – 31,000	25,500
SP-SM	24,000 – 33,000	28,000
SC	21,500 – 28,000	24,000
SM	28,000 – 37,500	32,000
GW	39,500 – 42,000	41,000
GP	35,500 – 40,000	38,000
GW-GC	28,000 – 40,000	34,500
GW-GM	35,500 – 40,500	38,500
GP-GC	28,000 – 39,000	34,000
GP-GM	31,000 – 40,000	36,000
GC	24,000 – 37,500	31,000
GM	33,000 – 42,000	38,500

Appendix D: Permanent Traffic Recorder Stations (Vermont)



Appendix E: Performance Graded Binder Selection Table (Vermont)

Performance Graded Binder Selection Table

Adjusted PG Binder
on the Basis of Traffic Speed and Traffic Level

Design ESALs[1] (million)	Adjusted PG Binder Grade		
	Average Traffic Speed		
	< 20 km/h (12 mph)	20 to 70 km/h (12 to 44 mph)	> 70 km/h (44 mph)
< 0.3	PG 58-XX[2]	PG 58-XX	PG 58-XX
0.3 to < 3	PG 64-XX	PG 58-XX	PG 58-XX
3 to < 10	PG 70-28 [3]	PG 64-XX	PG 58-XX
10 to < 30	PG 70-28 [3]	PG 64-XX	PG 64-XX
> 30	PG 70-28 [3]	PG 64-XX	PG 64-XX

[1] Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period, regardless of the actual design life of the roadway.

[2] XX indicates the low temperature of the selected PG Binder determined from the Performance Graded Binder Selection Map, either -28 or -34.

[3] When the high-end temperature is adjusted two grades to a 70, the low-end temperature needs to be changed to a -28 if the selected PG binder is a PG 58-34. If selected PG binder is a PG 58-28, then no change to the low-end temperature is needed when changing the high-end temperature two grades to 70.

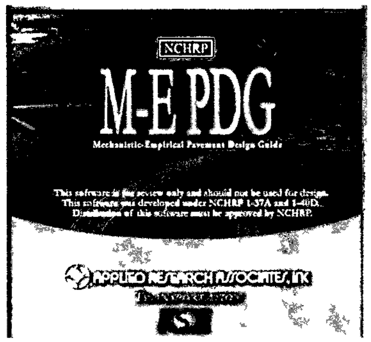
Appendix B: New York State M-E PDG Level 3 Report

NEW YORK STATE

RANGE OF VALUES FOR CRITICAL INPUT PARAMETERS

Department of Transportation

New York State



INPUT VALUE SELECTION FOR NEW YORK FOR M-E PDG RUNS

1. General Inputs

1.1 Design Life

- 20 years for a new pavement is recommended.

1.2 Construction & Traffic Opening Dates

- Base/subgrade construction month – August, 2010
- Pavement construction month - September, 2010
- Traffic opening date – October, 2010

1.3 Type of Pavement

This analysis is performed for a new flexible pavement.

1.4 Site/Project Identification

The site is located in East Syracuse, NY, 481 Highway (LTPP section # 36-1011-1)

- County: ONONDAGA
- Latitude, deg. 43.12
- Longitude, deg. -76.05
- Elevation, (ft) 395
- Org. construction date: 06/01/1984
- Constr. event date 09/14/1993
- Functional class: 11
- Years of climatic data 27

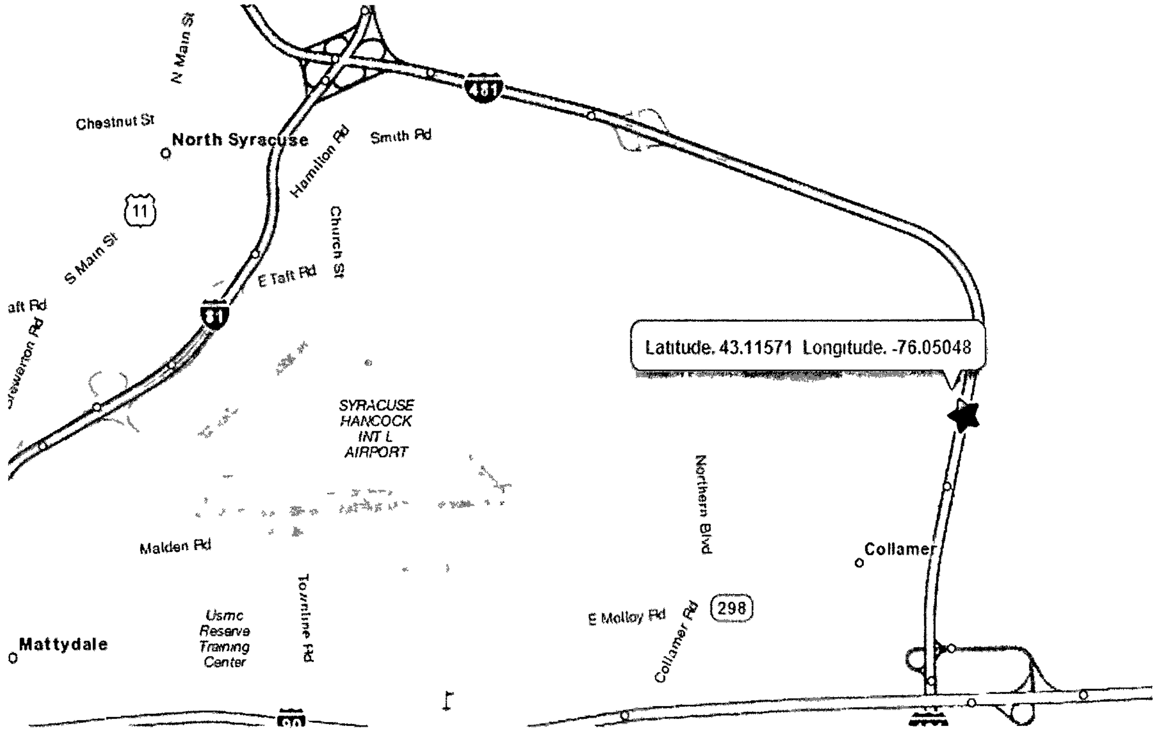


Figure 1B: LTPP Section 36-1011-1 Coordinates

1.5 LTPP Road Section Structure

Table 1B: Pavement Layers at Section 36-1011-1

Layer Type	Layer Thickness (in)
Original Surface Layer (layer Type: AC)	1.2”
AC Layer Below Surface (Binder Course)	8.6”
Base Layer (Layer Type: GB)	15.1”
Subgrade (Layer Type: SS)	Semi-infinite

LTPP road section # 36-1011-1 contains of 2 traffic lines in one direction.

2. Performance Criteria Inputs (Analysis Parameters)

Table 2B: Suggested Performance Criteria for Use in Pavement Design.*

Pavement Type	Performance Criteria	Max. Value at End of Design Life at Design Reliability
HMA pavement & overlays	HMA bottom up fatigue cracking (alligator cracking)	Interstate: 10 percent lane area Primary: 20 percent lane area Secondary: 45 percent lane area
	HMA longitudinal fatigue cracking (top down)	Interstate: 2,000-ft/mile Primary: 2,500-ft/mile Secondary: 3,000-ft/mile
	Permanent deformation (total mean rutting of both wheel paths)	Interstate: 0.40-in mean Primary: 0.50-in mean Others <40 mph: 0.75-in mean
	Thermal fracture (transverse cracks)	Interstate: Crack spacing > 70-ft (Crack length < 905-ft/mile) Primary/Secondary: Crack spacing > 50-ft (Crack length < 1267-ft/mile)
	IRI	Interstate/Primary: 169 in/mile maximum Secondary: 223 in/mile maximum

*Report No. UT-09.11a "Draft User's Guide for UDOT MEPDG"; October 2009

Table 3B: Analysis Parameters Used for NY State.

Analysis parameter	Maximum criteria at 90% Reliability
Initial IRI (in /mi)	75
Terminal IRI (in /mi)	172
AC Surface Down Cracking (ft/mi)	2000
AC Bottom Up Cracking (%)	25
AC Thermal Fracture (ft/mi)	1000
Permanent Deformation – Total Pavement (in)	0.75
Permanent Deformation – AC only (in)	0.25

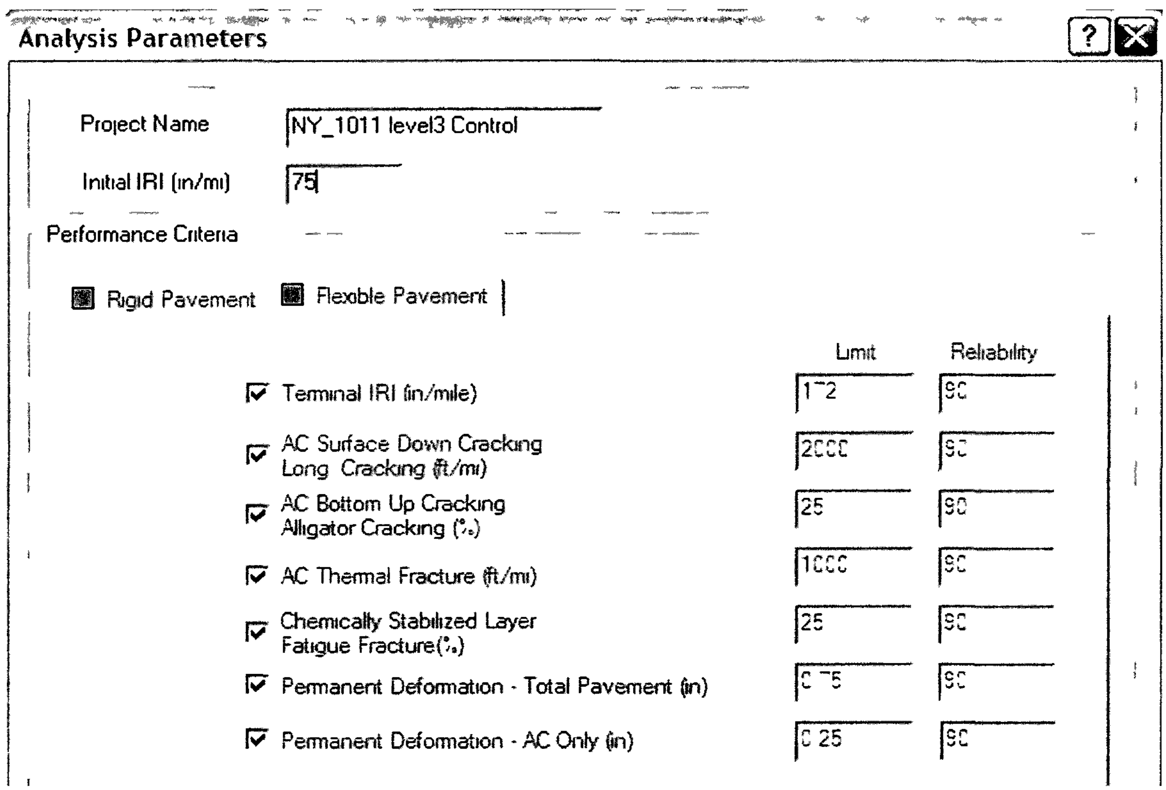


Figure 2B: Analysis Parameters Used in NY

Table 4B: NY State Level 3 Reliability Summary

Project: NY_1011 level3 Control Reliability Summary					
Performance Criteria	Distress Target	Reliability Target	Distress Predicted	Reliability Predicted	Acceptable
Terminal IRI (in/mi)	172	90	124.1	92.19	Pass
AC Surface Down Cracking (Long. Cracking) (ft/mile):	2000	90	3.5	99.98	Pass
AC Bottom Up Cracking (Alligator Cracking) (%):	25	90	0.1	99.999	Pass
AC Thermal Fracture (Transverse Cracking) (ft/mi):	1000	90	460.9	99.999	Pass
Chemically Stabilized Layer (Fatigue Fracture)	25	90			N/A
Permanent Deformation (AC Only) (in):	0.25	90	0.17	92.01	Pass
Permanent Deformation (Total Pavement) (in):	0.75	90	0.38	99.999	Pass

Table 5B: IRI Ranges Defined by FHWA Highway Statistics Publications

IRI Scale (in/mi)	Description
< 60	Very Smooth
61 – 120	Smooth
121 – 170	Fair
171 – 220	Rough
> 220	Very Rough

3. Design Reliability Input

Table 6B: Tentative Recommended Level of Reliability

Functional Classification	**Urban**	**Rural**
Interstate/Freeways	95	92
Principal Arterials	90	85
Collectors	80	75
Locals	70	60

A design reliability of 90 percent is selected for this analysis. A higher level of design reliability is not recommended, because of the significant cost increase.

4. Traffic Inputs

Table 7B: Recommended Traffic Value Inputs

Traffic Input	**Recommended Value**
Initial two way AADTT (class 4 and above)	Projected traffic for opening month from measured historical data.
Number of lanes in design direction	Actual or from design plans.
Percent of trucks in design direction (%)	50%, unless higher truck volume is measured in design direction
Percent of trucks in design lane (%)	Actual measured in design lane over 24-hours, otherwise use the following: • 100% for 1 lane in design direction • 95% for 2 lanes in design direction For unusual truck traffic situations (mountainous terrain or urban usage complexity), conduct on site truck lane usage counts over 24-hour period.
Operational Speed (mph)	Posted or Design Speed

4.1 Annual Average Daily Truck Traffic (AADTT)

Truck Traffic (AADTT) was calculated by taking 16.0 % of Annual Average Daily Traffic (AADT) as given in 2010 Traffic Data Viewer. The AADT for 481 Highway located in East Syracuse, NY (ONONDAGA County) was 26198 for the 2010 year. Control AADTT for this study is taken as 4192.

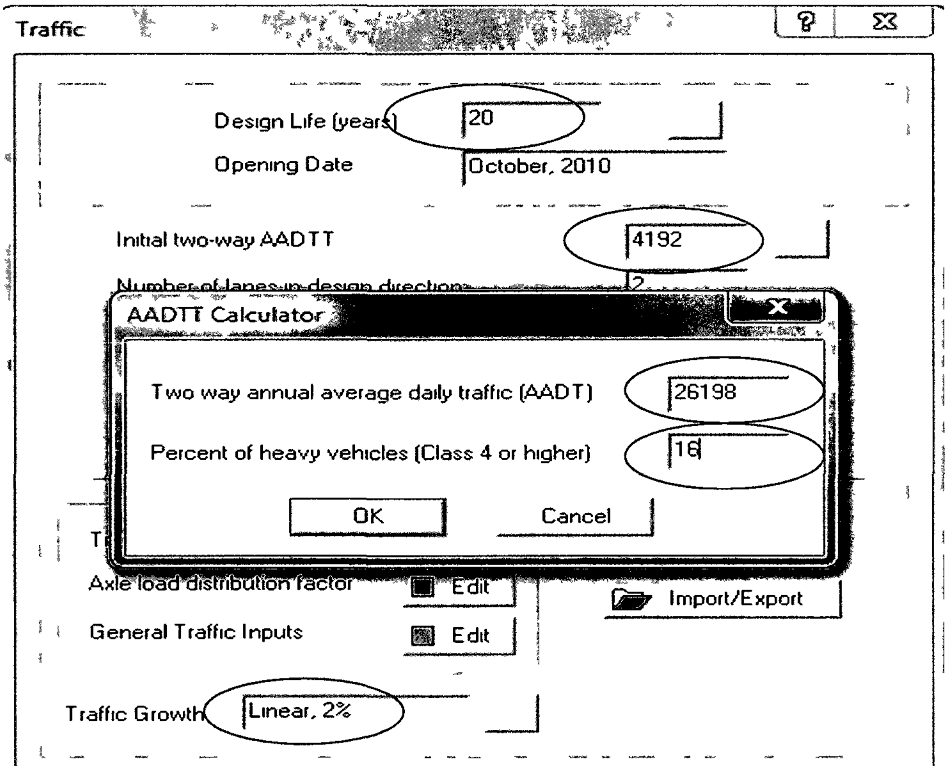


Figure 3B: Traffic Inputs for East Syracuse, NY

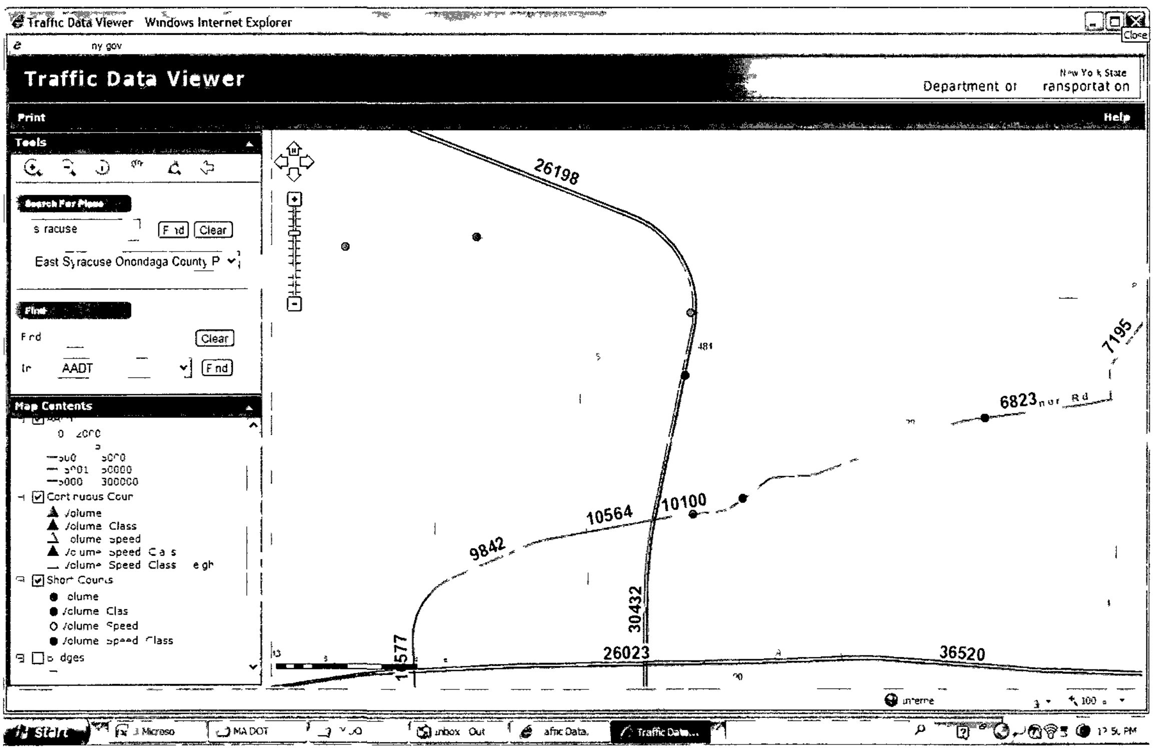


Figure 4B: Traffic Data Viewer October 2010

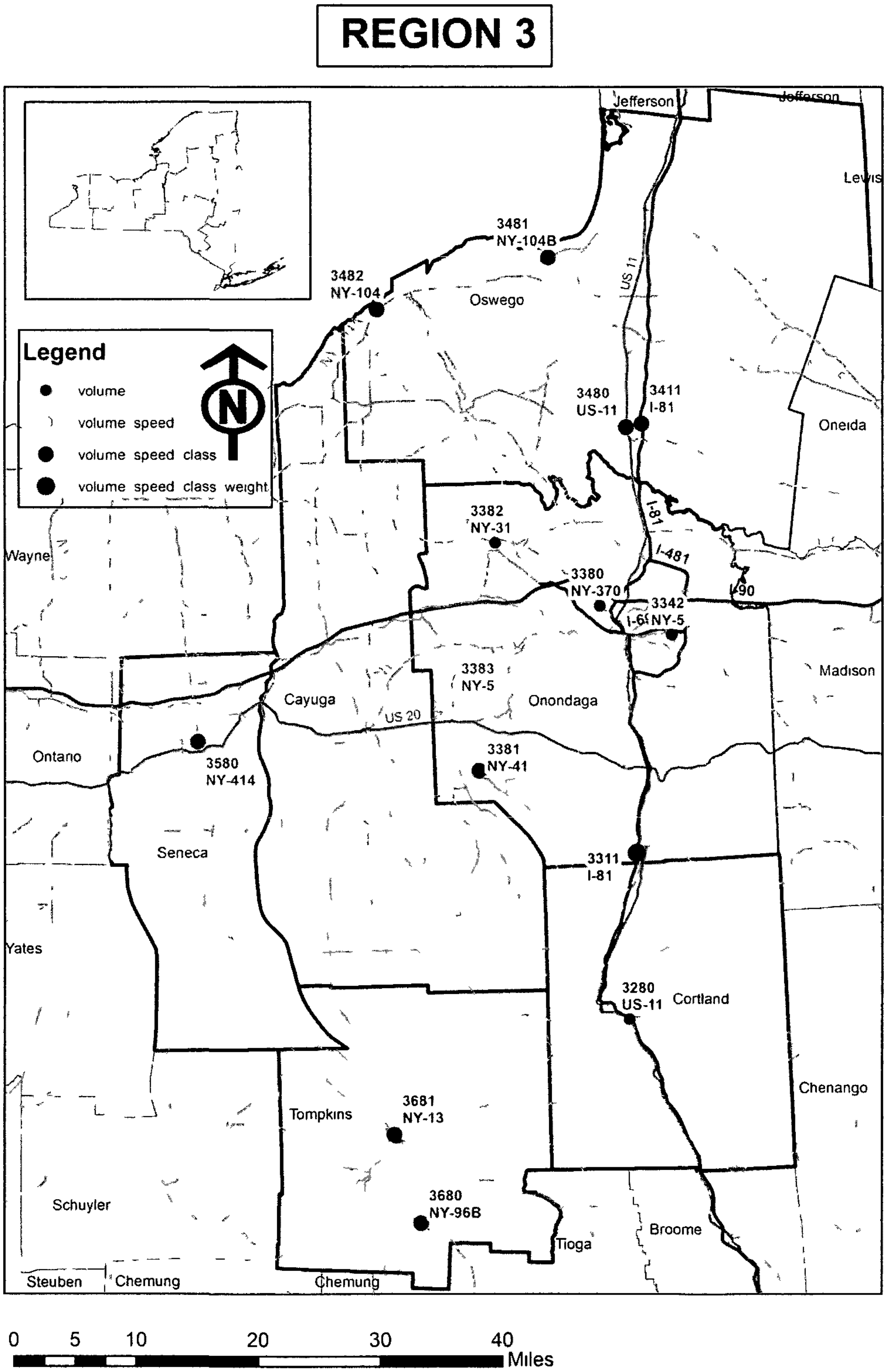


Figure 5B: NY State DOT Region 3 map

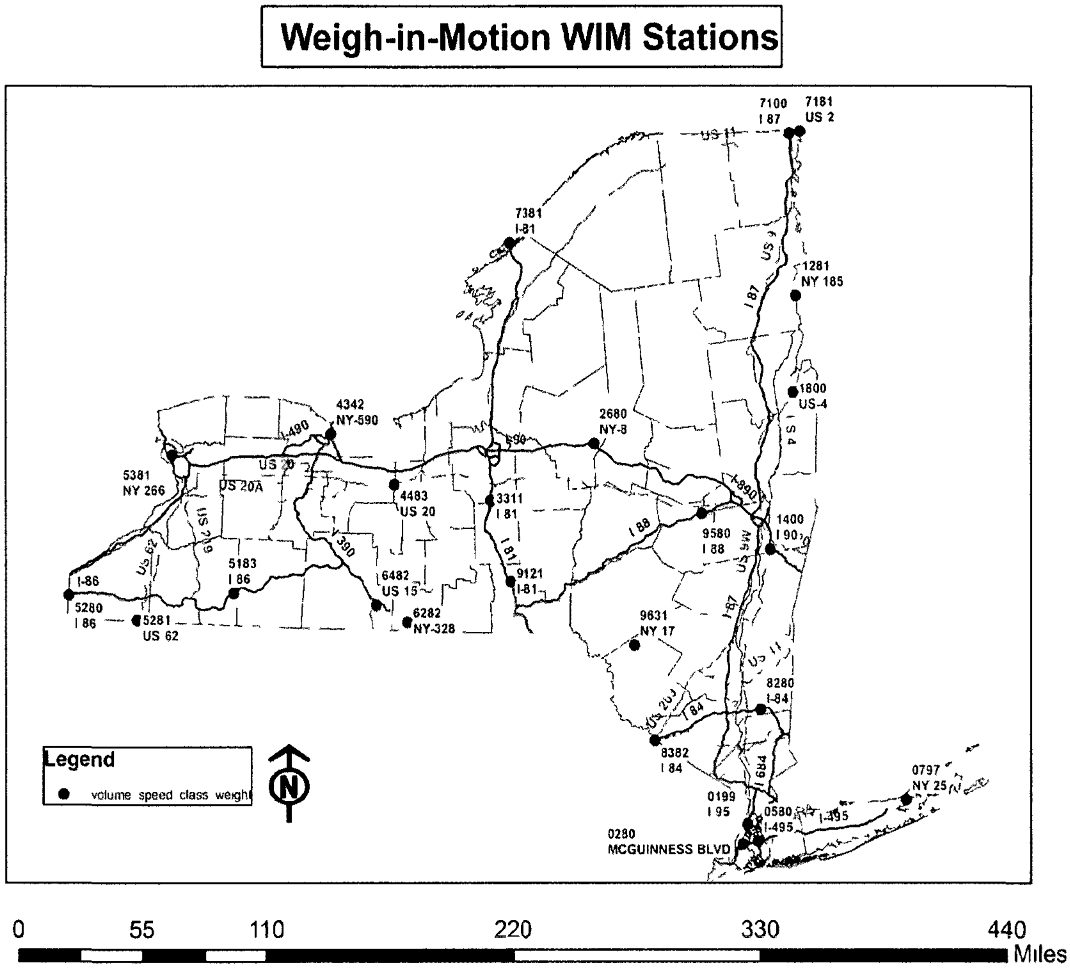


Figure 6B: NY State WIM Stations.

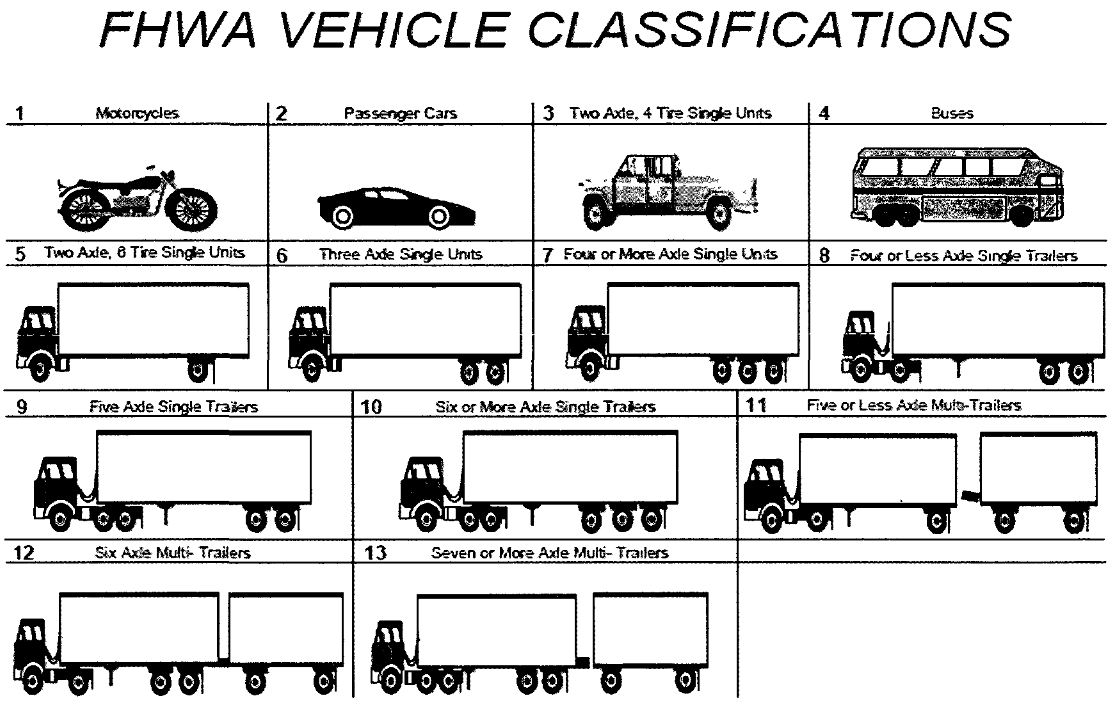


Figure 7B: Illustration of FHWA/AASHTO Vehicle Class Type Description

4.2 Truck Class Distribution selections

Table 8B: Truck Class Distribution Level 3 Summary

TRUCK CLASS	CODE			
	D (from LTPP)*	**D1 (low class)****	**D2 (high class)****	**D3 (Level 3-Control)**
4	N/A	5.2	0.1	1.8
5	N/A	38.9	0.6	24.6
6	N/A	35.8	0.8	7.6
7	N/A	10.2	0.6	0.5
8	N/A	5.6	6.8	5.0
9	N/A	3.5	9.2	31.3
10	N/A	0.2	25.8	9.8
11	N/A	0.3	36.4	0.8
12	N/A	0.2	16.5	3.3
13	N/A	0.1	3.2	15.3

* - no LTPP Truck Class Distribution data

**- Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

4.3 Rate of Traffic Growth

Table 9B: Selected Traffic Growth Rates for New York State

Code	Traffic Growth Rate
R1	1.0 % linear
R2 (Control)	2.0 % linear
R3	3.0 % linear

4.4 Traffic Operational Speed

Table 10B: Selected Traffic Operational Speeds

Code	Traffic Operational Speed (mph)	Binder Grades
U1	5	G1, G2, G3
U2	25	G1, G2, G3
U3 (Control)	65	G1, G2, G3

4.5 Annual Average Daily Truck Traffic (AADTT)

Table 11B: Calculated AADTT Values

Code	Station ID/location	Traffic Volume (AADTT)
Q1 (Control)	East Syracuse, NY	4192
Q2	I-90 exit	6154
Q3	South of I-90	7161

* - Figure 8 Traffic data Viewer map

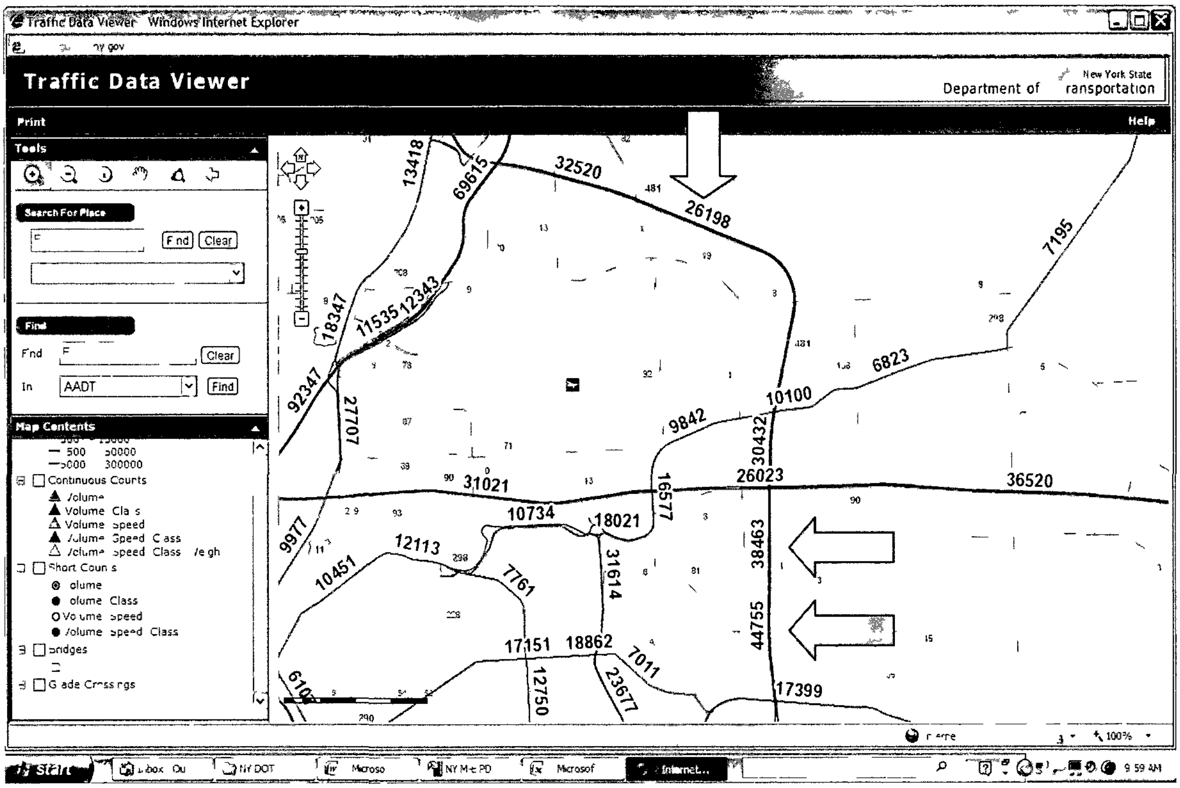


Figure 8B: NY 481 Interstate AADT Values (Yellow Color - Control AADT)

4.6 The Monthly Traffic Adjustment Factors

Table 12B: Monthly Adjustment Factors (MAF) for Pavement Design in East Syracuse, NY*

Location	Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
East Syracuse, NY	Jan	1	1	1	1	1	1	1	1	1	1
	Feb	1	1	1	1	1	1	1	1	1	1
	Mar	1	1	1	1	1	1	1	1	1	1
	Apr.	1	1	1	1	1	1	1	1	1	1
	May	1	1	1	1	1	1	1	1	1	1
	Jun	1	1	1	1	1	1	1	1	1	1
	Jul	1	1	1	1	1	1	1	1	1	1
	Aug	1	1	1	1	1	1	1	1	1	1
	Sep	1	1	1	1	1	1	1	1	1	1
	Oct	1	1	1	1	1	1	1	1	1	1
	Nov	1	1	1	1	1	1	1	1	1	1
	Dec	1	1	1	1	1	1	1	1	1	1

* - level 3 default value

4.7 The MADT to AADT factor

Table 13B: Collected MADT's for Selected Location

	MADT* TO AADT FACTOR**		
Month	East Syracuse, NY		
Jan.	n/c	n/c	n/c
Feb.	n/c	n/c	n/c
Mar.	n/c	n/c	n/c
Apr.	n/c	n/c	n/c
May	n/c	n/c	n/c
Jun.	n/c	n/c	n/c
Jul.	n/c	n/c	n/c
Aug.	n/c	n/c	n/c
Sep.	n/c	n/c	n/c
Oct.	n/c	n/c	n/c
Nov.	n/c	n/c	n/c
Dec.	n/c	n/c	n/c

*- MADT – monthly average daily traffic
**- AADT – annual average daily traffic
n/c – not collected

5. Climate Inputs

Five climate stations were selected from available climate data base in the M-E PDG. The five stations have been chosen as they were more geographically dispersed. These stations are: Albany, Buffalo, Saratoga (control), Massena and Poughkeepsie.

Figure 9B: New York State Map - Climate Station Location

5.1 Sensitivity to Climate Data Interpolation

Table 14B: Selected Locations Climate Data

STATION	Nearest 3 Stations	Latitude	Longitude	Distance	#Months of data
Buffalo, NY	Niagara Falls, NY	43.07	-78.57	16.7	54
	Dunkirk, NY	42.29	-79.16	41.2	110
	Rochester, NY	43.07	-77.41	54.5	116
Albany, NY	Bennington, VT	42.53	-73.15	29.3	87
	North Adams, MA	42.42	-73.1	32.3	116
	Pittsfield, MA	42.26	-73.17	34.2	85
Massena, NY	Saranac Lake, NY	44.23	-74.13	49.1	93
	Plattsburgh, NY	44.41	-73.31	67.6	92
	Watertown, NY	43.59	-76.01	87.2	62
Poughkeepsie, NY	Montgomery, NY	41.31	-74.16	21.4	98
	Danbury, CT	41.22	-73.29	27.7	94
	White Plains, NY	41.04	-73.43	40.1	59
Syracuse, NY	Fulton, NY	43.21	-76.23	21.5	116
	Penn Yan, NY	42.38	-77.04	59.2	98
	Watertown, NY	43.59	-76.01	87.2	62

5.2 Water Table Depth Variation

Table 15B: Selected WT Depth for East Syracuse, NY

CODE	Depth of Water Table	Well Location	Combination with A-7-6 Subgrade
WT1	3 ft	Buffalo	E1WT1
WT2	6 ft	Massena	E1WT2
WT3 (Control)	10 ft	Syracuse	E1WT3
WT4	1 ft	Shawnee	E1WT4

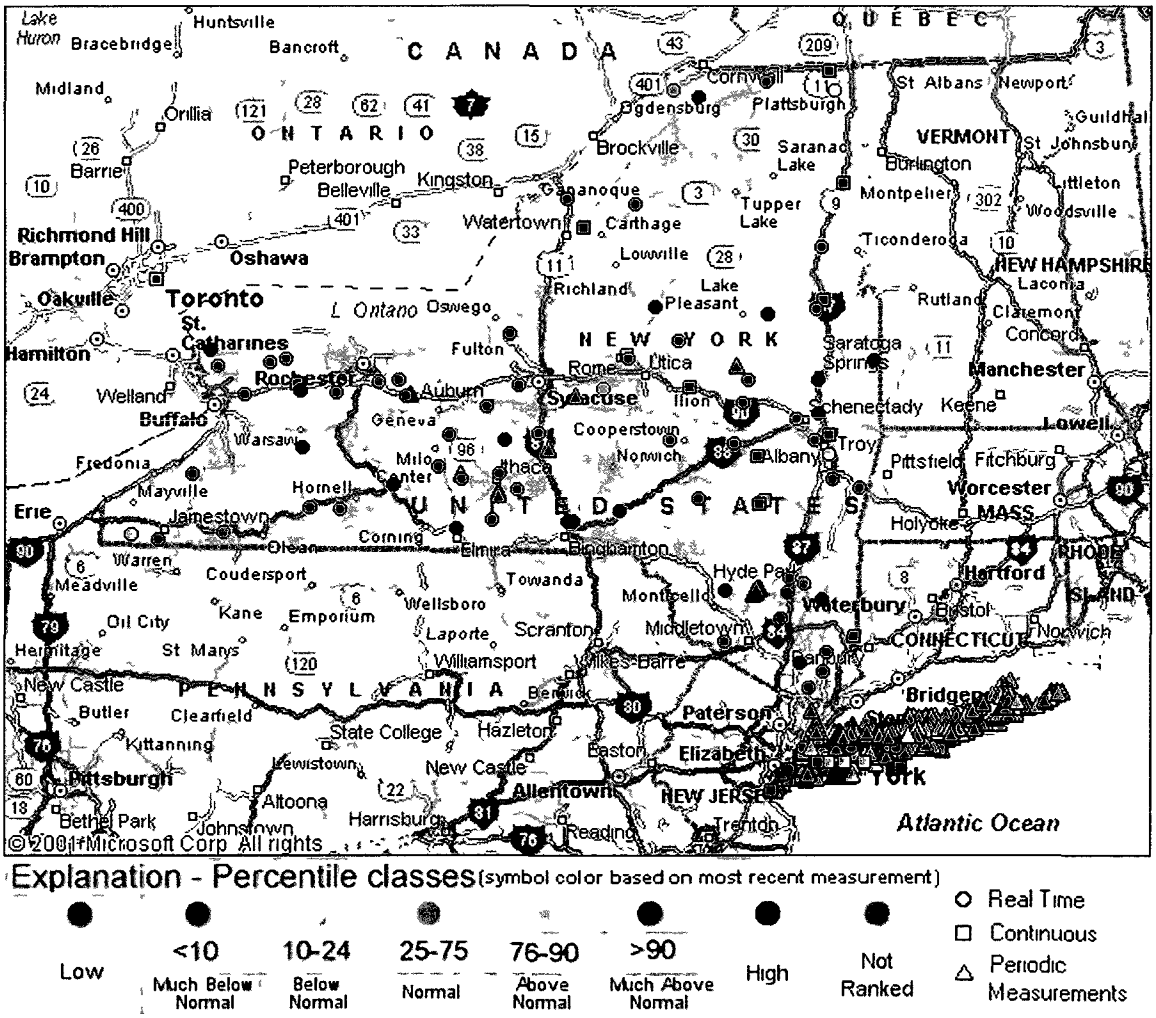


Figure 10B: New York Active Water Level Network

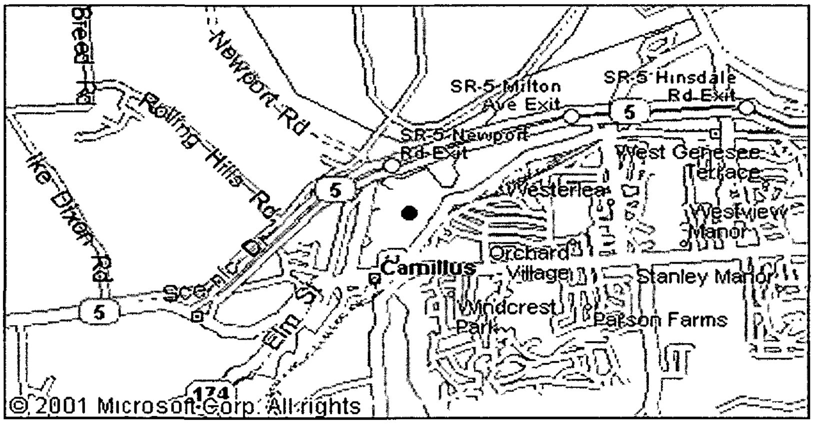


Figure 11B: Camillus, NY Well Location (Site Number: 430243076180401 - Local Number, Od-1825)

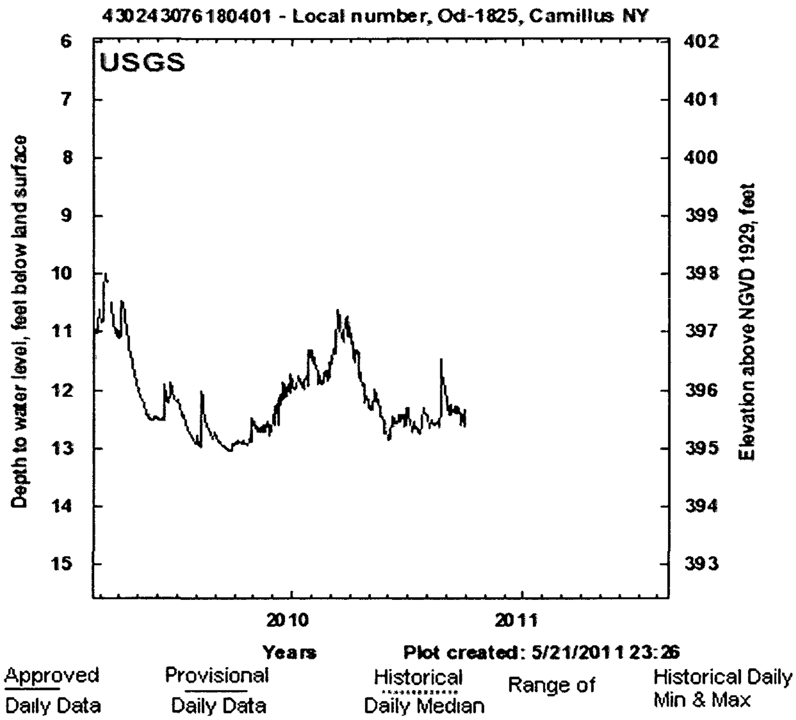


Figure 12B: Ground Water Table Level

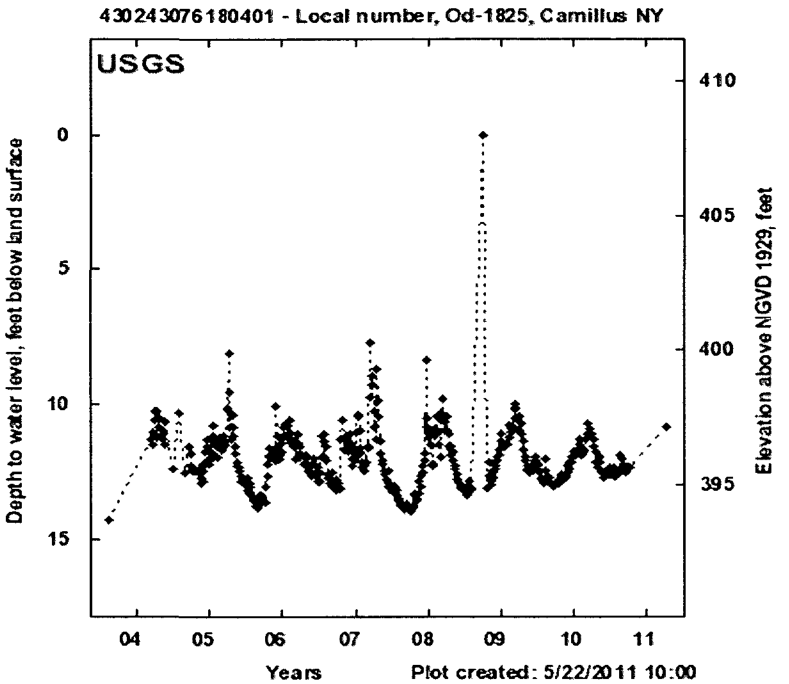


Figure 13B: Historic Data for Depth to Water Level in Camillus, NY (Well # Od-1825)

Table 16B: Water Level Measurement Records at Camillus Well

Highest WL	Date of Highest WL	Lowest WL	Date of Lowest WL
0.0	10/01/08	14.31	08/12/03

Table 17B: Most Recent Data Value: 10.82 on 4/12/2011 at Camillus, NY Well

Month	Average Monthly Minimum	Monthly Median	Average Monthly Maximum	Number of Months
Jan	11.01	11.36	11.85	6
Feb	11.01	11.39	12.25	6
Mar	9.70	11.07	11.58	7
Apr	10.24	10.99	11.93	8
May	11.13	12.30	12.46	7
Jun	12.18	12.52	13.07	7
Jul	10.30	12.60	13.23	7
Aug	12.52	12.94	14.31	8
Sep	11.69	13.00	13.87	6
Oct	12.37	12.54	13.84	7
Nov	11.37	12.64	13.09	6
Dec	11.57	11.84	12.14	6

6. Material Inputs

6.1 HMA Thickness

An HMA thickness for the control file is 9.8". To see the effect of HMA thickness on predicting distresses values two more HMA thicknesses has been selected:

Table 18B: Selected HMA Layer Thickness

CODE	Total HMA Thickness (in)
T1	8.0
T2 (Control)	9.8
T3	11.0

6.2 Number of HMA Layers

Two HMA layers are going to be used for the M-E PDG analysis:

- AC original surface – 1.2" (w/ 9.5 mm mix gradation)
- AC binder course – 8.6" (w/ 19.0 mm mix gradation)

A total HMA thickness for a control value is taken as 9.8".

6.3 HMA Mix Gradation

HMA mix gradation for New York State conforms to Superpave specifications.

Table 19B: Range of Values of HMA Mix Gradation – Superpave Specifications

NMAS of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
3/4" sieve	0	0 – 10	10 – NR	NR	NR
3/8" sieve	0 – 10	10 – NR	NR	NR	NR
# 4 sieve	10 – NR	NR	NR	NR	NR
#200 sieve	2 – 10	2 – 10	2 – 8	1 – 7	0 – 6

* NR – No restriction on the value

Table 20B: Tolerance for HMA Mix Gradation

NMAS of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
Cum. % Ret 3/4" sieve		± 4%	± 5%	± 7%	
Cum. % Ret 3/8" sieve		± 4%	± 5%	± 7%	
Cum. % Ret # 4 sieve	± 4%	± 3%	± 4%	± 4%	± 6%
#200 sieve	± 0.8%	± 0.8%	± 0.8%	± 0.8%	± 0.8%

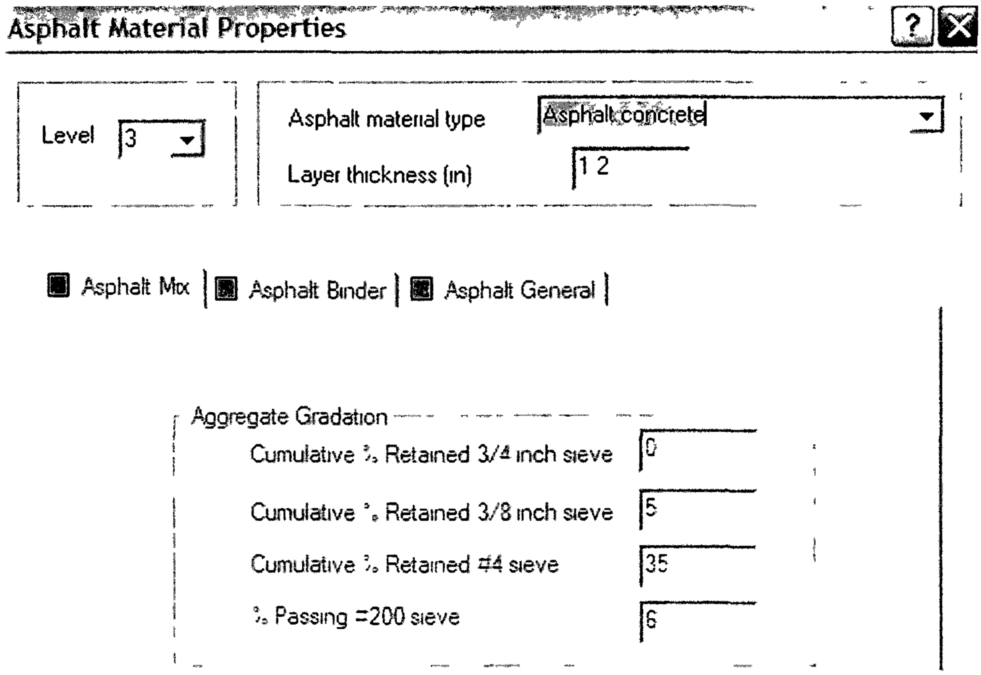


Figure 14B: 3/8" (9.5 mm) Asphalt Mix Aggregate Gradation

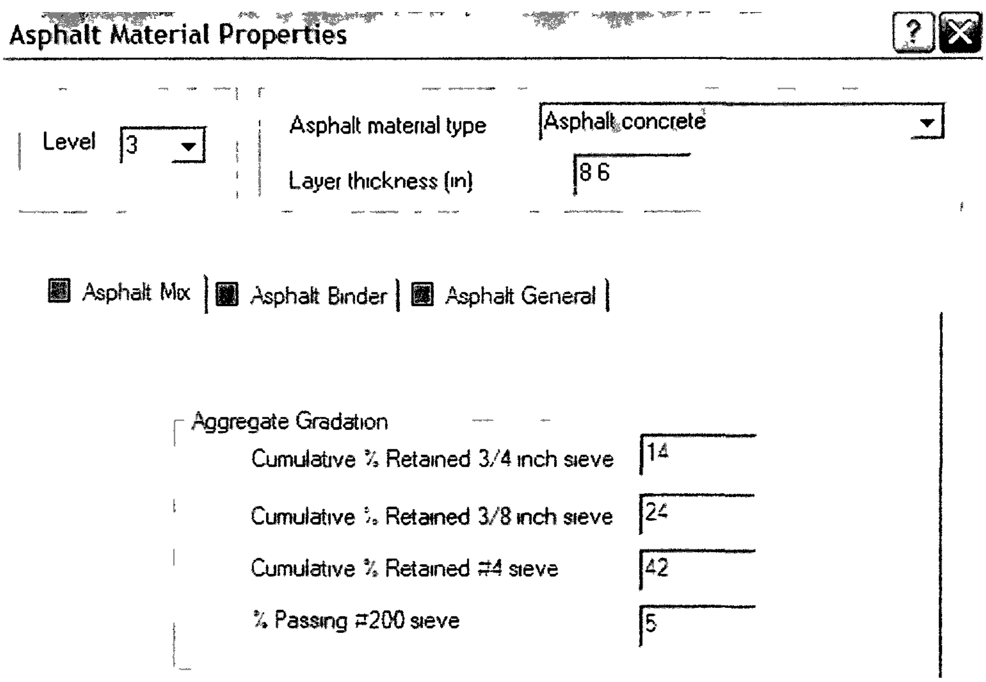


Figure 15B: ¾" (19.0 mm) Asphalt Mix Aggregate Gradation

Table 21B: Recommended Typical NY State HMA Mix Gradations Input

Gradation Mix Designation	Percent Retained				Percent Passing
	¾-in Sieve	½-in Sieve	3/8-in Sieve	#4-in Sieve	#200 Sieve
1-in (25.0 mm)	15	30	48	62	4
¾-in (19.0 mm)	5	20	40	58	5
½-in (12.5 mm)	0	5	25	52	6
⅜-in (9.5 mm)	0	0	5	45	6

6.4 PG Binder Grade

Five different binder grades are chosen from among the PG binders that are suitable for use in the state of New York. The PG 64-22 is used as the binder grade for the control case. The binder grade is tested in conjunction with operational speed of vehicle.

Table 22B: PG Binder Grades Used in New York State

CODE	PG BINDER GRADE
G1	PG 58-34
G2	PG 64-28
G3 (Control)	PG 64-22
G4	PG 70-22
G5	PG 76-22

6.5 Unbound Layer Inputs

ASTM D 2940, Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports. The gradation for base material from this standard is given below.

Table 23B: ASTM D 2940 Gradation for Dense-Graded Bases and Subbases

Sieve Size	Percent Passing
2 in. (50 mm)	100
1½ in. (37.5 mm)	95 – 100
3/4 in. (19.0 mm)	70 – 92
½ in. (9.5 mm)	50 – 70
No. 4 (4.75 mm)	35 – 55
No. 30 (0.600 mm)	12 – 25
No. 200 (0.075 mm)	0 – 8

6.6 Base Course Resilient Modulus

Table 24B: Base Course Aggregate Gradations (Level 3)

CODE	M1	M2	M3
Type of course	**Crushed Gravel**	**Crushed Stone**	**River-Run Gravel**
Sieve Size	**Percent Passing by Weight**		
3 ½ in (90 mm)	-	-	97.6
3 in (75 mm)	100	-	-
2 in (50 mm)	97.5	100	91.6
1 ½ in (37.5 mm)	-	92.5	85.6
1 in (25 mm)	70.0	-	78.8
¾ in (19 mm)	-	60.0	72.7
#4 (4.75 mm)	39.5	27.5	44.7
#200 (0.075 mm)	6.0	2.5	8.7
Resilient Modulus	25000 psi	30000 psi	15000 psi

Table 25B: Base Course Resilient Modulus Level 3 Values for NY State

CODE	M_R (psi)
M1 (Control)	25000
M2	30000
M3	15000

Table 26B: Untreated Base Course gradation Limits

Gradation Limits		
Sieve Size	Job Mix Gradation Target Band	Job Mix Gradation Tolerance
$1^1/_2$ inch	100	
1 inch	90 – 100	±9.0
$^3/_4$ inch	70 – 85	±9.0
$^1/_2$ inch	65 – 80	±9.0
$^3/_8$ inch	55 – 75	±9.0
No. 4	40 – 65	±7.0
No. 16	25 – 40	±5.0
No. 200	7 – 11	±3.0

6.7 Subgrade Resilient Modulus M_R

Table 27B: Subgrade Types and Subgrade Resilient Modulus

CODE	SUBGRADE TYPE	Material Classification	RESILIENT MODULUS (psi)	
			Level 2	Level 3
E1	Clayey soils	A-7-6	n/c*	8000
E2 (Control)	Fine sand, some silt	A-2-4	n/c	25000
E3	Coarse to fine gravelly, coarse to medium sand, some fine sand	A-1-a	n/c	30000

* n/c – not collected

6.8 Effective Binder Content V_{be}, % (AASHTO T308)

Table 28B: Effective Binder Content

CODE	In-situ VMA, percent	EFFECTIVE BINDER CONTENT
F1	13.0	9.0
F2 (Control)	15.0	11.0
F3	17.0	13.0

Table 29B: HMA Mix Gradation Input Values

% of Aggregate	9.5 mm (3/8")			19.0 mm (3/4")		
	A1	A2	A3	B1	B2	B3
Retained on 3/4" sieve	0	0	0	14.0	18.6	12.0
Retained on 3/8" sieve	5.0	8.2	3.6	24.0	32.4	19.8
Retained on #4 sieve	35.0	48.3	22.1	42.0	52.0	34.5
Passing #200 sieve	6.0	2.8	8.5	5.0	2.8	7.2

1 Mean values of the allowable range of values

2 – Coarse mix gradation

3 – Fine mix gradation

6.9 Air Voids Content, %

Table 30B: Air Voids Percentage (Mixture design)

CODE	PERCENT AIR VOIDS
V1	3.0
V2 (Control)	4.0
V3	5.5

None mixture design Air Voids (in-situ air voids at construction site) will be based on percent compaction in specification:

- Range 3.5 to 9.5 (90.5 to 96.5)
- Target 6.5 (93.5) – recommended

6.10 Mix Coefficient of Thermal Contraction (CTC)

Table 31B: Mix Coefficient of Thermal Contraction

CODE	COEFFICIENT OF THERMAL CONTRACTION
N1	1.0 E-07
N2 (Control)	1.3 E-05
N3	1.0 E-04

The Mix CTC default value of 1.3 E-05 is used for Level 3 sensitivity analysis.

To see the effect of the CTC value on the sensitivity analysis the ranges were selected based on the M-E PDG help menu from 1.0×10^{-7} to 1.0×10^{-4}.

6.11 Initial IRI Values for New Pavement Design

Table 32B: Suggested Initial IRI Values for New Pavement Design

PAVEMENT TYPE	IRI, IN/MI		
	MINIMUM	AVERAGE	MAXIMUM
NEW HMA AND HMA/HMA*	32	70	106

*- Initial IRI for HMA pavements shall be set within the range of 70 to 85 in/mi.

Table 33B: Sensitivity Analysis Initial IRI Values

CODE	Initial IRI (in/mi)
S1	32
S2 (Control)	75
S3	106

6.12 Aggregate Coefficient of Thermal Contraction

The M-E PDG default value is $5.0*10^{-6}/^{o}F$.

7. NY State M-E PDG Level 3 Sensitivity Analysis

7.1 Effect of Traffic Inputs on Pavement Distresses

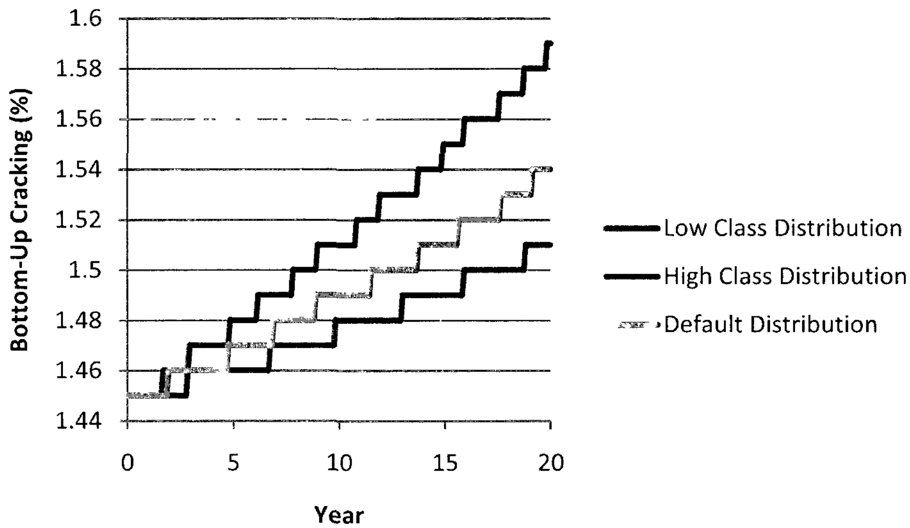


Figure 16B: Effect of Truck Class Distribution on Bottom-Up Cracking

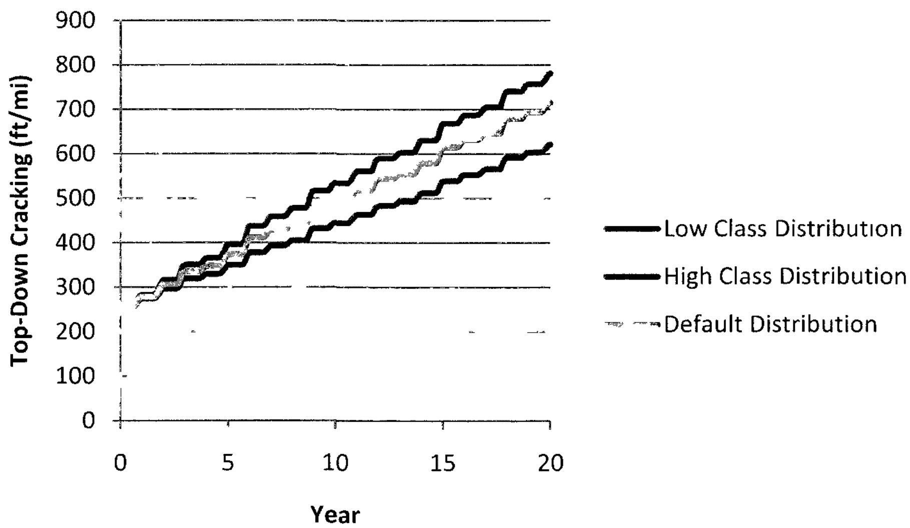


Figure 17B: Effect of Truck Class Distribution on Top-Down Cracking

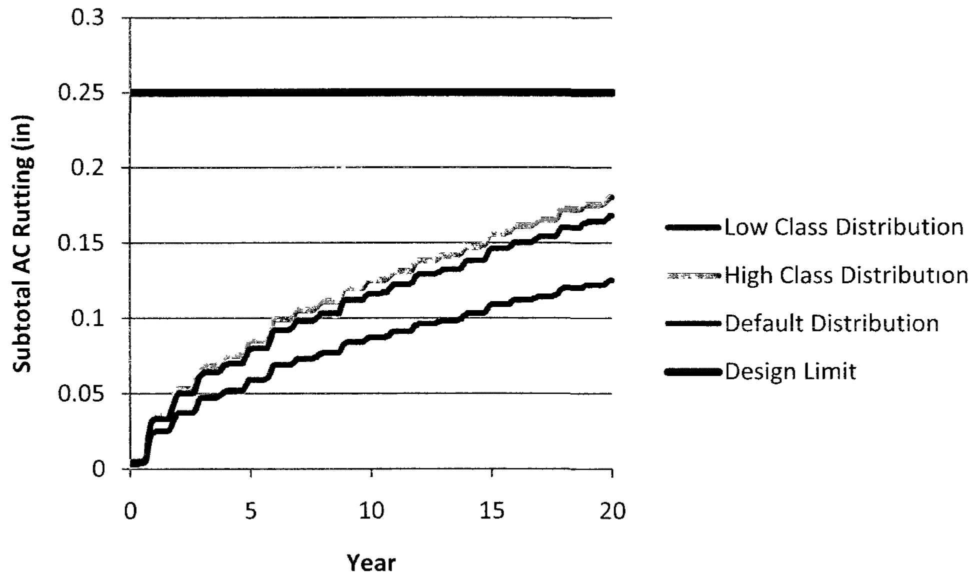


Figure 18B: Effect of Truck Class Distribution on Subtotal AC Rutting

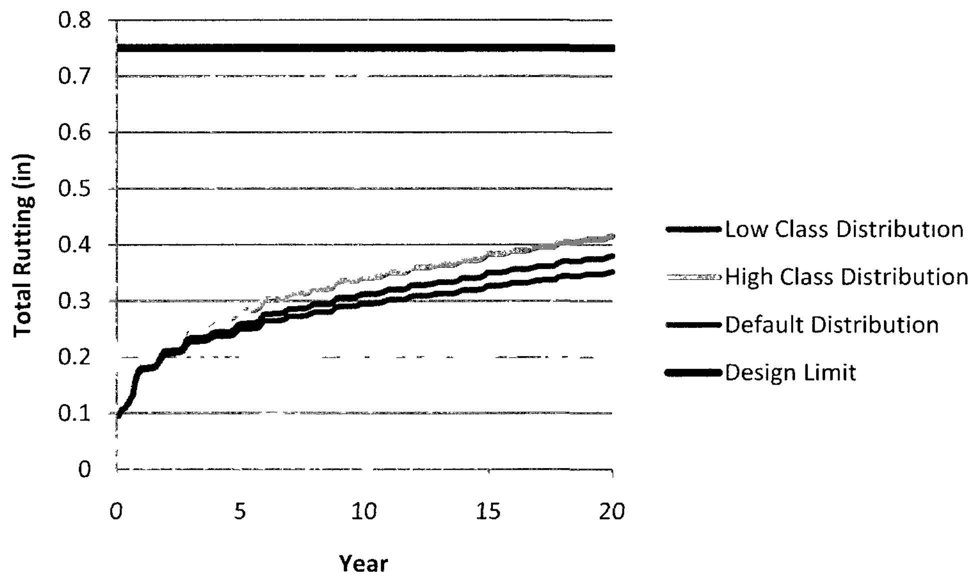


Figure 19B: Effect of Truck Class Distribution on Total Rutting

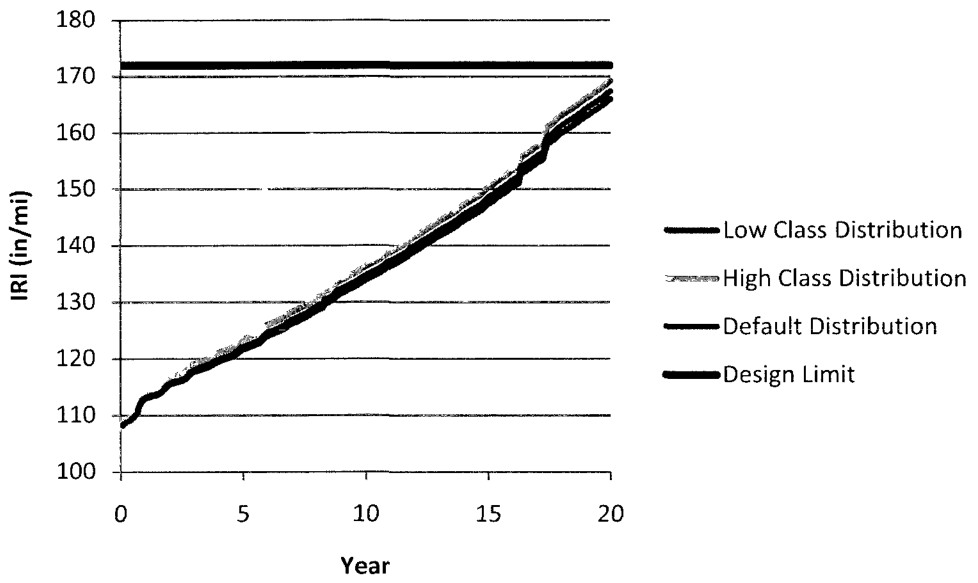


Figure 20B: Effect of Truck Class Distribution on IRI

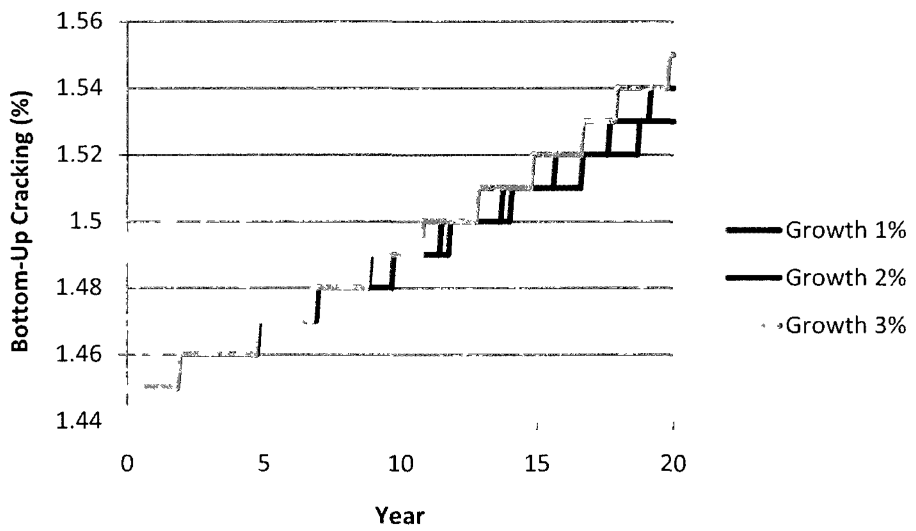


Figure 21B: Effect of Traffic Growth Rate at Bottom-Up Cracking

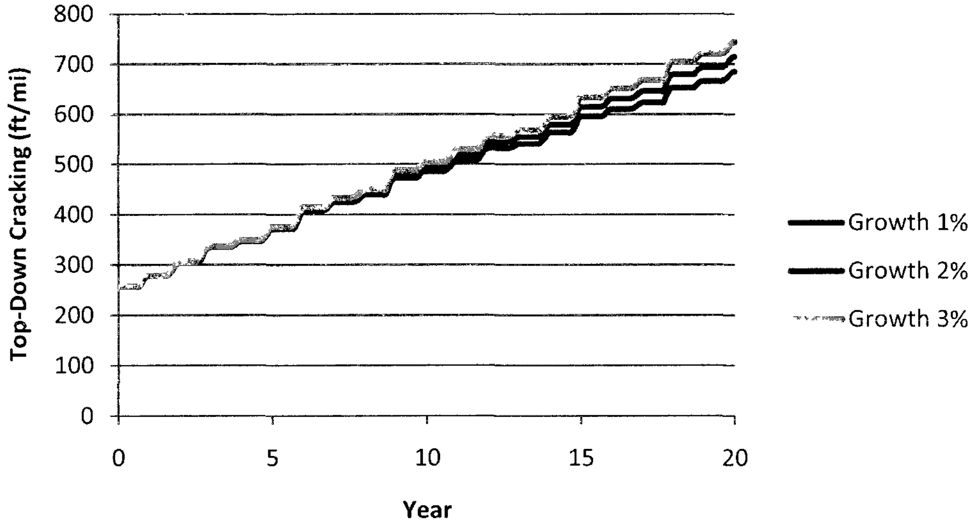


Figure 22B: Effect of Traffic Growth Rate on Top-Down Cracking

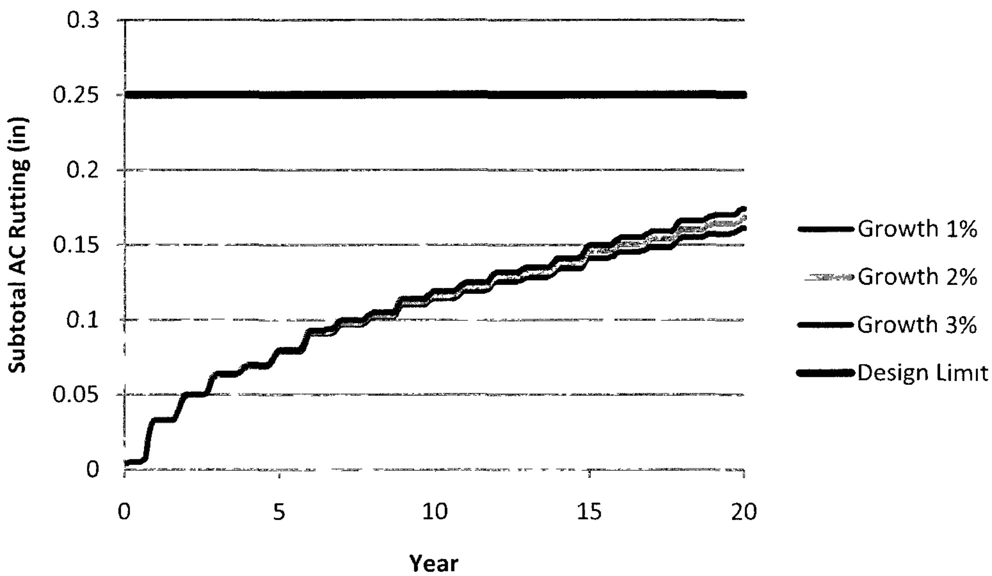


Figure 23B: Effect of Traffic Growth on Subtotal AC Rutting

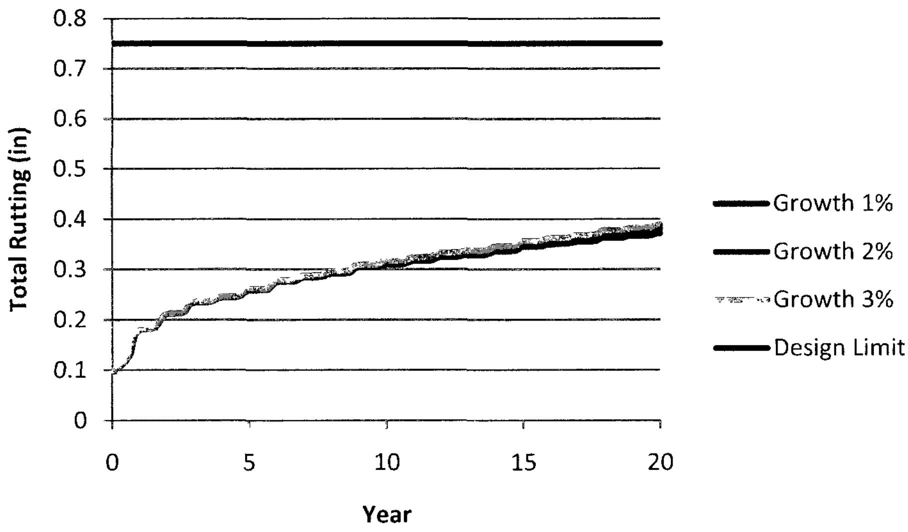


Figure 24B: Effect of Traffic Growth Rate on Total Rutting

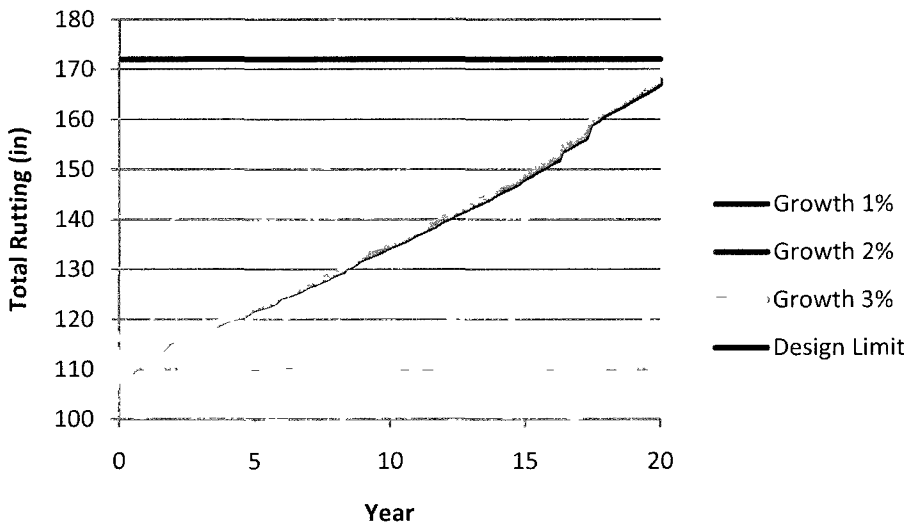


Figure 25B: Effect of Traffic Growth Rate on IRI

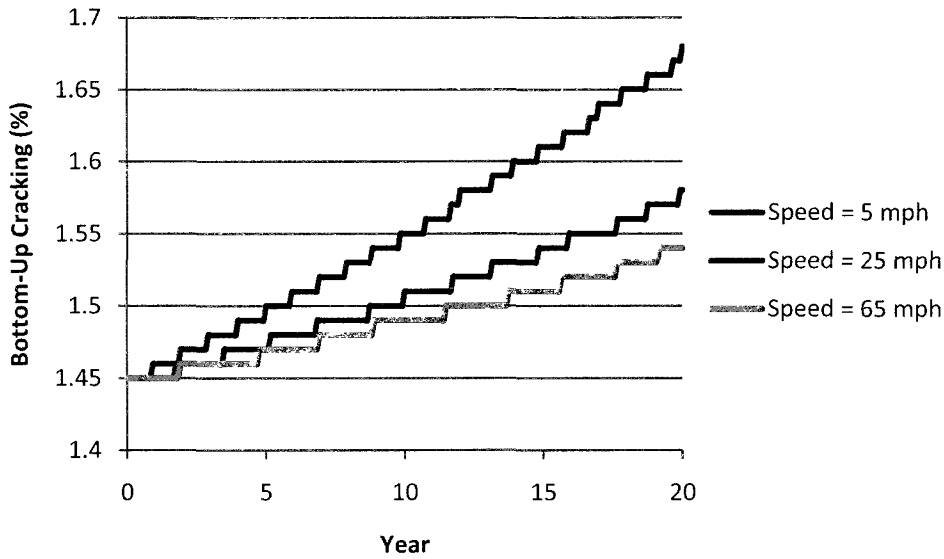


Figure 26B: Effect of Traffic Speed on Bottom-Up Cracking with PG 64-22

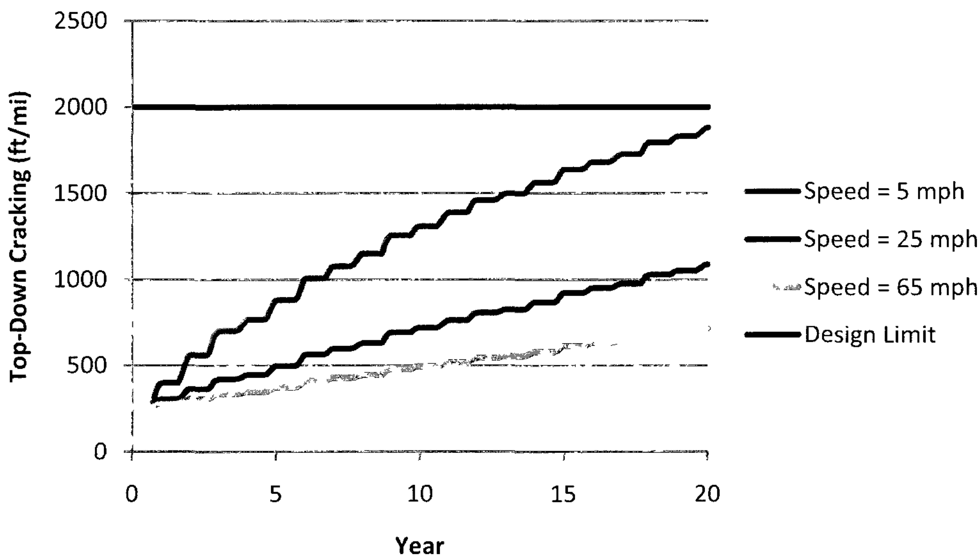


Figure 27B: Effect of Traffic Speed on Top-Down Cracking with PG 64-22

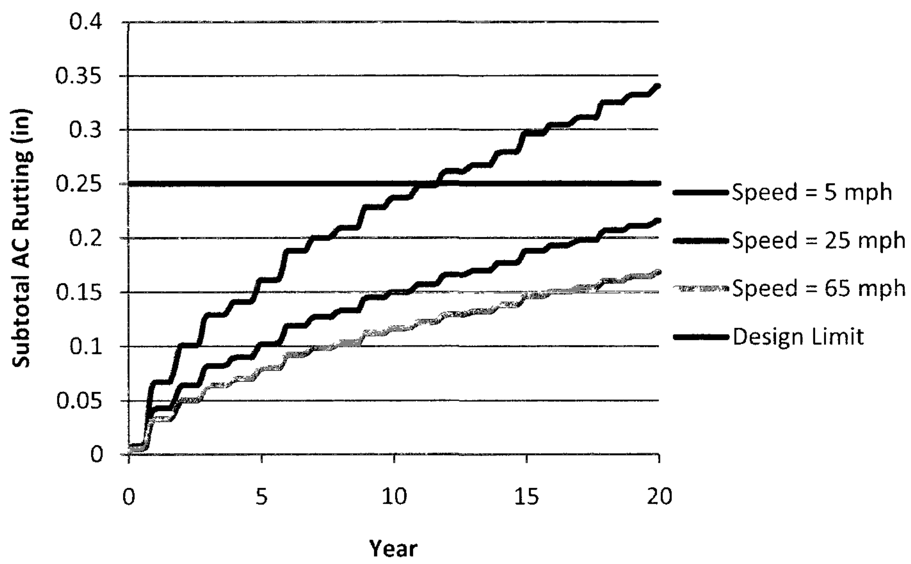


Figure 28B: Effect of Traffic Speed on Subtotal AC Rutting with PG 64-22

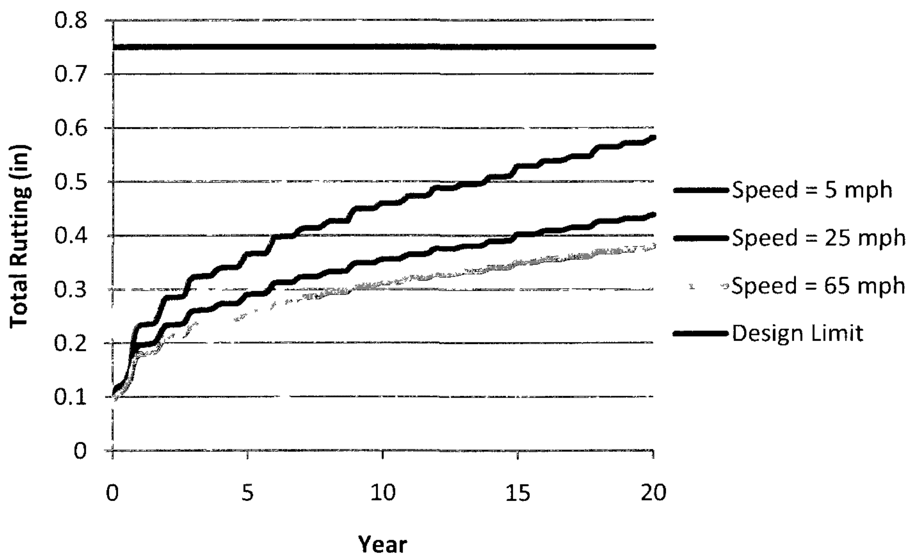


Figure 29B: Effect of Traffic Speed on Total Rutting with PG 64-22

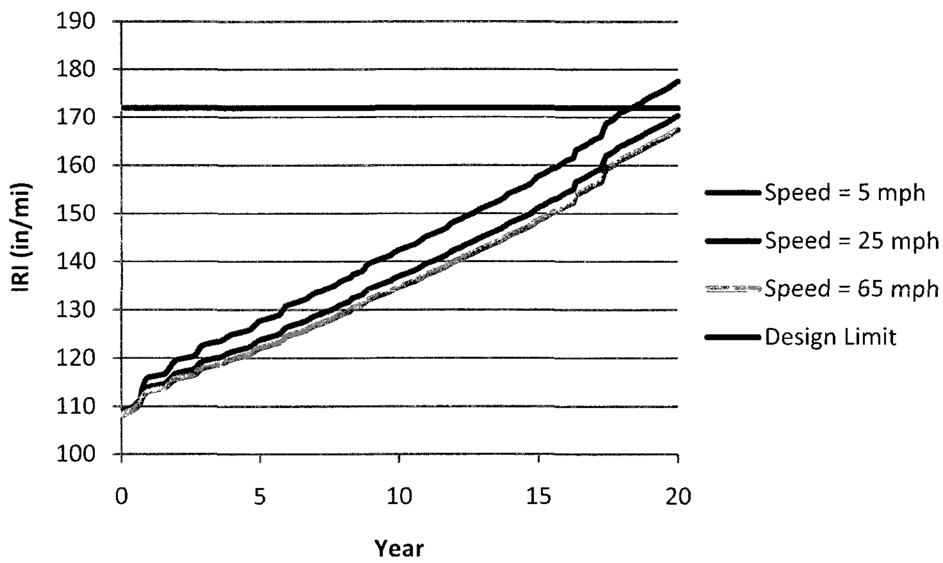


Figure 30B: Effect of Traffic Speed on IRI with PG 64-22

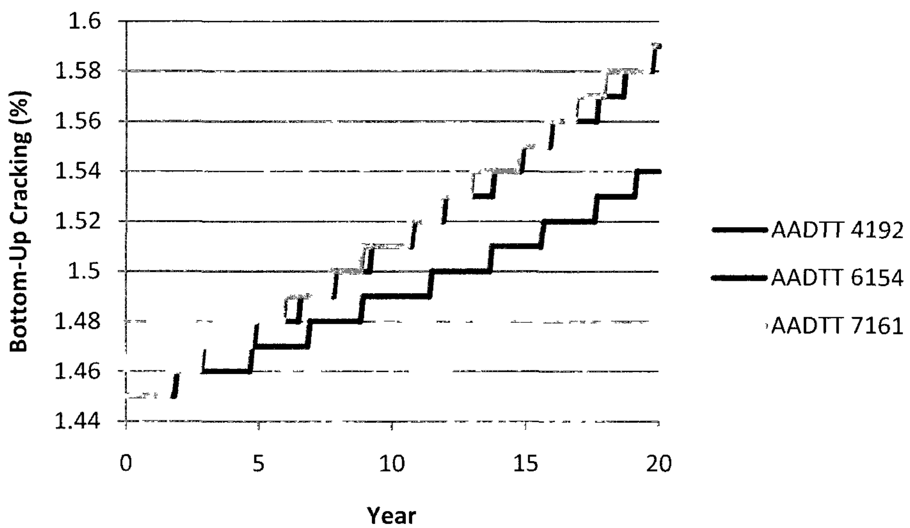


Figure 31B: Effect of AADTT on Bottom-Up Cracking

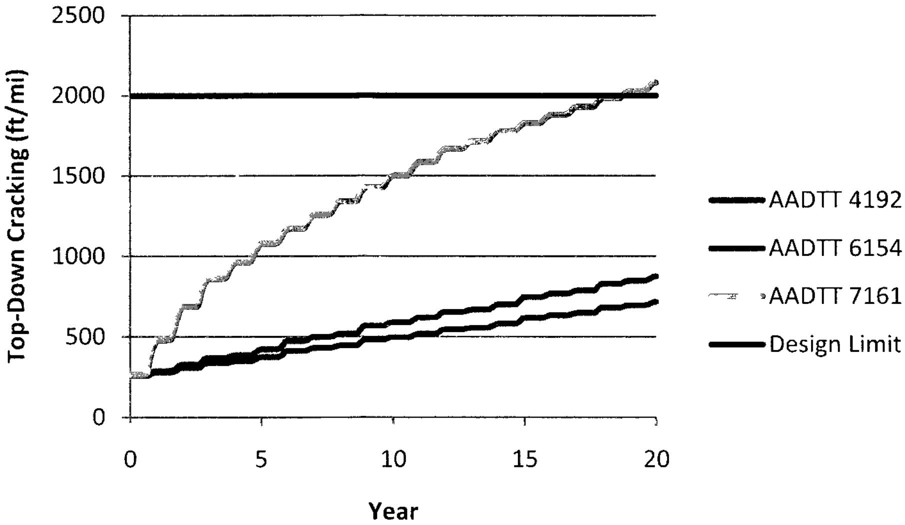


Figure 32B: Effect of AADTT on Top-Down Cracking

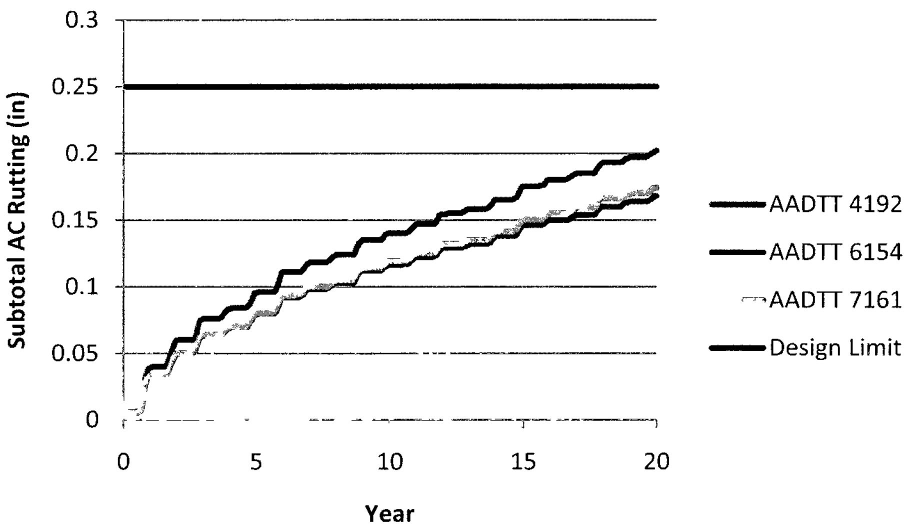


Figure 33B: Effect of AADTT on Subtotal AC Rutting

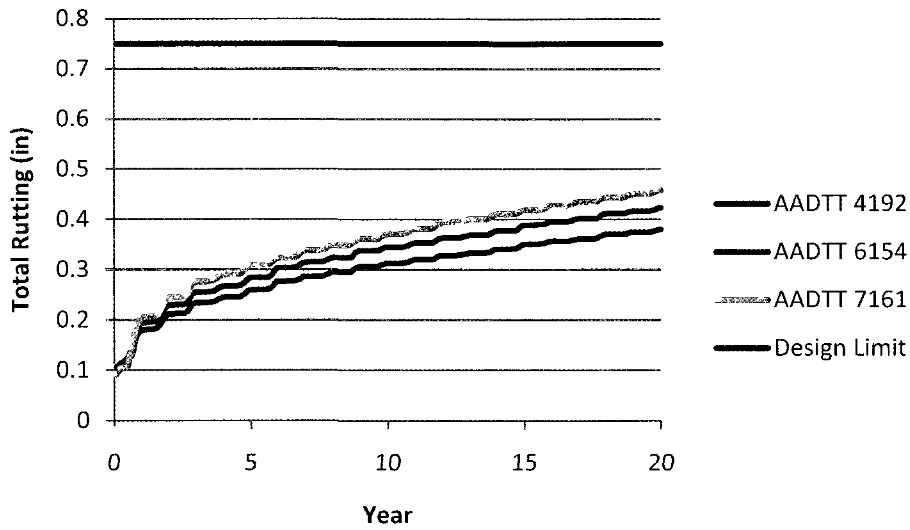


Figure 34B: Effect of AADTT on Total Rutting

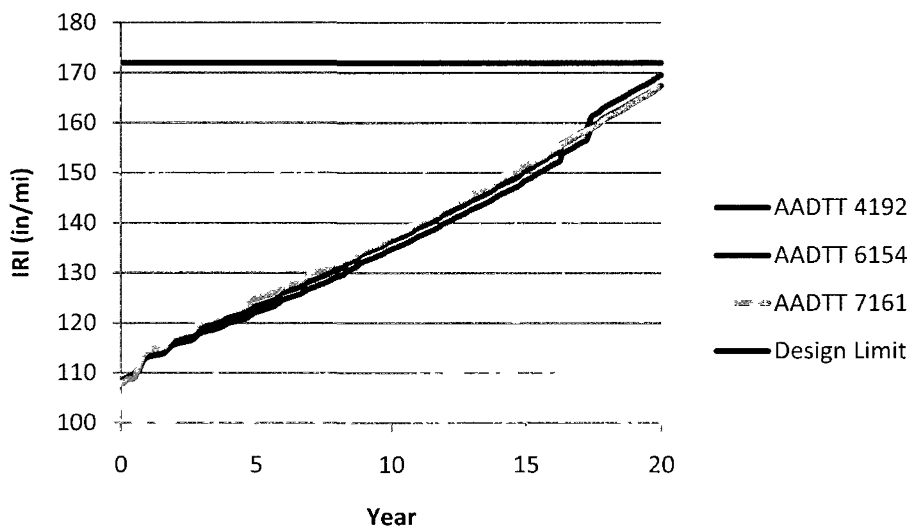


Figure 35B: Effect of AADTT on IRI

7.2 Effect of Climate Inputs on Pavement Distresses

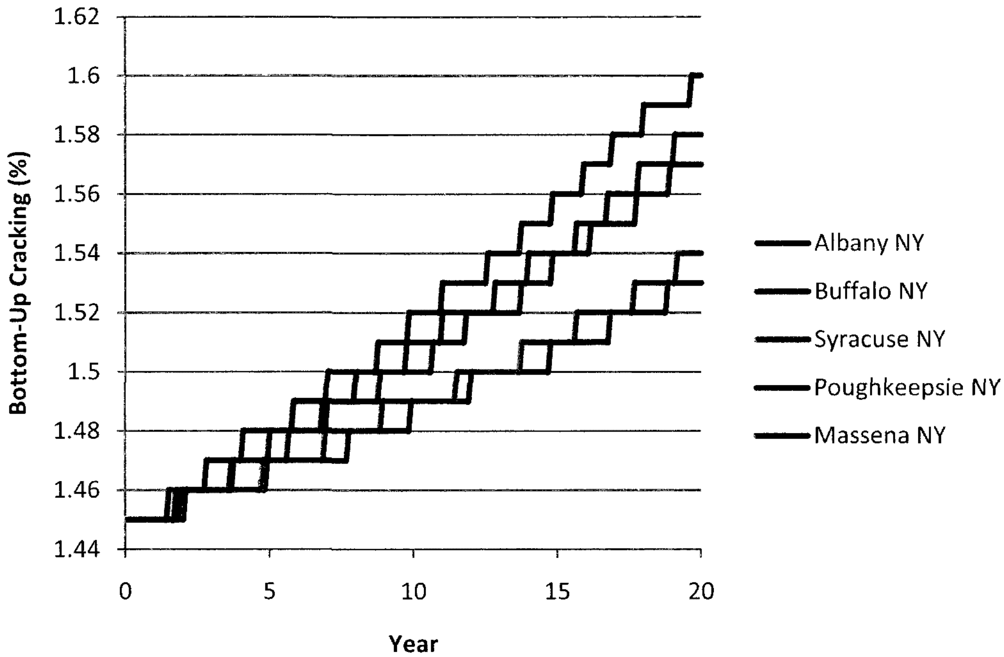


Figure 36B: Effect of Climate on Bottom-Up Cracking

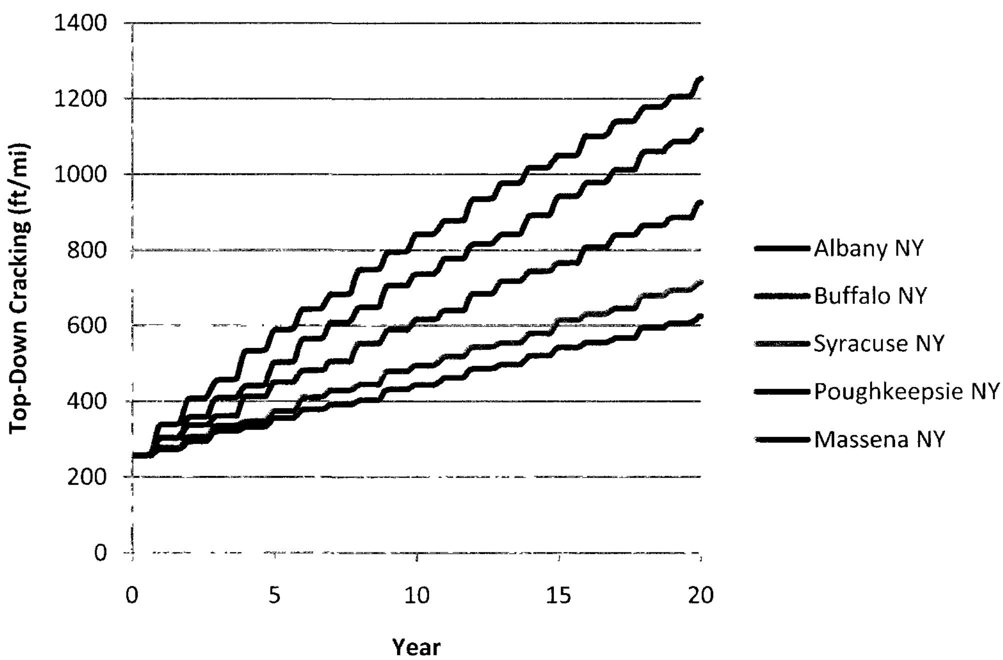


Figure 37B: Effect of Climate on Top-Down Cracking

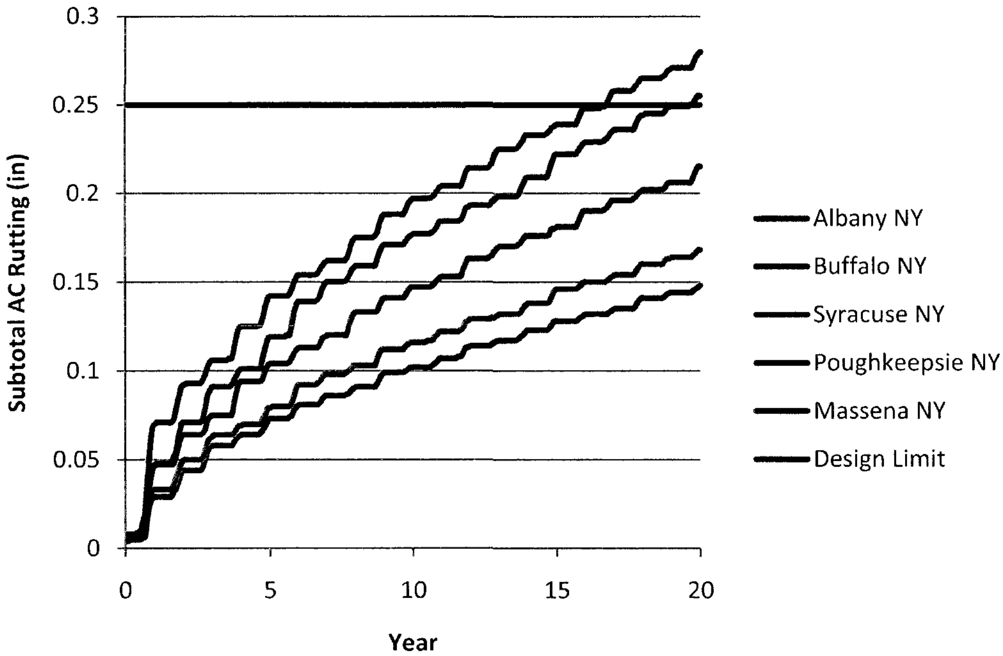


Figure 38B: Effect of Climate on Subtotal AC Rutting

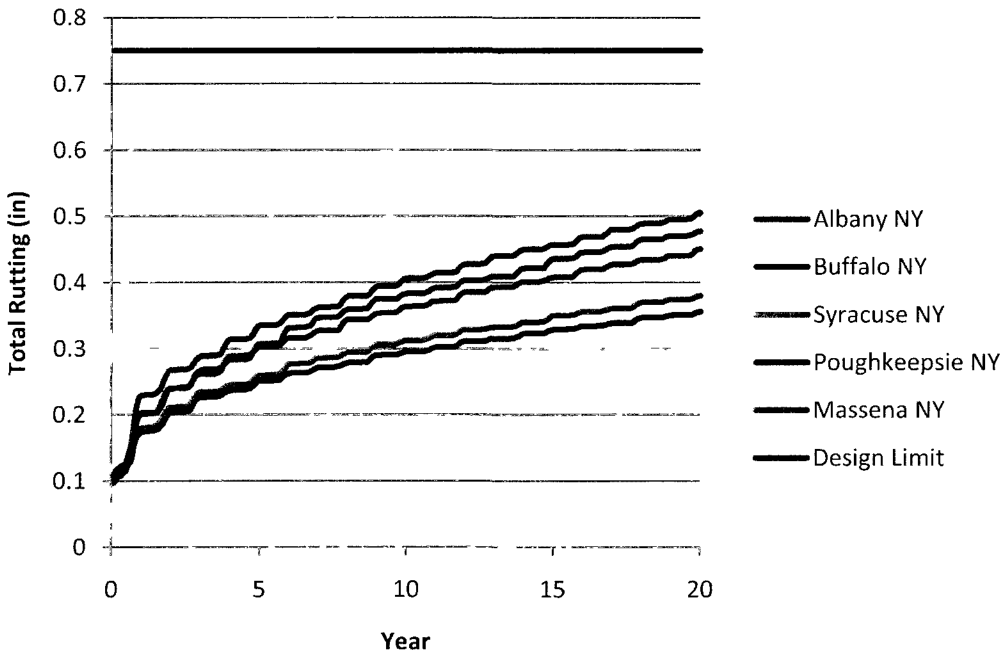


Figure 39B: Effect of Climate on Total Rutting

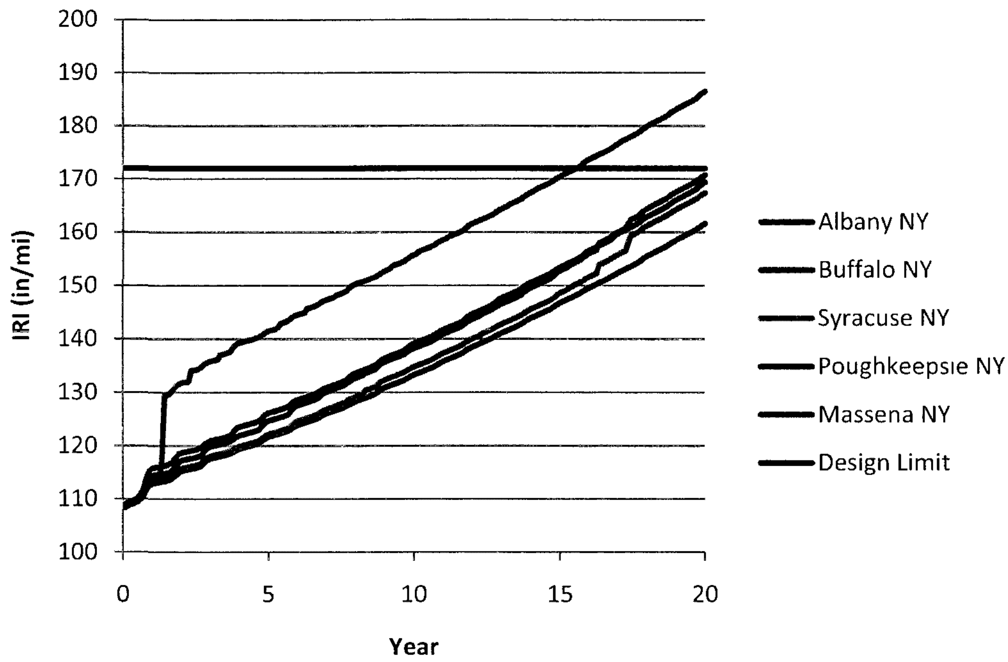


Figure 40B: Effect of Climate on IRI

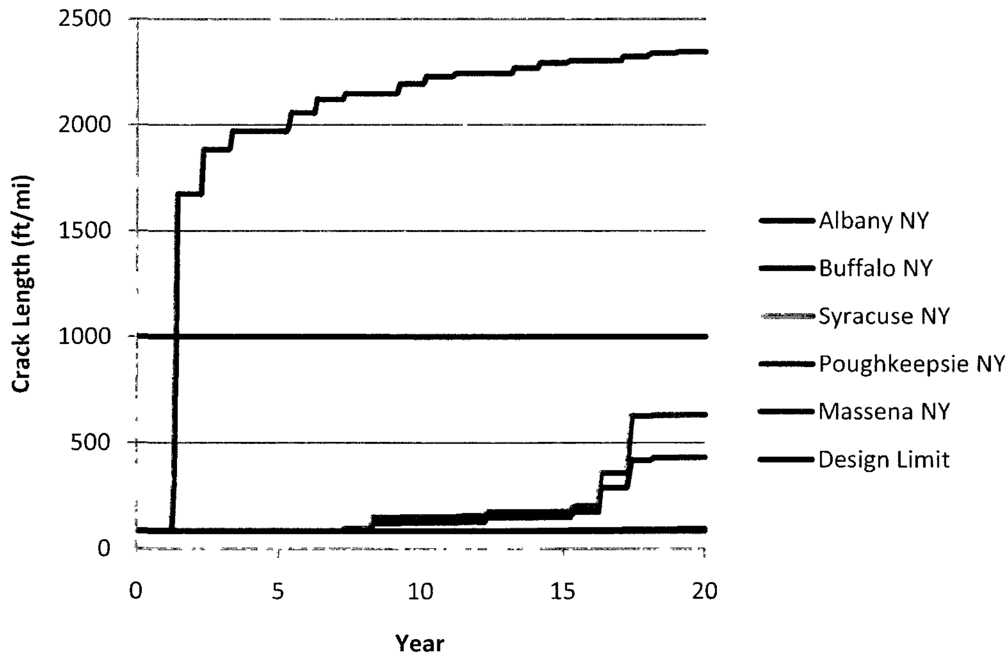


Figure 41B: Effect of Climate on Thermal Cracking

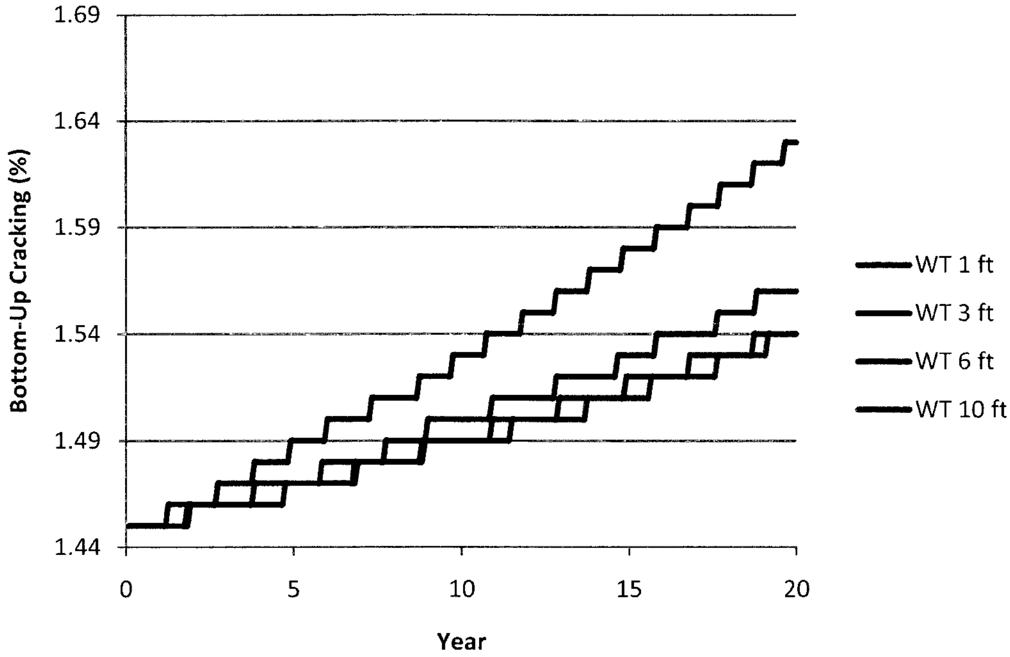


Figure 42B: Effect of Water Table Depth on Bottom-Up Cracking

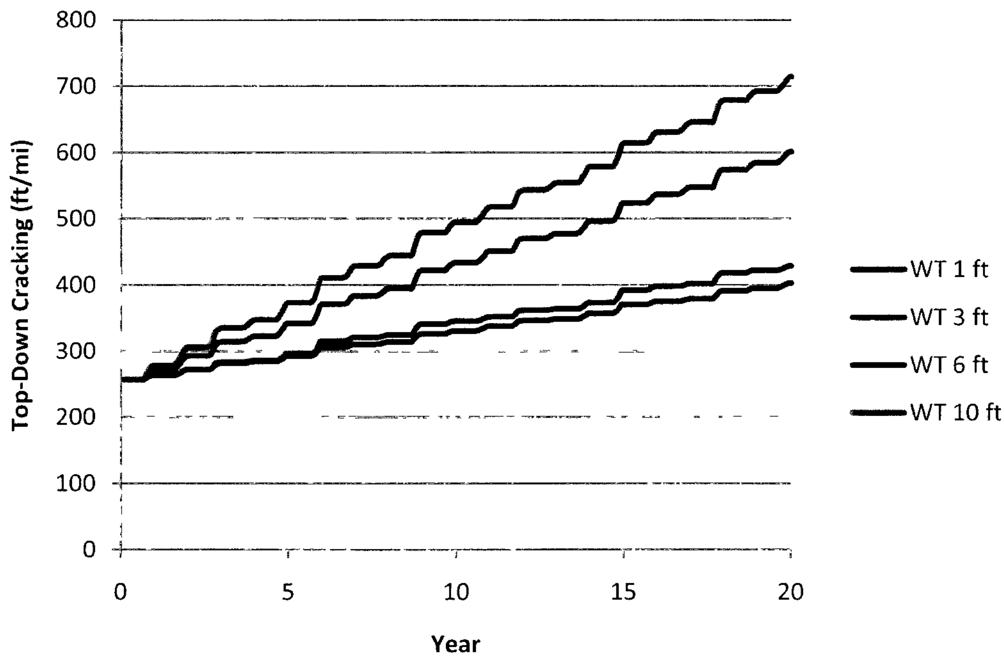


Figure 43B: Effect of Water Table Depth on Top-Down Cracking

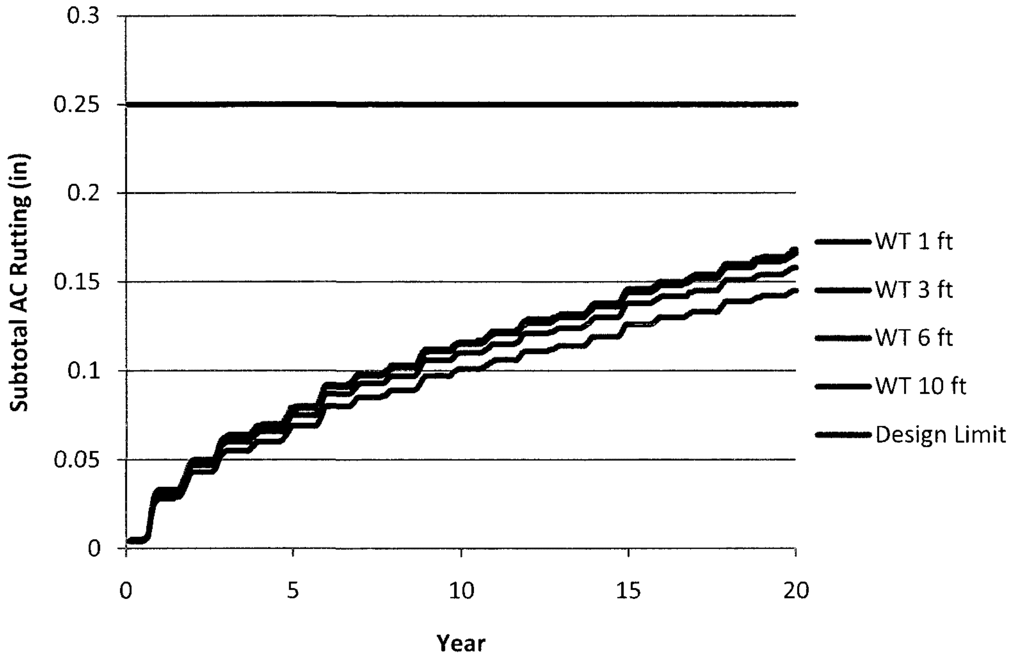


Figure 44B: Effect of Water Table Depth on Subtotal AC Rutting

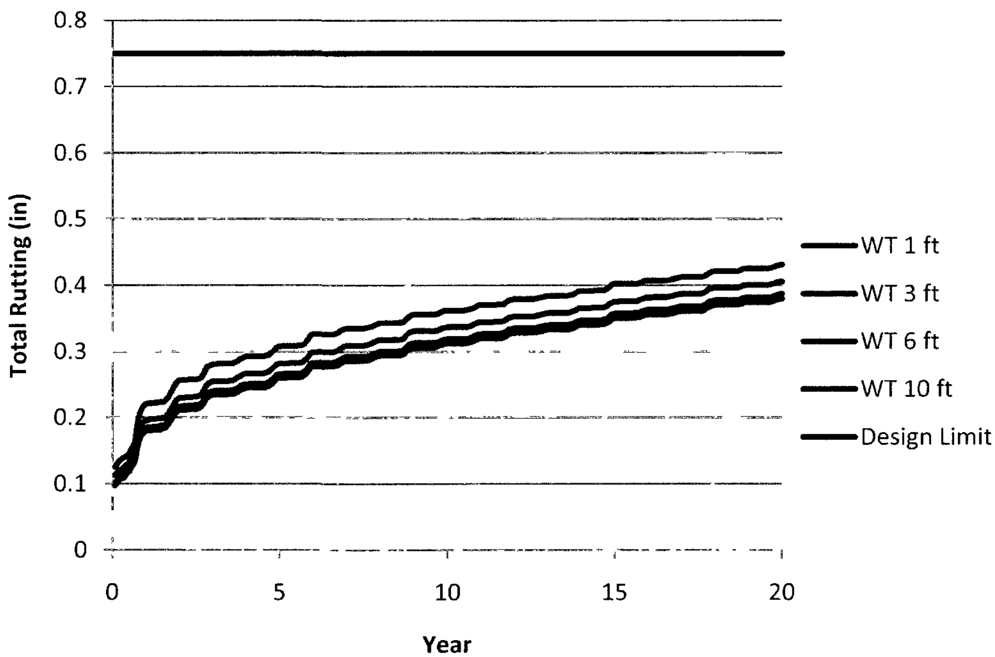


Figure 45B: Effect of Water Table Depth on Total Rutting

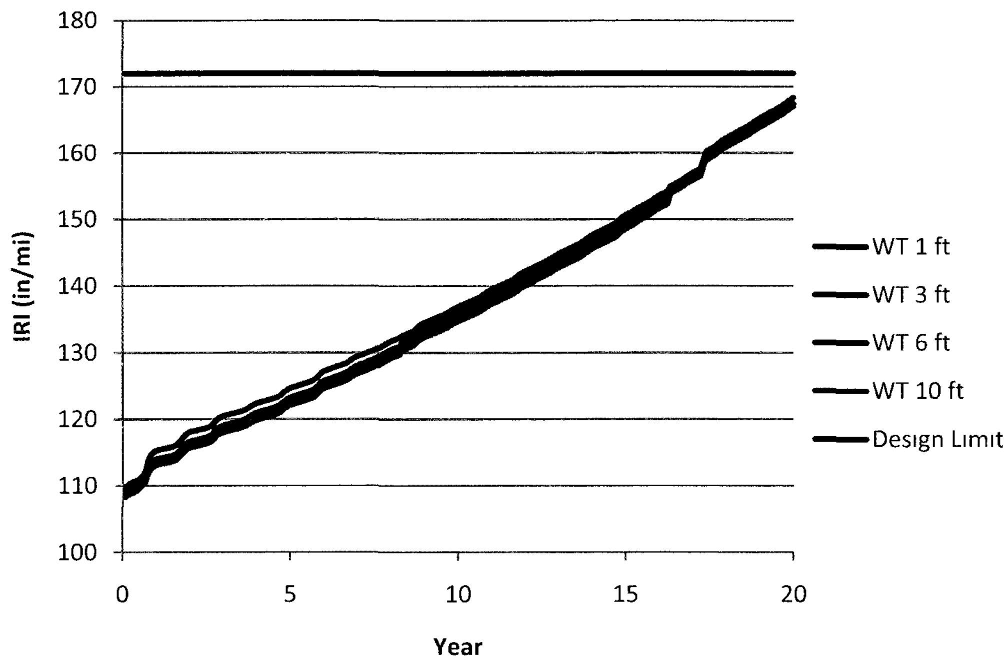


Figure 46B: Effect of Water Table Depth on IRI

7.3 Effect of Material Inputs on Pavement Distresses

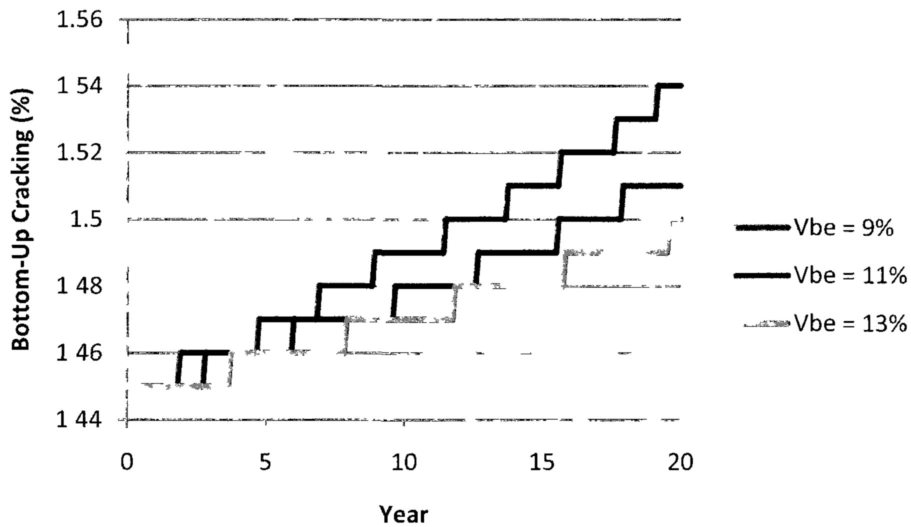


Figure 47B: Effect of Effective Binder Content on Bottom-Up Cracking

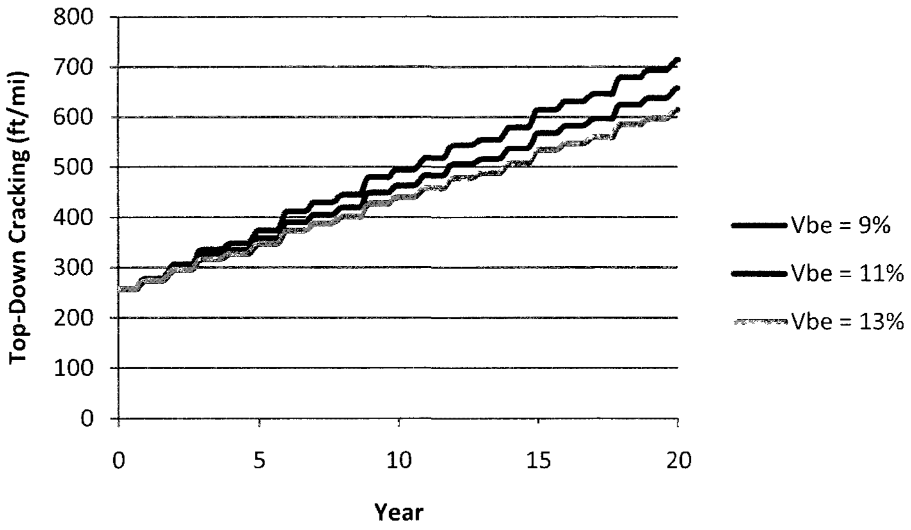


Figure 48B: Effect of Effective Binder Content on Top-Down Cracking

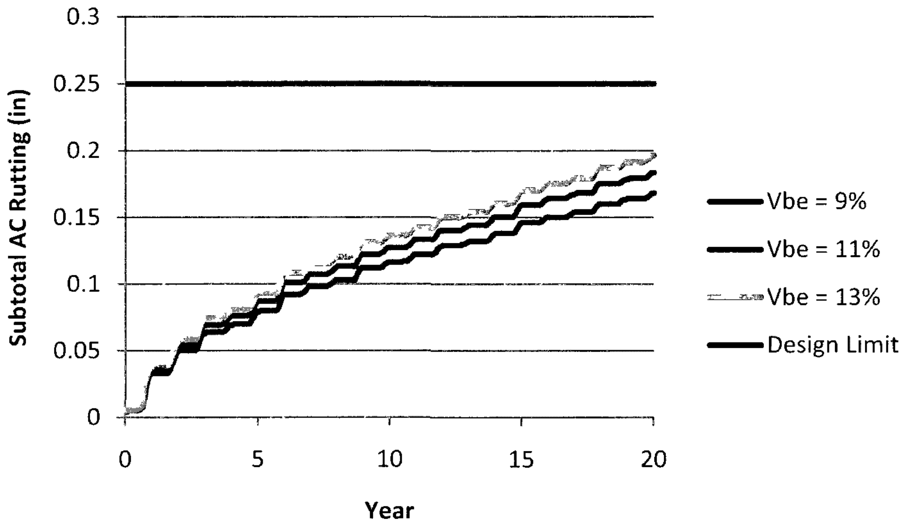


Figure 49B: Effect of Effective Binder Content on Subtotal AC Rutting

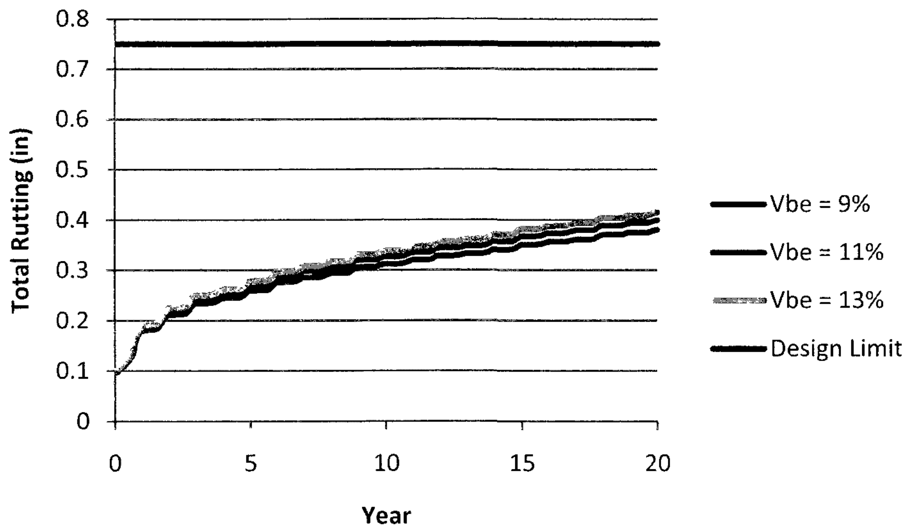


Figure 50B: Effect of Effective Binder Content on Total Rutting

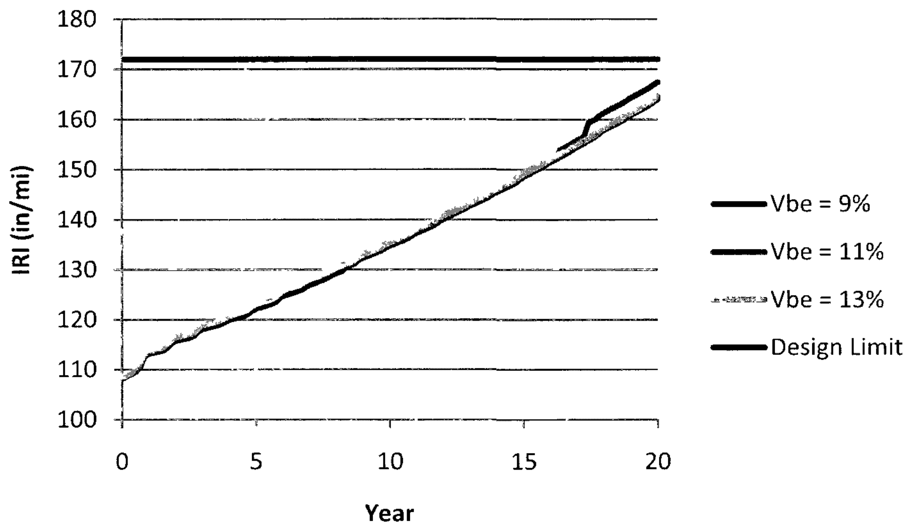


Figure 51B: Effect of Effective Binder Content on IRI

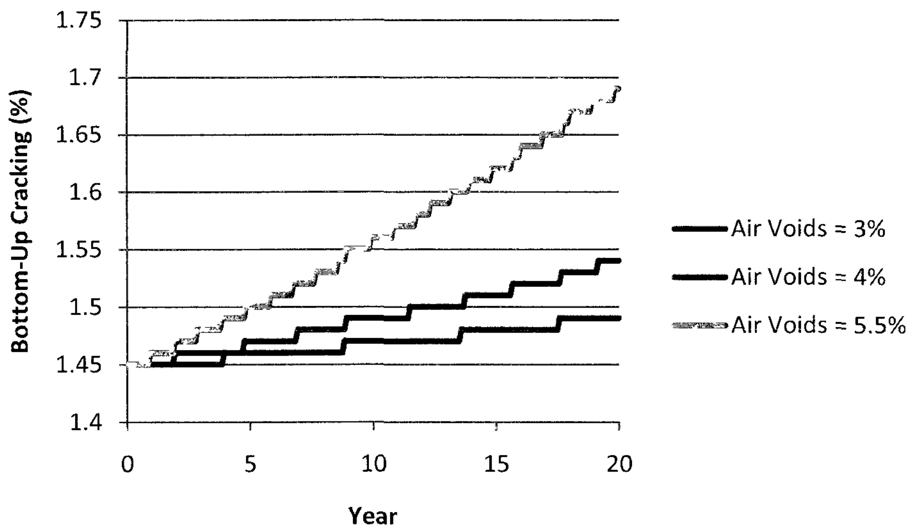


Figure 52B: Effect of Percent Air Voids on Bottom-Up Cracking

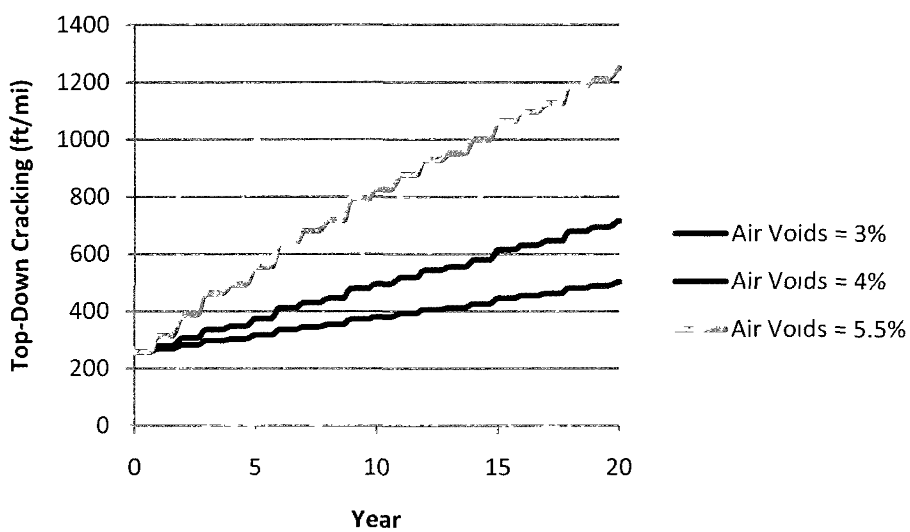


Figure 53B: Effect of Percent Air Voids on Top-Down Cracking

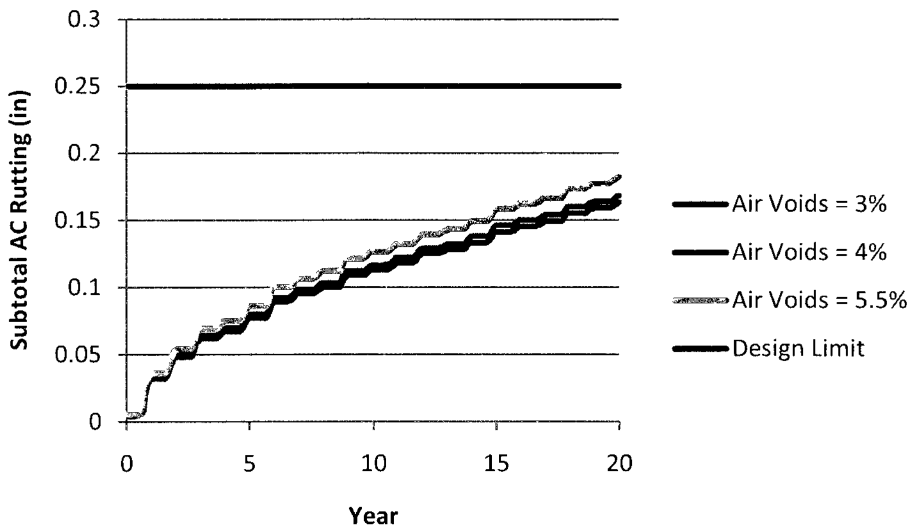


Figure 54B: Effect of Percent Air Voids on Subtotal AC Rutting

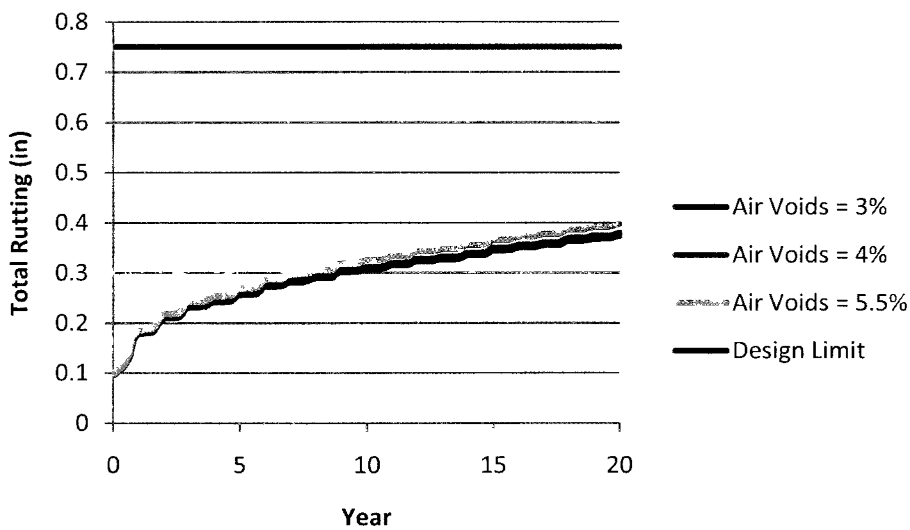


Figure 55B: Effect of Percent Air Voids on Total Rutting

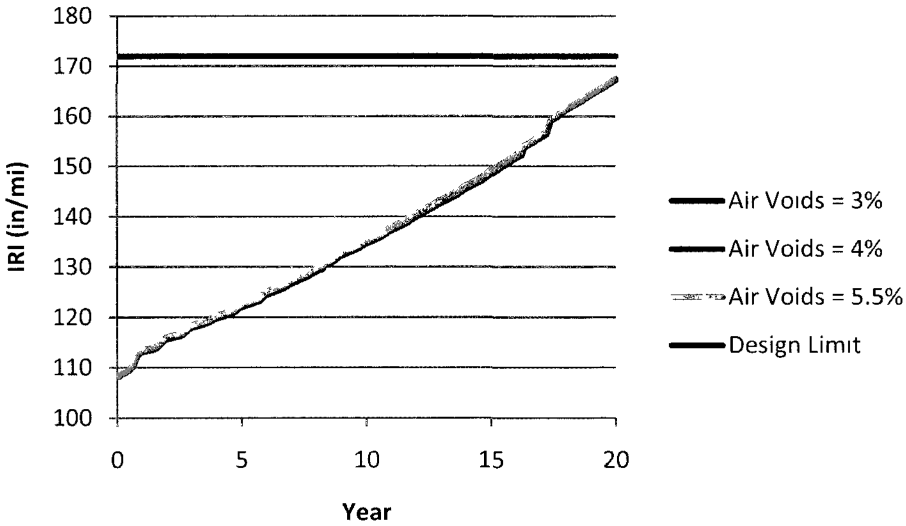


Figure 56B: Effect of Percent Air Voids on IRI

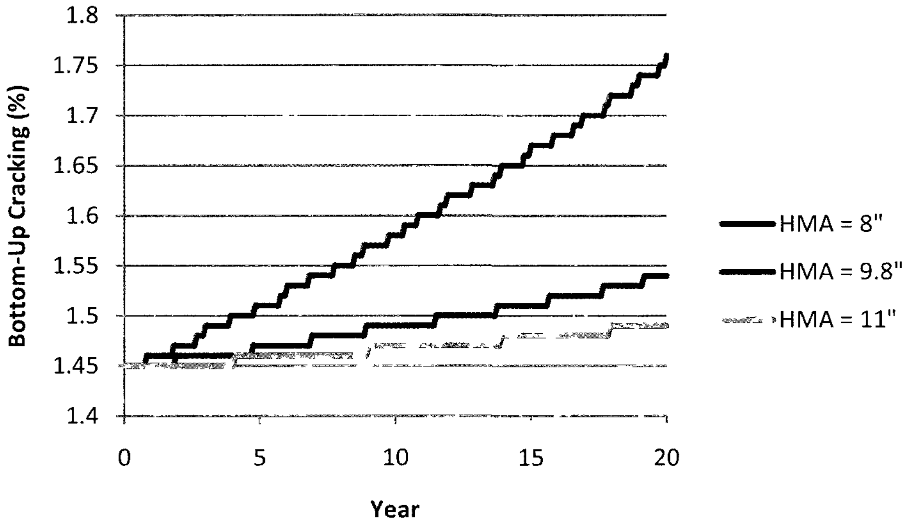


Figure 57B: Effect of AC Layer Thickness on Bottom-Up Cracking

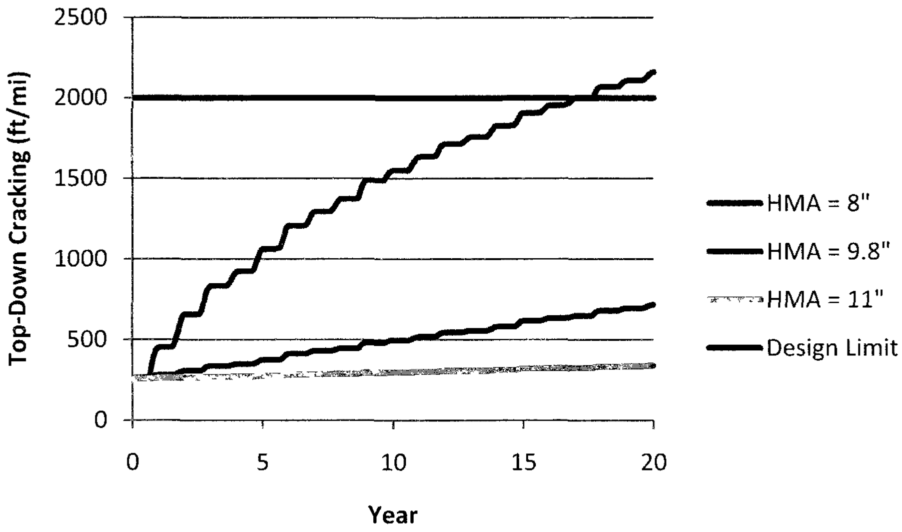


Figure 58B: Effect of AC Layer Thickness on Top-Down Cracking

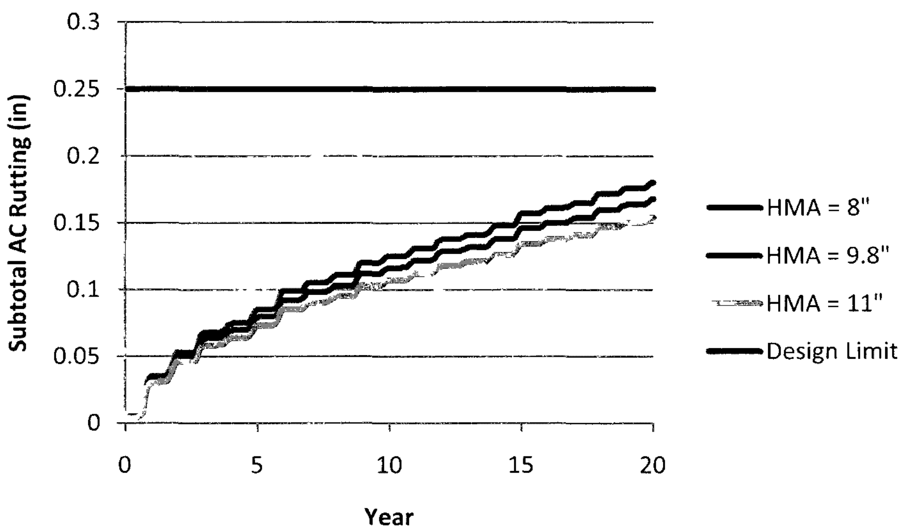


Figure 59B: Effect of AC Layer Thickness on Subtotal AC Rutting

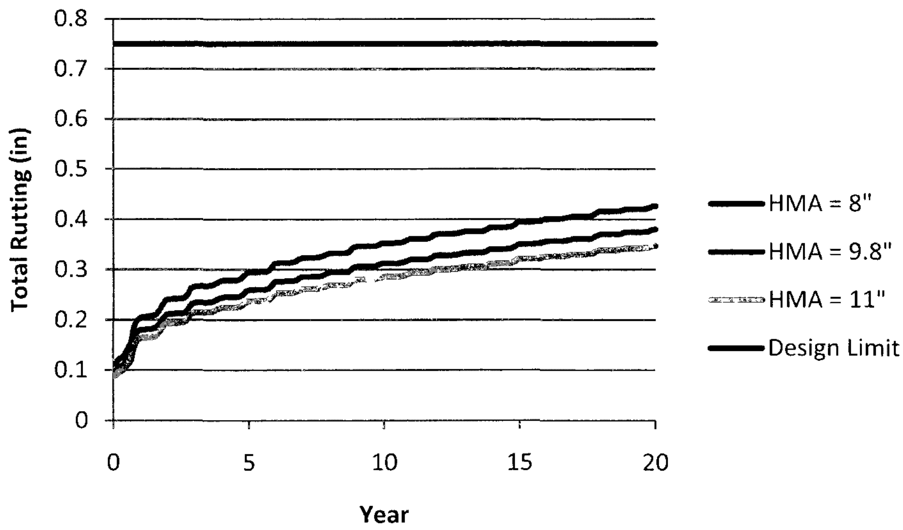


Figure 60B: Effect of AC Layer Thickness on Total Rutting

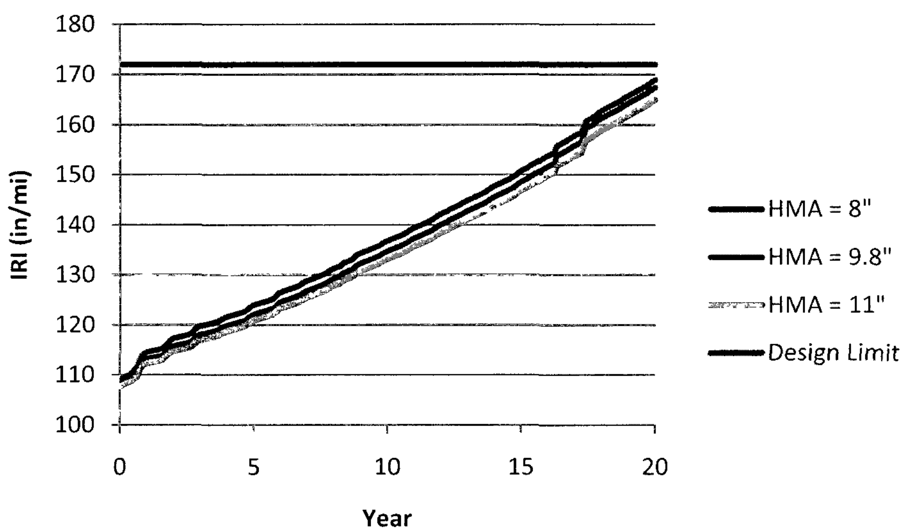


Figure 61B: Effect of AC Layer Thickness on IRI

7.4 Effect of Asphalt Concrete Mix Gradation

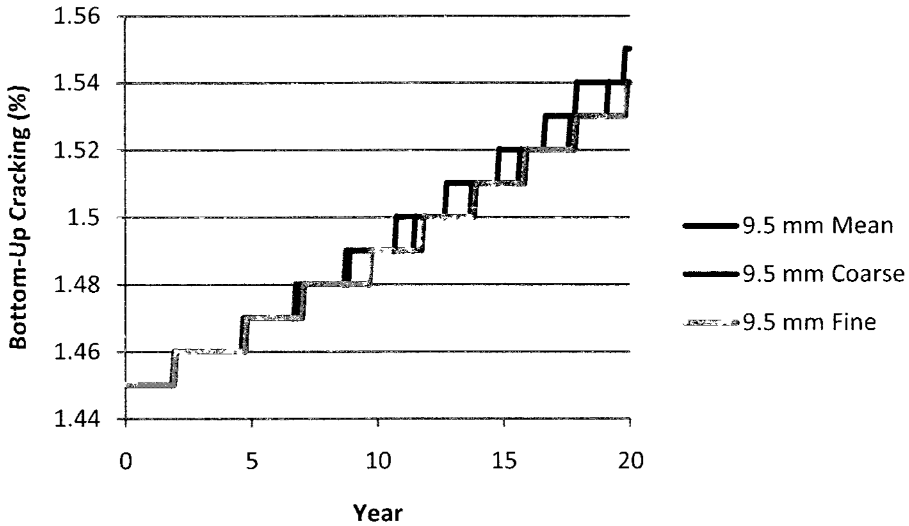


Figure 62B: Effect of Aggregate Gradation of 9.5 mm AC mix on Bottom-Up Cracking

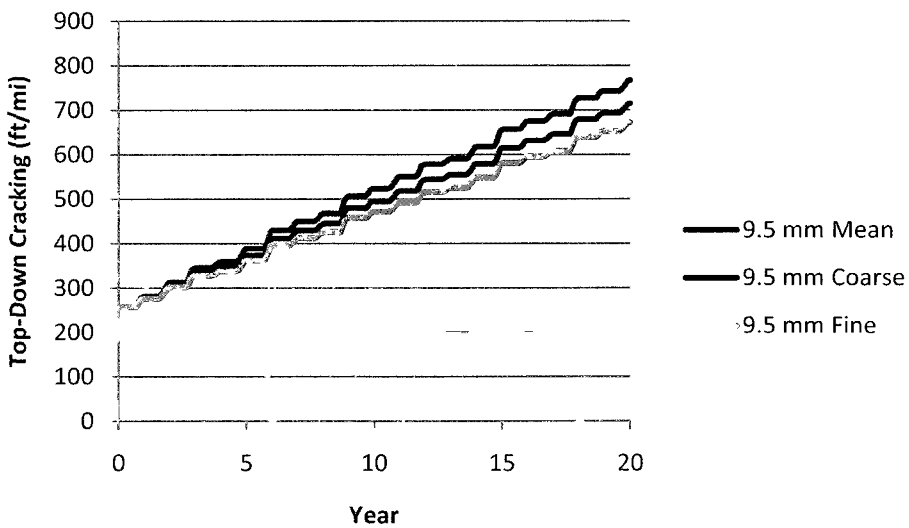


Figure 63B: Effect of Aggregate Gradation of 9.5 mm AC mix on Top-Down Cracking

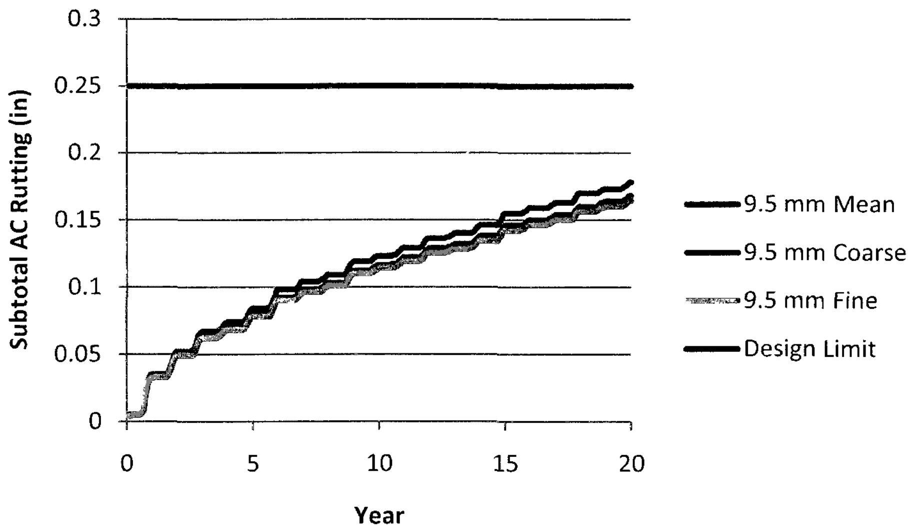


Figure 64B: Effect of Aggregate Gradation of 9.5 mm AC mix on Subtotal AC Rutting

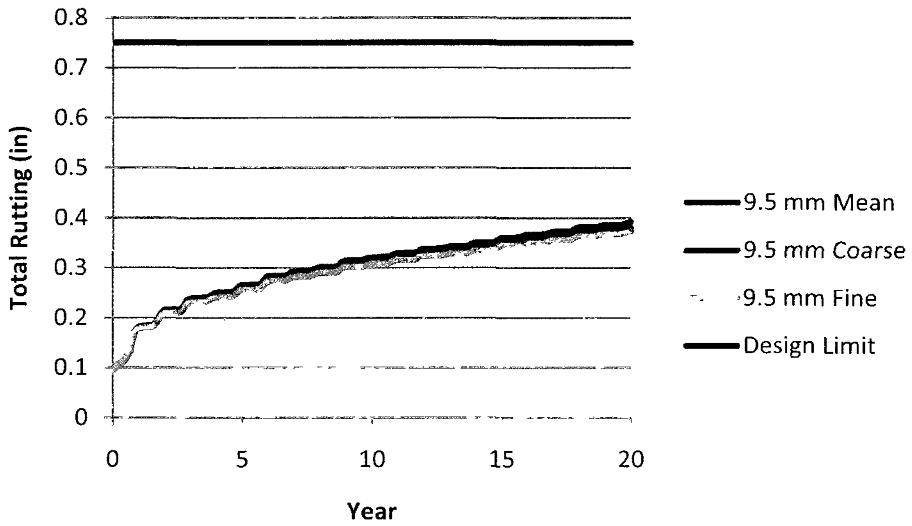


Figure 65B: Effect of Aggregate Gradation of 9.5 mm AC mix on Total Rutting

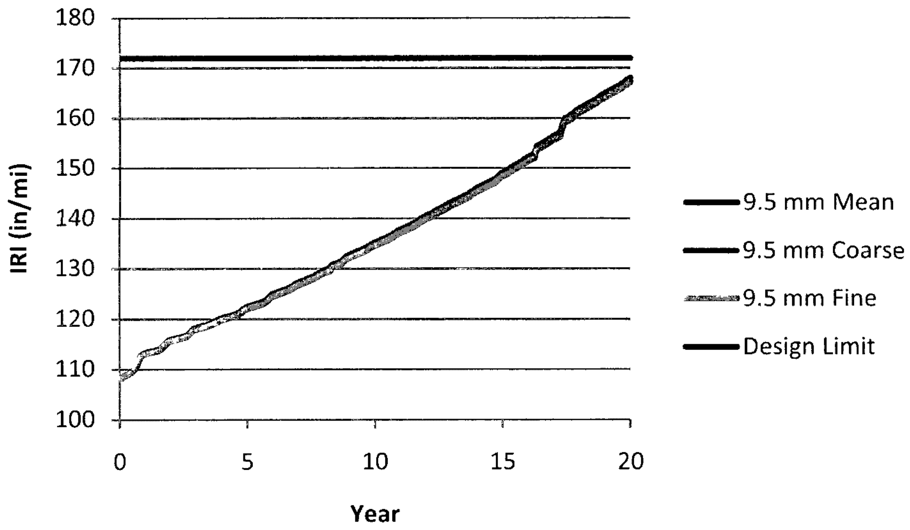


Figure 66B: Effect of Aggregate Gradation of 9.5 mm AC mix on IRI

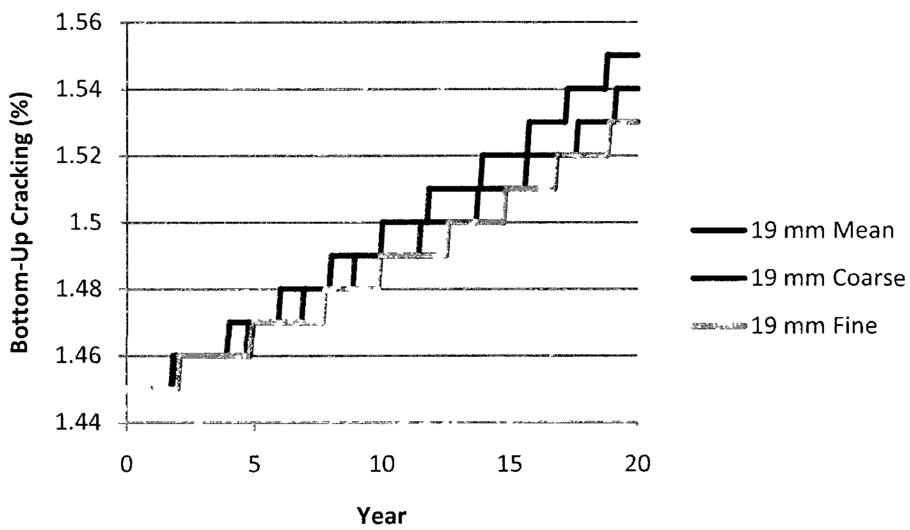


Figure 67B: Effect of Aggregate Gradation of 19.0 mm mix on Bottom-Up Cracking

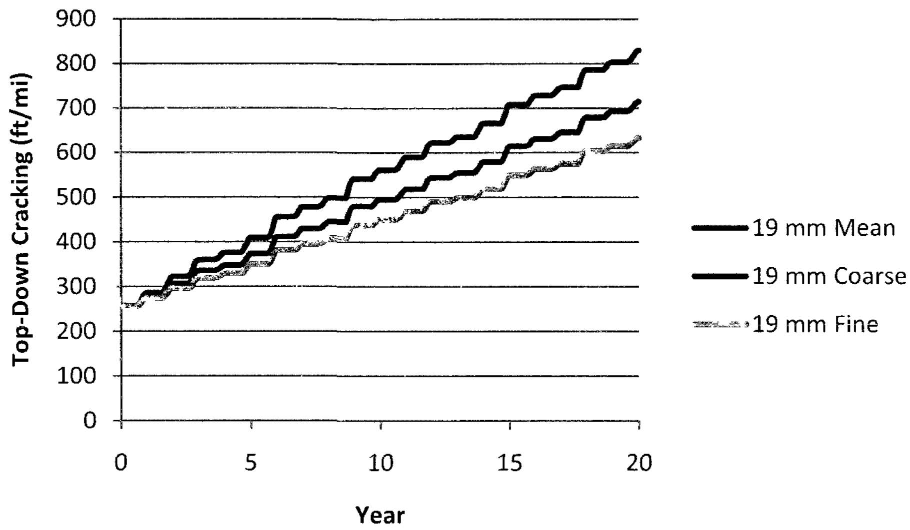


Figure 68B: Effect of Aggregate Gradation of 19.0 mm mix on Top-Down Cracking

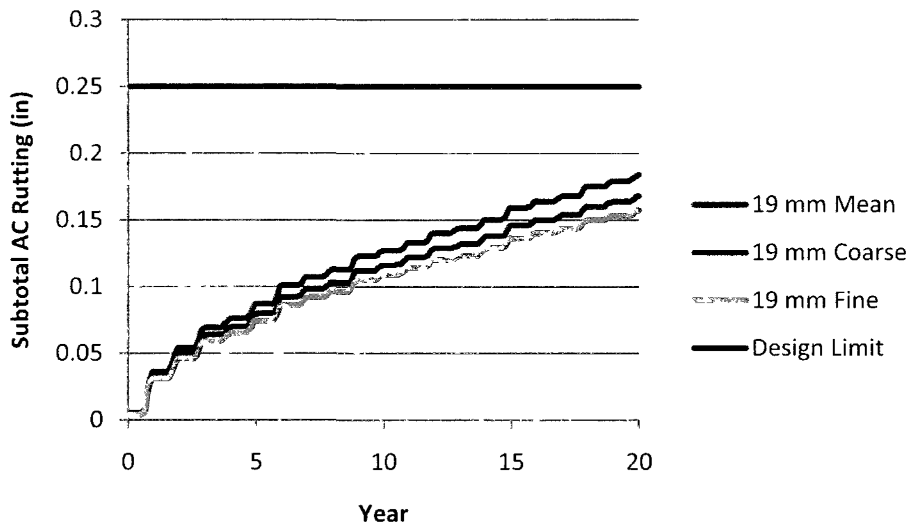


Figure 69B: Effect of Aggregate Gradation of 19.0 mm mix on Subtotal AC Rutting

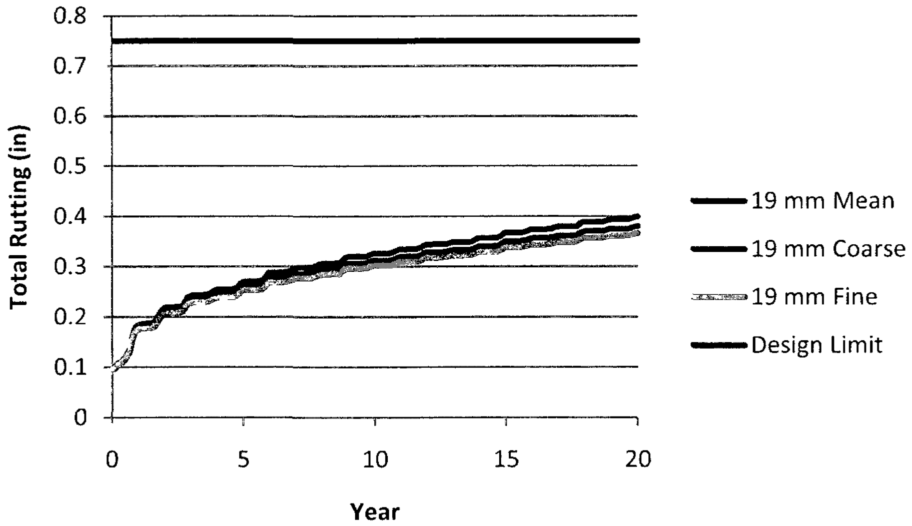


Figure 70B: Effect of Aggregate Gradation of 19.0 mm mix on Total Rutting

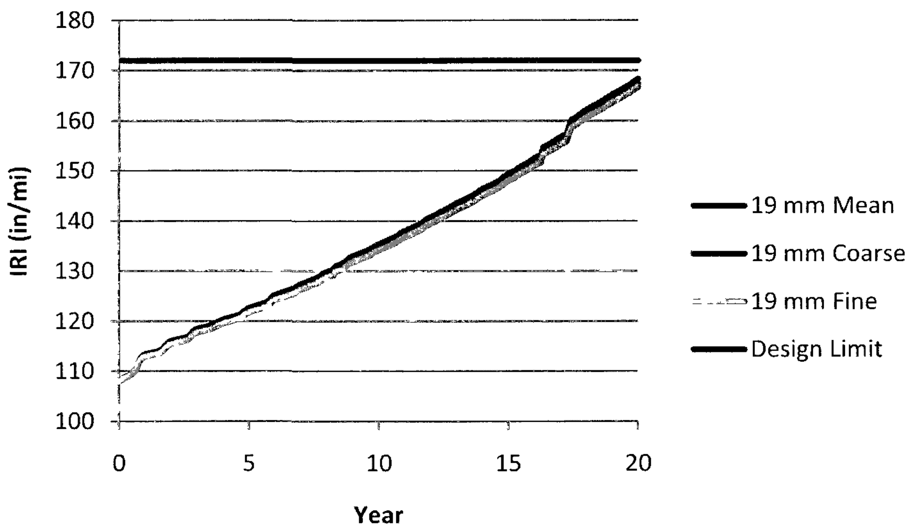


Figure 71B: Effect of Aggregate Gradation of 19.0 mm mix on IRI

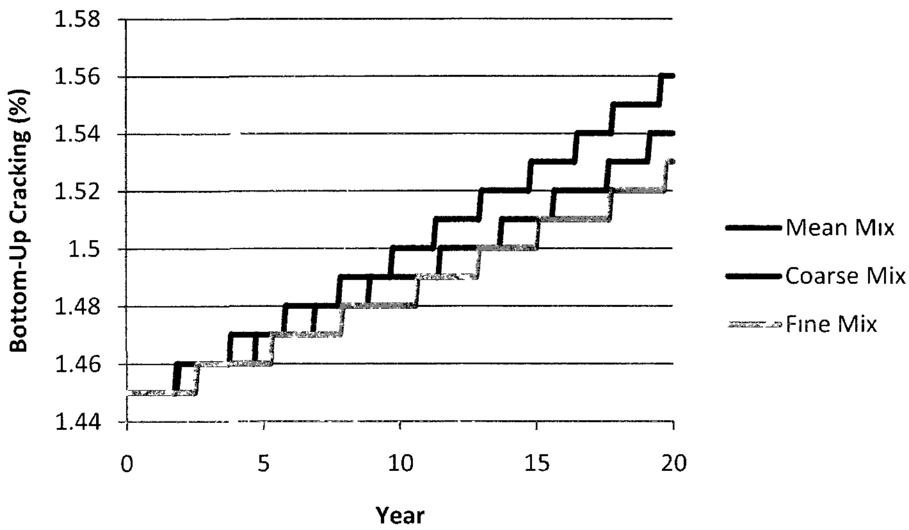


Figure 72B: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Bottom-Up Cracking

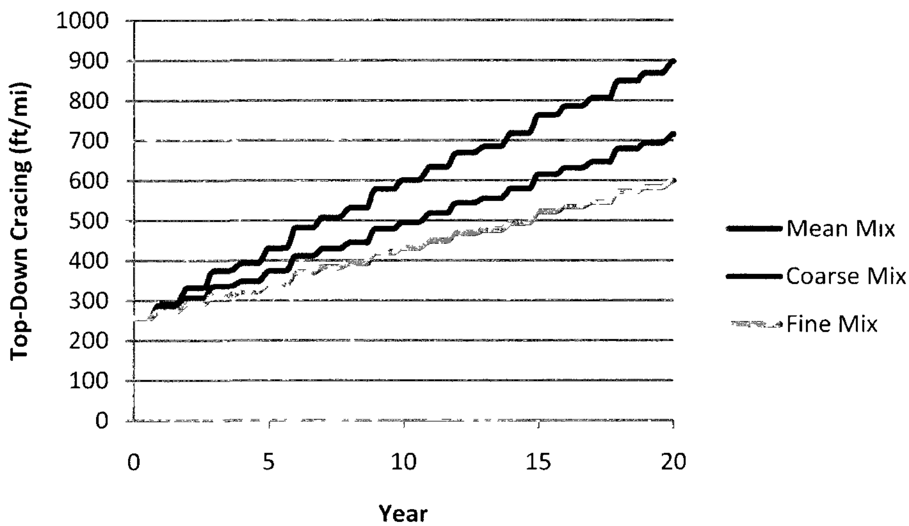


Figure 73B: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Top-Down Cracking

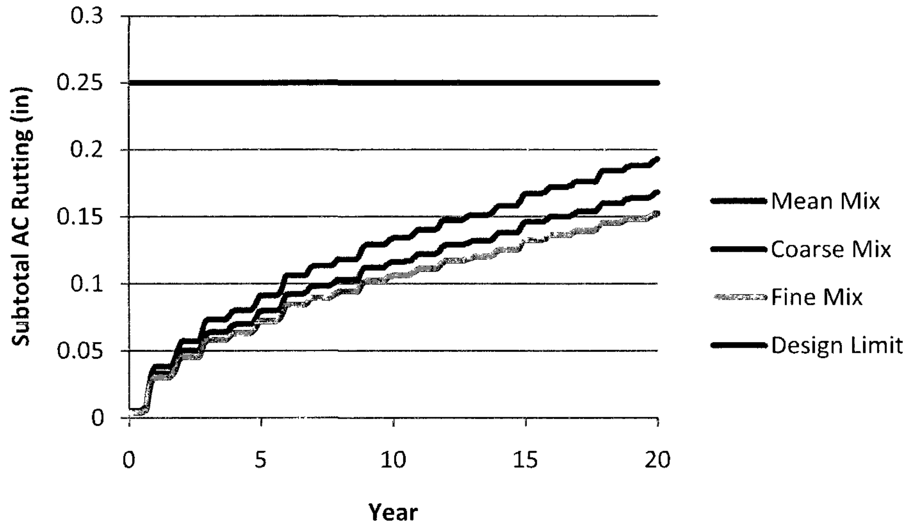


Figure 74B: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Subtotal AC Rutting

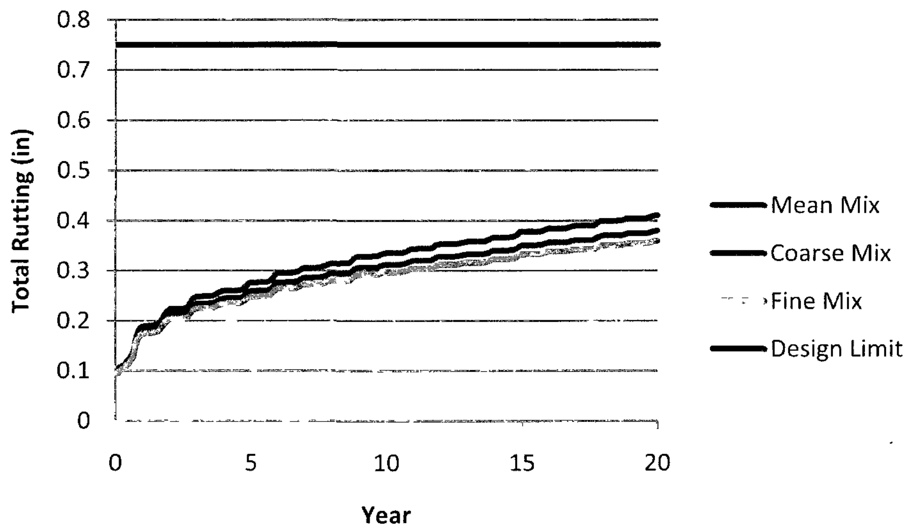


Figure 75B: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Total Rutting

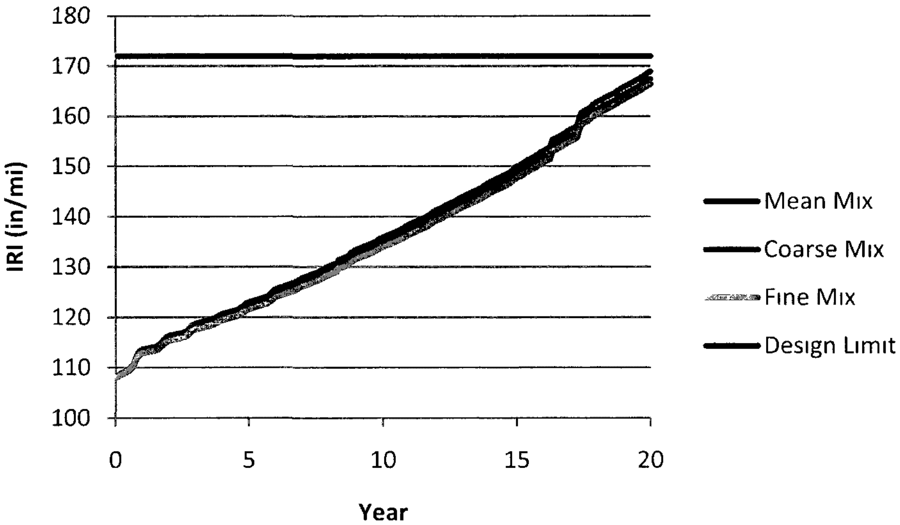


Figure 76B: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on IRI

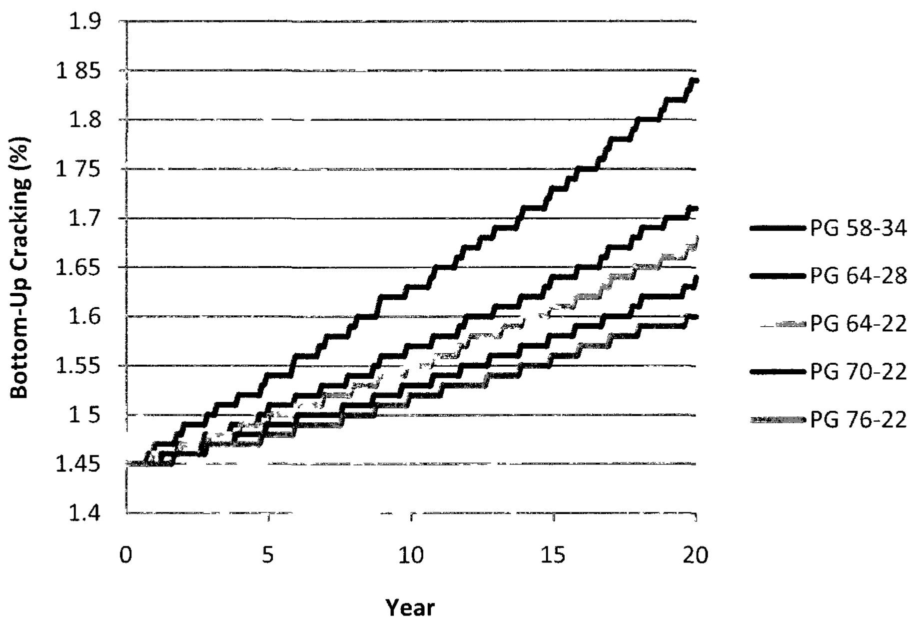


Figure 77B: Effect of Binder Grade on Bottom-Up Cracking at Speed 5 mph

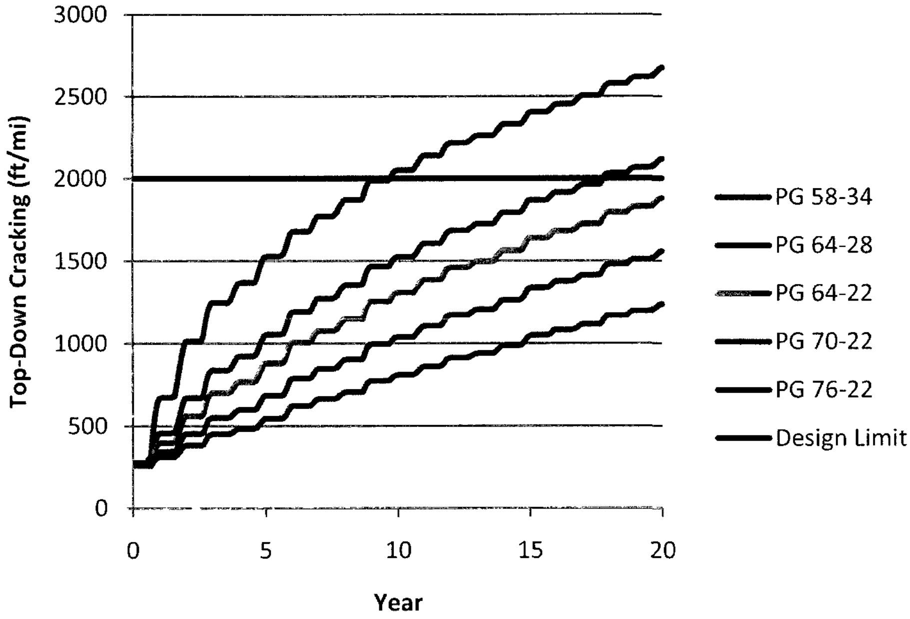


Figure 78B: Effect of Binder Grade on Top-Down Cracking at Speed 5 mph

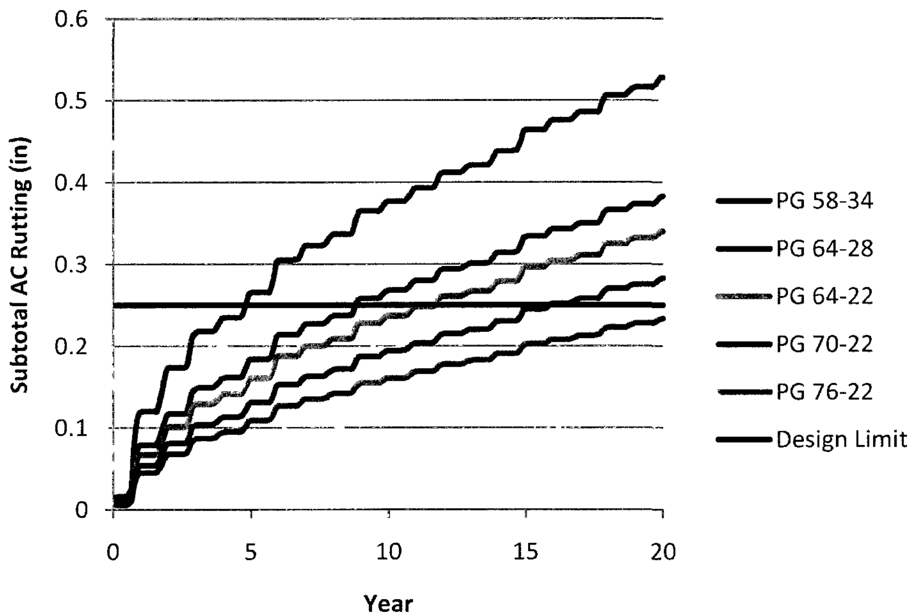


Figure 79B: Effect of Binder Grade on Subtotal AC Rutting at Speed 5 mph

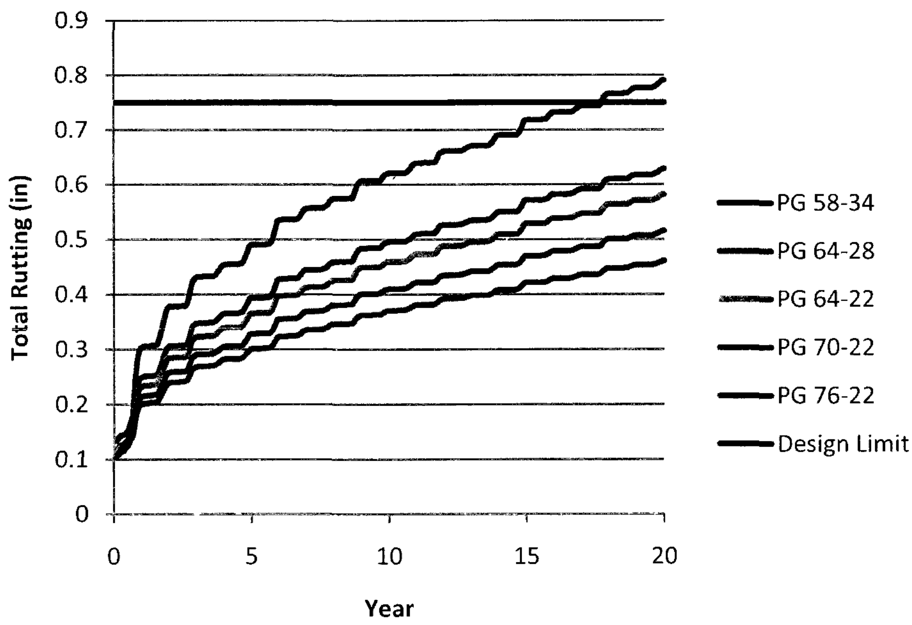


Figure 80B: Effect of Binder Grade on Total Rutting at Speed 5 mph

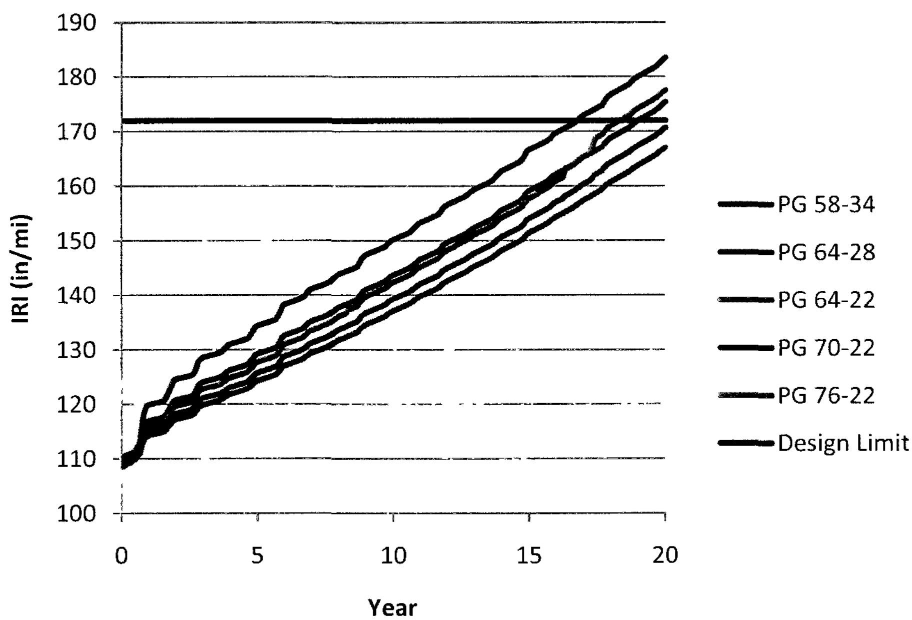


Figure 81B: Effect of Binder Grade on IRI at Speed 5 mph

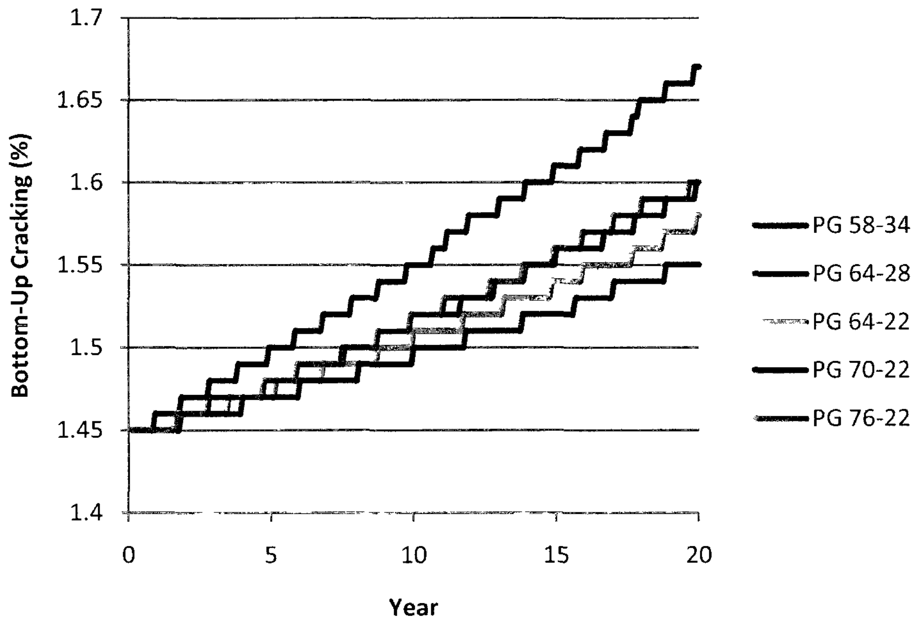


Figure 82B: Effect of Binder Grade on Bottom-Up Cracking at Speed 25 mph

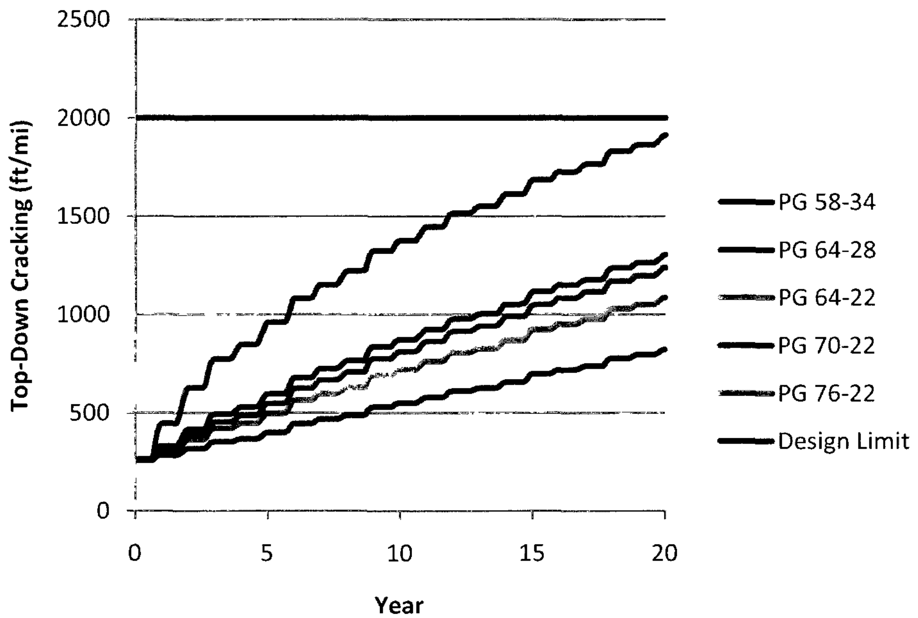


Figure 83B: Effect of Binder Grade on Top-Down Cracking at Speed 25 mph

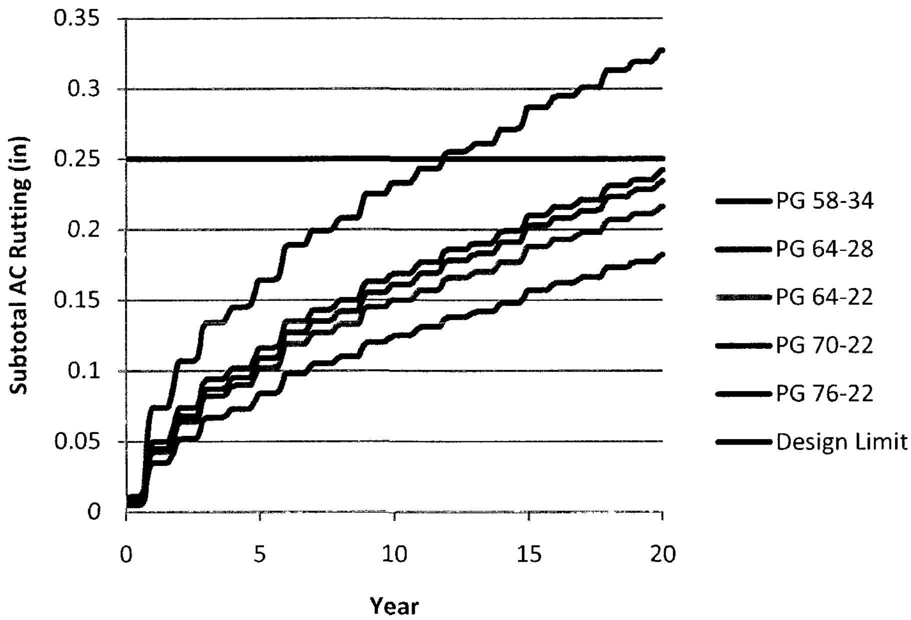


Figure 84B: Effect of Binder Grade on Subtotal AC Rutting at Speed 25 mph

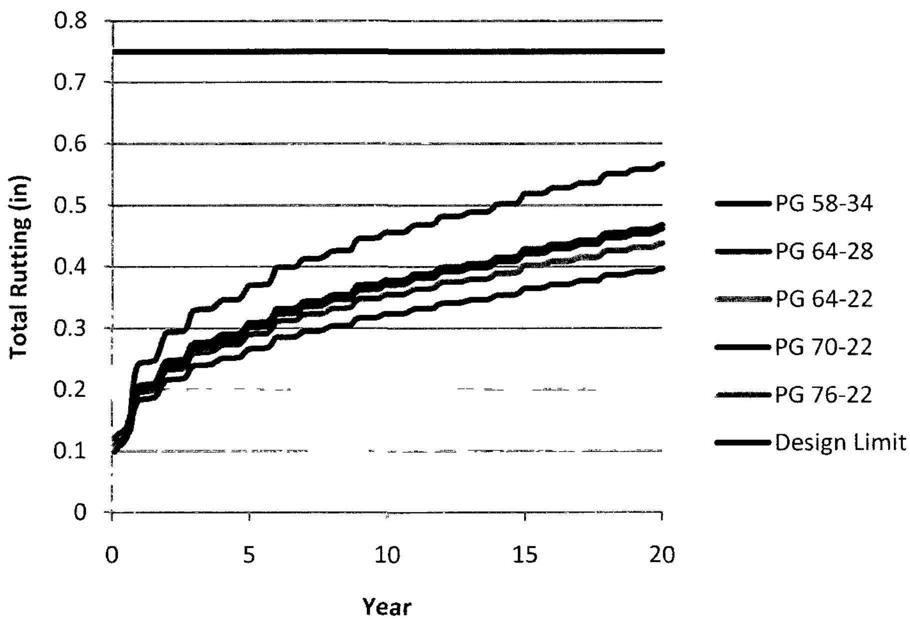


Figure 85B: Effect of Binder Grade on Total Rutting at Speed 25 mph

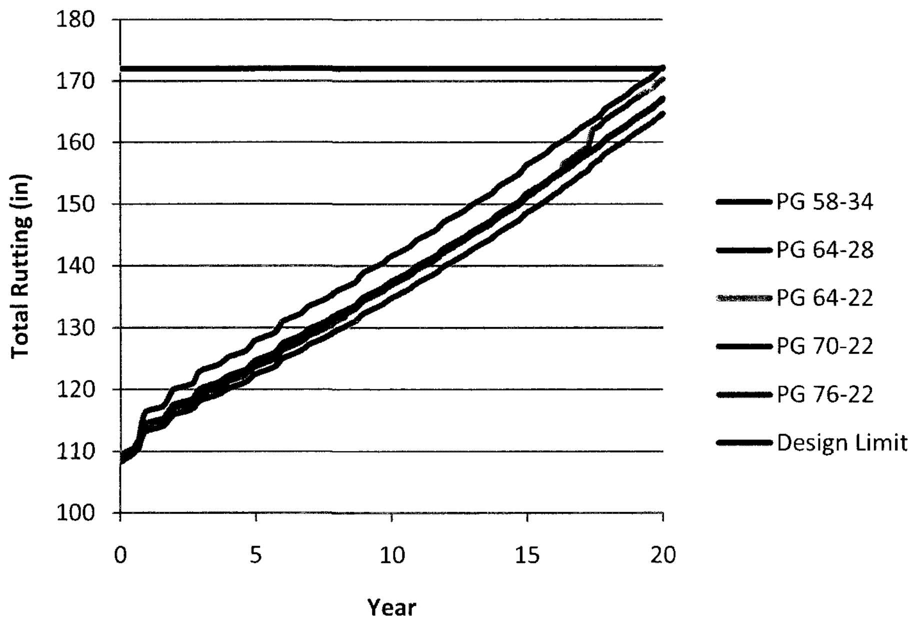


Figure 86B: Effect of Binder Grade on IRI at Speed 25 mph

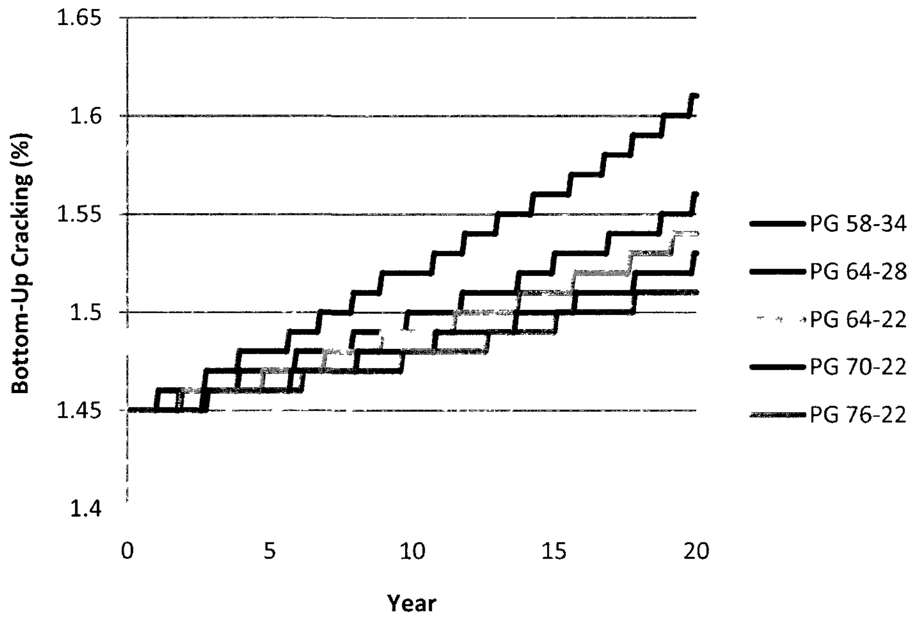


Figure 87B: Effect of Binder Grade on Bottom-Up Cracking at Speed 65 mph

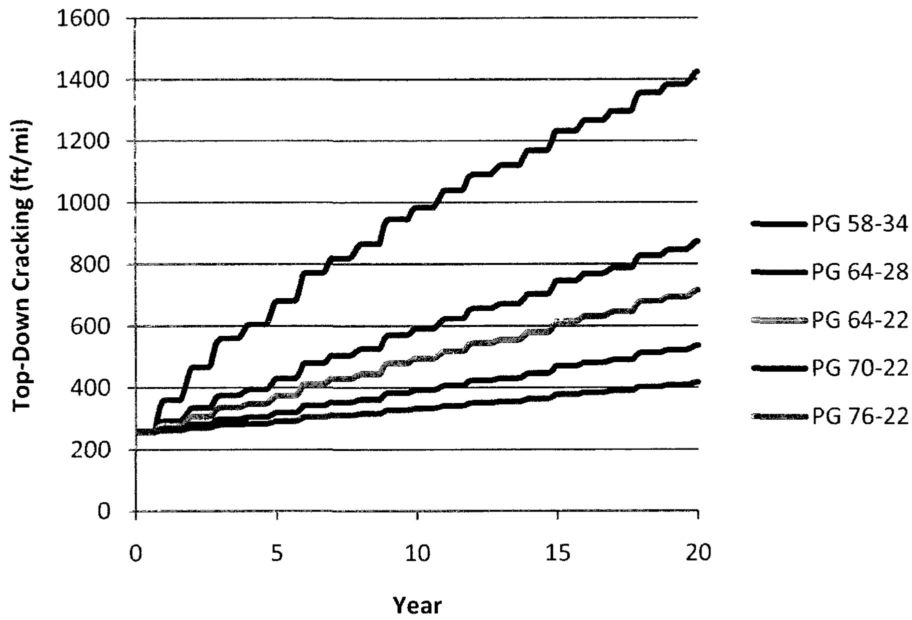


Figure 88B: Effect of Binder Grade on Top-Down Cracking at Speed 65 mph

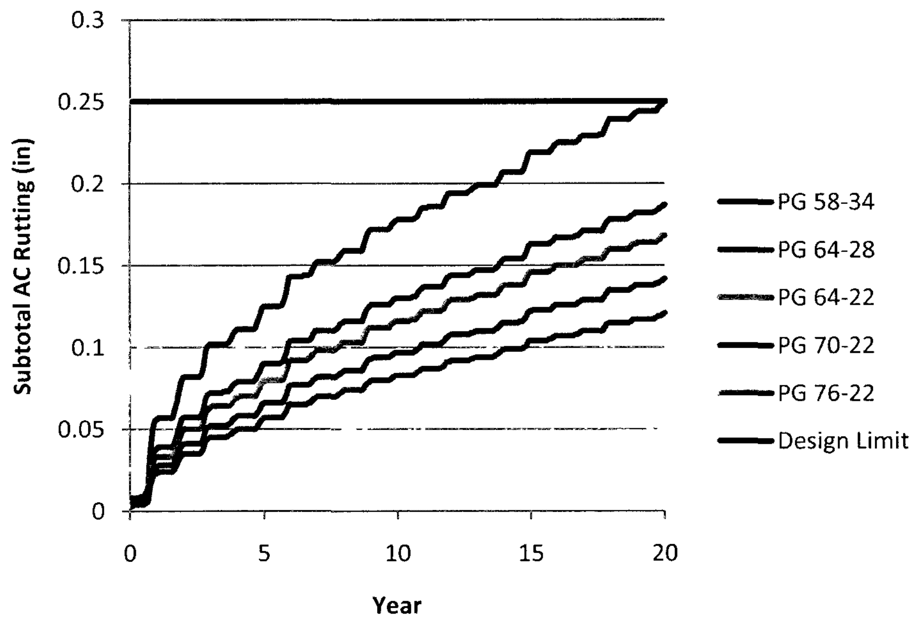


Figure 89B: Effect of Binder Grade on Subtotal AC Rutting at Speed 65 mph

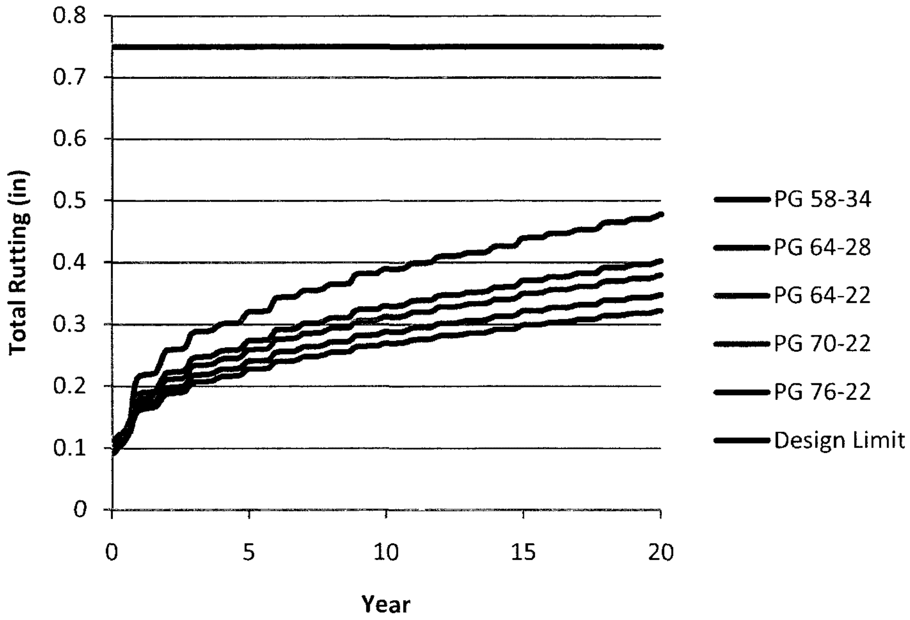


Figure 90B: Effect of Binder Grade on Total Rutting at Speed 65 mph

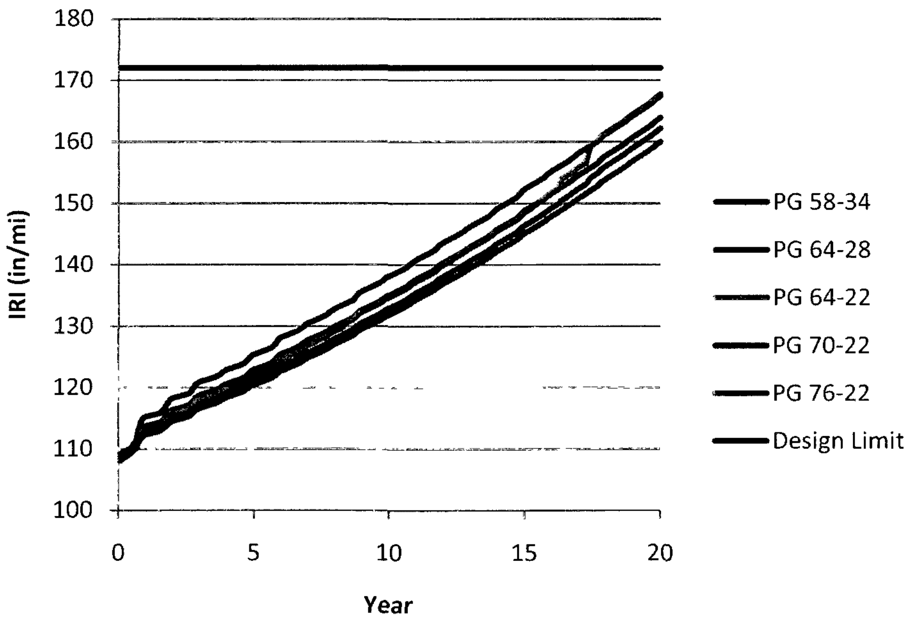


Figure 91B: Effect of Binder Grade on IRI at Speed 65 mph

7.5 Effect of Base/Subbase Inputs on Pavement Distresses

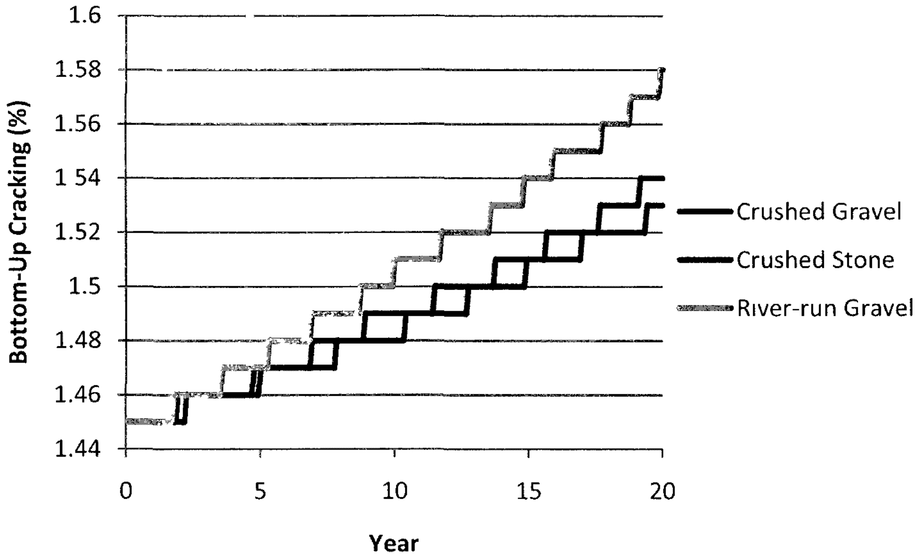


Figure 92B: Effect of Base Course Material on Bottom-Up Cracking

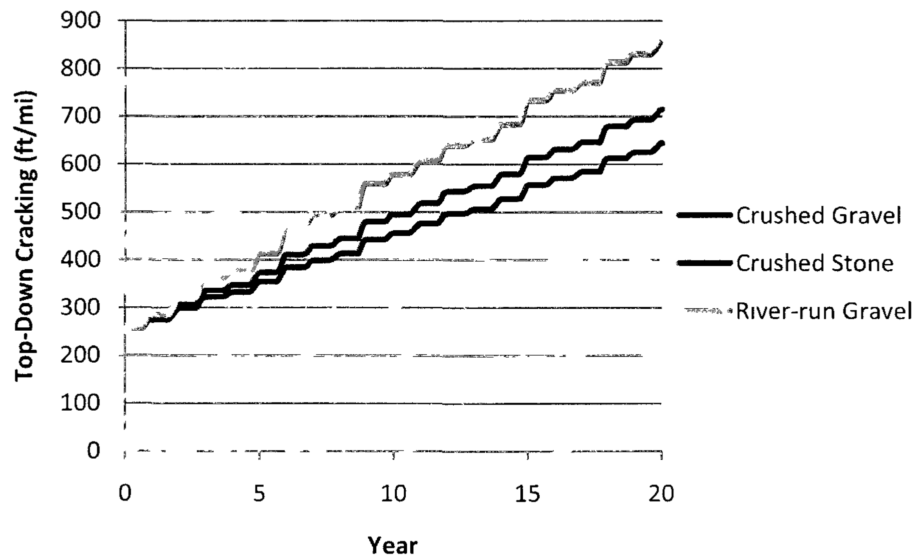


Figure 93B: Effect of Base Course Material on Top-Down Cracking

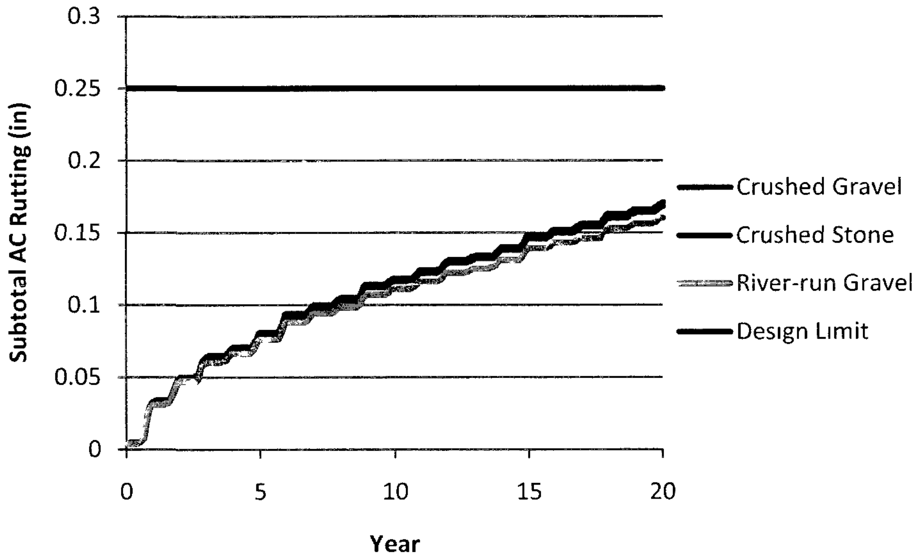


Figure 94B: Effect of Base Course Material on Subtotal AC Rutting

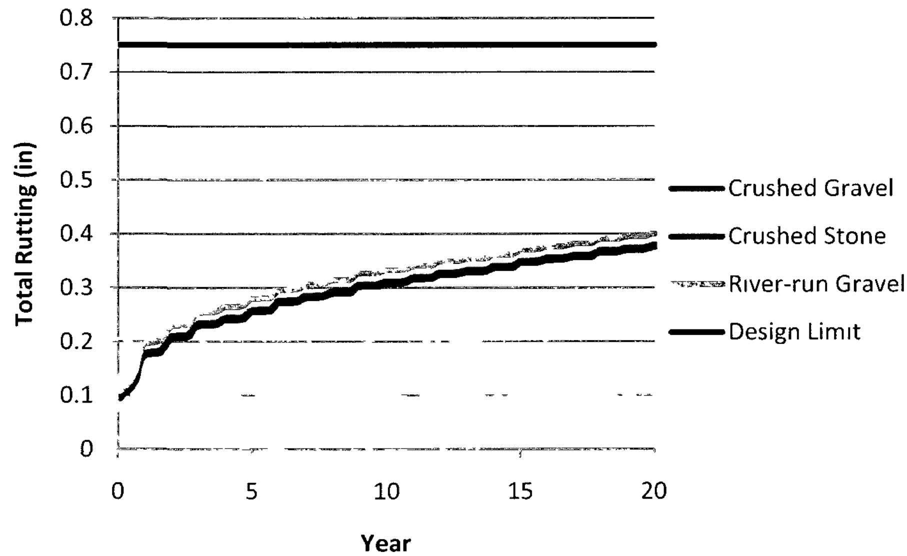


Figure 95B: Effect of Base Course Material on Total Rutting

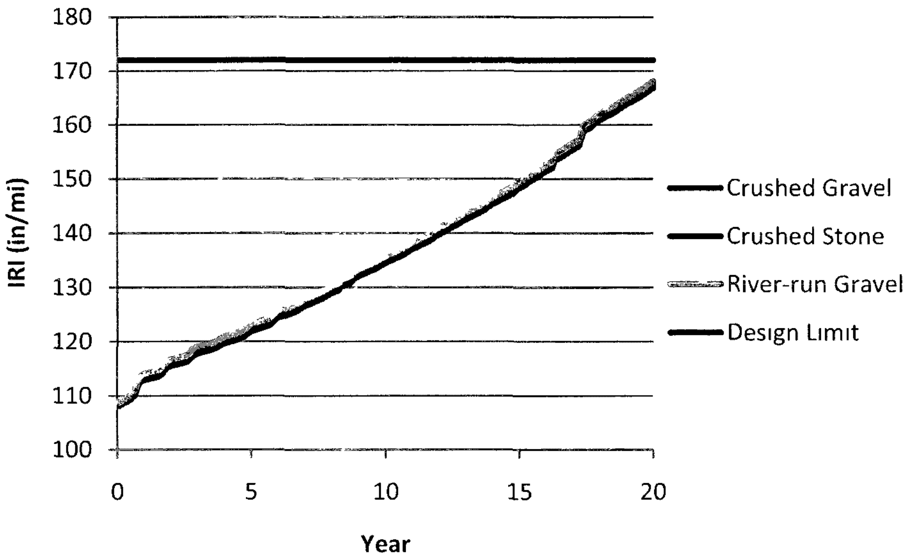


Figure 96B: Effect of Base Course Material on IRI

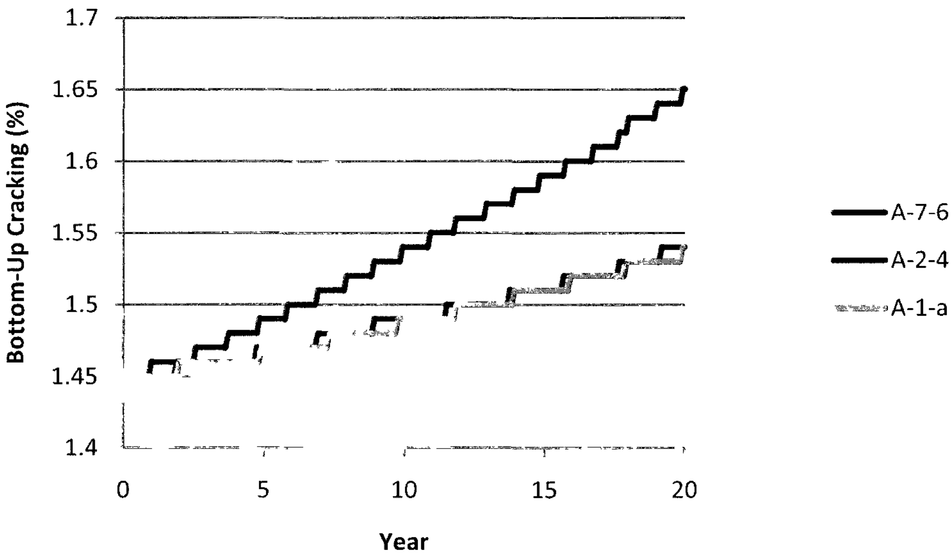


Figure 97B: Effect of Subgrade Type on Bottom-Up Cracking

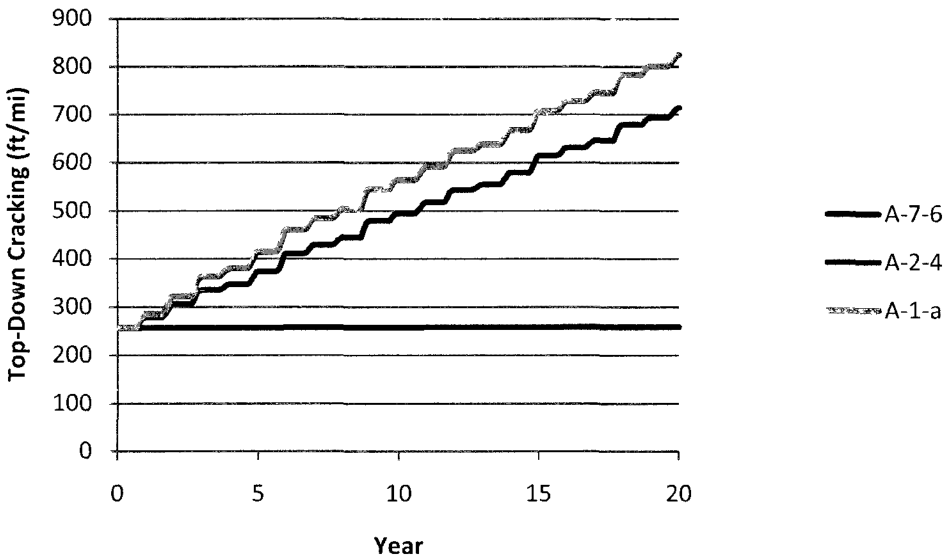


Figure 98B: Effect of Subgrade Type on Top-Down Cracking

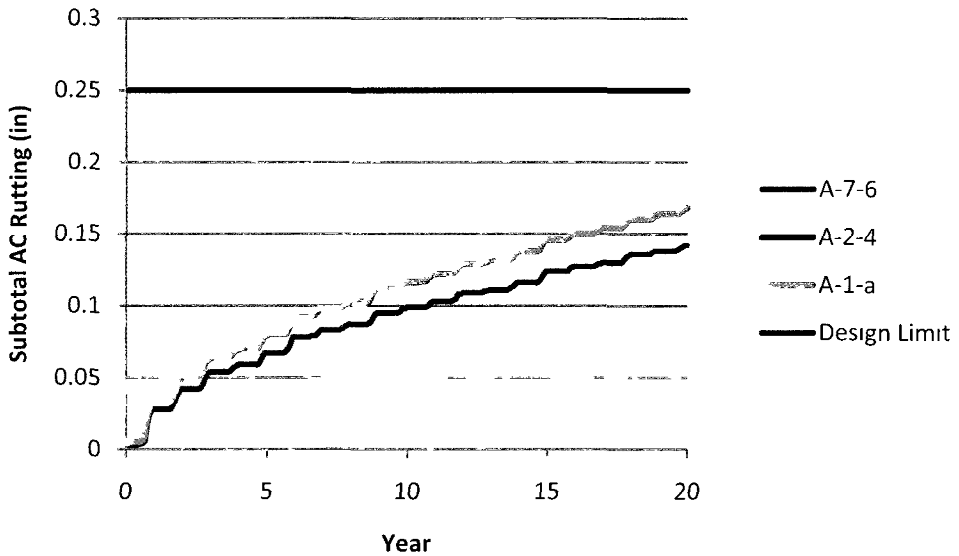


Figure 99B: Effect of Subgrade Type on Subtotal AC Rutting

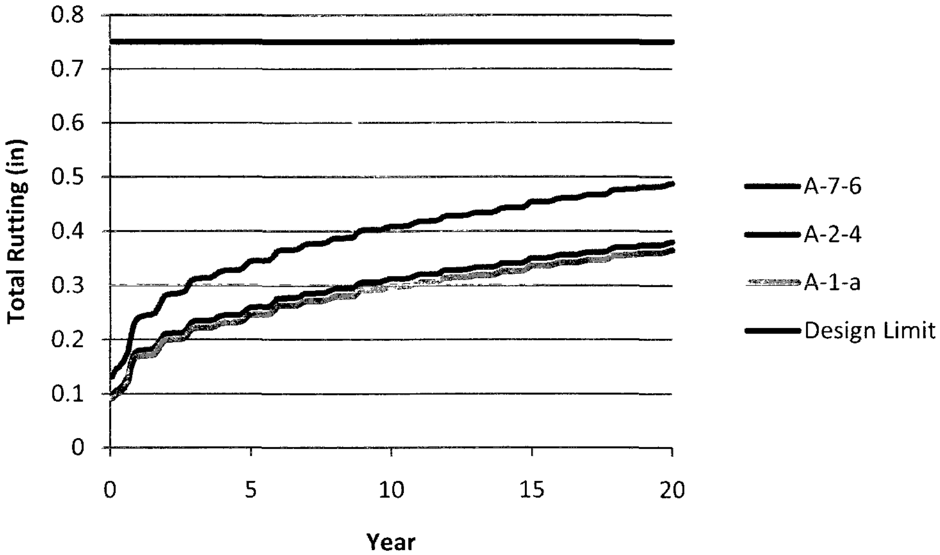


Figure 100B: Effect of Subgrade Type on Total Rutting

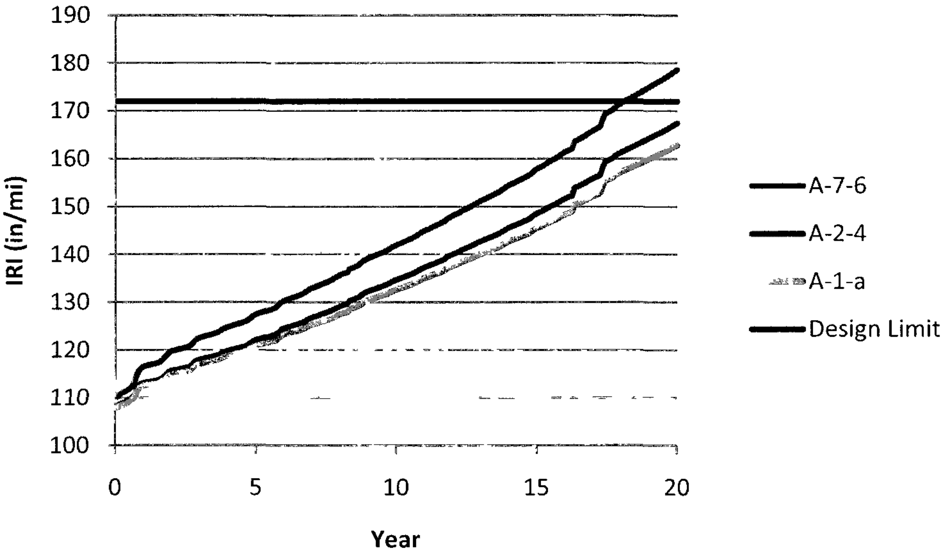


Figure 101B: Effect of Subgrade Type on IRI

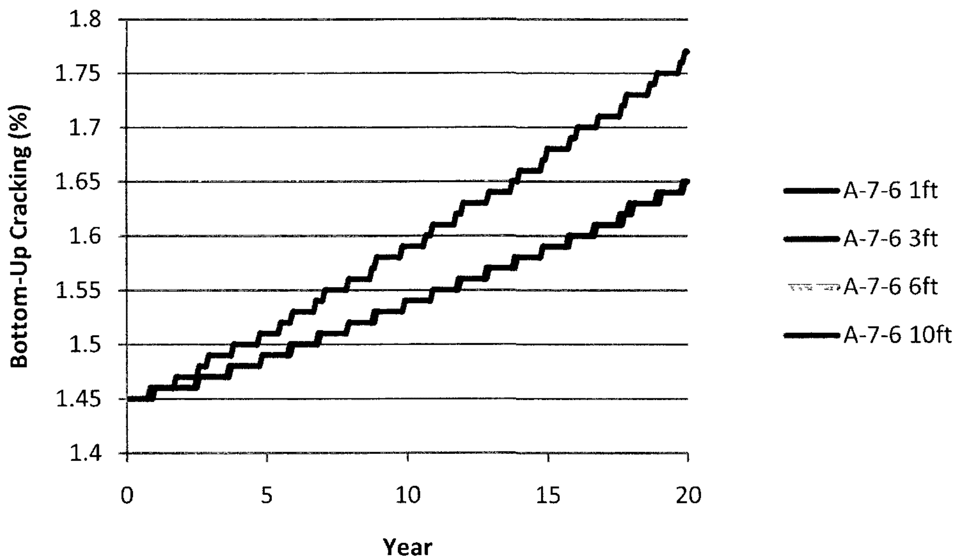


Figure 102B: Effect of Water Table on Bottom-Up Cracking with Weakest Subgrade

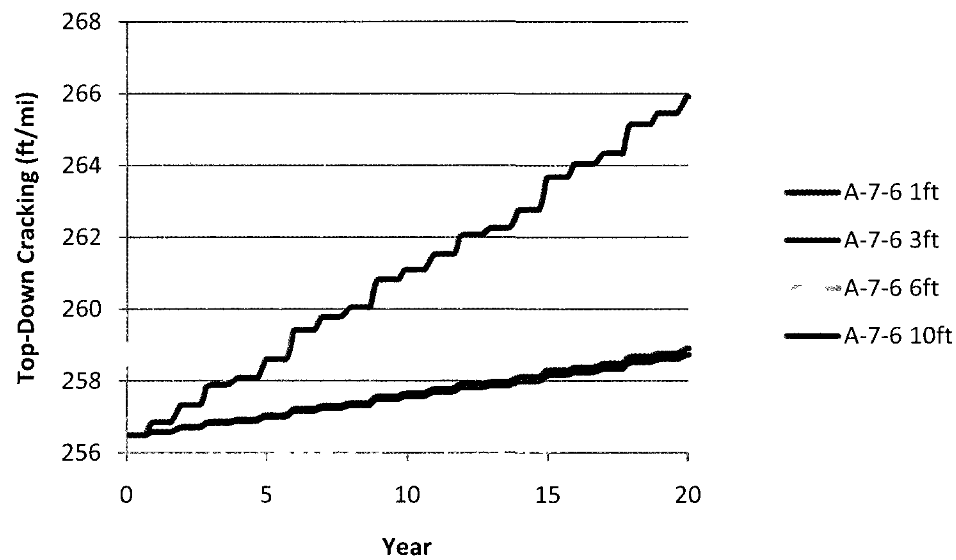


Figure 103B: Effect of Water Table on Top-Down Cracking with Weakest Subgrade

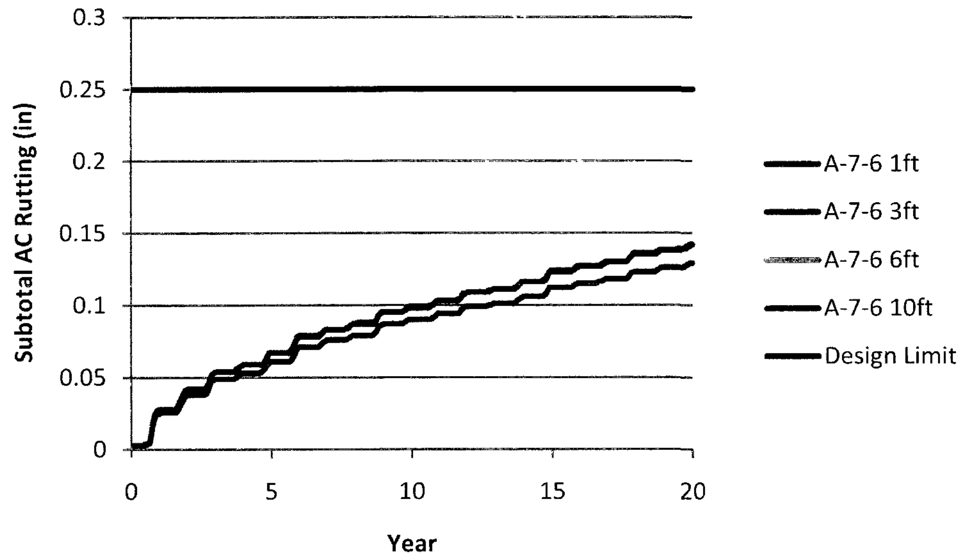


Figure 104B: Effect of Water Table on Subtotal AC Rutting with Weakest Subgrade

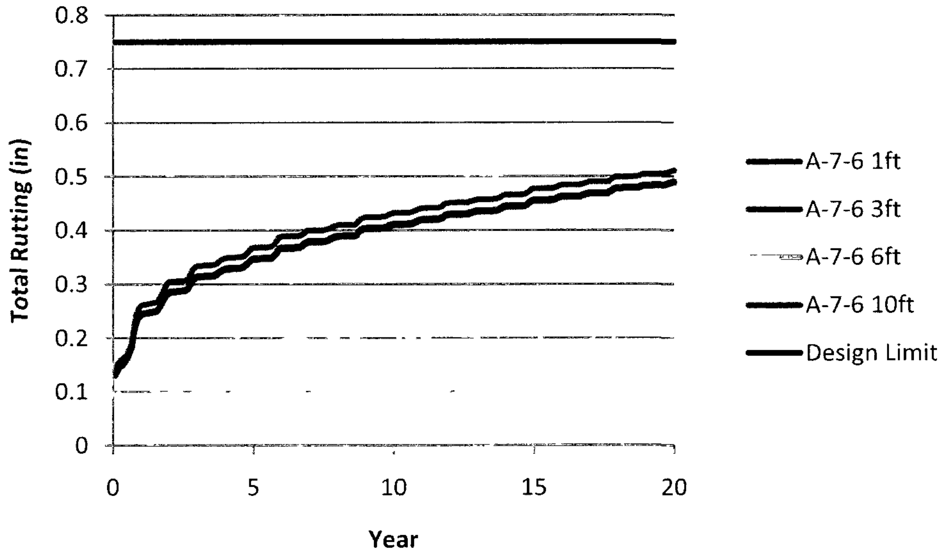


Figure 105B: Effect of Water Table on Total Rutting with Weakest Subgrade

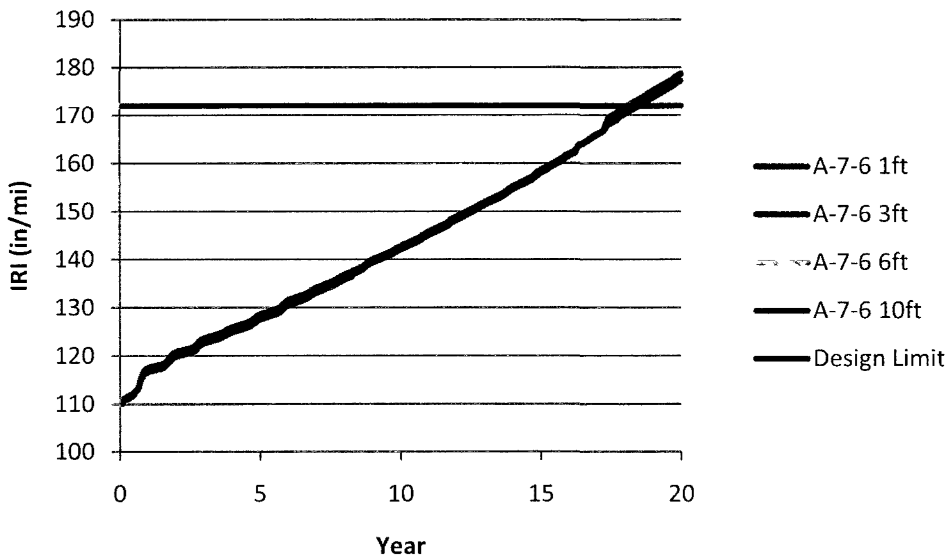


Figure 106B: Effect of Water Table on IRI with Weakest Subgrade

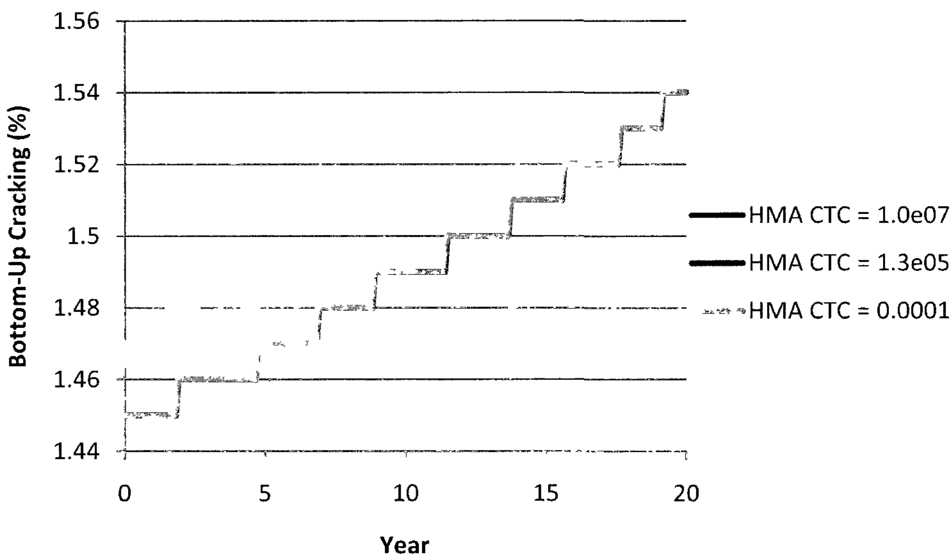


Figure 107B: Effect of HMA CTC on Bottom-Up Cracking

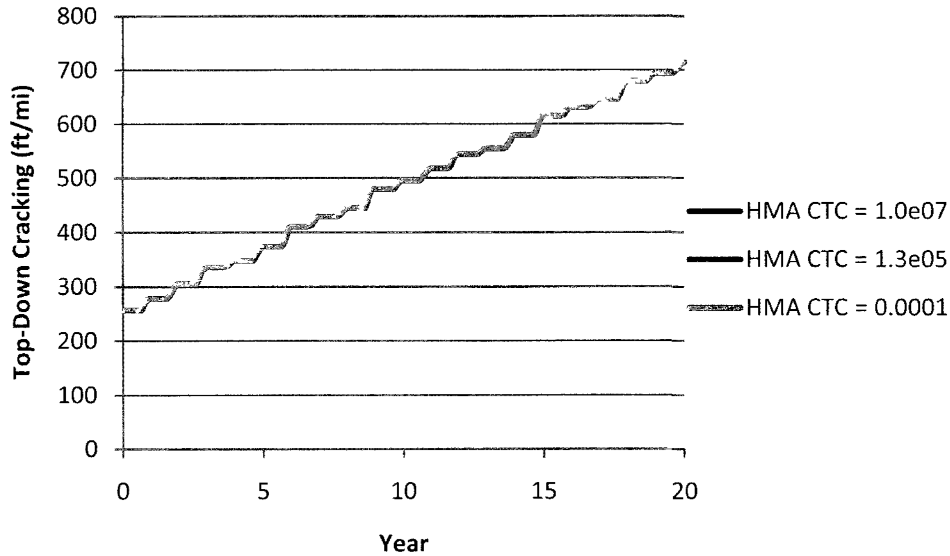


Figure 108B: Effect of HMA CTC on Top-Down Cracking

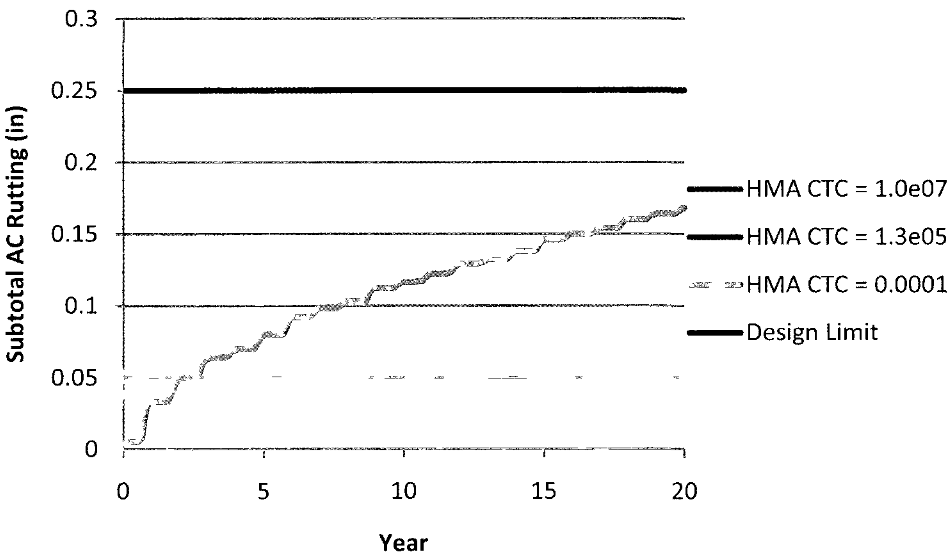


Figure 109B: Effect of HMA CTC on Subtotal AC Rutting

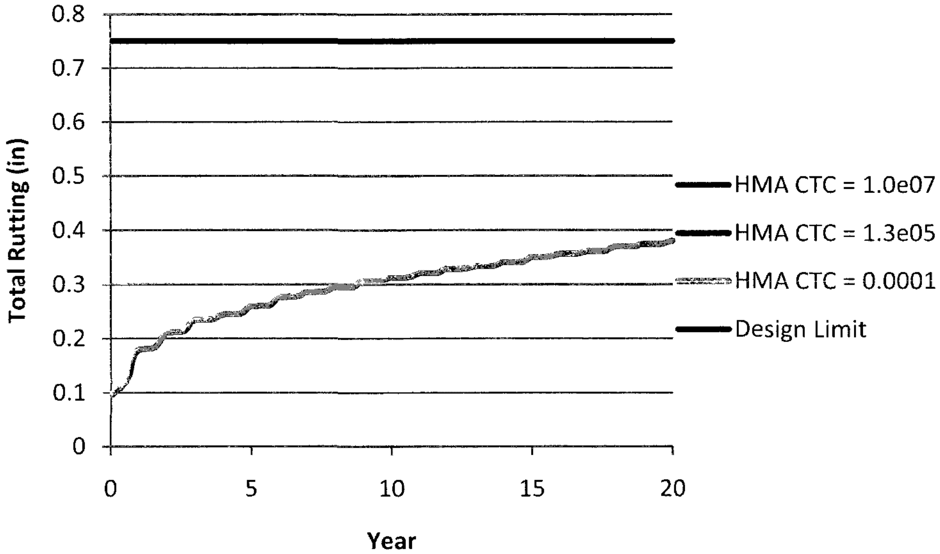


Figure 110B: Effect of HMA CTC on Total AC Rutting

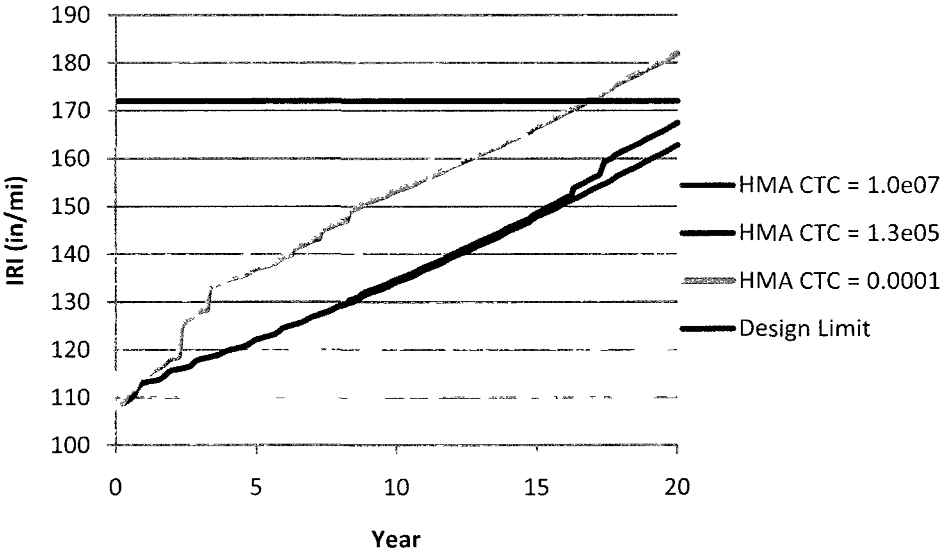


Figure 111B: Effect of HMA CTC on IRI

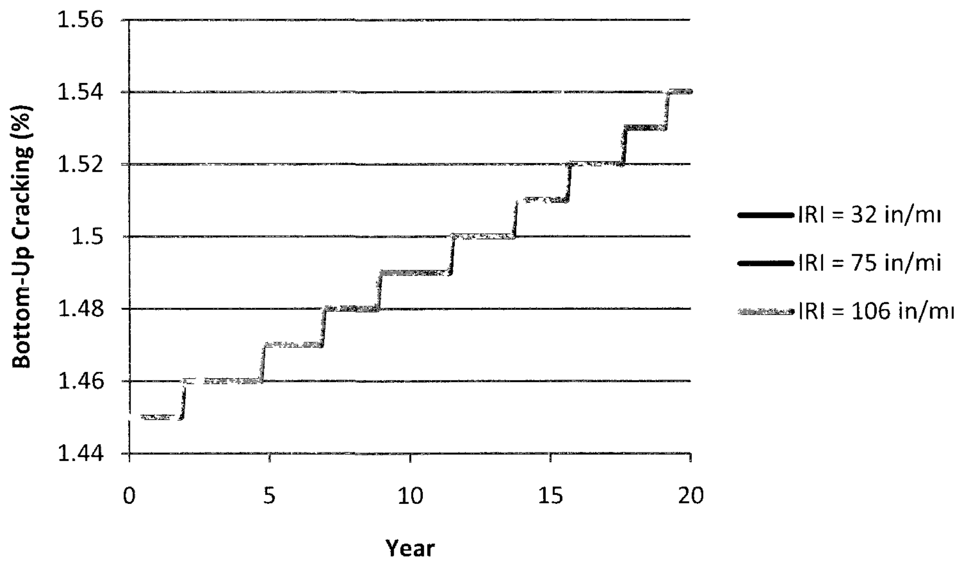


Figure 112B: Effect of Initial IRI on Bottom-Up Cracking

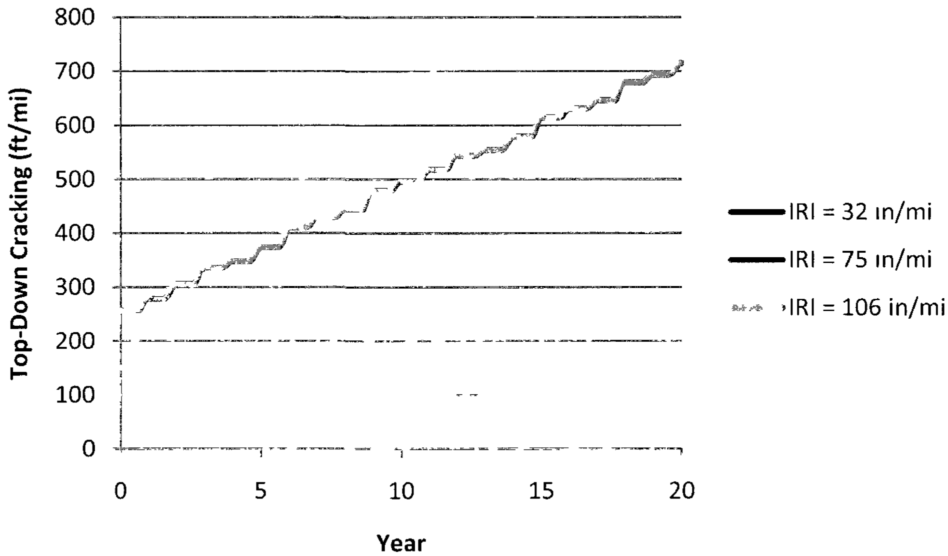


Figure 113B: Effect of Initial IRI on Top-Down Cracking

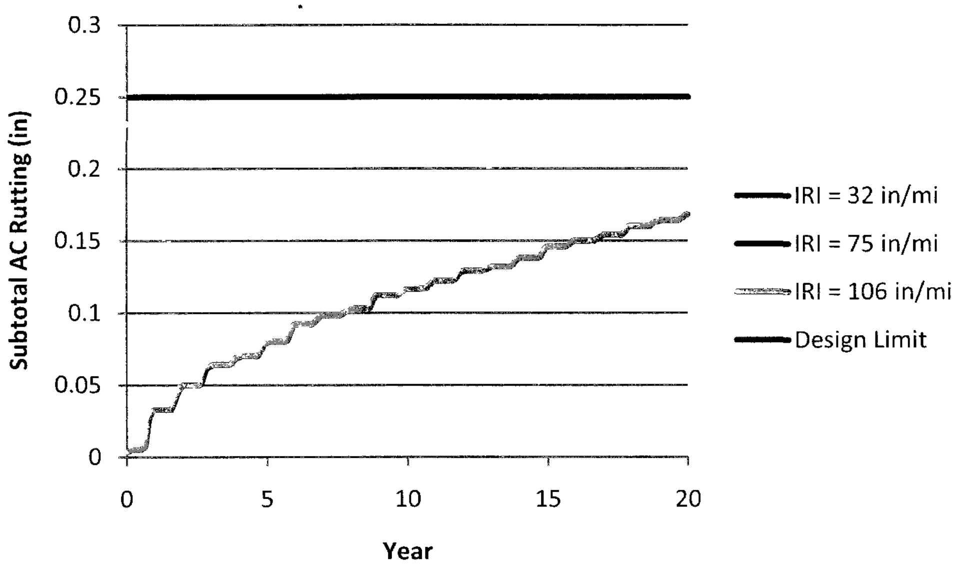


Figure 114B: Effect of Initial IRI on Subtotal AC Rutting

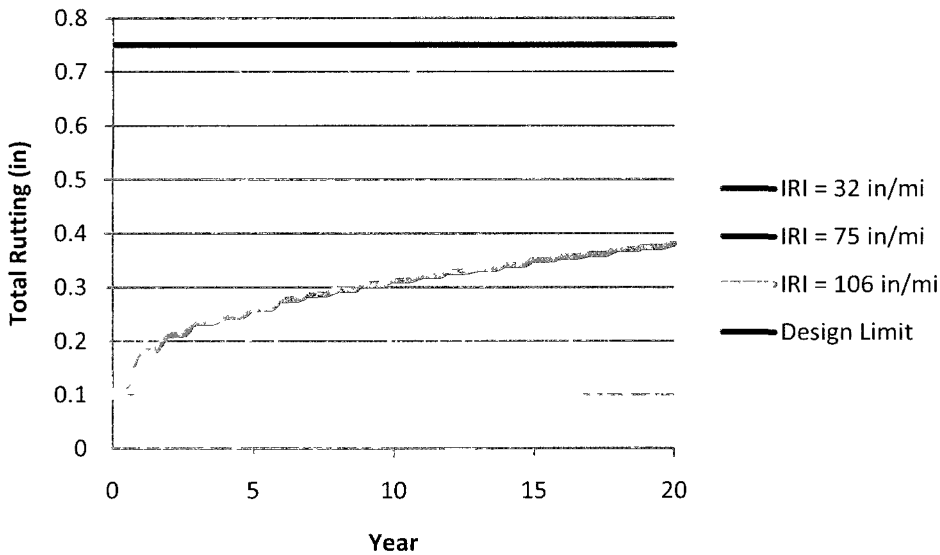


Figure 115B: Effect of Initial IRI on Total Rutting

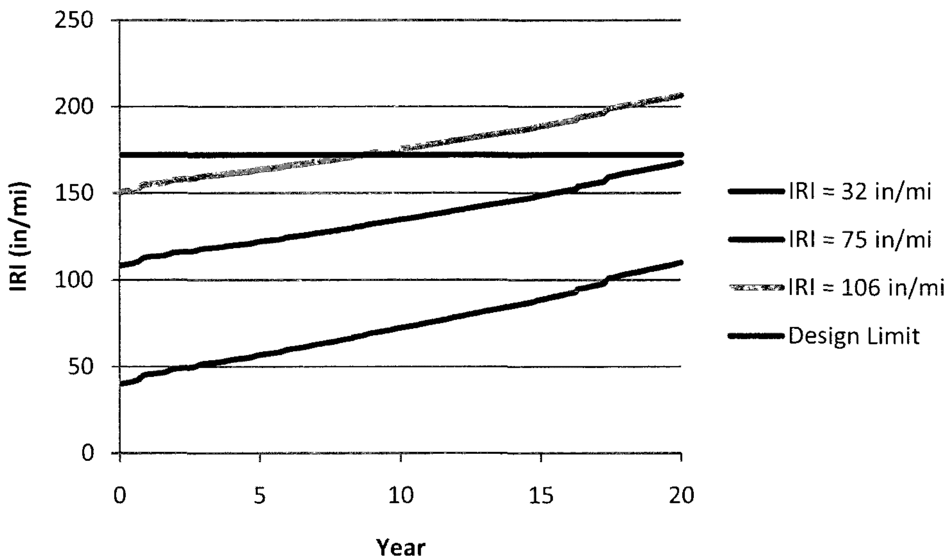


Figure 116B: Effect of Initial IRI on IRI

8. Sensitivity Analysis Summary Level 3

Normalization of the distresses was done to compare the effects of each input parameter on predicted distresses.

The normalized distress levels are calculated as the ratio of the difference between the maximum and minimum predicted distresses for each input variable to the distress levels corresponding to the control set of input values.

$$N = \frac{\textbf{Maximum Distress} - \textbf{Minimum Distress}}{\textbf{Distress for control input set}}$$

N - Normalized Value

Table 34B: Difference between Maximum and Minimum Distresses – Level 3

NEW YORK LEVEL 3					
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**
HMA thickness	0.27	1821.85	0.026	0.079	3.99
HMA mix gradation	0.03	297.93	0.041	0.051	2.55
HMA air voids	0.2	748.37	0.019	0.024	0.28
HMA effective binder content	0.04	100.54	0.028	0.034	3.42
HMA binder grade	0.1	1006.74	0.129	0.156	7.71
Base type/modulus	0.05	210.63	0.011	0.025	1.27
Subgrade type/modulus	0.12	861.79	0.029	0.15	17.06
Ground water table	0.09	311.81	0.023	0.051	1.3
WT with weakest subgrade	0.12	7.19	0.013	0.023	1.49
Climate	0.07	629.77	0.132	0.149	24.86
AADTT value	0.07	233.22	0.049	0.061	3.11
Operational speed	0.14	1166.93	0.172	0.201	10.14
Traffic growth rate	0.02	58.77	0.023	0.017	0.83
Traffic distribution	0.08	160.2	0.055	0.063	3.2
HMA CTC	0	0	0	0	19.2
Initial IRI	0	0	0	0	96.56

Table 35B: Normalized Values and Ranks for NY Level 3

Table 35B: Normalized Values and Ranks for NY Level 3

NEW YORK LEVEL 3										
Input Variable	**Bottom-Up**		**Top-Down**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA thickness	0.175	1	2.550	1	0.155	9	0.208	5	0.024	7
HMA mix gradation	0.019	11	0.417	8	0.244	6	0.134	8	0.015	10
HMA air voids	0.130	2	1.047	5	0.113	11	0.063	11	0.002	14
HMA effective binder content	0.026	10	0.141	12	0.167	8	0.089	9	0.020	8
HMA binder grade	0.065	5	1.409	3	0.768	3	0.411	2	0.046	6
Base type/modulus	0.032	9	0.295	10	0.065	13	0.066	10	0.008	12
Subgrade type/modulus	0.078	4	1.206	4	0.173	7	0.395	3	0.102	4
Ground water table	0.058	6	0.436	7	0.137	10	0.134	8	0.008	12
WT with weakest subgrade	0.078	4	0.010	14	0.077	12	0.061	12	0.009	11
Climate	0.045	8	0.881	6	0.786	2	0.392	4	0.149	2
AADTT value	0.045	8	0.326	9	0.292	5	0.161	7	0.019	9
Operational speed	0.091	3	1.633	2	1.024	1	0.529	1	0.061	5
Traffic growth rate	0.013	12	0.082	13	0.137	10	0.045	13	0.005	13
Traffic distribution	0.052	7	0.224	11	0.327	4	0.166	6	0.019	9
HMA CTC	0.000	13	0.000	15	0.000	14	0.000	14	0.115	3
Initial IRI	0.000	13	0.000	15	0.000	14	0.000	14	0.577	1

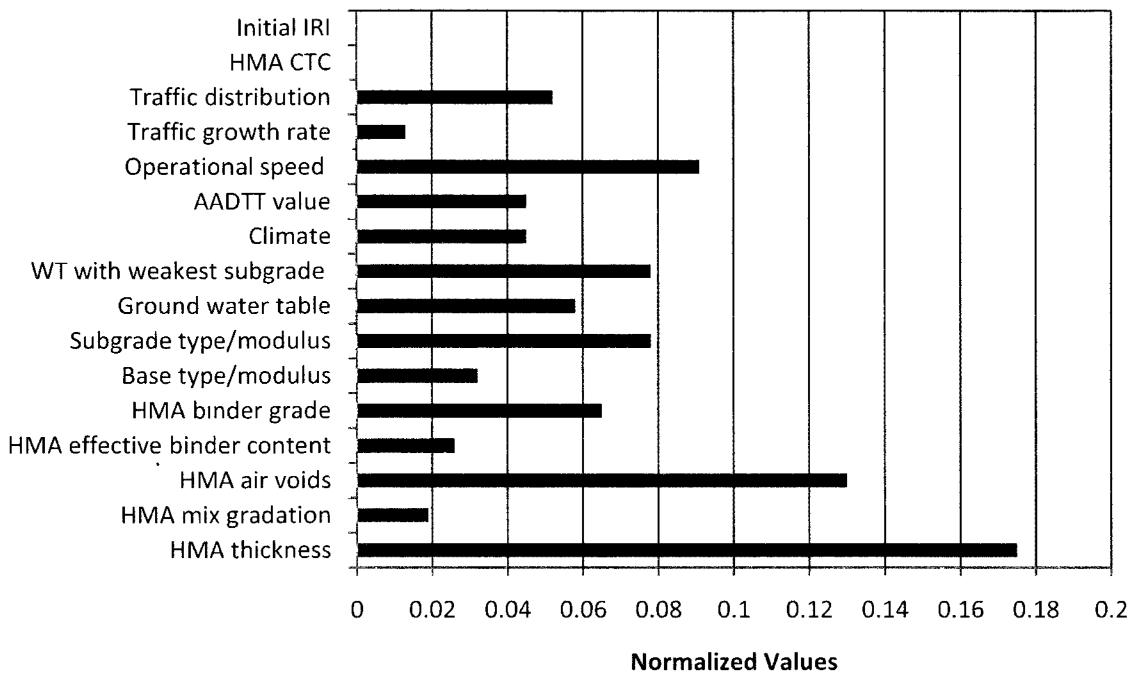


Figure 117B: Significance of Effect of Input Variables on Bottom-Up Cracking

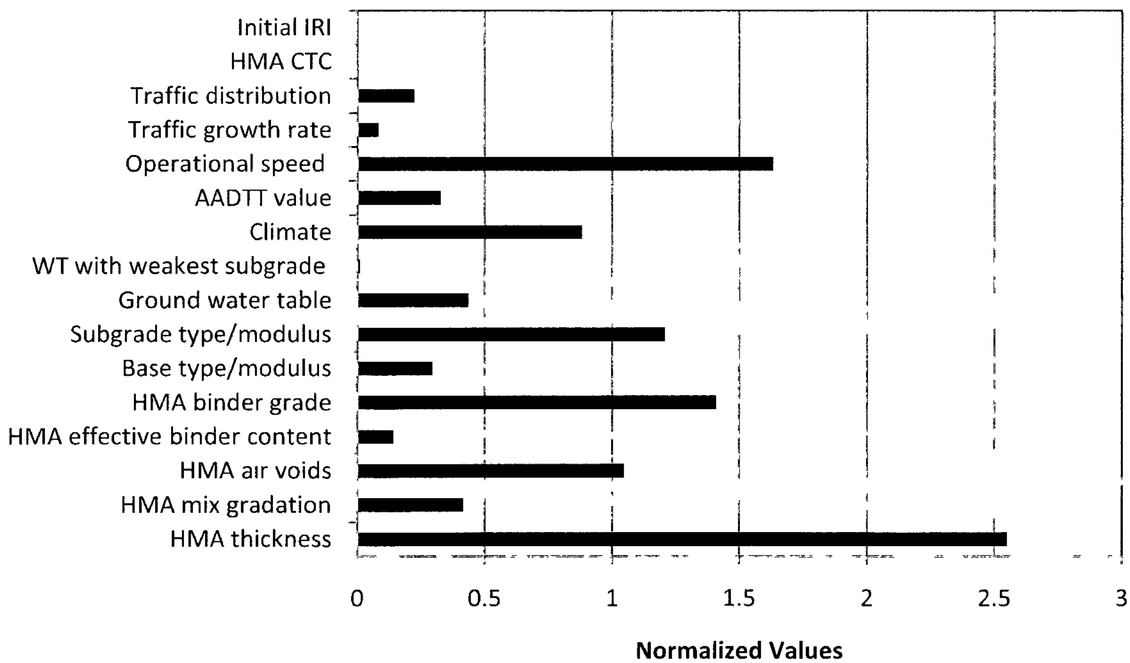


Figure 118B: Significance of Effect of Input Variables on Top-Down Cracking

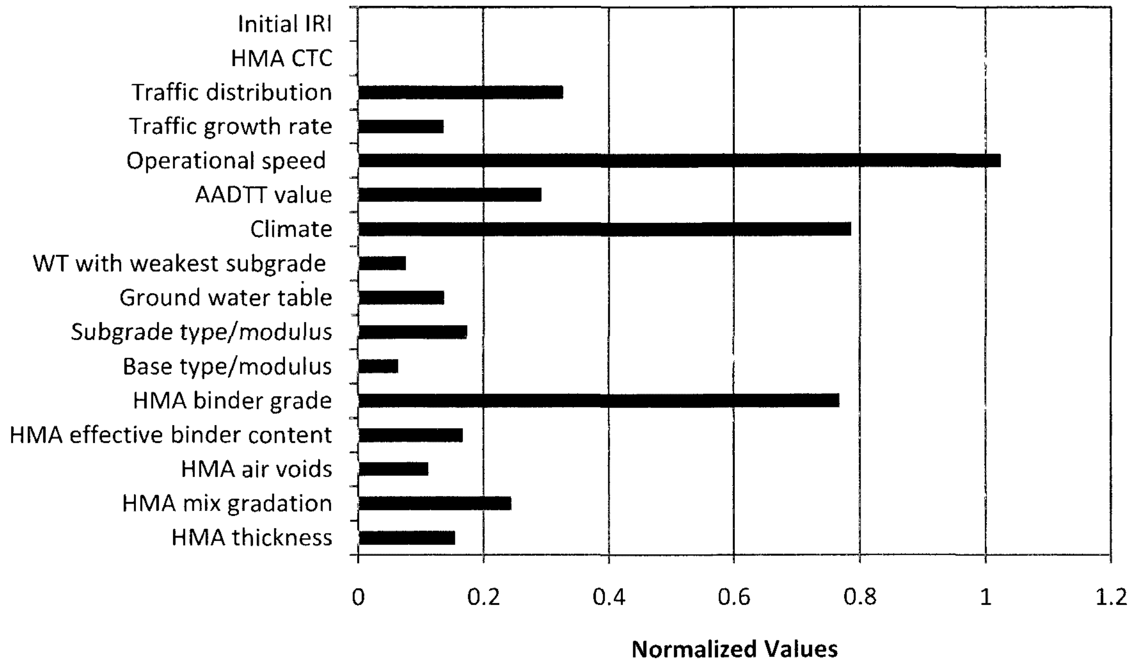


Figure 119B: Significance of Effect of Input Variables on AC Rutting

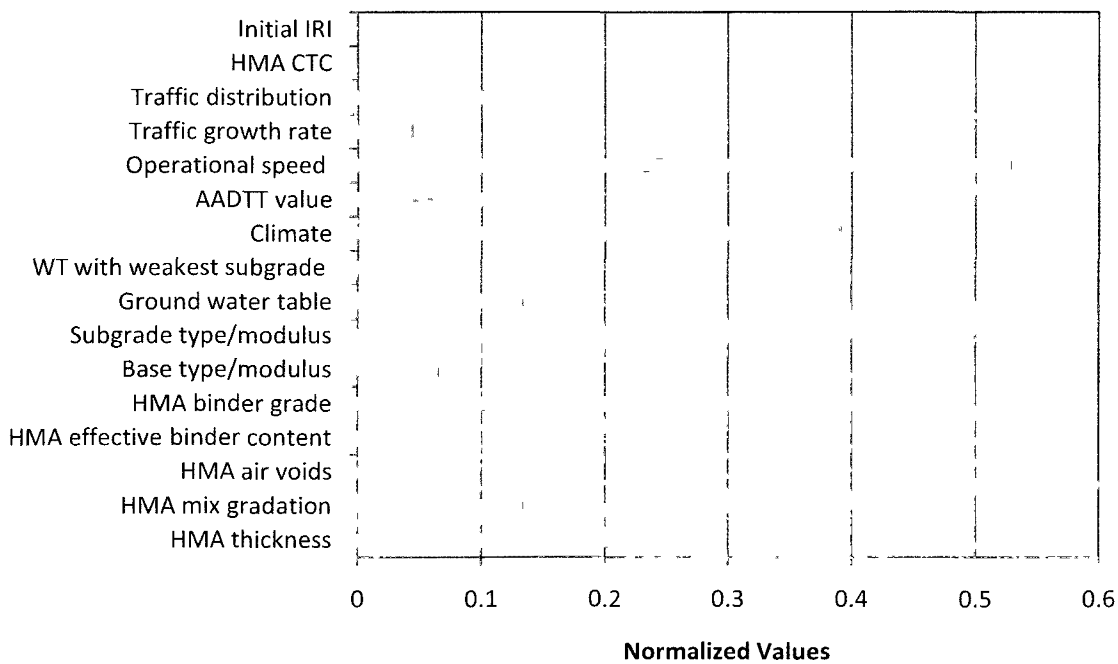


Figure 120B: Significance of Effect of Input Variables on Total Rutting

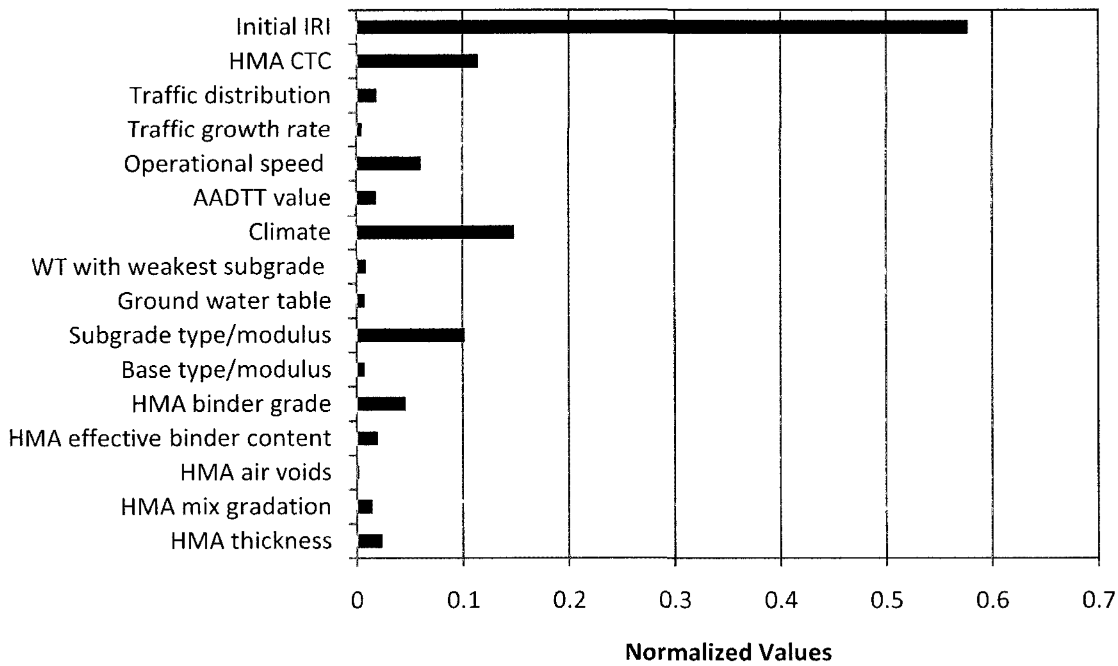


Figure 121B: Significance of Effect of Input Variables on IRI

Table 36B: NY Sensitivity Analysis Results Level 3

Bottom-Up	Top-Down	AC Rutting	Total Rutting	IRI
HMA thickness	HMA thickness	Operational speed	Operational speed	Initial IRI
HMA air voids	Operational speed	Climate	HMA binder grade	Climate
Operational speed	HMA binder grade	HMA binder grade	Subgrade type/modulus	HMA CTC
Subgrade type/modulus	Subgrade type/modulus	Traffic distribution	Climate	Subgrade type/modulus
WT with weakest subgrade	HMA air voids	AADTT value	HMA thickness	Operational speed
HMA binder grade	Climate	HMA mix gradation	Traffic distribution	HMA binder grade

Table 37B: Sensitivity Analysis Summary Level 3

Design/ Material Variable	Distress/Smoothness				
	Bottom-Up Cracking (%)	**Top-Down Cracking (ft/mi)**	**AC Rutting (in)**	**Total Rutting (in)**	**IRI (in/mi)**
HMA thickness	XXX	XXX	X	XX	
HMA mix gradation	X	X	XX	XX	
HMA air voids	XXX	XX	X	X	
HMA effective binder content	X	X	X	X	
HMA binder grade	XX	XX	XXX	XXX	X
Base type/modulus	X	X	X	X	
Subgrade type/modulus	XX	XX	X	XXX	X
Ground water table	XX	X	X	XX	
WT with weakest subgrade	XX		X	X	
Climate	X	XX	XXX	XXX	XX
AADTT value	X	X	XX	XX	
Operational speed	XX	XXX	XXX	XXX	X
Traffic growth rate	X	X	X	X	
Traffic distribution	XX	X	XX	XX	
HMA CTC					X
Initial IRI					XXX

Note: **X – Small effect**
XX – moderate effect
XXX – large effect

Table 38B: NY Overall Ranking Summary of Significance of Each Input Parameter on the Performance of Flexible Pavement

NEW YORK LEVEL 3							
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**	**Total Ranking Points**	**Overall Order of Significance**
	Rank	Rank	Rank	Rank	Rank		
HMA thickness	1	1	9	5	7	23	**4**
HMA mix gradation	11	8	6	8	10	43	**7**
HMA air voids	2	5	11	11	14	43	**7**
HMA effective binder content	10	12	8	9	8	47	**8**
HMA binder grade	5	3	3	2	6	19	**2**
Base type/modulus	9	10	13	10	12	54	**10**
Subgrade type/modulus	4	4	7	3	4	22	**3**
Ground water table	6	7	10	8	12	43	**7**
WT with weakest subgrade	4	14	12	12	11	53	**9**
Climate	8	6	2	4	2	22	**3**
AADTT value	8	9	5	7	9	38	**6**
Operational speed	3	2	1	1	5	12	**1**
Traffic growth rate	12	13	10	13	13	61	**13**
Traffic distribution	7	11	4	6	9	37	**5**
HMA CTC	13	15	14	14	3	59	**12**
Initial IRI	13	15	14	14	1	57	**11**

References (New York)

1. http://groundwaterwatch.usgs.gov
2. http://www.ltpp-products.com/DataPave/index.asp
3. Sensitivity Study of Design Input Parameters for Two Flexible Pavement Systems Using the MEPDG; Sunghwan Kim, Iowa State University, (August 2005).
4. NYS DOT Comprehensive Pavement Design Manual (July, 2002) and Revision (January, 2009).
   https://www.nysdot.gov/divisions/engineering/design/dqab/cpdm
   https://www.nysdot.gov/divisions/engineering/design/dqab/cpdm/cpdm-revision-log
5. Sensitivity Analysis of Pavement Performance Predicted Using the M-E PDG; Dinesh Ayyala, (May 2009).
6. NYS DOT HIGHWAY DESIGN MANUAL (February, 1999).
7. Pavement Data Report Region 3 (2009).
8. Network Level Pavement Condition Assessment (March, 2010).
9. Superpave Series No. 1 (SP-1) and No. 2 (SP-2)
10. Report No. UT-09.11a Draft User's Guide for UDOT MEPDG; October 2009.
11. ASTM Standards Volume 04.03, 2008
12. ASTM Standards Volume 04.08, 2009

Appendix A: Code Descriptions (New York)

CODE	DESCRIPTION
A1, A2, A3	3/8" (9.5 mm) HMA mix gradation
B1, B2, B3	3/4" (19 mm) HMA mix gradation
A1B1, A2B2, A3B3	Mean, coarse, fine HMA mix gradation
D1, D2, D3, D4	Truck class distribution
E1, E2, E3	Subgrade type
F1, F2, F3	Effective binder content
G1, G2, G3	AC Binder grade
M1, M2, M3	Base course aggregate gradation level 3
N1, N2, N3	Coefficient of Thermal Contraction
Q1, Q2, Q3	AADTT value
R1, R2, R3	Traffic growth rate
S1, S2, S3	Initial IRI
T1, T2, T3	HMA layer thickness
U1, U2, U3	Traffic operational speed
V1, V2, V3	Binder air content
WT1, WT2, WT3	Ground water table level

Appendix B: Seasonal Adjustment Factors (New York)

SEASONAL ADJUSTMENT FACTORS FOR TRAFFIC COUNT PROCESSING 2010

Based on Continuous Count Site Data 2007 - 2009

WORK WEEK

FACTOR GROUP		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	29	0.306	0.923	0.970	1.009	1.049	1.049	1.055	1.052	1.023	1.024	0.989	0.949
urban	30	0.953	0.972	1.023	1.056	1.091	1.105	1.096	1.039	1.074	1.074	1.030	0.996
	31	1.006	1.027	1.082	1.107	1.136	1.167	1.140	1.150	1.129	1.130	1.073	1.048
	39	0.777	0.787	0.833	0.879	0.986	1.015	1.060	1.091	0.972	0.956	0.857	0.822
suburban	40	0.840	0.856	0.901	0.953	1.049	1.084	1.161	1.183	1.057	1.020	0.938	0.891
	41	0.914	0.939	0.982	1.041	1.121	1.163	1.284	1.232	1.160	1.094	1.035	0.972
	59	0.615	0.637	0.640	0.670	0.911	1.040	1.316	1.328	0.981	0.813	0.694	0.528
recreational	60	0.688	0.707	0.738	0.733	1.000	1.141	1.479	1.481	1.063	0.920	0.783	0.676
	61	0.701	0.796	0.873	0.971	1.107	1.264	1.688	1.673	1.101	1.011	0.897	0.939

Factor Group	% Precision with 95% Confidence
urban - 30	1.93%
suburban - 40	4.0%
recreational - 60	31.5%

For each factor group, the percent precision value is the maximum value out of all months

The FHWA Traffic Monitoring Guide 2001 states

The reliability levels recommended are 10 percent precision with 95 percent confidence, 95-10, for each individual seasonal group, excluding recreational groups where no precision requirement is specified

New York State Department of Transportation
Highway Data Services Bureau
MO-TrafficDataViewer@dot state ny us
(518) 457-1965

8/9/2010

Appendix C: Axle Adjustment Factors for 2010 Traffic Count Processing (New York)

AXLE ADJUSTMENT FACTORS FOR 2010 TRAFFIC COUNT PROCESSING
BASED ON 2004 - 2009 VEHICLE CLASSIFICATION DATA

RURAL

FC	REGION 1	2	3	4	5	6	7	8	9	10	11	STATEWIDE
01	0.774	0.786	0.800	0.786	0.812	0.720	0.763	0.786	0.792			0.786
02	0.915	0.939	0.940	0.882	0.930	0.897	0.914	0.965	0.912			0.921
06	0.955	0.956	0.944	0.952	0.938	0.955	0.950	0.962	0.956	0.955		0.955
07	0.970	0.974	0.950	0.968	0.963	0.963	0.946	0.978	0.971	0.965		0.965
08	0.976	0.977	0.976	0.979	0.975	0.976	0.972	0.984	0.979			0.976
09	0.982	0.979	0.982	0.982	0.981	0.982	0.965	0.986	0.978	0.982		0.982

URBAN

FC	REGION 1	2	3	4	5	6	7	8	9	10	11	STATEWIDE
11	0.881	0.881	0.889	0.947	0.887	0.881	0.881	0.881	0.881	0.881	0.881	0.881
12	0.979	0.962	0.961	0.979	0.977	0.961		0.977	0.945	0.987	0.961	0.961
14	0.972	0.979	0.969	0.969	0.976	0.950	0.963	0.979	0.950	0.973	0.984	0.969
16	0.978	0.974	0.982	0.984	0.982	0.981	0.976	0.985	0.977	0.982	0.982	0.982
17	0.982	0.983	0.987	0.989	0.989	0.988	0.981	0.988	0.983	0.985	0.982	0.982
19	0.984	0.990	0.984	0.992	0.991	0.984	0.984	0.990	0.984	0.984	0.984	0.984

Blank cell indicates there are no highway segments in this FC in this region

Shaded cell indicates insufficient data (< 10 highway segments) - statewide average was used

Appendix D: Heavy Vehicle (Class 04-13) Percentages for 2009 (New York)

HEAVY VEHICLE (F04 - F13) PERCENTAGES 2009
BASED ON 2004 - 2009 VEHICLE CLASSIFICATION DATA

RURAL

FC	REGION 1	2	3	4	5	6	7	8	9	10	11	STATEWIDE
01	25 1%		24 0%	21 6%	23 5%	36 0%	26 9%	19 3%	25 1%			25 2%
02	13 2%	11 6%	10 1%	17 0%	10 9%	15 5%	13 5%	7 5%	13 6%			12 5%
06	10 4%	7 7%	10 0%	9 8%	11 3%	10 2%	10 0%	8 9%	10 2%	6 0%		9 5%
07	8 8%	6 0%	10 0%	9 7%	8 8%	10 9%	10 5%	7 0%	8 7%			8 9%
08	7 2%	6 1%	8 6%	5 1%	6 3%	5 7%	7 4%	7 7%	6 8%			6 8%
09	7 7%	5 5%		8 0%	7 1%		8 7%	6 3%	6 4%			7 1%

URBAN

FC	REGION 1	2	3	4	5	6	7	8	9	10	11	STATEWIDE
11	9 3%	11 3%	5 7%	8 4%	14 9%	21 2%	16 8%	15 5%	23 4%		13 3%	15 0%
12	4 9%	7 5%	7 6%	4 9%	4 6%	16 0%		4 8%	9 2%	3 9%	2 9%	6 6%
14	6 4%	5 6%	6 2%	6 2%	5 7%	8 6%	6 9%	5 8%	8 8%	6 2%	7 0%	6 7%
16	6 4%	5 8%	5 5%	4 5%	5 0%	5 6%	6 4%	5 1%	6 4%	5 3%	3 5%	5 4%
17	6 0%	5 0%	5 0%	4 1%	4 4%	5 1%	6 8%	5 1%	5 7%	5 5%	14 6%	6 1%
19	5 8%	3 7%	4 4%	3 3%	3 5%		4 9%	5 4%	6 9%	5 5%	7 4%	5 1%

(dotted box) Blank cell indicates there are no highway segments in this FC in this region

(solid box) Shaded cell indicates no data or insufficient data (< 10 highway segments)

FUNCTIONAL CLASSIFICATION (FC) CODES

RURAL		URBAN	
01	Principal Arterial - Interstate	11	Principal Arterial Interstate
02	Principal Arterial - Other	12	Principal Arterial - Other Freeway or Expressway
06	Minor Arterial	14	Principal Arterial - Other
07	Major Collector	16	Minor Arterial
08	Minor Collector	17	Collector
09	Local	19	Local

Appendix E: Material Classification (New York)

Material Classification	M_r Range	Typical M_r*
A-1-a	38,500 – 42,000	40,000
A-1-b	35,500 – 40,000	38,000
A-2-4	28,000 – 37,500	32,000
A-2-5	24,000 – 33,000	28,000
A-2-6	21,500 – 31,000	26,000
A-2-7	21,500 – 28,000	24,000
A-3	24,500 – 35,500	29,000
A-4	21,500 – 29,000	24,000
A-5	17,000 – 25,500	20,000
A-6	13,500 – 24,000	17,000
A-7-5	8,000 – 17,500	12,000
A-7-6	5,000 – 13,500	8,000
CH	5,000 – 13,500	8,000
MH	8,000 – 17,500	11,500
CL	13,500 – 24,000	17,000
ML	17,000 – 25,500	20,000
SW	28,000 – 37,500	32,000
SP	24,000 – 33,000	28,000
SW-SC	21,500 – 31,000	25,500
SW-SM	24,000 – 33,000	28,000
SP-SC	21,500 – 31,000	25,500
SP-SM	24,000 – 33,000	28,000
SC	21,500 – 28,000	24,000
SM	28,000 – 37,500	32,000
GW	39,500 – 42,000	41,000
GP	35,500 – 40,000	38,000
GW-GC	28,000 – 40,000	34,500
GW-GM	35,500 – 40,500	38,500
GP-GC	28,000 – 39,000	34,000
GP-GM	31,000 – 40,000	36,000
GC	24,000 – 37,500	31,000
GM	33,000 – 42,000	38,500

Appendix F: Performance Graded Binder Selection – Standard (New York)

Performance Graded Binder Selection - Standard

Location	Location by Counties	Performance Grade (Spec Number)
Upstate	All Other Counties Not Listed Under Downstate	64-22[1] (702-6422)
Downstate	Orange, Putnam, Rockland, Westchester, Nassau, Suffolk Counties and City of New York	70-22 (702-7022)

1. For high volume roadways in Dutchess County, PG 70-22 or PG 76-22 may be specified with the concurrence of the Regional materials Engineer.

Appendix G: Performance Graded Binder Selection – Polymer Modified (New York)

Performance Graded Binder Selection – Polymer Modified

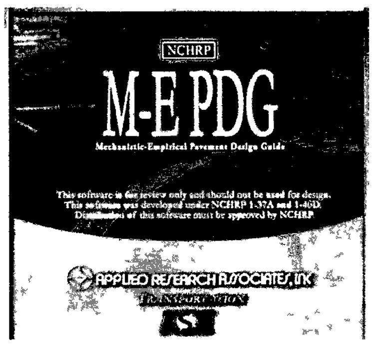
Conditions for Use	Location	Performance Grade (Spec Number)[1]
Cold temperature data warrants its use with the concurrence of the Regional Materials Engineer Typically Adirondack Region	Jefferson, Lewis, St Lawrence, Franklin, Clinton, Essex, and the Northern Sections of Herkimer, Oswego, Hamilton, Warren, and Washington Counties	58-34 (702-5834)
Multiple course overlays, reconstruction, or new construction where cold temperature data warrants its use with the concurrence of the Regional Materials Engineer	Upstate	64-28 (702-6428)
Multiple course overlays, reconstruction, new construction or roadway segments containing (a) grades in excess of 4 0% or (b) intersections that have traffic control signals (3 light signal) with the concurrence of the Region Materials Engineer	Upstate	64-22 (702-6422)
Where the traffic level is greater than 30 million ESALs based on a 20-year design life or the roadway segment contains (a) grades in excess of 4 0% or (b) intersections that have traffic control signals (3 light signal)	Downstate	76-22 (702-7622)

1 Other PG binder grades may be specified in a given location with approval from the Regional Materials Engineer and the Materials Bureau

Appendix C: Massachusetts M-E PDG Level 3 Report

MASSACHUSETTS

RANGE OF VALUES FOR CRITICAL INPUT PARAMETERS



INPUT VALUE SELECTION FOR MA FOR M-E PDG RUNS

1. General Inputs

1.1 Design Life

- 20 years for a new pavement is recommended

1.2 Construction & Traffic Opening Dates

- Base/subgrade construction month – June, 2010
- Pavement construction month - July, 2010
- Traffic opening date – August, 2010

1.3 Type of Pavement

- This analysis is performed for a new flexible pavement.

1.4 Site/Project Identification

The site is located in New Bedford, MA, I-195 Highway (LTPP section # 25-1004-1)

- County: BRISTOL
- Latitude, deg.: 41.65
- Longitude, deg.: -70.9
- Elevation, (ft): 49
- Org. Construction Date: 7/1/1974
- Constr. Event Date: 9/1/2002
- Functional Class: 11
- Years of Climatic Data: 59

Figure 1C: New Bedford, MA, Highway I-195

Figure 2C: LTPP Section Coordinates Lat/Lon: 41.65/70.9

Table 1C: Pavement Layers at LTPP Section 25-1004-1

Layer Type	Layer Thickness (in)
Original Surface Layer (layer Type: AC)	1.4
AC Layer Below Surface (Binder Course)	8.2
Base Layer (Layer Type: GB)	25.6
Subgrade (Layer Type: SS)	Semi-infinite

The LTPP Section selected for the analysis has four layers of materials: two asphalt layers and two unbound material layers.

LTPP road section # 25-1004-1 contains of 2 traffic lines in one direction.

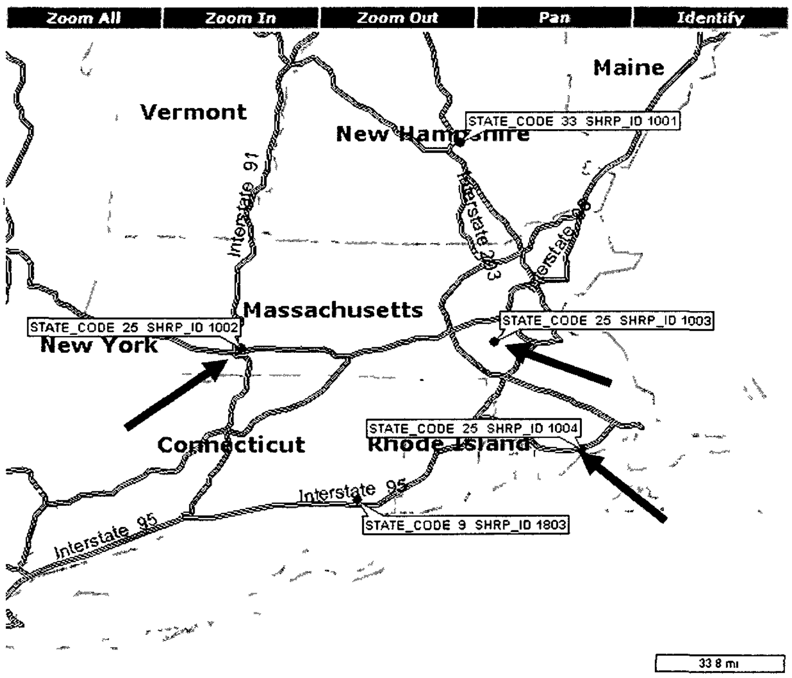


Figure 3C: Three LTPP Sections Located in MA

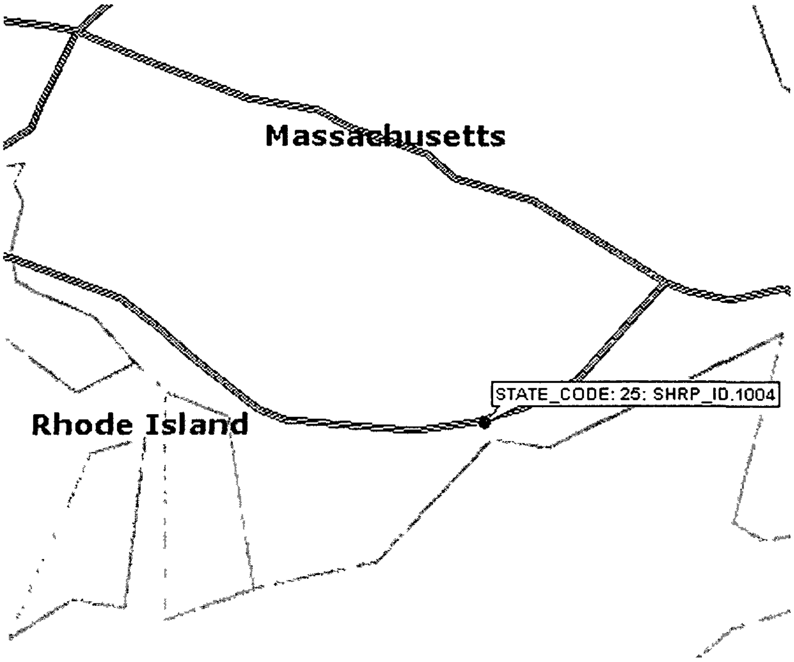


Figure 4C: LTPP Station 25_1004 at I-195 Used for the M-E PDG Sensitivity Analysis

2. Performance Criteria Inputs (Analysis Parameters)

Table 2C: Suggested Performance Criteria for Use in Pavement Design*

Pavement Type	**Performance Criteria**	**Max. Value at End of Design Life at Design Reliability**
	HMA bottom up fatigue cracking (alligator cracking)	Interstate: 10 percent lane area Primary: 20 percent lane area Secondary: 45 percent lane area
	HMA longitudinal fatigue cracking (top down)	Interstate: 2,000-ft/mile Primary: 2,500-ft/mile Secondary: 3,000-ft/mile
HMA pavement & overlays	Permanent deformation (total mean rutting of both wheel paths)	Interstate: 0.40-in mean Primary: 0.50-in mean Others <40 mph: 0.75-in mean
	Thermal fracture (transverse cracks)	Interstate: Crack spacing > 70-ft (Crack length < 905-ft/mile) Primary/Secondary: Crack spacing > 50-ft (Crack length < 1267-ft/mile)
	IRI	Interstate/Primary: 169 in/mile maximum Secondary: 223 in/mile maximum

*- Report No. UT-09.11a Draft User's Guide for UDOT MEPDG; October 2009.

Table 3C: Analysis Parameters Used in MA State

Analysis parameter	Maximum criteria at 90% Reliability
Initial IRI (in./mi)	75
Terminal IRI (in./mi)	172
AC Surface Down Cracking (ft/mi)	2000
AC Bottom Up Cracking (%)	25
AC Thermal Fracture (ft/mi)	1000
Permanent Deformation – Total Pavement (in)	0.75
Permanent Deformation – AC only (in)	0.25

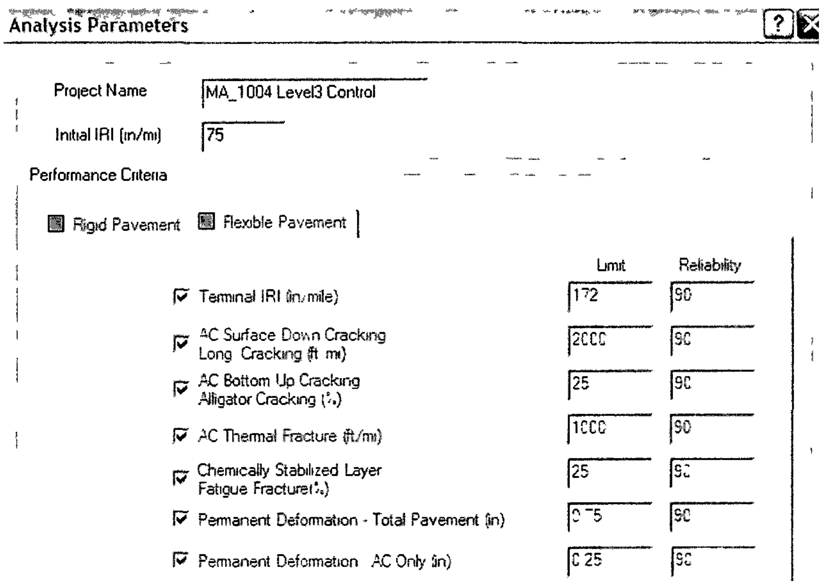


Figure 5C: Analysis Parameters Used in MA

Table 4C: MA level 3 Control Reliability Summary

Project: MA_1004 level3 Control **Reliability Summary**					
Performance Criteria	**Distress Target**	**Reliability Target**	**Distress Predicted**	**Reliability Predicted**	**Acceptable**
Terminal IRI (in/mi)	172	90	122.1	93.27	Pass
AC Surface Down Cracking (Long. Cracking) (ft/mile):	2000	90	4.1	99.97	Pass
AC Bottom Up Cracking (Alligator Cracking) (%):	25	90	0.1	99.999	Pass
AC Thermal Fracture (Transverse Cracking) (ft/mi):	1000	90	0.1	99.999	Pass
Chemically Stabilized Layer (Fatigue Fracture)	25	90			N/A
Permanent Deformation (AC Only) (in):	0.25	90	0.19	80.63	Fail*
Permanent Deformation (Total Pavement) (in):	0.75	90	0.42	99.99	Pass

*It was impossible to achieve the acceptable Reliability result for the Permanent Deformation using allowable (according to the state specification) inputs data.

Table 5C: IRI Ranges Defined by FHWA Highway Statistics Publications

IRI Scale (in/mi)	**Description**
< 60	Very Smooth
61 – 120	Smooth
121 – 170	Fair
171 – 220	Rough
> 220	Very Rough

3. Design Reliability Input

Table 6C: Tentative Recommended Level of Reliability

Functional Classification	Urban	Rural
Interstate/Freeways	95	92
Principal Arterials	90	85
Collectors	80	75
Locals	70	60

The I-195 Interstate is located in the urban area, so the reliability value for the analysis should be 95 percent. Because of the low truck traffic value in this area a lower reliability was selected (90%) for the sensitivity analysis. Higher level of design reliability is not recommended, because of the significant cost increase.

4. Traffic Inputs

Table 7C: Recommended Traffic Value Inputs

Traffic Input	**Recommended Value**
Initial two way AADTT (class 4 and above)	Projected traffic for opening month from measured historical data.
Number of lanes in design direction	Actual or from design plans.
Percent of trucks in design direction (%)	50%, unless higher truck volume is measured in design direction
Percent of trucks in design lane (%)	Actual measured in design lane over 24-hours, otherwise use the following: • 100% for 1 lane in design direction • 95% for 2 lanes in design direction For unusual truck traffic situations (mountainous terrain or urban usage complexity), conduct on site truck lane usage counts over 24-hour period.
Operational Speed (mph)	Posted or Design Speed

4.1 Annual Average Daily Truck Traffic (AADTT)

Truck Traffic (AADTT) is calculated by taking 5.00% of AADT as given in 2005 Mass DOT Traffic Statistic. The 2005 year was selected, because of the higher traffic value (AADT=73,500) compared to year 2008 (AADT=64,400). Control AADTT for I-195 in New Bedford (Bristol County) for this study is taken as 3675.

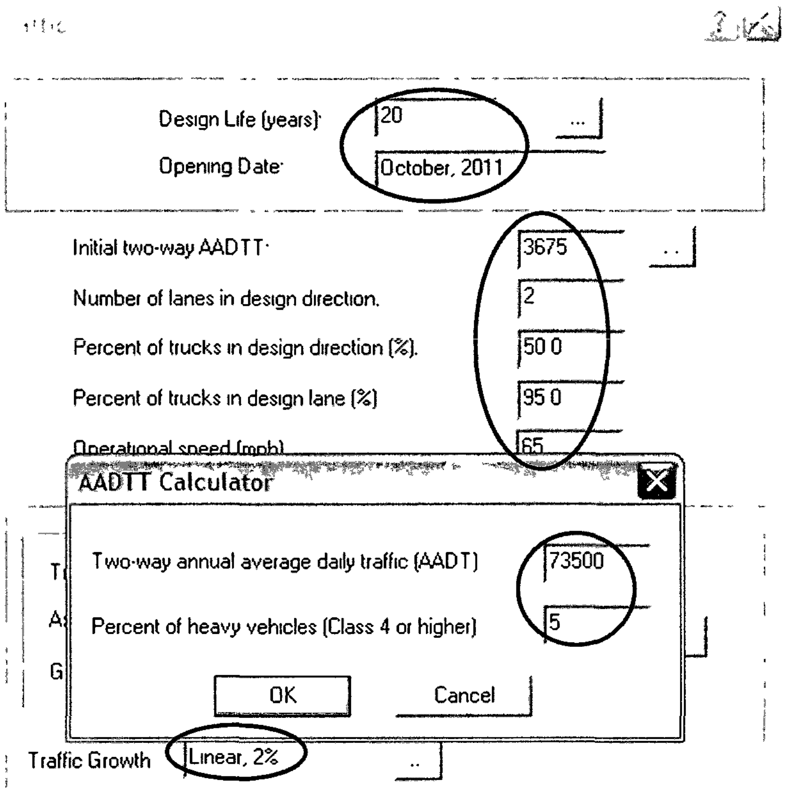


Figure 6C: Traffic Inputs for New Bedford, MA

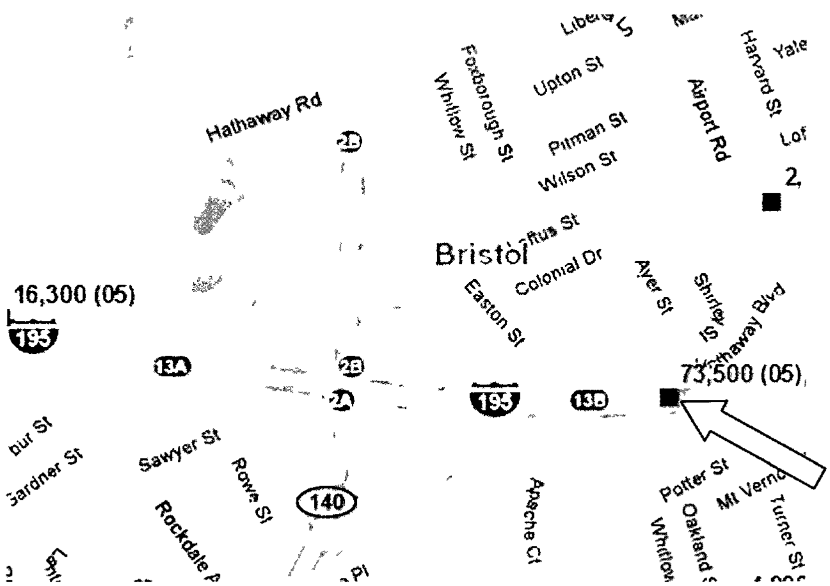


Figure 7C: Two-Way AADT in New Bedford, MA (2005)

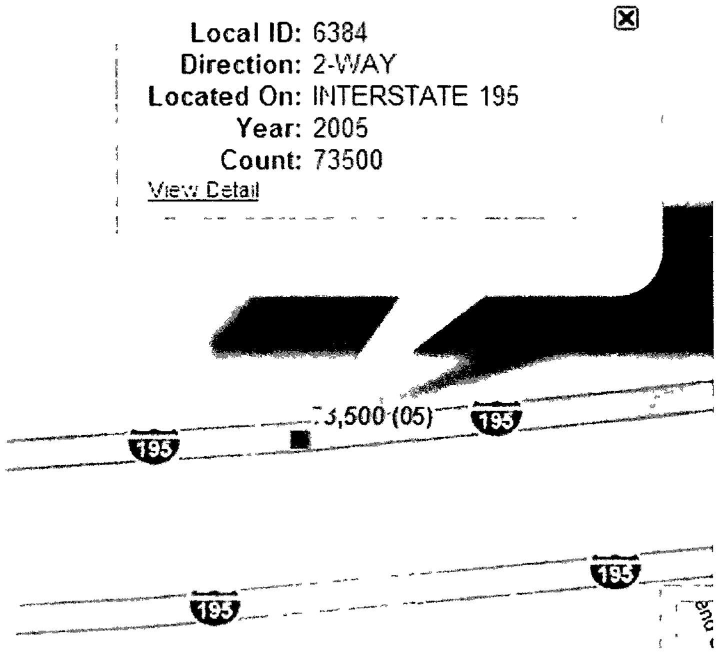


Figure 8C: New Bedford, MA WIM Station (ID # 6384)

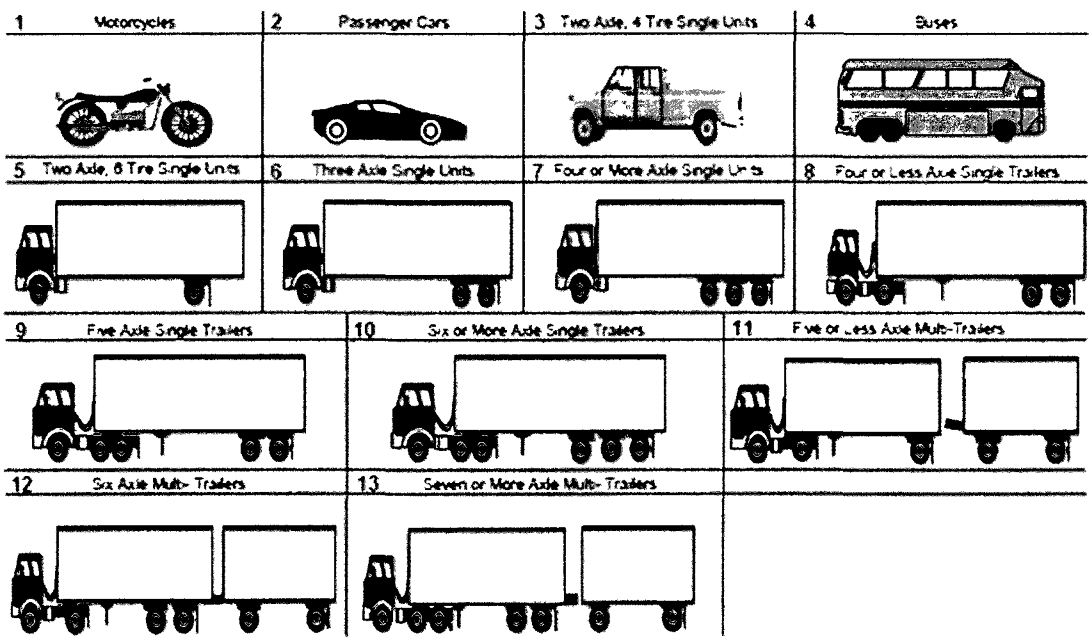


Figure 9C: Illustration of FHWA/AASHTO Vehicle Class Type Description

4.2 Truck Class Distribution selections

Table 8C: Truck Class Distribution Summary

TRUCK CLASS	CODE			
	D1(LTPP-Control)	**D2 (low class)***	**D3 (high class)***	**D4 (MEPDG Level 3)**
4	3.5	5.2	0.1	1.8
5	47.2	38.9	0.6	24.6
6	9.7	35.8	0.8	7.6
7	0.5	10.2	0.6	0.5
8	8.8	5.6	6.8	5.0
9	29.8	3.5	9.2	31.3
10	0.4	0.2	25.8	9.8
11	0.1	0.3	36.4	0.8
12	0.0	0.2	16.5	3.3
13	0.0	0.1	3.2	15.3

*Based on Sensitivity Study of Design Input Parameters for Flexible Pavement Systems using M-E PDG in Iowa DOT, 2004

4.3 Rate of Traffic Growth

Table 9C: Selected Traffic Growth Rates for Massachusetts

Code	Traffic Growth Rate
R1	1.0 % linear
R2 (Control)	2.0 % linear
R3	3.0 % linear

4.4 Traffic Operational Speed

Table 10C: Selected Traffic Operational Speeds

Code	Traffic Operational Speed (mph)	Binder Grades
U1	5	G1, G2, G3
U2	25	G1, G2, G3
U3 (Control)	65	G1, G2, G3

The effect of operational speed is analyzed in conjunction with binder grade and the traffic operational speed input values.

4.5 Annual Average Daily Truck Traffic (AADTT)

Table 11C: Calculated AADTT Values

Code	Station ID	Traffic Volume (AADTT)
Q1 (Control)	#6383 - New Bedford	3675
Q2	#6526 - Fall River	4080
Q3	#0007 L - Mattapoisett	1819

4.6 The Monthly Traffic Adjustment Factors

Table 12C: Monthly Adjustment Factors (MAF) for Pavement Design in New Bedford, MA, (1997 LTPP data)

Location	Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
New Bedford	Jan.	0.48	0.96	0.84	0.72	0.84	0.84	0.6	0.72	n/d*	n/d*
	Feb.	0.6	0.96	0.84	0.72	0.84	0.72	0.6	0.72	n/d	n/d
	Mar.	0.6	0.84	0.72	0.72	0.84	0.84	0.84	0.72	n/d	n/d
	Apr.	0.84	0.96	0.84	0.96	0.96	0.96	0.84	1.4	n/d	n/d
	May	1.2	1.08	1.08	1.32	1.26	1.16	1.2	1.39	n/d	n/d
	Jun.	1.32	1.08	0.96	0.96	1.08	1.16	1.2	0.72	n/d	n/d
	Jul.	1.08	1.08	1.08	0.96	1.08	1.08	1.2	0.72	n/d	n/d
	Aug.	1.2	0.96	1.08	0.96	0.96	1.08	0.84	0.72	n/d	n/d
	Sep.	1.44	0.96	1.08	1.2	1.08	1.08	1.2	0.72	n/d	n/d
	Oct.	1.44	1.08	1.32	1.32	1.26	1.16	1.44	1.39	n/d	n/d
	Nov.	0.84	0.96	1.08	1.08	0.84	0.96	0.84	1.39	n/d	n/d
	Dec.	0.96	1.08	1.08	1.08	0.96	0.96	1.2	1.39	n/d	n/d

*- no data available

Table 13C: Monthly Adjustment Factors (MAF) for Pavement Design for Fall River and Mattapoisett, MA (Level 3 default)

Location	Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
Fall River	Jan.	1	1	1	1	1	1	1	1	1	1
	Feb.	1	1	1	1	1	1	1	1	1	1
	Mar.	1	1	1	1	1	1	1	1	1	1
	Apr.	1	1	1	1	1	1	1	1	1	1
	May	1	1	1	1	1	1	1	1	1	1
	Jun.	1	1	1	1	1	1	1	1	1	1
	Jul.	1	1	1	1	1	1	1	1	1	1
	Aug.	1	1	1	1	1	1	1	1	1	1
	Sep.	1	1	1	1	1	1	1	1	1	1
	Oct.	1	1	1	1	1	1	1	1	1	1
	Nov.	1	1	1	1	1	1	1	1	1	1
	Dec.	1	1	1	1	1	1	1	1	1	1
Mattapoisett	Jan.	1	1	1	1	1	1	1	1	1	1
	Feb.	1	1	1	1	1	1	1	1	1	1
	Mar.	1	1	1	1	1	1	1	1	1	1
	Apr.	1	1	1	1	1	1	1	1	1	1
	May	1	1	1	1	1	1	1	1	1	1
	Jun.	1	1	1	1	1	1	1	1	1	1
	Jul.	1	1	1	1	1	1	1	1	1	1

Mattapoisett Continued	Aug.	1	1	1	1	1	1	1	1	1	1
	Sep.	1	1	1	1	1	1	1	1	1	1
	Oct.	1	1	1	1	1	1	1	1	1	1
	Nov.	1	1	1	1	1	1	1	1	1	1
	Dec.	1	1	1	1	1	1	1	1	1	1

4.7 The MADT to AADT factor

Table 14C: Collected MADT's to AADT's for Selected Locations

	MADT* TO AADT** FACTOR		
Month	**New Bedford**	**Fall River**	**Mattapoisett**
Jan.	0.75	n/d***	n/d
Feb.	0.75	n/d	n/d
Mar.	0.77	n/d	n/d
Apr.	0.97	n/d	n/d
May	1.21	n/d	n/d
Jun.	1.06	n/d	n/d
Jul.	1.04	n/d	n/d
Aug.	0.98	n/d	n/d
Sep.	1.10	n/d	n/d
Oct.	1.30	n/d	n/d
Nov.	1.00	n/d	n/d
Dec.	1.09	n/d	n/d

*- MADT – monthly average daily traffic
**- AADT – annual average daily traffic
***- no data available

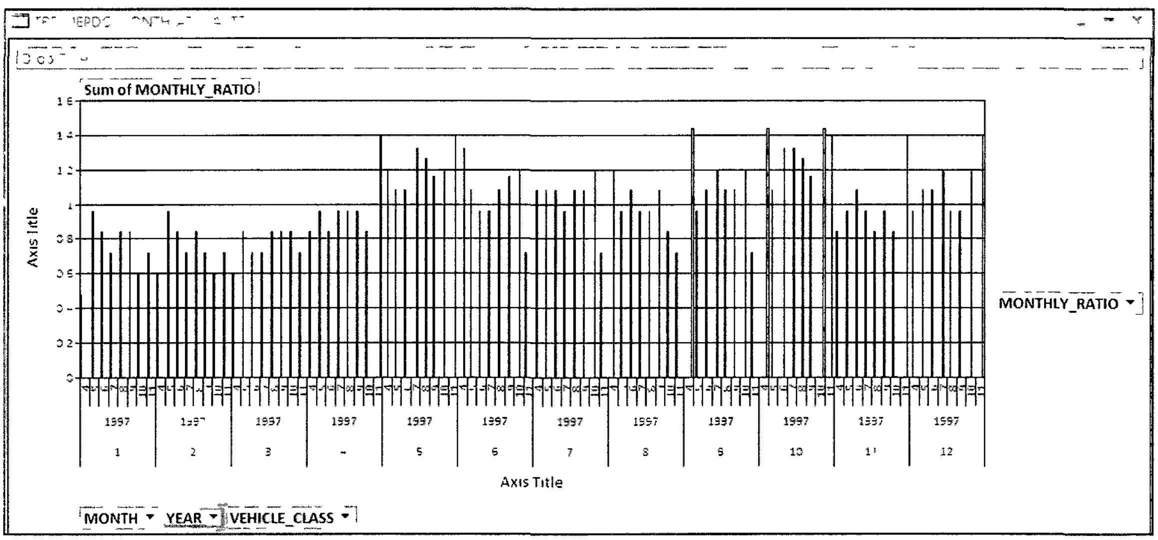


Figure 10C: MADT to AADT Factor for New Bedford, MA Vehicle Class 4 to 11 (Missing Data Class 12-13)

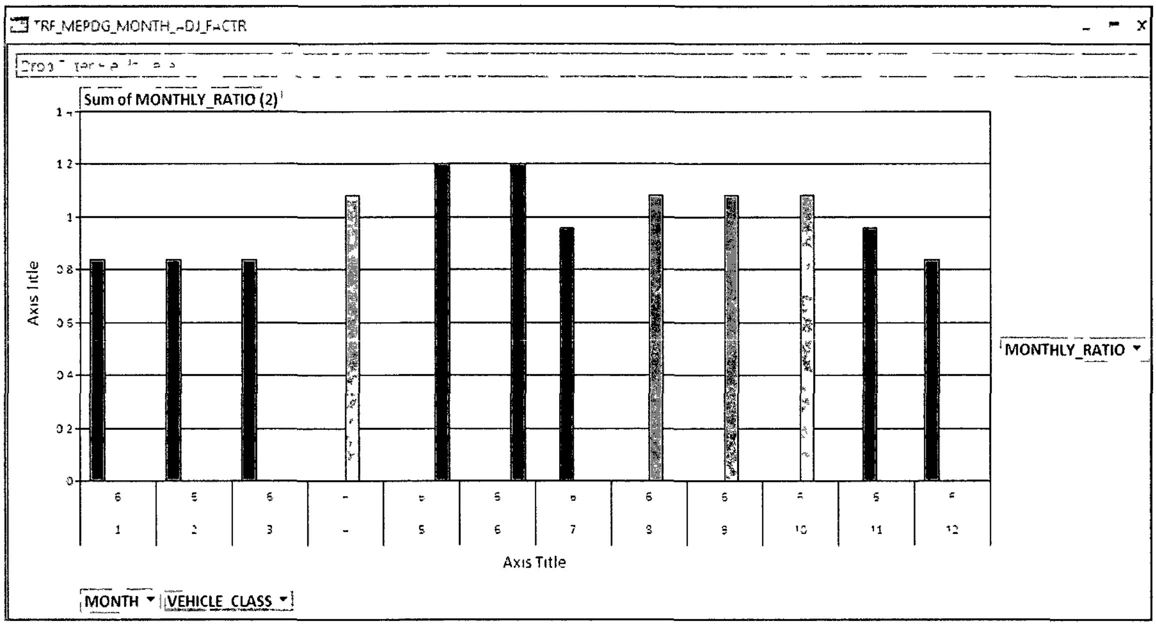


Figure 11C: Class 6 Monthly Adjustment Factors (MADTT to AADTT) for New Bedford, MA

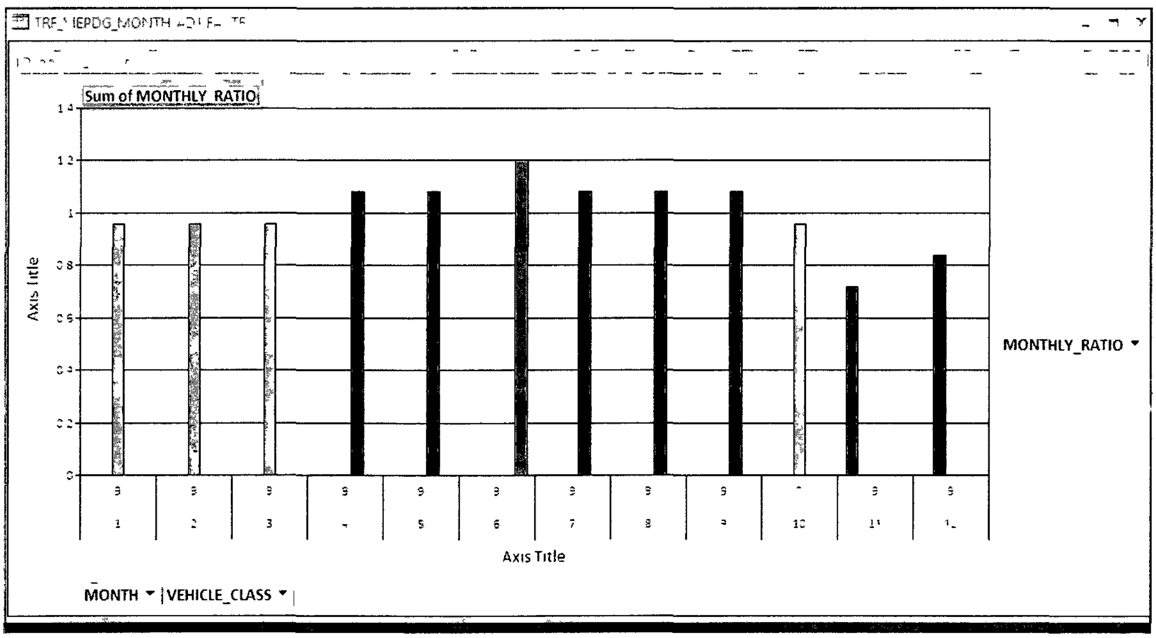


Figure 12C: Class 9 Monthly Adjustment Factors (MADTT to AADTT) for New Bedford, MA

5. Climate Inputs

Four climate stations were selected from the eighteen stations for which climate data is available in the M-E PDG. The four stations: New Bedford (control), Boston, Westfield-Springfield and Worcester were chose as they are more geographically dispersed.

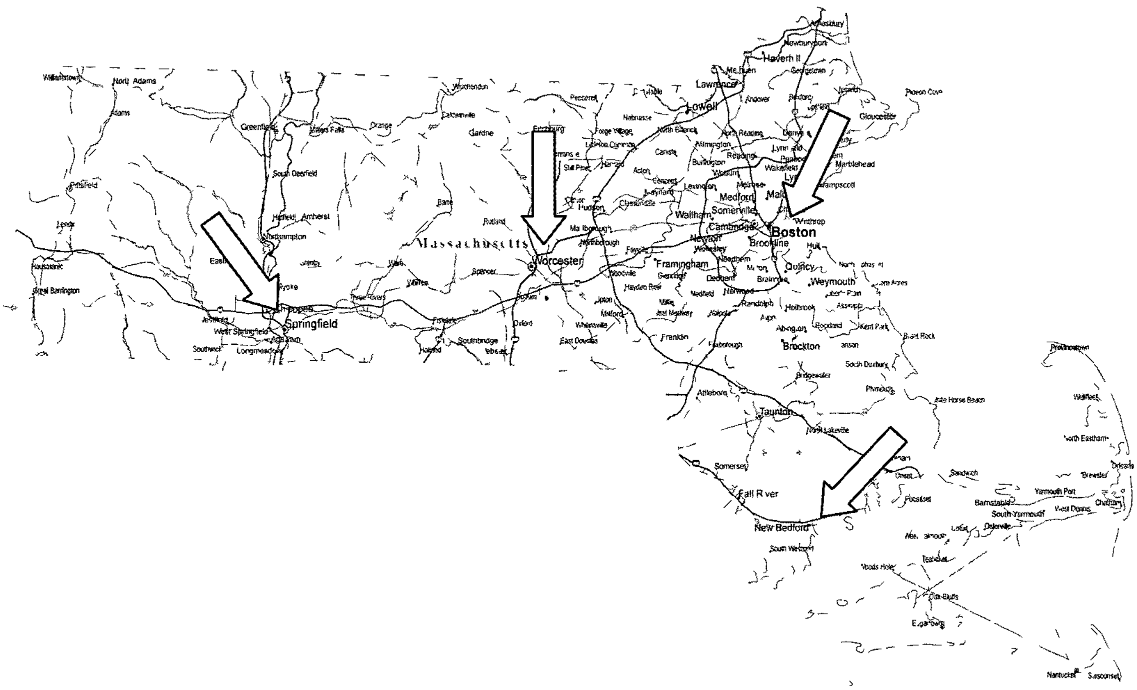


Figure 13C: Massachusetts Climate Station Locations

5.1 Sensitivity to Climate Data Interpolation

Table 15C: Selected Locations Climate Data

STATION	Nearest 3 Stations	Latitude	Longitude	Distance	#Months of data
New Bedford Lat. 41.41 Lon. -70.58 Elev. 78 ft	Taunton, MA	41.53	-71.01	14.0	99
	Newport, RI	41.32	-71.17	19.4	116
	Plymouth, MA	41.55	-70.44	20.1	116
Boston Lat. 42.22 Lon. -71.01 Elev. 180 ft	Norwood, MA	42.11	-71.1	14.8	93
	Bedford, MA	42.28	-71.17	15.2	91
	Beverly, MA	42.35	-70.55	15.8	87
Westfield/Springfield Lat. 42.1 Lon. -72.43 Elev. 276 ft	Windsor, CT	41.56	-72.41	16.2	116
	Hartford, CT	41.44	-72.39	30.1	105
	Pittsfield, MA	42.26	-73.17	34.3	85
Worcester Lat. 42.16 Lon. -71.53 Elev. 966 ft	Fitchburg, MA	42.33	-71.46	20.4	101
	Orange, MA	42.34	-72.17	29.1	116
	Bedford, MA	42.28	-71.17	15.2	91

5.2 Water Table Depth Variation

Table 16C: Selected WT Depths for New Bedford, MA

CODE	Depth of Water Table	Combination with A-2-4 and A-7-6 Subgrades
WT1	2 ft	WT1 E2, WT1 E1,
WT2 (Control)	4 ft	WT2 E2, WT2 E1
WT3	6 ft	WT3 E2, WT3 E1

The water table depth was selected based on average values from the MA-NGW 116 New Bedford, MA well.

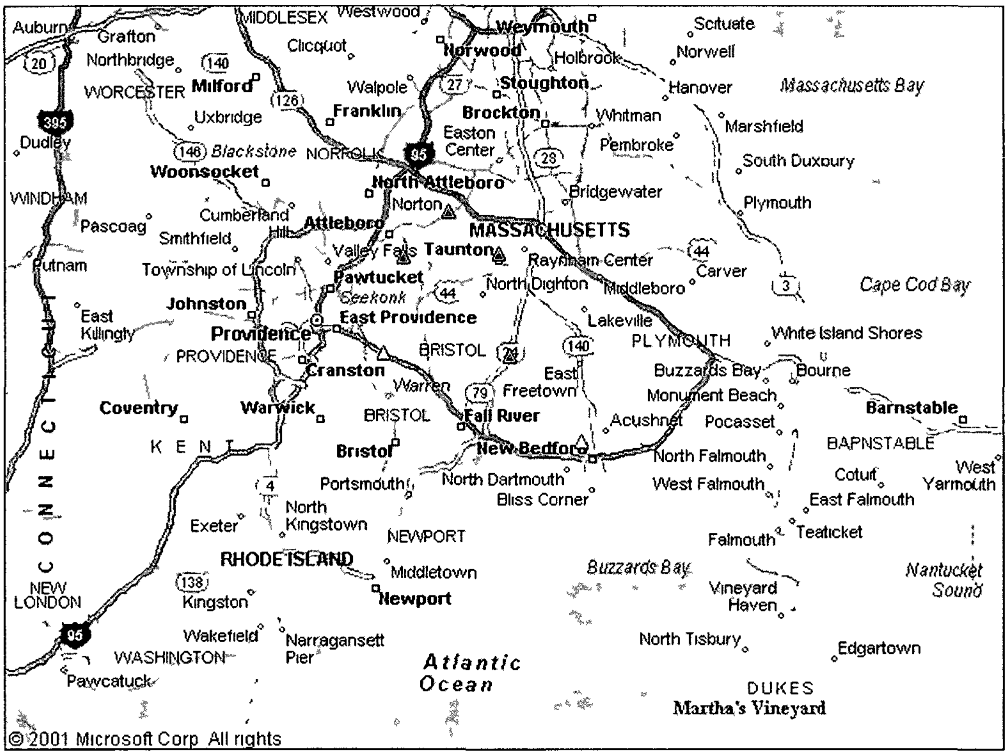


Figure 14C: Bristol County Active Wells

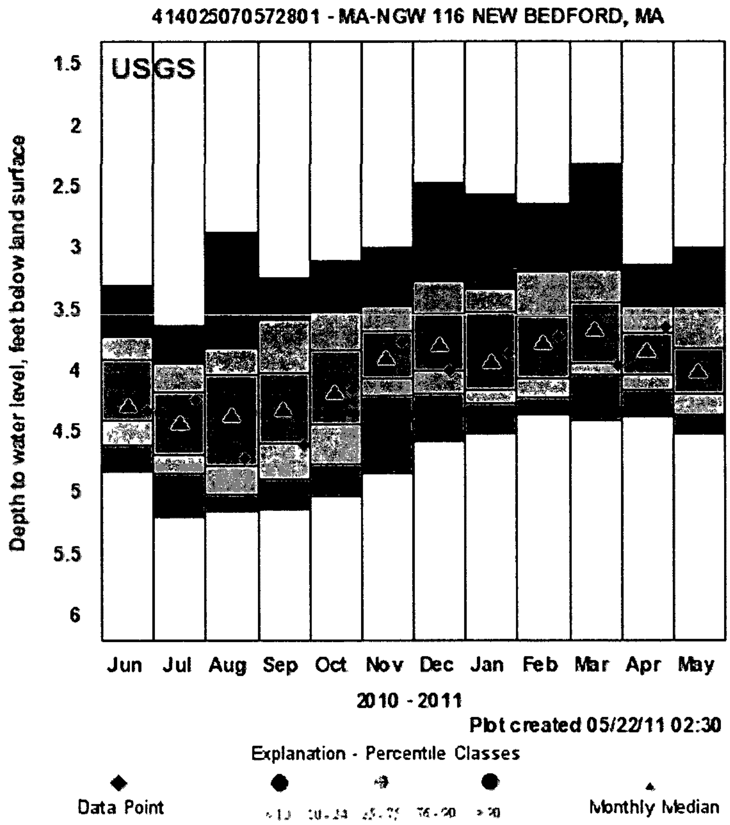


Figure 15C: Ground Water Table Levels for 2010-2011 (Site Number: 414025070572801)

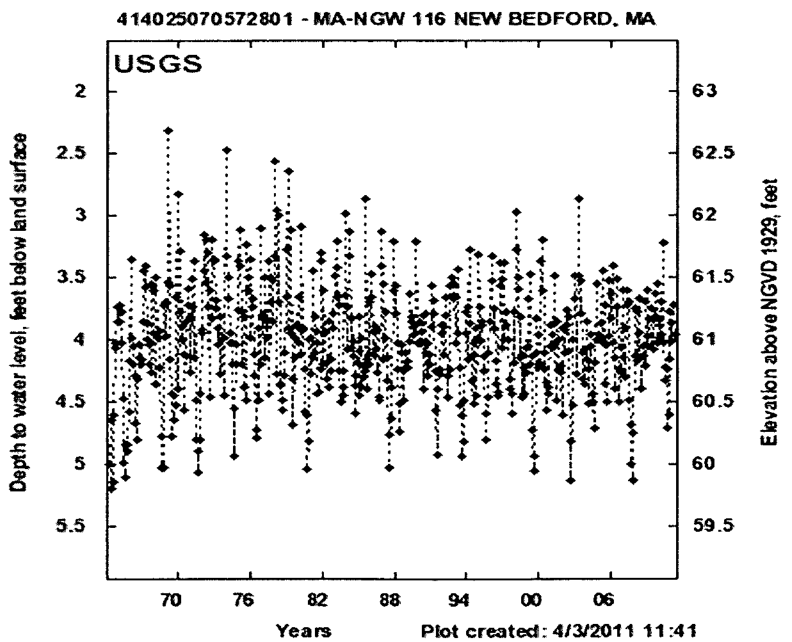


Figure 16C: Historic Data of a Ground Water Level in New Bedford, MA

Table 17C: Ground Water Table Most Recent Data Values on 03/28/2011(Depth to Water Level, Feet)

Month	Lowest Median	10th %ile	25th %ile	50th %ile	75th %ile	90th %ile	Highest Median	Number of Years
Jan	4.51	4.27	4.16	3.94	3.52	3.33	2.56	45
Feb	4.36	4.22	4.06	3.78	3.56	3.20	2.64	46
Mar	4.40	**4.04**	**3.94**	3.68	3.45	3.18	2.31	46
Apr	4.38	4.16	4.03	3.85	3.70	3.46	3.13	46
May	4.51	4.36	4.19	4.02	3.81	3.48	3.00	45
Jun	4.83	4.61	4.40	4.29	3.91	3.73	3.30	46
Jul	5.20	4.84	4.69	4.43	4.17	3.94	3.63	47
Aug	5.14	5.01	4.78	4.38	4.04	3.81	2.87	47
Sep	5.13	4.88	4.59	4.32	4.02	3.59	3.24	47
Oct	5.02	4.76	4.44	4.19	3.83	3.53	3.10	47
Nov	4.84	4.20	4.07	3.91	3.67	3.48	2.99	47
Dec	4.58	4.19	4.00	3.80	3.54	3.27	2.47	46

Note: Bold values in the table indicate closest statistic to the most recent data value.

Table 18C: Water Level Measurement Records at New Bedford Well

Highest WL	Date of Highest WL	Lowest WL	Date of Lowest WL
2.31	03/26/69	5.20	07/23/64

6. Material Inputs

6.1 HMA Thickness

An HMA thickness for the control file is 9.6". To see the effect of HMA thickness on predicting distresses values two more HMA thicknesses has been selected:

Table 19C: Selected HMA Layer Thickness

CODE	Total HMA Thickness (in)
T1	8.0
T2 (Control)	9.6
T3	11.0

The two HMA layers (surface and binder) will be treated as one layer with 19.0 mm asphalt mix gradation (mean).

6.2 Number of HMA Layers

Two HMA layers are going to be used for the M-E PDG analysis:

- AC original surface – 1.4" (w/ 9.5 mm mix gradation)
- AC binder course – 8.2" (w/ 19.0 mm mix gradation)

6.3 HMA Mix Gradation

HMA mix gradation for Massachusetts conforms to Superpave specifications.

Table 20C: Range of Values of HMA Mix Gradation – Superpave Specifications

NMAS* of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
3/4" sieve	0	0 – 10	10 – NR	NR**	NR
3/8" sieve	0 – 10	10 – NR	NR	NR	NR
# 4 sieve	10 – NR	NR	NR	NR	NR
#200 sieve	2 – 10	2 – 10	2 – 8	1 – 7	0 – 6

*- Nominal Maximum Aggregate Size
** – No restriction on the value

Table 21C: Tolerance for HMA Mix Gradation

NMAS of Mix	9.5 mm (3/8")	12.5 mm (1/2")	19.0 mm (3/4")	25.0 mm (1")	37.5 mm (1.5")
Cum. % Ret 3/4" sieve		± 4%	± 5%	± 7%	
Cum. % Ret 3/8" sieve		± 4%	± 5%	± 7%	
Cum. % Ret # 4 sieve	± 4%	± 3%	± 4%	± 4%	± 6%
#200 sieve	± 0.8%	± 0.8%	± 0.8%	± 0.8%	± 0.8%

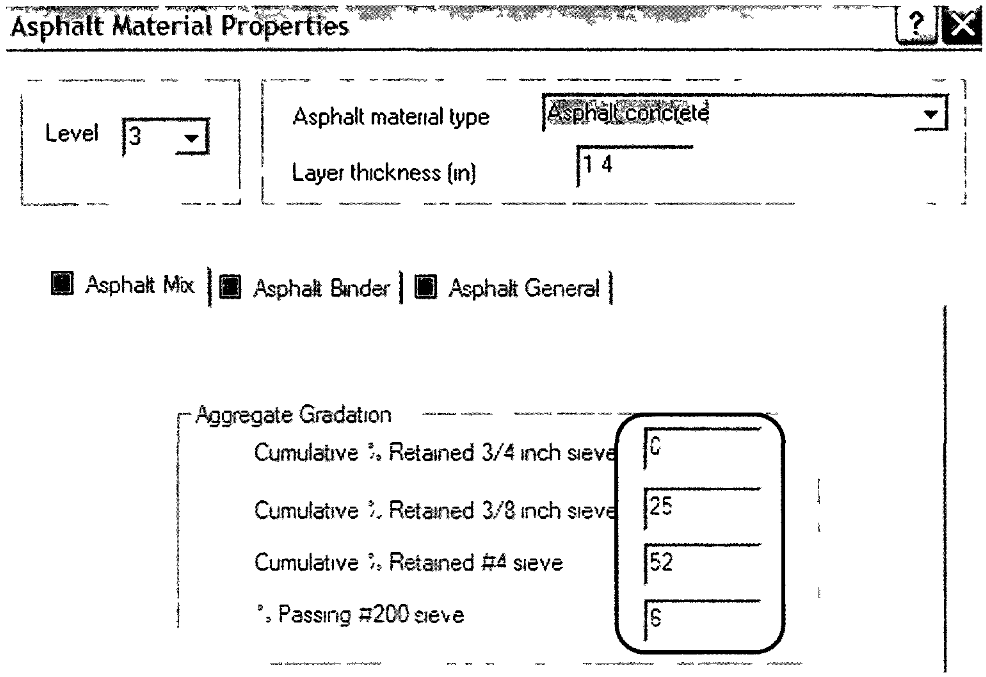


Figure 17C: 3/8" (9.5 mm) Asphalt Mix Aggregate Gradation

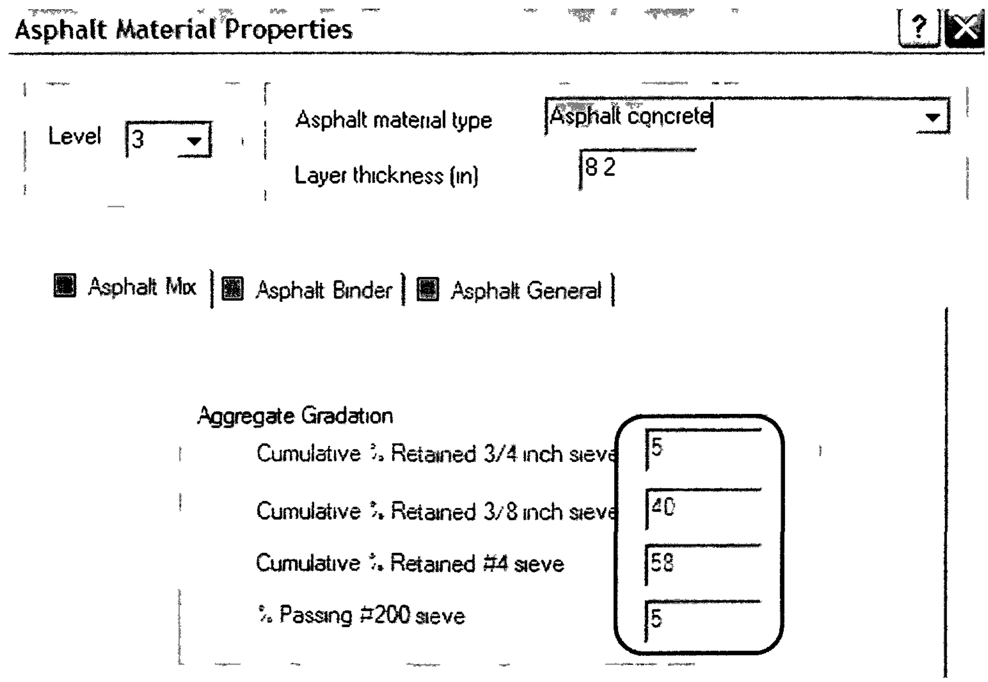


Figure 18C: 3/4" (19.0 mm) Asphalt Mix Aggregate Gradation

Table 22C: Recommended Typical Massachusetts HMA Mix Gradations Input

Gradation Mix Designation	Percent Retained				Percent Passing
	¾-in Sieve	½-in Sieve	3/8-in Sieve	#4-in Sieve	#200 Sieve
1-in (25.0 mm)	15	30	48	62	4
¾-in (19.0 mm)	5	20	40	58	5
½-in (12.5 mm)	0	5	25	52	6
⅜-in (9.5 mm)	0	0	5	45	6

6.4 PG Binder Grade

Based on Mass DOT asphalt supplier list, three asphalt PG grades were selected: PG 52-34, PG 64-22 and PG 64-28 for the M-E PDG sensitivity analysis. The PG 64-22 is used as the binder grade for the control case. The binder grade is tested in conjunction with operational speed of vehicle.

Table 23C: Massachusetts PG Binder Grades

CODE	PG BINDER GRADE
G1	PG 52-34
G2 (Control)	PG 64-22
G3	PG 64-28

6.5 Unbound Layer Inputs

ASTM D 2940, Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports. The gradation for base material from this standard is given below.

Table 24C: ASTM D 2940 Gradation for Dense-Graded Bases and Subbases

Sieve Size	Percent Passing
2 in. (50 mm)	100
1'/2 in. (37.5 mm)	95 – 100
3/4 in. (19.0 mm)	70 – 92
½ in. (9.5 mm)	50 – 70
No. 4 (4.75 mm)	35 – 55
No. 30 (0.600 mm)	12 – 25
No. 200 (0.075 mm)	0 – 8

6.6 Base Course Resilient Modulus

Table 25C: Base Course Aggregate Gradations (Level 3)

CODE	M1 (Control)	M2	M3
Type of course	Crushed Gravel	Crushed Stone	River-Run Gravel
Sieve Size	Percent Passing by Weight		
3 ½ in (90.0 mm)	-	-	97.6
3 in (75.0 mm)	100	-	-
2 in (50.0 mm)	97.5	100	91.6
1 ½ in (37.5 mm)	-	92.5	85.6
1 in (25.0mm)	70.0	-	78.8
¾ in (19.0 mm)	-	60.0	72.7
#4 (4.75 mm)	39.5	27.5	44.7
#200 (0.075 mm)	6.0	2.5	8.7
Resilient Modulus	**25000**	**30000**	**15000**

Table 26C: Untreated Base Course Gradation Limits

Gradation Limits		
Sieve Size	**Job Mix Gradation Target Band**	**Job Mix Gradation Tolerance**
1 1/2 inch	100	
1 inch	90 – 100	±9.0
3/4 inch	70 – 85	±9.0
1/2 inch	65 – 80	±9.0
3/8 inch	55 – 75	±9.0
No. 4	40 – 65	±7.0
No. 16	25 – 40	±5.0
No. 200	7 – 11	±3.0

6.7 Subgrade Resilient Modulus M_R

Table 27C: Subgrade Types and Subgrade Resilient Modulus

CODE	SUBGRADE TYPE	Material Classification	RESILIENT MODULUS (psi)	
			Level 2	Level 3
E1	Clayey soils	A-7-6	n/c*	8000
E2 (Control)	Fine sand, some silt	A-2-4	n/c	25000
E3	Coarse to fine gravelly, coarse to medium sand, some fine sand	A-1-a	n/c	30000

*- n/c not collected

6.8 Effective Binder Content V_{be}, % (AASHTO T308)

Table 28C: Effective Binder Content

CODE	In-situ VMA, percent	EFFECTIVE BINDER CONTENT
F1	14.0	10.0
F2 (Control)	15.0	11.0
F3	16.0	12.0

Table 29C: HMA Mix Gradation Input Values

% of Aggregate	9.5 mm (3/8")			19.0 mm (3/4")		
	A1	A2	A3	B1	B2	B3
Retained on 3/4" sieve	0	0	0	14.0	18.6	12.0
Retained on 3/8" sieve	5.0	8.2	3.6	24.0	32.4	19.8
Retained on #4 sieve	35.0	48.3	22.1	42.0	52.0	34.5
Passing #200 sieve	6.0	2.8	8.5	5.0	2.8	7.2

1 – Mean values of the allowable range of values

2 – Coarse mix gradation

3 – Fine mix gradation

6.9 Air Voids Content, %

Table 30C: Air Voids Percentage (Mixture design)

CODE	PERCENT AIR VOIDS
V1 (Control)	4.0
V2	5.0
V3	6.0

None mixture design Air Voids (in-situ air voids at construction site) will be based on percent compaction in specification:

- Range 3.5 to 9.5 (90.5 to 96.5)
- Target 6.5 (93.5) – recommended

6.10 Mix Coefficient of Thermal Contraction (CTC)

Table 31C: Mix Coefficient of Thermal Contraction

CODE	COEFFICIENT OF THERMAL CONTRACTION
N1	1.0 E-07
N2 (Control)	1.3 E-05
N3	1.0 E-04

The Mix CTC default value of 1.3 E-05 is used for Level 3 sensitivity analysis.

To see the effect of the CTC value on the sensitivity analysis the broad ranges were selected based on the M-E PDG help menu from 1.0×10^{-7} to 1.0×10^{-4}.

6.11 Aggregate Coefficient of Thermal Contraction

The M-E PDG default value is $5.0 * 10^{-6}$/°F.

6.12 Initial IRI values for new pavement design

Table 32C: Suggested Initial IRI Values for New Pavement Design

PAVEMENT TYPE	IRI (IN/MI)		
	MINIMUM	AVERAGE	MAXIMUM
NEW HMA AND HMA/HMA*	32	70	106

*- Initial IRI for HMA pavements shall be set within the range of 70 to 85 in/mi.

Table 33C: Sensitivity Analysis Initial IRI Values

CODE	Initial IRI (in/mi)
S1	32
S2 (Control)	75
S3	106

7. MA State M-E PDG Level 3 Sensitivity Analysis

7.1 Effect of Traffic Inputs on Pavement Distresses

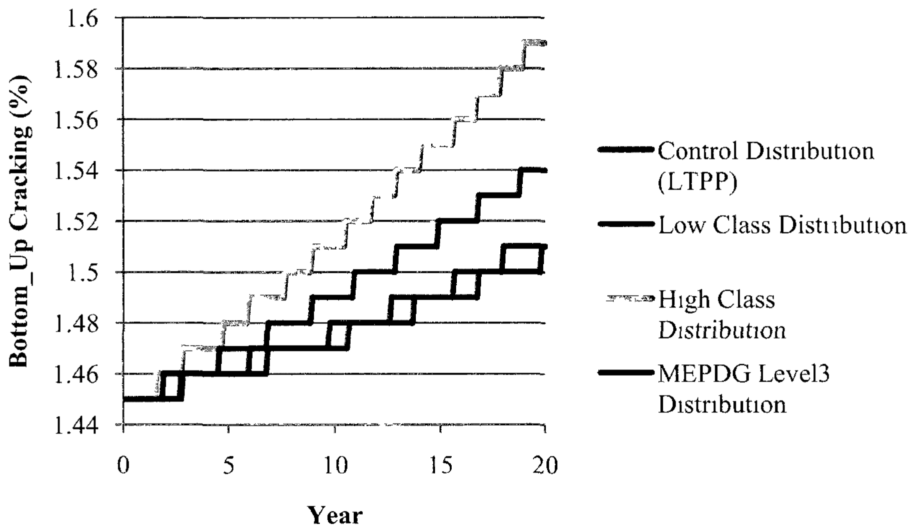


Figure 19C: Effect of Truck Class Distribution on Bottom-Up Cracking

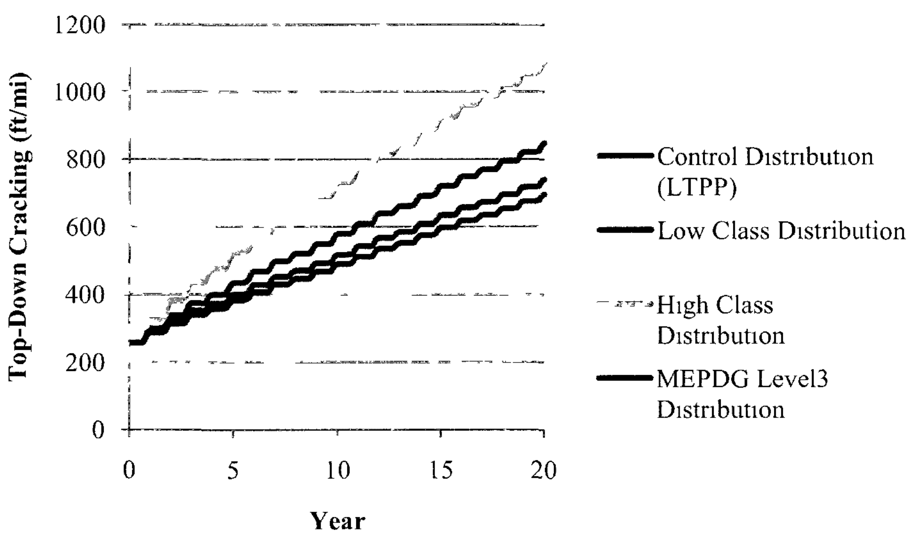


Figure 20C: Effect of Truck Class Distribution on Top-Down Cracking

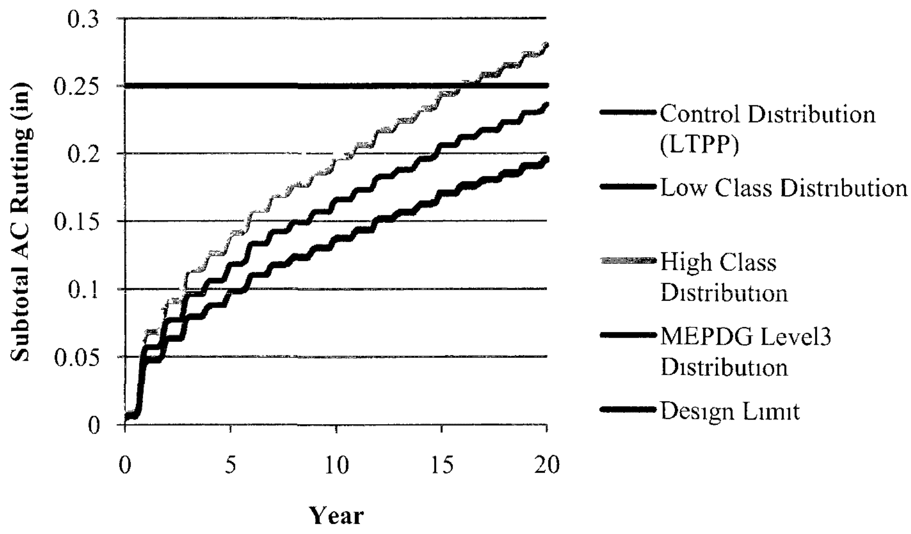


Figure 21C: Effect of Truck Class Distribution on Subtotal AC Rutting

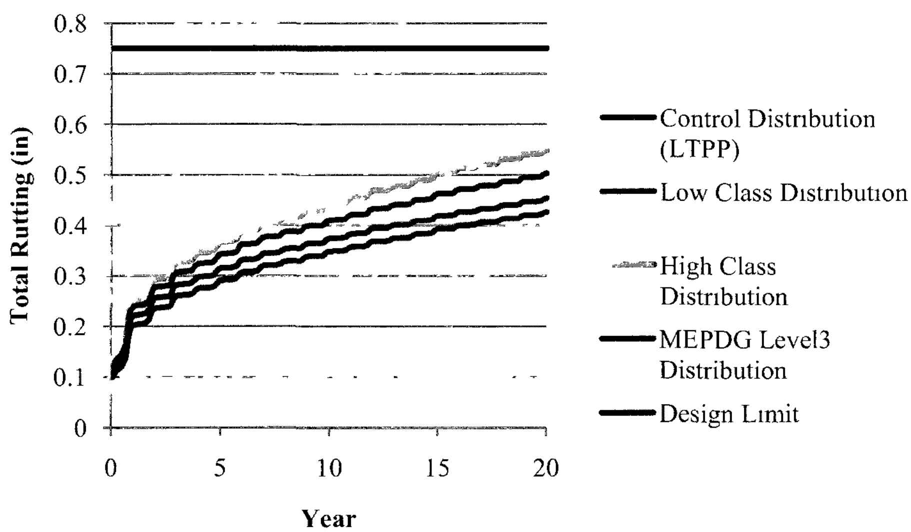


Figure 22C: Effect of Truck Class Distribution on Total Rutting

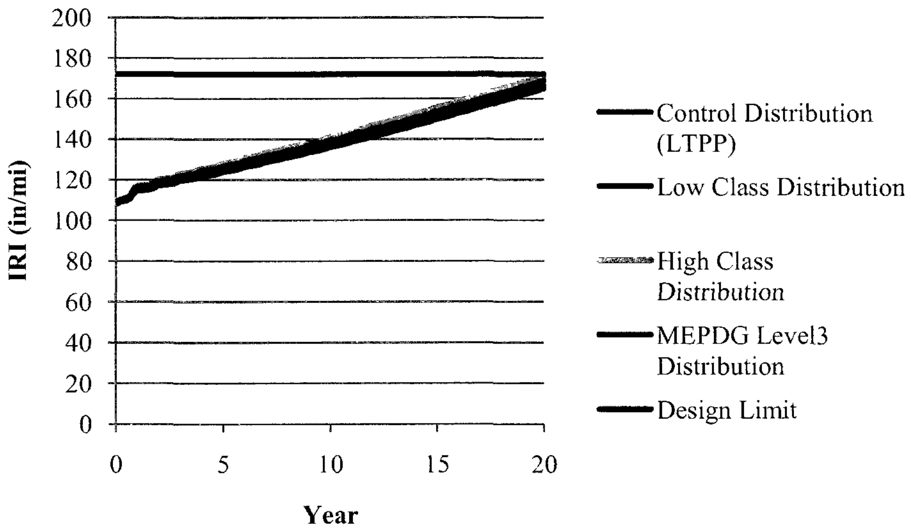


Figure 23C: Effect of Truck Class Distribution on IRI

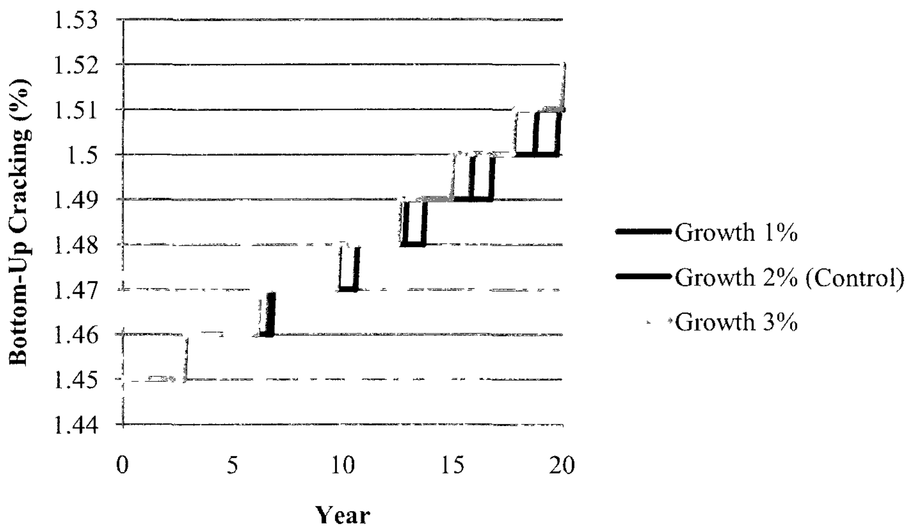


Figure 24C: Effect of Traffic Growth Rate at Bottom-Up Cracking

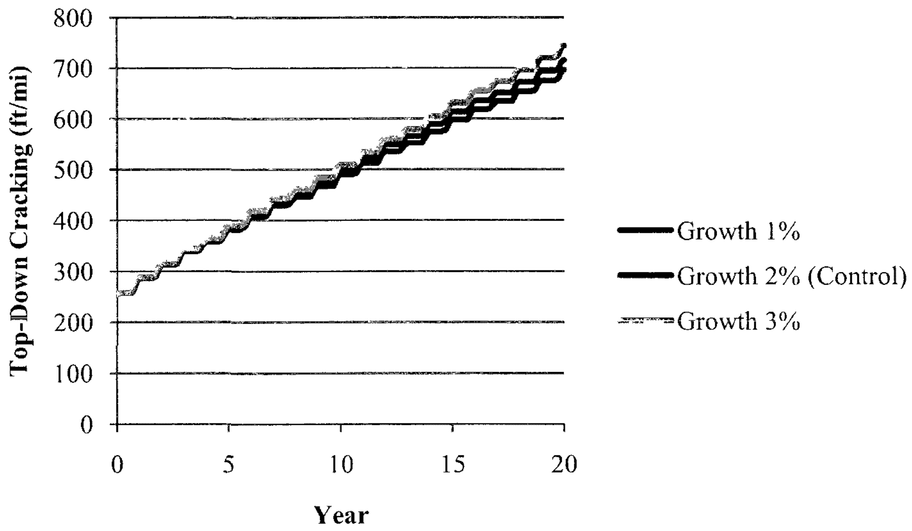


Figure 25C: Effect of Traffic Growth Rate on Top-Down Cracking

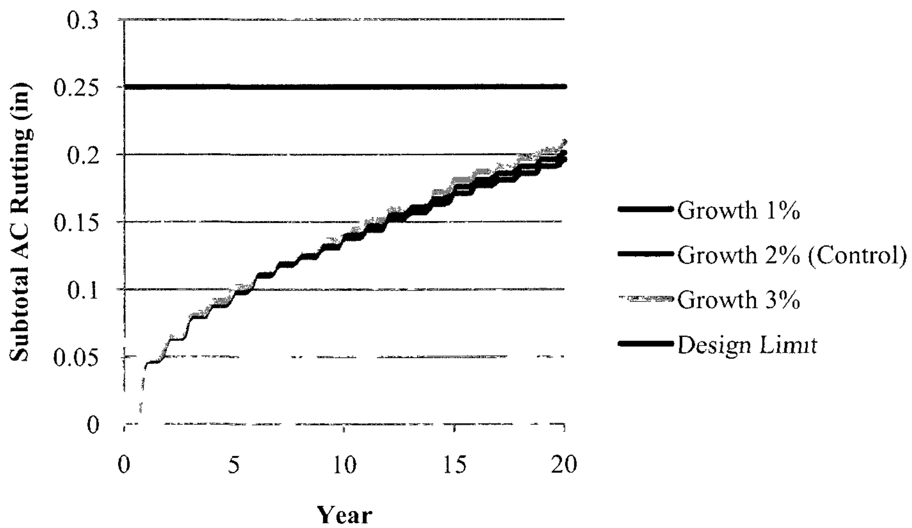


Figure 26C: Effect of Traffic Growth on Subtotal AC Rutting

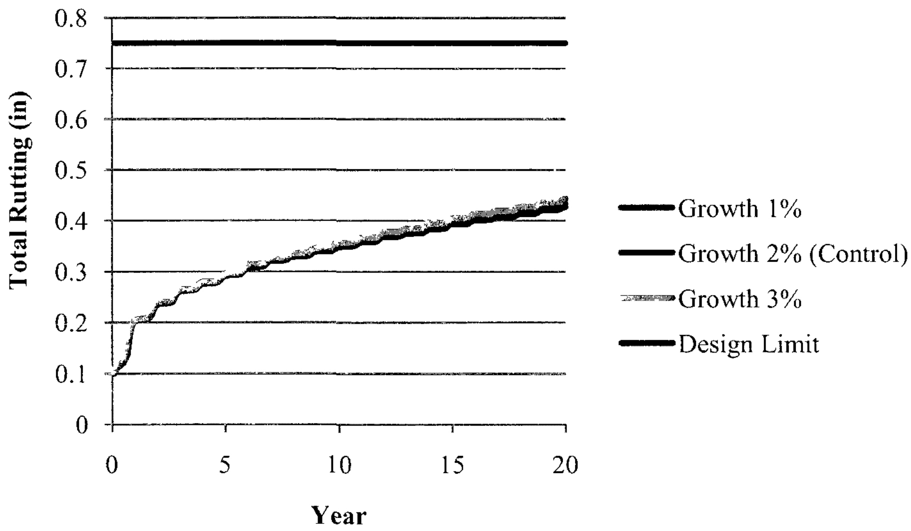


Figure 27C: Effect of Traffic Growth Rate on Total Rutting

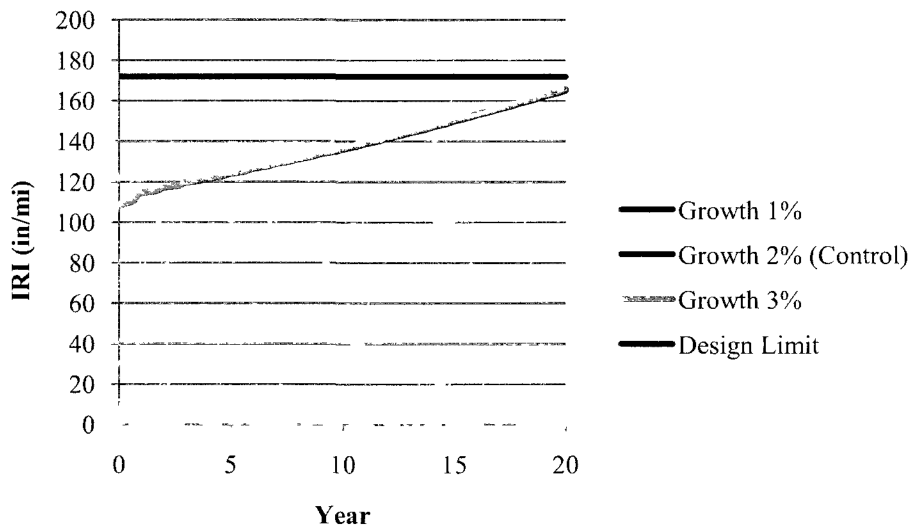


Figure 28C: Effect of Traffic Growth Rate on IRI

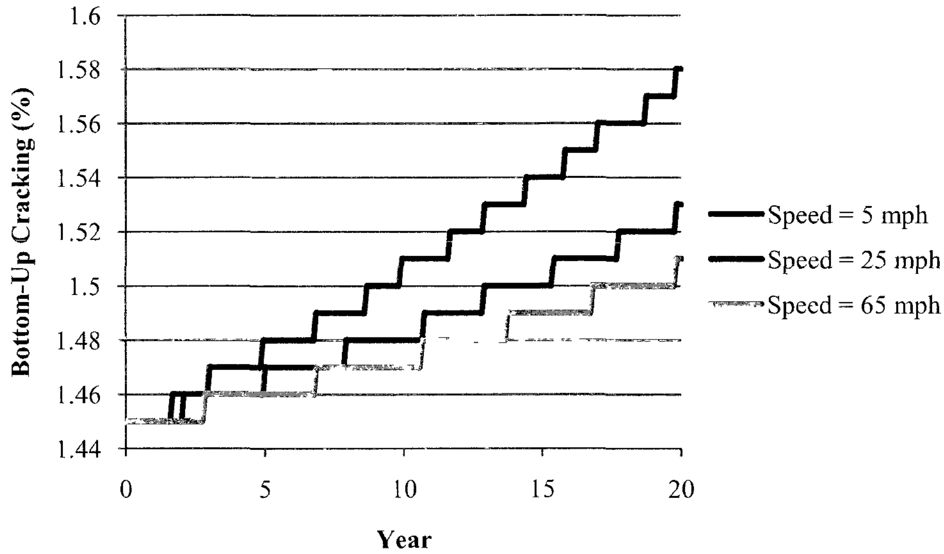


Figure 29C: Effect of Traffic Speed on Bottom-Up Cracking with PG 64-22

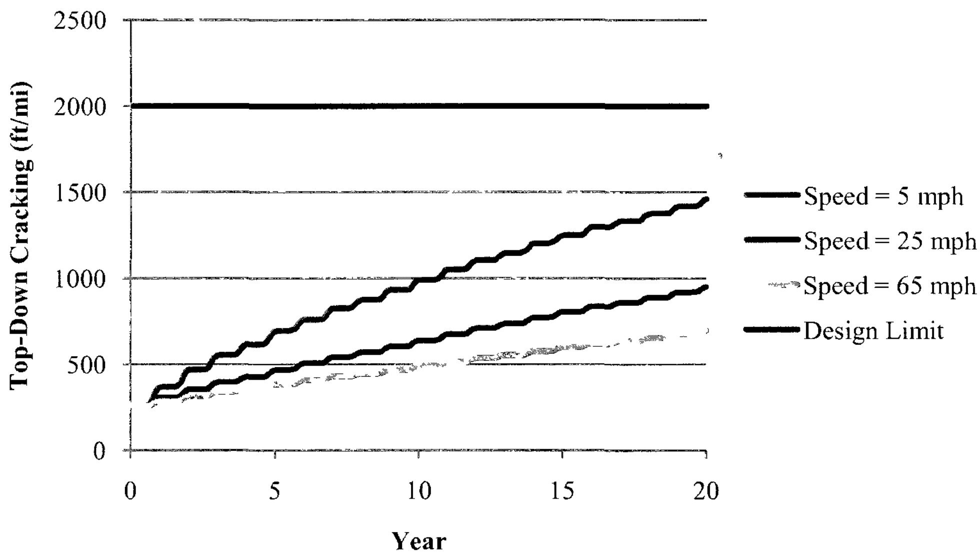


Figure 30C: Effect of Traffic Speed on Top-Down Cracking with PG 64-22

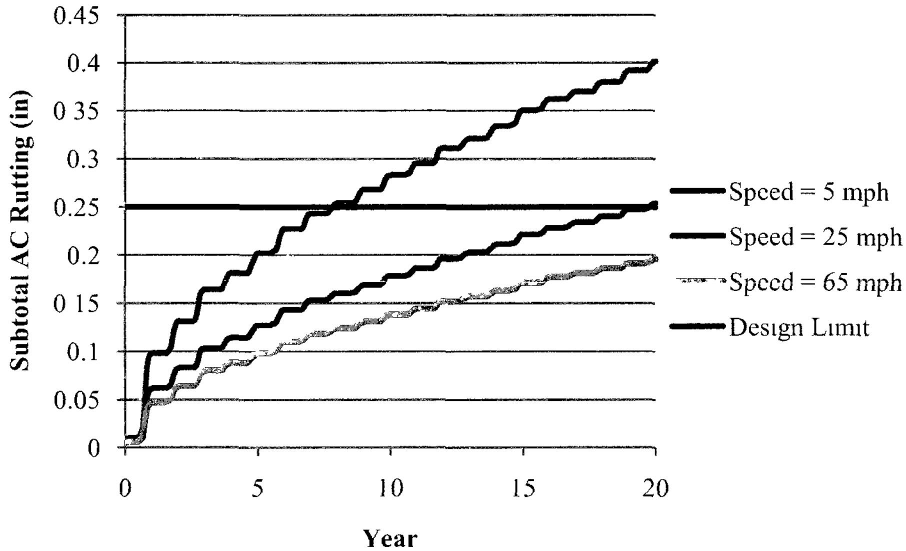


Figure 31C: Effect of Traffic Speed on Subtotal AC Rutting with PG 64-22

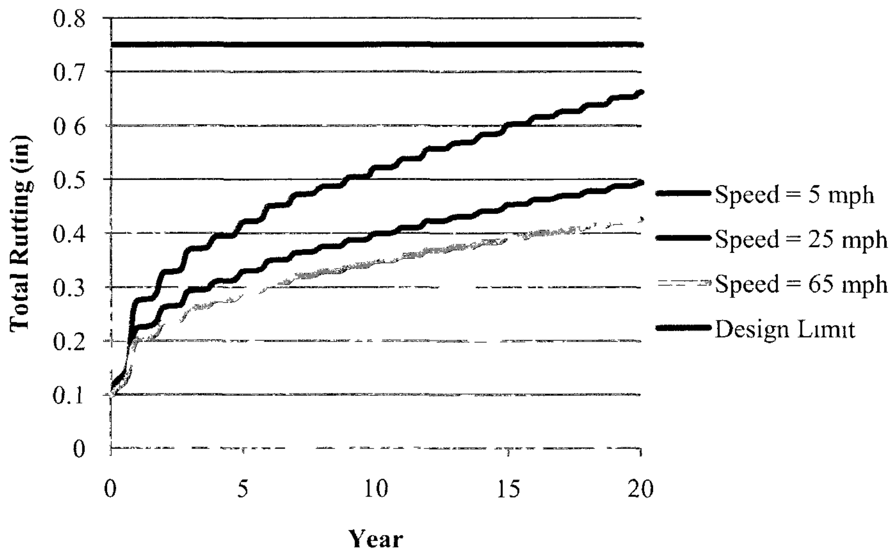


Figure 32C: Effect of Traffic Speed on Total Rutting with PG 64-22

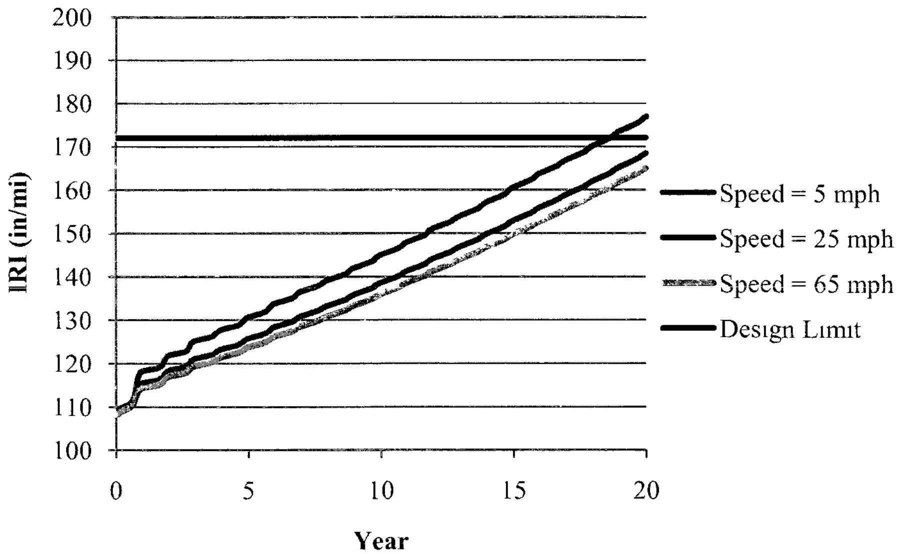


Figure 33C: Effect of Traffic Speed on IRI with PG 64-22

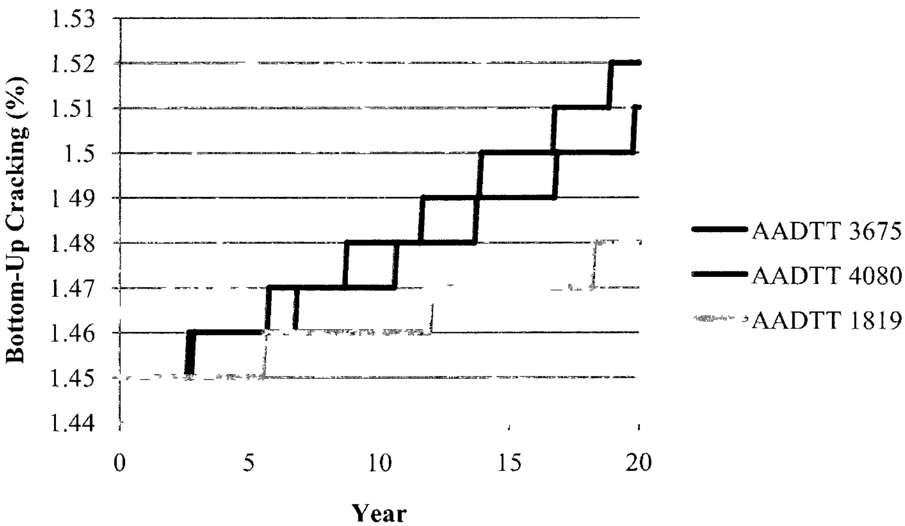


Figure 34C: Effect of AADTT on Bottom-Up Cracking

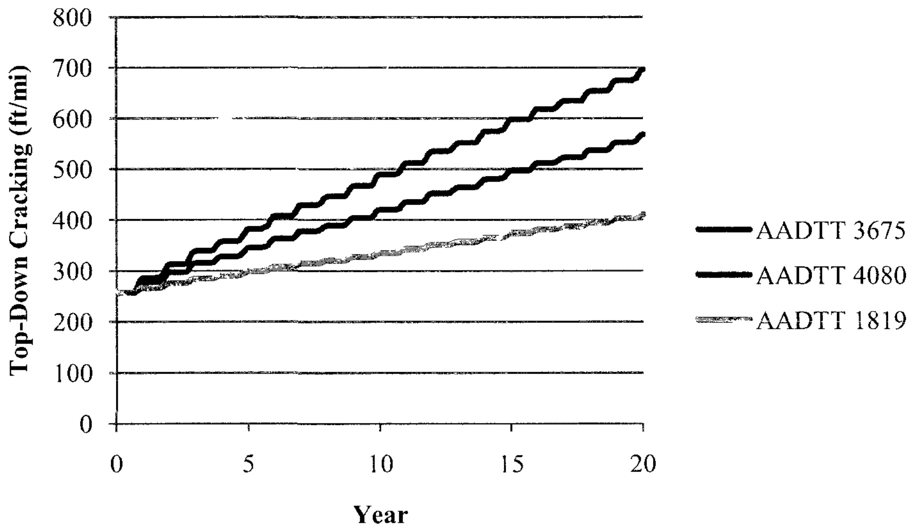


Figure 35C: Effect of AADTT on Top-Down Cracking

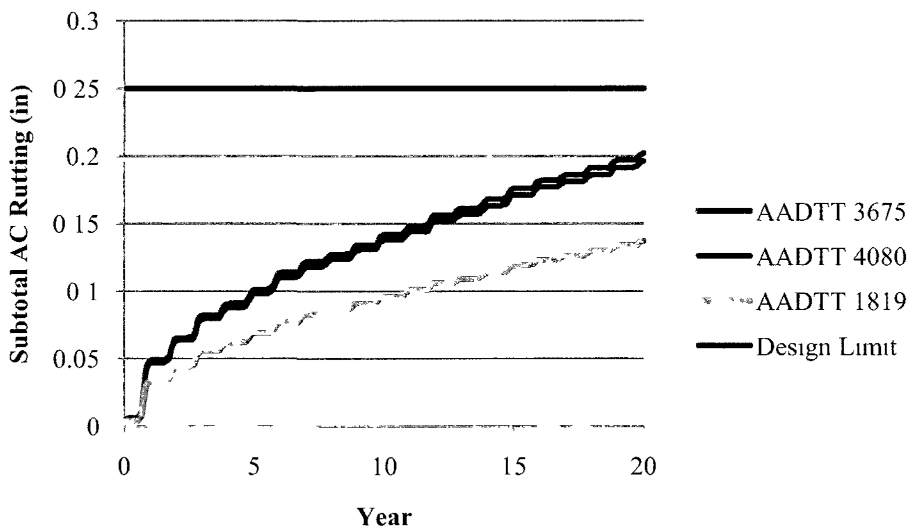


Figure 36C: Effect of AADTT on Subtotal AC Rutting

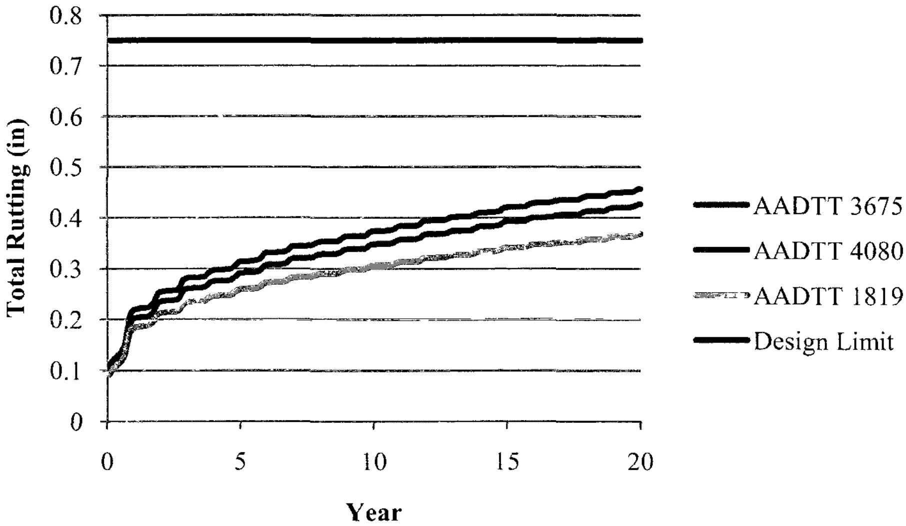


Figure 37C: Effect of AADTT on Total Rutting

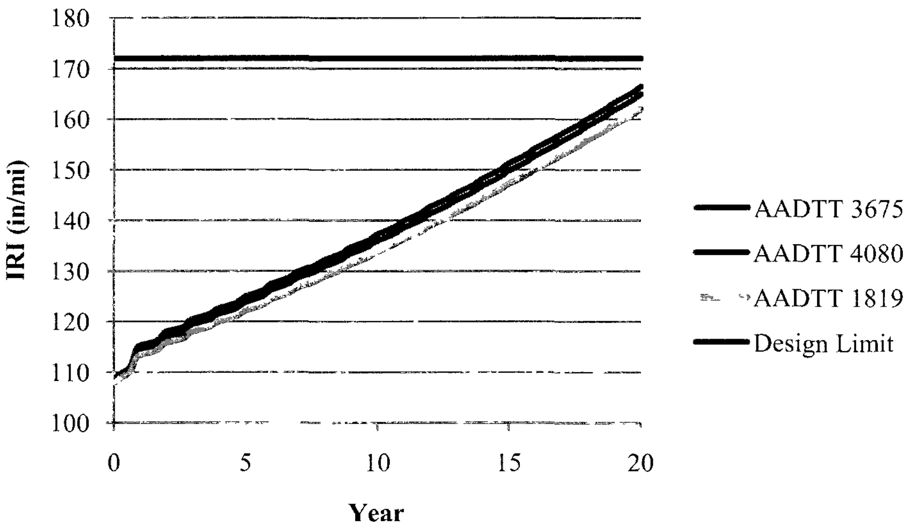


Figure 38C: Effect of AADTT on IRI

7.2 Effect of Climate Inputs on Pavement Distresses

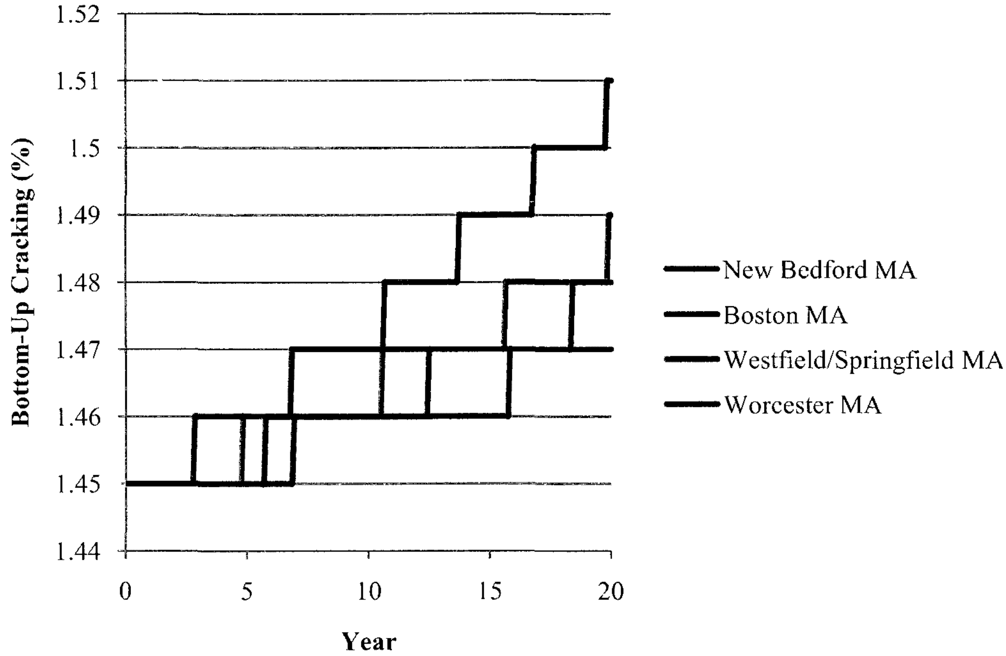


Figure 39C: Effect of Climate on Bottom-Up Cracking

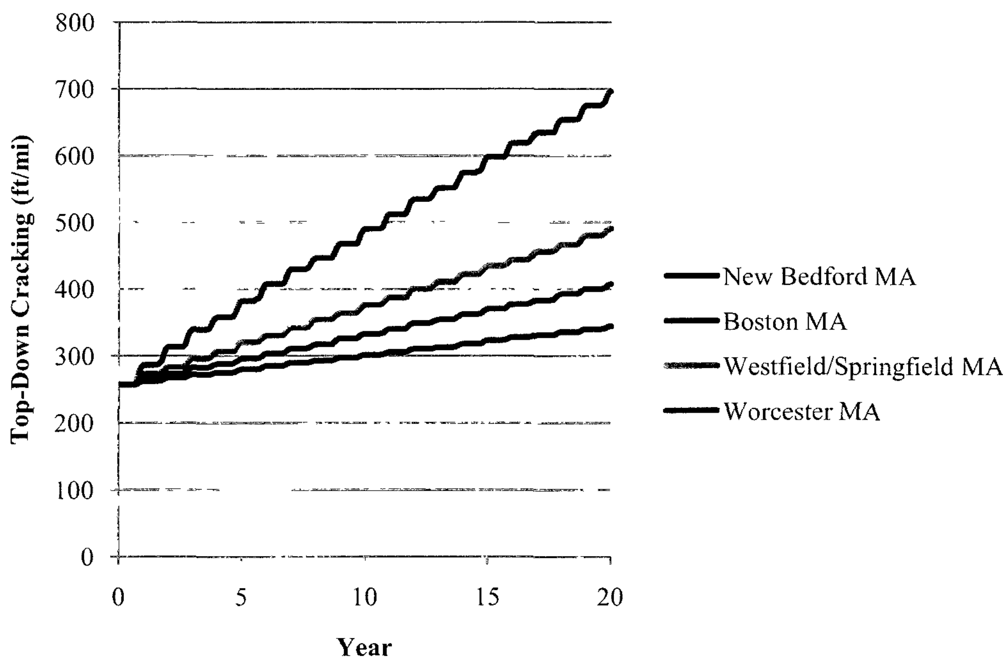


Figure 40C: Effect of Climate on Top-Down Cracking

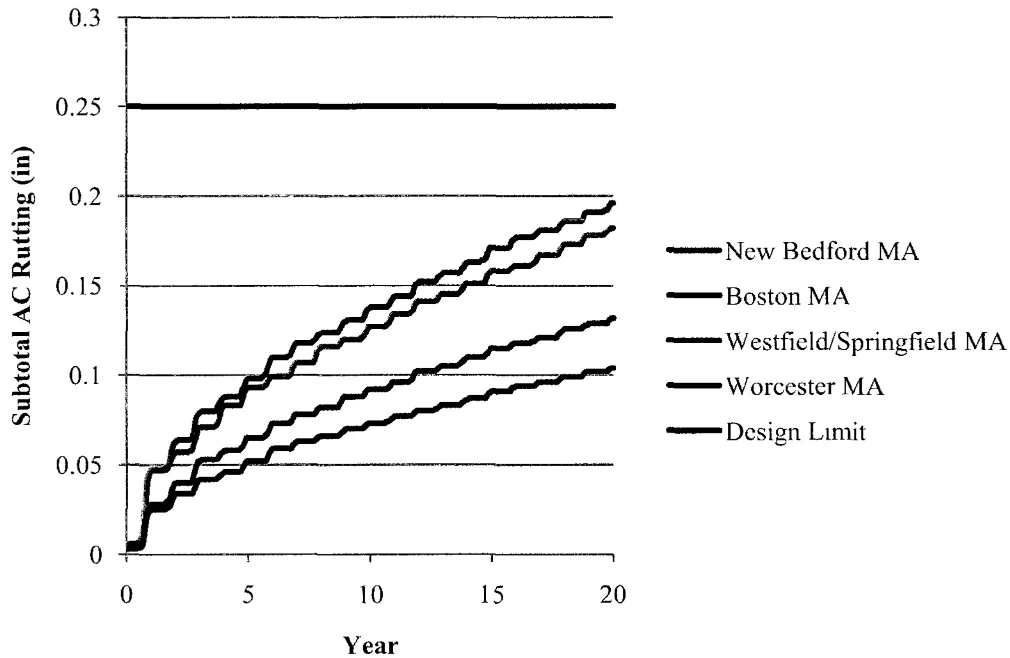


Figure 41C: Effect of Climate on Subtotal AC Rutting

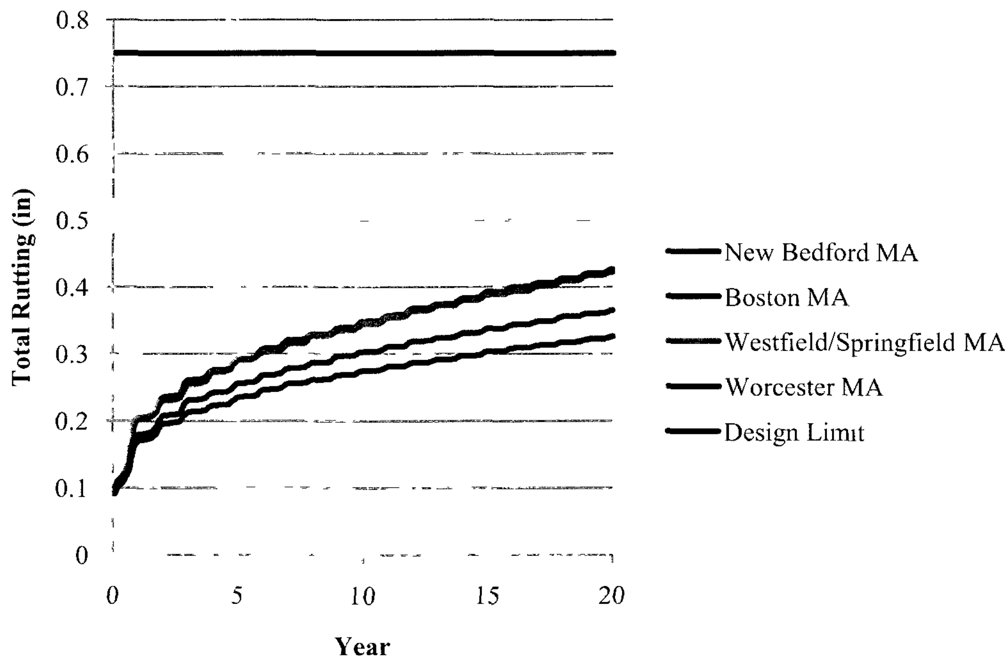


Figure 42C: Effect of Climate on Total Rutting

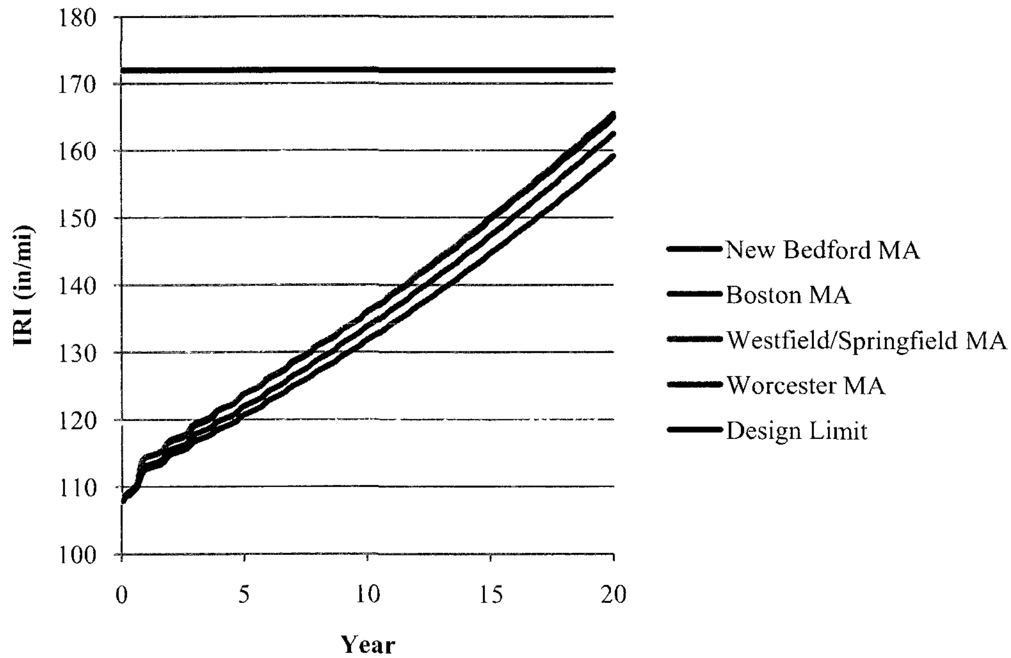


Figure 43C: Effect of Climate on IRI

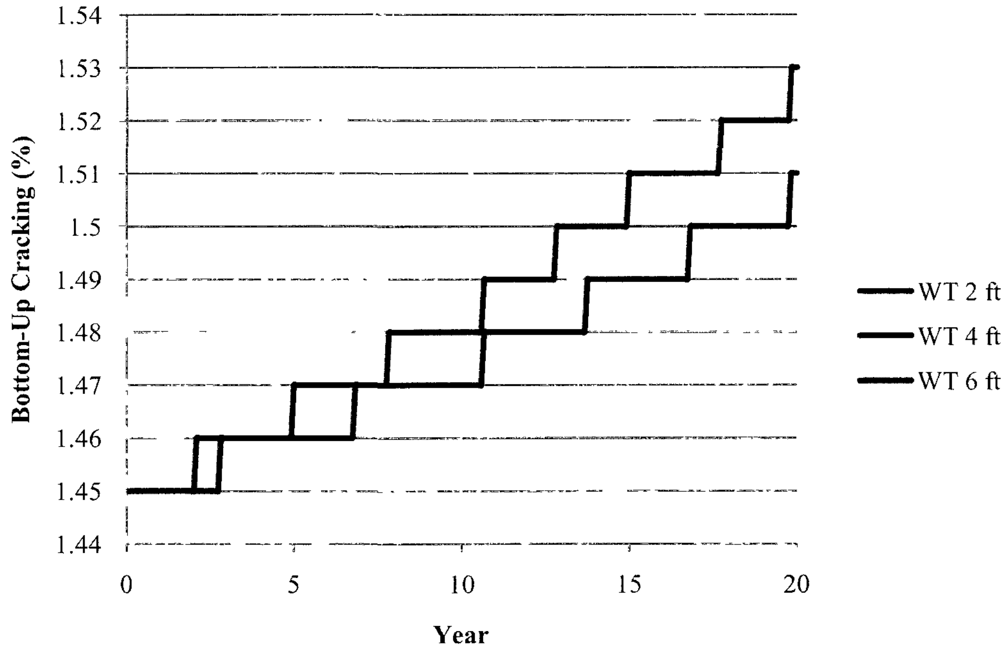


Figure 44C: Effect of Water Table Depth on Bottom-Up Cracking

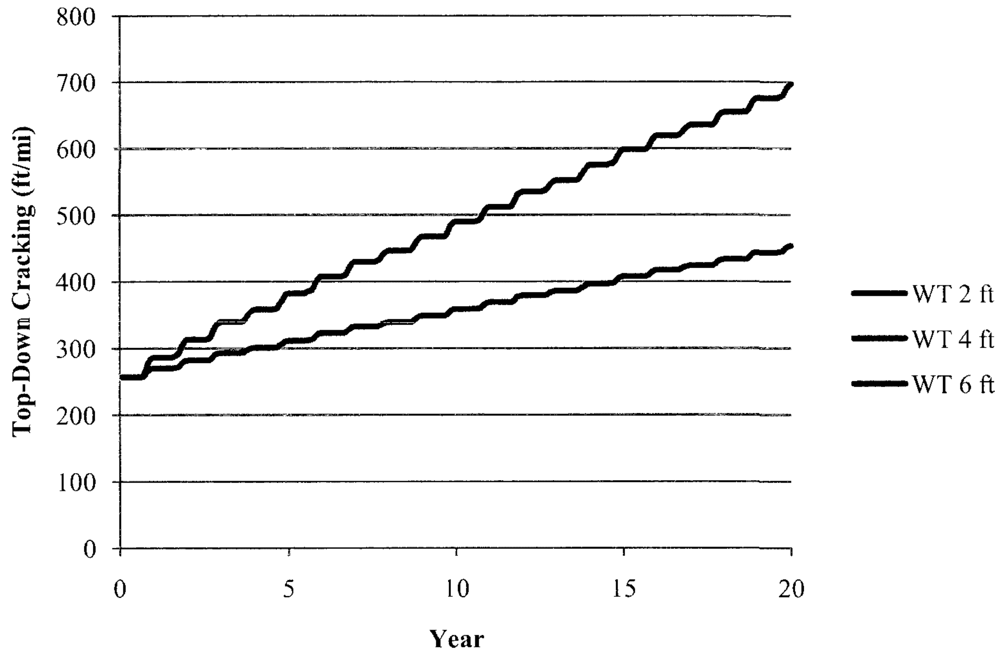


Figure 45C: Effect of Water Table Depth on Top-Down Cracking

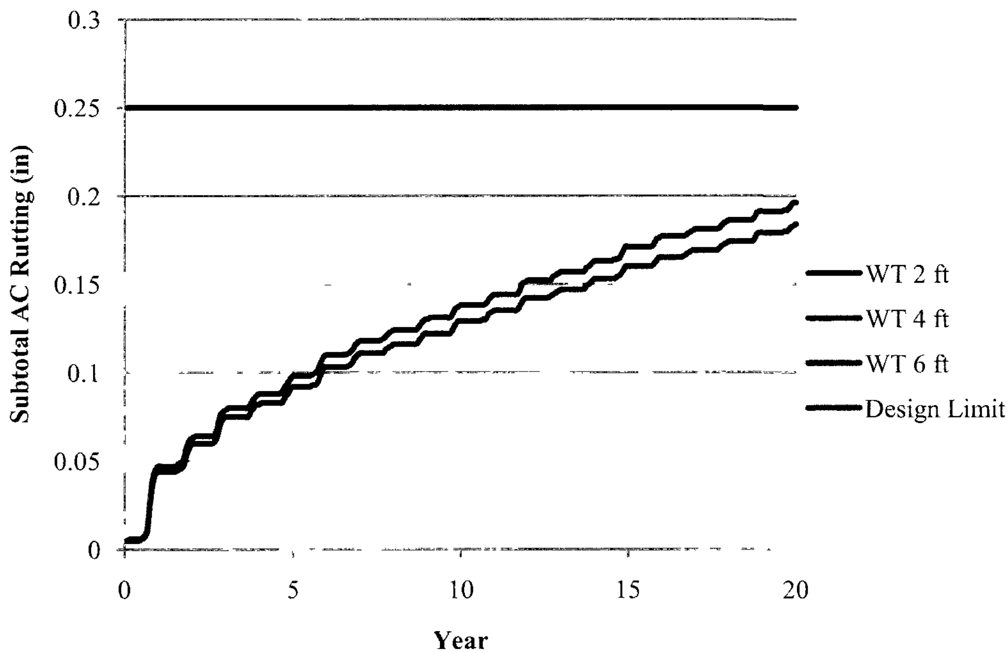


Figure 46C: Effect of Water Table Depth on Subtotal AC Rutting

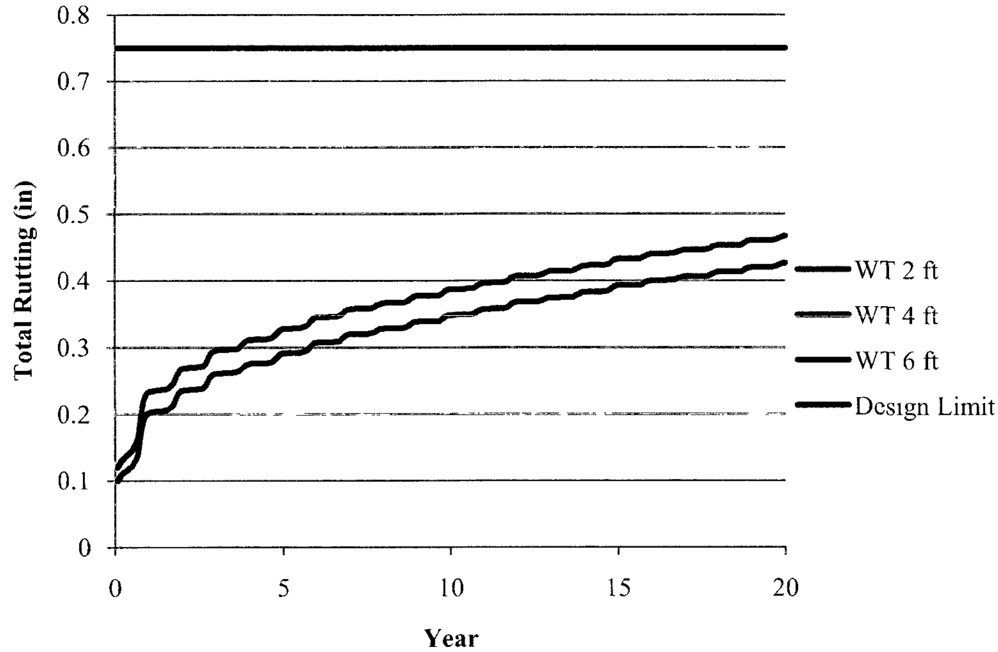


Figure 47C: Effect of Water Table Depth on Total Rutting

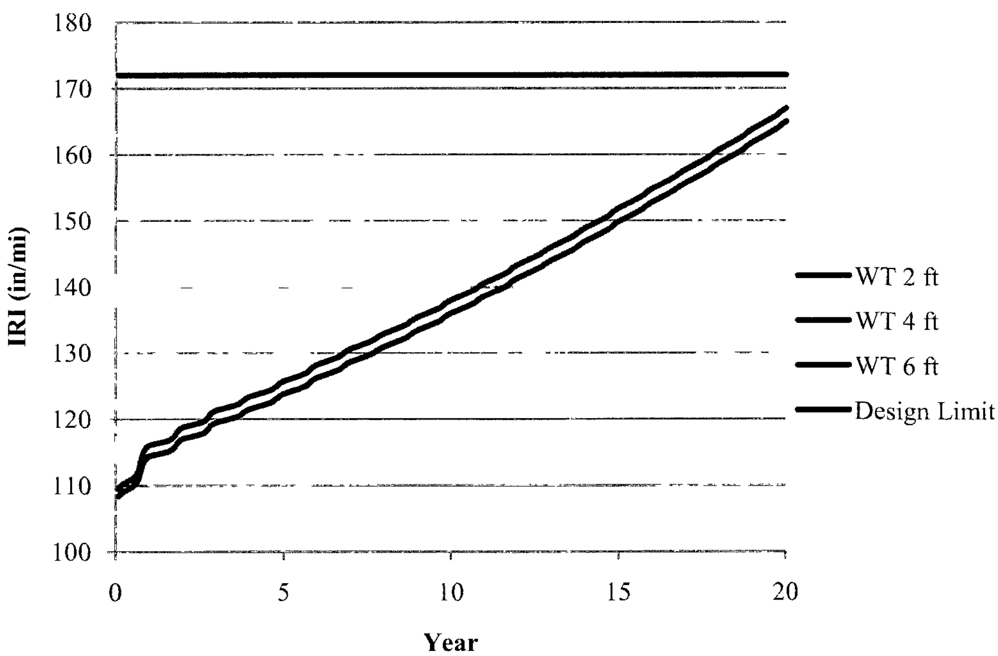


Figure 48C: Effect of Water Table Depth on IRI

7.3 Effect of Material Inputs on Pavement Distresses

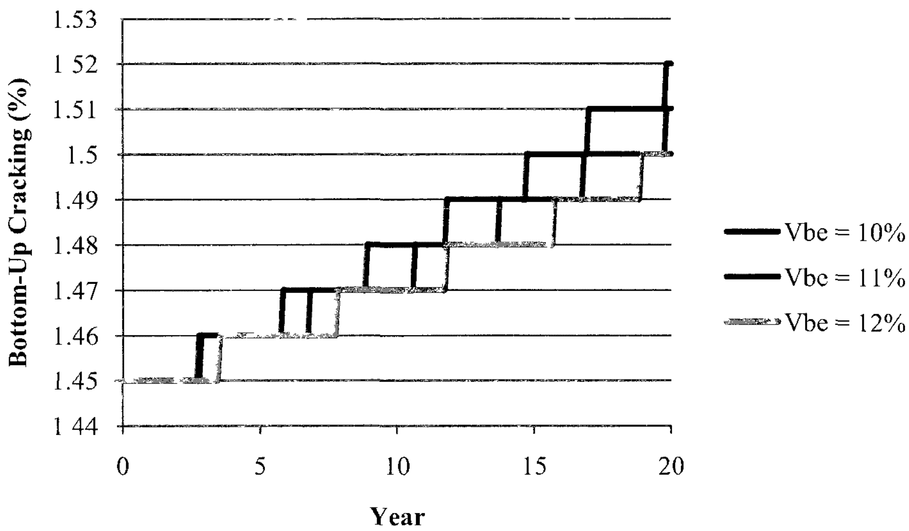


Figure 49C: Effect of Effective Binder Content on Bottom-Up Cracking

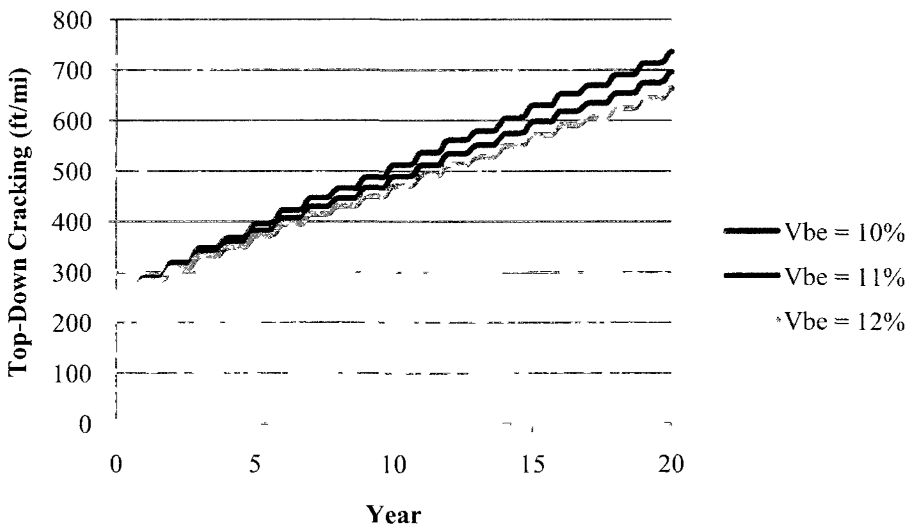


Figure 50C: Effect of Effective Binder Content on Top-Down Cracking

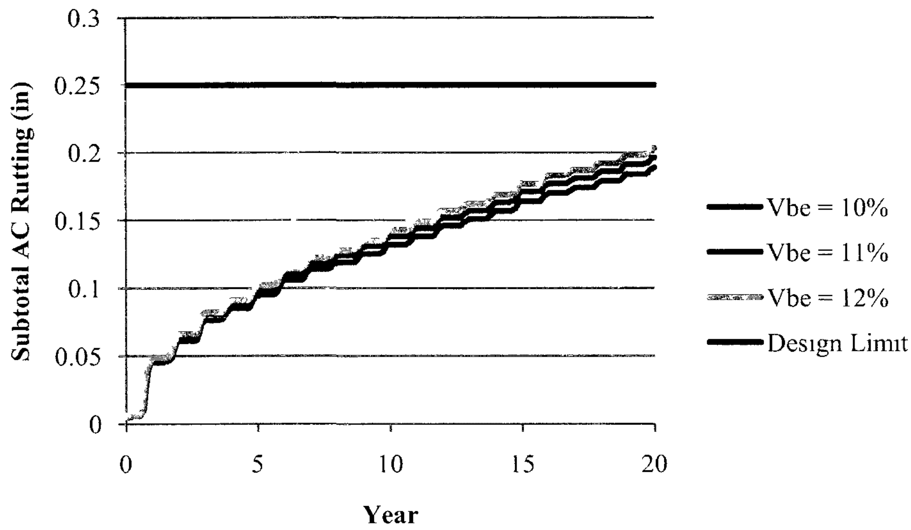


Figure 51C: Effect of Effective Binder Content on Subtotal AC Rutting

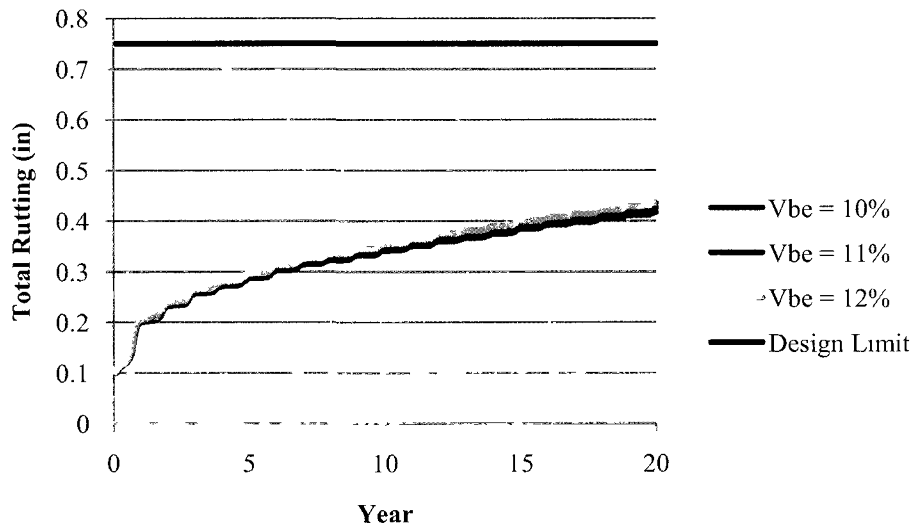


Figure 52C: Effect of Effective Binder Content on Total Rutting

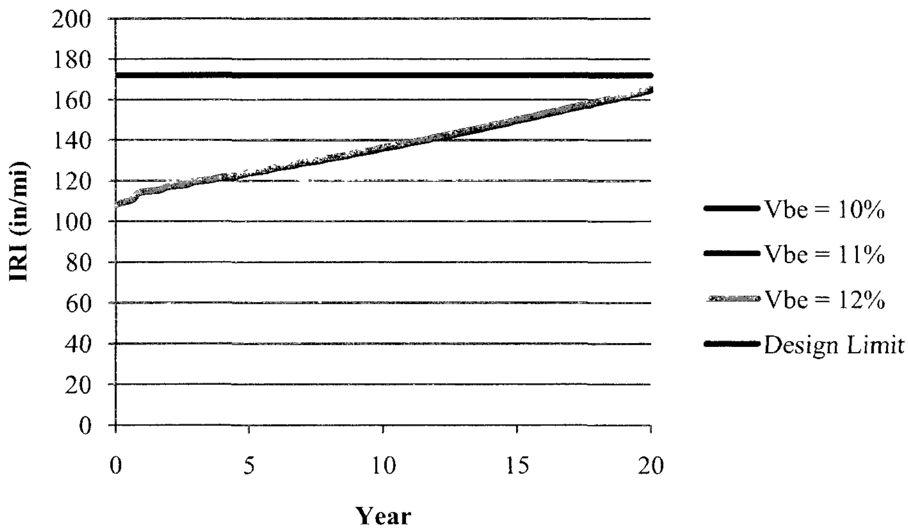


Figure 53C: Effect of Effective Binder Content on IRI

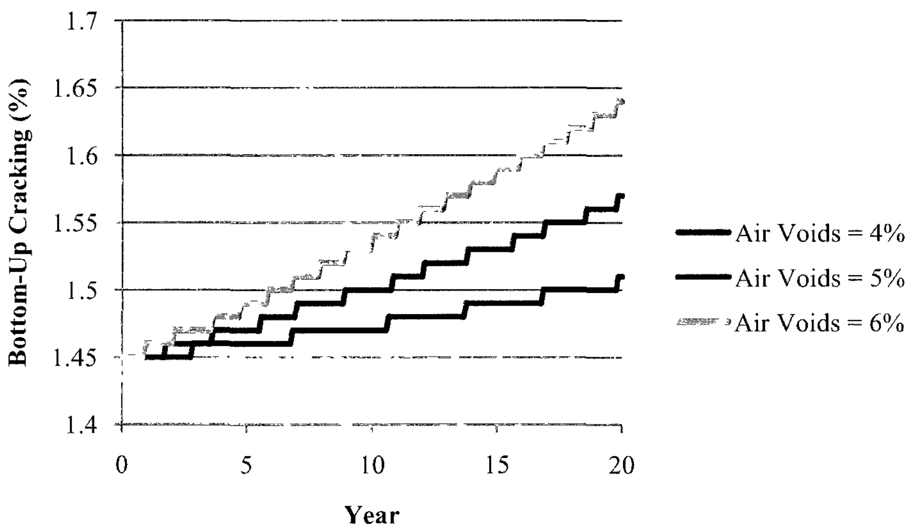


Figure 54C: Effect of Percent Air Voids on Bottom-Up Cracking

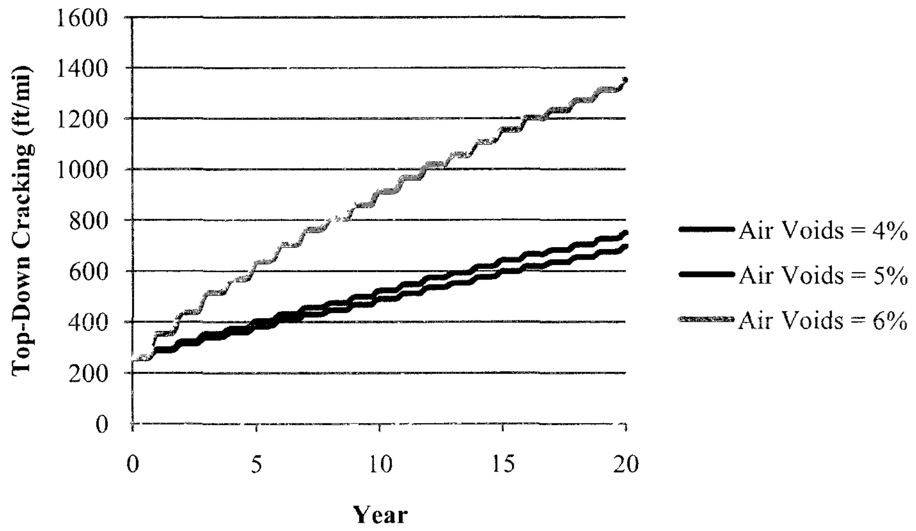


Figure 55C: Effect of Percent Air Voids on Top-Down Cracking

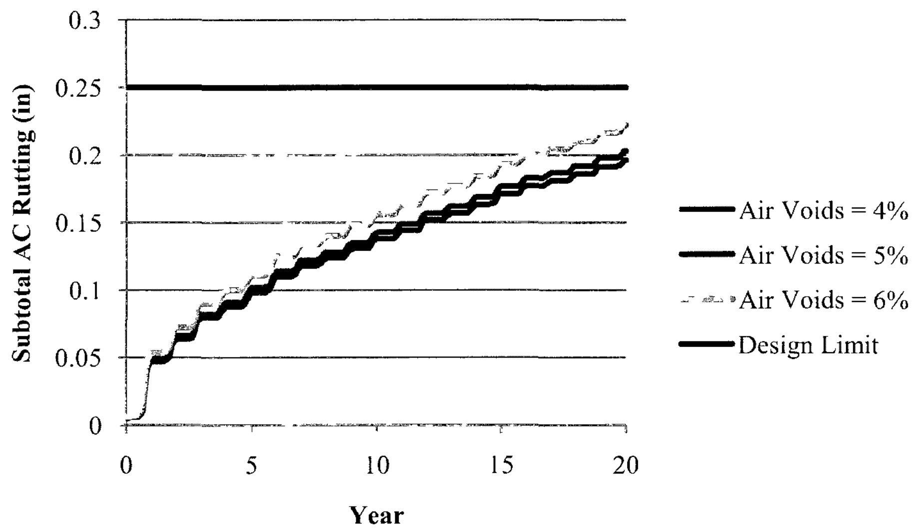


Figure 56C: Effect of Percent Air Voids on Subtotal AC Rutting

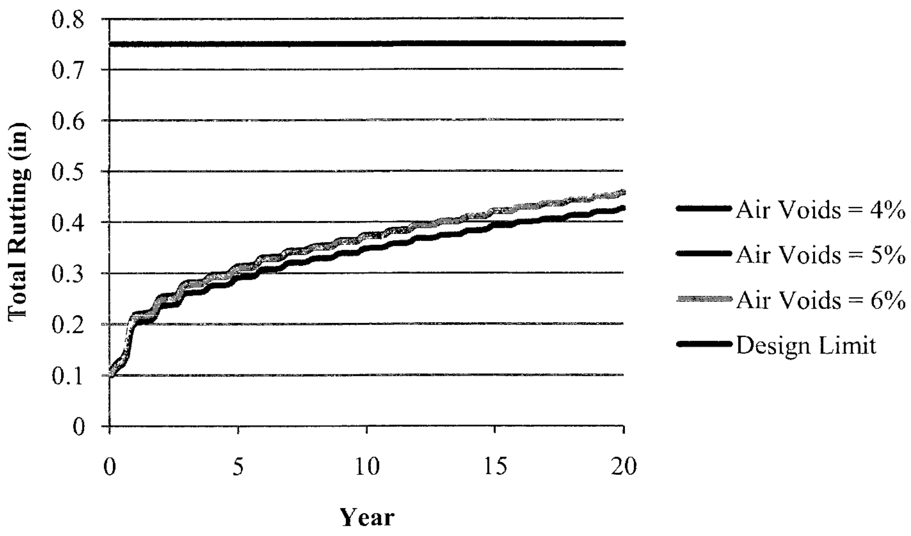


Figure 57C: Effect of Percent Air Voids on Total Rutting

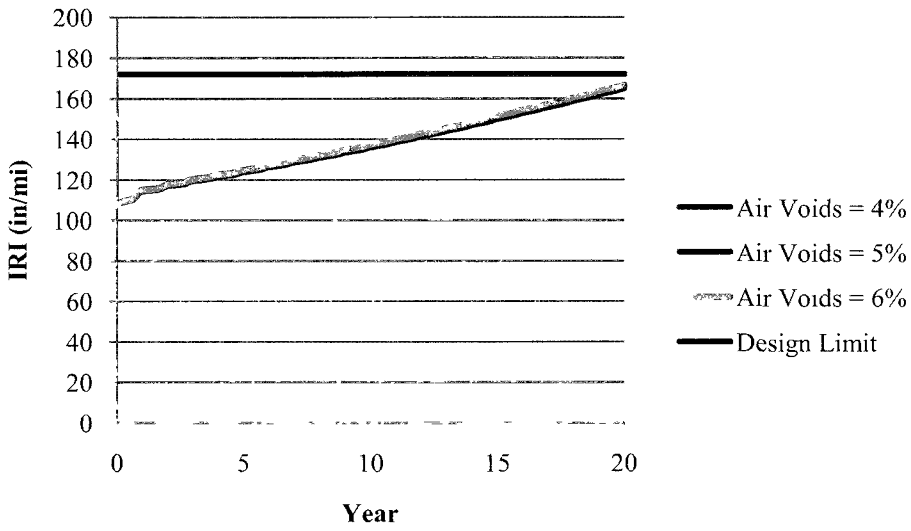


Figure 58C: Effect of Percent Air Voids on IRI

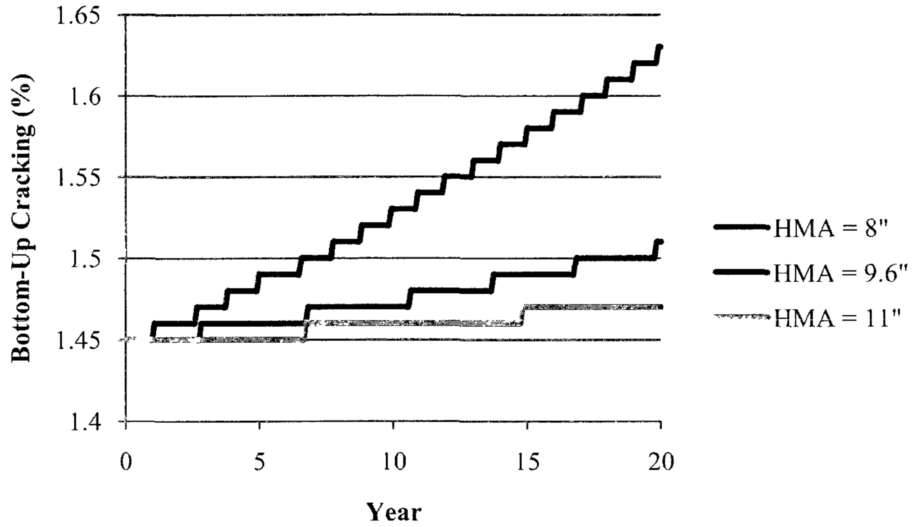


Figure 59C: Effect of AC Layer Thickness on Bottom-Up Cracking

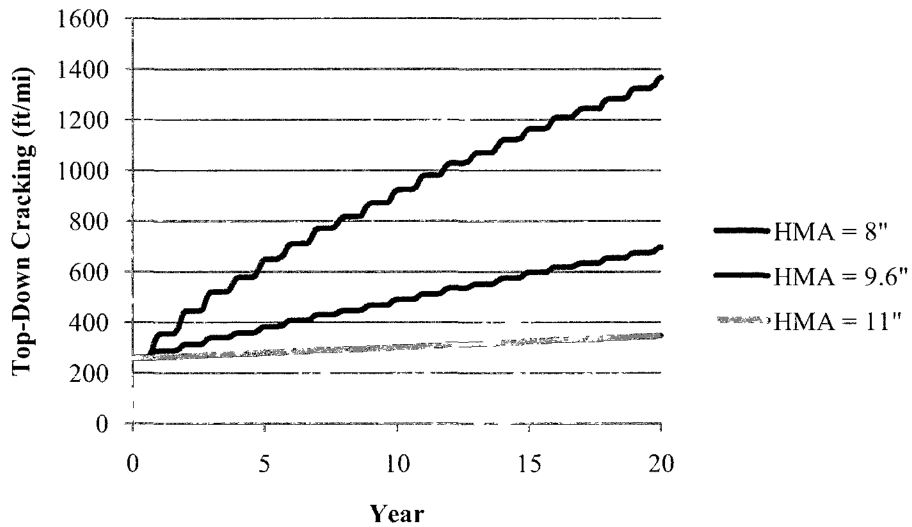


Figure 60C: Effect of AC Layer Thickness on Top-Down Cracking

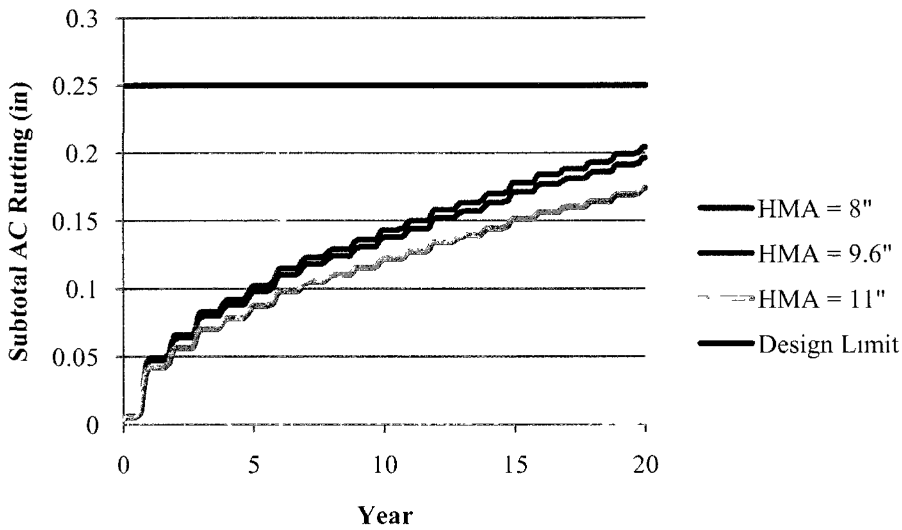


Figure 61C: Effect of AC Layer Thickness on Subtotal AC Rutting

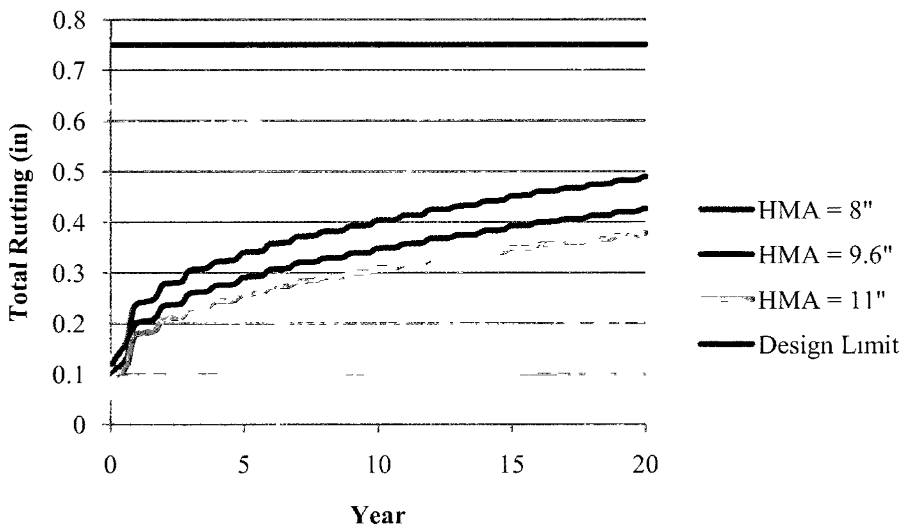


Figure 62C: Effect of AC Layer Thickness on Total Rutting

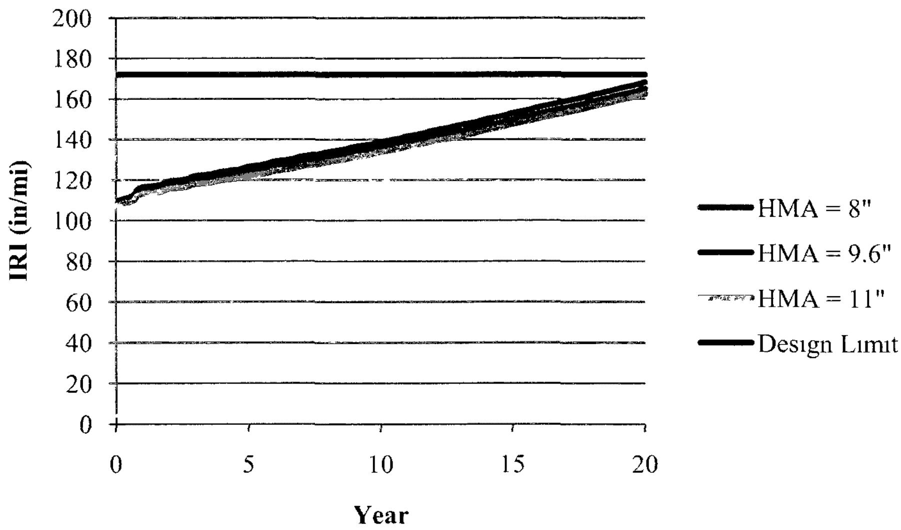


Figure 63C: Effect of AC Layer Thickness on IRI

7.4 Effect of Asphalt Concrete Mix Gradation

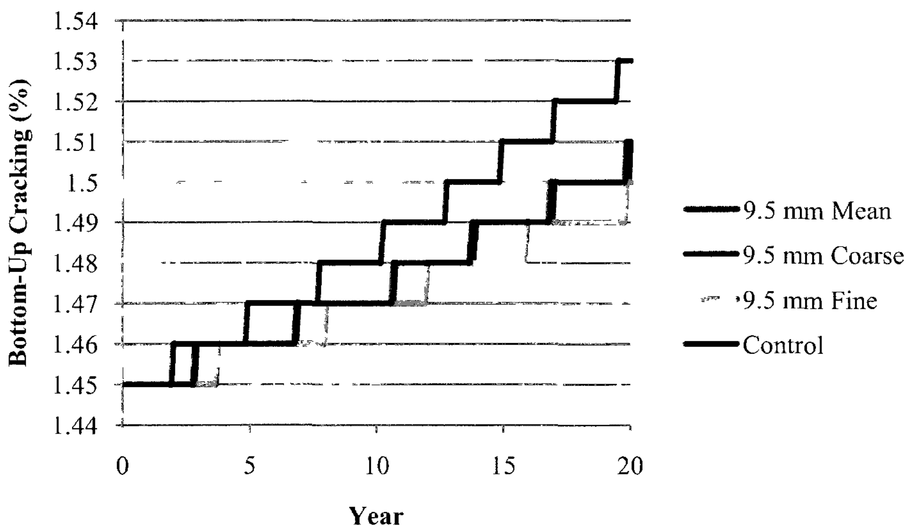


Figure 64C: Effect of Aggregate Gradation of 9.5 mm AC mix on Bottom-Up Cracking

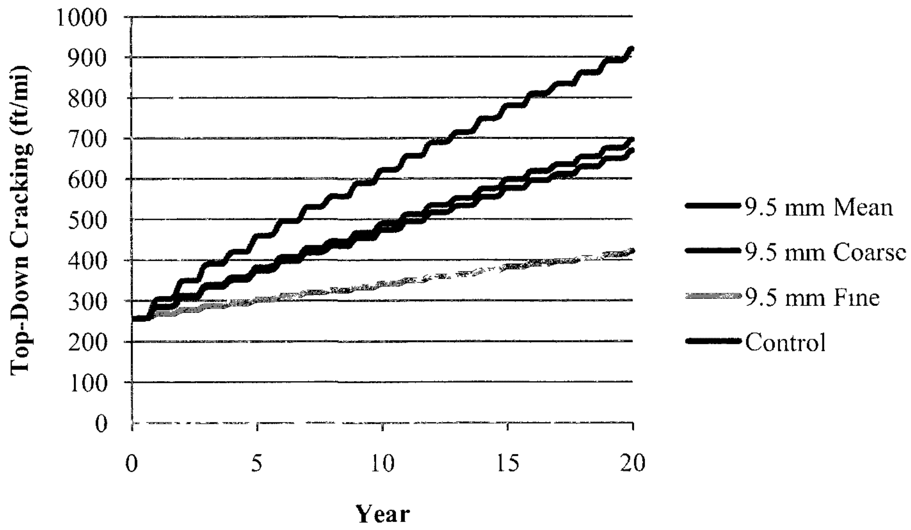


Figure 65C: Effect of Aggregate Gradation of 9.5 mm AC mix on Top-Down Cracking

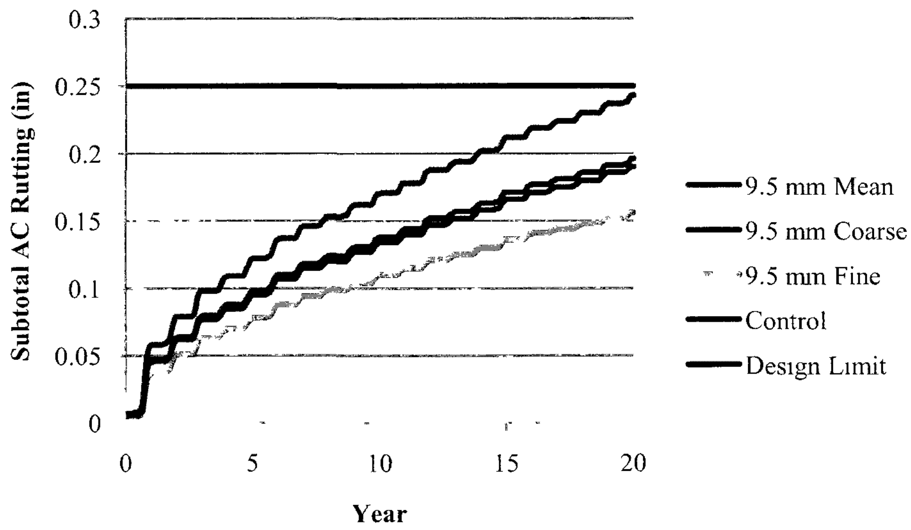


Figure 66C: Effect of Aggregate Gradation of 9.5 mm AC mix on Subtotal AC Rutting

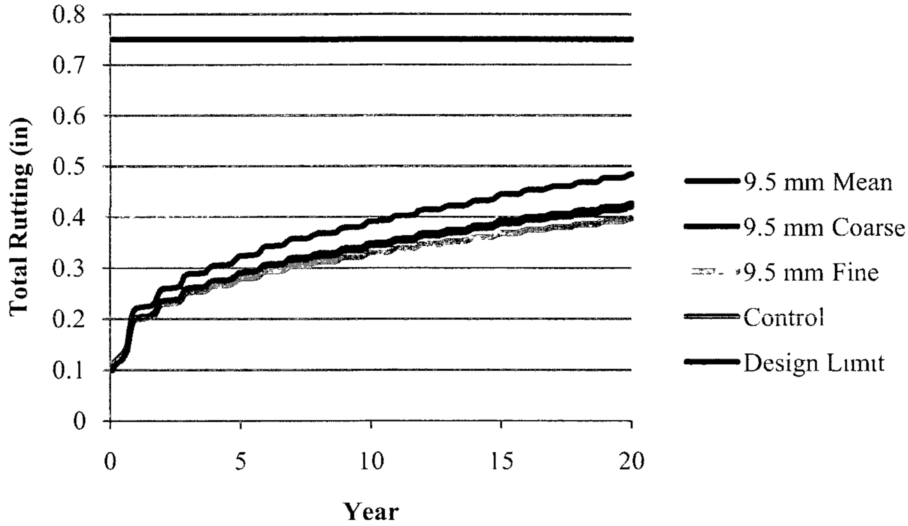


Figure 67C: Effect of Aggregate Gradation of 9.5 mm AC mix on Total Rutting

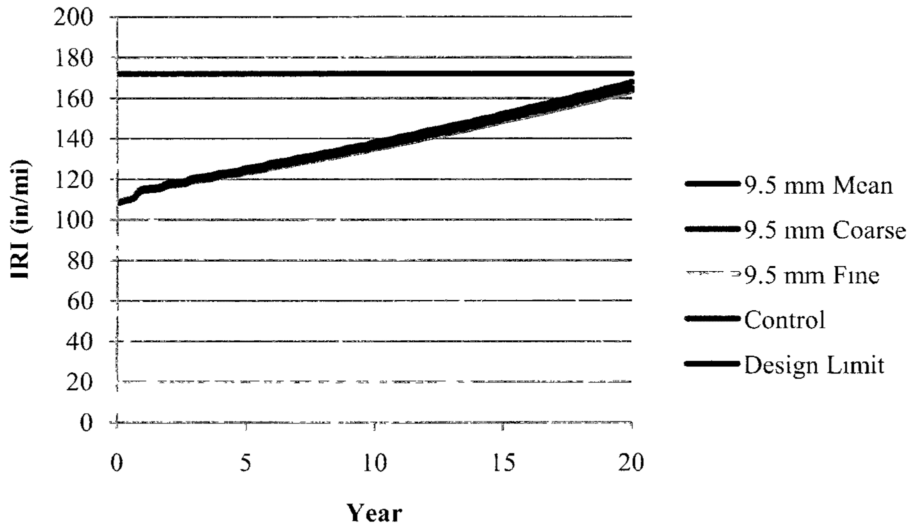


Figure 68C: Effect of Aggregate Gradation of 9.5 mm AC mix on IRI

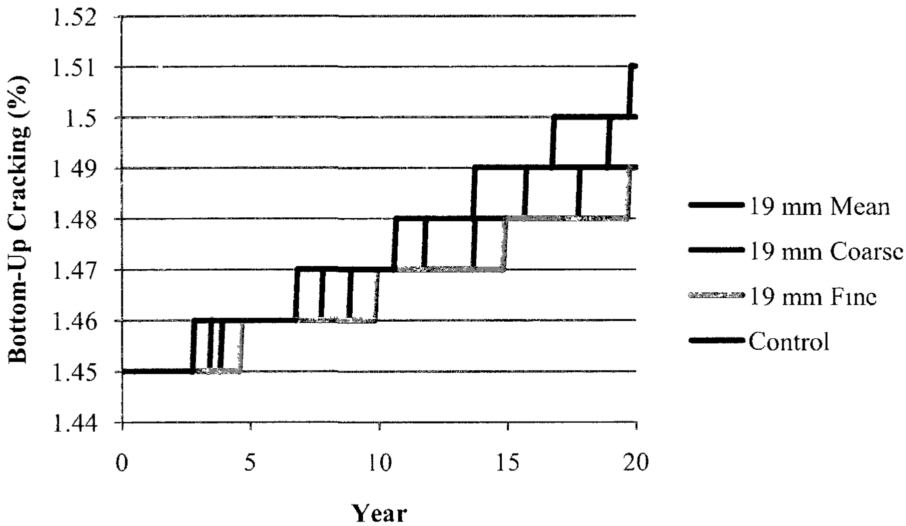


Figure 69C: Effect of Aggregate Gradation of 19.0 mm mix on Bottom-Up Cracking

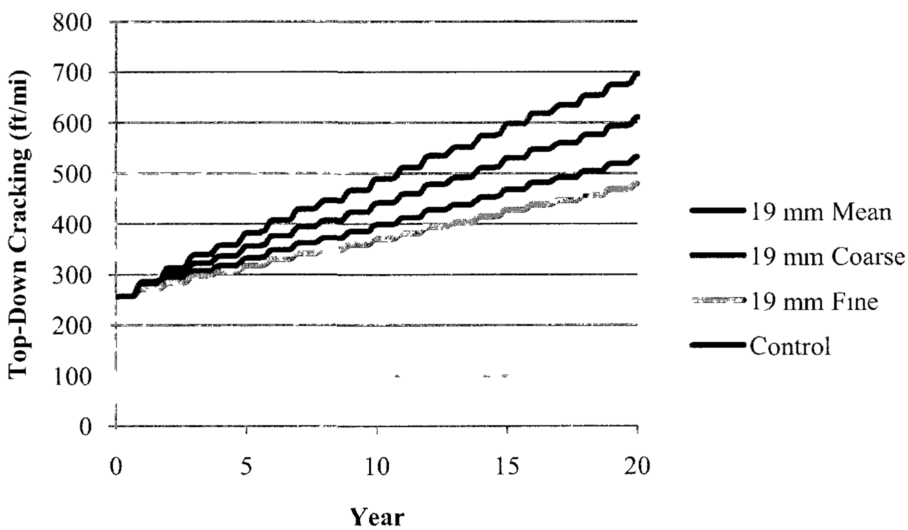


Figure 70C: Effect of Aggregate Gradation of 19.0 mm mix on Top-Down Cracking

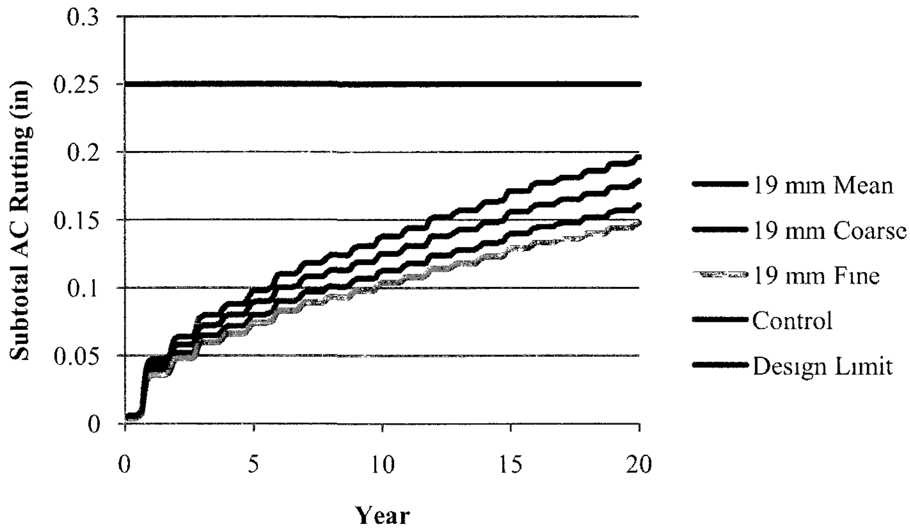


Figure 71C: Effect of Aggregate Gradation of 19.0 mm mix on Subtotal AC Rutting

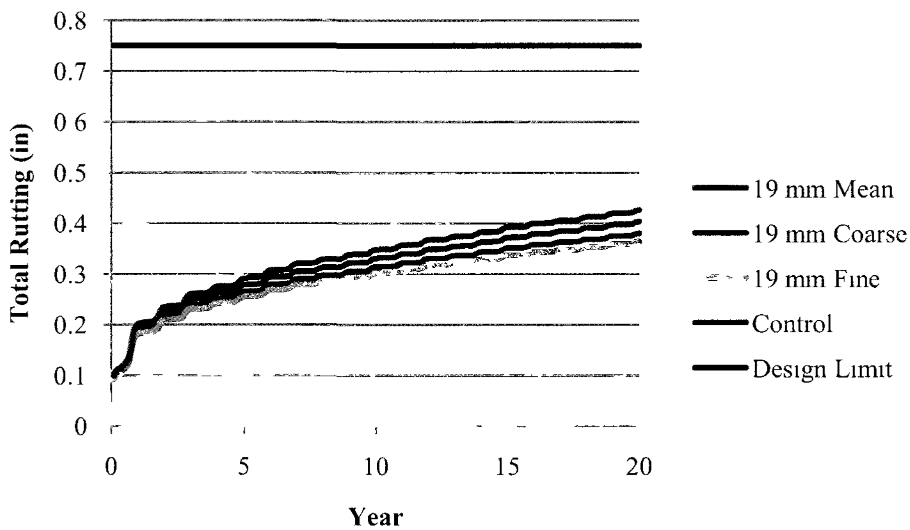


Figure 72C: Effect of Aggregate Gradation of 19.0 mm mix on Total Rutting

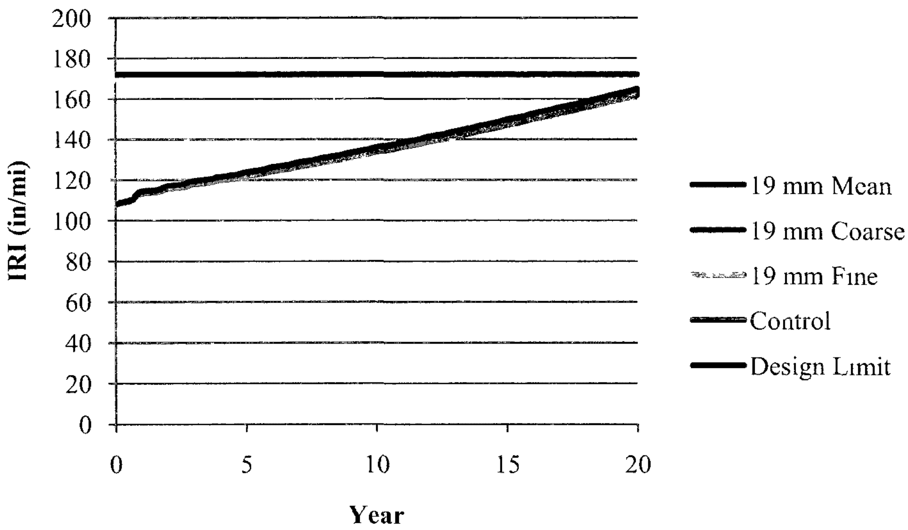


Figure 73C: Effect of Aggregate Gradation of 19.0 mm mix on IRI

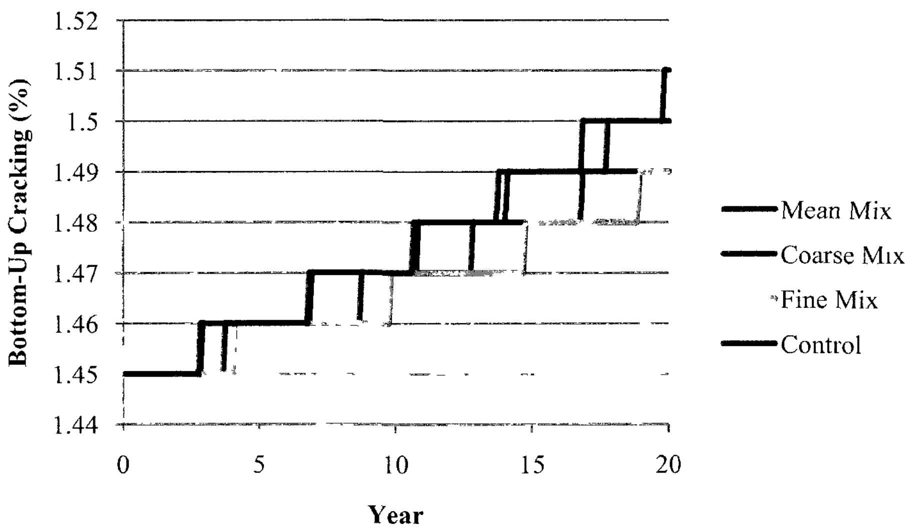


Figure 74C: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Bottom-Up Cracking

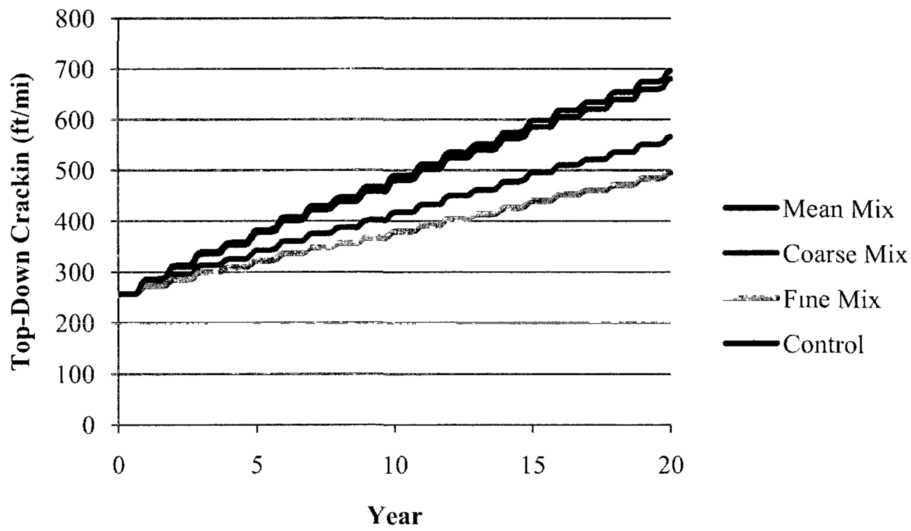


Figure 75C: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Top-Down Cracking

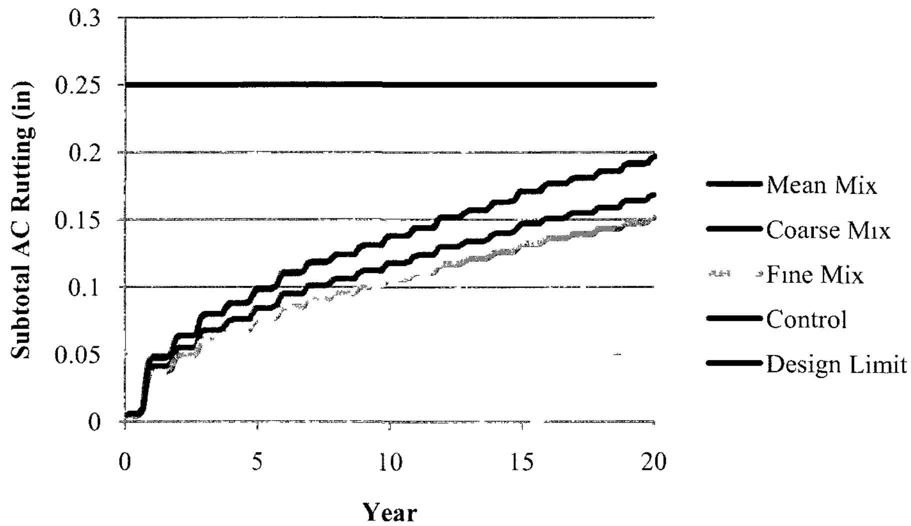


Figure 76C: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Subtotal AC Rutting

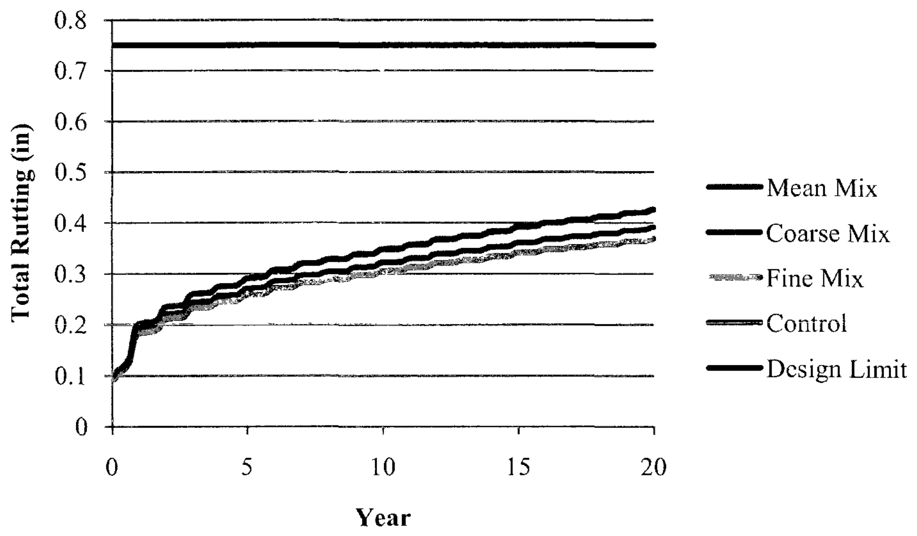


Figure 77C: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on Total Rutting

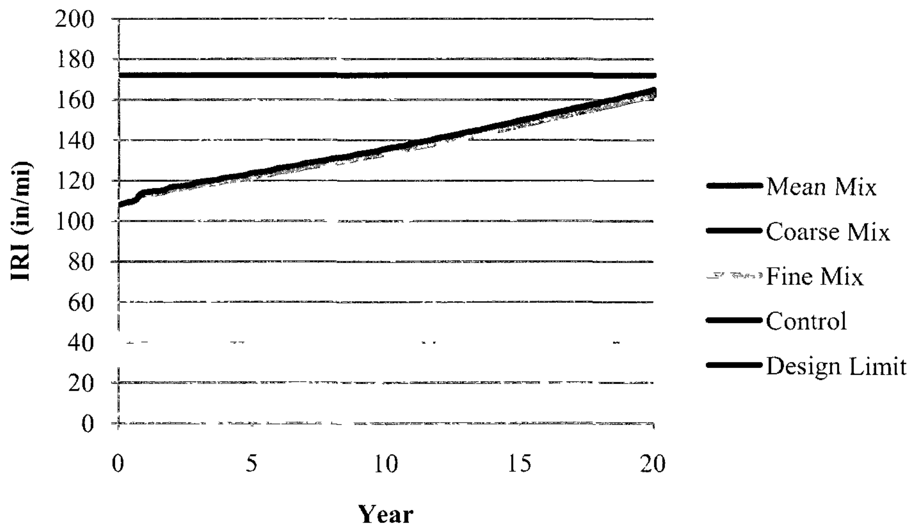


Figure 78C: Effect of Aggregate Gradation of 9.5 mm & 19.0 mm mix on IRI

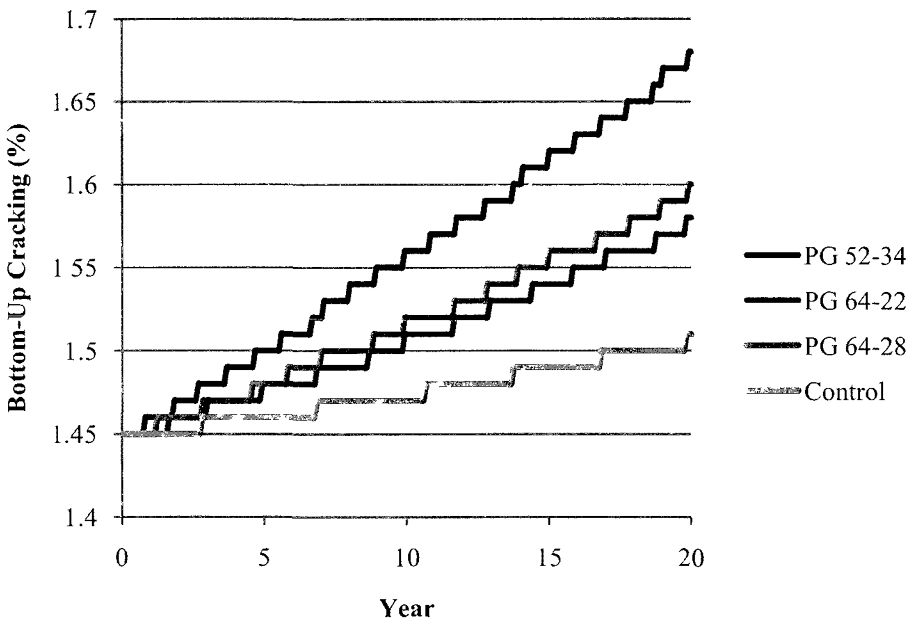


Figure 79C: Effect of Binder Grade on Bottom-Up Cracking at Speed 5 mph

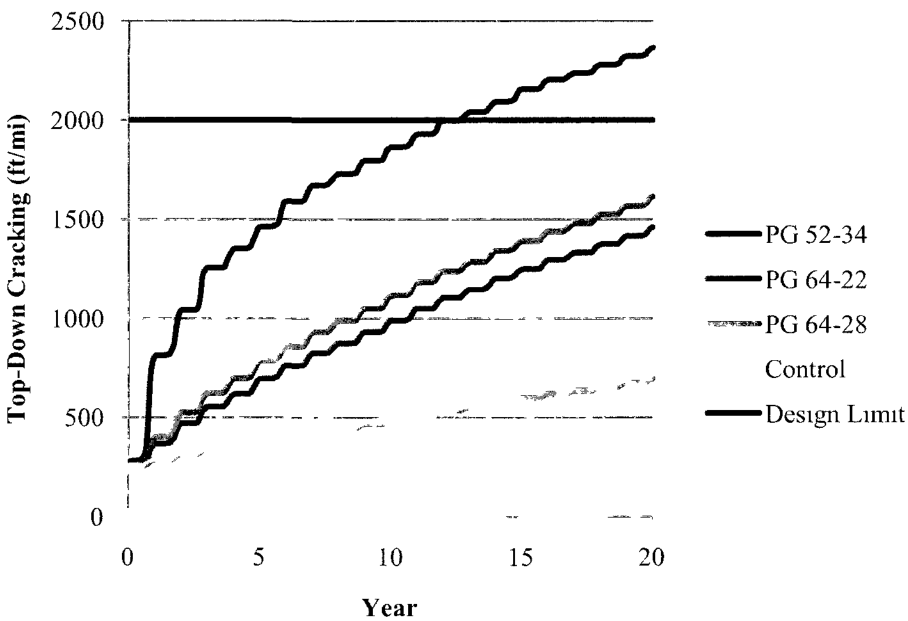


Figure 80C: Effect of Binder Grade on Top-Down Cracking at Speed 5 mph

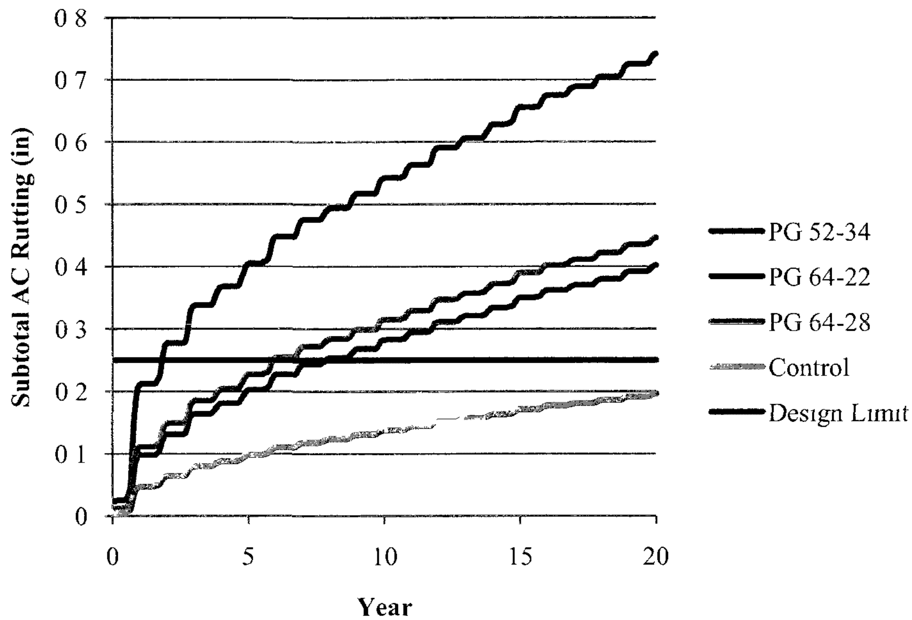


Figure 81C: Effect of Binder Grade on Subtotal AC Rutting at Speed 5 mph

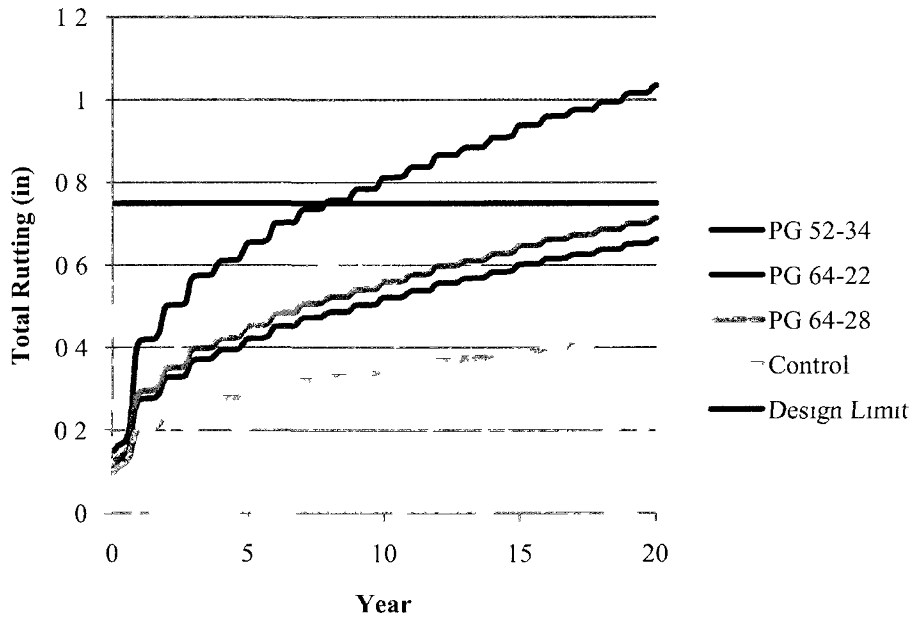


Figure 82C: Effect of Binder Grade on Total Rutting at Speed 5 mph

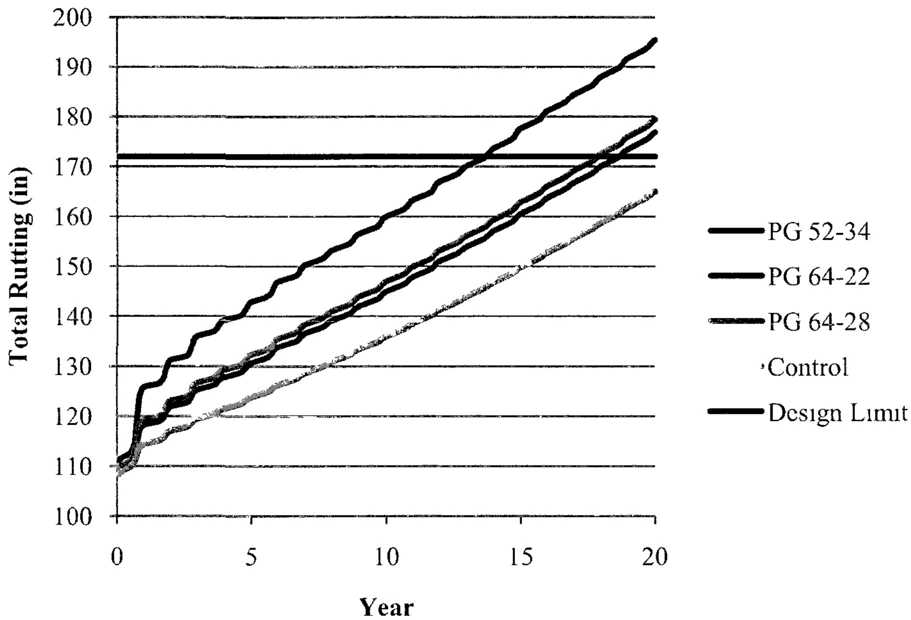


Figure 83C: Effect of Binder Grade on IRI at Speed 5 mph

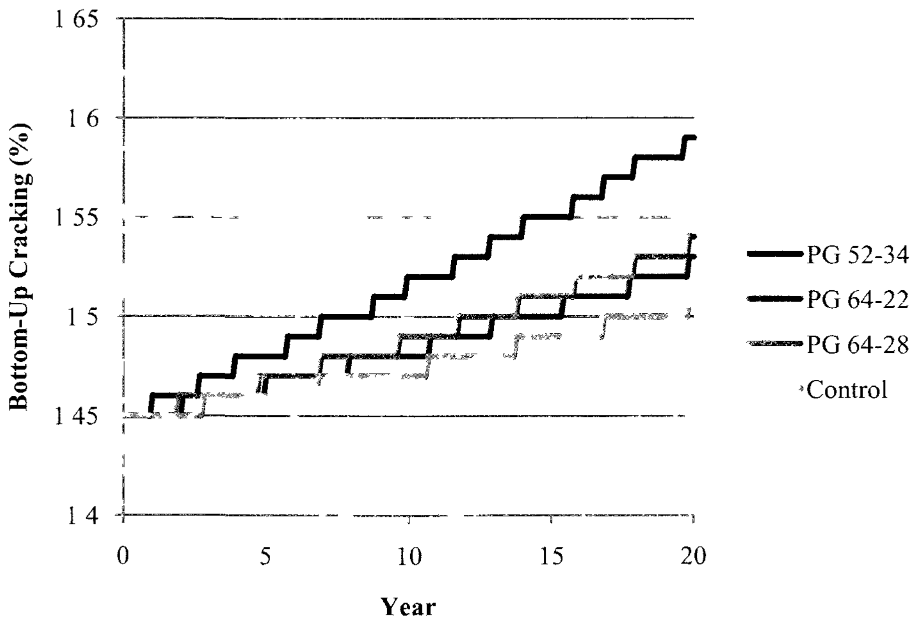


Figure 84C: Effect of Binder Grade on Bottom-Up Cracking at Speed 25 mph

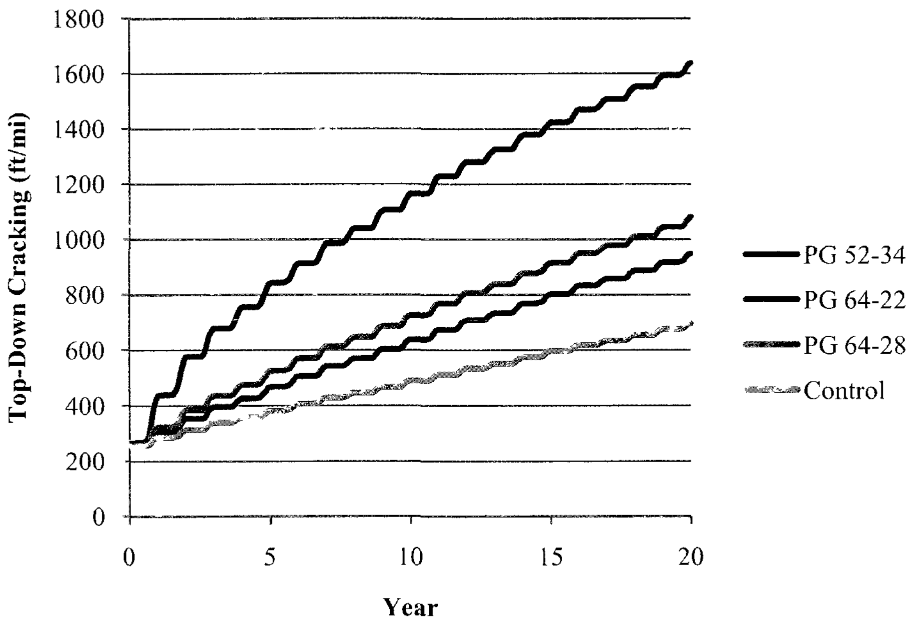


Figure 85C: Effect of Binder Grade on Top-Down Cracking at Speed 25 mph

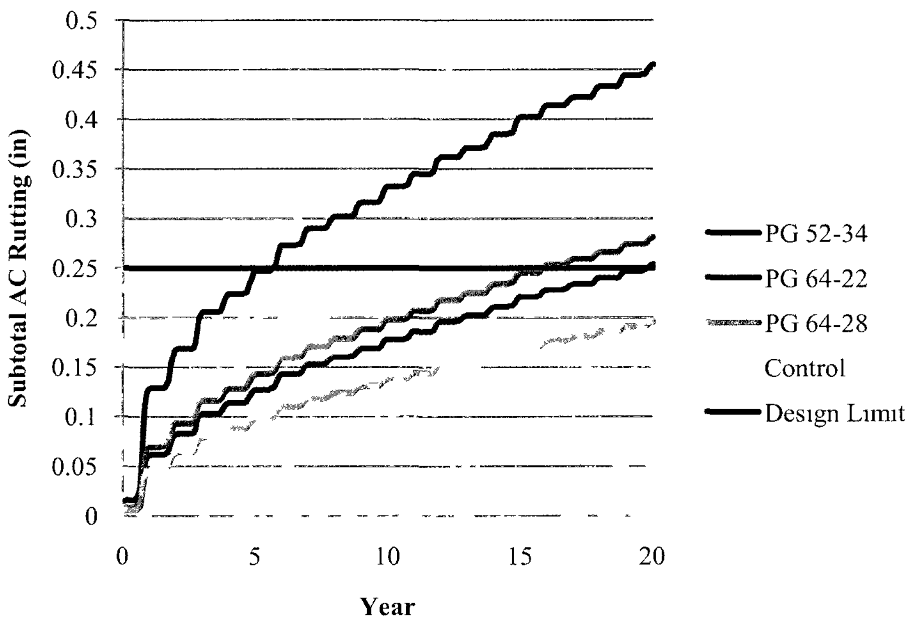


Figure 86C: Effect of Binder Grade on Subtotal AC Rutting at Speed 25 mph

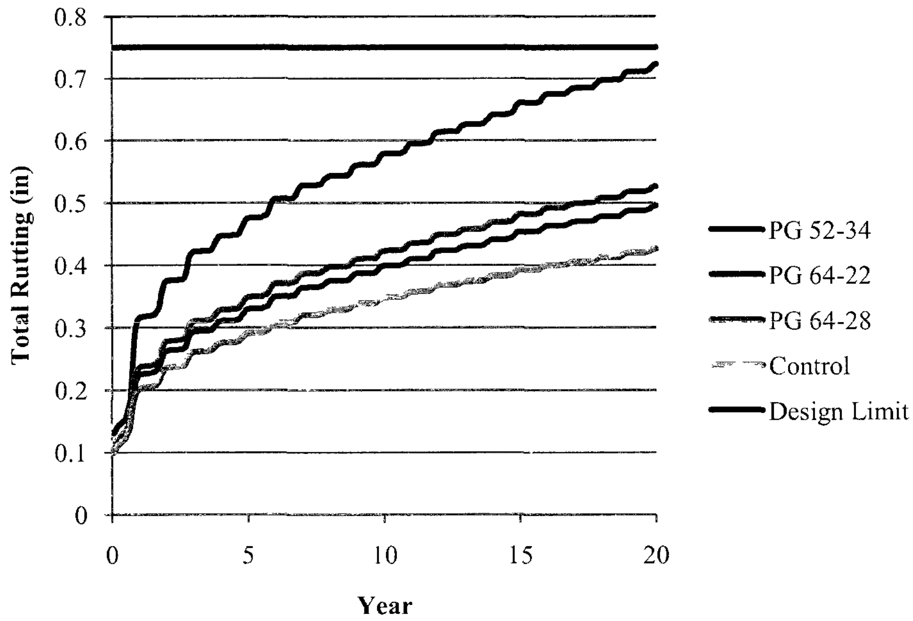


Figure 87C: Effect of Binder Grade on Total Rutting at Speed 25 mph

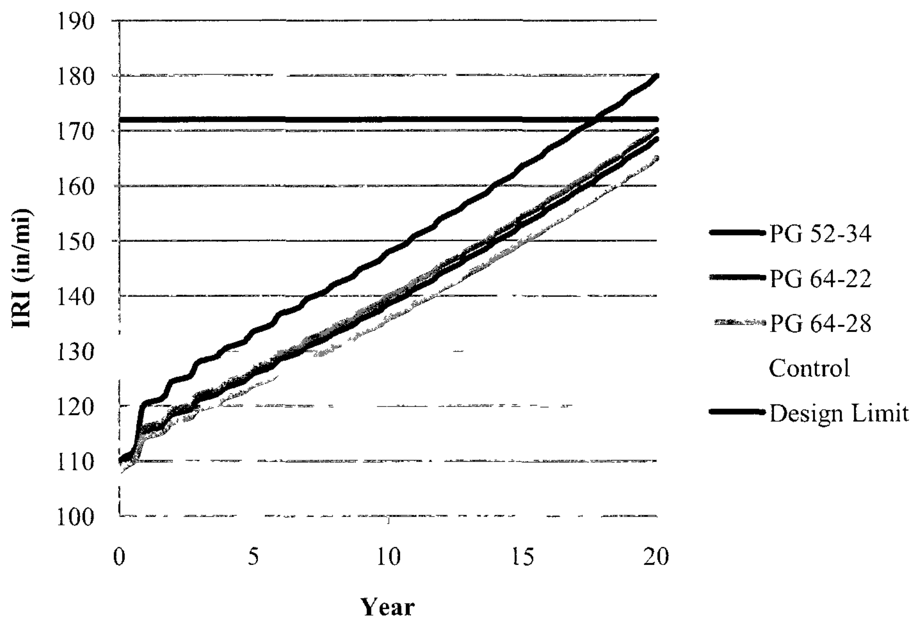


Figure 88C: Effect of Binder Grade on IRI at Speed 25 mph

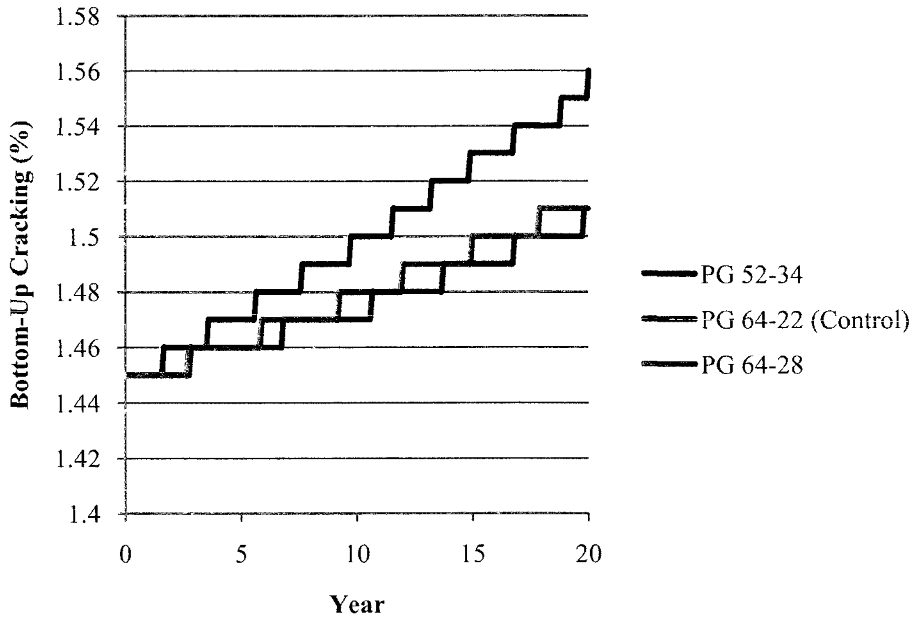


Figure 89C: Effect of Binder Grade on Bottom-Up Cracking at Speed 65 mph

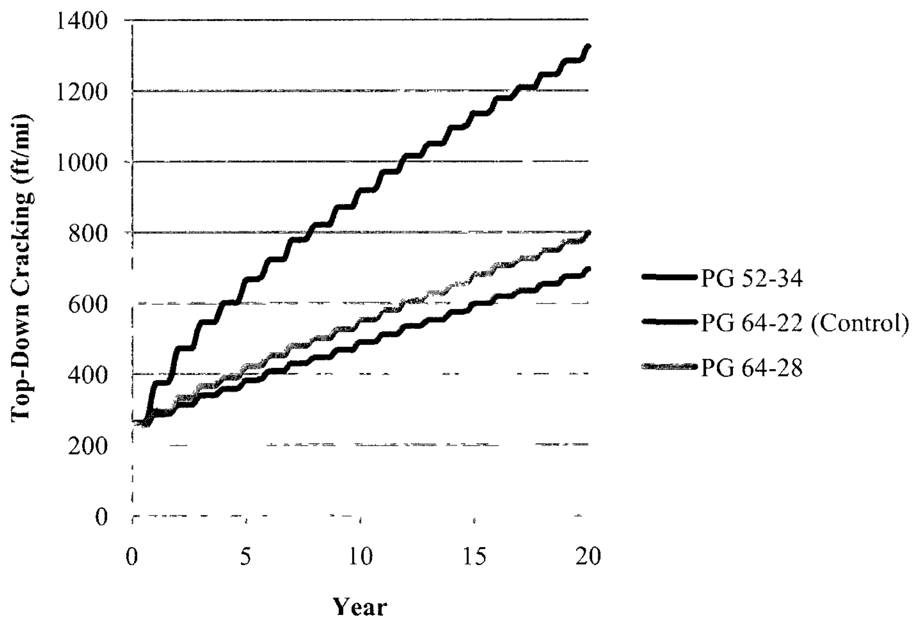


Figure 90C: Effect of Binder Grade on Top-Down Cracking at Speed 65 mph

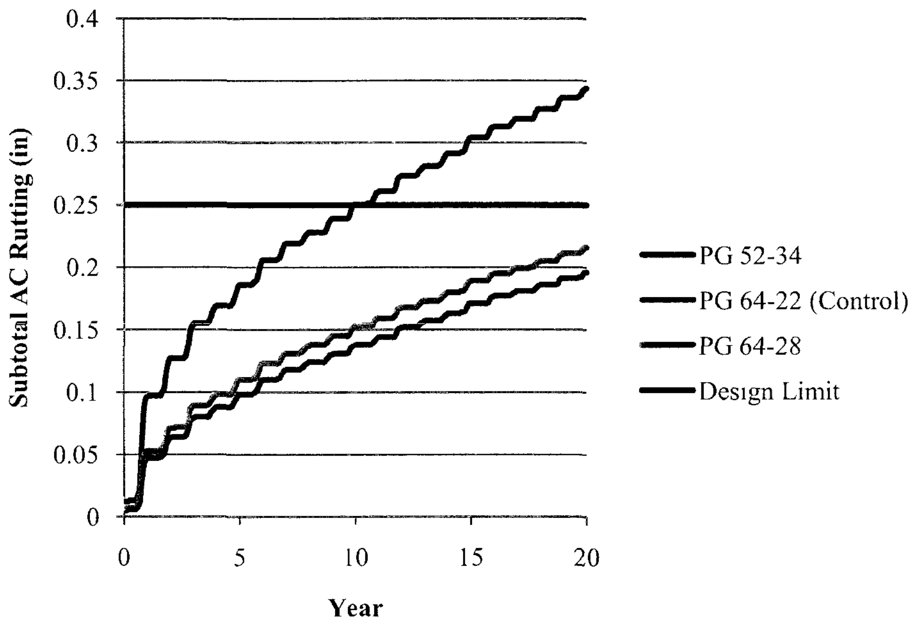


Figure 91C: Effect of Binder Grade on Subtotal AC Rutting at Speed 65 mph

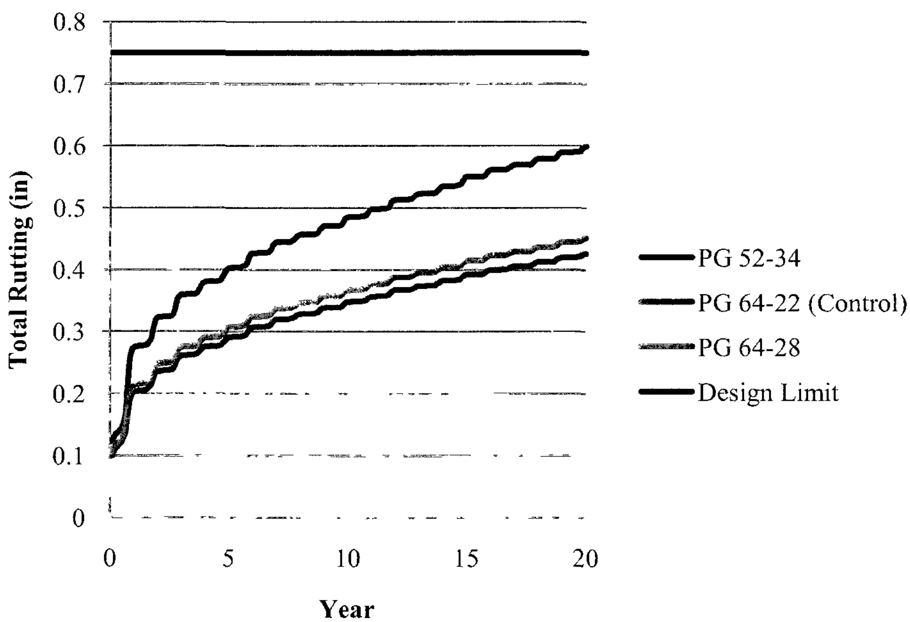


Figure 92C: Effect of Binder Grade on Total Rutting at Speed 65 mph

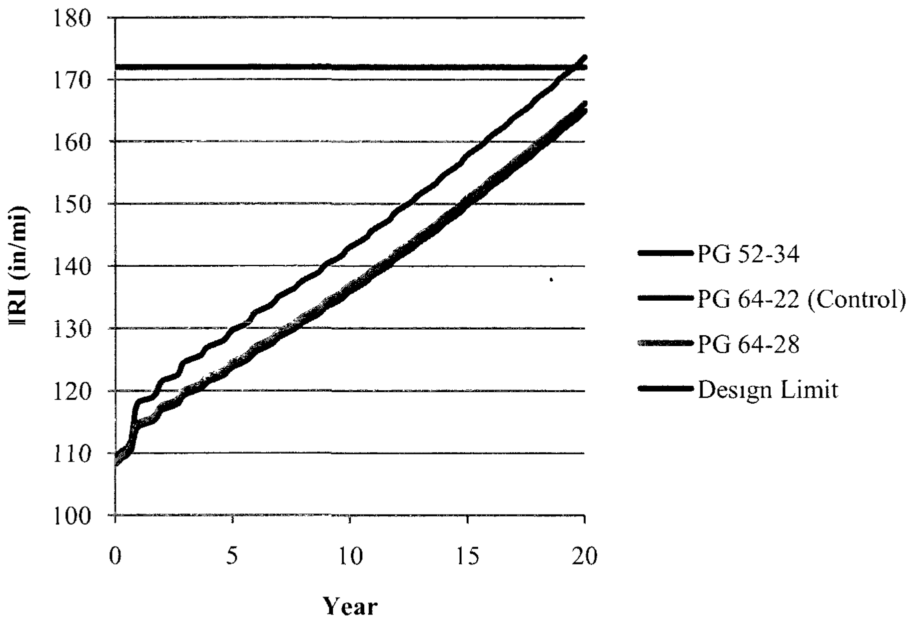


Figure 93C: Effect of Binder Grade on IRI at Speed 65 mph

7.5 Effect of Base Subbase Inputs on Pavement Distresses

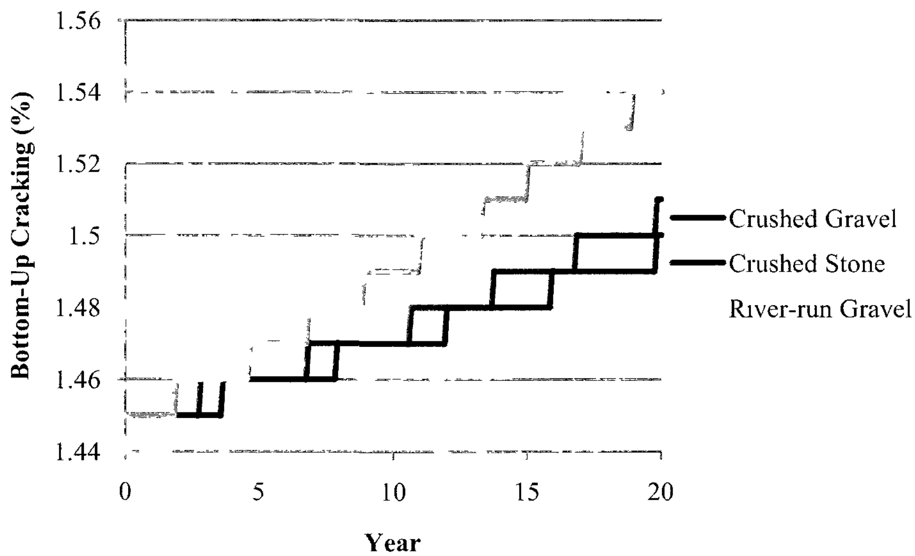


Figure 94C: Effect of Base Course Material on Bottom-Up Cracking

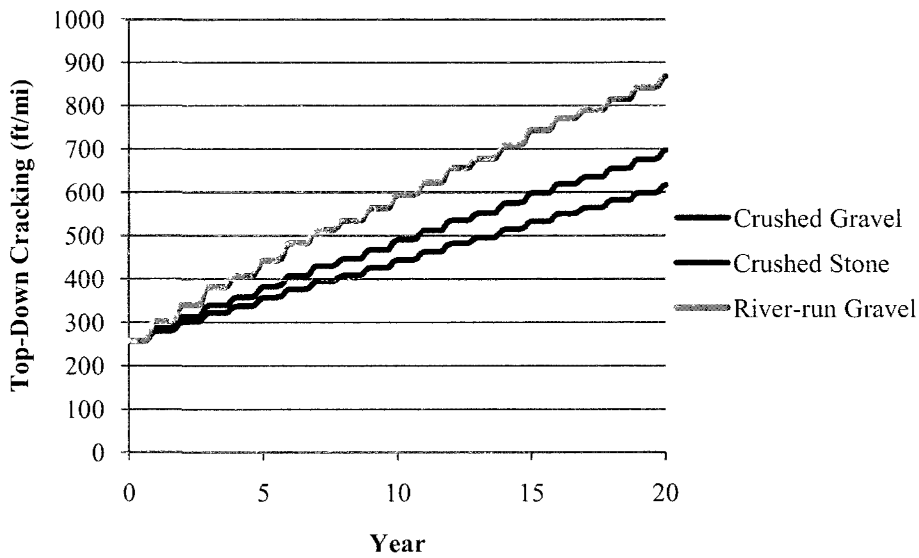


Figure 95C: Effect of Base Course Material on Top-Down Cracking

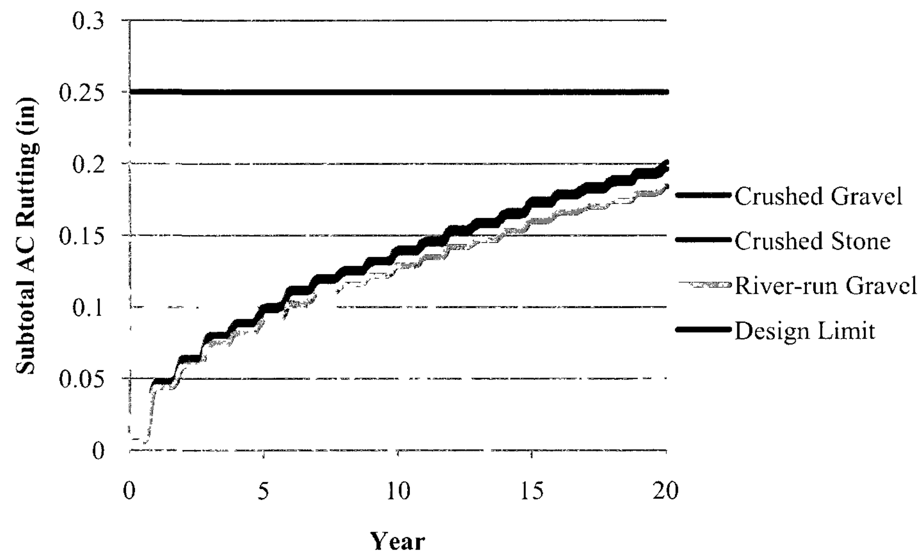


Figure 96C: Effect of Base Course Material on Subtotal AC Rutting

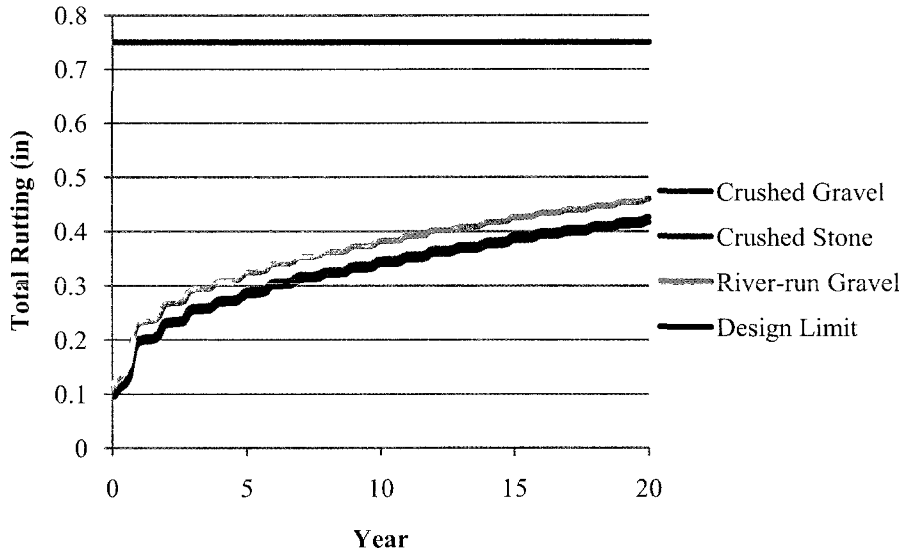


Figure 97C: Effect of Base Course Material on Total Rutting

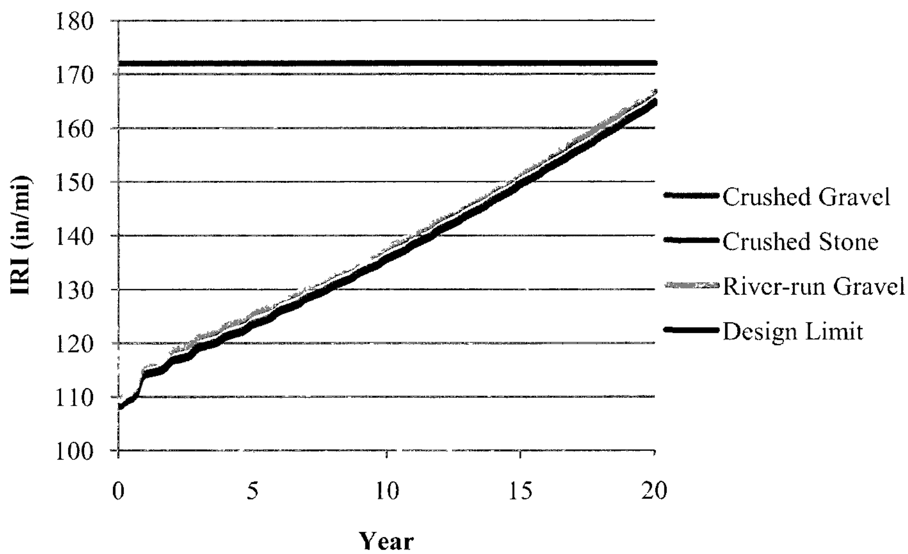


Figure 98C: Effect of Base Course Material on IRI

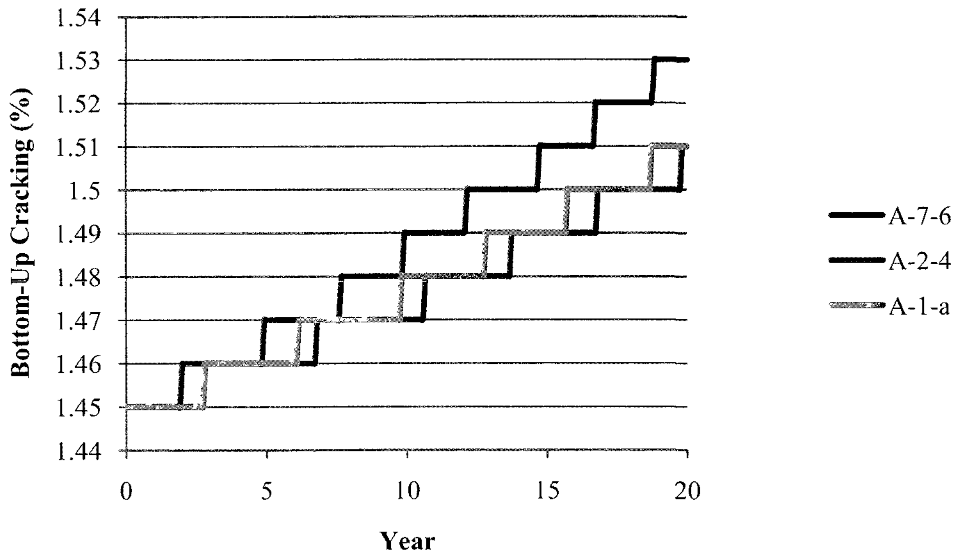


Figure 99C: Effect of Subgrade Type on Bottom-Up Cracking

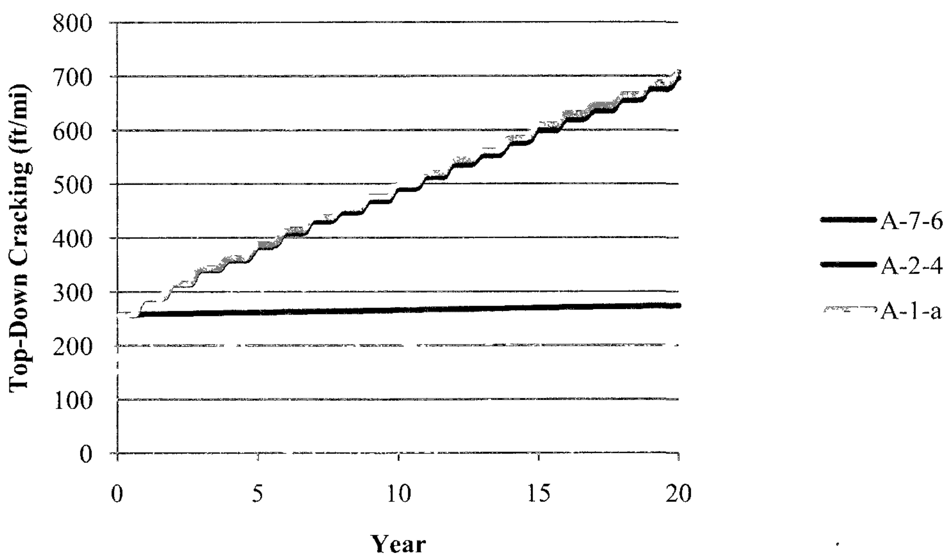


Figure 100C: Effect of Subgrade Type on Top-Down Cracking

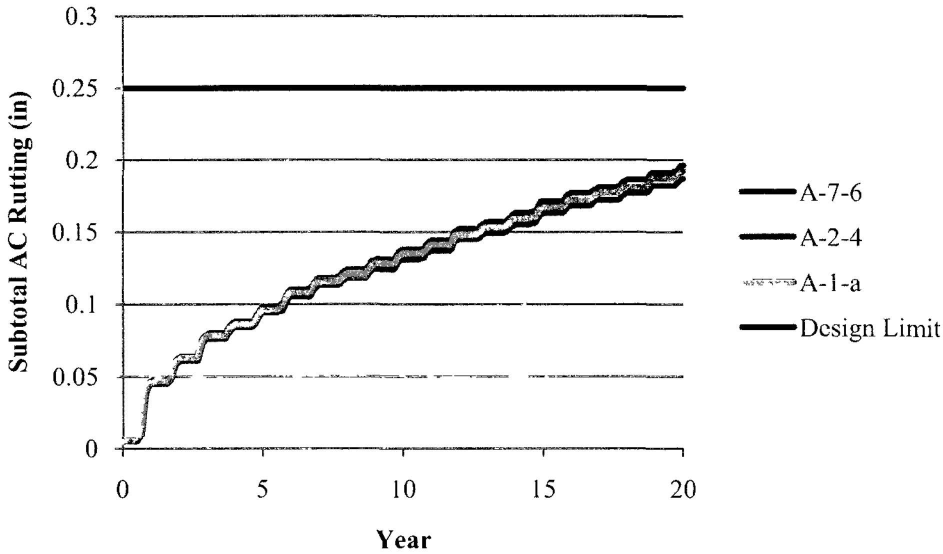


Figure 101C: Effect of Subgrade Type on Subtotal AC Rutting

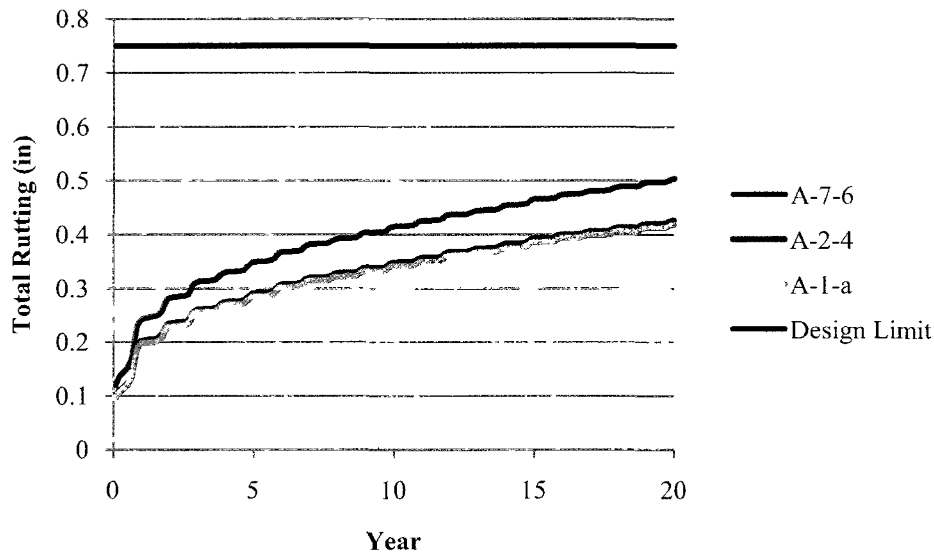


Figure 102C: Effect of Subgrade Type on Total Rutting

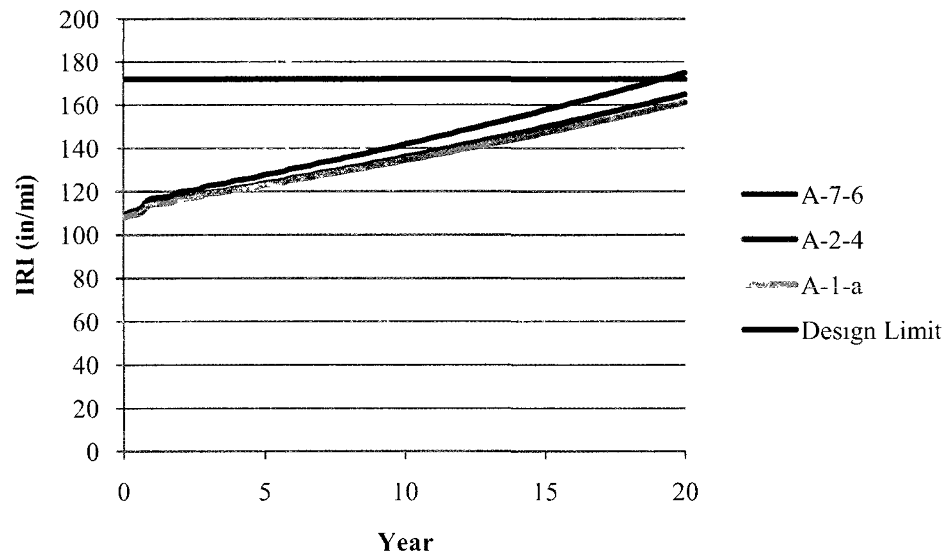


Figure 103C: Effect of Subgrade Type on IRI

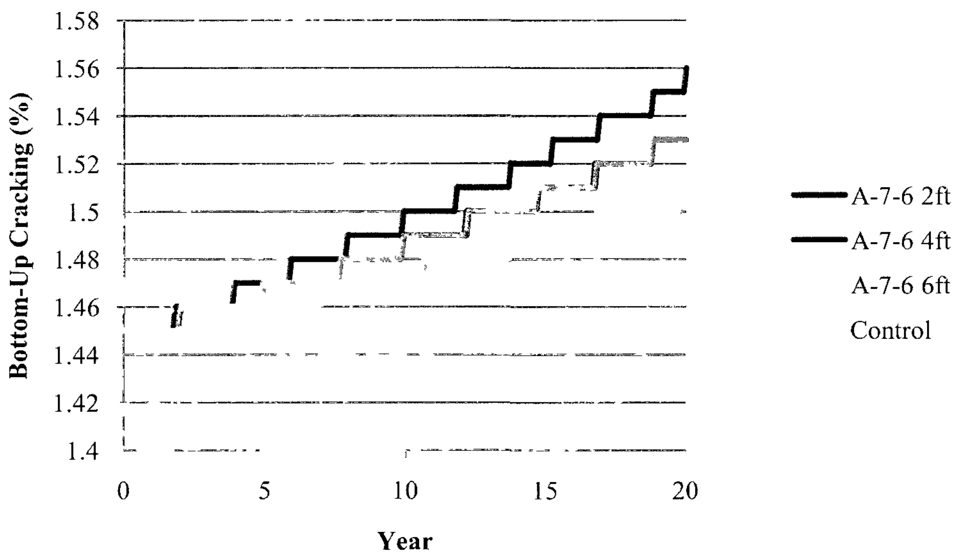


Figure 104C: Effect of Water Table on Bottom-Up Cracking with Weakest Subgrade

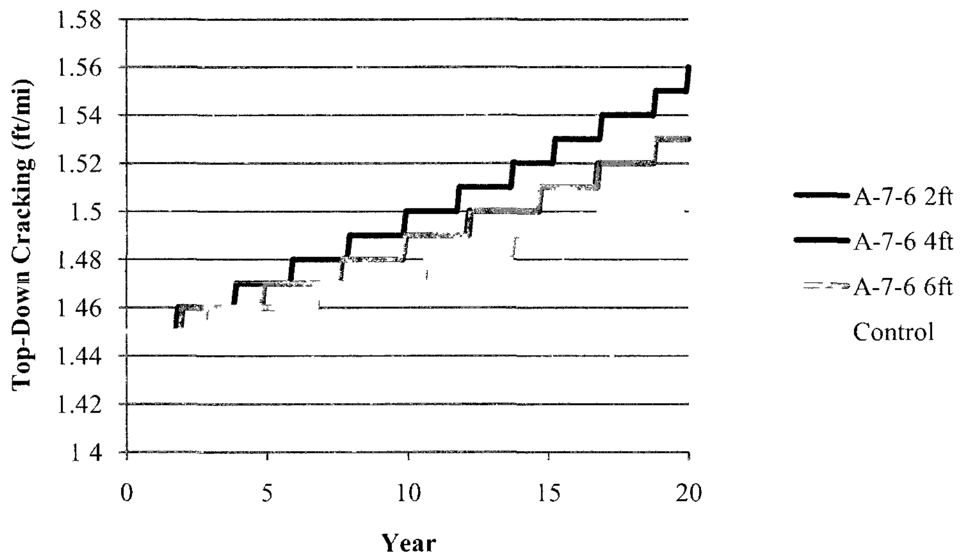


Figure 105C: Effect of Water Table on Top-Down Cracking with Weakest Subgrade

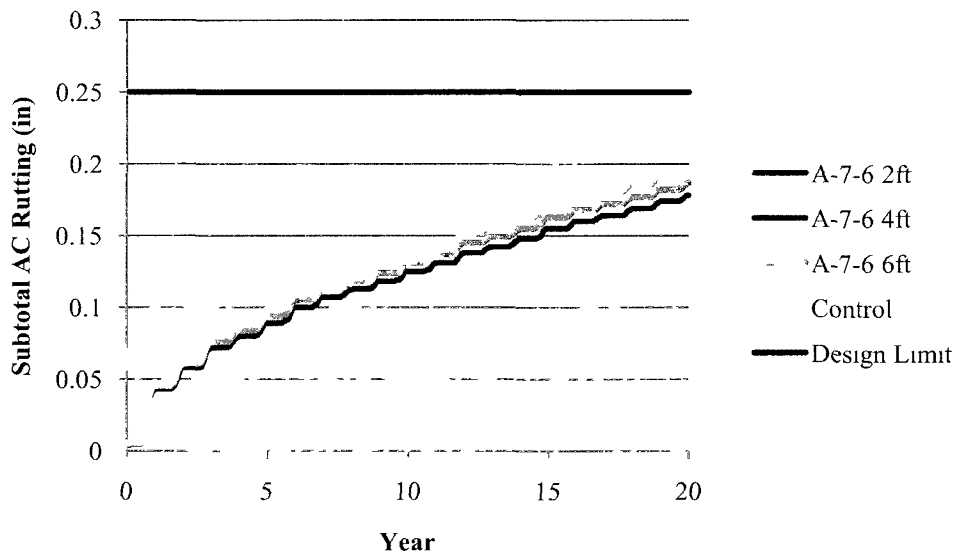


Figure 106C: Effect of Water Table on Subtotal AC Rutting with Weakest Subgrade

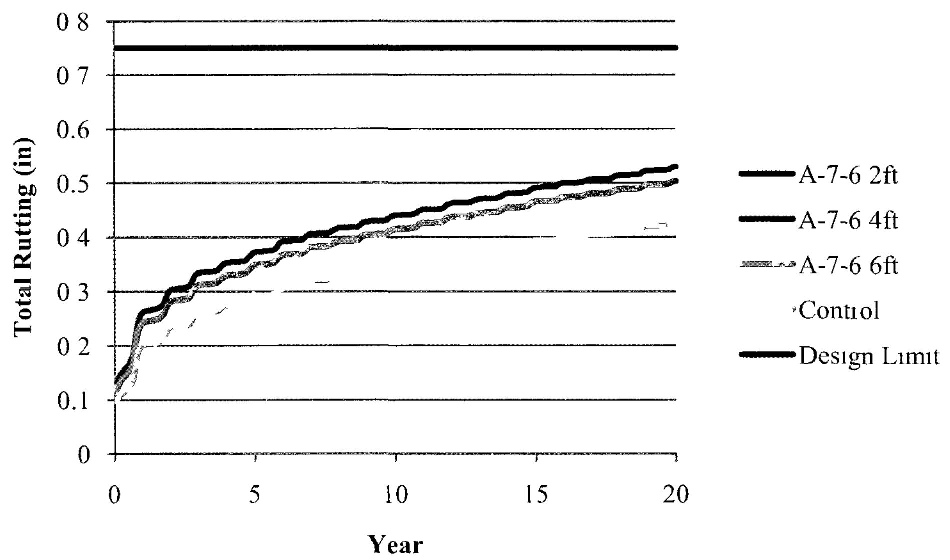


Figure 107C: Effect of Water Table on Total Rutting with Weakest Subgrade

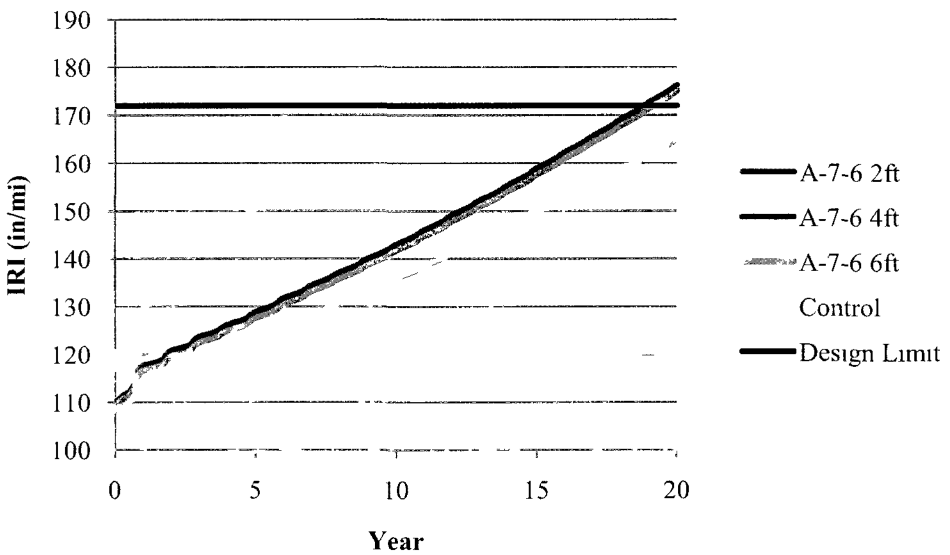


Figure 108C: Effect of Water Table on IRI with Weakest Subgrade

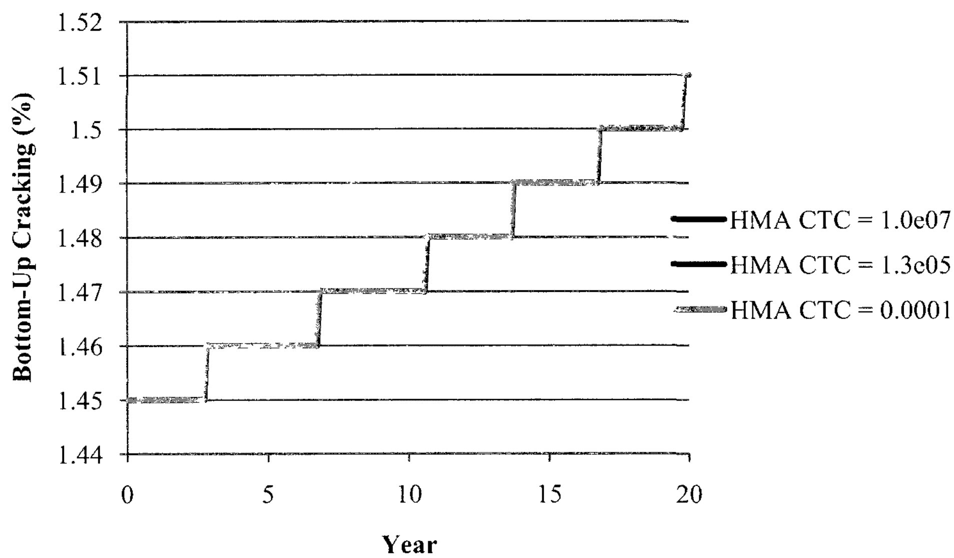


Figure 109C: Effect of HMA CTC on Bottom-Up Cracking

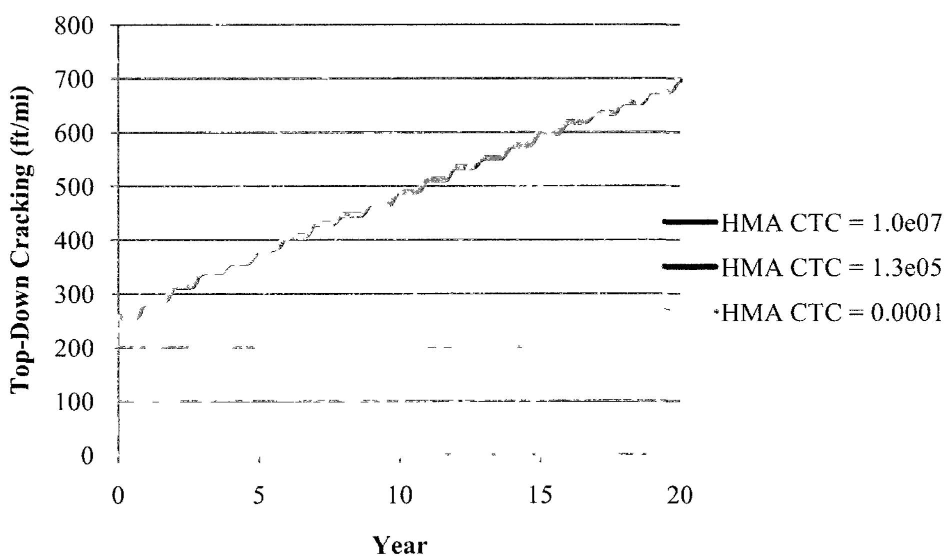


Figure 110C: Effect of HMA CTC on Top-Down Cracking

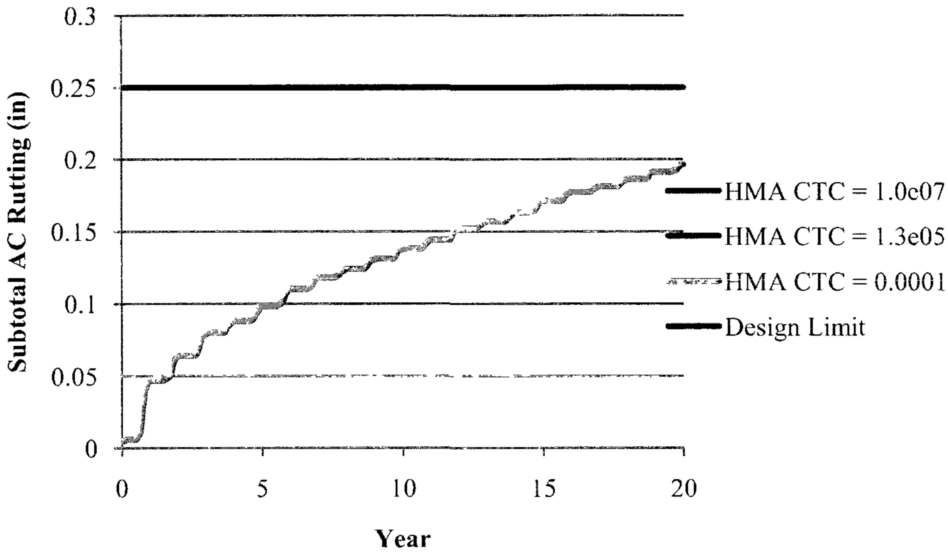


Figure 111C: Effect of HMA CTC on Subtotal AC Rutting

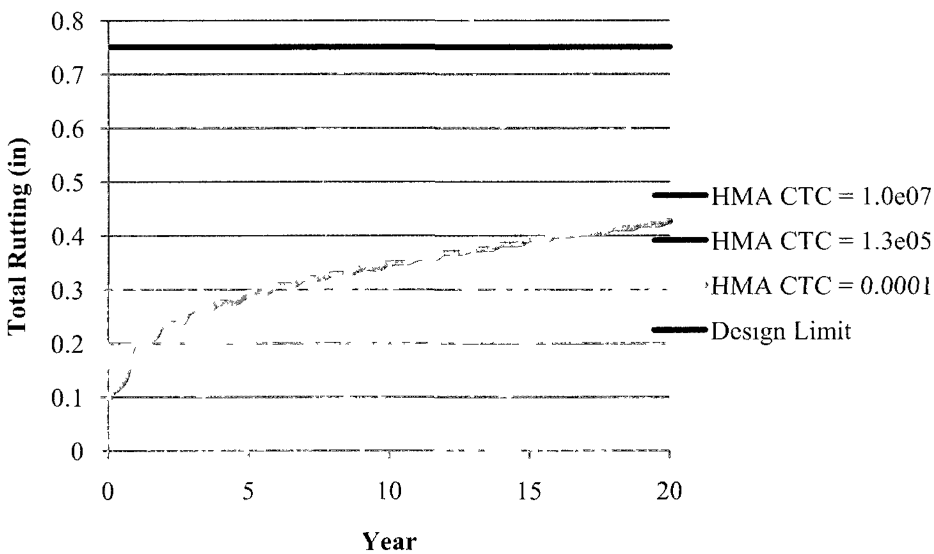


Figure 112C: Effect of HMA CTC on Total AC Rutting

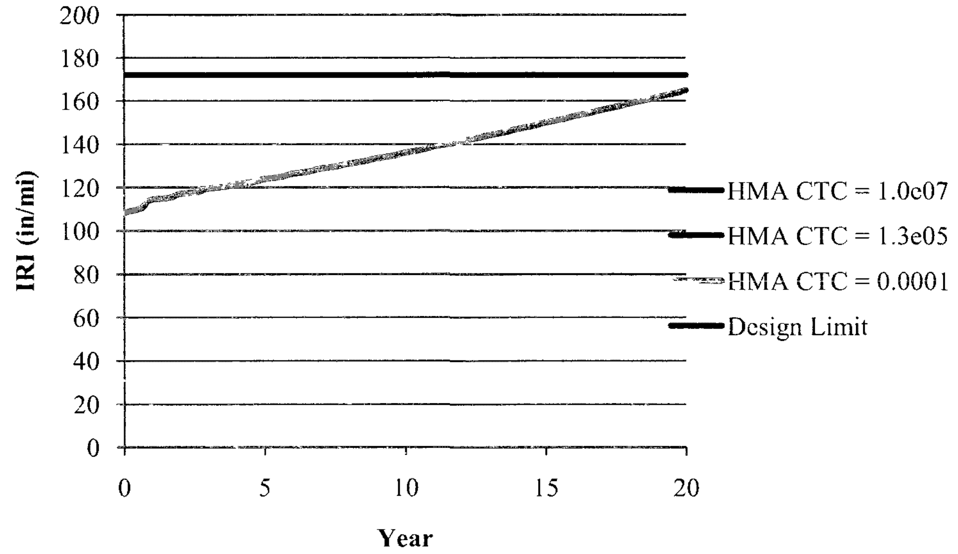


Figure 113C: Effect of HMA CTC on IRI

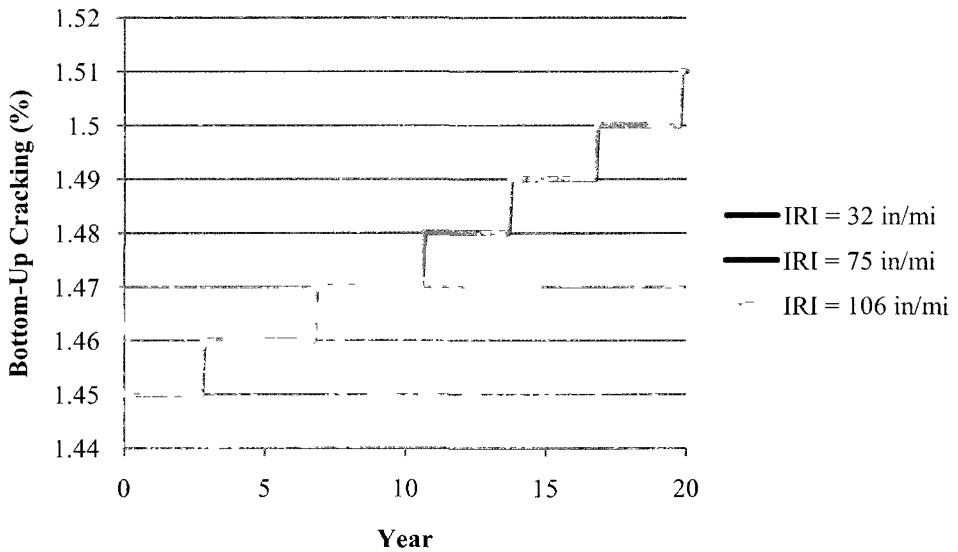


Figure 114C: Effect of Initial IRI on Bottom-Up Cracking

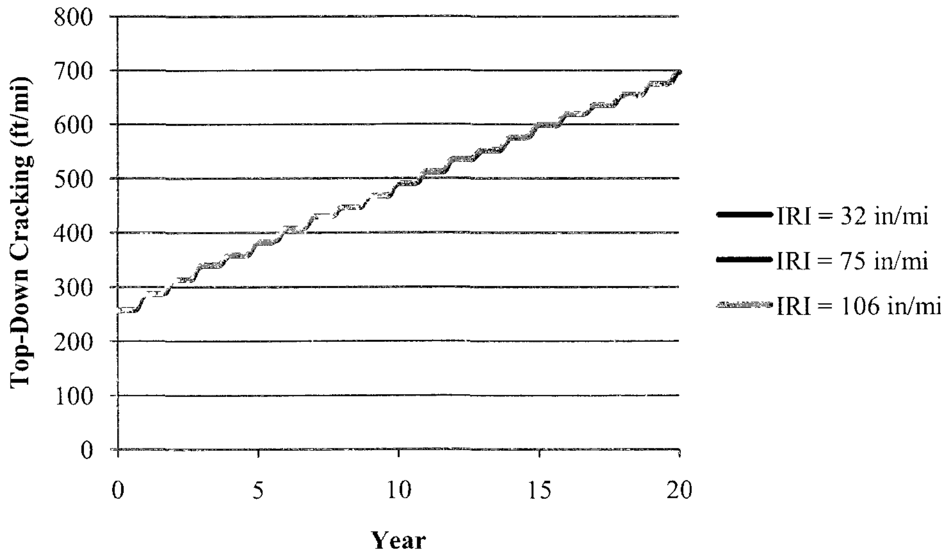


Figure 115C: Effect of Initial IRI on Top-Down Cracking

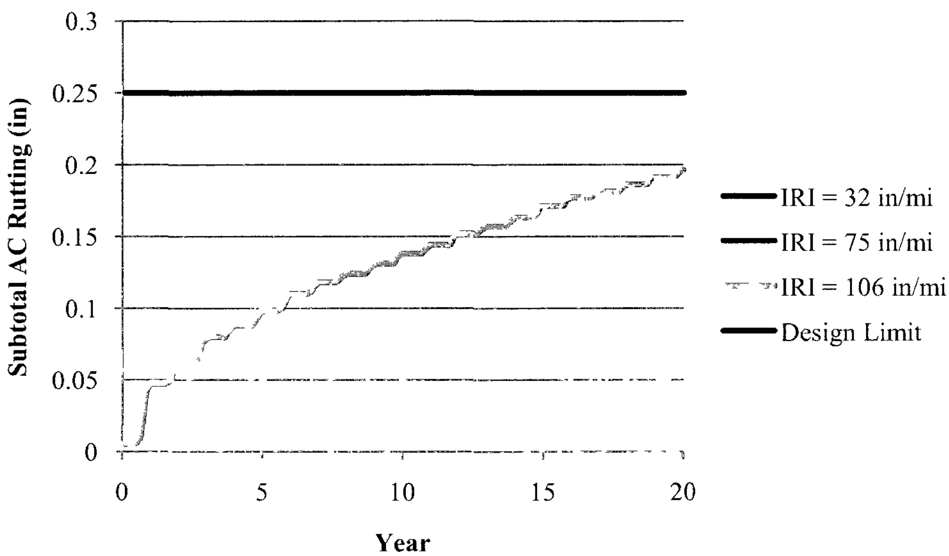


Figure 116C: Effect of Initial IRI on Subtotal AC Rutting

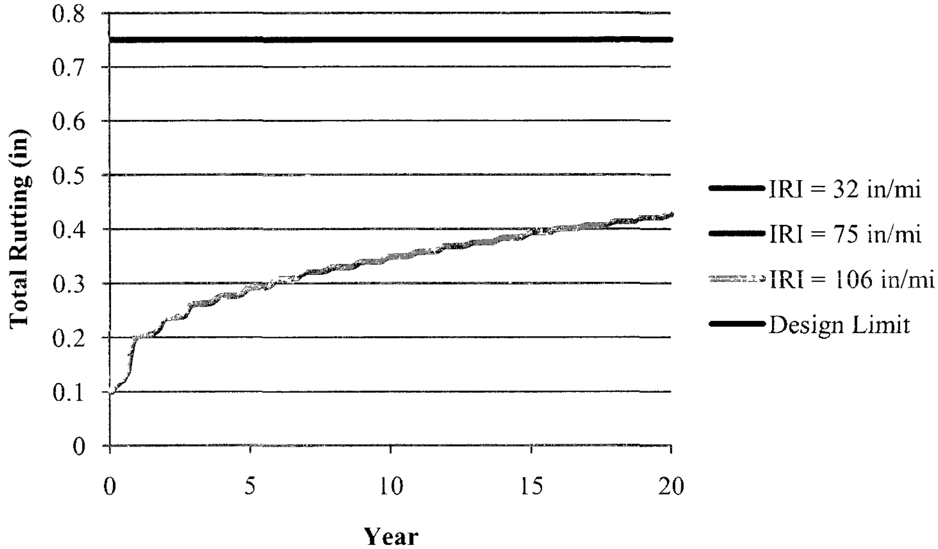


Figure 117C: Effect of Initial IRI on Total Rutting

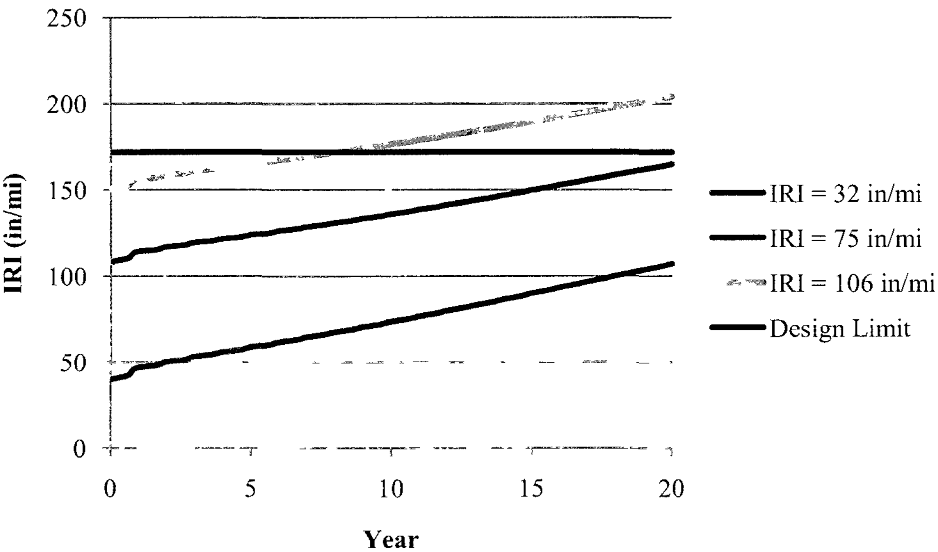


Figure 118C: Effect of Initial IRI on IRI

8. Sensitivity Analysis Summary Level 3

Normalization of the distresses was done to compare the effects of each input parameter on predicted distresses.

The normalized distress levels are calculated as the ratio of the difference between the maximum and minimum predicted distresses for each input variable to the distress levels corresponding to the control set of input values.

$$N = \frac{\text{Maximum Distress} - \text{Minimum Distress}}{\text{Distress for control input set}}$$

N - Normalized Value

Table 34C: Difference between Maximum and Minimum Distresses – Level 3

MA LEVEL 3					
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**
HMA thickness	0.16	1020.35	0.03	0.111	5.66
HMA mix gradation	0.02	201.37	0.046	0.057	2.89
HMA air voids	0.13	656.0	0.026	0.032	1.67
HMA effective binder content	0.02	71.91	0.014	0.018	0.89
HMA binder grade	0.05	628.13	0.148	0.173	8.67
Base type/modulus	0.04	251.04	0.017	0.043	2.18
Subgrade type/modulus	0.02	433.93	0.009	0.086	13.85
Ground water table	0.02	242.76	0.012	0.041	2.0
WT with weakest subgrade	0.03	10.24	0.009	0.027	1.33
Climate	0.04	352.37	0.092	0.1	6.39
AADTT value	0.04	286.01	0.065	0.088	4.45
Operational speed	0.07	763.21	0.206	0.237	11.9
Traffic growth rate	0.01	47.76	0.013	0.017	0.81
Traffic distribution	0.13	632.25	0.084	0.123	7.26
HMA CTC	0	0	0	0	14.34
Initial IRI	0	0	0	0	96.96

Table 35C: Normalized Values and Ranks for MA Level 3

MA LEVEL 3										
Input Variable	**Bottom-Up**		**Top-Down**		**AC Rutting**		**Total Rutting**		**IRI**	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
HMA thickness	0.106	1	1.465	1	0.153	7	0.261	4	0.034	8
HMA mix gradation	0.013	7	0.289	11	0.235	6	0.134	8	0.018	10
HMA air voids	0.086	2	0.942	3	0.133	8	0.075	11	0.010	13
HMA effective binder content	0.013	7	0.103	12	0.071	10	0.042	13	0.005	15
HMA binder grade	0.033	4	0.902	5	0.755	2	0.406	2	0.053	5
Base type/modulus	0.026	5	0.360	9	0.087	9	0.101	9	0.013	11
Subgrade type/modulus	0.013	7	0.623	6	0.046	13	0.202	7	0.084	3
Ground water table	0.013	7	0.349	10	0.061	12	0.096	10	0.012	12
WT with weakest subgrade	0.020	6	0.015	14	0.046	13	0.063	12	0.008	14
Climate	0.026	5	0.506	7	0.469	3	0.235	5	0.039	7
AADTT value	0.026	5	0.411	8	0.332	5	0.207	6	0.027	9
Operational speed	0.046	3	1.096	2	1.051	1	0.556	1	0.072	4
Traffic growth rate	0.007	8	0.069	13	0.066	11	0.040	14	0.005	15
Traffic distribution	0.086	2	0.908	4	0.429	4	0.289	3	0.044	6
HMA CTC	0.000	9	0.000	15	0.000	14	0.000	15	0.087	2
Initial IRI	0.000	9	0.000	15	0.000	14	0.000	15	0.588	1

Table 36C: Sensitivity Analysis Results Level 3

Bottom-Up	Top-Down	AC Rutting	Total Rutting	IRI
HMA thickness	HMA thickness	Operational speed	Operational speed	Initial IRI
HMA air voids	Operational speed	HMA binder grade	HMA binder grade	HMA CTC
Traffic distribution	HMA air voids	Climate	Traffic distribution	Subgrade type/modulus
Operational speed	Traffic distribution	Traffic distribution	HMA thickness	Operational speed
HMA binder grade	HMA binder grade	AADTT value	Climate	HMA binder grade
AADTT value	Subgrade type/modulus	HMA mix gradation	AADTT value	Traffic distribution

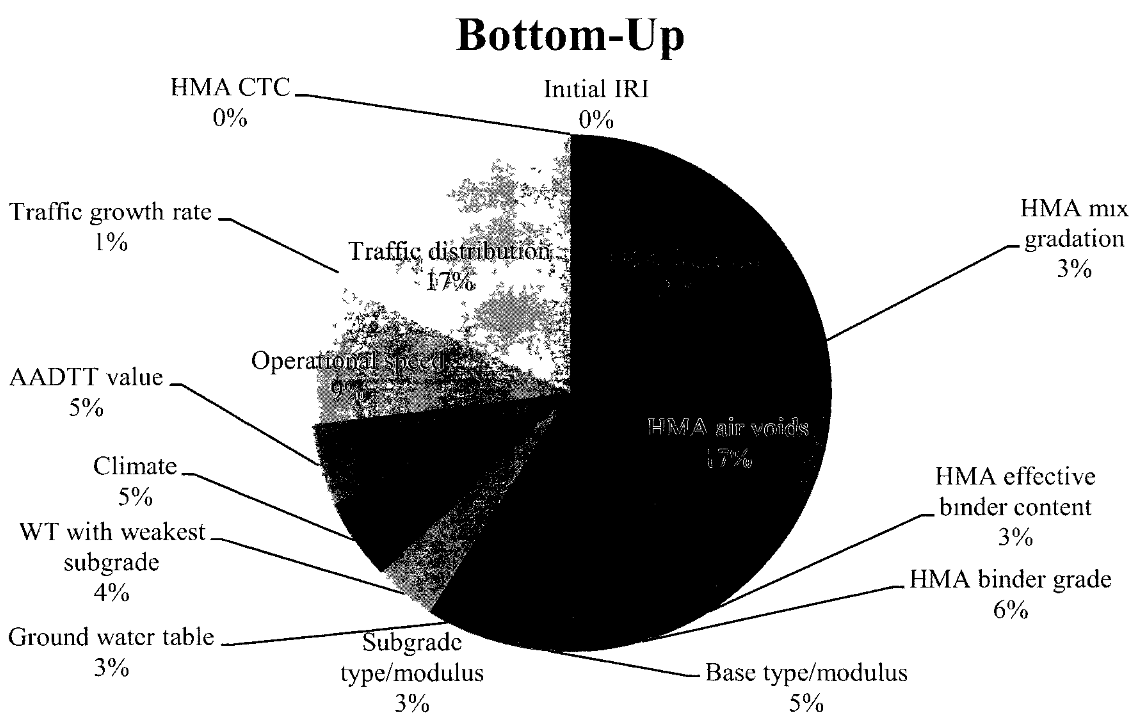


Figure 119C: Significance of Effect of Input Variables on Bottom-Up Cracking (Pie Graph)

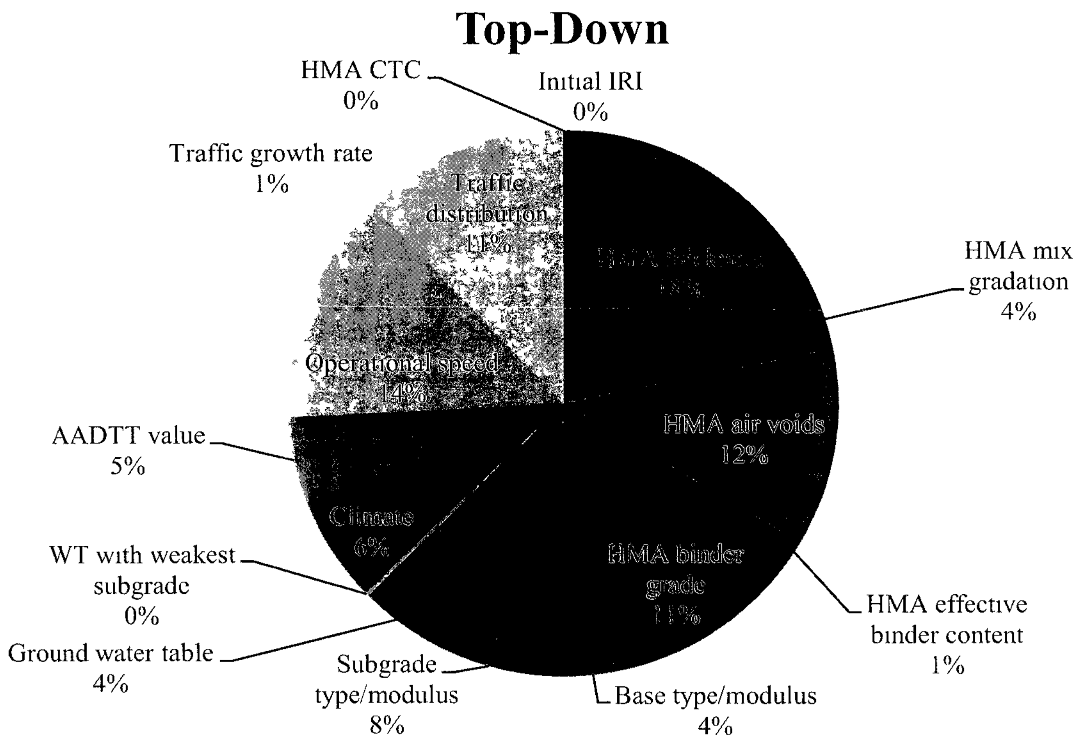


Figure 120C: Significance of Effect of Input Variables on Top-Down Cracking

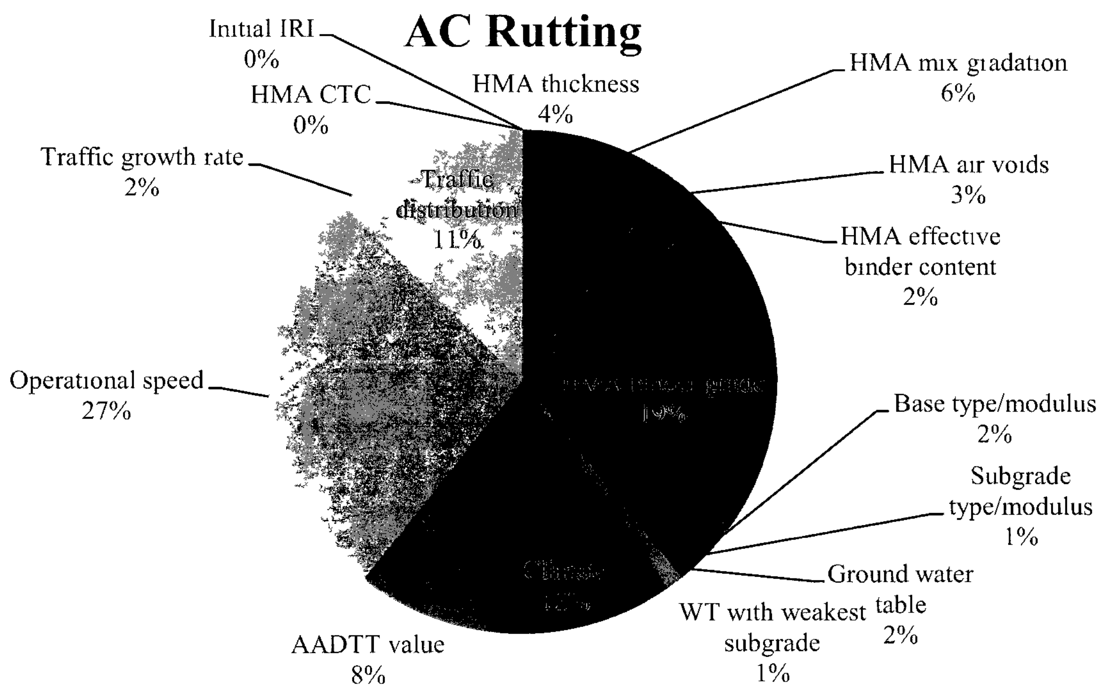


Figure 121C: Significance of Effect of Input Variables on AC Rutting

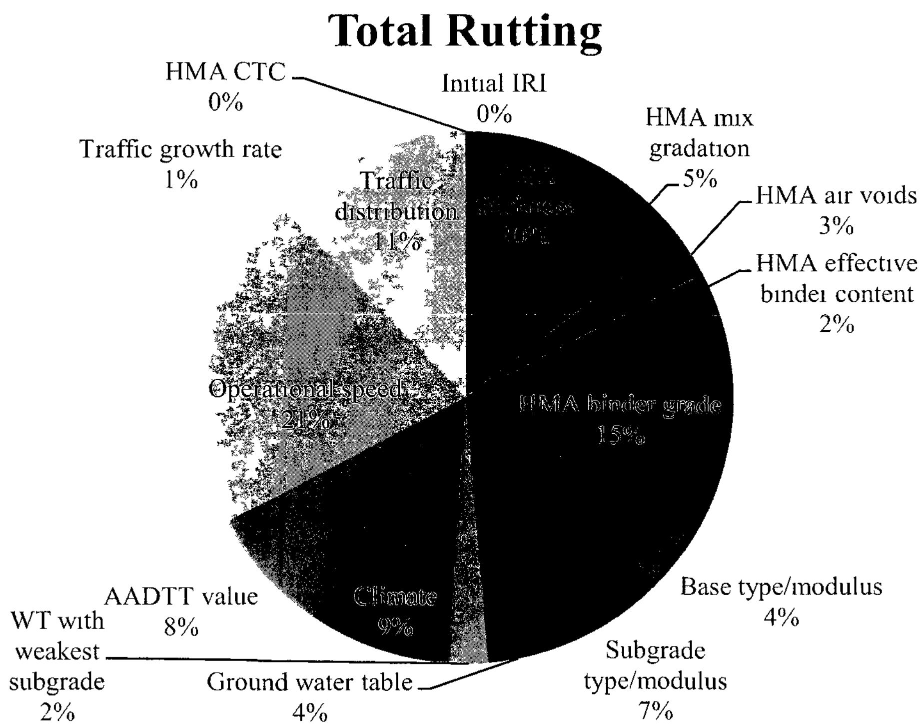


Figure 122C: Significance of Effect of Input Variables on Total Rutting

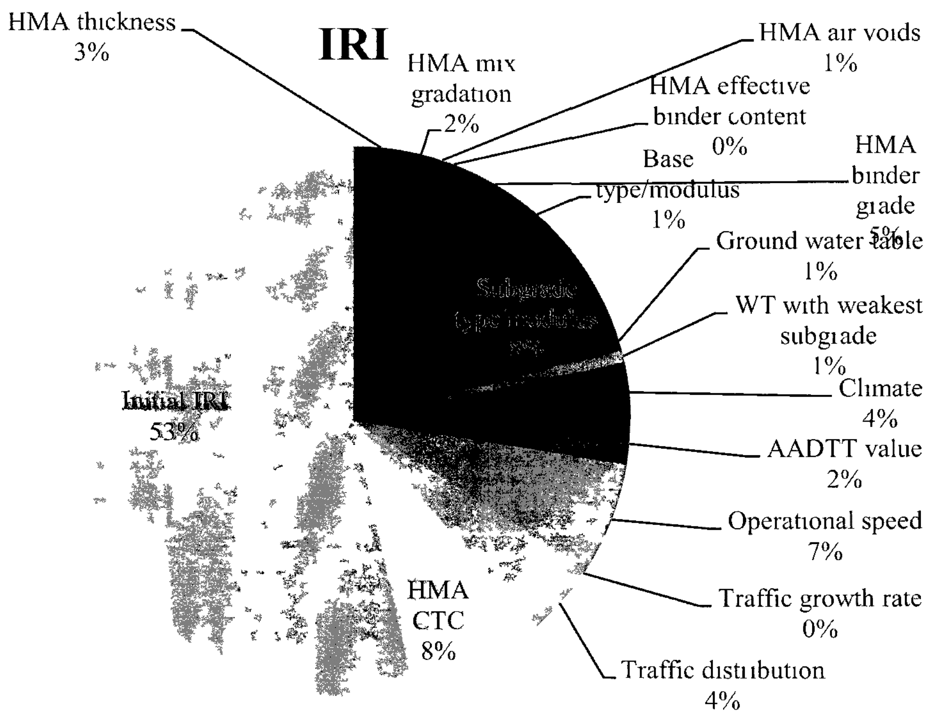


Figure 123C: Significance of Effect of Input Variables on IRI

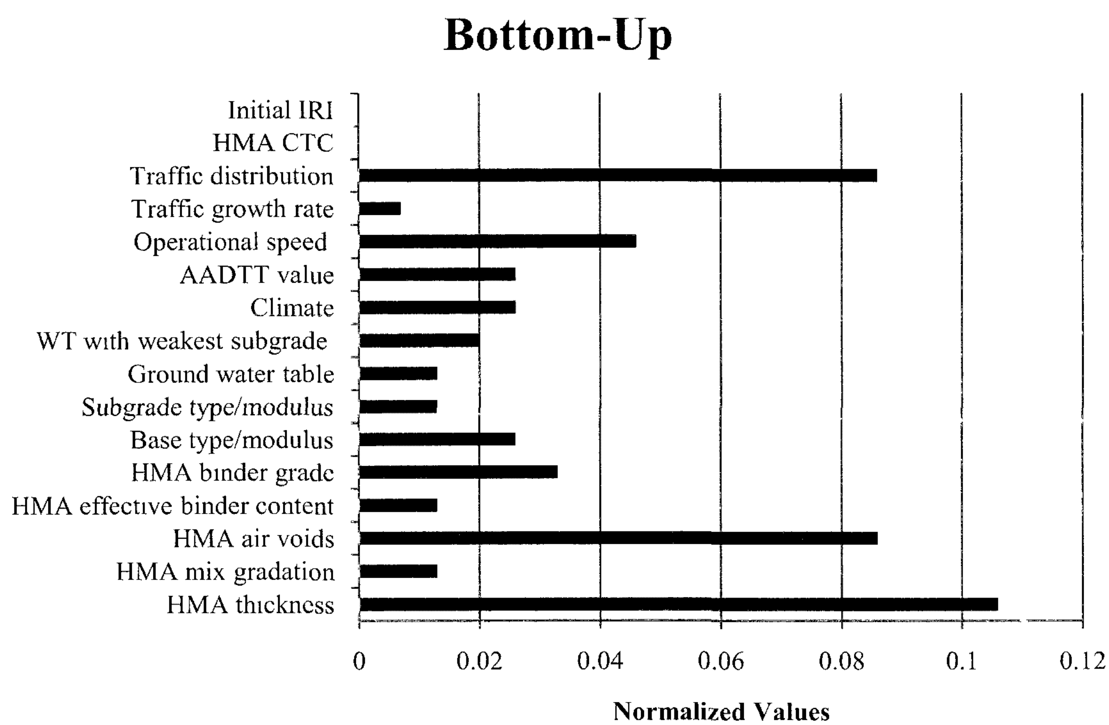


Figure 124C: Significance of Effect of Input Variables on Bottom-Up Cracking

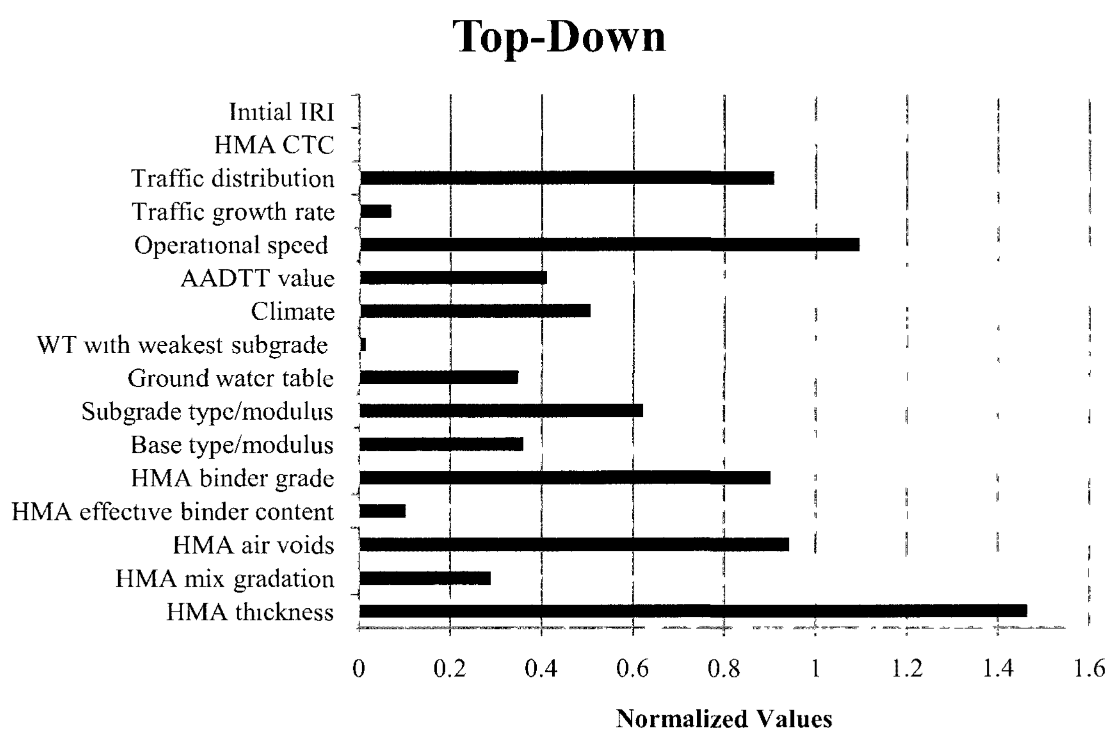


Figure 125C: Significance of Effect of Input Variables on Top-Down Cracking

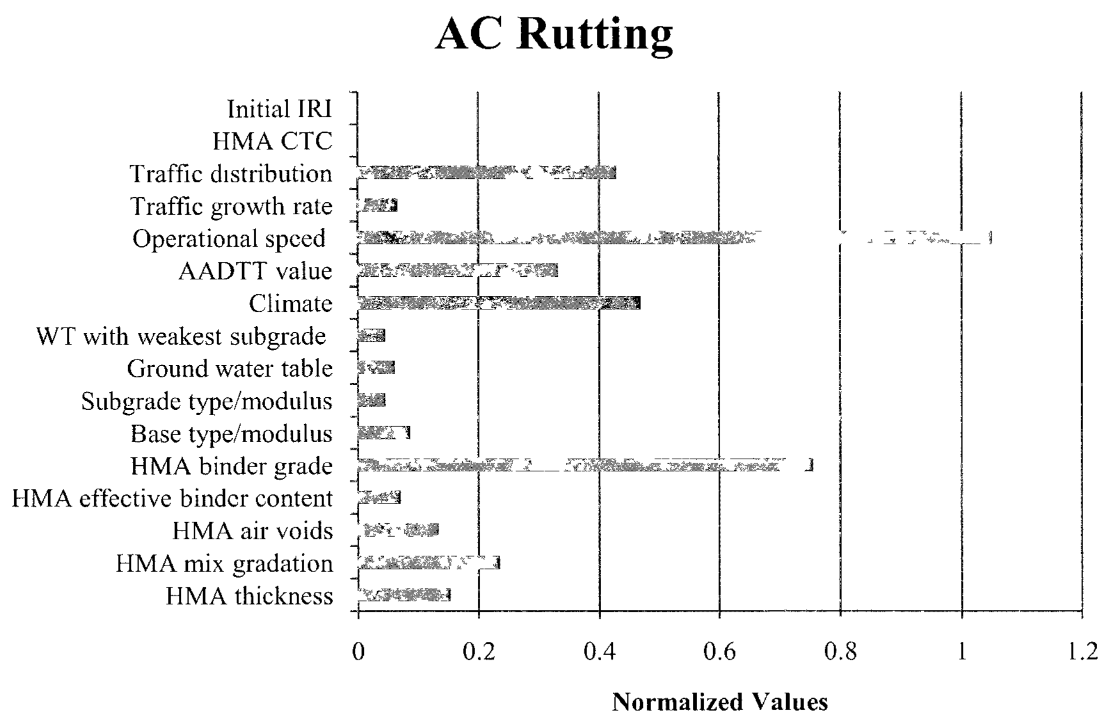


Figure 126C: Significance of Effect of Input Variables on AC Rutting

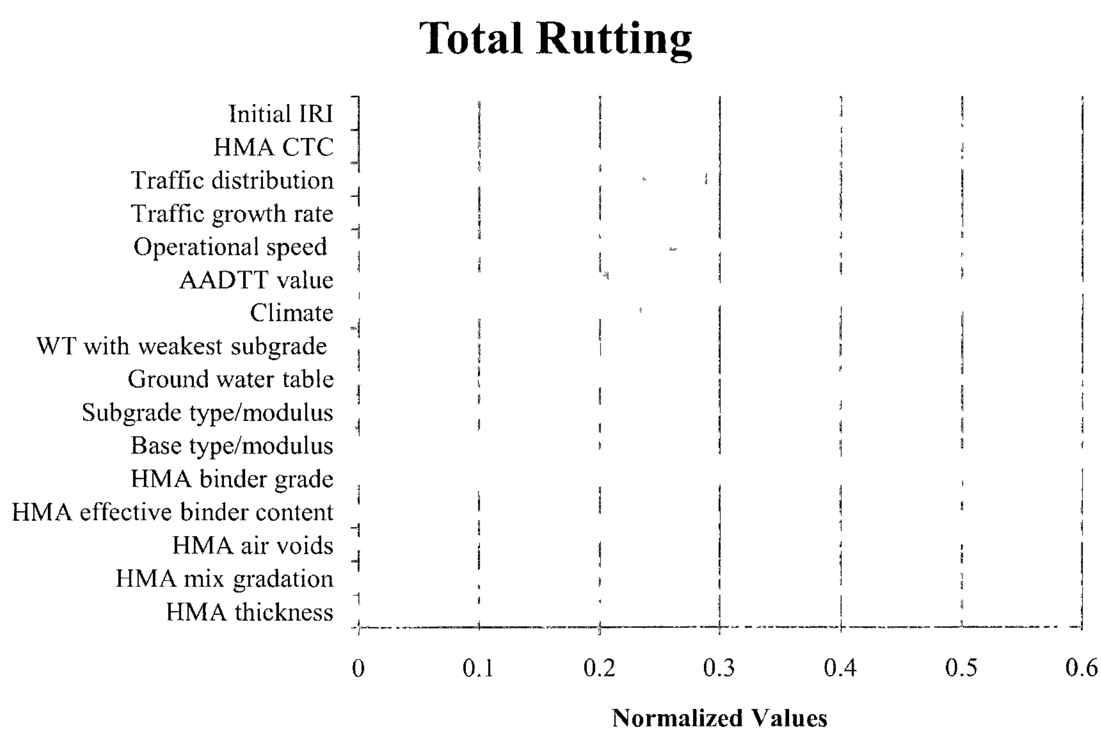


Figure 127C: Significance of Effect of Input Variables on Total Rutting

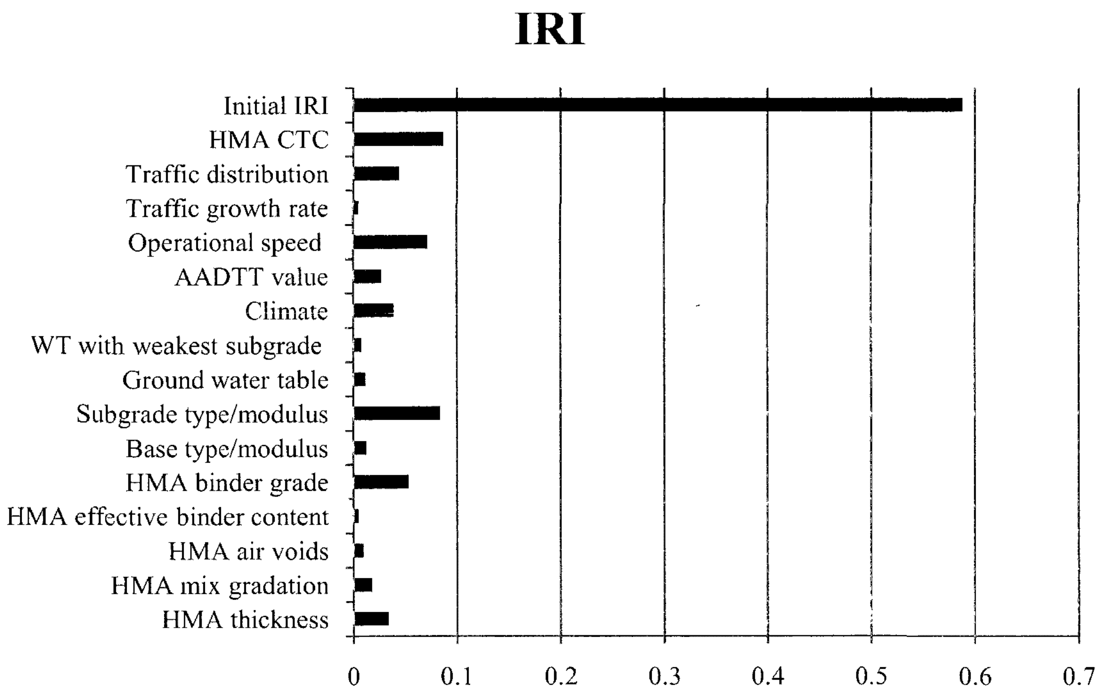


Figure 128C: Significance of Effect of Input Variables on IRI

Table 37C: MA Sensitivity Analysis Summary Level 3

Design/ Material Variable	Distress/Smoothness				
	Bottom-Up Cracking (%)	**Top-Down Cracking (ft/mi)**	**AC Rutting (in)**	**Total Rutting (in)**	**IRI (in/mi)**
HMA thickness	XXX	XXX	X	XXX	X
HMA mix gradation	X	XX	XX	XX	X
HMA air voids	XXX	XXX	X	X	
HMA effective binder content	X	X	X	X	
HMA binder grade	XX	XXX	XXX	XXX	XX
Base type/modulus	XX	XX	X	X	
Subgrade type/modulus	X	XX	X	XX	XX
Ground water table	X	XX	X	X	
WT with weakest subgrade	XX		X	X	
Climate	XX	XX	XXX	XXX	XX
AADTT value	XX	XX	XX	XX	X
Operational speed	XX	XXX	XXX	XXX	XX
Traffic growth rate	X	X	X	X	
Traffic distribution	XXX	XXX	XXX	XXX	XX
HMA CTC					XX
Initial IRI					XXX

Note: **X – Small effect**
XX – moderate effect
XXX – large effect

Table 38C: MA Overall Ranking Summary of Significance of Each Input Parameter on the Performance of Flexible Pavement

MASSACHUSETTS LEVEL 3							
Input Variable	**Bottom-Up**	**Top-Down**	**AC Rutting**	**Total Rutting**	**IRI**	**Total Ranking Points**	**Overall Order of Significance**
	Rank	Rank	Rank	Rank	Rank		
HMA thickness	1	1	7	4	8	**21**	**4**
HMA mix gradation	7	11	6	8	10	**42**	**9**
HMA air voids	2	3	8	11	13	**37**	**8**
HMA effective binder content	7	12	10	13	15	**57**	**14**
HMA binder grade	4	5	2	2	5	**18**	**2**
Base type modulus	5	9	9	9	11	**43**	**10**
Subgrade type modulus	7	6	13	7	3	**36**	**7**
Ground water table	7	10	12	10	12	**51**	**11**
WT with weakest subgrade	6	14	13	12	14	**59**	**15**
Climate	5	7	3	5	7	**27**	**5**
AADTT value	5	8	5	6	9	**33**	**6**
Operational speed	3	2	1	1	4	**11**	**1**
Traffic growth rate	8	13	11	14	15	**61**	**16**
Traffic distribution	2	4	4	3	6	**19**	**3**
HMA CTC	9	15	14	15	2	**55**	**13**
Initial IRI	9	15	14	15	1	**54**	**12**

References (Massachusetts)

1. http://groundwaterwatch.usgs.gov
2. http://www.ltpp-products.com/DataPave/index.asp
3. Sensitivity Study of Design Input Parameters for Two Flexible Pavement Systems Using the MEPDG; Sunghwan Kim, Iowa State University, (August 2005)
4. Standard Specification for Highway and Bridges, (1988)
5. Standard Special Provisions, Section M3, Bituminous Material (February, 2011)
6. Sensitivity Analysis of Pavement Performance Predicted Using the M-E PDG; Dinesh Ayyala, (May 2009)
7. http://www.massdot.state.ma.us/Highway/
8. Analysis of Vehicle Classification and Truck Weight Data of the New England States, Rick Schmoyer and Patricia S. Hu, (September, 1998)
9. Hot Mix Asphalt Job Mix Formulas
10. Performance-graded Asphalt Binder Suppliers, 2009
11. Network Level Pavement Condition Assessment (March, 2010)
12. Superpave Series No. 1 (SP-1) and No. 2 (SP-2)
13. Report No. UT-09.11a Draft User's Guide for UDOT MEPDG; October 2009
14. ASTM Standards Volume 04.03, 2008
15. ASTM Standards Volume 04.08, 2009

Appendix A: Code Descriptions (Massachusetts)

CODE	DESCRIPTION
A1, A2, A3	3/8" (9.5 mm) HMA mix gradation
B1, B2, B3	3/4" (19 mm) HMA mix gradation
A1B1, A2B2, A3B3	Mean, coarse, fine HMA mix gradation
D1, D2, D3, D4	Truck class distribution
E1, E2, E3	Subgrade type
F1, F2, F3	Effective binder content
G1, G2, G3	AC Binder grade
M1, M2, M3	Base course aggregate gradation level 3
N1, N2, N3	Coefficient of Thermal Contraction
Q1, Q2, Q3	AADTT value
R1, R2, R3	Traffic growth rate
S1, S2, S3	Initial IRI
T1, T2, T3	HMA layer thickness
U1, U2, U3	Traffic operational speed
V1, V2, V3	Binder air content
WT1, WT2, WT3	Ground water table level

Appendix B: Specification for Hot Mix Asphalt (Massachusetts)

Specifications for Hot Mix Asphalt
Percent by Weight Passing Sieve Designation

Sieve Designation and % Binder Content	HMA Base Course	HMA Base/ Intermed. Course - Binder	HMA Intermed. Course Dense Binder	HMA Surface Course - Dense Binder	HMA Surface Course – Standard Top	HMA Surface Course - Modified Top	HMA Dense Mix	HMA Surface Treatment	HMA OGFC
2 inches	100								
1 inch	57 – 87	100	100	100		100			
¾ inch		80 - 100	80 – 100	80 – 100		95 - 100			
5/8 inch					100				
½ inch	40 - 65	55 - 75	65 – 80	65 – 80	95 - 100	79 – 100	100		100
3/8 inch					80 - 100	68 – 88	80 - 100	100	90 –
No. 4	20 - 45	28 - 50	48 – 65	48 – 65	50 - 76	48 – 68	55 - 80	80 - 100	30 – 50
No. 8	15 - 33	20 - 38	37 – 49	37 – 49	37 - 49	33 – 46	48 - 59	64 - 85	5 – 15
No. 16					26 - 40	20 – 40	36 - 49	46 - 68	
No. 30	8 - 17	8 - 22	17 – 30	17 – 30	17 - 29	14 – 30	24 - 38	26 - 50	
No. 50	4 - 12	5 - 15	10 – 22	10 – 22	10 - 21	9 – 21	14 - 27	13 - 31	
No. 100					5 - 16	6 – 16	6 - 18	7 - 17	
No. 200	0 - 4	0 - 5	0 – 6	0 – 6	2 - 7	2 – 6	4 - 8	3 - 8	1 – 3
Binder	4 - 5	4.5 - 5.5	5 – 6	5.1 – 6	5.6 - 7.0	5.1 – 6	7 - 8	7 - 8	6 – 7

Appendix C: Engineering Limits for HMA Aggregate Gradation and PG Binder Content (Massachusetts)

Engineering Limits for HMA Aggregate Gradation and PG Binder Content

Sieve Designation / Binder Content	Engineering Limit for OGFC	Engineering Limit for all other mixes
Passing No. 4 sieve and larger sieve sizes	JMF Target ± 5%	JMF Target ± 7%
Passing No. 8 to No. 100 sieves (inclusive)	JMF Target ± 3%	JMF Target ± 4%
Passing No. 200 sieve	JMF Target ± 1%	JMF Target ± 2%
Binder	JMF Target ± .3%	JMF Target ± 0.4%

Appendix D: Material Classification (Massachusetts)

Material Classification	M_r Range	Typical M_r*
A-1-a	38,500 – 42,000	40,000
A-1-b	35,500 – 40,000	38,000
A-2-4	28,000 – 37,500	32,000
A-2-5	24,000 – 33,000	28,000
A-2-6	21,500 – 31,000	26,000
A-2-7	21,500 – 28,000	24,000
A-3	24,500 – 35,500	29,000
A-4	21,500 – 29,000	24,000
A-5	17,000 – 25,500	20,000
A-6	13,500 – 24,000	17,000
A-7-5	8,000 – 17,500	12,000
A-7-6	5,000 – 13,500	8,000
CH	5,000 – 13,500	8,000
MH	8,000 – 17,500	11,500
CL	13,500 – 24,000	17,000
ML	17,000 – 25,500	20,000
SW	28,000 – 37,500	32,000
SP	24,000 – 33,000	28,000
SW-SC	21,500 – 31,000	25,500
SW-SM	24,000 – 33,000	28,000
SP-SC	21,500 – 31,000	25,500
SP-SM	24,000 – 33,000	28,000
SC	21,500 – 28,000	24,000
SM	28,000 – 37,500	32,000
GW	39,500 – 42,000	41,000
GP	35,500 – 40,000	38,000
GW-GC	28,000 – 40,000	34,500
GW-GM	35,500 – 40,500	38,500
GP-GC	28,000 – 39,000	34,000
GP-GM	31,000 – 40,000	36,000
GC	24,000 – 37,500	31,000
GM	33,000 – 42,000	38,500

Appendix E: MassDOT Hot Mix Asphalt Formulas (Massachusetts)

PLANTS TO BE USED	ID#	Batch/Drum Size	Automatic Controls (X)	PC BINDER TANKS	MIX SILOS Insul/Heat (X)
	___	___Ton/ ___Tph	part___ full___w/ prntr___	___@ ________ gals	___@ ___Ton Ins___ Htd___
	___	___Ton/ ___Tph	part___ full___w/ prntr___	___@ ________ gals	___@ ___Ton Ins___ Htd___
		___Ton/ ___Tph	part___ full___w/ prntr___	___@ ________ gals	___@ ___Ton Ins___ Htd___

ALLOWABLE TOLERANCES

Sieve Designation/ Binder Content	Engineering Limit all mixes	Engineering Limit QC C
Passing #4 sieve and larger sieve sizes	JMF Target ± 7 %	JMF Target ± 5 %
Passing #8 to #100 sieve sizes (inclusive)	JMF Target ± 4 %	JMF Target ± 3 %
Passing #200	JMF Target ± 2 %	JMF Target ± 1 %
% Binder	JMF Target ± 0.4 %	JMF Target ± 0.3 %

COMPONENT MATERIALS

COARSE AGGREGATE Nom Sizes ________ Producer & City

FINE AGGREGATE BLEND ___ % Screenings ___ % Stone Sand ___ % Natural Sand — Producer & City

RAP FOR: Base =___% ______ w/PG______ modifier; Intermediate =___% ______ w/PG______ modifier; Surface =___% ______ w/PG______ modifier

MINERAL FILLER % and Kind ______

PC BINDER/MODIFIER Grade & Source

SPECIAL MATL

ANTI-STRIP % of Bit Kind

OGFC Polymer % and Kind

SILICONE oz Per gals

NOTE LIMITATIONS (Unless Design Data Approved) Unless authorized by the Engineer no Job Mix Formula will be approved which specifies

* Less than 6 % binder for HMA Surface Course Standard Top

** Less than 5.5 % binder for HMA Surface Course Dense Binder and Modified Top for mixes containing RAP

FORMULAS (MR=Master Range of Specifications JM=Job Mix Formula)

Aggregate percentages below are proportional percentages of total aggregate for the mix

Sieve Size	HMA Base Course BASE MR	JM	HMA Base/ Intermediate Course BINDER MR	JM	HMA Intermediate Course DENSE BINDER MR	JM	** HMA Surface Course DENSE BINDER MR	JM	* HMA Surface Course STANDARD TOP MR	JM	** HMA Surface Course MODIFIED TOP MR	JM	HMA DENSE MIX MR	JM	HMA Surface Treatment MR	JM	HMA OGFC MR	JM	MR	JM
2	100																			
1	57 87		100		100		100				100									
3/4			80 100		80 100		80 100				95 100									
5/8									100											
1/2	40 65		55 75		67 80		65-80		95 100		79 100		100				100			
3/8									80 100		68 88		80 100		100		90 100			
#4	20 45		28 50		48 57		48 65		[illegible]0 76		48 68		55 80		80 100		30 50			
#8	15 33		20 38		37 49		37 49		37 49		33 46		48 59		64 85		5 15			
#16									25 40		20 40		35 49		45 68					
#30	8 17		8 22		17 30		17 30		17 29		14 30		24 38		26 40					
#50	4 12		5 15		10 22		10 22		10 21		9 21		14 27		13 31					
#100									5 16		6 16		6 18		7 17					
#200	0 4		0 5		0 5		0 6		2 7		2 6		4 8		3 8		1 3			
%Bnd	4.0 5.0		4.5 5.5		5.0 6.0		5.1 6.0		5.6 7.0		5.1 6.0		7.0 8.0		7.0 8.0		6.0 7.0			
Max Theo Sp Gr																				

Appendix D: AASHTO and Unified Material Classifications

Type	Material Classification	M_r Range	Typical M_r
AASHTO	A-1-a	38,500 – 42,000	40,000
	A-1-b	35,500 – 40,000	38,000
	A-2-4	28,000 – 37,500	32,000
	A-2-5	24,000 – 33,000	28,000
	A-2-6	21,500 – 31,000	26,000
	A-2-7	21,500 – 28,000	24,000
	A-3	24,500 – 35,500	29,000
	A-4	21,500 – 29,000	24,000
	A-5	17,000 – 25,500	20,000
	A-6	13,500 – 24,000	17,000
	A-7-5	8,000 – 17,500	12,000
	A-7-6	5,000 – 13,500	8,000
Unified	CH	5,000 – 13,500	8,000
	MH	8,000 – 17,500	11,500
	CL	13,500 – 24,000	17,000
	ML	17,000 – 25,500	20,000
	SW	28,000 – 37,500	32,000
	SP	24,000 – 33,000	28,000
	SW-SC	21,500 – 31,000	25,500
	SW-SM	24,000 – 33,000	28,000
	SP-SC	21,500 – 31,000	25,500
	SP-SM	24,000 – 33,000	28,000
	SC	21,500 – 28,000	24,000
	SM	28,000 – 37,500	32,000
	GW	39,500 – 42,000	41,000
	GP	35,500 – 40,000	38,000
	GW-GC	28,000 – 40,000	34,500
	GW-GM	35,500 – 40,500	38,500
	GP-GC	28,000 – 39,000	34,000
	GP-GM	31,000 – 40,000	36,000
	GC	24,000 – 37,500	31,000
	GM	33,000 – 42,000	38,500