PAVEMENT THICKNESS DESIGN FOR LOCAL ROADS IN IOWA

Final Report TR-586
February 2010

Sponsored by
Iowa Highway Research Board

Conducted by
Hosin "David" Lee
Yongjoo "Thomas" Kim
Jeremy Purvis

Public Policy Center
University of Iowa

Disclaimer Notice

Statement of Non-Discrimination

1. REPORT NO. IHRB Report TR-586	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Pavement Thickness Design for Local Roads in Iowa		5. REPORT DATE February 2010
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Hosin “David” Lee, Yongjoo “Thomas” Kim and Jeremy Purvis		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Public Policy Center University of Iowa 227 South Quadrangle Iowa City, IA 52242-1192		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO
12. SPONSORING AGENCY NAME AND ADDRESS Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way, Ames, IA 50010		13. TYPE OF REPORT AND PERIOD COVERED Final Report
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

Three pavement design software packages were compared with regards to how they were different in determining design input parameters and their influences on the pavement thickness. StreetPave designs the concrete pavement thickness based on the PCA method and the equivalent asphalt pavement thickness. The WinPAS software performs both concrete and asphalt pavements following the AASHTO 1993 design method. The APAI software designs asphalt pavements based on pre-mechanistic/empirical AASHTO methodology. First, the following four critical design input parameters were identified: traffic, subgrade strength, reliability, and design life. The sensitivity analysis of these four design input parameters were performed using three pavement design software packages to identify which input parameters require the most attention during pavement design.

Based on the current pavement design procedures and sensitivity analysis results, a prototype pavement design and sensitivity analysis (PD&SA) software package was developed to retrieve the pavement thickness design value for a given condition and allow a user to perform a pavement design sensitivity analysis. The prototype PD&SA software is a computer program that stores pavement design results in database that is designed for the user to input design data from the variety of design programs and query design results for given conditions. The prototype Pavement Design and Sensitivity Analysis (PA&SA) software package was developed to demonstrate the concept of retrieving the pavement design results from the database for a design sensitivity analysis. This final report does not include the prototype software which will be validated and tested during the next phase.

17. KEY WORDS pavement thickness design, StreetPave software, WinPas software, APAI software, design sensitivity analysis PD&SA software		18. DISTRIBUTION STATEMENT No restrictions.	
19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES 77	22. PRICE N/A

Pavement Thickness Design for Local Roads in Iowa

Final Report TR-586
February 2010

Principal Investigator

Hosin "David" Lee, Ph. D., P. E.

Associate Professor

Public Policy Center, Department of Civil and Environmental Engineering,

University of Iowa

Researcher

Yongjoo "Thomas" Kim, Ph. D.

Postdoctoral Research Scholar

Public Policy Center, Department of Civil and Environmental Engineering,

University of Iowa

Research Assistant

Jeremy Purvis

Graduate Research Assistant

Public Policy Center, Department of Civil and Environmental Engineering,

University of Iowa

Sponsored by

Iowa Highway Research Board

A report from

Public Policy Center
University of Iowa
227 South Quadrangle
Iowa City, IA 52242-1192
http://ppc.uiowa.edu

Technical Advisory Committee

Chris Brakke, Iowa DOT, chris.brakke@dot.iowa.gov

Donna Buchwald, Iowa DOT, donna.buchwald@dot.iowa.gov

John Dostart, Iowa DOT, john.dostart@dot.iowa.gov

Cathy Nicholas, Black Hawk County, cnicholas@co.black-hawk.ia.us

Myron Parizek, Benton County, mparizek@prairieinet.net

Duane Wittstock, West Des Moines, duane.wittstock@wdm-ia.com

Larry Stevens, SUDAS, lstevens@iastate.edu

Bill Rosener, APAI, ex officio member, billr@apai.net

Larry Mattusch, APAI, ex officio member, lmatt2@mchsi.com

Gordon Smith, ICPA, ex officio member, gsmith@iowaconcretepaving.org

John Cunningham, ICPA, ex officio member, jcunningham@iowaconcretepaving.org

Table of Contents

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

To minimize the life-cycle cost of building and maintaining pavements, it is critical to determine the most appropriate pavement thickness for given traffic level, subgrade condition and environmental factor. In Iowa, the statewide urban design and specifications (SUDAS) currently utilize a simplified version of the AASHTO 1993 pavement design guide, which can be considered conservative based on placement of the pavement on natural subgrade, distribution of truck classifications and other design parameters. Therefore, there is a need for a modified pavement design methodology to be used for determining the most appropriate pavement thickness for local roads in Iowa.

1.1 Objectives

The main objectives of this research are to: 1) identify the most critical design input parameters, 2) determine the minimum pavement thickness, and 3) develop a new pavement design and sensitivity analysis (PD&SA) software package which can provide the most appropriate design thickness for a broad range of pavement conditions. The proposed study in the proposal includes five major tasks: 1) synthesis of local road pavement thickness determination procedures in adjoining States, 2) sensitivity analysis of input parameters using new sensitivity analysis software; 3) mechanistic analysis for minimum pavement thickness; 4) development of a new SUDAS pavement design procedure and software; and 5) preparation of the final report and a new pavement design software manual.

All tasks were performed and documented in this report as proposed except the tasks 3) and 4) and why they were not completed as originally proposed are discussed next. Throughout the study, based on the literature search, we have learned that the mechanistic analysis for the minimum pavement thickness would result in an unrealistic thickness in practice. Therefore, with a consultation and a subsequent approval from the TAC, it was decided that the survey should be made to state departments of transportation adjacent to Iowa instead of proceeding with the mechanistic analysis of pavement to determine the minimum thickness. The prototype software PD&SA was developed to demonstrate the concept of storing the pavement design results obtained from the existing software packages. Given various pavement design results using three software packages, it was recommended that the prototype PD&SA software should be enhanced to include pavement design results from AASHTO Darwin and Asphalt Institute software packages. It was also recommended that the PD&SA software should be modified to provide a single pavement thickness value which can be adopted as a standard SUDAS design thickness for all cities and counties in Iowa. Therefore, this final report does not include the PD&SA software which will be validated and tested during the next phase.

1.2 Benefits

The most critical input parameters were identified and their typical values for local roads in Iowa were used to run three existing pavement design software packages. A prototype PD&SA software package was developed to store the pavement design values in the database so that a user can determine the optimum pavement thickness by retrieving the pavement design values from the database without running the actual pavement design programs. The prototype PD&SA software can be used to make comparisons from the pavement design catalog that was developed for the database.

2. PAVEMENT DESIGN PROCEDURES ADOPTED BY SIX STATE DEPARTMENT OF TRANSPORTATION ADJACENT TO IOWA

Most states have developed their own pavement design procedures for low-volume roads. As shown in Figure 2-1, forty state DOT's currently use the AASHTO 1993 guide for designing low-volume road pavements (Hall and Bettis 2000). The main features of asphalt pavement design procedures adopted by some state DOT's for low-volume roads are summarized in Table 2-1.

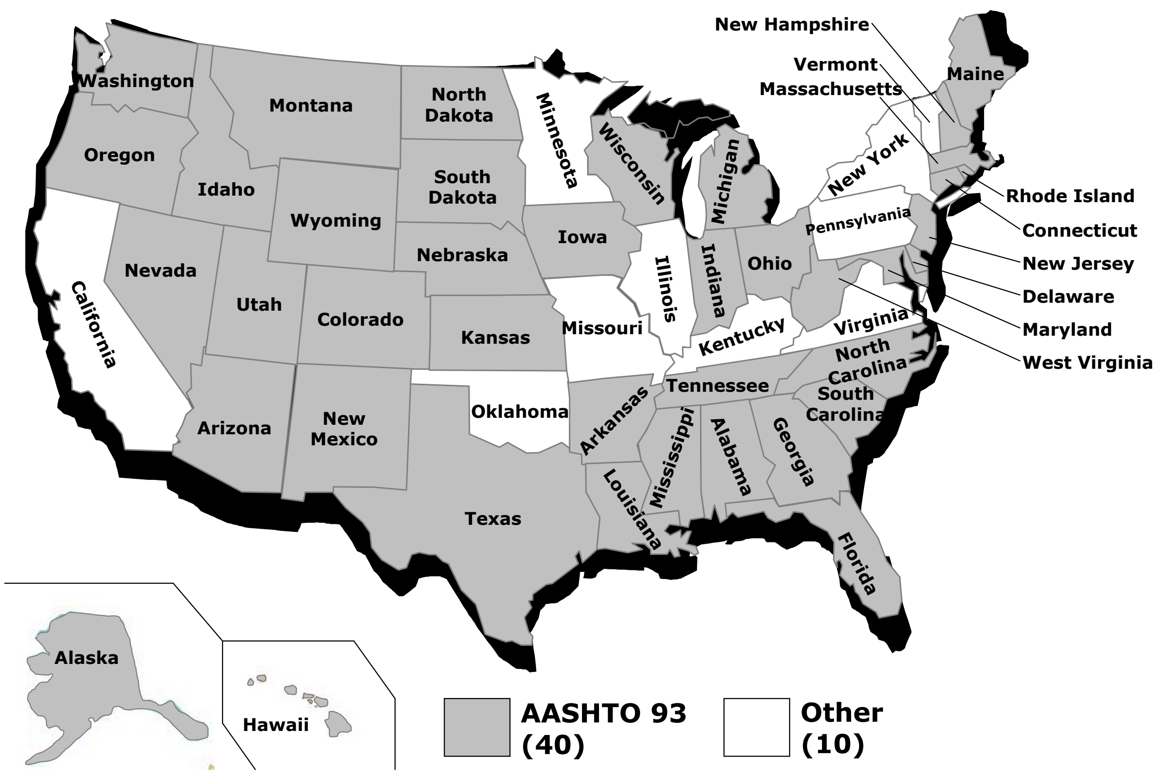


Figure 2-1. Survey of low-volume pavement design procedure

Table 2-1. Summary of low-volume road pavement design procedures in select state departments of transportation

State	Main Features of Pavement Design Procedure
Illinois	▪ Road with less than 400 ADT. ▪ Required inputs: traffic (% heavy vehicles) and subgrade modulus. ▪ Design period of 15 or 20 years. ▪ Estimated using the ADT for the year representing one-half of the design period.
Kentucky	▪ Road with less than 500 ADT ▪ Required inputs: ADT and aggregate thickness. ▪ Aggregate thickness is estimated by a design chart relating to total pavement structure thickness.
Minnesota	▪ Two procedures: 1) Gravel Equivalency method and 2) R-value method. ▪ Required inputs: soil strength and traffic load structural requirements were considerably influenced by R-value ▪ GE method was less conservative than R-value method
Mississippi	▪ Required inputs: Soil strength (Soil support value found from using CBR), design life (5-8 years), traffic loads (ADT and ADL) ▪ Soil support value = 30289 log base 10 * (CBR) + 1.421 ▪ 4-inch minimum subbase required for all full depth asphalt construction.
Pennsylvania	▪ Required inputs: traffic (18-kip ESALs), the soil strength (CBR), and the effects of freeze-thaw action (Design Freezing Index, DFI). ▪ No traffic data necessary for each type of truck.
Texas	▪ Required inputs: traffic (18-kip ESALs) and soil strength. ▪ Designed for a design period of 20 years. ▪ Layer moduli values are back-calculated from FWD data

2.1 Questionnaire about Local Road Pavement Thickness Design

As shown in Figure 2-2, six adjoining state departments of transportation (Minnesota, Wisconsin, Illinois, Missouri, Nebraska and South Dakota) were surveyed with respect to their pavement design procedures for low-volume roads. A survey form was sent out to each of six departments of transportation and all but Nebraska have returned the survey. A follow-up interview was also performed with contact persons listed in Figure 2-2.

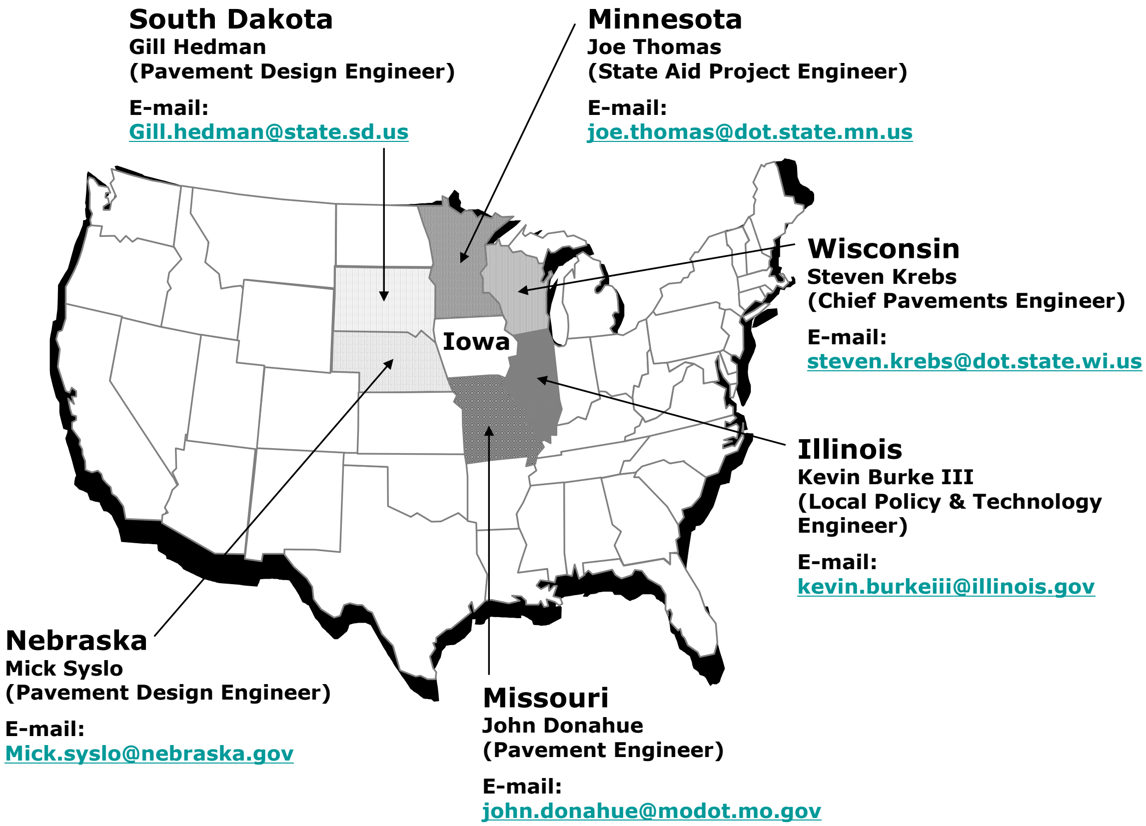


Figure 2-2. Contact information at adjoining state DOT's

As shown in Table 2-2, a questionnaire was prepared to identify pavement thickness design methods and their common input parameters for local roads adopted by adjoining state DOT's. It should be noted that the state departments of transportation have jurisdiction over a limited amount of streets and local roads. This study's TAC and researchers recognize that local agency engineers and technicians would need to be surveyed as to the best methods for pavement design. The survey of state DOT's is used herein as a means to identify general design procedures that might be employed.

Table 2-2. Questionnaire about local road pavement design procedures

No.	Question
1.	What kind of pavement design methodology do you use for local road?
2.	What kind of pavement thickness design software do you use for local road?
3.	How does your state agency classify road as local road?
4.	Has your state agency developed a pavement thickness design procedure for local road?
5.	What are the layer types and thicknesses of a typical local road (asphalt pavement) in your states?
6.	What are the layer types and thicknesses of a typical local road (concrete pavement) in your state?
7.	What are the most important factors for designing local road?
8.	What type of soil is most common in your state?
9.	How do you estimate subgrade strength for local road design?
10.	What kind of soil parameter does your state agency typically use for local road design?
11.	What type of paving materials and properties does your state agency use for local road design?
12.	What type of traffic input do you use for local road design?
13.	What type of drainage features does your agency commonly use for local road design?
14.	Does your state agency use a serviceability index to local road?
15.	What level of the design reliability does your state agency use for local road?
16.	What are the important characteristics of asphalt pavement for local road design?
17.	What are the important characteristics of concrete pavement for local road design?

2.2 Survey Results

Five state departments of transportation adjacent to Iowa (Nebraska was the only exclusion) returned the survey. Survey results are summarized for each question below.

Question 1: What kind of pavement design methodology do you use for local road?

Answer:

- Illinois DOT: Other (mechanistic empirical design developed by U of I and IL DOT)
- Missouri DOT: AASHTO
- Minnesota DOT: Other (charts and tables for soil factor and R-value)
- South Dakota DOT: AASHTO
- Wisconsin DOT: Other (WisPave based on AASHTO 72)

Question 2: What kind of pavement design software do you use for local road?

Answer:

- Illinois DOT: None
- Missouri DOT: Mechanistic-empirical pavement design guide
- Minnesota DOT: http://www.dot.state.mn.us/materials/pvmtdesign/software.html
- South Dakota DOT: 1993 AASHTO design guide and the DARWIN software
- Wisconsin DOT: Other (WisPave based on AASHTO 72)

Question 3: How does your state agency classify road as local road?

Answer:

- Illinois DOT: less than 400 ADT and less than 0.25 traffic factor
- Missouri DOT: less than 1000 AADT and less than a 100 trucks a day
- Minnesota DOT: less than 1000 ADT
- South Dakota DOT: None
- Wisconsin DOT: less than 400 AADT

Question 4: Has your agency developed a pavement design procedure for local road?

Answer:

- Illinois DOT: Yes (http://www.dot.il.gov/blr/manuals/Chapter%2037.pdf)
- Missouri DOT: No
- Minnesota DOT: Yes

(http://www.dot.state.mn.us/materials/pvmtdesign/docs/RValueChart.pdf)

- South Dakota DOT: No
- Wisconsin DOT: No

Question 5: What are the layer types and thicknesses of a typical local road (asphalt pavement) in your state?

Answer:

- Illinois DOT: Surface (HMA: 3”), Base (Class A aggregate: 8”), Subbase (Modified soil: 8”)
- Missouri DOT: Surface (HMA: 7-8”), Base (crushed stone: 4”), Subbase (N/A)
- Minnesota DOT: Surface (HMA: minimum 3”), Base (Class 5 or 6: 6-8”), Subbase (Existing soils: N/A)
- South Dakota DOT: Surface (HMA: 3-4”), Base (N/A: 10-12”), Subbase (8”)
- Wisconsin DOT: Surface (HMA: 3”), Base (Dense graded aggregate: 8”), Subbase (None)

Question 6: What are the layer types and thicknesses of a typical local road (concrete pavement) in your state?

Answer:

- Illinois DOT: Not used
- Missouri DOT: Surface (JPCP: 6-7”), Base (crushed stone: 4”), Subbase (N/A)
- Minnesota DOT: Surface (Concrete: 7-9”), Base (Class 5 or 6: 0-6”), Subbase (Existing soils: N/A)
- South Dakota DOT: Not used
- Wisconsin DOT: Not used

Question 7: What are the most important factors for designing local road?

Answer:

- Illinois DOT: Traffic and paving materials
- Missouri DOT: Subgrade and load
- Minnesota DOT: Traffic and subgrade
- South Dakota DOT: Traffic, subgrade and load
- Wisconsin DOT: Traffic, load, and pavement performance criteria

Question 8: What type of soil is most common in your state?

Answer:

- Illinois DOT: A-1 to A-7
- Missouri DOT: A-4, A-7-5, and A-7-6
- Minnesota DOT: A-1 through A-6 and A-7-5 and A-7-6
- South Dakota DOT: A-6 to A-7
- Wisconsin DOT: A-2. A-2-4, A-4, A-6 and A-7-6

Question 9: How do you estimate subgrade strength for local road design?

Answer:

- Illinois DOT: No response
- Missouri DOT: Assume resilient modulus value from AASHTO class
- Minnesota DOT: R-value derived from soil tests
- South Dakota DOT: typical liquid limit value and convert to a resilient modulus value
- Wisconsin DOT: No response

Question 10: What kind of soil parameter does your state agency typically use for local road design?

Answer:

- Illinois DOT: No response
- Missouri DOT: Resilient modulus (Mr)
- Minnesota DOT: Soil factor and/or R-value
- South Dakota DOT: Resilient modulus (Mr)
- Wisconsin DOT: k-value, soil support value (SSV), and design group index (DGI) base on pedology is primary. DGI ranges from 0 (best) to 20 with 10-14 being most common

Question 11: What type of paving materials and properties does your state agency use for local road design?

Answer:

- Illinois DOT: HMA (E; elastic modulus)
- Missouri DOT: Granular (CBR or Mr), HMA (E; elastic modulus) and PCC (E; elastic modulus, f'c; compressive strength, S'c ; flexible strength)
- Minnesota DOT: HMA (E; elastic modulus)
- South Dakota DOT: Granular (CBR or Mr), HMA (E; elastic modulus)
- Wisconsin DOT: Granular (CBR or Mr) and HMA (E; elastic modulus)

Question 12: What type of traffic input do you use for local road design?

Answer:

- Illinois DOT: ESAL (< 10,000; 10,000-50,000; 50,000-100,000)
- Missouri DOT: Load spectra in the MEPDG
- Minnesota DOT: ADT and ESAL (100,000-250,000)
- South Dakota DOT: ESAL (50,000-100,000)
- Wisconsin DOT: ADT and ESAL (10,000-50,000; 50,000-100,000)

Question 13: What type of drainage features does your agency commonly use for local road design?

Answer:

- Illinois DOT: Ditches
- Missouri DOT: Ditches
- Minnesota DOT: Ditches
- South Dakota DOT: Ditches
- Wisconsin DOT: Ditches

Question 14: Does your state agency use a serviceability index for local road pavement design?

Answer:

- Illinois DOT: No response
- Missouri DOT: PASER rating system (IRI and visual distress data)
- Minnesota DOT: QI – Ride quality Index, ranges from 0 -5 (best).
- South Dakota DOT: 4.5 to 2.5
- Wisconsin DOT: IRI, ranges from 0 -5 (worst)and PDI, ranges 0-100

Question 15: What level of the design reliability does your state agency use for local road?

Answer:

- Illinois DOT: No response
- Missouri DOT: 50%
- Minnesota DOT: 80%
- South Dakota DOT: 90%
- Wisconsin DOT: 50%

Question 16: What are the important characteristics of asphalt pavement for local road design?

Answer:

- Illinois DOT: No response
- Missouri DOT: Adequate structure and proper compaction of lower layers
- Minnesota DOT: Subgrade and ADT/HCADT
- South Dakota DOT: No response
- Wisconsin DOT: thickness, PG grade, gradation, asphalt content

Question 17: What are the important characteristics of concrete pavement for local road design?

Answer:

- Illinois DOT: No response
- Missouri DOT: Short joint spacing and proper compaction of lower layer
- Minnesota DOT: Subgrade and ADT/HCADT
- South Dakota DOT: traffic, subgrade, and loads
- Wisconsin DOT: N/A

2.3 Summary of Survey Results

The survey responses from five state departments of transportation are summarized in Table 2-3. South Dakota DOT uses the 1993 AASHTO design guide and the DARWIN Software to design low-volume road pavements. Illinois DOT developed a local agency pavement design procedure described in Ch. 37 of the BLRS Manual. Missouri DOT does not have a separate pavement design procedure for low-volume roads but uses the AASHTO 93 design guide and mechanistic-empirical pavement design guide (M-EPDG) software to design low-volume roads. The survey form and complete survey responses from five state DOT's are included in Appendix B.

Table 2-3. Summary of survey results on local road pavement thickness design procedures from five state DOT's

Q	Illinois DOT	Missouri DOT	Minnesota DOT	South Dakota DOT	Wisconsin DOT
1	Mechanistic Empirical Design developed by U of I and IL DOT	1993 AASHTO	Charts and tables for soil factor and R-value	1993 AASHTO	1972 AASHTO
2	None	Mechanistic-Empirical Pavement Design Guide	MnDOT Flexible MnDOT Rigid	DARWIN software	WisPave
3	400 ADT (Traffic Factor < 0.25)	less than 1000 AADT and less than a 100 trucks a day	ADT less than 1000	Don't have a low volume road classification	< 400 ADT
4	Conventional Flexible Design (Chapter 37-3 of the BLRS Manual)	No	Yes	No	No
5	Surface: HMA 3" Base: Class A Agg 8" Subgrade: Modified Soil 8"	Surface: HMA 7"-8" Base: crushed stone 4" Subgrade: N/A	Surface: HMA min 3" Base: Class 5 or 6, 6" Subgrade: Existing Soil	Surface: 3"-4" Base: 10"-12" Subgrade: 8" (if needed)	Surface: SuperPave E-0.3 12.5mm-3" Base: dense graded aggregate 8" Subgrade: N/A
6	No Response	Surface: JPCP 6"-7" Base: crushed stone 4" Subgrade: N/A	Surface: Concrete 7-9" Base: Class 5 or 6, 0-6" Subgrade: Existing Soil	Surface: 3"-4" Base: 10"-12" Subgrade 8" (if needed)	N/A
7	Traffic Paving Materials	Subgrade, Loads	Traffic, Subgrade	Traffic, Subgrade, Loads,	Traffic, Load, Pavement Performance, Criteria
8	No Response	A-4, A-7-5, and A-7-6	A-1 through A-6 and A-7-5 and A-7-6	A-6 to A-7	A-3, A-2-4, A-4, A-6, A-7-6

Table 2-3. Summary of survey results on local road pavement thickness design procedures from five state DOT's (conti.)

Q	Illinois DOT	Missouri DOT	Minnesota DOT	South Dakota DOT	Wisconsin DOT
9	No Response	Assume resilient modulus value from AASHTO class	R-Value derived from soil tests	Use the typical liquid limit value for the family of soils and convert that number to a resilient modulus value	No Response
10	No Response	Resilient Modulus (Mr)	Soil Factor and/or R-Value	Resilient Modulus (Mr)	k-value and SSV
11	HMA (E: elastic modulus)	Granular (CBR or Mr) HMA (E: elastic modulus) PCC(E: elastic modulus), f'c (compressive strength), S'c (flexural strength)	HMA (E: elastic modulus)	Granular (CBR or Mr) HMA (E: elastic modulus)	Granular (CBR or Mr) HMA (E: elastic modulus)
12	ESAL <10,000 10,000-50,000 50,000-100,000 100,000-250,000	Load spectra in the MEPDG	ADT ESAL 100,000 – 250,000	ESAL 50,000-100,000	ADT ESAL 10,000-50,000 50,000-100,000
13	Ditches	Ditches	Ditches	Ditches	Ditches
14	No Response	Use IRI and visible distress data	RQI – Ride quality Index, ranges from 0 -5 (best)	2.5 – 4.5	Use IRI and PDI
15	No Response	50%	80%	90%	50%
16	No Response	Adequate structure and proper compaction of lower layers	Subgrade and ADT/HCADT	Traffic Subgrade Loads	Thickness, PG grade Gradation, % AC
17	No Response	Short joint spacing and proper compaction of lower layers	Subgrade and ADT/HCADT	Not typically pave a low-volume road with PCCP	N/A

3. PAVEMENT THICKNESS DESIGN SOFTWARE PACKAGES USED IN IOWA

To minimize the life-cycle cost of maintaining pavements, it is critical to determine the most appropriate pavement thickness for a given traffic level, subgrade condition and environmental factor. There are several pavement software packages available which would give different pavement thicknesses for the similar soil and traffic conditions. In addition, the impacts of design parameters on the pavement thickness are not transparent to a user. Therefore, there is a critical need for comparing these software packages and identifying the critical design input parameters through the sensitivity analysis.

In the past, Bergeson and Barber (1998) developed a pavement design method for low-volume roads in Iowa by utilizing the reclaimed hydrated Class C fly ash as an aggregate for base and Sharma et al. (2005) developed a guide to improve the quality of subgrade and subbase. The following three pavement design software packages were evaluated on how they are different in determining design input parameters and their influences on the pavement thickness: 1) StreetPave software based on the ACPA thickness design for concrete highway and street pavements and PCA method (PCA 1984; ACPA 2006), 2) WinPAS software based on ASSHTO 1993 pavement design guide (ACPA 2006), and 3) APAI software based on pre-mechanistic/empirical AASHTO methodology (APAI 1990).

3.1 StreetPave Software

StreetPave is a concrete pavement thickness design software package tailored for local road pavements (PCA 1984; ACPA 2006). This software package generates the optimum concrete pavement thickness for city, municipal, county, and state roadways. ACPA claims that it incorporates an asphalt pavement design process based on the Asphalt Institute method and creates an equivalent asphalt design for the given load carrying capacity requirement. A life cycle cost analysis module allows a user to perform a detailed cost/benefits analysis. The input values include project information, traffic information, pavement design parameters and pavement maintenance schedule. As shown in Figure 3-1, the StreetPave software displays the optimum concrete thickness, the equivalent asphalt thickness and the life cycle cost analysis. It also provides the sensitivity analysis module with regards to k-value, concrete strength, design life, reliability and percentage of cracked slabs.

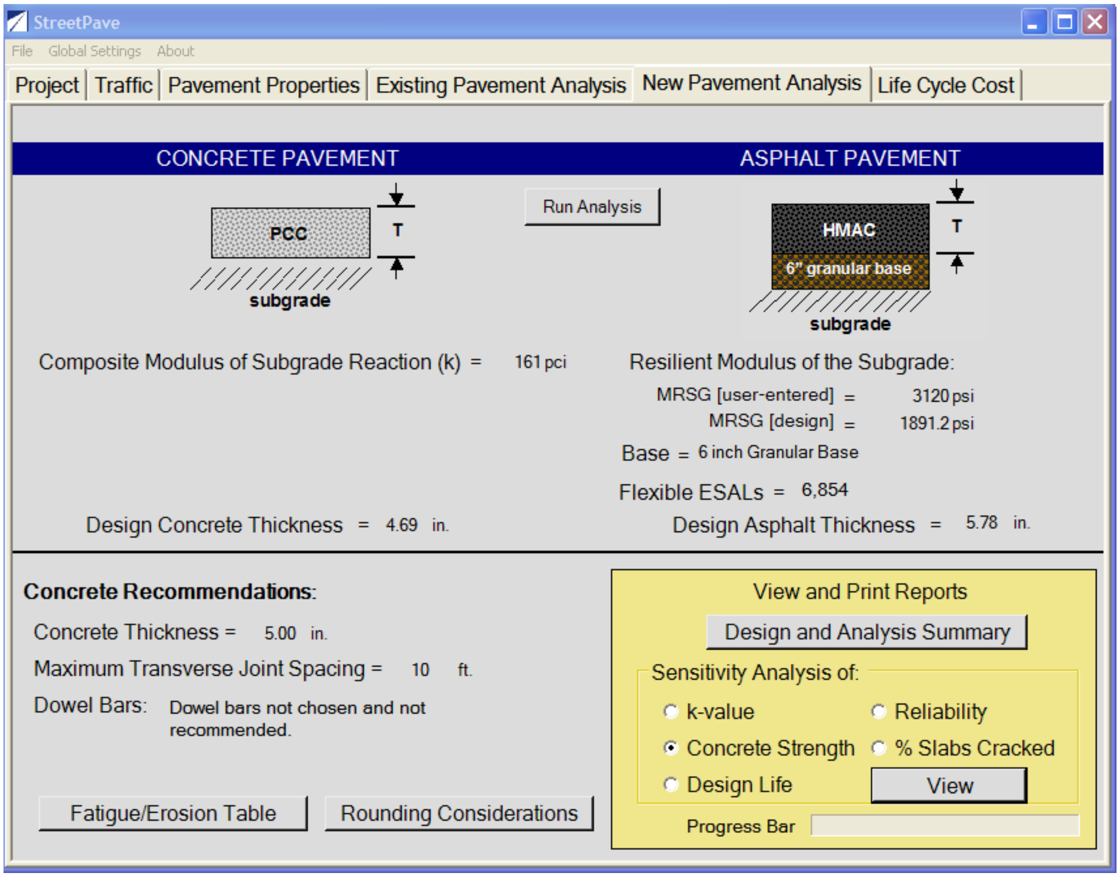


Figure 3-1. Screenshot of StreetPave pavement design software

According to the PCA design manual (1984), weights, frequencies, and type of truck axle loads are needed. But, if specific axle load data is not available, as shown in Table 3-1, a simple design table by PCA can be used that represents different categories of road and street type.

Table 3-1. Axle load categories used in StreetPave software

Axle Load Category	Description	Traffic			Maximum Axle Loads, kips	
		ADT	AADT			
			%	Per Day	Single Axles	Tandem Axles
1	Residential Streets Rural and secondary roads (low to medium)	200-800	1-3	Up to 25	22	36
2	Collector Streets Rural and secondary roads (high) Arterial streets and primary roads (low)	700-5,000	5-18	40-1,000	26	44
3	Arterial streets and primary roads (medium) Expressways and urban and rural interstate (low to medium)	3,000-12,000 (2 lane) 3,000-50,000 (4 lane or more)	8-30	500-5,000+	30	52
4	Arterial streets, primary roads , expressways (high) Urban and rural interstate (medium to high)	3,000-150,000 (4 lane or more)	8-30	1,500-8,000+	34	60

**High, medium, and low refer to the weights of axle loads for the type of street or road*

3.2 WinPAS Software

The WinPAS software package performs roadway pavement thickness design and evaluation following the AASHTO 1993 design guide for pavement structures (ACPA 2006). This software package also provides a life-cycle cost module to allow a user to compare alternative pavement designs. As shown in Figure 3-2, the input values include project information, traffic information and pavement design parameters. The report module prints out optimized concrete thickness design and the results of life cycle cost analysis in a predefined report format. This software package provides a simple user interface and an effective help module.

Table 3-2 shows a comparison between rigid and flexible ESAL's with the same traffic stream (ACPA 2006). As can be seen from Table 3-2, there is a significant difference between asphalt and concrete ESAL's where asphalt ESAL's are about 1/3 less than concrete.

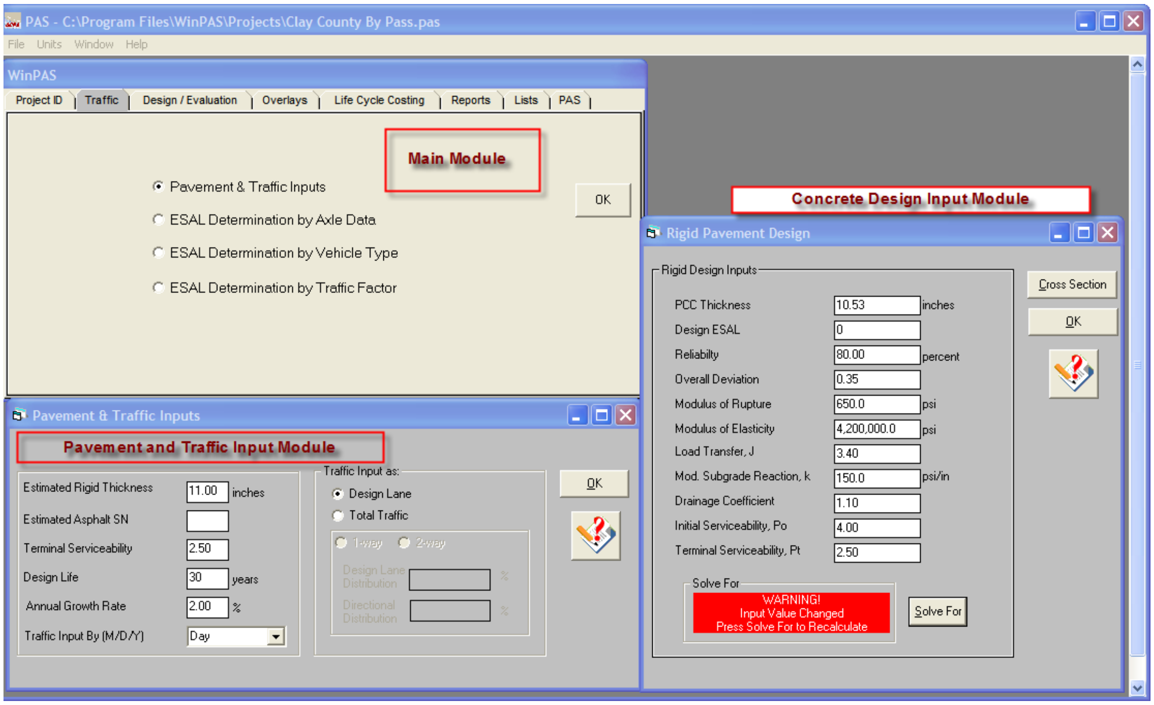


Figure 3-2. WinPAS pavement design software

Table 3-2. Concrete and asphalt ESAL's generated by a mixed traffic stream

Vehicle	Number	ESAL	
		Concrete	Asphalt
Busses	5	13.55	8.73
Panel Trucks	10	10.89	11.11
Single Unit, 2 axle trucks	20	6.38	6.11
Semi-Tractor Trailer, 3 axles	10	20.06	13.41
Semi-Tractor Trailer, 4 axles	15	39.43	29.88
Semi-Tractor Trailer, 5 axles	15	57.33	36.87
Automobile, Pick-up, Van	425	1.88	2.25
Total	500	149.52	108.36

3.3 APAI Software

The APAI asphalt pavement design software package was developed to help the user design asphalt pavements, which is based upon pre-mechanistic-empirical AASHTO methodology and Iowa SUDAS (APAI 1990). This software package is limited to traffic less than 30 million ESAL's. As shown in Figure 3-3, the APAI software calculates the required structure number (SN) which is then converted into a combination of thicknesses of surface layer, intermediate layer and base layer. The APAI software uses 0.44 as a surface layer's structural coefficient and 0.40 as intermediate and base layers' structural coefficients.

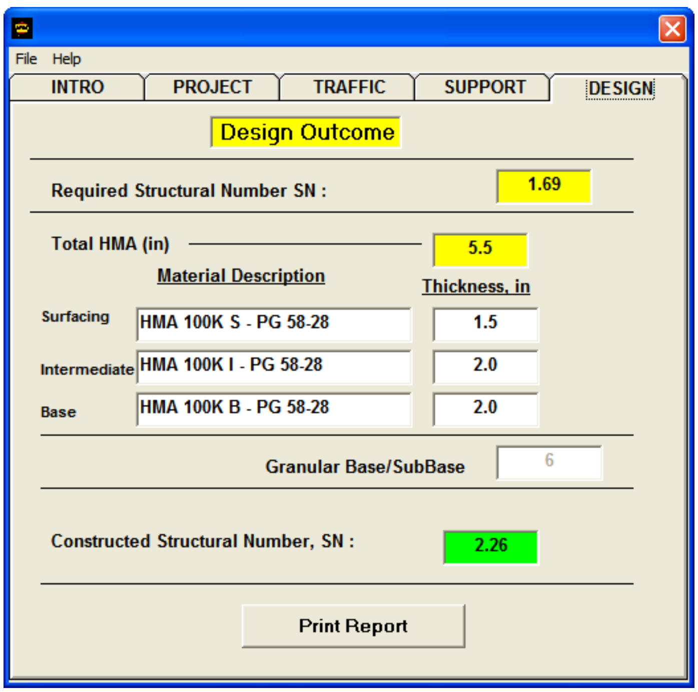


Figure 3-3 Screenshot of APAI pavement design software

APAI software estimates ESALs based on two cases: 1) generic traffic distributions for each category (rural-residential, urban-collector, etc.) and starting year ADT and growth rate, or 2) a user input on truck distribution and truck factor data and starting year ADT and growth rate. From these inputs and the reliability factor, the ESALs are estimated.

According to the AASHTO system, soils are grouped in classification of A-1 through A-7 where the classifications of the soils are based on the sieve analysis, plasticity index, and liquid limit. Figure 4-4 shows a general soil classification map of Iowa, which show relatively poor soils ranging from A-7-6 to A-4 (APAI 1990).

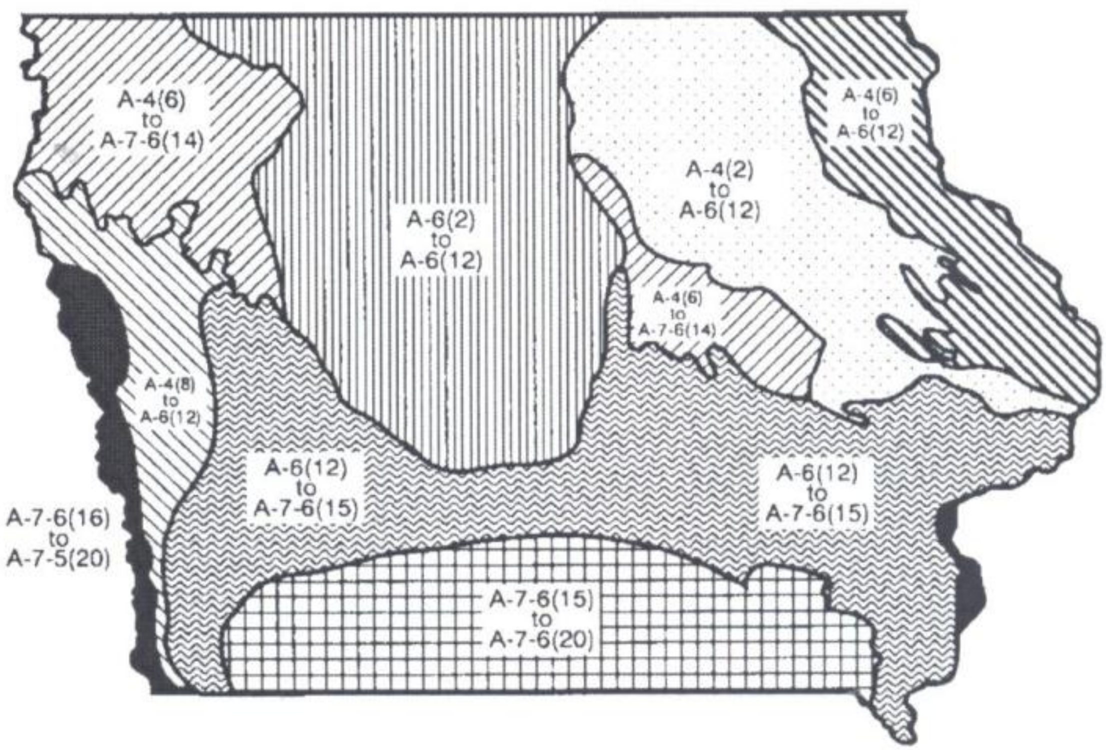


Figure 3-4. Approximate soil classification areas in Iowa (APAI 1990)

APAI software permits the use of either AASHTO or Unified soil classification. Having selected a soil type, say ML (Unified) or A-6 (AASHTO), an appropriate range of CBR can be found from a number of different sources. In the APAI software, the user can select a drainage quality. For example, if a granular layer is selected by the user, the APAI software assigns a layer coefficient of 0.125, which can be adjusted by the drainage condition.

The AASHTO flexible pavement design method does not use CBR, but uses resilient modulus. Therefore, to estimate resilient modulus, the APAI software computes the lesser of 1) M_r = 1500 x CBR and 2) $1941.488*CBR^{0.06844709}$. The reliability used in the AASHTO method is applied to the logarithm of the ESAL's and the APAI requires 80% as a minimum reliability.

4. SENSITIVITY ANALYSIS OF DESIGN INPUT PARAMETERS USING THREE PAVEMENT DESIGN SOFTWARE PACKAGES

The sensitivity analysis examined the design input parameters for each of three current pavement design software packages discussed earlier: StreetPave, WinPAS and APAI. As shown in Figure 4-1, four critical design input parameters were identified and the sensitivity analysis of each parameter was performed using each of three pavement design software packages.

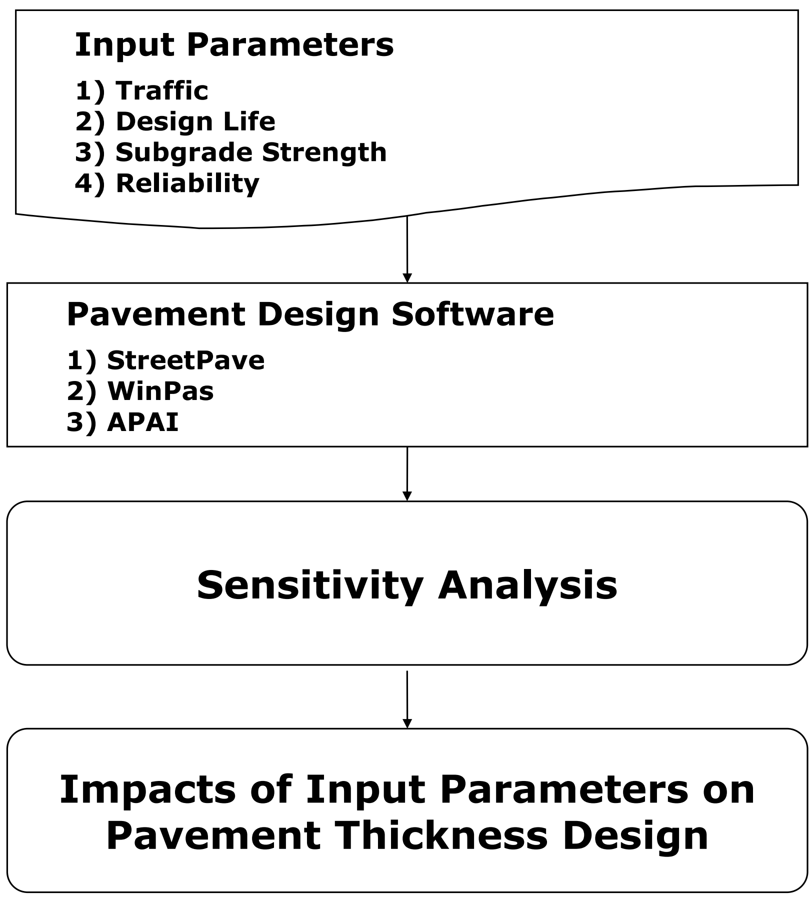


Figure 4-1. Sensitivity analysis flow chart of input parameters for pavement thickness design

4.1 Input Parameters

To identify the input parameters that affect the pavement thickness the most, the sensitivity analysis was performed. Table 4-1 and Table 4-2 show the common input parameters and traffic information, respectively, which were used in the sensitivity analysis. Average daily truck traffic (ADTT) was used as a traffic input parameter for all three software packages.

Table 4-1. Common design input parameters used for sensitivity analysis

Parameter	Input Values Used
Number of Lanes	2
Directional Distribution	50%
Design Lane Distribution	100%
Traffic Growth	2%
Terminal Serviceability (P_t)	2.0

Table 4-2. Traffic input parameters used for sensitivity analysis

Parameter	Input Values Used		
Road Classification	ADT	% Trucks	ADTT
Residential	100	5	20
Collector	1,000	10	100
Minor Arterial	1,665	15	250
Major Arterial 1	2,500	20	500
Major Arterial 2	4,000	20	1,000

The reliability is used in the AASHTO design equation in the form of Z_R S_0 where Z_R represents the normal deviate for a given reliability and S_0 is the standard deviation in the design equation. The standard deviation is the amount of statistical error present in the pavement design equation which represents the amount of scatter between predicted performance and actual performance and different values are often used for asphalt (typically 0.45) and concrete pavements (typically 0.35). Both WinPAS and APAI software packages use this reliability concept. However, StreetPave software applies the reliability to the flexural fatigue equation for concrete pavements and to the resilient modulus of the subgrade for asphalt pavements. All three pavement design software packages were run using two design lives of 20 and 40 years and three levels of reliability of 50%, 80%, and 90%. However, the APAI pavement design software could not be run for the 50% reliability because the lowest level allowed was 80%.

Additional inputs were needed for the APAI software to complete the design procedure. As shown in Figure 4-2, there is an option of choosing the truck type and the ESAL factor and, for this study, 33.3% panel truck, 33.3% Dump, and 33.4% Semi with an ESAL factor of 1.0 were used. This may represent about twice of the actual ESAL per truck in local roads in Iowa but it is adopted here for the relative comparisons only. We also applied the ESAL factor of 1.0 for WinPAS software but we could not do so for StreetPave software because it automatically generates ESAL from the ADTT. As shown in Figure 4-3, the APAI software has an option to select a drainage condition as: 1) good, 2) fair, 3) poor, and 4) bad/none. In all cases, to obtain lower CBR values, a bad/none drainage condition was chosen. As can be seen from Table 4-3, the WinPAS software requires the most amount of input parameters in order to complete the design procedure.

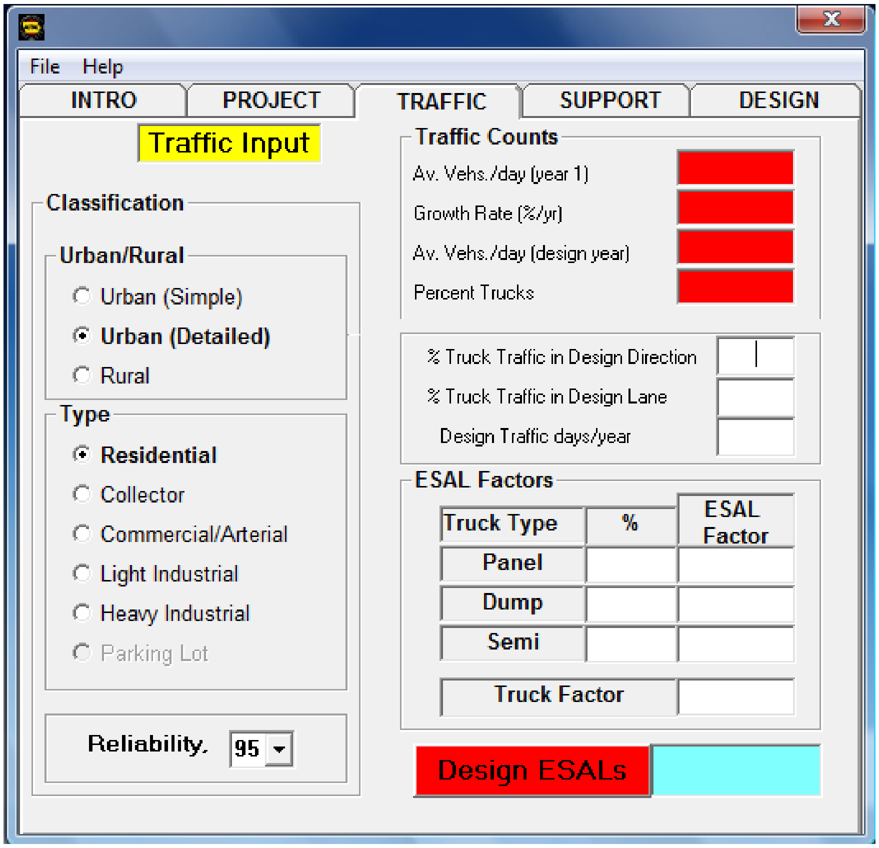


Figure 4-2. Traffic inputs required for APAI software

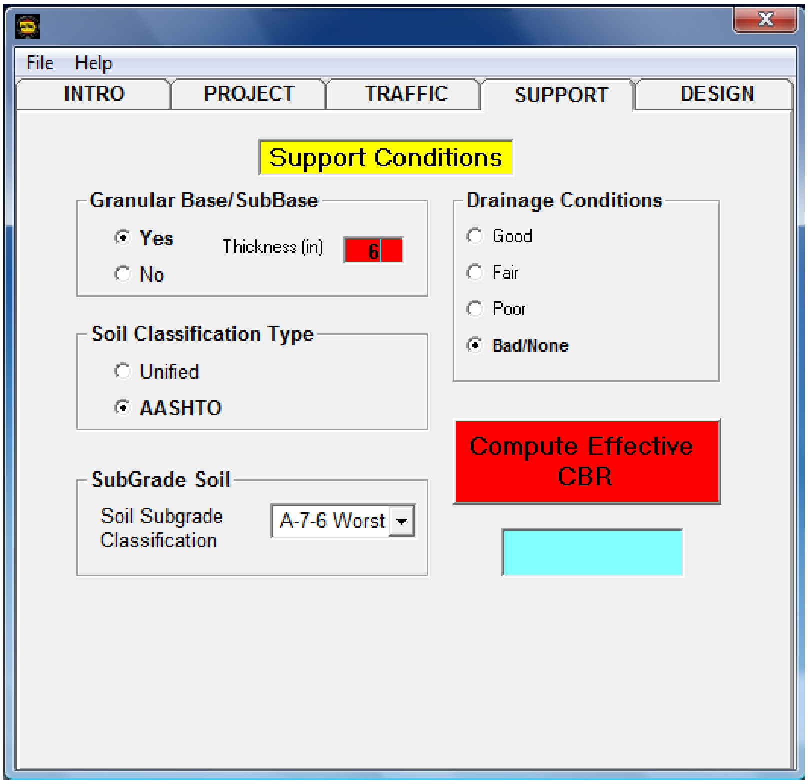


Figure 4-3. Subgrade inputs required for APAI software

Table 4-3. Additional input parameters required for WinPAS software

Parameter	Input Value Used
Overall Deviation	0.35 (Concrete), 0.45 (Asphalt)
Modulus of Rupture	650 psi
Modulus of Elasticity	4,200,000 psi
Load Transfer (J)	3.20
Drainage Coefficient	1.0
Initial Serviceability (P_0)	4.5

Each software package uses different terms in determining the subgrade strength; California Bearing Ratio (CBR) for APAI software, resilient modulus for StreetPave software and k-value for WinPAS software. For the APAI software, the following five CBR values of 2.9, 5.3, 9.0, 11.0 and 14.0 were used based on five soil types of A-7-6, A-

7-5, A-6, A-5, and A-4, respectively after adjusted for no/poor drainage condition. The APAI software converts these CBR values to resilient moduli of 4350 psi, 7429psi, 10426psi, 11854psi, and 15067psi. Following the StreetPave software manual, the equivalent resilient modulus values of 4350psi, 7950psi, 8735psi, 10020psi, and 11820psi were used for StreetPave software. The conversion from CBR to resilient modulus was based on 1500 *CBR (for CBR values of 2.9 and 5.3) and 1941.488* $CBR^{0.06844709}$ (for CBR values of 9.0, 11.0 and 14.0). It should be noted that the equivalent resilient modulus values used for StreetPave software were lower than the ones used for APAI software particularly for CBR values of 9.0, 11.0 and 14.0.

To design concrete pavement using, WinPAS converts the resilient modulus values to k-value using the relationship $k = M_R/19.4$ based on an analysis of a 30-inch plate bearing test. However, due to the small size of the plate used to develop this relationship, this conversion equation results in too large k-values. Therefore, using the conversion chart from CBR to k-value developed by Packard (1973), the following equivalent k-values were used for the WinPAS software: 97pci, 146pci, 190pci, 206pci and 222pci.

4.2 Analysis Results Using StreePave Software

4.2.1 Concrete Pavement

StreetPave software package recommends the concrete pavement a minimum thickness of 3.5 inches for 25 ADT with 1% truck traffic, 50% reliability, and the best subgrade strength whereas the AASTHO 1993 design guide recommends 5.0 inches as a minimum design thickness. Table 4-4 and Table 4-5 show the sensitivity analysis results of concrete pavement thickness and the diameter of the dowel bar for the design life of 20 years and 40 years, respectively. StreetPave software assume the edge support and recommend the dowel bar with a diameter of 1.5 inches for the pavement thickness greater than 10 inches; 1.25 inches for the pavement thickness between 8 and 10 inches; 1.0 inch for the pavement thickness less than 8 inches only when the erosion is a cause of failure. It should be noted that all tables include the design ESAL values that were generated by the software packages and they are quite different from the manually computed ESAL values with 2.0% annual growth rate. The ESAL values generated by StreetPave software reported as flexible ESAL's for the concrete pavement design which indicates the ESAL's are based on conversion factor for flexible pavements.

Figure 4-4 shows concrete pavement thickness against traffic level at low and high subgrade strengths for three different levels of reliability and the design life of 20 years. As can be seen from Figure 4-4, the pavement thickness is more sensitive to traffic at a lower traffic level up to 1.17 million (increase in thickness by 1.5 inches) than the higher traffic level from 1.17 million to 5.42 million ESAL (increase in thickness by 1.0 inch). Reliability had a limited impact on the thickness, increasing the thickness by up to 0.5 inch, when the reliability increased from 50% to 90%.

Table 4-4. Sensitivity analysis results of concrete pavement thickness for design life of 20 years using StreetPave Software

50% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)/ Dowel (in)	ESALs	Thickness (in)/ Dowel (in)	ESALs	Thickness (in)/ Dowel(in)	ESALs	Thickness (in)/ Dowel (in)	ESALs	Thickness (in)/ Dowel (in)	ESALs
Residential	20	1.0	177,371	4.51	45,504	4.12	45,039	4.06	44,962	3.97	44,843	3.88	44,723
Collector	100	1.0	886,855	5.20	242,016	4.78	240,964	4.71	240,749	4.62	240,458	4.51	240,082
Minor Arterial	250	1.0	2,217,138	6.08	1,170,882	5.61	1,172,185	5.54	1,172,229	5.44	1,172,220	5.32	1,172,101
Major Arterial	500	1.0	4,434,276	6.67	2,711,829	6.17	2,721,003	6.10	2,722,254	5.99	2,724,185	5.87	2,726,231
Major Arterial 2	1000	1.0	8,868,551	6.86	5,416,756	6.47	5,431,032	6.43	5,423,509	6.37	5,434,719	6.28	5,438,018

80% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	177,371	4.84	45,829	4.44	45,426	4.38	45,358	4.29	45,251	4.18	45,115
Collector	100	1.0	886,855	5.58	242,571	5.14	241,893	5.08	241,760	4.98	241,519	4.86	241,197
Minor Arterial	250	1.0	2,217,138	6.52	1,168,275	6.03	1,171,100	5.95	1,171,412	5.85	1,171,734	5.72	1,172,036
Major Arterial	500	1.0	4,434,276	7.16	2,703,173	6.63	2,712,564	6.55	2,714,039	6.44	2,716,070	6.31	2,718,461
Major Arterial 2	1000	1.0	8,868,551	7.35	5,400,218	6.82	5,418,194	6.74	5,421,096	6.63	5,425,127	6.49	5,430,293

90% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Recommend Thickness (in)	ESALs	Recommend Thickness (in)	ESALs
Residential	20	1.0	177,371	5.11	46,035	4.69	45,690	4.63	45,631	4.53	45,526	4.42	45,404
Collector	100	1.0	886,855	5.89	242,729	5.43	242,399	5.36	242,298	5.26	242,130	5.14	241,893
Minor Arterial	250	1.0	2,217,138	6.86	1,165,604	6.36	1,169,355	6.28	1,169,841	6.17	1,170,446	6.04	1,171,058
Major Arterial	500	1.0	4,434,276	7.53/1.0	2,697,421	6.99	2,706,076	6.91	2,707,486	6.79	2,709,639	6.66	2,712,012
Major Arterial 2	1000	1.0	8,868,551	7.74/1.0	5,389,176	7.19	5,405,350	7.10	5,408,364	6.99	5,412,153	6.85	5,417,114

Table 4-5. Sensitivity analysis results of concrete pavement thickness for design life of 40 years using StreetPave Software

50% Reliability

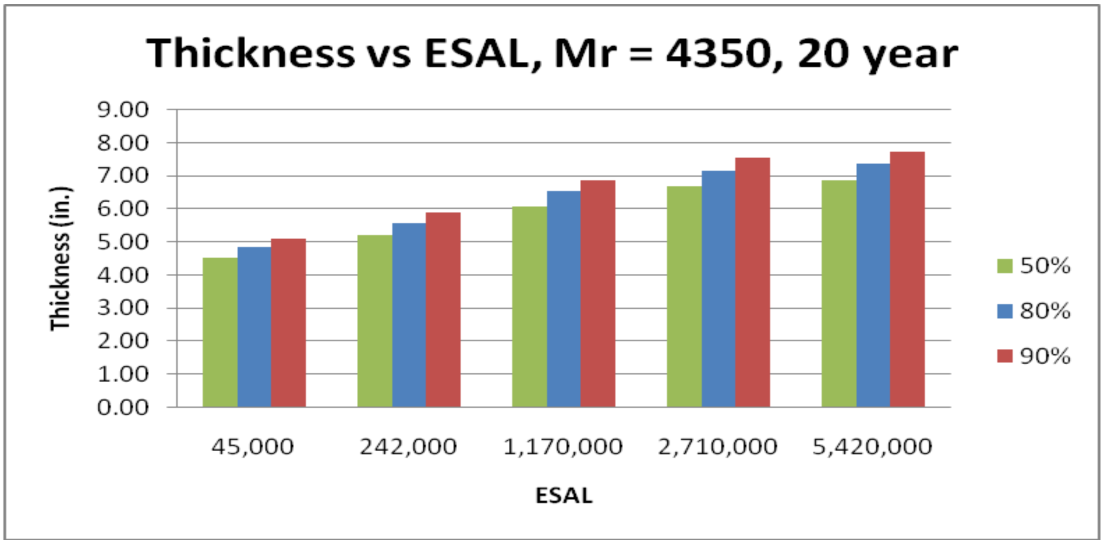
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi) M_R=4,350 Thickness(in)/ Dowel (in)	ESALs	M_R=7,950 Thickness(in)/ Dowel(in)	ESALs	M_R=8,735 Thickness(in)/ Dowel(in)	ESALs	M_R=10,020 Thickness (in)/ Dowel(in)	ESALs	M_R=11,820 Thickness (in)/ Dowel(in)	ESALs
Residential	20	1.0	440,935	4.70	113,608	4.30	112,521	4.24	112,340	4.15	112,060	4.05	111,740
Collector	100	1.0	2,204,673	5.41	602,523	4.97	600,339	4.91	599,946	4.81	599,245	4.70	598,411
Minor Arterial	250	1.0	5,511,683	6.30	2,907,870	5.86	2,912,797	5.82	2,913,071	5.76	2,913,424	5.68	2,913,783
Major Arterial	500	1.0	11,023,365	6.92/1.0	6,730,226	6.40/1.0	6,753,840	6.33/1.0	6,757,039	6.50	6,749,253	6.42	6,752,924
Major Arterial 2	1000	1.0	22,046,730	7.09/1.0	13,445,753	6.57/1.0	13,492,079	6.50/1.0	13,498,505	6.38/1.0	13,509,511	6.25/1.0	13,521,344

80% Reliability

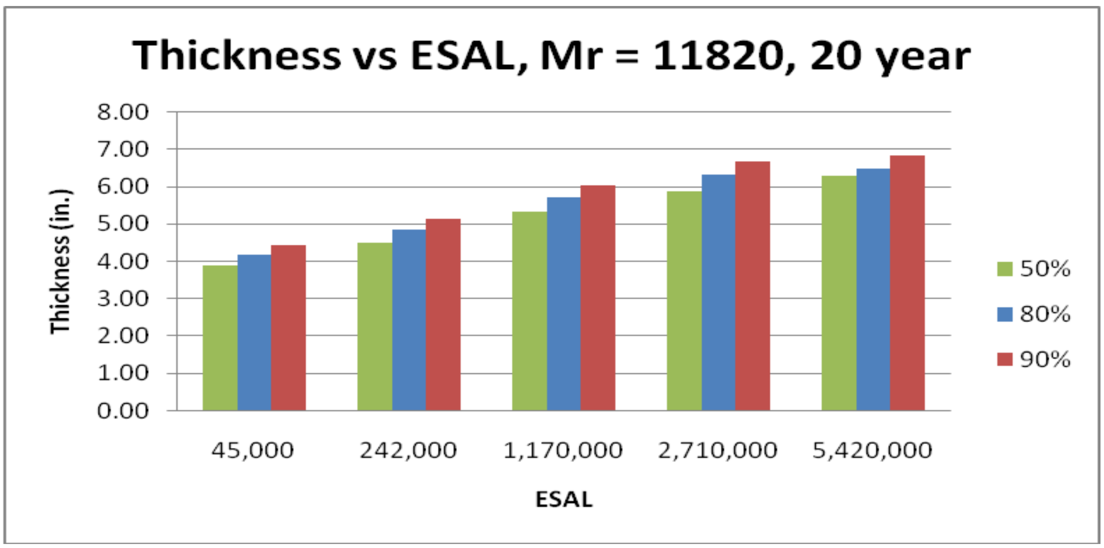
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi) M_R=4,350 Design Thickness (in)	ESALs	M_R=7,950 Design Thickness (in)	ESALs	M_R=8,735 Design Thickness (in)	ESALs	M_R=10,020 Design Thickness (in)	ESALs	M_R=11,820 Design Thickness (in)	ESALs
Residential	20	1.0	440,935	5.05	114,339	4.63	113,435	4.57	113,281	4.48	113,039	4.37	112,728
Collector	100	1.0	2,204,673	5.80	603,365	5.35	602,30	5.28	602,011	5.18	601,539	5.07	600,945
Minor Arterial	250	1.0	5,511,683	6.76	2,899,694	6.26	2,908,451	6.18	2,909,539	6.07	2,910,864	5.95	2,912,068
Major Arterial	500	1.0	11,023,365	7.41	6,710,040	6.88	6,731,995	6.80	6,735,571	6.68	6,741,007	6.55	6,746,957
Major Arterial 2	1000	1.0	22,046,730	7.60/1.25	13,406,408	7.05	13,449,156	6.97/1.0	13,456,068	6.86/1.0	13,465,770	6.72/1.0	13,478,375

90% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi) M_R=4,350 Design Thickness (in)	ESALs	M_R=7,950 Design Thickness (in)	ESALs	M_R=8,735 Design Thickness (in)	ESALs	M_R=10,020 Recommend Thickness (in)	ESALs	M_R=11,820 Recommend Thickness (in)	ESALs
Residential	20	1.0	440,935	5.33	114,750	4.90	114,054	4.83	113,906	4.74	113,703	4.62	113,410
Collector	100	1.0	2,204,673	6.12	603,295	5.65	603,164	5.58	603,018	5.47	602,720	5.35	602,301
Minor Arterial	250	1.0	5,511,683	7.12	2,891,971	6.60	2,902,812	6.52	2,904,271	6.41	2,906,15	6.28	2,908,163
Major Arterial	500	1.0	11,023,365	7.81/1.25	6,696,451	7.25	6,716,272	7.16	6,719,945	7.05	6,724,578	6.91	6,730,667
Major Arterial 2	1000	1.0	22,046,730	8.00/1.25	13,382,264	7.43	13,418,580	7.35	13,424,658	7.23	13,434,157	7.09	13,445,753



(a) Low subgrade strength



(b) High subgrade strength

Figure 4-4. Impacts of traffic level and reliability on concrete pavement thickness given low and high subgrade strength for 20 years of design life

Figure 4-5 shows an impact of traffic level and subgrade strength on concrete pavement thickness given the reliability of 80% and the design life of 20 years. It can be seen that the concrete pavement thickness was sensitive to the subgrade strength, with a decrease in thickness up to 1.0 inch, at the higher traffic level but not as sensitive to the subgrade strength, decreasing by only 0.5 inch at the lower traffic level. Figure 4-6 shows an impact of design life on concrete pavement thickness and, given 80% reliability, to double the design life, the pavement thickness needs to be increased by only 0.25 inch.

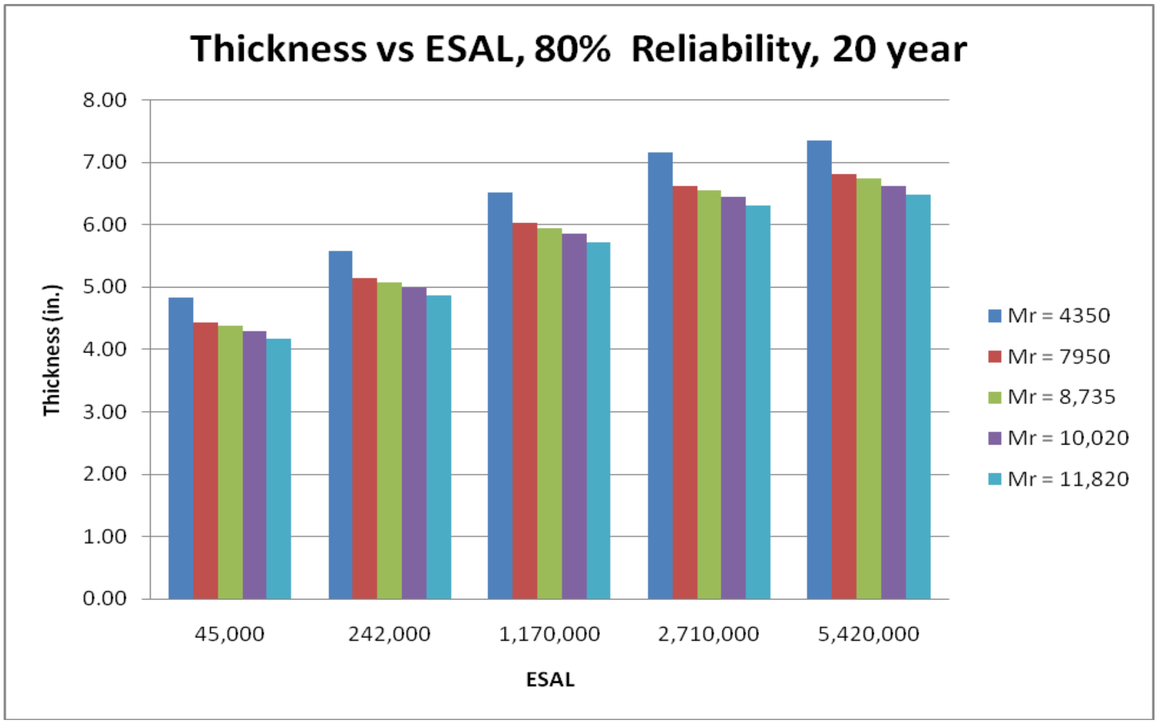


Figure 4-5. Impact of traffic level and subgrade strength on concrete pavement thickness given reliability of 80% and the design life of 20 years

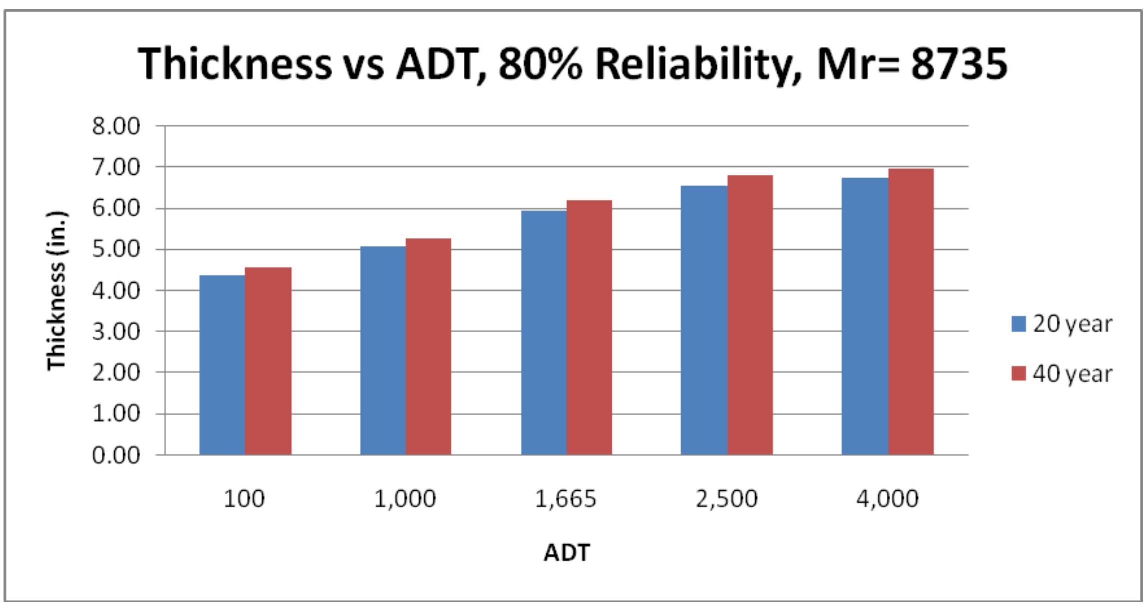


Figure 4-6. Impact of traffic level and design life at 80% reliability on concrete pavement thickness

4.2.2 Asphalt Pavement

For the lowest traffic level, the minimum thickness for asphalt pavement is 1.2 inches at 50% reliability and the best subgrade strength (3.5 inches for concrete pavement). Table 4-6 and Table 4-7 show the sensitivity analysis results of asphalt pavement thickness with 6-inch granular base for design life of 20 and 40 years, respectively.

Figure 4-7 shows impacts of traffic level and reliability on the asphalt pavement thickness for a given low and high subgrade strengths. The asphalt pavement thickness increased more rapidly at the low traffic level than at the high traffic level. Contrary to the concrete pavement, the reliability had a greater impact on the pavement thickness at the lower traffic level where asphalt pavement thickness increased by about 2.0 inches when the reliability increased from 50% to 90%. At the higher traffic level, asphalt pavement thickness increased by about 1.5 inches when the reliability increased from 50% to 90%.

Table 4-6. Sensitivity analysis results of asphalt pavement thickness for design life of 20 years using StreetPave software

50% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	177,371	4.75	45,504	3.11	45,039	2.87	44,962	2.54	44,843	2.16	44,723
Collector	100	1.0	886,855	6.52	242,016	4.95	240,964	4.71	240,749	4.37	240,458	3.98	240,082
Minor Arterial	250	1.0	2,217,138	8.67	1,170,882	7.21	1,172,185	6.98	1,172,229	6.65	1,172,220	6.26	1,172,101
Major Arterial	500	1.0	4,434,276	10.06	2,711,829	8.68	2,721,003	8.46	2,722,254	8.14	2,724,185	7.76	2,726,231
Major Arterial 2	1000	1.0	8,868,551	11.36	5,416,756	10.05	5,431,032	9.84	5,423,509	9.53	5,434,719	9.15	5,438,018

80% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	177,371	5.87	45,829	4.14	45,426	3.88	45,358	3.51	45,251	3.08	45,115
Collector	100	1.0	886,855	7.55	242,571	5.94	241,893	5.70	241,760	5.34	241,519	4.92	241,197
Minor Arterial	250	1.0	2,217,138	9.58	1,168,275	8.14	1,171,100	7.92	1,171,412	7.58	1,171,734	7.18	1,172,036
Major Arterial	500	1.0	4,434,276	10.90	2,703,173	9.57	2,712,564	9.35	2,714,039	9.04	2,716,070	8.65	2,718,461
Major Arterial 2	1000	1.0	8,868,551	12.13	5,400,218	10.90	5,418,194	10.70	5,421,096	10.39	5,425,127	10.02	5,430,293

90% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	177,371	6.71	46,035	4.93	45,690	4.66	45,631	4.28	45,526	3.82	45,404
Collector	100	1.0	886,855	8.30	242,729	6.69	242,399	6.44	242,298	6.08	242,130	5.64	241,893
Minor Arterial	250	1.0	2,217,138	10.21	1,165,604	8.82	1,169,355	8.60	1,169,841	8.27	1,170,446	7.87	1,171,058
Major Arterial	500	1.0	4,434,276	11.46	2,697,421	10.20	2,706,076	9.99	2,707,486	9.68	2,709,639	9.31	2,712,012
Major Arterial 2	1000	1.0	8,868,551	12.63	5,389,176	11.49	5,405,350	11.30	5,408,364	11.01	5,412,153	10.65	5,417,114

Table 4-7. Sensitivity analysis results of asphalt pavement thickness for design life of 40 years using StreetPave software

50% Reliability

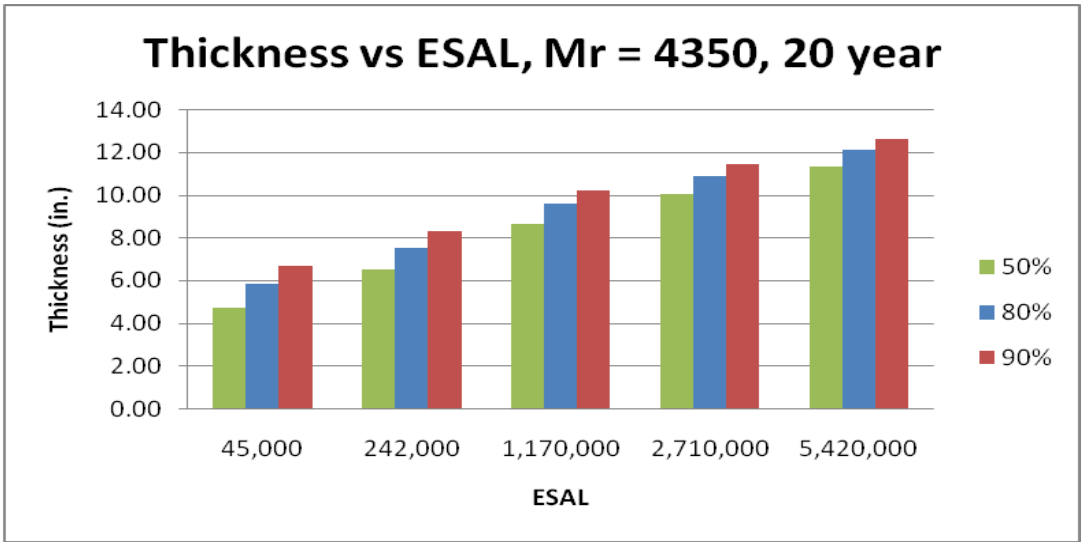
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	440,935	5.66	113,608	4.05	112,521	3.81	112,340	3.48	112,060	3.09	111,740
Collector	100	1.0	2,204,673	7.70	602,523	6.18	600,339	5.95	599,946	5.61	599,245	5.22	598,411
Minor Arterial	250	1.0	5,511,683	10.19	2,907,870	8.81	2,912,797	8.59	2,913,071	8.27	2,913,424	7.89	2,913,783
Major Arterial	500	1.0	11,023,365	11.80	6,730,226	10.52	6,753,840	10.31	6,757,039	10.00	6,749,253	9.62	6,752,924
Major Arterial 2	1000	1.0	22,046,730	13.30	13,445,753	12.10	13,492,079	11.90	13,498,505	11.61	13,509,511	11.25	13,521,344

80% Reliability

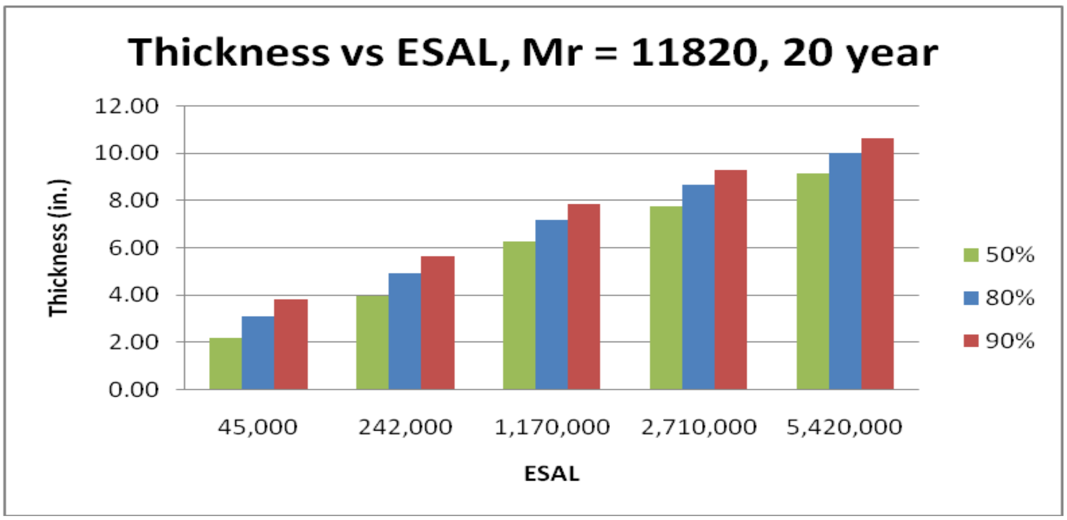
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	440,935	6.74	114,339	5.07	113,435	4.81	113,281	4.45	113,039	4.03	112,728
Collector	100	1.0	2,204,673	8.66	603,365	7.15	602,30	6.91	602,011	6.56	601,539	6.15	600,945
Minor Arterial	250	1.0	5,511,683	11.01	2,899,694	9.70	2,908,451	9.48	2,909,539	9.17	2,910,864	8.78	2,912,068
Major Arterial	500	1.0	11,023,365	12.54	6,710,040	11.35	6,731,995	11.15	6,735,571	10.85	6,741,007	10.49	6,746,957
Major Arterial 2	1000	1.0	22,046,730	13.97	13,406,408	12.88	13,449,156	12.70	13,456,068	12.42	13,465,770	12.07	13,478,375

90% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	440,935	7.54	114,750	5.84	114,054	5.58	113,906	5.21	113,703	4.76	113,410
Collector	100	1.0	2,204,673	9.35	603,295	7.86	603,164	7.62	603,018	7.28	602,720	6.86	602,301
Minor Arterial	250	1.0	5,511,683	11.57	2,891,971	10.33	2,902,812	10.12	2,904,271	9.81	2,906,15	9.43	2,908,163
Major Arterial	500	1.0	11,023,365	13.03	6,696,451	11.93	6,716,272	11.74	6,719,945	11.45	6,724,578	11.10	6,730,667
Major Arterial 2	1000	1.0	22,046,730	14.39	13,382,264	13.42	13,418,580	13.24	13,424,658	12.98	13,434,157	12.65	13,445,753



(a) Low subgrade strength



(b) High subgrade strength

Figure 4-7. Impacts of traffic level and reliability on asphalt pavement thickness given low and high subgrade strength and design life of 20 years

Figure 4-8 shows an impact of traffic level and subgrade strength on asphalt pavement thickness given a reliability of 80% and design life of 20 years. Contrary to the concrete pavement, the subgrade strength had the greatest impact on the pavement thickness at the lowest traffic level where the asphalt pavement thickness decreased by up to 3.0 inches. At the high traffic level, however, the asphalt pavement thickness decreased by up to 2.0 inches when the subgrade strength increased from 4,350psi to 11,820psi.

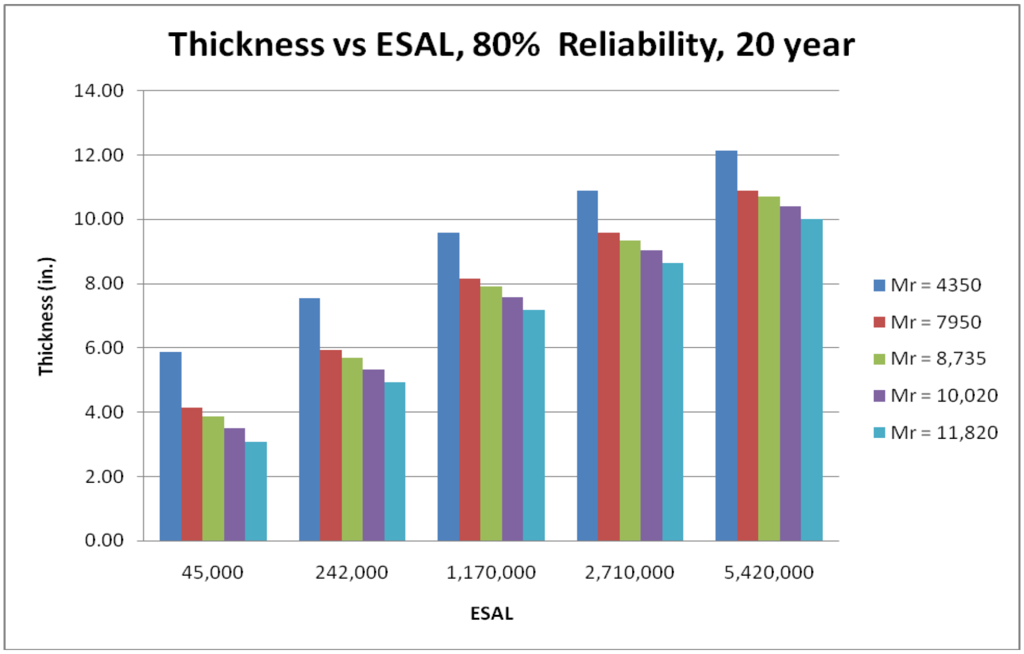


Figure 4-8. Impact of traffic level and subgrade strength on asphalt pavement thickness given reliability of 80% and design life of 20 years

4.3 Analysis Results Using WinPAS Software

4.3.1 Concrete Pavement

The minimum concrete pavement design thickness allowed is 4.0 inches at a traffic level of 1000 ADT with 2% truck. Table 4-8 and Table 4-9 show the sensitivity analysis results of the concrete pavement thicknesses without dowel (load transfer factor of 3.2) and with dowel (load transfer factor of 2.7) for design life of 20 years and 40 years, respectively. As can be seen from these tables, the use of dowel would consistently reduce the pavement thickness by 0.5 to 0.75 inch. Unless mentioned otherwise, the default load transfer value used for WinPAS software is 3.2. Figure 4-9 shows impacts of traffic level and reliability on the concrete pavement thickness for a given low and high subgrade strengths. As shown in Figure 4-9, traffic had the greatest impact on the concrete pavement thickness as the concrete pavement thickness increased by 3.0 to 4.0 inches when traffic increased from low to high level. Reliability had the greater impact at the higher traffic level, with the thickness increasing by about 1.25 inches when the reliability increased from 50% to 90%. At the low traffic level, the pavement thickness increased by only 0.5 to 1.0 inch when the reliability increased from 50% to 90%.

Table 4-8. Sensitivity analysis results of concrete pavement thickness for design life of 20 years using WinPAS software

50% Reliability													
				k-value (pci)									
				k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	177,371	4.00/4.00	88,746	4.00/4.00	88,746	4.00/n.a.	88,746	4.00/n.a	88,746	N/A	N/A
Collector	100	1.0	886,855	4.98/4.47	443,731	4.78/4.23	443,731	4.57/4.02	443,731	4.50/4.00	443,731	4.44/4.00	443,731
Minor Arterial	250	1.0	2,217,138	5.85/5.26	1,109,327	5.64/5.04	1,109,327	5.47/4.86	1,109,327	5.42/4.74	1,109,327	5.36/4.74	1,109,327
Major Arterial	500	1.0	4,434,276	6.59/5.94	2,218,654	6.39/5.73	2,218,654	6.24/5.56	2,218,654	6.18/5.45	2,218,654	6.13/5.45	2,218,654
Major Arterial 2	1000	1.0	8,868,551	7.40/6.69	4,437,307	7.21/6.49	4,437,307	7.06/6.33	4,437,307	7.01/6.23	4,437,307	6.97/6.23	4,437,307

80% Reliability													
				k-value (pci)									
				k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	177,371	4.21/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746
Collector	100	1.0	886,855	5.61/5.04	443,731	5.40/4.82	443,731	5.23/4.63	443,731	5.17/4.57	443,731	5.11/4.50	443,731
Minor Arterial	250	1.0	2,217,138	6.58/5.32	1,109,327	6.37/5.71	1,109,327	6.22/5.54	1,109,327	6.16/5.49	1,109,327	6.11/5.43	1,109,327
Major Arterial	500	1.0	4,434,276	7.39/6.67	2,218,654	7.19/6.47	2,218,654	7.04/6.31	2,218,654	6.99/6.26	2,218,654	6.95/6.21	2,218,654
Major Arterial 2	1000	1.0	8,868,551	8.26/7.49	4,437,307	8.07/7.30	4,437,307	7.93/7.15	4,437,307	7.89/7.10	4,437,307	7.85/7.05	4,437,307

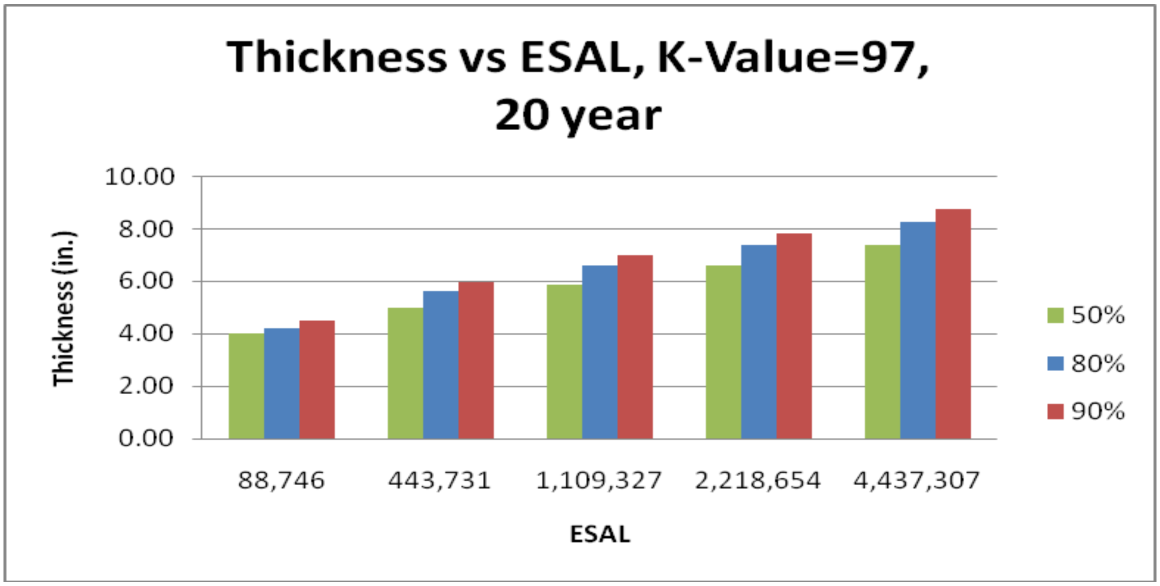
90% Reliability													
				k-value (pci)									
				k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	177,371	4.49/4.02	88,746	4.25/4.00	88,746	4.05/4.00	88,746	4.00/4.00	88,746	4.00/4.00	88,746
Collector	100	1.0	886,855	5.97/5.37	443,731	5.76/5.15	443,731	5.60/4.97	443,731	5.54/4.91	443,731	5.48/4.85	443,731
Minor Arterial	250	1.0	2,217,138	6.98/6.30	1,109,327	6.78/6.09	1,109,327	6.63/5.93	1,109,327	6.58/5.88	1,109,327	6.53/5.82	1,109,327
Major Arterial	500	1.0	4,434,276	7.83/7.08	2,218,654	7.63/6.89	2,218,654	7.49/6.73	2,218,654	7.44/6.68	2,218,654	7.40/6.64	2,218,654
Major Arterial 2	1000	1.0	8,868,551	8.73/7.93	4,437,307	8.55/7.74	4,437,307	8.42/7.60	4,437,307	8.37/7.56	4,437,307	8.33/7.51	4,437,307

Table 4-9. Sensitivity analysis results of concrete pavement thickness for design life of 40 years using WinPAS software

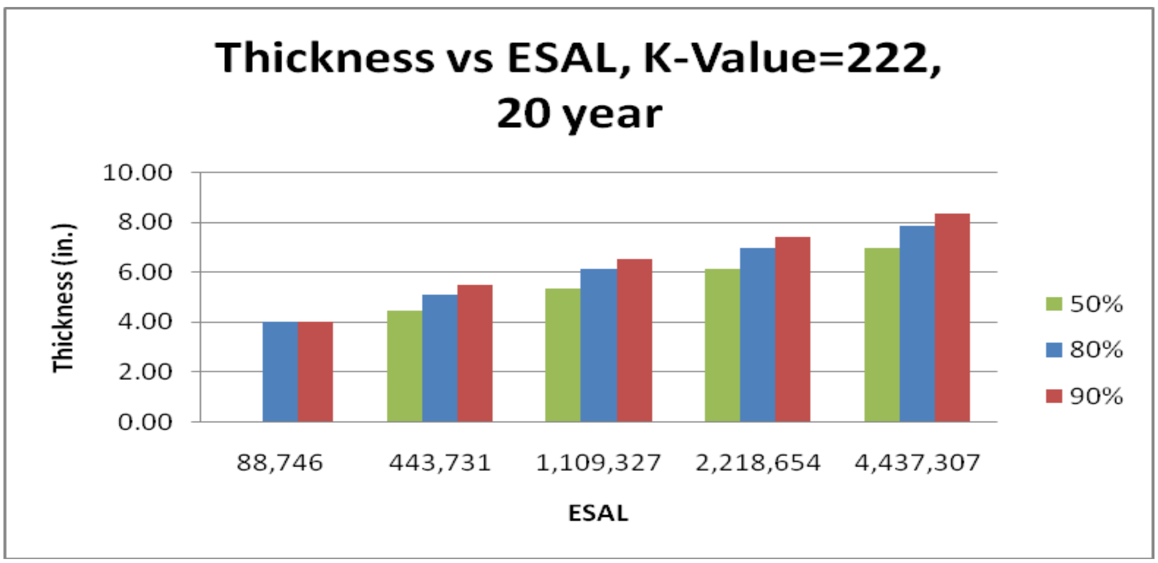
50% Reliability													
				k-value (pci)									
				k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	440,935	4.40/4.00	220,618	4.15/4.00	220,618	4.00/4.00	220,618	4.00/4.00	220,618	4.00/4.00	220,618
Collector	100	1.0	2,204,673	5.85/5.25	1,103,091	5.63/5.03	1,103,091	5.46/4.86	1,103,091	5.41/4.79	1,103,091	5.35/4.73	1,103,091
Minor Arterial	250	1.0	5,511,683	6.84/6.17	2,757,728	6.64/5.96	2,757,728	6.49/5.80	2,757,728	6.44/5.74	2,757,728	6.39/5.69	2,757,728
Major Arterial	500	1.0	11,023,365	7.67/6.94	5,515,456	7.48/6.74	5,515,456	7.34/6.59	5,515,456	7.29/6.54	5,515,456	7.24/6.49	5,515,456
Major Arterial 2	1000	1.0	22,046,730	8.57/7.78	11,030,912	8.39/7.59	11,030,912	8.25/7.44	11,030,912	8.20/7.40	11,030,912	8.16/7.35	11,030,912

80% Reliability													
				k-value (pci)									
				k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	440,935	4.96/4.45	220,618	4.73/4.21	220,618	4.55/4.00	220,618	4.48/4.00	220,618	4.42/4.00	220,618
Collector	100	1.0	2,204,673	6.57/5.92	1,103,091	6.375.70	1,103,091	6.21/5.54	1,103,091	6.16/5.48	1,103,091	6.10/5.43	1,103,091
Minor Arterial	250	1.0	5,511,683	7.65/6.92	2,757,728	7.46/6.72	2,757,728	7.32/6.57	2,757,728	7.27/6.52	2,757,728	7.22/6.47	2,757,728
Major Arterial	500	1.0	11,023,365	8.55/7.76	5,515,456	8.36/7.57	5,515,456	8.23/7.43	5,515,456	8.18/7.38	5,515,456	8.14/7.33	5,515,456
Major Arterial 2	1000	1.0	22,046,730	9.52/8.66	11,030,912	9.34/8.48	11,030,912	9.21/8.34	11,030,912	9.17/8.34	11,030,912	9.13/8.25	11,030,912

90% Reliability													
				k-value (pci)									
				k-value = 97		k-value = 146		k-value = 190		k-value = 206		k-value = 222	
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs	Design Thickness (in)	ESALs
Residential	20	1.0	440,935	5.28/4.74	220,618	5.06/4.51	220,618	4.89/4.32	220,618	4.82/4.25	220,618	4.76/4.18	220,618
Collector	100	1.0	2,204,673	6.98/6.29	1,103,091	6.78/6.09	1,103,091	6.63/5.93	1,103,091	6.57/5.87	1,103,091	6.53/5.82	1,103,091
Minor Arterial	250	1.0	5,511,683	8.10/7.34	2,757,728	7.92/7.15	2,757,728	7.78/7.00	2,757,728	7.73/6.95	2,757,728	7.68/6.90	2,757,728
Major Arterial	500	1.0	11,023,365	9.04/8.21	5,515,456	8.86/8.03	5,515,456	8.72/7.89	5,515,456	8.68/7.84	5,515,456	8.63/7.80	5,515,456
Major Arterial 2	1000	1.0	22,046,730	10.06/9.16	11,030,912	9.88/8.98	11,030,912	9.75/8.84	11,030,912	9.71/8.80	11,030,912	9.66/8.76	11,030,912



(a) Low subgrade strength



(b) High subgrade strength

Figure 4-9. Impacts of traffic level and reliability on concrete pavement thickness given low and high subgrade strength and design life of 20 years

Figure 4-10 shows an impact of traffic level and subgrade strength on concrete pavement thickness given a reliability of 80% and design life of 20 years. Traffic had a greater impact on concrete pavement thickness than the subgrade strength. The concrete pavement thickness was not sensitive to subgrade strength because the thickness decreased by only 0.5 inch when the subgrade strength increased from 97 pci to 222 pci.

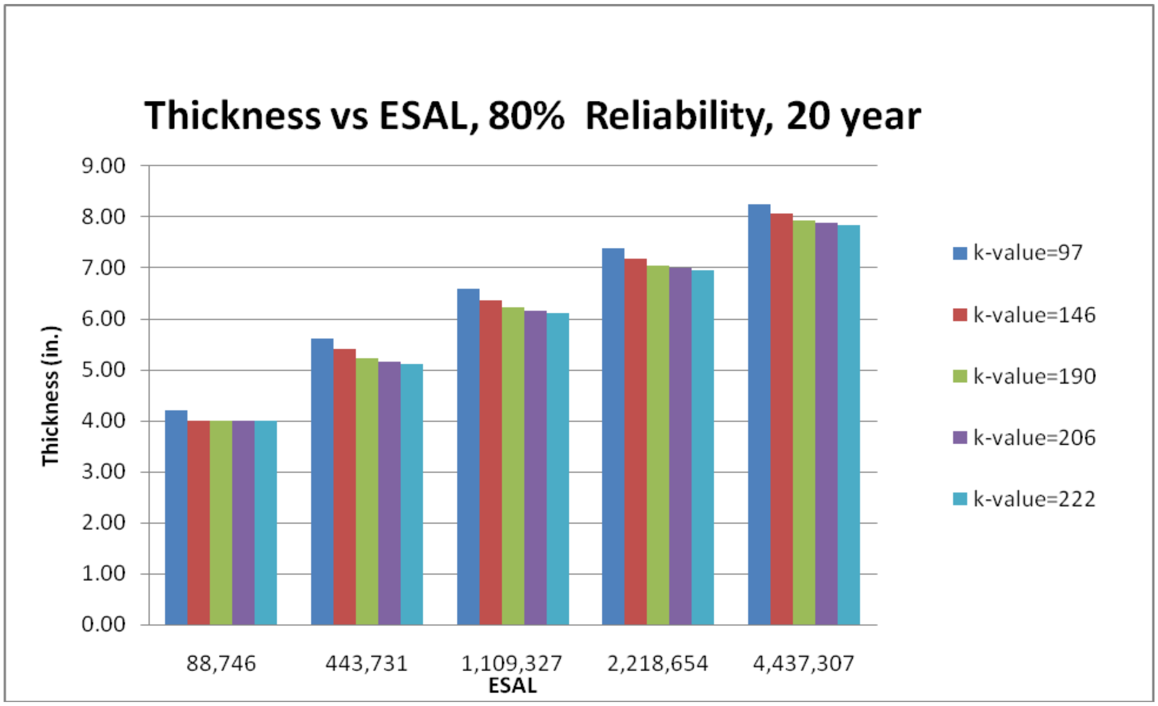


Figure 4-10. Impact of traffic level and subgrade strength on concrete pavement thickness given reliability of 80% and design life of 20 years

4.3.2 Asphalt Pavement

For the lowest traffic level, using the WinPAS software, the minimum asphalt pavement design thickness is 3.6 inches at a traffic level of 230 ADT with 1% truck. Table 4-10 and Table 4-11 show the sensitivity analysis results of asphalt pavement thickness for design life of 20 and 40 years, respectively.

Figure 4-11 shows impacts of traffic level and reliability on the asphalt pavement thickness for a given low and high subgrade strengths. As shown in Figure 4-11, traffic had the greatest impact on the asphalt pavement thickness as the asphalt pavement thickness was increased by 4.0 inches to 4.5 inches when traffic increased from low to high level. Reliability had the greater impact at the higher traffic level, with asphalt pavement thickness increasing by about 1.5 inches when the reliability increased from 50% to 90%.

Figure 4-12 shows an impact of traffic level and subgrade strength on the asphalt pavement thickness for a given a reliability of 80% and design life of 20 years. The subgrade strength had the greatest impact at the high traffic level, decreasing the thickness by 2.5 inches when the subgrade strength increased from 4,350psi to 11,820psi.

Table 4-10. Sensitivity analysis results of asphalt pavement thickness for design life of 20 years using WinPAS software

50% Reliability													
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	177,371	5.11	88,746	4.07	88,746	3.93	88,746	3.73	88,746	3.48	88,746
Collector	100	1.0	886,855	6.52	443,731	5.27	443,731	5.09	443,731	4.86	443,731	4.57	443,731
Minor Arterial	250	1.0	2,217,138	7.45	1,109,327	6.07	1,109,327	5.86	1,109,327	5.59	1,109,327	5.27	1,109,327
Major Arterial	500	1.0	4,434,276	8.23	2,218,654	6.73	2,218,654	6.52	2,218,654	6.20	2,218,654	5.86	2,218,654
Major Arterial 2	1000	1.0	8,868,551	9.05	4,437,307	7.43	4,437,307	7.20	4,437,307	6.89	4,437,307	6.50	4,437,307
80% Reliability													
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	177,371	5.84	88,746	4.70	88,746	4.55	88,746	4.32	88,746	4.05	88,746
Collector	100	1.0	886,855	7.41	443,731	6.02	443,731	5.84	443,731	5.57	443,731	5.25	443,731
Minor Arterial	250	1.0	2,217,138	8.43	1,109,327	6.91	1,109,327	6.68	1,109,327	6.39	1,109,327	6.02	1,109,327
Major Arterial	500	1.0	4,434,276	9.27	2,218,654	7.64	2,218,654	7.39	2,218,654	7.07	2,218,654	6.68	2,218,654
Major Arterial 2	1000	1.0	8,868,551	10.18	4,437,307	8.41	4,437,307	8.16	4,437,307	7.80	4,437,307	7.39	4,437,307
90% Reliability													
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	177,371	6.25	88,746	5.05	88,746	4.89	88,746	4.64	88,746	4.36	88,746
Collector	100	1.0	886,855	7.91	443,731	6.45	443,731	6.25	443,731	5.95	443,731	5.61	443,731
Minor Arterial	250	1.0	2,217,138	8.98	1,109,327	7.36	1,109,327	7.14	1,109,327	6.82	1,109,327	6.45	1,109,327
Major Arterial	500	1.0	4,434,276	9.86	2,218,654	8.14	2,218,654	7.89	2,218,654	7.55	2,218,654	7.14	2,218,654
Major Arterial 2	1000	1.0	8,868,551	10.82	4,437,307	8.95	4,437,307	8.68	4,437,307	8.32	4,437,307	7.89	4,437,307

Table 4-11. Sensitivity analysis results of asphalt pavement thickness for design life of 40 years using WinPAS software

50% Reliability

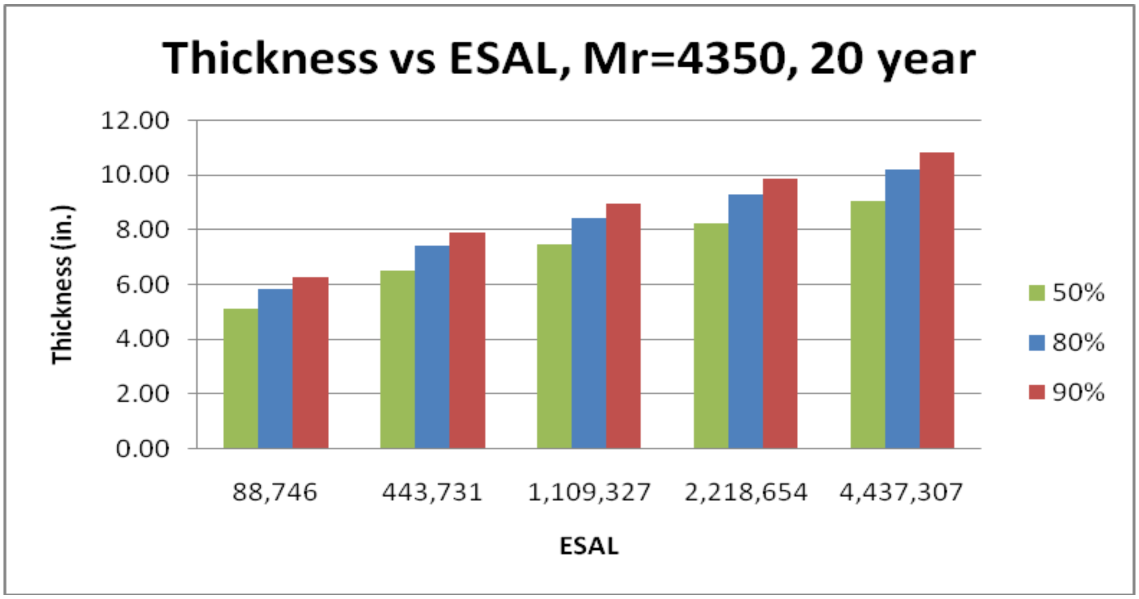
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	440,935	5.89	220,618	4.73	220,618	4.57	220,618	4.34	220,618	4.07	220,618
Collector	100	1.0	2,204,673	7.43	1,103,091	6.07	1,103,091	5.86	1,103,091	5.59	1,103,091	5.27	1,103,091
Minor Arterial	250	1.0	5,511,683	8.48	2,757,728	6.93	2,757,728	6.73	2,757,728	6.41	2,757,728	6.07	2,757,728
Major Arterial	500	1.0	11,023,365	9.32	5,515,456	7.66	5,515,456	7.43	5,515,456	7.09	5,515,456	6.73	5,515,456
Major Arterial 2	1000	1.0	22,046,730	10.23	11,030,912	8.45	11,030,912	8.20	11,030,912	7.84	11,030,912	7.43	11,030,912

80% Reliability

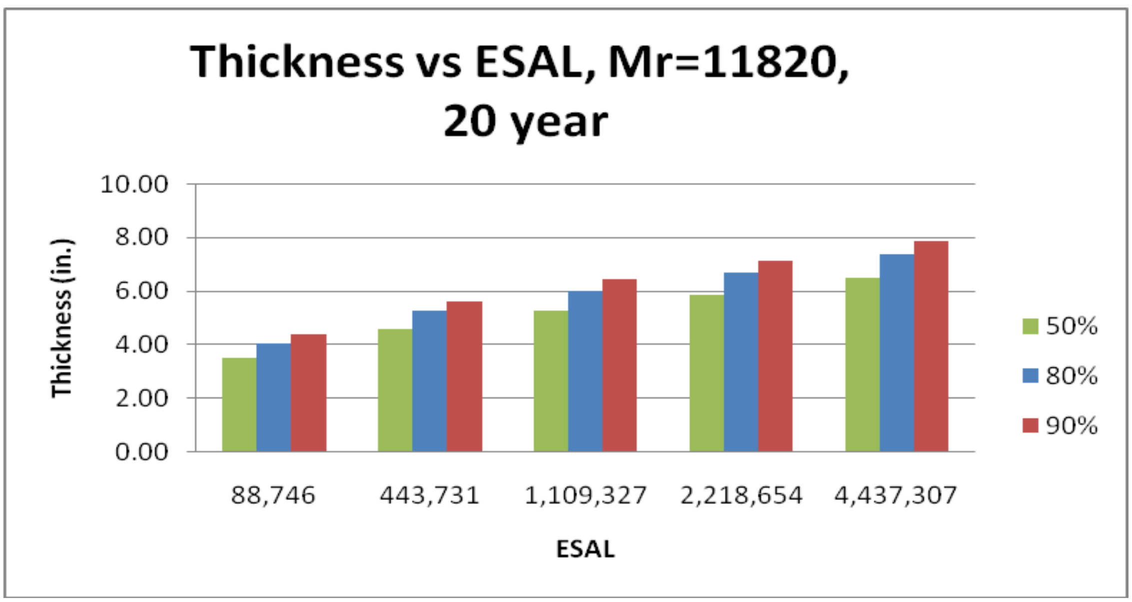
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	440,935	6.68	220,618	5.43	220,618	5.25	220,618	4.98	220,618	4.68	220,618
Collector	100	1.0	2,204,673	8.41	1,103,091	6.89	1,103,091	6.68	1,103,091	6.39	1,103,091	6.02	1,103,091
Minor Arterial	250	1.0	5,511,683	9.55	2,757,728	7.86	2,757,728	7.64	2,757,728	7.30	2,757,728	6.89	2,757,728
Major Arterial	500	1.0	11,023,365	10.48	5,515,456	8.66	5,515,456	8.41	5,515,456	8.05	5,515,456	7.61	5,515,456
Major Arterial 2	1000	1.0	22,046,730	11.48	11,030,912	9.52	11,030,912	9.25	11,030,912	8.86	11,030,912	8.41	11,030,912

90% Reliability

Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	Resilient Modulus, M_r (psi)									
				M_R=4,350		M_R=7,950		M_R=8,735		M_R=10,020		M_R=11,820	
				Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs	Thickness (in)	ESALs
Residential	20	1.0	440,935	7.16	220,618	5.82	220,618	5.61	220,618	5.36	220,618	5.05	220,618
Collector	100	1.0	2,204,673	8.98	1,103,091	7.36	1,103,091	7.14	1,103,091	6.82	1,103,091	6.45	1,103,091
Minor Arterial	250	1.0	5,511,683	10.16	2,757,728	8.39	2,757,728	8.14	2,757,728	7.77	2,757,728	7.36	2,757,728
Major Arterial	500	1.0	11,023,365	11.14	5,515,456	9.23	5,515,456	8.95	5,515,456	8.57	5,515,456	8.11	5,515,456
Major Arterial 2	1000	1.0	22,046,730	12.18	11,030,912	10.14	11,030,912	9.84	11,030,912	9.43	11,030,912	8.95	11,030,912



(a) Low subgrade strength



(b) High subgrade strength

Figure 4-11. Impacts of traffic level and reliability on asphalt pavement thickness given low and high subgrade strength and design life of 20 years

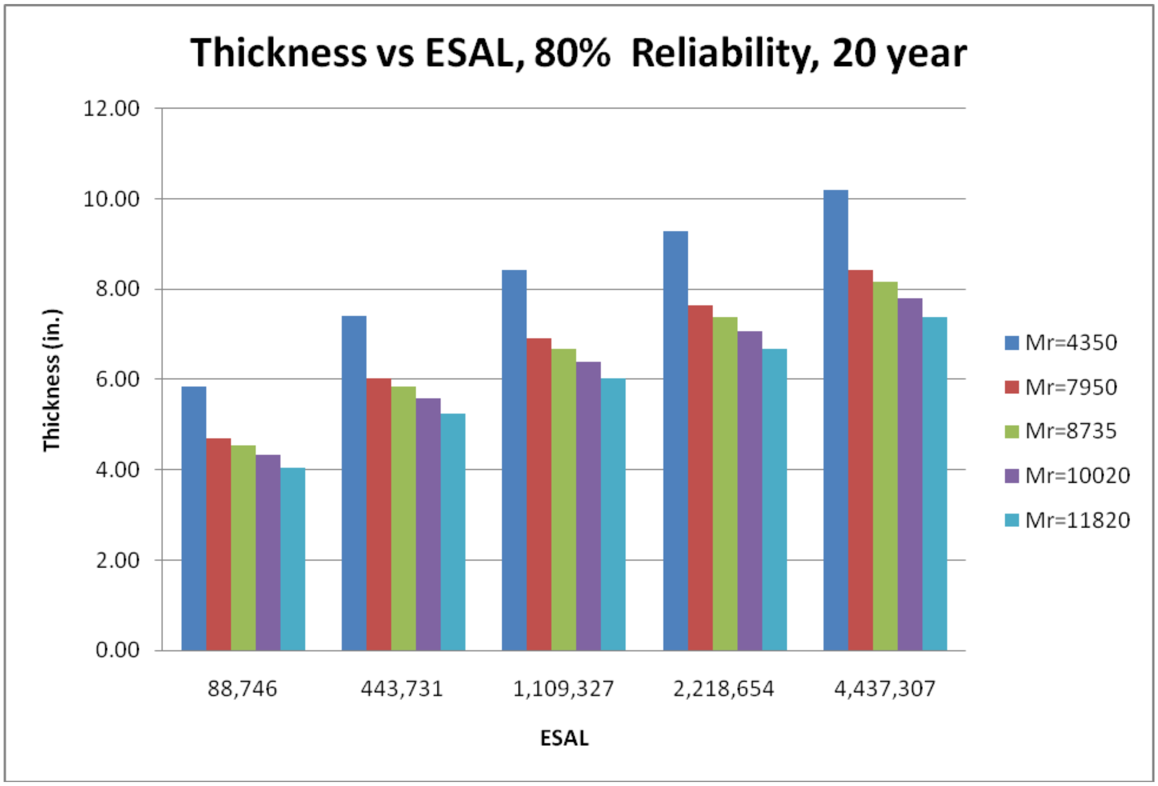


Figure 4-12. Impact of traffic level and subgrade strength on asphalt pavement thickness given reliability of 80% and design life of 20 years

4.4 Analysis Results Using APAI Software

The APAI software reports the thickness for the surface layer, intermediate layer, and base layer as well as the constructed structural number (SN) and type of pavement material and binder to use. To determine the thickness of the surface layer without intermediate and base layers, the SN was divided by the typical asphalt surface layer coefficient of 0.44. The minimum pavement design thickness is SN of 1.28, which corresponds to 2.9 inches of the surface layer. Table 4-12 and Table 4-13 show the sensitivity analysis results of asphalt pavement thickness for design lives of 20 years and 40 years, respectively.

Figure 4-13 shows impacts of traffic level and reliability on the asphalt pavement thickness for a given the low and high subgrade strengths. As can be seen from Figure 4-13, traffic has the greatest impact on the asphalt pavement thickness whereas the reliability has a minimum impact such that the pavement thickness was increased by just

0.5 inch when the reliability increased from 80% to 90%.

Figure 4-14 shows impacts of the traffic level and subgrade strength on asphalt pavement thickness for a given the reliability of 80% and design life of 20 years. The asphalt pavement thickness was more sensitive to the subgrade strength at the high traffic level by decreasing the thickness by up to 4.0 inches. As shown in Figure 4-15, there seems to be an error in determining the A-3 subgrade strength where the A-3 subgrade exhibited a sharp increase in the CBR value.

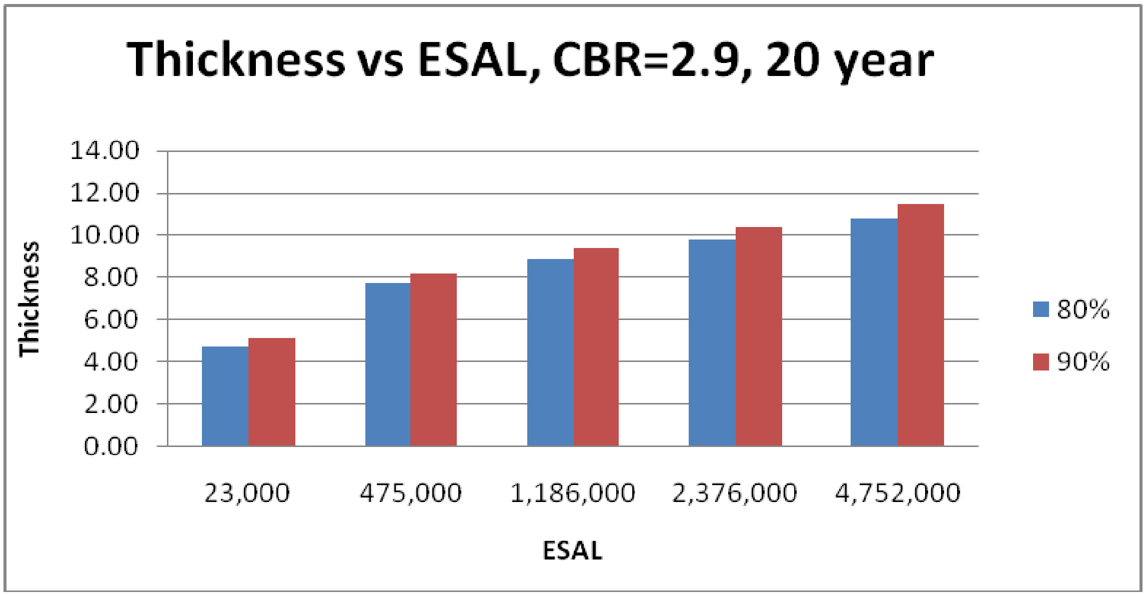
Table 4-12. Sensitivity analysis results of asphalt pavement thickness for design life of 20 years using APAI software

80% Reliability													
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	California Bearing Capacity									
				CBR=2.9		CBR=5.3		CBR=9.0		CBR=11.0		CBR=14.0	
				Thickness	ESALs	Thickness	ESALs	Thickness	ESALs	Thickness	ESALs	Thickness	ESALs
Residential	20	1.0	177,371	4.73	23,000	3.80	23,000	3.30	23,000	3.09	23,000	2.91	23,000
Collector	100	1.0	886,855	7.73	475,000	6.32	475,000	5.57	475,000	5.27	475,000	4.98	475,000
Minor Arterial	250	1.0	2,217,138	8.86	1,186,000	7.30	1,186,000	6.45	1,186,000	6.11	1,186,000	5.77	1,186,000
Major Arterial	500	1.0	4,434,276	9.80	2,376,000	8.11	2,376,000	7.20	2,376,000	6.82	2,376,000	6.45	2,376,000
Major Arterial 2	1000	1.0	8,868,551	10.82	4,752,000	8.98	4,752,000	8.00	4,752,000	7.59	4,752,000	7.20	4,752,000
90% Reliability													
Road Classification	ADTT	ESAL Factor	Manual Computed ESALs	California Bearing Capacity									
				CBR=2.9		CBR=5.3		CBR=9.0		CBR=11.0		CBR=14.0	
				Thickness	ESALs	Thickness	ESALs	Thickness	ESALs	Thickness	ESALs	Thickness	ESALs
Residential	20	1.0	177,371	5.09	23,000	4.09	23,000	3.55	23,000	3.34	23,000	3.14	23,000
Collector	100	1.0	886,855	8.20	475,000	6.73	475,000	5.95	475,000	5.64	475,000	5.32	475,000
Minor Arterial	250	1.0	2,217,138	9.39	1,186,000	7.75	1,186,000	6.89	1,186,000	6.52	1,186,000	6.16	1,186,000
Major Arterial	500	1.0	4,434,276	10.39	2,376,000	8.61	2,376,000	7.66	2,376,000	7.27	2,376,000	6.89	2,376,000
Major Arterial 2	1000	1.0	8,868,551	11.45	4,752,000	9.55	4,752,000	8.50	4,752,000	8.07	4,752,000	7.66	4,752,000

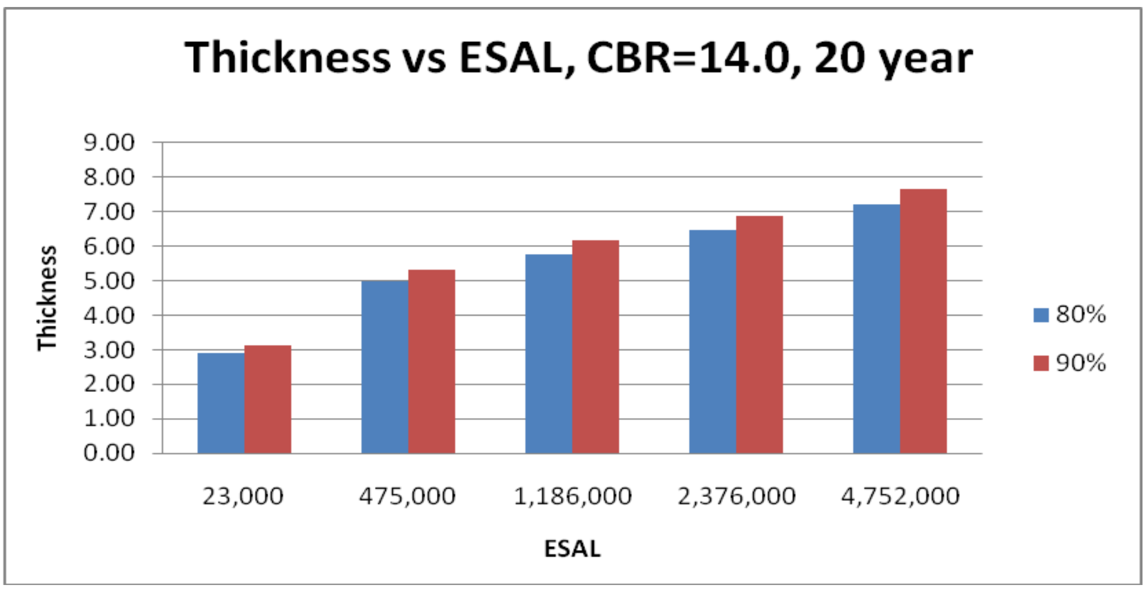
Table 4-13. Sensitivity analysis results of asphalt pavement thickness for design life of 40 years using APAI software

80% Reliability													
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	California Bearing Capacity									
				CBR=2.9		CBR=5.3		CBR=9.0		CBR=11.0		CBR=14.0	
				Thickness	Flexible ESALs	Thickness	Flexible ESALs	Thickness	Flexible ESALs	Thickness	Flexible ESALs	Thickness	Flexible ESALs
Residential	20	1.0	440,935	5.50	59,000	4.45	59,000	3.91	59,000	3.68	59,000	3.45	59,000
Collector	100	1.0	2,204,673	8.84	1,180,000	7.27	1,180,000	6.45	1,180,000	6.11	1,180,000	5.77	1,180,000
Minor Arterial	250	1.0	5,511,683	10.11	2,949,000	8.36	2,949,000	7.43	2,949,000	7.07	2,949,000	6.68	2,949,000
Major Arterial	500	1.0	11,023,365	11.16	5,904,000	9.27	5,904,000	8.27	5,904,000	7.84	5,904,000	7.45	5,904,000
Major Arterial 2	1000	1.0	22,046,730	12.30	11,808,000	10.25	11,808,000	9.16	11,808,000	8.70	11,808,000	8.27	11,808,000

90% Reliability													
Road Classification	ADTT	ESAL Factor	Manually Computed ESALs	California Bearing Capacity									
				CBR=2.9		CBR=5.3		CBR=9.0		CBR=11.0		CBR=14.0	
				Thickness	Flexible ESALs	Thickness	Flexible ESALs	Thickness	Flexible ESALs	Thickness	Flexible ESALs	Thickness	Flexible ESALs
Residential	20	1.0	440,935	5.86	59,000	4.77	59,000	4.18	59,000	3.95	59,000	3.70	59,000
Collector	100	1.0	2,204,673	9.39	1,180,000	7.75	1,180,000	6.89	1,180,000	6.52	1,180,000	6.16	1,180,000
Minor Arterial	250	1.0	5,511,683	10.70	2,949,000	8.89	2,949,000	7.91	2,949,000	7.52	2,949,000	7.11	2,949,000
Major Arterial	500	1.0	11,023,365	11.82	5,904,000	9.84	5,904,000	8.77	5,904,000	8.34	5,904,000	7.91	5,904,000
Major Arterial 2	1000	1.0	22,046,730	12.98	11,808,000	10.86	11,808,000	9.73	11,808,000	9.25	11,808,000	8.80	11,808,000



(a) Low subgrade strength



(b) High subgrade strength

Figure 4-13. Impacts of traffic level and reliability on asphalt pavement thickness given low and high subgrade strength and design life of 20 years

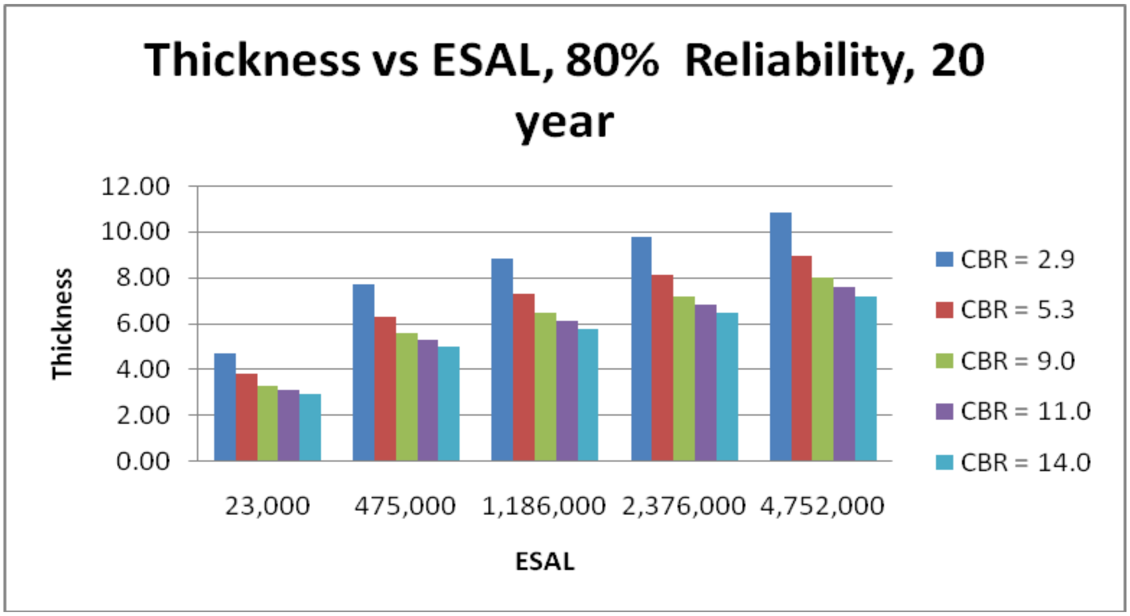


Figure 4-14. Impact of traffic level and suggrade strength on asphalt pavement thickness given reliability of 80% and design life of 20 years

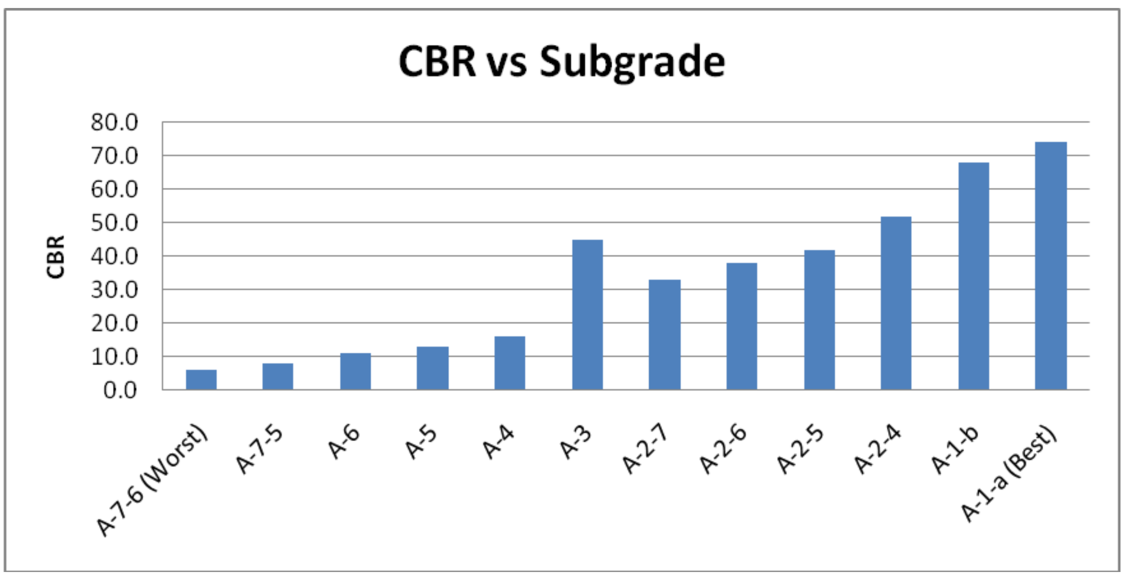


Figure 4-15. CBR versus soil classification used in APAI software

4.5 Comparison of Sensitivity Analysis Results

As summarized in Table 4-14, WinPAS software provides a slightly wider range of concrete pavement thickness from 4.0 inches to 10.0 inches than StreetPave software with a thickness from 3.9 inches to 8.0 inches. For both StreetPave and WinPAS software, the increased subgrade strength decreased the thickness by less than 1.0 inch. The impact of subgrade strength on concrete thickness was greater at the high traffic level for StreetPave software but similar for all traffic levels for WinPAS software. When the design life was doubled from 20 to 40 years, StreetPave software increased the thickness by 0.25 inch but WinPAS software increased the thickness by up to 1.25 inches at high traffic level and by up to 1.0 inch at low traffic level.

As summarized in Table 4-15, the sensitivity of traffic level on asphalt pavement thickness was highest with StreetPave software (thickness increase by up to 7.0 inches) and APAI software (thickness increase by up to 7.0 inches) and WinPAS software (thickness increase by up to 5.0 inches). Using the 80% reliability as the lowest level (because APAI does not provide 50% reliability), the design thickness range was also highest with StreetPave software from 3.08 inches to 14.4 inches, followed by APAI software from 3.0 inches to 13.0 inches, and WinPAS software from 4.05 inches to 12.18 inches.

Figure 4-16 (a) (b) show comparisons of the WinPAS software against the StreetPave software for thickness design of concrete pavement given 80% reliability and “low” and “high” subgrade strengths, respectively. For the low traffic level of 100 ADTT, the StreetPave software recommended the thicker concrete pavement than WinPAS software, but, as the traffic load increases up to 1,000 ADTT, StreetPave software recommended a thinner concrete pavement by up to 1.0 inch. The impact of traffic loading is greater with WinPAS software based on the AASHTO design method than the StreetPave software based on the PCA method.

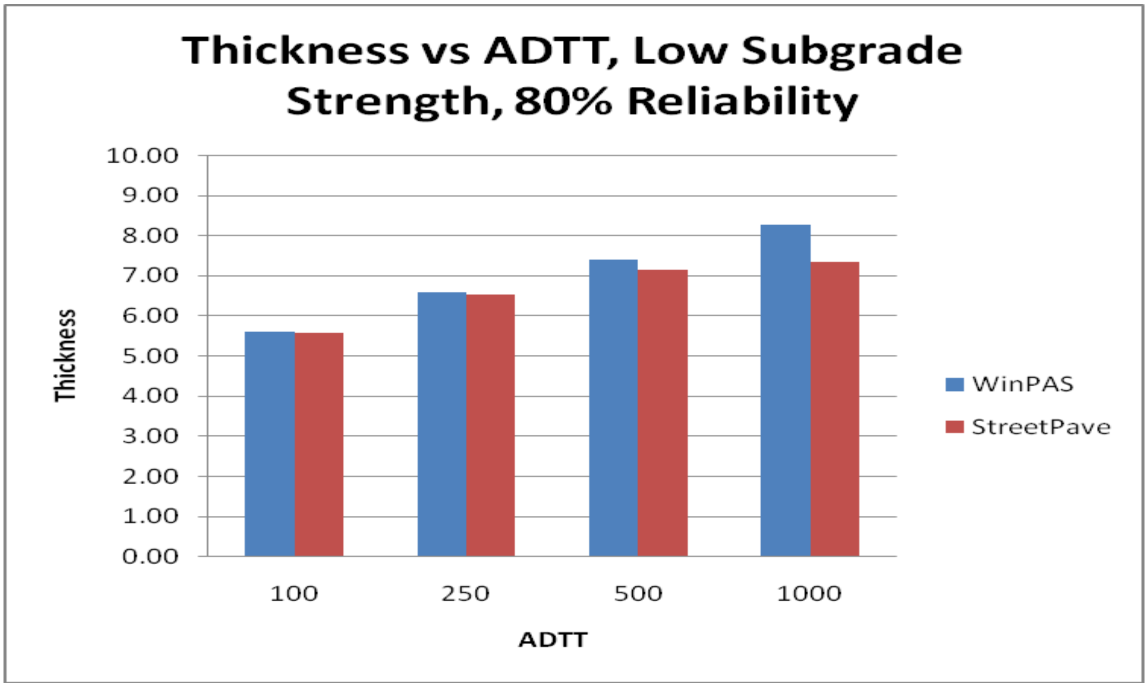
Figure 4-17 (a) (b) show comparisons of three software packages for thickness design of asphalt pavement with 80% reliability and “low” and “high” subgrade strengths, respectively. The StreetPave software recommended the thickest asphalt pavement followed by APAI and WinPAS, particularly at the higher traffic level.

Table 4-14. Comparisons of sensitivity analysis results for concrete pavement using StreetPave and WinPAS software

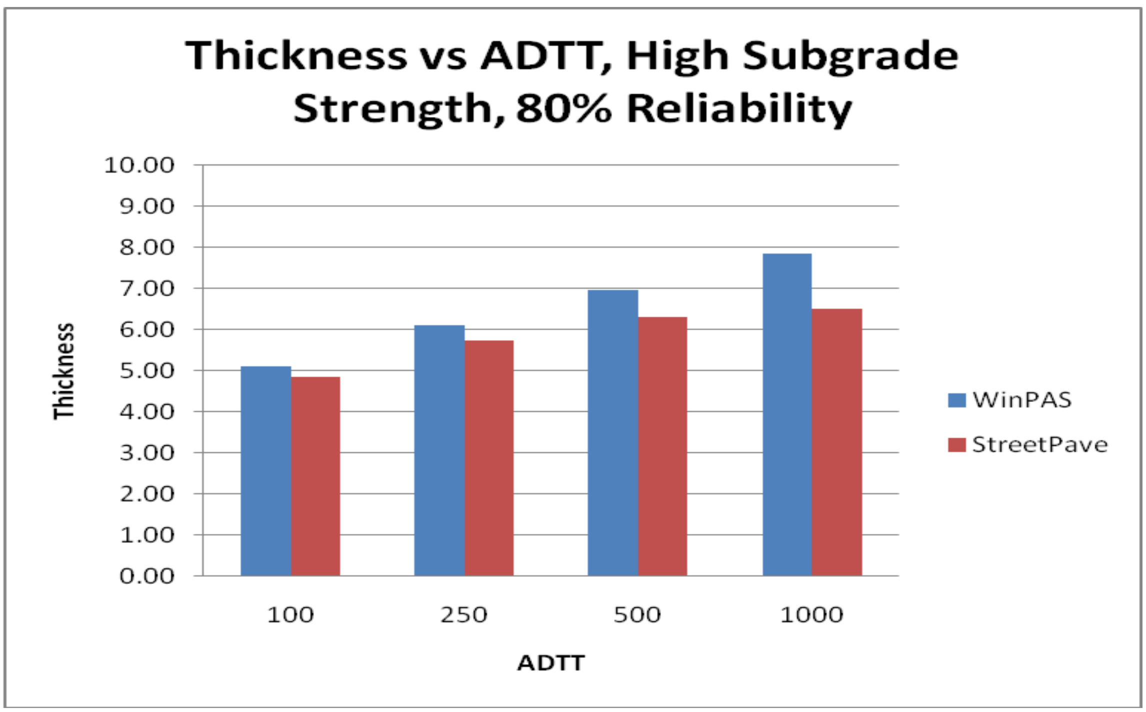
Input Parameter	StreetPave Software	WinPAS Software
Traffic	✓ Low to High Traffic levels: Δ 2.5 inches	✓ Low to High Traffic levels:Δ 3.5-4.5 inches
Reliability	✓ Higher impact at higher traffic level: Δ 0.75 inch	✓ Higher impact at higher traffic level: Δ 1.25 inches
Subgrade Strength	✓ Higher impact at higher traffic level: Δ 1.0 inch	✓ Higher impact at higher traffic level: Δ 0.5 inch
Design Life	✓ Constant change for all traffic levels: Δ 0.25 inch	✓ Constant change for all traffic levels: Δ 1.25 inches

Table 4-15. Comparisons of sensitivity analysis results for asphalt pavement using StreetPave, APAI, and WinPas software

Input Parameter	StreetPave Software	APAI Software	WinPAS Software
Traffic	✓ Low to High Traffic: Δ 6.0-7.0 inches	✓ Low to High Traffic: Δ 6.0-7.0 inches	✓ Low to High Traffic: Δ 4.0-5.0 inches
Reliability	✓ Higher Impact at Lower Traffic Level: Δ 0.75 inch from 80% to 90%	✓ Higher impact at Higher Traffic level: Δ 0.5 inch from 80% to 90% ✓ Little impact at low traffic level	✓ Higher impact at Higher Traffic Level: Δ 0.5 inch from 80% to 90%
Subgrade Strength	✓ Higher Impact at Lower Traffic Level: Δ 2.5-3.0 inches	✓ High Traffic had biggest impact (Δ 3.0-3.5 inches)	✓ Higher Impact at Higher Traffic Level: Δ 2.5-3.0 inches
Design Life	✓ Higher Impact at Higher Traffic: Δ 2.0 inches for high, Δ 1 inch for low traffic level	✓ Higher Impact at High Traffic Level: Δ 1.5-1.25 inches for high, Δ 0.25-0.5 inch for low traffic level	✓ Higher Impact at Higher Traffic Level: Δ 1.25 inches for high, Δ 0.75 inch for low traffic level

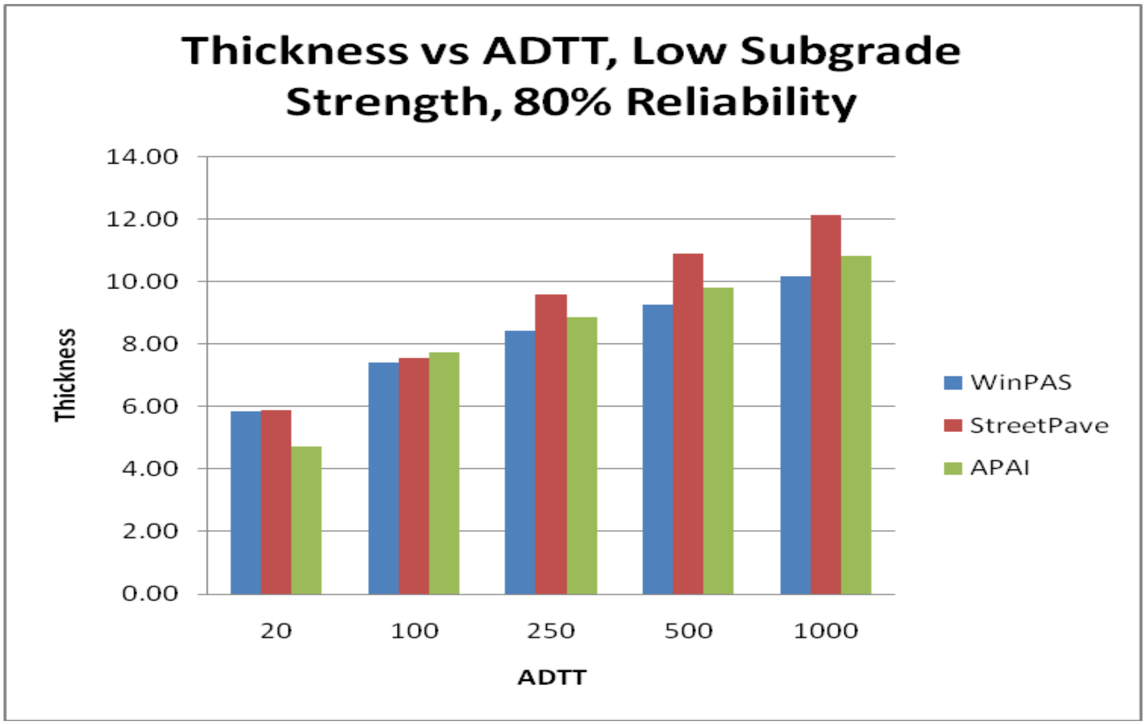


(a) Low subgrade strength

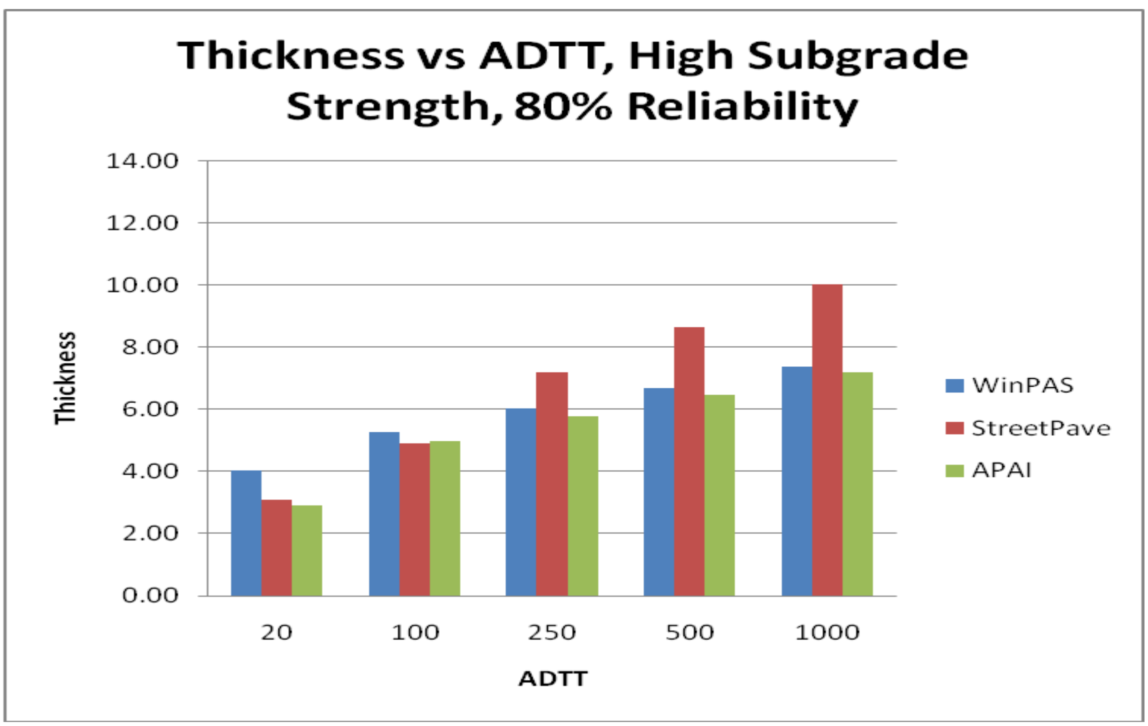


(b) High subgrade strength

Figure 4-16. Comparison of WinPAS and StreetPave software for thickness design of concrete pavement given reliability of 80% at low and high subgrade strength



(a) Low subgrade strength



(b) High subgrade strength

Figure 4-17. Comparison of the WinPAS, StreetPave, and APAI software for thickness design of asphalt pavement given low and high subgrade strength

5. DEVELOPMENT OF PROTOTYPE PAVEMENT DESIGN AND SENSITIVITY ANALYSIS SOFTWARE

As discussed earlier, there exist a number of pavement design software packages that generate different thicknesses for the given condition. Some pavement design software packages takes a significant amount of time to run without providing a user with a design value. In addition, most of these pavement design software packages do not give a user an option to perform the design sensitivity analysis by generating multiple designs by automatically varying input values.

The main purpose of this prototype pavement design and sensitivity analysis (PD&SA) software is to store the pavement design values in the database so that a user can perform the pavement design by retrieving the pavement design values from the database without running the actual pavement design programs.

First, a number of pavement design values were generated by running different pavement design software packages by varying input parameters. Second, the generated pavement design values were stored in the database. Third, the pavement design and sensitivity analysis (PD&SA) software was then developed to retrieve the pavement design data from the database and perform a sensitivity analysis with respect to various design input parameters.

5.1 Literature Review on Pavement Design and Sensitivity Analysis Software

PAvement Design system for new and existing Asphalt Pavements (PADAP) pavement simulation software was developed aiming for designing new pavements and reconstruction/ rehabilitation of existing ones considering axle loads, environmental conditions and seasonal nonlinear material properties of unbound granular layers and subgrade soils (Uddin and Ricalde 2000). The PADAP program is intended to evaluate asphalt pavement performance models by simulating seasonal temperature variations, moisture content predictions, and axle load configurations.

The Federal Aviation Administration (FAA) developed new airfield pavement design software named FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layered Design). It incorporates three-dimensional finite element (3D-FE) stress computation for design of new rigid pavements (Brill 2004). The sensitivity analysis can be performed to compare the new design method against the previous design method, LEDFAA (Layered Elastic Design FAA), which was developed based on 1970's full-scale tests (McQueen and Guo 2004).

The National Cooperative Highway Research Program initiated NCHRP 1-37A project to develop a pavement design software based on 2002 Mechanistic-Empirical Pavement Design Guide (M-EPDG) (ARA 2004). It is intended to be user-friendly software and provide pavement designers with answers to analyze not to design pavements. It asks a user to enter the pavement design thickness and expect a user to do a trial and error procedure until the design entered by a user satisfies the performance requirement. The software adopted hierarchical approach to design inputs to provide the designer with a lot of flexibility in obtaining the design inputs. In addition, the software has very limited capability in performing the design sensitivity analysis except for drainage requirements. Efforts have been made to analyze unbound granular layer of the flexible pavement structure of the 2002 M-EPDG software (Masad and Little 2004). It was found that the fatigue life predicted using the nonlinear anisotropic approach is higher than the life predicted using the nonlinear isotropic approach. The sensitivity analysis of the 2002 M-EPDG model showed that the base modulus and thickness have significant influence on the international roughness index and the longitudinal cracking.
Kannekanti and Harvey (2005, 2006) performed the sensitivity analysis of 2002 M-EPDG rigid pavement distress prediction models. They ran 2002 M-EPDG software for all combinations of the key variables including traffic volume, axle load distribution, climate zone, thickness, shoulder type, joint spacing, load transfer efficiency, concrete strength, base type, and subgrade type. They concluded that the 2002 M-EPDG produces reasonable predictions of rigid pavement performance. However, it was stated that some of the inputs required by the software are hard to obtain such that the designer has to rely on default values suggested by the design guide or use approximate values.

Schwartz (2007) compared the 2002 M-EPDG pavement designs with 1993 AASHTO design method and performed the sensitivity analysis of the 2002 M-EPDG pavement design guide by varying the key design input parameters. It was reported that 2002 M-EPDG underestimated the performance of pavements in warm locations compared to 1993 AASHTO guide. Particularly, it was discovered that the sensitivity of predicted performance to the distress model calibration coefficients is much greater than for most other design parameters considered in their study.

5.2 Prototype Pavement Design and Sensitivity Analysis Software

The PD&SA software is a computer program that combines pavement design function and sensitivity analysis capability. The user interface is designed for the pavement designer to enter pavement design data, which were generated using the existing software packages, into database. When a user enters the input parameters, the PD&SA software retrieves the most appropriate pavement design from the database for the given condition. At the same time, the software produces graphs of multiple designs for various input parameters that would allow a user to consider different design thicknesses for varying input values. The PD&SA software works as a design database and provides the user with an easy-to-use tool for pavements design and sensitivity analysis.

The PD&SA software consists of four modules: asphalt pavement design, concrete pavement design, input pavement design data and run sensitivity analysis. The asphalt and concrete pavement design modules provide the user with a tool to query the design database. The design data input module provides a spreadsheet user interface to input design data and the sensitivity analysis module provides a graphic user interface to run a sensitivity analysis.

The PD&SA software was developed using the Microsoft Visual Studio 2008 and .NET class libraries that were designed based on Object-Oriented Programming (OOP) principles. Figure 5-1 shows the class diagram of PD&SA software which provides quick access to methods, properties, and fields of each class. The “Program” class is the entry point of the program and runs “MainForm” class. If the user sets to display “Welcome” dialog, the “StartUpForm” will show up at the startup to provide shortcuts to frequently used modules. The “AcpNewForm” class contains parameters for asphalt pavement design. It queries asphalt pavement design data with user input and displays its result. “Print” button on this form displays design report which can be exported in PDF, Excel, and Text formats. The “DesignDataInputForm” class provides an interface for the user to input design data. The “SensitivityForm” class is designed to run sensitivity analysis and display charts with its results. “DesignLifeForm”, “ReliabilityForm”, “TrafficForm”, “PropertiesForm”, “SubbaseForm” classes provide interface for the user to edit database tables described in sensitivity analysis section.

Figure 5-2 shows the user interface which includes asphalt pavement design, concrete pavement design, design data input, sensitivity analysis, report generation and basic parameter settings.

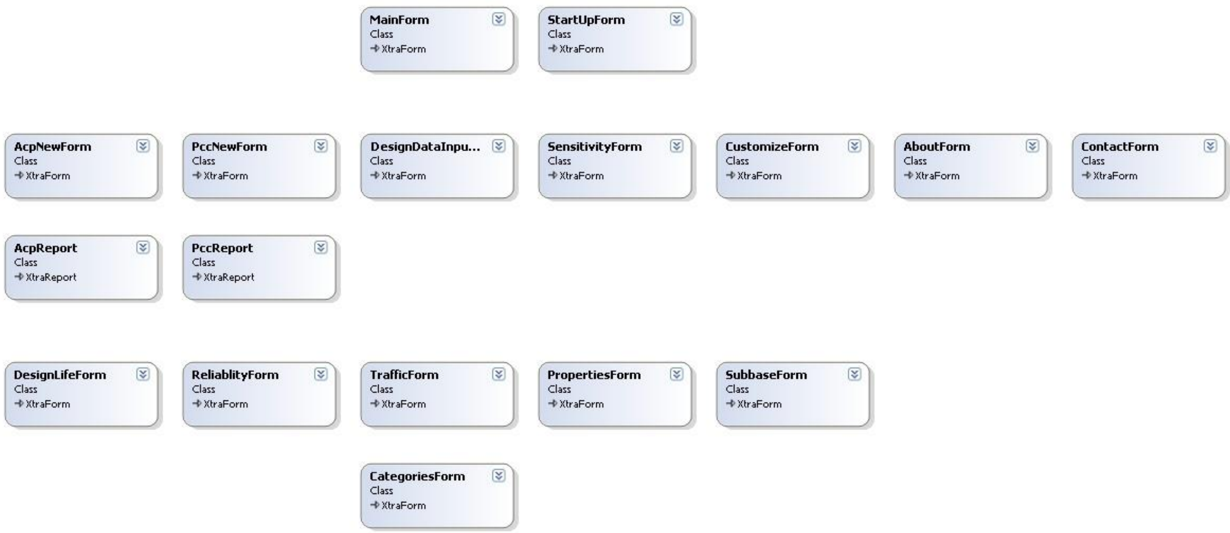


Figure 5-1. Class diagram of pavement design and sensitivity analysis software

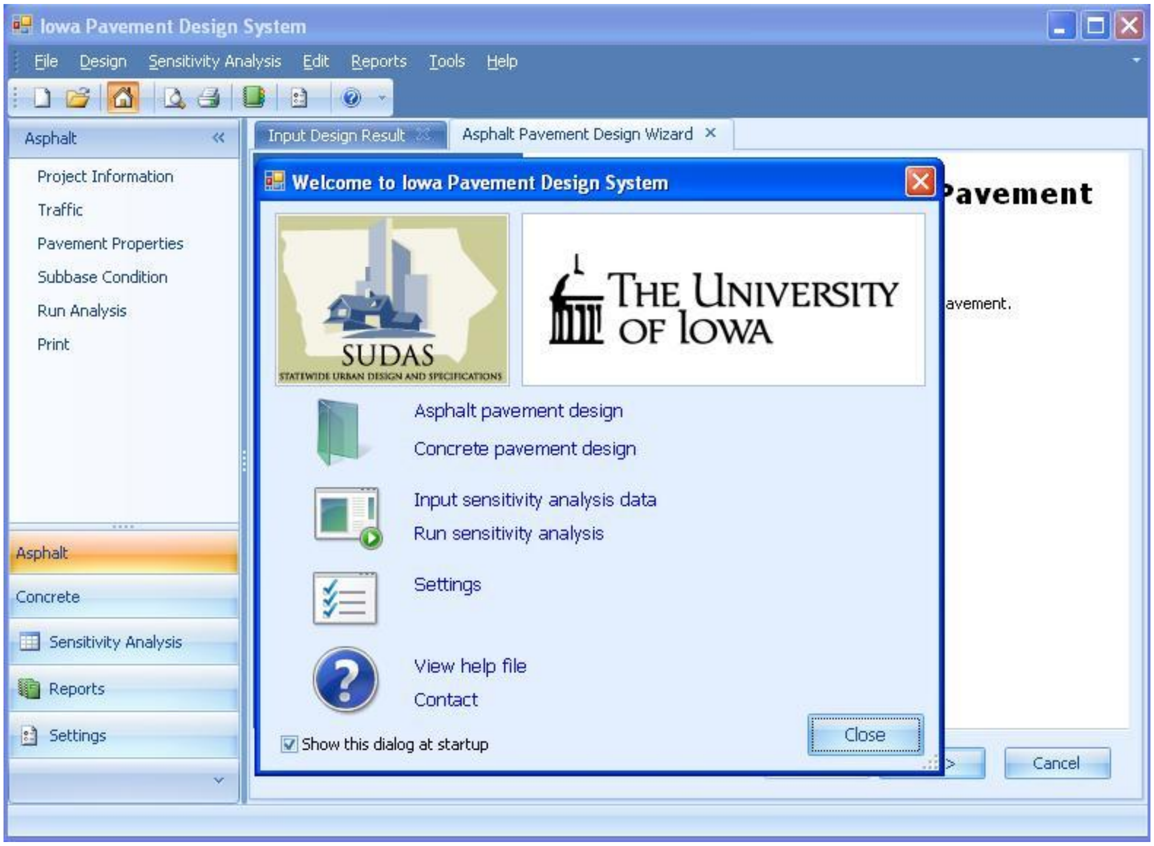
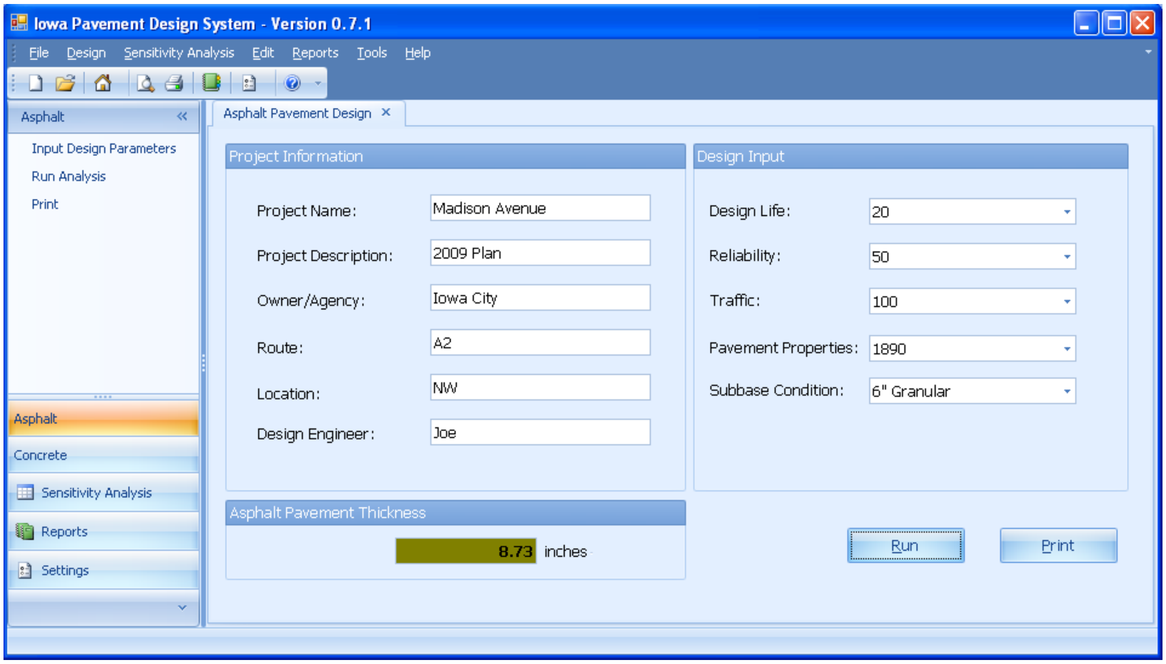


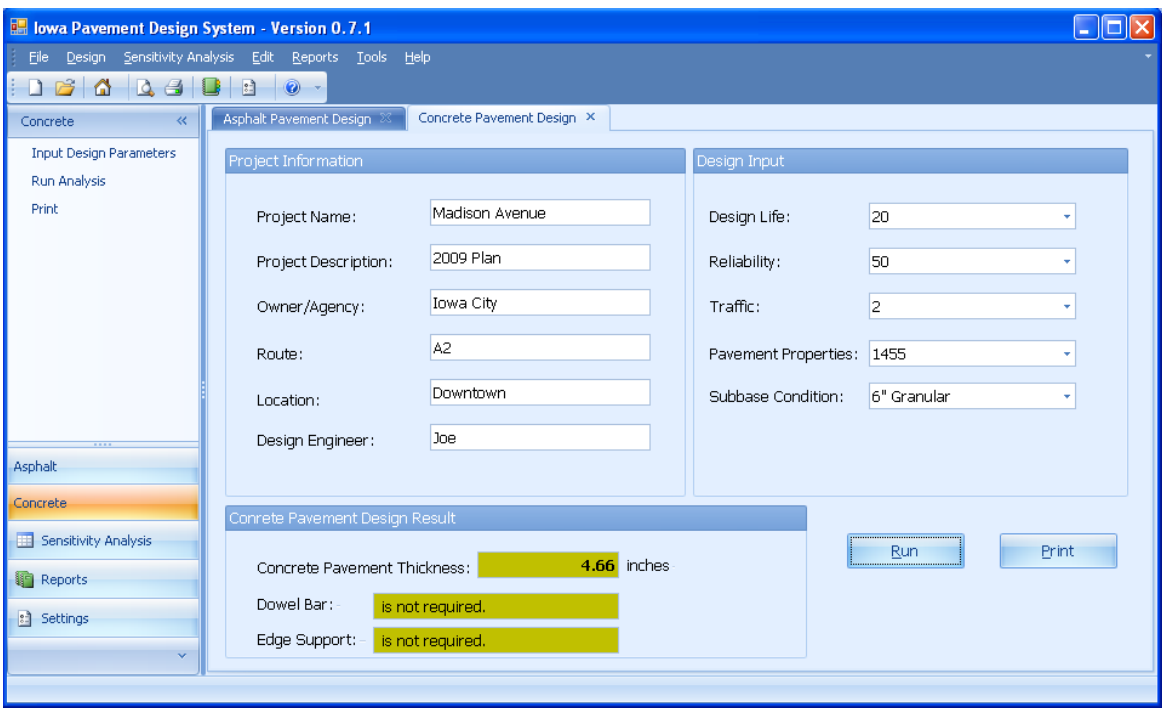
Figure 5-2. User interface of pavement design and sensitivity analysis software

5.2.1 Asphalt and Concrete Pavement Thickness Design Modules

As shown in Figure 5-3, both asphalt and concrete pavement thickness design modules will include input screen to allow a user to input project information and design inputs such as design life, reliability, traffic and subgrade condition. Once a user provides a necessary input values and choose the pavement design method, the pavement thickness is displayed by retrieving the most appropriate pavement design value from the database. The project information, design inputs and the design output can be then printed in a report format.



(a) Asphalt pavement thickness design module



(b) Concrete pavement thickness design module

Figure 5-3. User interface for asphalt and concrete pavement thickness design modules

5.2.2 Pavement Design Input and Sensitivity Analysis Module

The PD&SA program stores the pavement design data in a Microsoft Access format. Figure 5-4 shows database entities, attributes and their relationship that consists of the main tbDesign table with associated tables which include tbPavementProperty, tbSubbaseCondition, tbDesignLife, tbTraffic and tbReliability. The tbPavementProperty table stores basic structural properties of a pavement including a tbLayer subtable where layer data associated with the pavement is stored. Similarly, the tbSubbaseCondition, tbTraffic, tbDesignLife, and tbReliability tables are designed to store information about subbase, traffic, design life, and reliability factors, respectively. With integrated database, the entered data can easily be reused for various different pavement design conditions. Thus, the user is not required to input same data repeatedly in contrast to other pavement design software packages most of which do not utilize a database. The pavement design result generated from other pavement design software packages can be saved and utilized later for pavement design and sensitivity analysis.

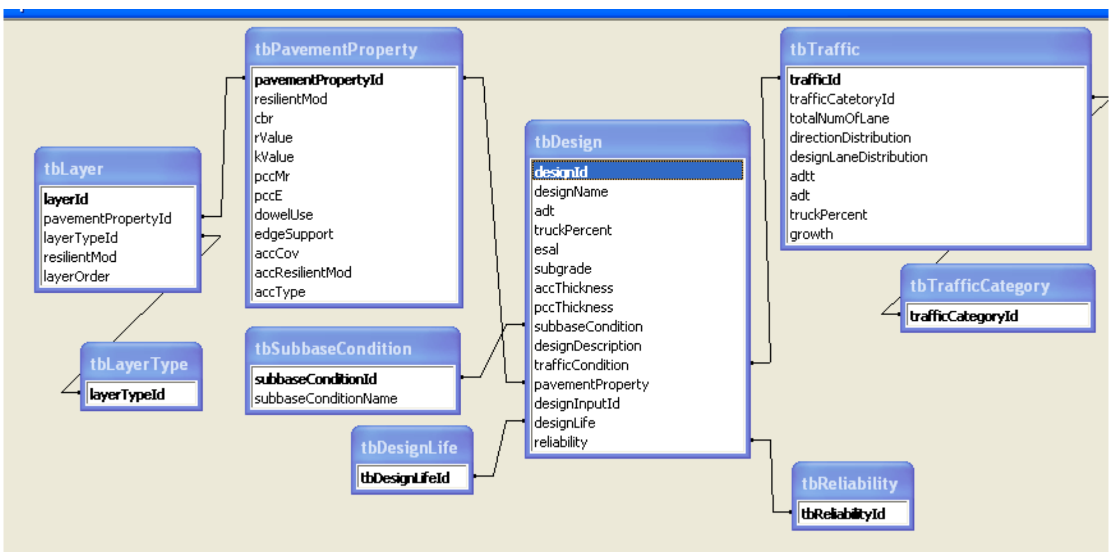


Figure 5-4. Database structure and relationship in Microsoft Access database

Figure 5-5 shows a flow chart for inputting the pavement design data and running sensitivity analysis. First, the pavement design data obtained by running other pavement design software packages should be entered into the pavement design database. Once the pavement design data is saved in the database, the user can then select design input parameters such as pavement type, design life, reliability, traffic, and subgrade conditions. The PD&SA software runs the SQL query based on the user selections and then displays sensitivity analysis charts for the user to review sensitivity of input parameters.

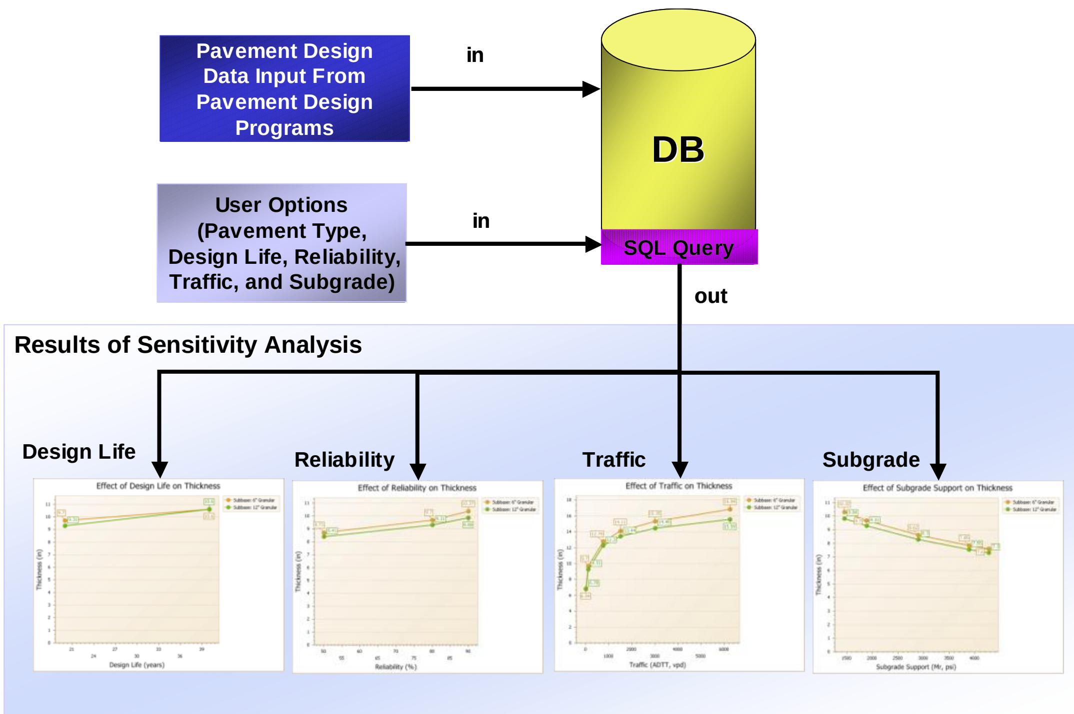


Figure 5-5. Flow chart of pavement design data input and sensitivity analysis module

The sensitivity analysis module provides a tool for the user to input design data, run sensitivity analysis and export the analysis results to PDF or image file for printing. As shown in Figure 5-6, the pavement design data are stored in the database and the user can perform the sensitivity analysis instantaneously against pavement design parameters such as a design life, a reliability, a traffic level and a subgrade condition. Figure 5-7 and Figure 5-8 show a sensitivity analysis result to illustrate the influence of the design life, reliability, traffic, and subgrade support on the pavement thickness. By clicking on the tab on the top of the main screen, the sensitivity analysis result based on other input parameters such as design life, traffic level and soil condition can be instantaneously displayed.

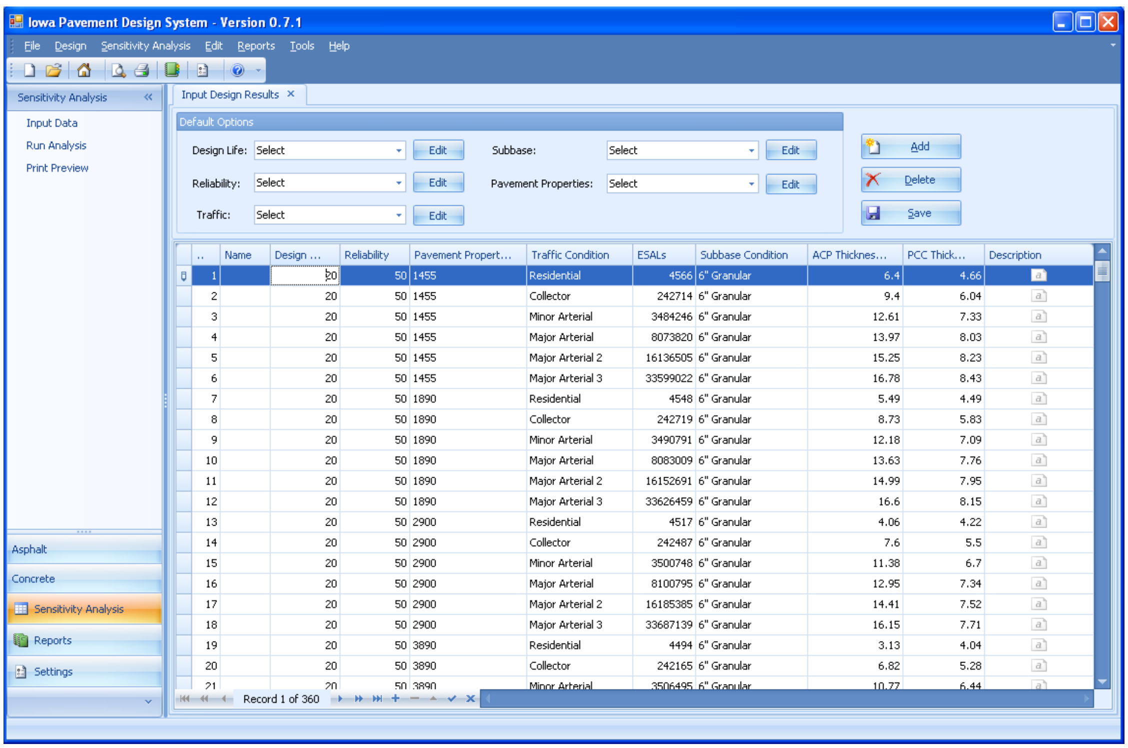
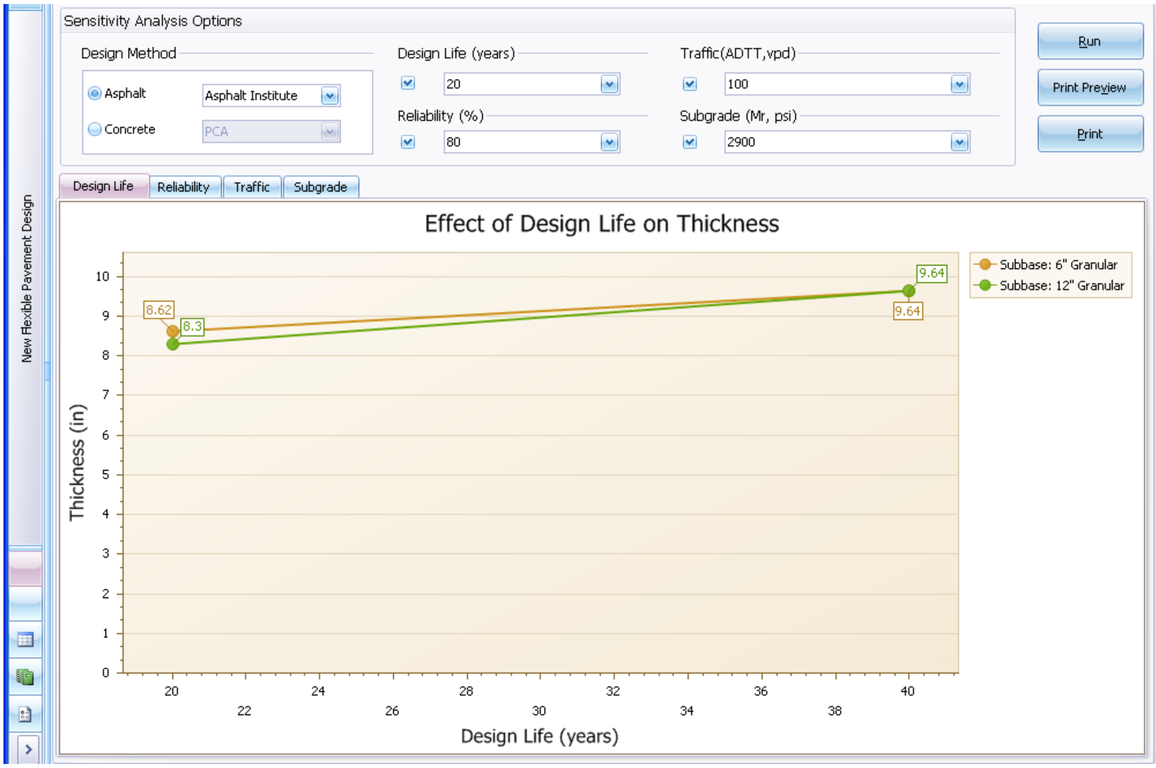
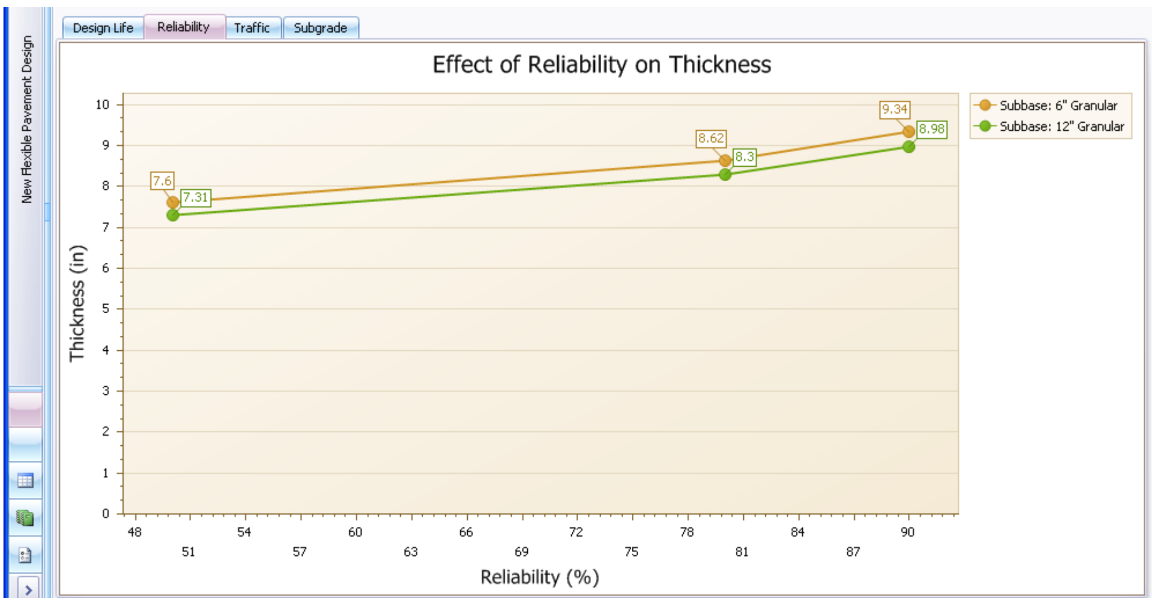


Figure 5-6. Screenshot of pavement design database

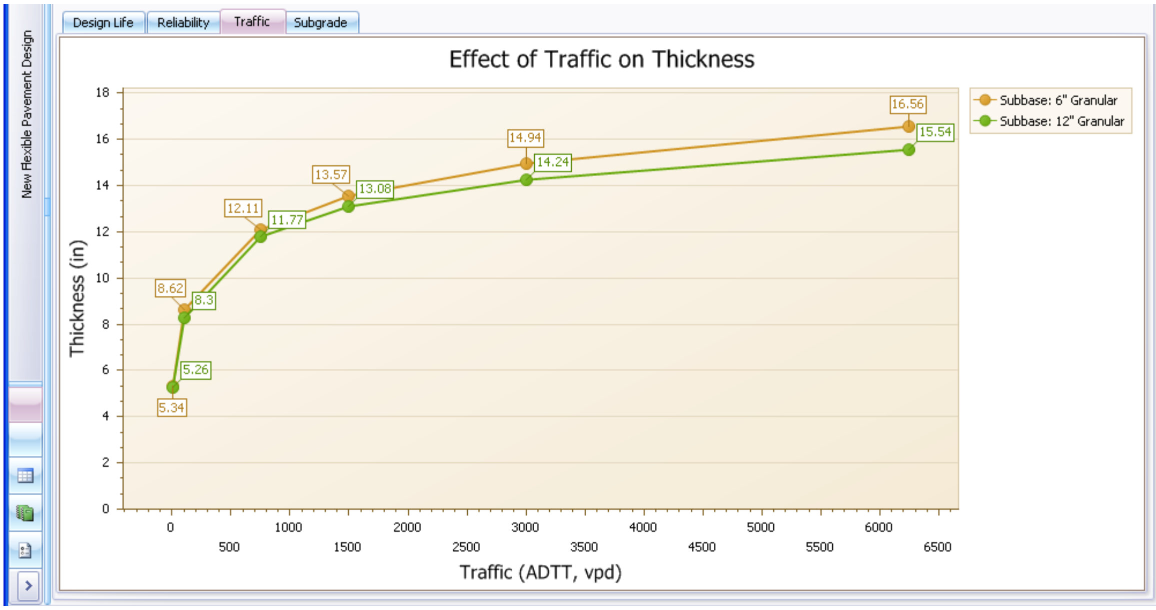


(a) Sensitivity analysis showing effect of design life on thickness

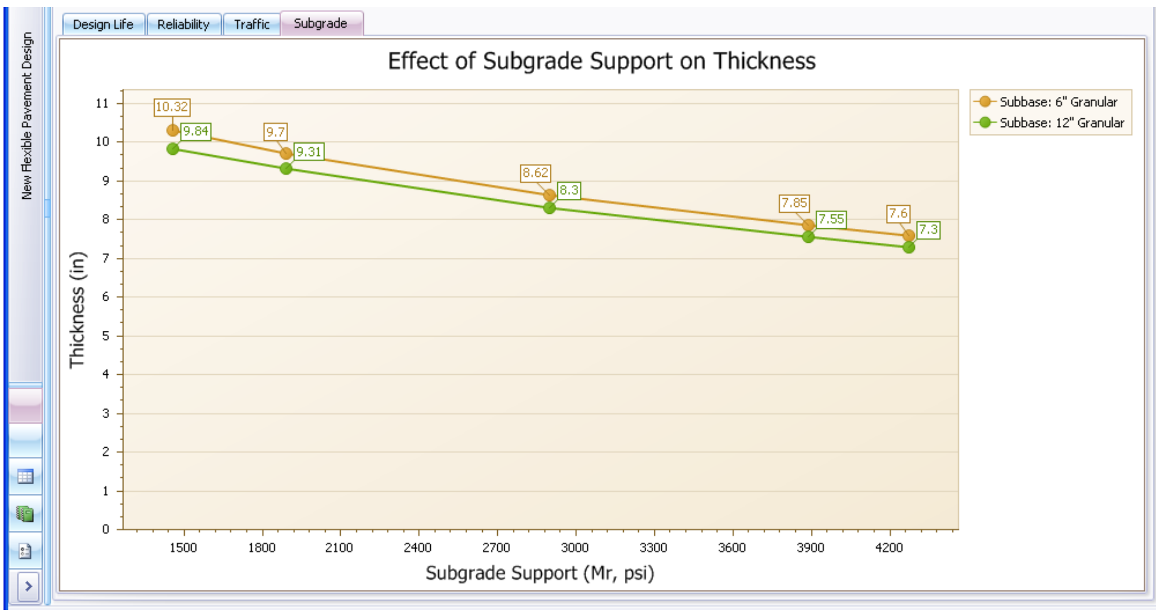


(b) Sensitivity analysis showing effect of reliability on thickness

Figure 5-7. Screenshots of sensitivity analysis of design life and reliability on pavement thickness



(c) Sensitivity analysis showing effect of traffic on thickness



(d) Sensitivity analysis showing effect of subgrade support on thickness

Figure 5-8. Screenshots of sensitivity analysis of traffic and subgrade support on pavement thickness

6. SUMMARY AND CONCLUSIONS

Statewide urban design and specifications (SUDAS) currently utilizes a simplified version of the AASHTO 1993 pavement design guide, which is conservative based on placement of the pavement on natural subgrade, distribution of truck classifications and other design parameters. Therefore, there is a need for a modified pavement design methodology to be used for determining the optimum pavement thickness in local roads in Iowa.

First, the survey was performed to identify pavement thickness design procedures for low volume roads and common input parameters from the adjoining state departments of transportation to Iowa. Another survey was performed to identify the minimum pavement thicknesses under the lowest traffic level and the strongest subgrade condition from 50 state departments of transportation.

Three pavement design software packages were compared with respect to how they were different in determining design input parameters and their influences on the pavement thickness. StreetPave designs the concrete pavement thickness based on the PCA method and the equivalent asphalt pavement thickness. The WinPAS software performs both concrete and asphalt pavement following the AASHTO 1993 design method. The APAI software designs asphalt pavement based on pre-mechanistic/empirical AASHTO methodology and Iowa SUDAS.

Four critical design input parameters were identified: traffic, subgrade strength, reliability and design life. The sensitivity analysis of these four design input parameters were performed using three pavement design software packages in order to identify which input parameters would require the most attention during pavement design and how these three software packages' design outputs differ. Based on the current pavement design procedures and sensitivity analysis results, a prototype pavement design and sensitivity analysis (PD&SA) software package was developed to allow a user to perform pavement design sensitivity analysis.

Conclusions

Based on the limited research, the following conclusions are derived:

1. A sensitivity analysis revealed that three pavement design software packages may recommended slightly different pavement thicknesses for the similar condition. To confirm this finding, a further analysis of ESAL's, load transfer factor, reliability and subgrade support is needed.
2. When the design life was doubled from 20 to 40 years, the StreetPave increased the concrete pavement thickness by 0.25 inch whereas the WinPAS increased the thickness by up to 1.25 inches.
3. For the same input parameters for designing asphalt pavements, the StreetPave software recommended the thickest asphalt pavement followed by the WinPAS and APAI software. For the high subgrade strength and low traffic level, however, the WinPAS software recommended the thicker asphalt pavement than the StreetPave and the APAI software.
4. Based on the sensitivity analysis result of three pavement design software packages, the traffic level has the highest impact on both concrete and asphalt pavement design followed by the subgrade strength, reliability and design life.
5. The prototype Pavement Design and Sensitivity Analysis (PA&SA) software package was developed to demonstrate the concept of storing the pavement design results in the database for a design sensitivity analysis. This final report does not include the prototype software which will be validated and tested during the next phase

Future Studies

1. Minimum pavement thickness survey should be conducted among engineers from cities and counties in Iowa and surrounding states with regard their design process and scenario. This survey should be to get "typical" pavement thicknesses for flexible and rigid pavements from local agencies.
2. Additional sensitivity analysis using DARWIN and the Asphalt Institute software should be performed to be compared against the sensitivity analysis results from StreetPave, WinPas, and APAI software packages.
3. Traffic mix and its conversion to ESAL should be clarified to determine their effects on the pavement thickness.

4. Traffic mix, ESAL conversion factor, equivalency of subgrade strengths should be investigated to ensure the design inputs for each software package would represent the equivalent traffic level and subgrade strength.
5. PD&SA software should be modified to add more design input parameters, i.e., edge support and dowel bar, and the updated the sensitivity analysis results from DARWIN and Asphalt Institute software packages.
6. The PD&SA software should be modified to show the sensitivity analysis of different pavement design values generated by various pavement design software packages on the same screen.
7. For a given condition, the PD&SA software should provide a single pavement design thickness value as the SUDAS standard design.

REFERENCES

AI (1983) "Asphalt Pavement Thickness Design Asphalt." Information Series No. 181 (IS-181), Asphalt Institution, College Park, Maryland.

APAI (1990) "Asphalt Paving Design Guide." Asphalt Paving Association of Iowa, West Des Moines, Iowa.

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

ACPA (2006) "Design of Concrete Pavement for Street and Roads." American Concrete Pavement Association, Washington, D.C.

ARA, Inc and ERES Consultants Division (2004). "NCHRP 1-37A: Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures." National Cooperative Highway Research Program, TRB, National Research Council, Washington D.C.

Masad, S. and Little, D. N. (2004) "Sensitivity Analysis of Flexible Pavement Response and AASHTO 2002 Design Guide to Properties of Unbound Layers." ICAR-504-1, International Center for Aggregates Research, Austin, Texas.

Brill, D. R., Kawa, I., and Hayhoe, G. F. (2004) "Development of FAARFIELD Airport Pavement Design Software." Transportation Systems 2004 Workshop, Ft. Lauderdale, Florida.

Bergeson, K. L. and Barber, A. G. (1998) "Iowa Thickness Design Guide for Low Volume Roads Using Reclaimed Hydrated Class C Fly Ash Bases." Transportation Conference Proceedings, Washington D.C.

Freeme and Marais (1973) "Thin Bituminous Surfaces: Their Fatigue Behavior and Prediction." Special Report 140, Highway research Board, pp. 158-179.

Hall, K. D. and Bettis, J. W. (2000) "Development of Comprehensive Low-Volume Pavement Design Procedures." Arkansas Highway and Transportation Department, Report No. MBTC 1070, Little Rock, Arkansas.

Hwang, Y. H. (2004). "Pavement Analysis and Design." Prentice Hall.

Kannekanti V. and Harvey, J. (2005) "Sensitivity Analysis of 2002 Design Guide Rigid Pavement Distress Prediction Models." Pavement Research Center, University of California, Davis, University of California, Berkeley.

Kannekanti V. and Harvey, J. (2006) "Sensitivity Analysis of 2002 Design Guide Distress Prediction Models for Jointed Plain Concrete Pavement." Transportation Research Record 1947, TRB, National Research Council, Washington, D.C., pp. 91-100.

McQueen, R. D., and Guo, E. H. (2004) "Sensitivity Analysis of Major Parameters in Rigid Pavement Design Procedures." Transportation Systems 2004 Workshop, Ft. Lauderdale, Florida.

Packard, R. G. (1973) "Design of Concrete Airport Pavement." Portland Cement Association (PCA), EB 050.03P, Skokie, Illinois

PCA (1984) "Thickness Design for Concrete Highway and Street Pavements." Portland Cement Association (PCA), EB 109P, Skokie, Illinois

Sharma, R., Stevens, L., Ceylan, H., White, D., and Schaefer, V. (2005) "Design Guide for Improved Quality of Roadway Subgrades and Subbases." Iowa Highway Research Board, TR-525, Iowa DOT, Ames, Iowa.

Schwartz, C. W. (2007) "Implementation of the NCHRP 1-37A Design Guide Final Report Volume 1: Summary of Findings and Implementation Plan." MDSHA Project No.

SP0077B41 UMD FRS No. 430572, Lutherville, Maryland.

Uddin, W. and Ricalde, L. (200) “An Environmental and Load Simulation Software for Designing Longer Lasting Asphalt Highways.” Infrastructure and Transportation, Memphis Area Engineering Societies Conference (MAESC), Memphis, Tennessee.

APPENDIX

A. Minimum Pavement Thickness

B. Survey Form and Survey Responses

C. Sensitivity Analysis Results

Appendix A

A-1. Minimum Pavement Thickness

MINIMUM PAVEMENT THICKNESS

AASHTO 1993 pavement design guide lists a minimum asphalt pavement thickness as 1.0 inch and the minimum concrete pavement thickness as 5.0 inches for the lowest traffic level ranging from 50,000 to 100,000 ESAL's. However, for the similar traffic level, the asphalt institute (1983) recommends a minimum of 3.0 inches for asphalt pavement and the PCA (1984) recommends a minimum of 7.0 inches of concrete pavement. ACPA (2006) recommends a lower limit for pavement thickness of 4.0 inches for automobiles and 5.0 inches for limited truck traffic. According to the ACPA design table, a minimum concrete pavement thickness for light residential street is 4.0 inches.

Summary of Survey Results

To identify the minimum pavement thickness on the strongest subgrade under the lowest level of traffic, a survey was sent to fifty state DOT's. Fifty state DOT employees were asked about their minimum thicknesses for both asphalt and concrete pavements of roads with the lowest traffic loading that have 6" subgrade on good soil with a good drainage condition. It is cautioned, however, that our survey result should not be viewed as the representative value for each state because it was based on the survey of a single person from each state DOT, rather than local agency, who may not necessarily be familiar with the practices performed by all local agencies in her/his state.

As shown in Figure A-1, 24 states have returned their responses. As can be seen from Table A-1, there is a wide variation among states regarding minimum asphalt pavement thickness ranging from 1.25 inch to 6.0 inches but the minimum concrete pavement thickness ranges narrowly from 6.0 inches to 8.0 inches. The minimum thicknesses of asphalt and concrete pavements adopted by 24 states are plotted in Figure A-2 and Figure A-3, respectively. It should be noted that the state DOT's have jurisdiction over a limited amount of local roads. The survey of the state DOT's is used herein as a means to identify general design procedures that might be employed. Again, it should be emphasized that our survey result may not represent the practices by numerous local agencies in each state and the results are too variable to be useful.

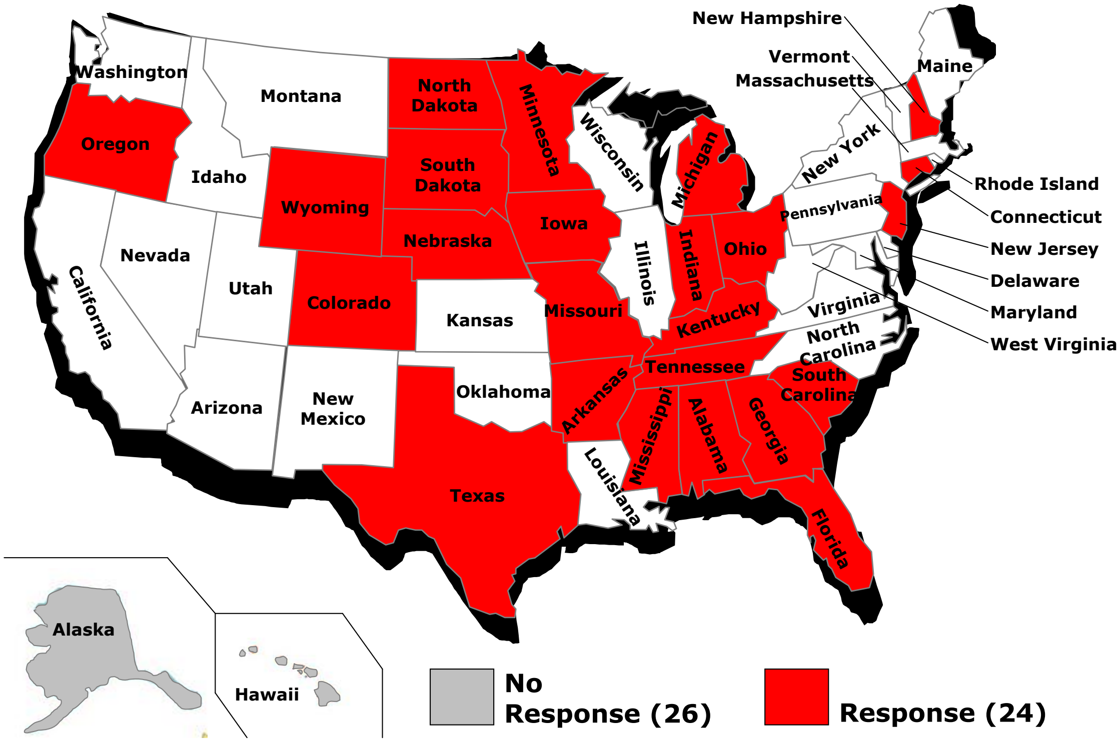


Figure A-1. Survey responses on the status of minimum pavement thickness usage

Table A-1. Survey results of minimum thickness for asphalt and concrete pavements adopted by 24 states

State		Thickness (in.)	
		Asphalt Pavement	Concrete Pavement
1	Alabama	4″	No Design
2	Alaska		
3	Arizona		
4	Arkansas	2"	No Design
5	California		
6	Colorado	2"	6"
7	Connecticut	4"	No Design
8	Delaware		
9	Florida		8″
10	Georgia		6″
11	Hawaii		
12	Idaho		
13	Illinois		
14	Indiana	4"	7"
15	Iowa	6″	7"
16	Kansas		
17	Kentucky	1.25"	8"
18	Louisiana		
19	Maine		
20	Maryland		
21	Massachusetts		
22	Michigan		8"
23	Minnesota	3.0"	7"
24	Mississippi	3.5"	No Design
25	Missouri		

State		Thickness (in.)	
		Asphalt Pavement	Concrete Pavement
26	Montana		
27	Nebraska	6"	8″
38	Nevada		
29	New Hampshire	4"	No Design
30	New Jersey	4"	8"
31	New Mexico	3"	8"
32	New York	No minimum	8"
33	North Carolina		
34	North Dakota	4"	8"
35	Ohio		
36	Oklahoma		
37	Oregon	2"	No Design
38	Pennsylvania	3″	8″
39	Rhode Island	3.25″	No Design
40	South Carolina	No minimum	8″
41	South Dakota		
42	Tennessee	4"	No Design
43	Texas		
44	Utah		
45	Vermont		
46	Virginia		
47	Washington	4″	No Design
48	West Virginia	3"	8"
49	Wisconsin	No minimum	8"
50	Wyoming		

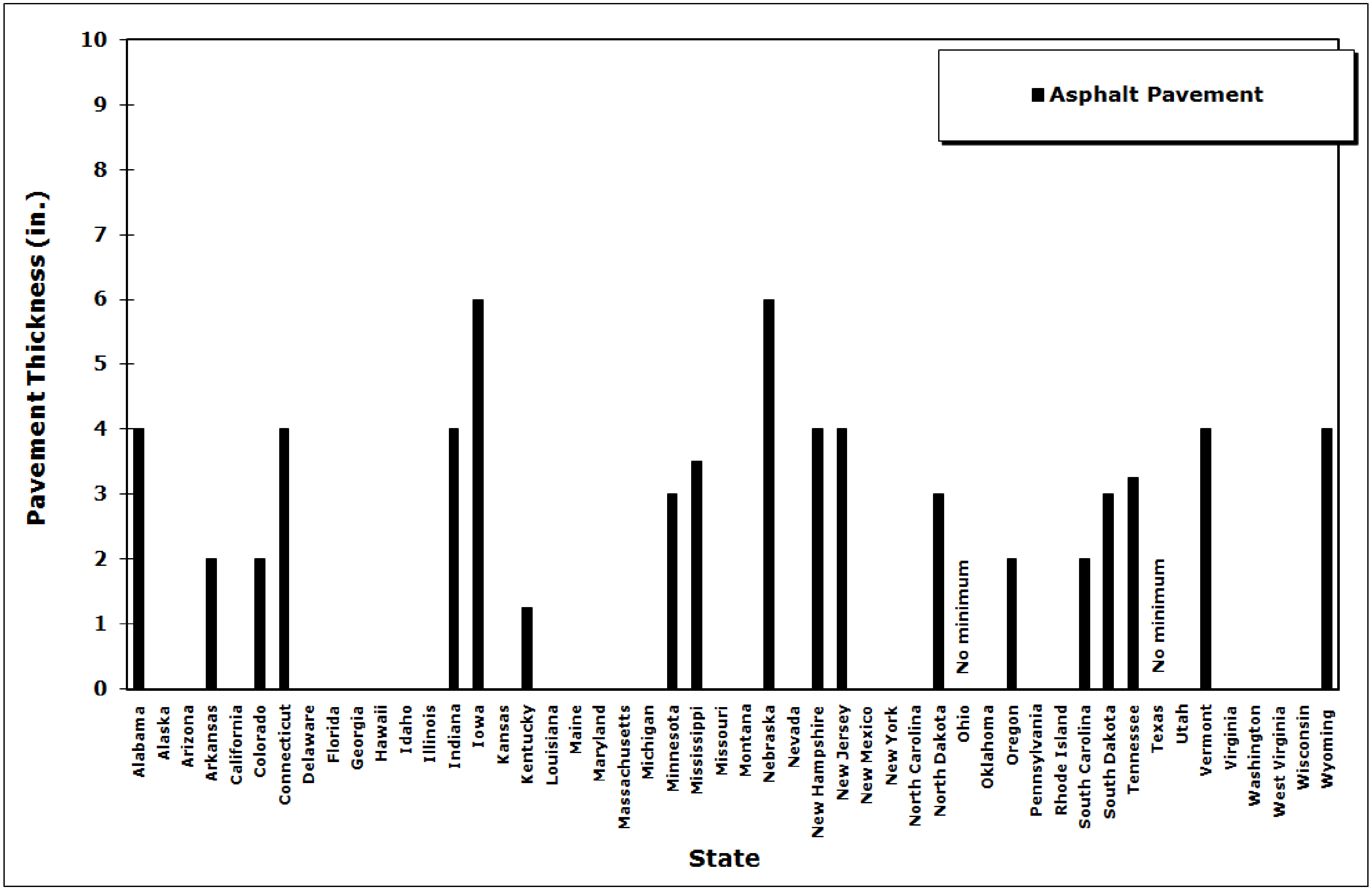


Figure A-2. Comparisons of minimum thickness for asphalt pavement from 24 sates

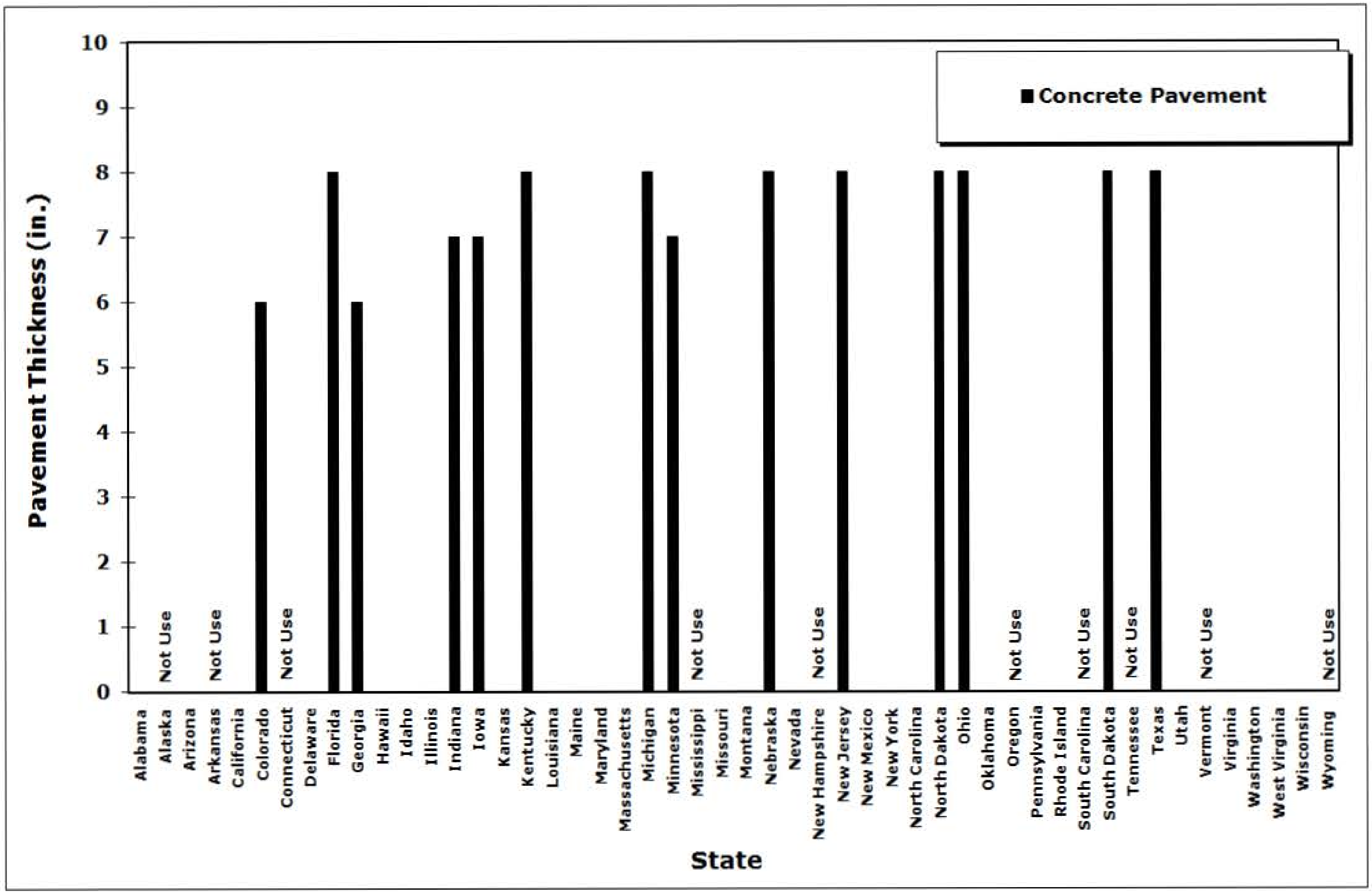


Figure A-3. Comparisons of minimum thickness for concrete pavement from 24 sates

Appendix B

B-1. Survey Form

B-2. Survey Responses

- Illinois DOT
- Missouri DOT
- Minnesota DOT
- South Dakota DOT
- Wisconsin DOT

B-1. Survey Form

Survey on Local Road Pavement Thickness Design Procedures

Prepared by:

Hosin “David” Lee, Ph.D., P.E.

Public Policy Center, 227 SQ

Civil and Environmental Engineering

Iowa City, IA 52242-1192

University of Iowa

E-mail: hlee@engr.uiowa.edu

Phone: 319-335-6818

Fax: 319-335-6801

INSTRODUCTION: University of Iowa is initiating in conducting a research project on "*Pavement Thickness Design for Local Roads in Iowa*". This survey is part of a research effort sponsored by the Iowa Department of Transportation. The principal investigator is Professor Hosin "David" Lee at the University of Iowa. On behalf of our research committee, we would like to solicit your opinion on the status of local road pavement thickness design procedures in your state. The main objective of this survey is to investigate pavement thickness design procedure for low-volume roads and identify design parameters needed for low-volume pavement design in adjoining States. All participants will receive a summary of the survey results by e-mail after all of the responses have been compiled. Thank you for your willingness to participate!

QUESTIONNAIRE SURVEY FORM

Participant:
Name:
Position Title:
Phone Number:
E-mail Address:
Organization Name:

1. What kind of pavement design methodology do you use for low volume road?

- ☐ American Association of State Highway and Transportation Officials (AASHTO)
- ☐ Asphalt Institute (AI)
- ☐ Portland Cement Association (PCA)
- ☐ American Concrete Pavement Association (ACPA)
- ☐ American Concrete Pavement Association (ACPA)
- ☐ US Army Corps of Engineers (UCSA)
- ☐ Other (Please note)

2. What kind of pavement thickness design software do you use for low volume road? Please mark all that apply.

- ☐ Asphalt Institute (AI)
- ☐ WinPas Pavement Design Software
- ☐ Street Pave Software
- ☐ Other (please note)

3. How does your state agency classify as low-volume road? What roads may be designated as a low-volume road?

4. Has your state agency developed a pavement thickness design procedure for low-volume road?

- ☐ Yes (if yes, please explain the procedure or send me specification documentation)
- ☐ No

5. What are the layer types and thicknesses of a typical flexible low-volume road in your states? Please include units.

1) Surface: material description: type here; thickness: type here
2) Base: material description: type here; thickness: type here
3) Subbase: material description: type here; thickness: type here
4) Other features: type here

6. What are the layer types and thicknesses of a typical rigid low-volume road in your state? Please include units.

1) Surface: material description: type here; thickness: type here
2) Base: material description: type here; thickness: type here
3) Subbase: material description: type here; thickness: type here
4) Other features: type here

7. What are the most important of below factors for designing low-volume road?

- ☐ Traffic
- ☐ Drainage
- ☐ Subgrade
- ☐ Paving Materials
- ☐ Loads
- ☐ Pavement Performance Criteria
- ☐ Desired Reliability

8. What type of soils do you have?

(A-1 to A-7)

9. How do you estimate subgrade strength for low-volume road design?

1) Soil classification (Describe: type here)
2) Laboratory testing (Describe: type here)
3) Field experience (Describe: type here)
4) Other: type here

10. What soil parameter does your state agency typically use for low-volume load design?

- ☐ California Bearing Ratio (CBR)
- ☐ Resilient Modulus (Mr)
- ☐ Modulus of Subgrade Reaction (k-value)

11. What paving materials and properties does your state agency typically use for low volume road design?

- ☐ Granular (CBR or Mr)
- ☐ Treated Granular (MR (resilient modulus))
- ☐ Hot Mix Asphalt (E (elastic modulus))
- ☐ Portland Cement Concrete (E (elastic modulus), f'c (compressive strength), S'c (flexural strength))

12. What type of traffic input do you use for low-volume road design?

- ☐ Maximum Load
- ☐ ADT
- ☐ ESAL (if, what the typical ESAL range does your state agency use for low-volume load?)
  - ☐ <10,000
  - ☐ 10,000-50,000
  - ☐ 50,000-100,000
  - ☐ 100,000-250,000
  - ☐ 250,000-500,000

13. What types of drainage features does your agency commonly use for low-volume road design?

- ☐ Ditches
- ☐ Edge Drains
- ☐ Drainage Layer
- ☐ Other (please note)

14. Does your state agency use a serviceability index to low volume load?

15. What design reliability does your state agency use for low volume load?

16. What are the important characteristics of flexible pavement for low-volume road design?

17. What are the important characteristics of rigid pavement for low-volume road design?

B-2. Survey Responses

- Illinois DOT
- Missouri DOT
- Minnesota DOT
- South Dakota DOT
- Wisconsin DOT

QUESTIONNAIRE SURVEY FORM

Participant
Name: Kevin Burke III
Position Title: Local Policy & Technology Engineer
Phone Number: (217) 7855048
E-mail Address: kevin.burkeiii@illinois.gov
Organization Name: Illinois Department of Transportation

1. What kind of pavement design methodology do you use for low volume road?
   - ☐ American Association of State Highway and Transportation Officials (AASHTO)
   - ☐ Asphalt Institute (AI)
   - ☐ Portland Cement Association (PCA)
   - ☐ American Concrete Pavement Association (ACPA)
   - ☐ American Concrete Pavement Association (ACPA)
   - ☐ US Army Corps of Engineers (UCSA)
   - ☑ Other (Please note)

   Mechanistic Empirical Design developed by U of I and IL DOT

2. What kind of pavement thickness design software do you use for low volume road? Please mark all that apply.
   - ☐ Asphalt Institute (AI)
   - ☐ WinPas Pavement Design Software
   - ☐ Street Pave Software
   - ☑ Other (please note)

   None

3. How does your state agency classify as low-volume road? What roads may be designated as a low-volume road?
   400 ADT; Traffic Factor<0.25

4. Has your state agency developed a pavement thickness design procedure for low-volume road?
   - ☑ Yes (if yes, please explain the procedure or send me specification documentation)
   - ☐ No

   Conventional Flexible Design (Chapter 37-3 of the BLRS Manual
   http://www.dot.il.gov/blr/manuals/Chapter%2037.pdf

5. What are the layer types and thicknesses of a typical flexible low-volume road in your states? Please include units.
   1) Surface: material description: HMA; thickness: 3”
   2) Base: material description: Class A Aggregate: thickness: 8”
   3) Subbase: material description: Modified Soil; thickness: 8”
   4) Other features: type here

6. What are the layer types and thicknesses of a typical rigid low-volume road in your state? Please include units.
   5) Surface: material description: type here; thickness: type here
   6) Base: material description: type here; thickness: type here
   7) Subbase: material description: type here; thickness: type here
   8) Other features: type here

7. What are the most important of below factors for designing low-volume road?

- [x] Traffic
- [ ] Drainage
- [ ] Subgrade
- [x] Paving Materials
- [ ] Loads
- [ ] Pavement Performance Criteria
- [ ] Desired Reliability

8. What type of soils do you have?
   (A-1 to A-7)

9. How do you estimate subgrade strength for low-volume road design?
   5) Soil classification (Describe: type here)
   6) Laboratory testing (Describe: type here)
   7) Field experience (Describe: type here)
   8) Other: type here

10. What soil parameter does your state agency typically use for low-volume load design?

- [ ] California Bearing Ratio (CBR)
- [ ] Resilient Modulus (Mr)
- [ ] Modulus of Subgrade Reaction (k-value)

11. What paving materials and properties does your state agency typically use for low volume road design?

- ☐ Granular (CBR or Mr)
- ☐ Treated Granular (MR (resilient modulus))
- ☑ Hot Mix Asphalt (E (elastic modulus))
- ☐ Portland Cement Concrete (E (elastic modulus), f'c (compressive strength), S'c (flexural strength)

12. What type of traffic input do you use for low-volume road design?

- ☐ Maximum Load
- ☐ ADT
- ☑ ESAL (if, what the typical ESAL range does your state agency use for low-volume load?)
  - ☑ <10,000
  - ☑ 10,000-50,000
  - ☑ 50,000-100,000
  - ☑ 100,000-250,000
  - ☐ 250,000-500,000

13. What types of drainage features does your agency commonly use for low-volume road design?

- ☑ Ditches
- ☐ Edge Drains
- ☐ Drainage Layer
- ☐ Other (please note)

14. Does your state agency use a serviceability index to low volume load?

15. What design reliability does your state agency use for low volume load?

16. What are the important characteristics of flexible pavement for low-volume road design?

17. What are the important characteristics of rigid pavement for low-volume road design?

QUESTIONNAIRE SURVEY FORM

Participant
Name: John Donahue
Position Title: Pavement Engineer
Phone Number: (573) 526-4334
E-mail Address: john.donahue@modot.mo.gov
Organization Name: Missouri Department of Transportation

1. What kind of pavement design methodology do you use for low volume road?
   - [x] American Association of State Highway and Transportation Officials (AASHTO)
   - [ ] Asphalt Institute (AI)
   - [ ] Portland Cement Association (PCA)
   - [ ] American Concrete Pavement Association (ACPA)
   - [ ] American Concrete Pavement Association (ACPA)
   - [ ] US Army Corps of Engineers (UCSA)
   - [ ] Other (Please note)

2. What kind of pavement thickness design software do you use for low volume road? Please mark all that apply.
   - [ ] Asphalt Institute (AI)
   - [ ] WinPas Pavement Design Software
   - [ ] Street Pave Software
   - [x] Other (please note)

   Mechanistic-Empirical Pavement Design Guide

3. How does your state agency classify as low-volume road? What roads may be designated as a low-volume road?
   MoDOT currently defines nearly all non-principle arterial routes as minor, which may or may not mean they're low volume. For planning purposes we don't have any official substratification of the 'minor' category. However, from a designer's perspective, routes that merit mention as 'low volume', using functional classification terms, would consist of nearly all rural major and minor collectors and some minor arterials. Traffic-wise, low volume means less than 1000 AADT and less than a 100 trucks a day. Since this survey concerns designing these types of route, keep in mind that we almost never build new or reconstruct existing ones. The few cases where this occurs are generally for short approaches to bridge replacements and adding turn lanes. Our budget, particularly at this crucial time, will not allow the luxury of much more than a 1" surface level course every ten years or so on true low volume routes. So, these answers are somewhat hypothetical in the sense that we seldom do what I'm explaining in these other answers. But for the times that we do, the MEPDG is our primary design tool for low volume routes, the same as if we were working on I-70 or I-44.

4. Has your state agency developed a pavement thickness design procedure for low-volume road?

- ☐ Yes (if yes, please explain the procedure or send me specification documentation)
- ☑ No

5. What are the layer types and thicknesses of a typical flexible low-volume road in your states? Please include units.
   1) Surface: material description: hot mix asphalt; thickness: 7” – 8”
   2) Base: material description: crushed stone; thickness: 4”
   3) Subbase: material description: N/A
   4) Other features: type here

6. What are the layer types and thicknesses of a typical rigid low-volume road in your state? Please include units.
   1) Surface: material description: JPCP; thickness: 6” – 7”
   2) Base: material description: crushed stone; thickness: 4”
   3) Subbase: material description: N/A
   4) Other features: type here

7. What are the most important of below factors for designing low-volume road?

- ☐ Traffic
- ☐ Drainage
- ☑ Subgrade
- ☐ Paving Materials
- ☑ Loads
- ☐ Pavement Performance Criteria
- ☐ Desired Reliability

8. What type of soils do you have?
   (A-1 to A-7): Primarily A-4, A-7-5, and A-7-6 soils. In the SE part of Missouri there are some A-3 areas.

9. How do you estimate subgrade strength for low-volume road design?
   1) Soil classification (Usually assume resilient modulus value from AASHTO Class)
   2) Laboratory testing (Describe: type here)
   3) Field experience (Describe: type here)
   4) Other: type here

10. What soil parameter does your state agency typically use for low-volume load design?

- [ ] California Bearing Ratio (CBR)
- [x] Resilient Modulus (Mr)
- [ ] Modulus of Subgrade Reaction (k-value)

11. What paving materials and properties does your state agency typically use for low volume road design?

- [x] Granular (CBR or Mr)
- [ ] Treated Granular (MR (resilient modulus))
- [x] Hot Mix Asphalt (E (elastic modulus))
- [x] Portland Cement Concrete (E (elastic modulus), f'c (compressive strength), S'c (flexural strength))

12. What type of traffic input do you use for low-volume road design?

- [ ] Maximum Load
- [ ] ADT
- [ ] ESAL (if, what the typical ESAL range does your state agency use for low-volume load?)
  - [ ] <10,000
  - [ ] 10,000-50,000
  - [ ] 50,000-100,000
  - [ ] 100,000-250,000
  - [ ] 250,000-500,000

Load spectra in the MEPDG. We'll use a default truck classification table since we never have WIM's and AVC's installed at low volume road locations for actual counts.

13. What types of drainage features does your agency commonly use for low-volume road design?

- [x] Ditches
- [ ] Edge Drains
- [ ] Drainage Layer
- [ ] Other (please note)

14. Does your state agency use a serviceability index to low volume load?

Some of our Districts use the PASER rating system. Our Automated Road Analyzer (ARAN) makes forays onto a small percentage of low volume routes, which enables us to have IRI and visible distress data.

15. What design reliability does your state agency use for low volume load?
    50%

16. What are the important characteristics of flexible pavement for low-volume road design?
    Adequate structure and proper compaction of lower layers.

17. What are the important characteristics of rigid pavement for low-volume road design?
    Short joint spacing and proper compaction of lower layers.

QUESTIONNAIRE SURVEY FORM

Participant:
Name: Joe Thomas, P.E.
Position Title: State Aid Project Engineer
Phone Number: 651-366-3831
E-mail Address: joe.thomas@dot.state.mn.us
Organization Name: Minnesota Department of Transportation – State Aid Division

1. What kind of pavement design methodology do you use for low volume road?

- [ ] American Association of State Highway and Transportation Officials (AASHTO)
- [ ] Asphalt Institute (AI)
- [ ] Portland Cement Association (PCA)
- [ ] American Concrete Pavement Association (ACPA)
- [ ] American Concrete Pavement Association (ACPA)
- [ ] US Army Corps of Engineers (UCSA)
- [x] Other (Please note)

Charts and tables for soil factor and R-value

2. What kind of pavement thickness design software do you use for low volume road? Please mark all that apply.

- [ ] Asphalt Institute (AI)
- [ ] WinPas Pavement Design Software
- [ ] Street Pave Software
- [x] Other (please note)

See Pavement Design website:
http://www.dot.state.mn.us/materials/pvmtdesign/software.html

3. How does your state agency classify as low-volume road? What roads may be designated as a low-volume road?
   ADT less than 1000

4. Has your state agency developed a pavement thickness design procedure for low-volume road?
   - [x] Yes (if yes, please explain the procedure or send me specification documentation)
   - [ ] No

http://www.dot.state.mn.us/materials/pvmtdesign/docs/RValueChart.pdf (10 ton)
See attached pdf. for 7 ton and 9 ton design

5. What are the layer types and thicknesses of a typical flexible low-volume road in your states? Please include units.
   1) Surface: material description: **Bituminous** ; thickness: **Minimum 3”**
   2) Base: material description: Class 5 or 6; thickness: **6-8”**
   3) Subbase: material description: **Existing soils**; thickness: type here
   4) Other features: type here

6. What are the layer types and thicknesses of a typical rigid low-volume road in your state? Please include units.
   1) Surface: material description: **Concrete**; thickness: **7-9”**
   2) Base: material description: **Class 5 or 6**; thickness: **0-6”**
   3) Subbase: material description :**Existing soils**; thickness: type here
   4) Other features: type here

7. What are the most important of below factors for designing low-volume road?

- [x] Traffic
- [ ] Drainage
- [x] Subgrade
- [ ] Paving Materials
- [ ] [illegible]
- [ ] Pavement Performance Criteria
- [ ] Desired Reliability

8. What type of soils do you have?
   A-1 through A-6 and A-7-5 and A-7-6

9. How do you estimate subgrade strength for low-volume road design?
   9) Soil classification (Describe: See Word attachment: Plans and Proposal, section C3)
   10) Laboratory testing (Describe: See Word attachment: Plans and Proposal, section C3)
   11) Field experience (Describe: type here)
   12) Other: type here

10. What soil parameter does your state agency typically use for low-volume load design?

- [ ] California Bearing Ratio (CBR)
- [ ] Resilient Modulus (Mr)
- [ ] Modulus of Subgrade Reaction (k-value)

Soil Factor and/or R-Value

11. What paving materials and properties does your state agency typically use for low volume road design?

- ☐ Granular (CBR or Mr)
- ☐ Treated Granular (MR (resilient modulus))
- ☑ Hot Mix Asphalt (E (elastic modulus))
- ☐ Portland Cement Concrete (E (elastic modulus), f'c (compressive strength), S'c (flexural strength)

12. What type of traffic input do you use for low-volume road design?

- ☐ Maximum Load
- ☑ ADT
- ☑ ESAL (if, what the typical ESAL range does your state agency use for low-volume load?)
  - ☐ <10,000
  - ☐ 10,000-50,000
  - ☐ 50,000-100,000
  - ☑ 100,000-250,000
  - ☐ 250,000-500,000

13. What types of drainage features does your agency commonly use for low-volume road design?

- ☑ Ditches
- ☐ Edge Drains
- ☐ Drainage Layer
- ☐ Other (please note)

14. Does your state agency use a serviceability index to low volume load?

RQI – Ride quality Index, ranges from 0 -5 (best). Obtained from International Roughness Index (IRI)and Surface Rating (SR) values

15. What design reliability does your state agency use for low volume load?

80%

16. What are the important characteristics of flexible pavement for low-volume road design?

Subgrade and ADT/HCADT

17. What are the important characteristics of rigid pavement for low-volume road design?

Subgrade and ADT/HCADT

QUESTIONNAIRE SURVEY FORM

Participant:
Name: Gill L Hedman
Position Title: Pavement Design Engineer
Phone Number: (605) 773-5503
E-mail Address: gill.hedman@state.sd.us
Organization Name: South Dakota Department of Transportation

1. What kind of pavement design methodology do you use for low volume road?
   - [x] American Association of State Highway and Transportation Officials (AASHTO)
   - [ ] Asphalt Institute (AI)
   - [ ] Portland Cement Association (PCA)
   - [ ] American Concrete Pavement Association (ACPA)
   - [ ] American Concrete Pavement Association (ACPA)
   - [ ] US Army Corps of Engineers (UCSA)
   - [ ] Other (Please note)

2. What kind of pavement thickness design software do you use for low volume road? Please mark all that apply.
   - [ ] Asphalt Institute (AI)
   - [ ] WinPas Pavement Design Software
   - [ ] Street Pave Software
   - [x] Other (please note)

   We use the 1993 AASHTO Design Guide and the DARWIN Software to design low volume pavements

3. How does your state agency classify as low-volume road? What roads may be designated as a low-volume road?

   We in South Dakota don't have a low volume road classification; the classification of our system is set up by usage.

4. Has your state agency developed a pavement thickness design procedure for low-volume road?
   - [ ] Yes (if yes, please explain the procedure or send me specification documentation)
   - [x] No

5. What are the layer types and thicknesses of a typical flexible low-volume road in your states? Please include units.
   1) Surface: material description: Asphalt Concrete; thickness: 3” to 4”
   2) Base: material description: Base Course; thickness: 10” to 12”
   3) Subbase: material description: Subbase; thickness: If Used – 8”
   4) Other features: type here

6. What are the layer types and thicknesses of a typical rigid low-volume road in your state? Please include units.
   1) Surface: material description: type here; thickness: type here
   2) Base: material description: type here; thickness: type here
   3) Subbase: material description: type here; thickness: type here
   4) Other features: type here

7. What are the most important of below factors for designing low-volume road?

- ☑ Traffic
- ☐ Drainage
- ☑ Subgrade
- ☐ Paving Materials
- ☑ Loads
- ☐ Pavement Performance Criteria
- ☐ Desired Reliability

8. What type of soils do you have?
   (A-1 to A-7): Typical Soils are A-6 to A-7

9. How do you estimate subgrade strength for low-volume road design?
   1) Soil classification (We use the typical Liquid Limit value for the family of soils on the project and convert that number to a Resilient Modulus Value)
   2) Laboratory testing (Describe: type here)
   3) Field experience (Describe: type here)
   4) Other: type here

10. What soil parameter does your state agency typically use for low-volume load design?

- ☐ California Bearing Ratio (CBR)
- ☑ Resilient Modulus (Mr)
- ☐ Modulus of Subgrade Reaction (k-value)

11. What paving materials and properties does your state agency typically use for low volume road design?

- [x] Granular (CBR or Mr)
- [ ] Treated Granular (MR (resilient modulus))
- [x] Hot Mix Asphalt (E (elastic modulus))
- [ ] Portland Cement Concrete (E (elastic modulus), f'c (compressive strength), S'c (flexural strength)

12. What type of traffic input do you use for low-volume road design?

- [ ] Maximum Load
- [ ] ADT
- [x] ESAL (if, what the typical ESAL range does your state agency use for low-volume load?)
    - [ ] <10,000
    - [ ] 10,000-50,000
    - [x] 50,000-100,000
    - [ ] 100,000-250,000
    - [ ] 250,000-500,000

13. What types of drainage features does your agency commonly use for low-volume road design?

- [x] Ditches
- [ ] Edge Drains
- [ ] Drainage Layer
- [ ] Other (please note)

14. Does your state agency use a serviceability index to low volume load?

4.5 to 2.5

15. What design reliability does your state agency use for low volume load?

90%

16. What are the important characteristics of flexible pavement for low-volume road design?

They were detailed above in question #7.

17. What are the important characteristics of rigid pavement for low-volume road design?

We will not typically pave a low volume road with PCCP unless it would

QUESTIONNAIRE SURVEY FORM

Participant:

Name: Laura L. Fenley, P.E.
Position Title: Pavement Structural Engineer_
Phone Number: 608-246-5455_
E-mail address: laura.fenley@dot.state.wi.us
Organization Name: Wisconsin Department of Transportation_

1. What kind of pavement design methodology do you use for low volume road?

- [x] American Association of State Highway and Transportation Officials (AASHTO)
- [ ] Asphalt Institute (AI)
- [ ] Portland Cement Association (PCA)
- [ ] American Concrete Pavement Association (ACPA)
- [ ] American Concrete Pavement Association (ACPA)
- [ ] US Army Corps of Engineers (UCSA)
- [x] Other

(See Q #2)

2. What kind of pavement thickness design software do you use for low volume road? Please mark all that apply.

- [ ] Asphalt Institute (AI)
- [x] WinPas Pavement Design Software
- [ ] Street Pave Software
- [x] Other

(WisPave based on AASHTO 72)

3. How does your state agency classify as low-volume road? What roads may be designated as a low-volume road?

<400 AADT.

4. Has your state agency developed a pavement thickness design procedure for low-volume road?

☐ Yes (if yes, please explain the procedure or send me specification documentation)

☑ No

We use the same procedure for all volume, including low-volume. However, many roadways w/volumes that low are not WisDOT designed

5. What are the layer types and thicknesses of a typical flexible low-volume road in your states? Please include units.

5) Surface: Material description: Asphalt Concrete; thickness: Superpave 12.5mm E-0.3, 3”
6) Base: Material description: Base Course; thickness: dense graded aggregate 8”
7) Subbase: Material description: Subbase; thickness: If Used – None
8) Other features: Type here

6. What are the layer types and thicknesses of a typical rigid low-volume road in your state? Please include units.

1. Surface: Material description: Asphalt Concrete; thickness:
2. Base: Material description: Base Course; thickness:”
3. Subbase: Material description: Subbase; thickness: If Used
4. Other features: Type here

It would not be typical to use concrete for a low-volume road

7. What are the most important of below factors for designing low-volume road?

☑ Traffic
☐ Drainage
☑ Subgrade
☐ Paving Materials
☑ Loads
☑ Pavement Performance Criteria
☐ Desired Reliability

8. What type of soils do you have?

A-3; A-2-4; A-4; A-6; A-7-6

9. How do you estimate subgrade strength for low-volume road design?

1. Soil classification (Describe).
2. Laboratory testing (Describe: Type here)
3. Field experience (Describe: Type here)
4. Other: Type here

10. What soil parameter does your state agency typically use for low-volume load design?

☐ California Bearing Ratio (CBR)

☐ Resilient Modulus (Mr)

☐ Modulus of Subgrade Reaction (k-value)

We employ k-value and soil support vale (SSV) – DGI (design group index) based on pedology. DGI is primary. Our DGI ranges from 0 (best) to 20 with 10-14 being most common.

11. What paving materials and properties does your state agency typically use for low volume road design?

☑ Granular (CBR or Mr) (not if WisDOT designed)

☐ Treated Granular (MR (resilient modulus))

☑ Hot Mix Asphalt (E (elastic modulus))

☐ Portland Cement Concrete (E (elastic modulus), f'c (compressive strength), S'c (flexural strength))

12. What type of traffic input do you use for low-volume road design?

- ☐ Maximum Load
- ☑ ADT
- ☑ ESAL (if, what the typical ESAL range does your state agency use for low-volume load?)
    - ☑ <10,000
    - ☑ 10,000-50,000
    - ☐ 50,000-100,000
    - ☐ 100,000-250,000
    - ☐ 250,000-500,000

Typically less than 50,000

13. What types of drainage features does your agency commonly use for low-volume road design?

- ☑ Ditches
- ☐ Edge Drains
- ☐ Drainage Layer
- ☐ Other (please note)

14. Does your state agency use a serviceability index to low volume load?

All designs consider IRI and PDI (pavement distress index)

IRI of 0-5 (worst) and PDI 0-100 (60-70 dictates rehabilitation)

15. What design reliability does your state agency use for low volume load?

50%

16. What are the important characteristics of flexible pavement for low-volume road design?

Thickness, PG grade, gradation and %AC

17. What are the important characteristics of rigid pavement for low-volume road design?

N/A

Appendix C

C-1. StreetPave Software

- C-1.1 Concrete Pavement (Design Life: 20 years)
- C-1.2 Concrete Pavement (Design Life: 40 years)
- C-1.3 Concrete Pavement (20 years vs. 40 years)
- C-1.4 Asphalt Pavement (Design Life: 20 years)
- C-1.5 Asphalt Pavement (Design Life: 40 years)
- C-1.6 Asphalt Pavement (20 years vs. 40 years)

C-2. WinPas Software

- C-2.1 Concrete Pavement (Design Life: 20 years)
- C-2.2 Concrete Pavement (Design Life: 40 years)
- C-2.3 Concrete Pavement (20 years vs. 40 years)
- C-2.1 Asphalt Pavement (Design Life: 20 years)
- C-2.2 Asphalt Pavement (Design Life: 40 years)
- C-2.3 Asphalt Pavement (20 years vs. 40 years)

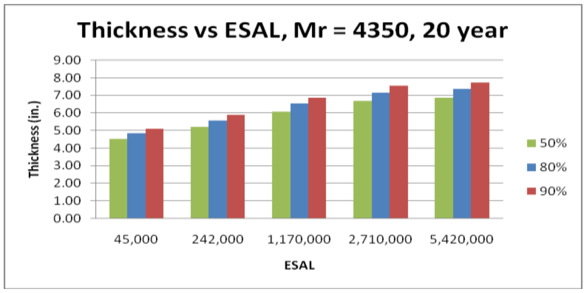
C-3. APAI Software

- C-3.1. Asphalt Pavement (Design Life: 20 years)
- C-3.2. Asphalt Pavement (Design Life: 40 years)
- C-3.3. Asphalt Pavement (20 years vs. 40 years)

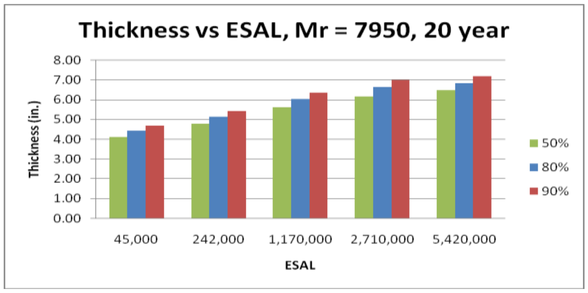
C-4. Comparison

- C-4.1 Asphalt Pavement (WinPas vs. StreetPave vs. APAI)
- C-4.2 Concrete Pavement (WinPas vs. StreetPave)

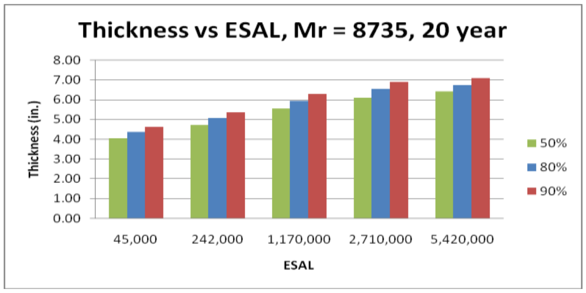
Appendix C-1.1 Concrete Pavement (Design Life: 20 years)



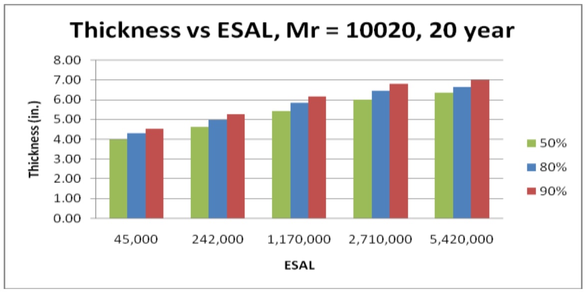
(a) Mr=4350



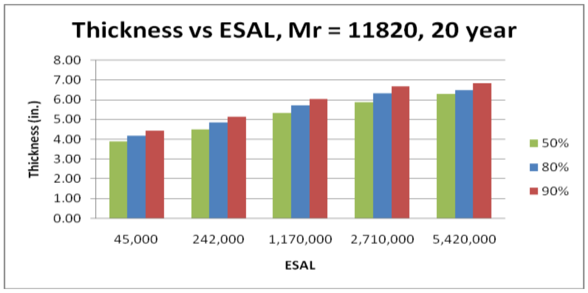
(b) Mr=7950



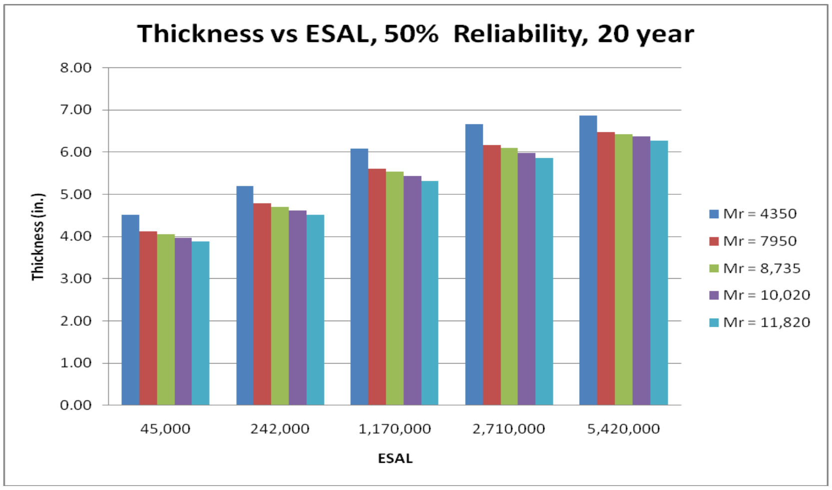
(c) Mr=8735



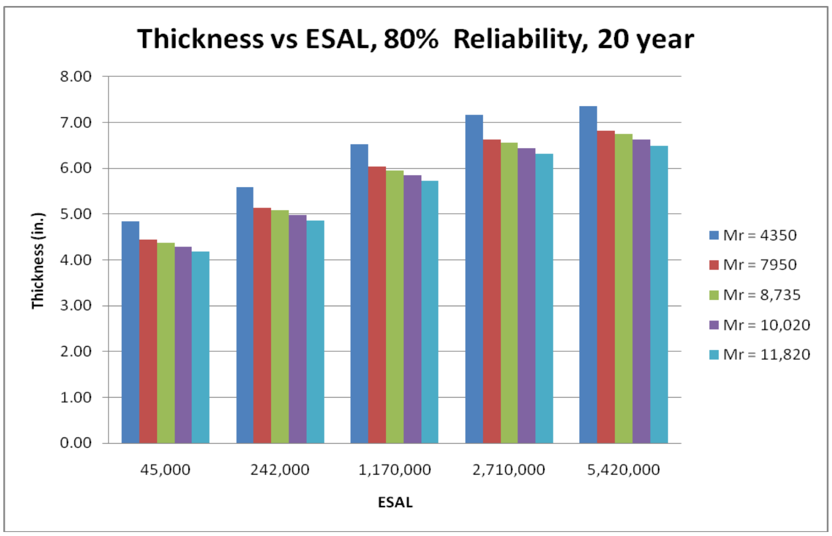
(d) Mr=10020



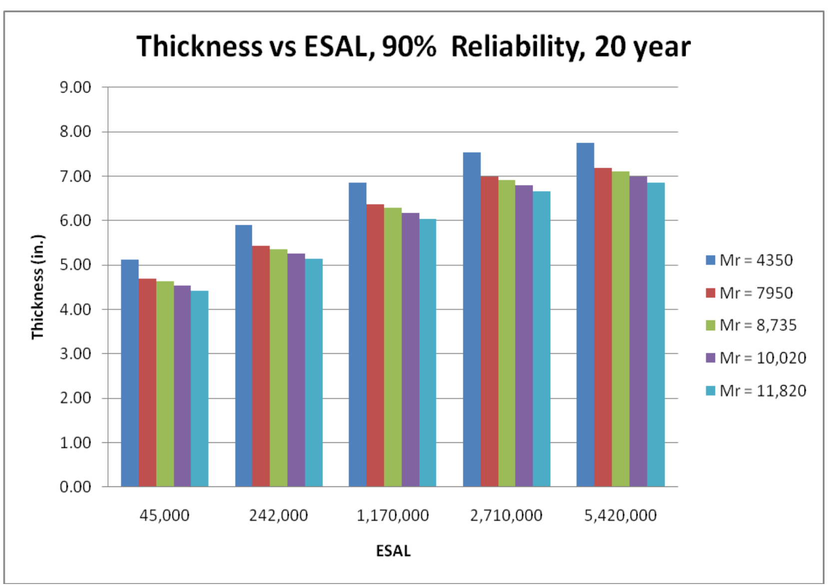
(e) Mr=11820



(f) Reliability: 50%

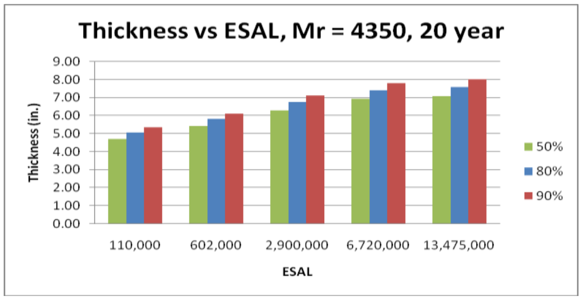


(g) Reliability: 80%

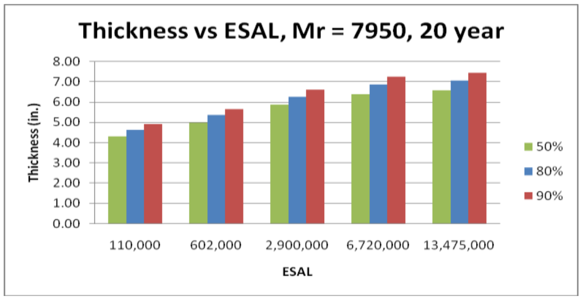


(h) Reliability: 90%

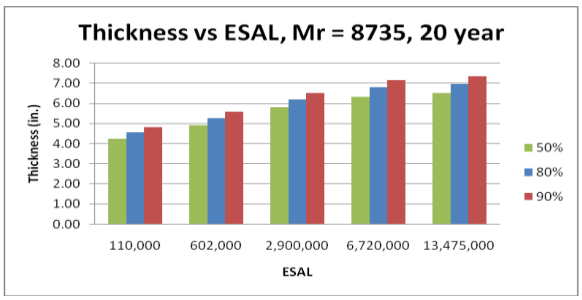
Appendix C-1.2 Concrete Pavement (Design Life: 40 years)



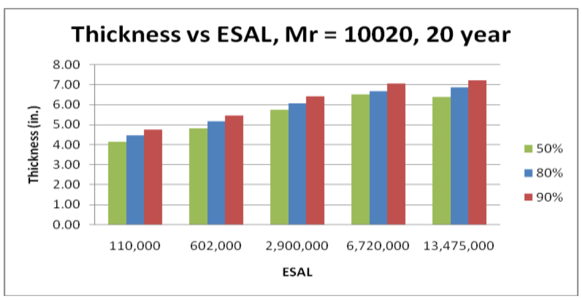
(a) Mr=4350



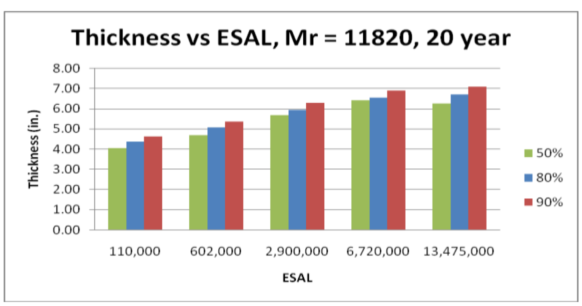
(b) Mr=7950



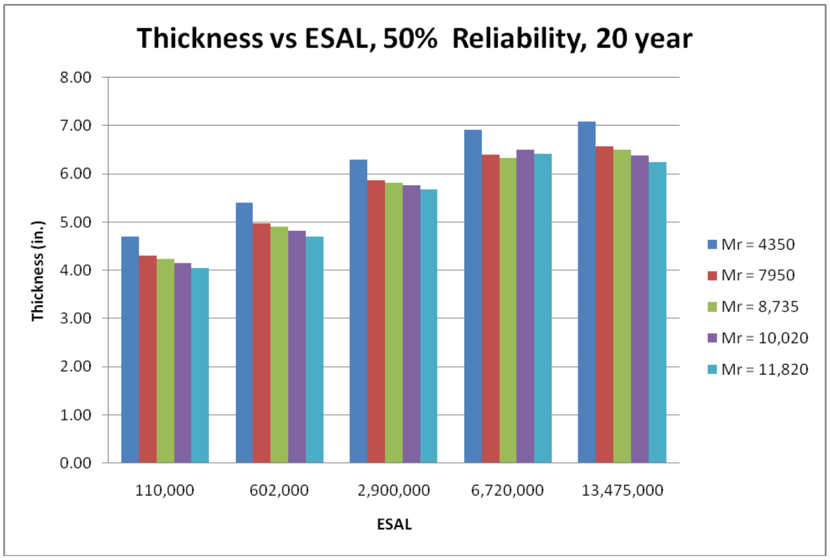
(c) Mr=8735



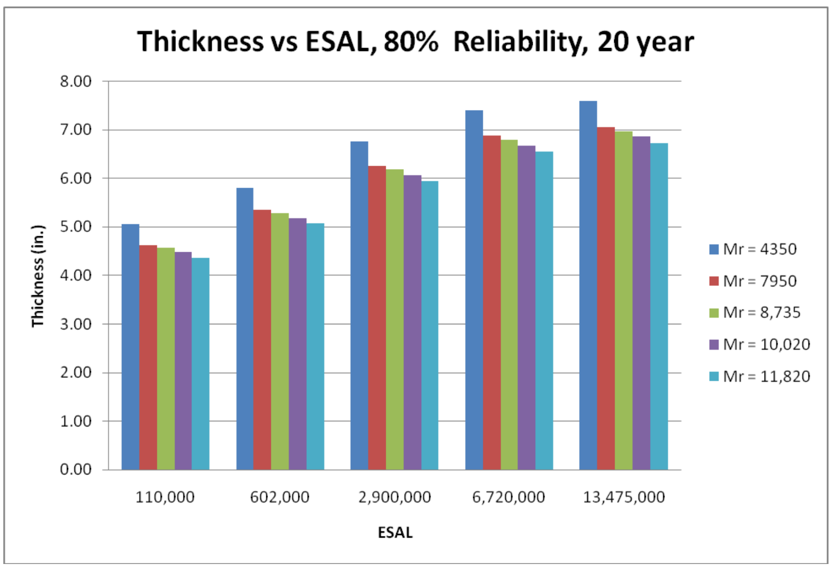
(d) Mr=10020



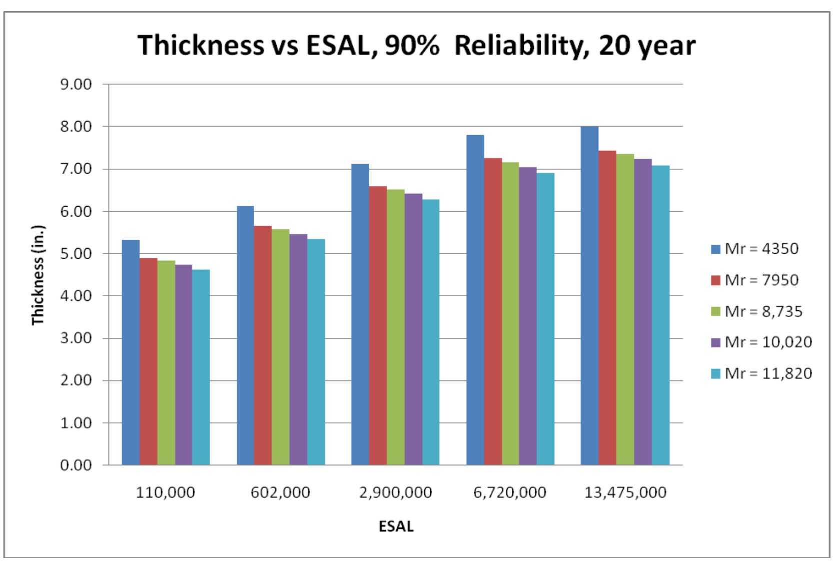
(e) Mr=11820



(e) Reliability: 50%

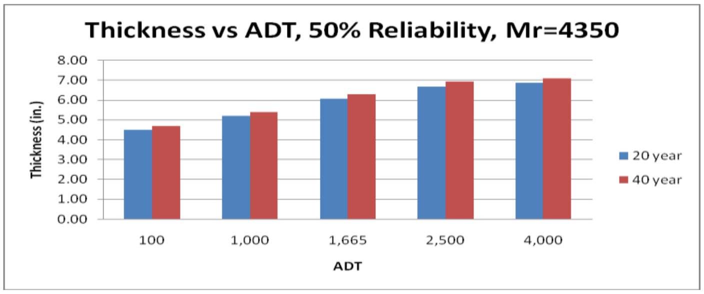


(f) Reliability: 80%

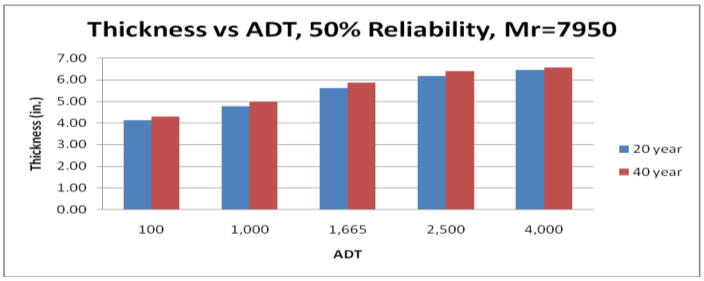


(g) Reliability: 90%

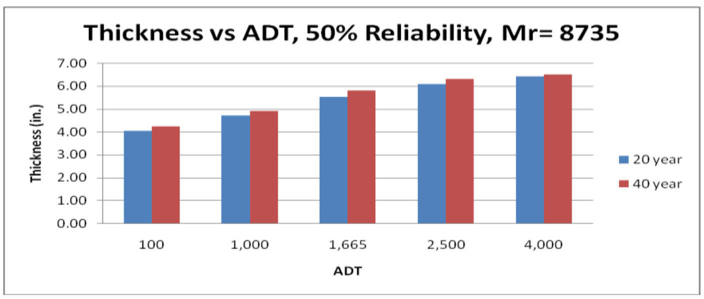
Appendix C-1.3 Concrete Pavement (20 years vs. 40 years)



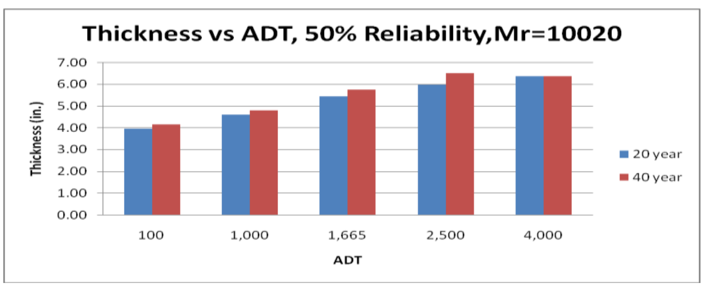
(a) Mr=4350 (Reliability: 50%)



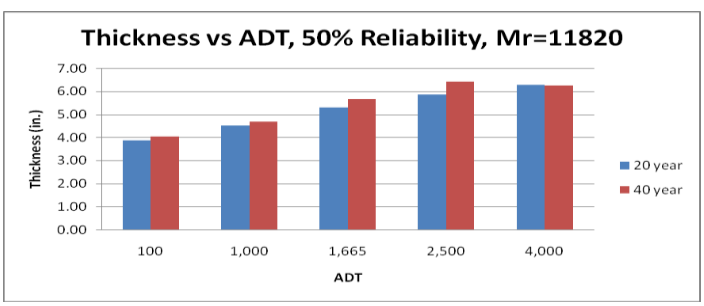
(b) Mr=7950 (Reliability: 50%)



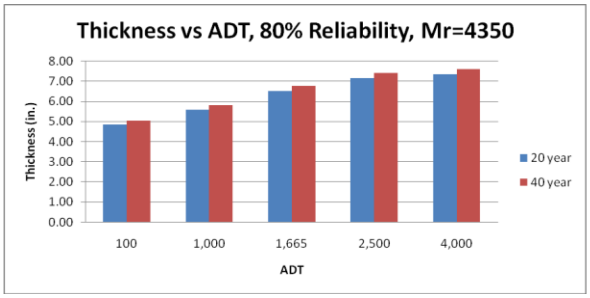
(c) Mr=8735 (Reliability: 50%)



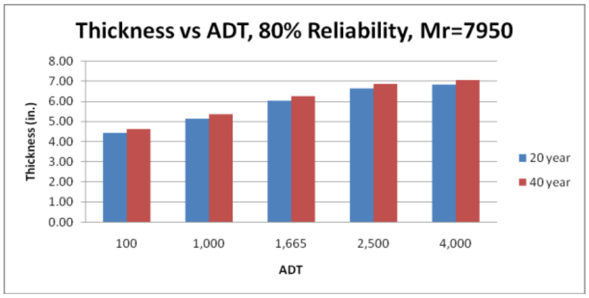
(d) Mr=10020 (Reliability: 50%)



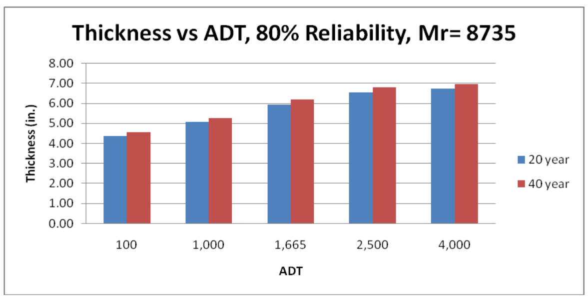
(e) Mr=11820 (Reliability: 50%)



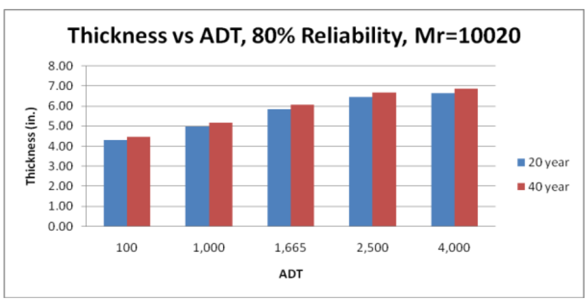
(f) Mr=4350 (Reliability: 80%)



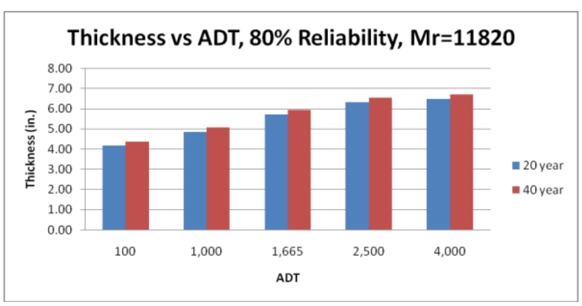
(g) Mr=7950 (Reliability: 80%)



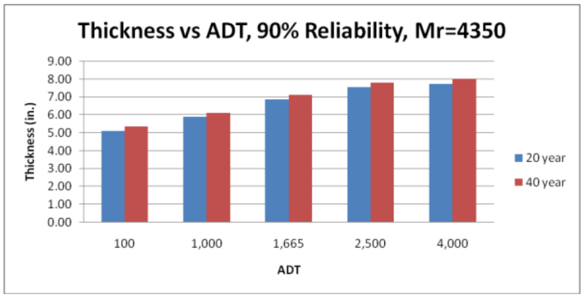
(h) Mr=8735 (Reliability: 80%)



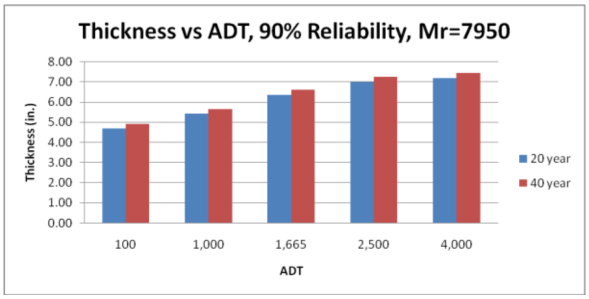
(i) Mr=10020 (Reliability: 80%)



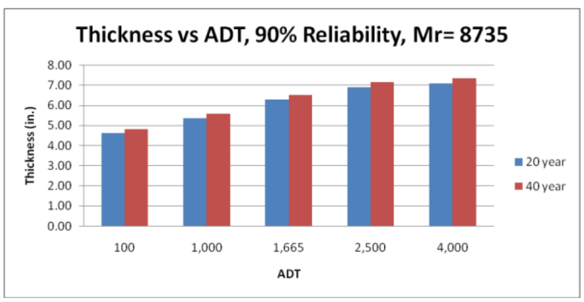
(j) Mr=11820 (Reliability: 80%)



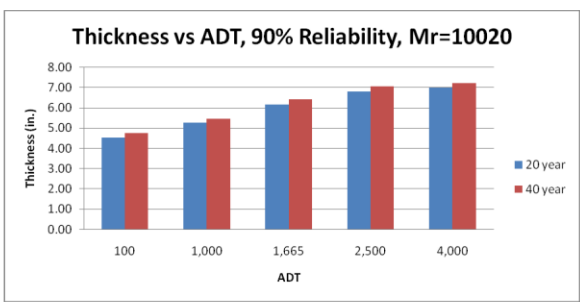
(k) Mr=4350 (Reliability: 90%)



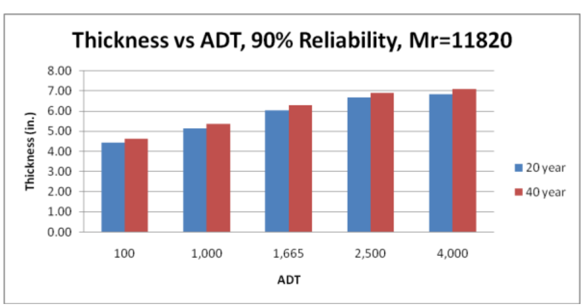
(l) Mr=7950 (Reliability: 90%)



(m) Mr=8735 (Reliability: 90%)

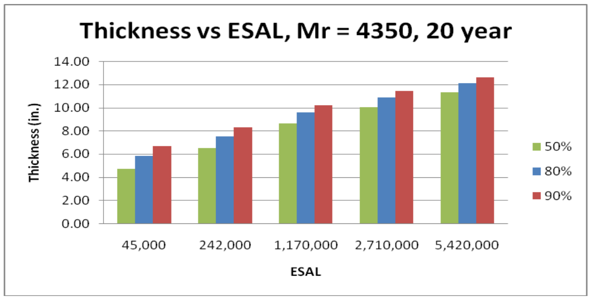


(n) Mr=10020 (Reliability: 90%)

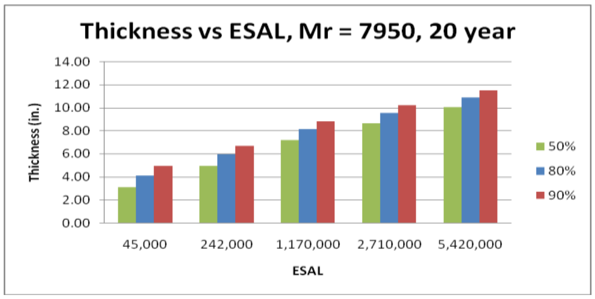


(o) Mr=11820 (Reliability: 90%)

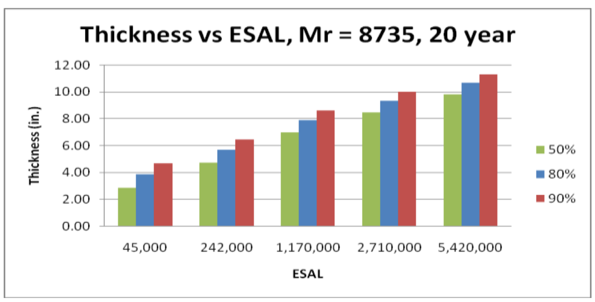
Appendix C.1.4 Asphalt Pavement (Design Life: 20 years)



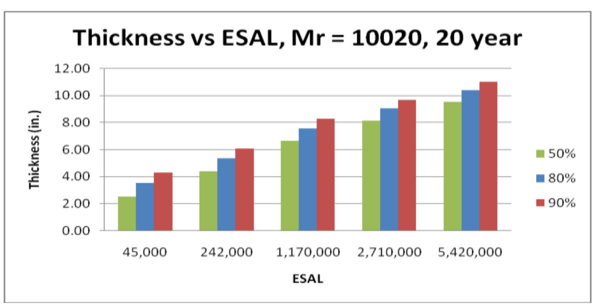
(a) Mr=4350



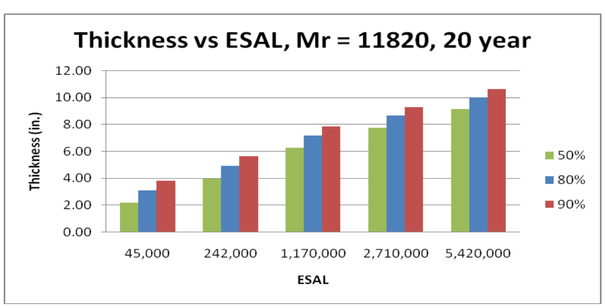
(b) Mr=7950



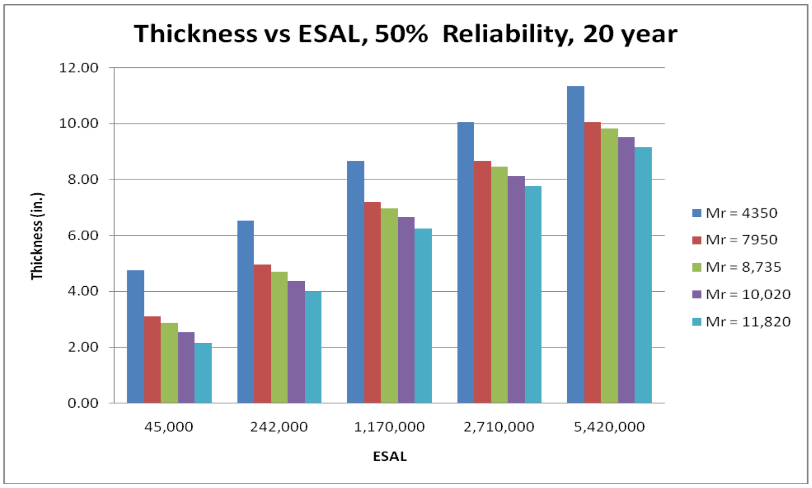
(c) Mr=8735



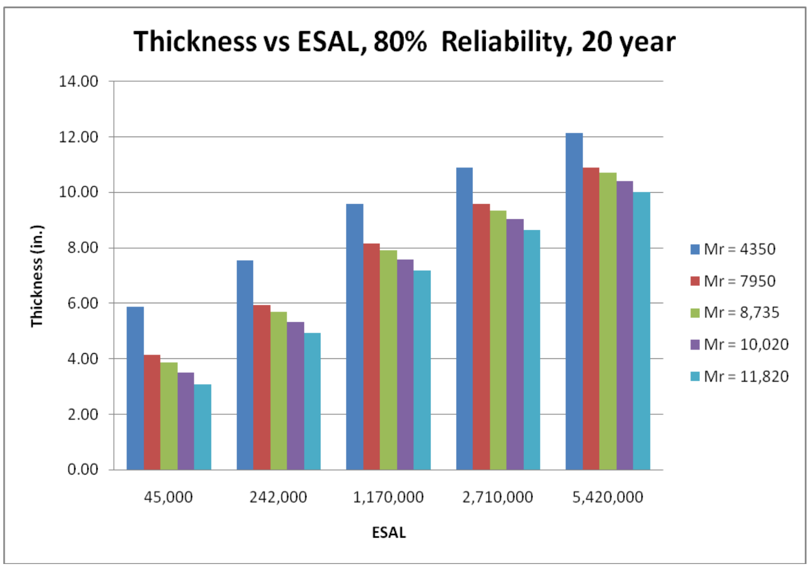
(d) Mr=10020



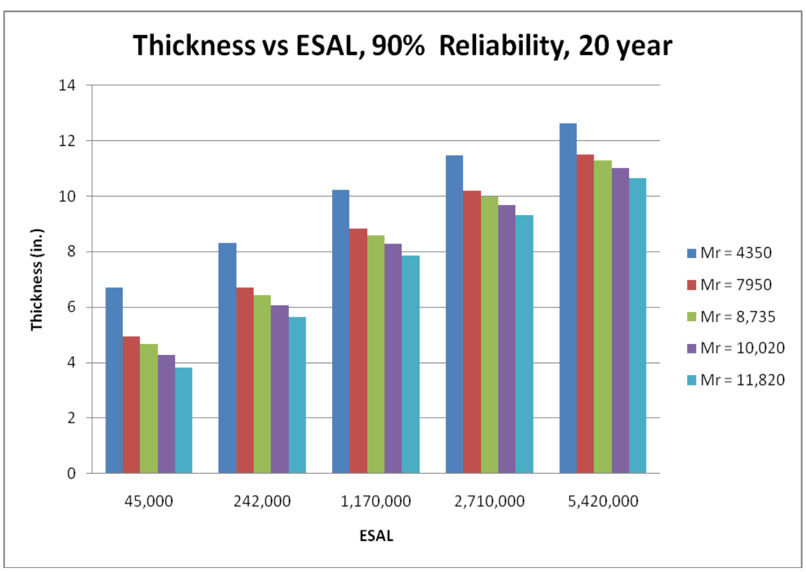
(e) Mr=11820



(f) Reliability: 50%

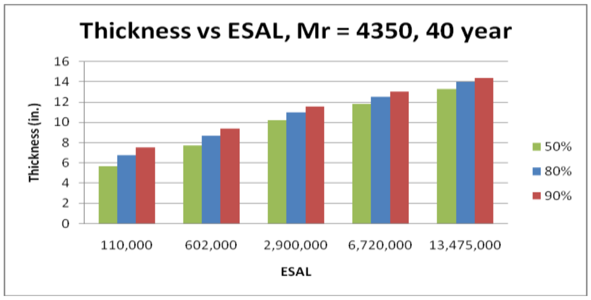


(g) Reliability: 80%

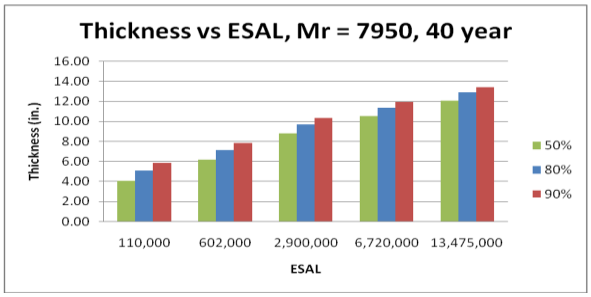


(h) Reliability: 90%

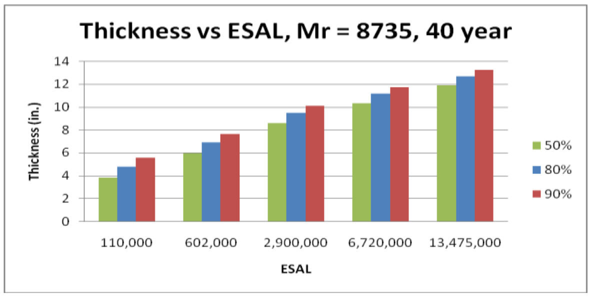
Appendix C.1.5 Asphalt Pavement (Design Life: 40 years)



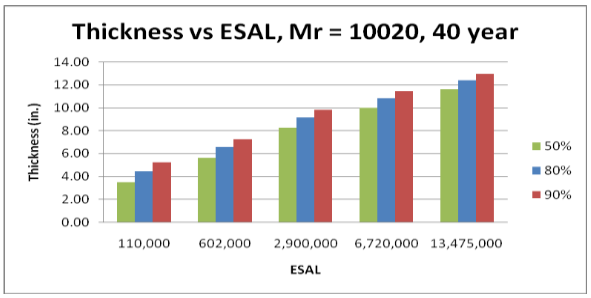
(a) Mr=4350



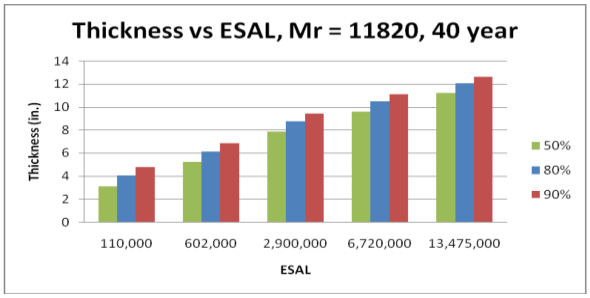
(b) Mr=7950



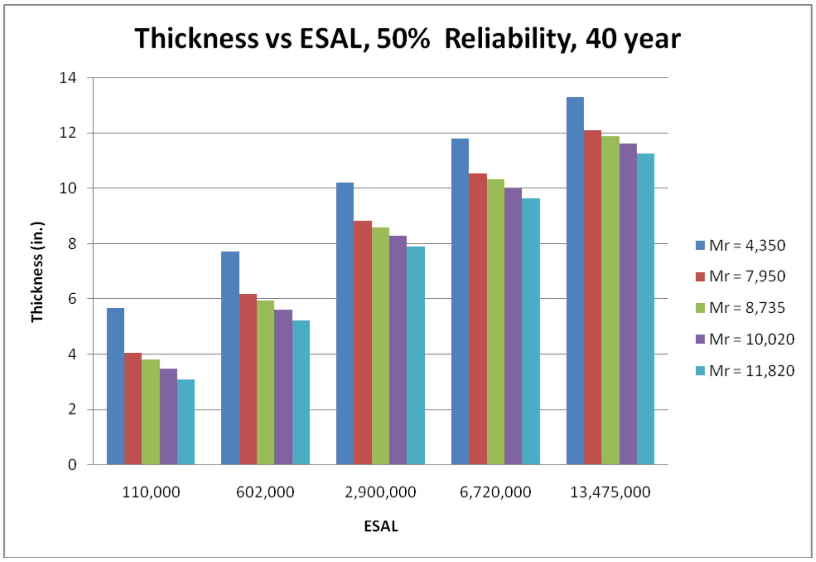
(c) Mr=8735



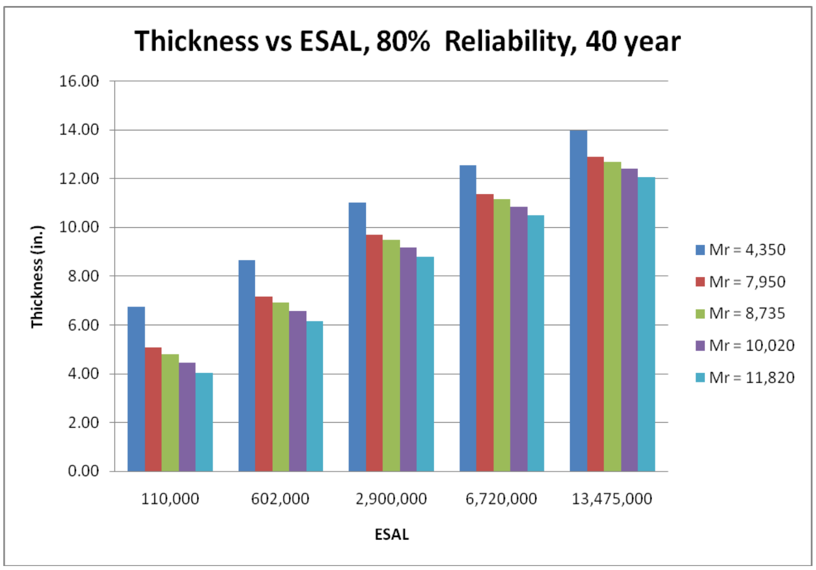
(d) Mr=10020



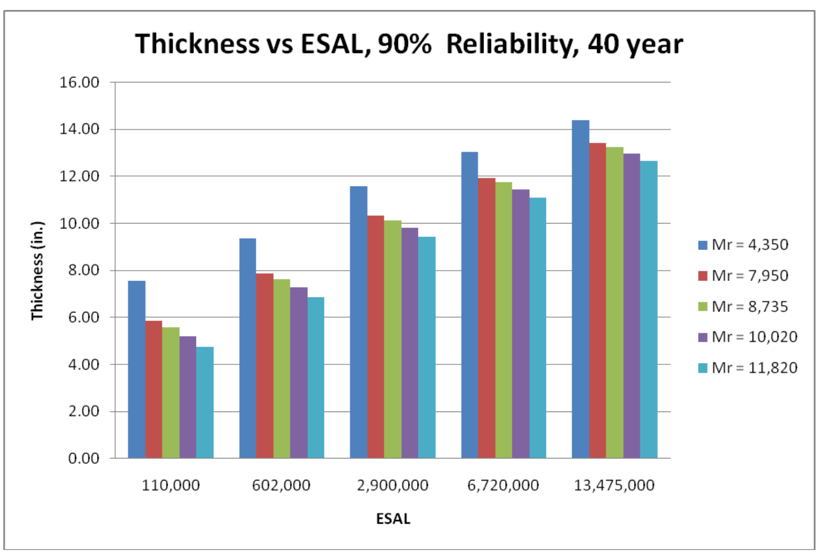
(e) Mr=11820



(f) Reliability: 50%

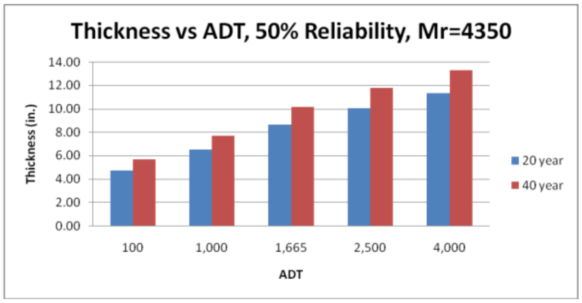


(h) Reliability: 80%

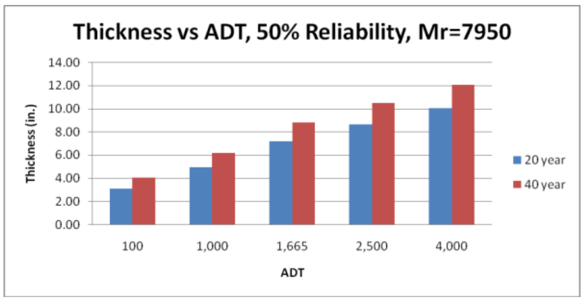


(i) Reliability: 90%

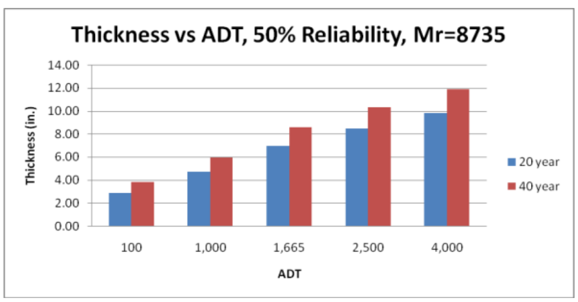
Appendix C.1.6 Asphalt Pavement (20 years vs. 40 years)



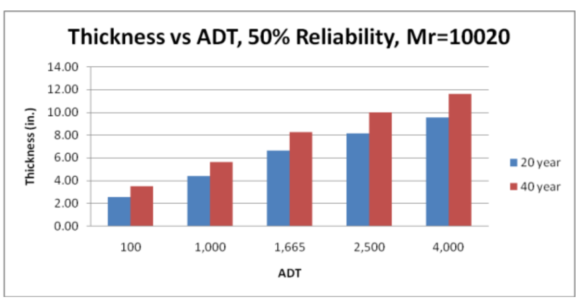
(a) Mr=4350 (Reliability: 50%)



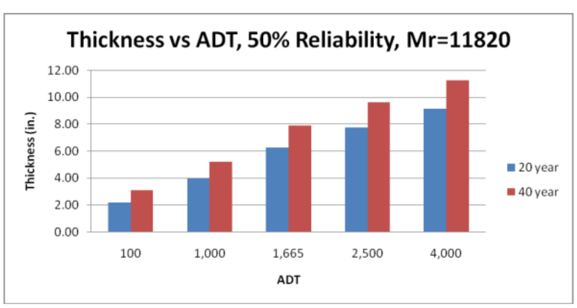
(b) Mr=7950 (Reliability: 50%)



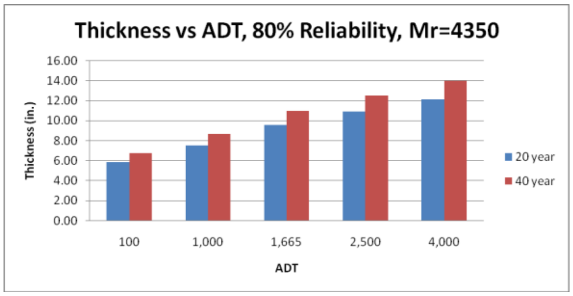
(c) Mr=8735 (Reliability: 50%)



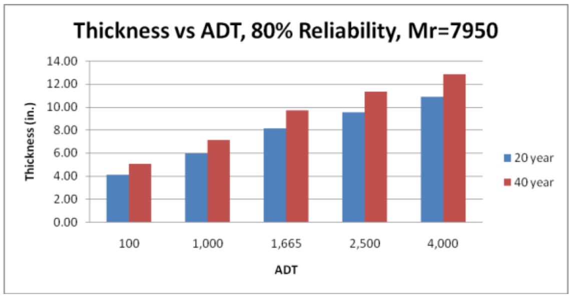
(d) Mr=10020 (Reliability: 50%)



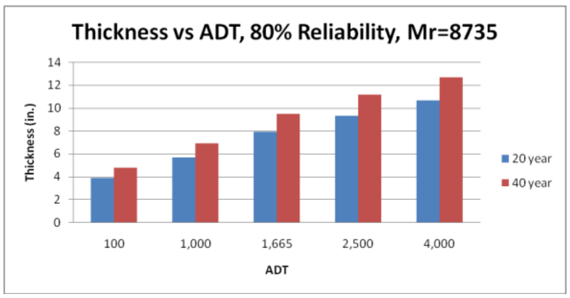
(e) Mr=11820 (Reliability: 50%)



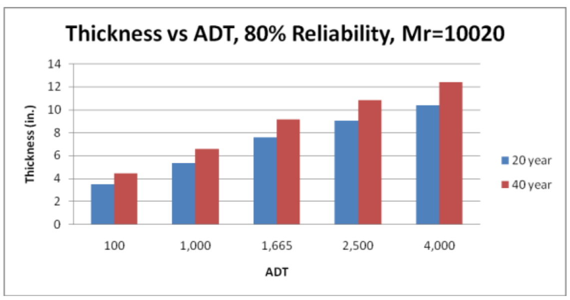
(f) Mr=4350 (Reliability: 80%)



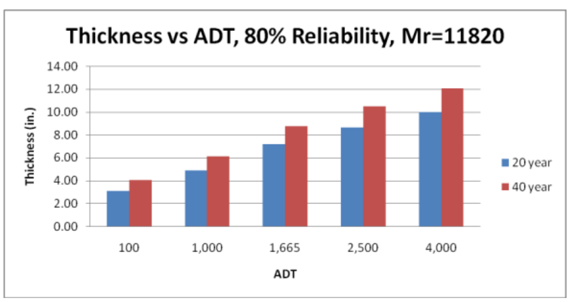
(g) Mr=7950 (Reliability: 80%)



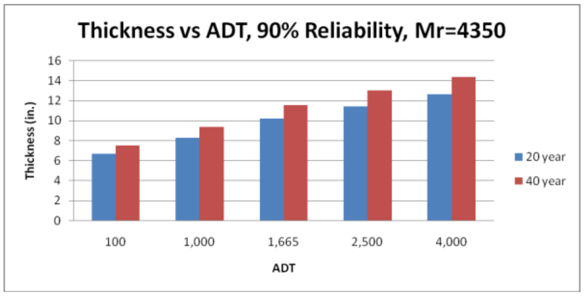
(h) Mr=8735 (Reliability: 80%)



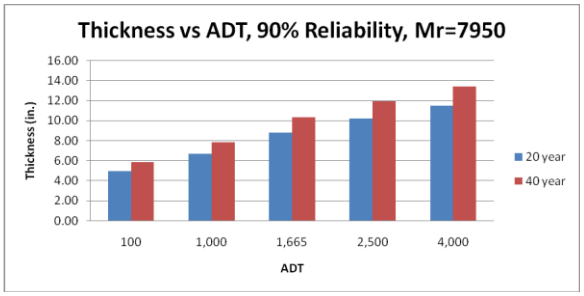
(i) Mr=10020 (Reliability: 80%)



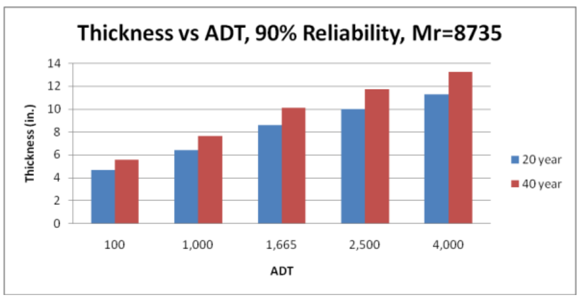
(j) Mr=11820 (Reliability: 80%)



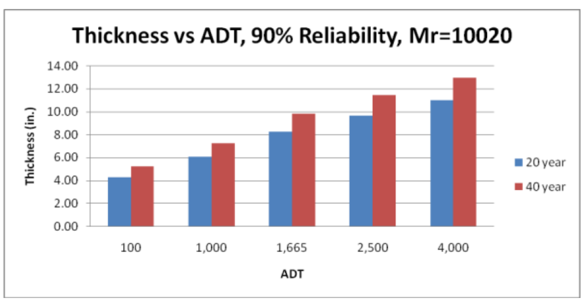
(k) Mr=4350 (Reliability: 90%)



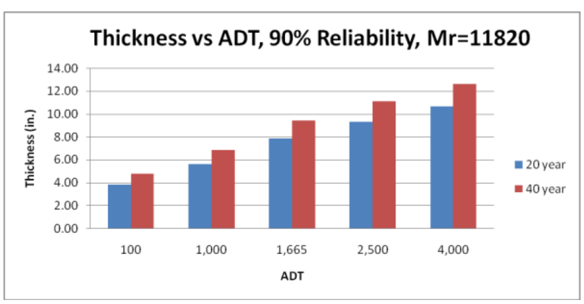
(l) Mr=7950 (Reliability: 90%)c



(n) Mr=8735 (Reliability: 90%)



(m) Mr=10020 (Reliability: 90%)

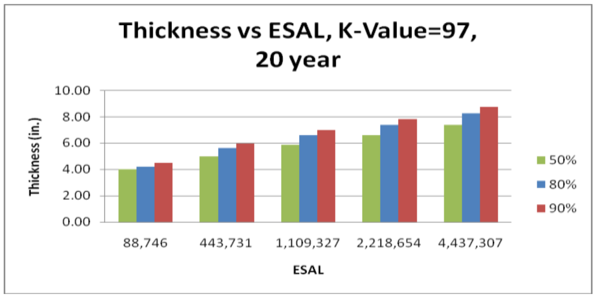


(o) Mr=11820 (Reliability: 90%)

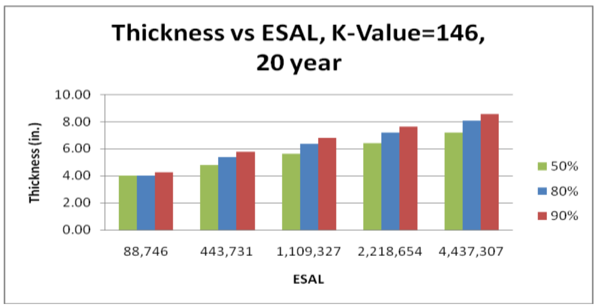
C-2 WinPas Software

- C-2.1 Concrete Pavement (Design Life: 20 years)
- C-2.2 Concrete Pavement (Design Life: 40 years)
- C-2.3 Concrete Pavement (20 years vs. 40 years)
- C-1.4 Asphalt Pavement (Design Life: 20 years)
- C-1.5 Asphalt Pavement (Design Life: 40 years)
- C-1.6 Asphalt Pavement (20 years vs. 40 years)

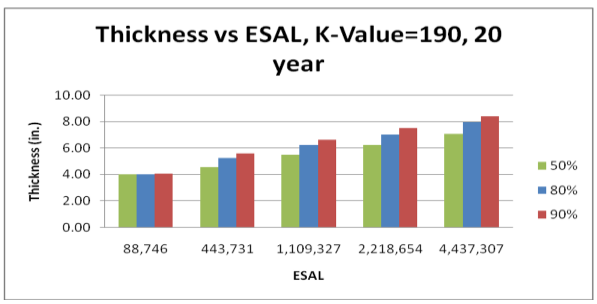
Appendix C-2.1 Concrete Pavement (Design Life: 20 years)



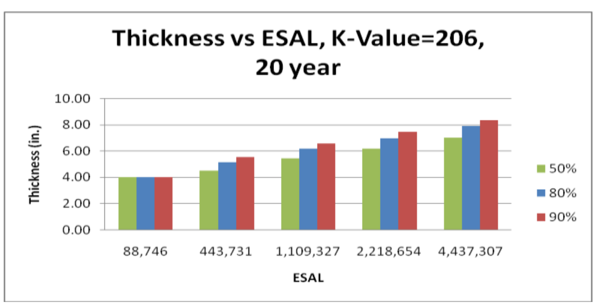
(a) k-value= 97



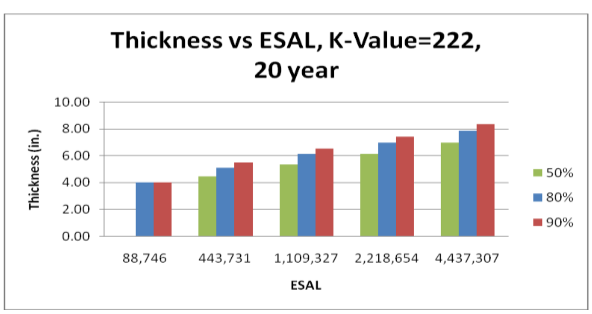
(b) k-value= 146



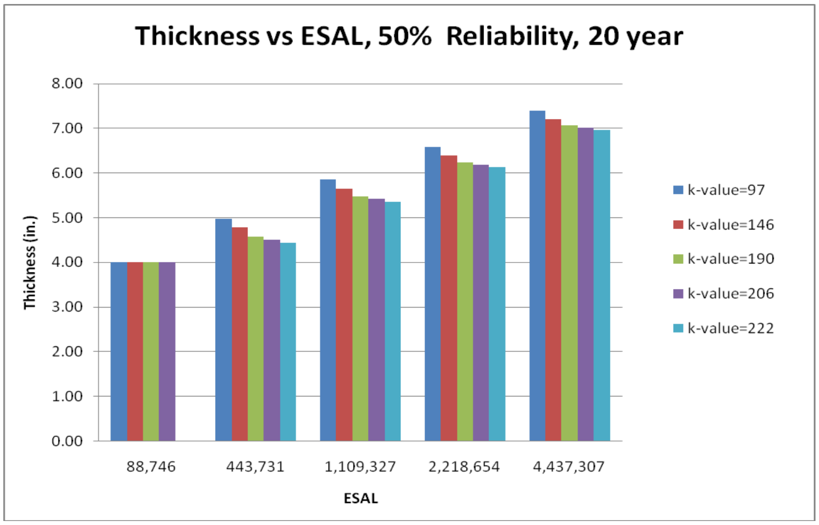
(c) k-value= 190



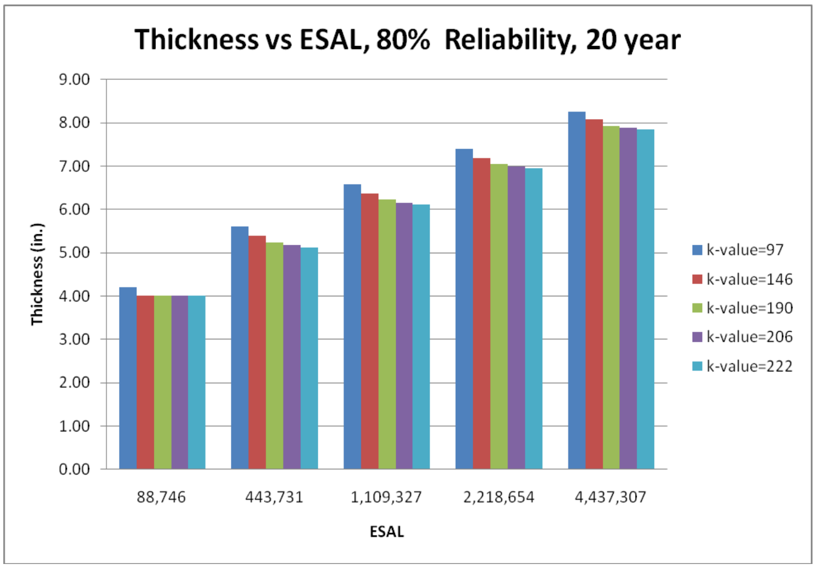
(d) k-value= 206



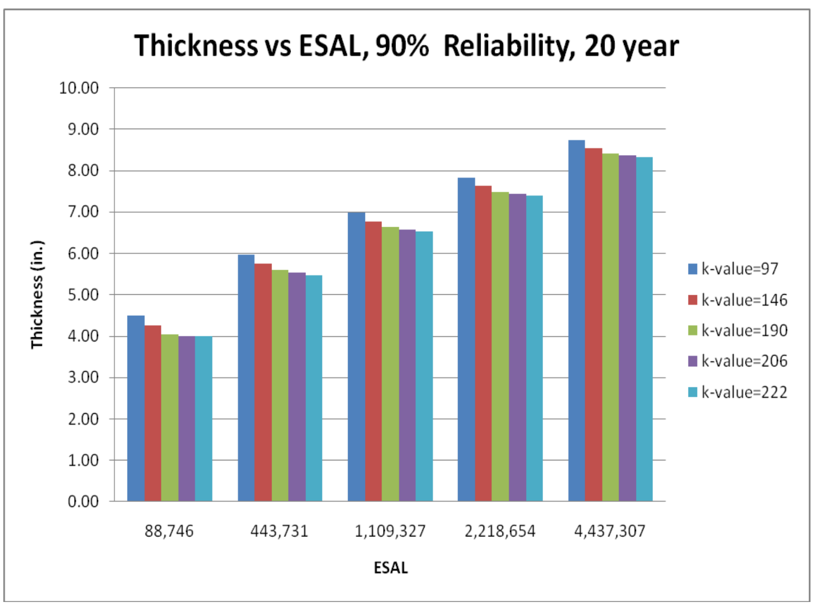
(e) k-value= 222



(f) Reliability: 50%

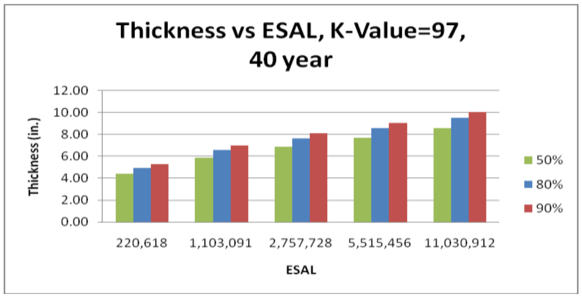


(g) Reliability: 80%

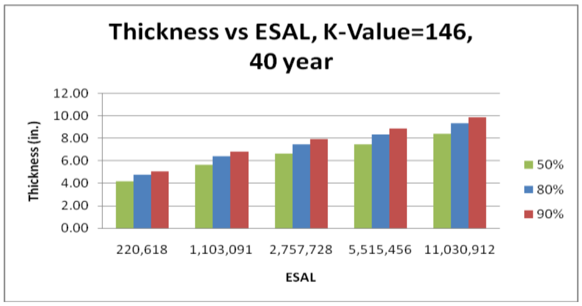


(h) Reliability: 90%

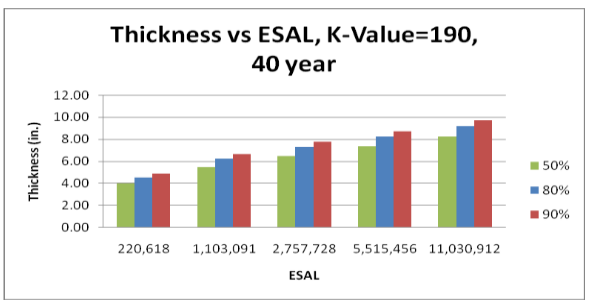
Appendix C-2.2 Concrete Pavement (Design Life: 40 years)



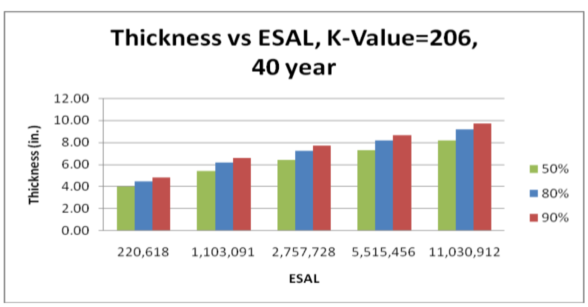
(a) k-value=97



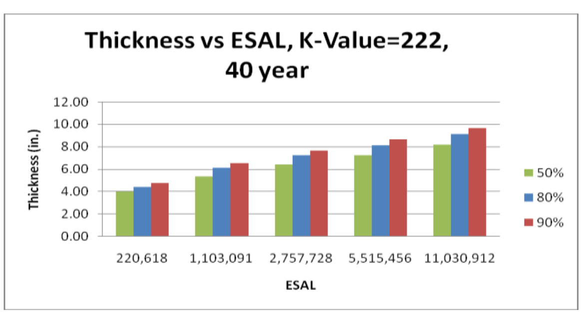
(b) k-value=146



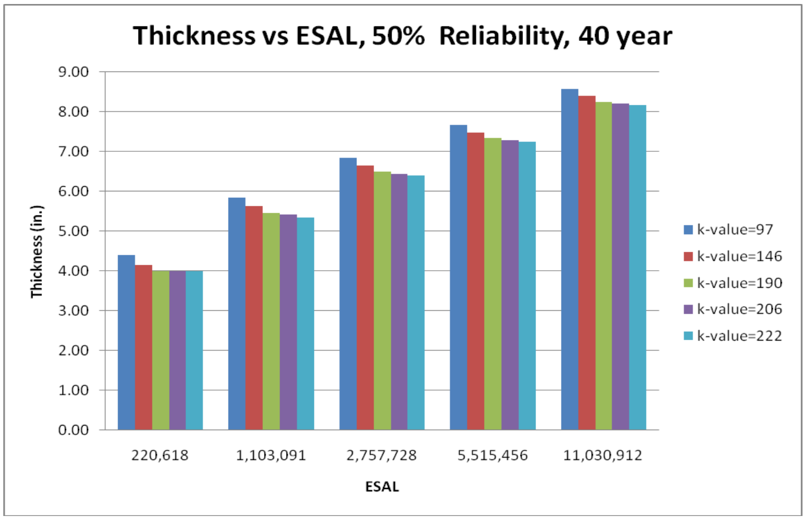
(c) k-value=190



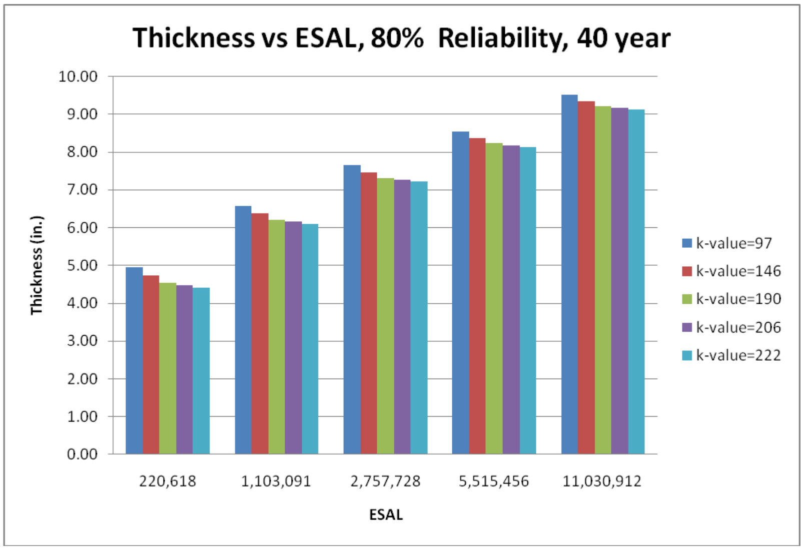
(d) k-value=206



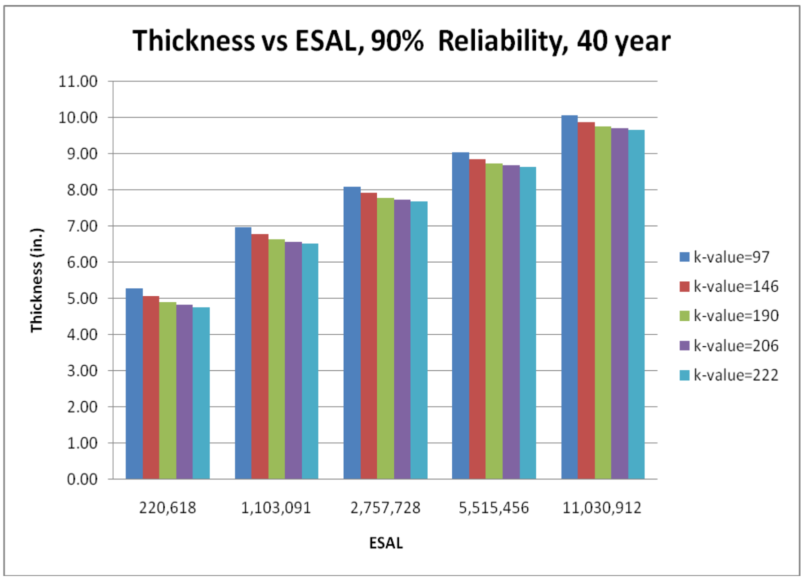
(e) k-value=222



(f) Reliability: 50%

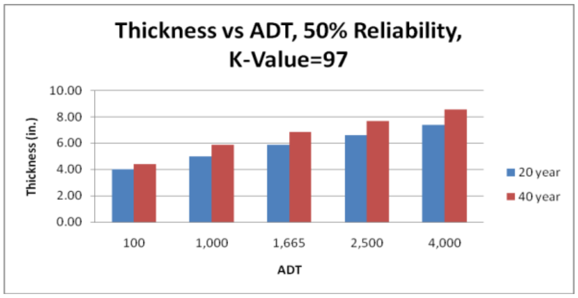


(g) Reliability: 80%

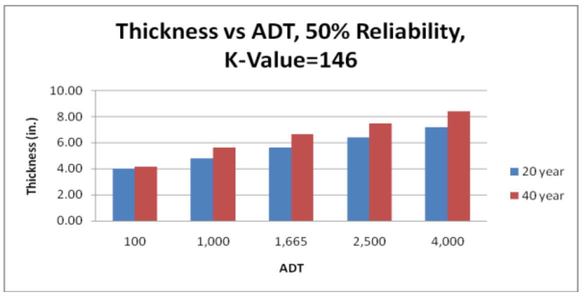


(h) Reliability: 90%

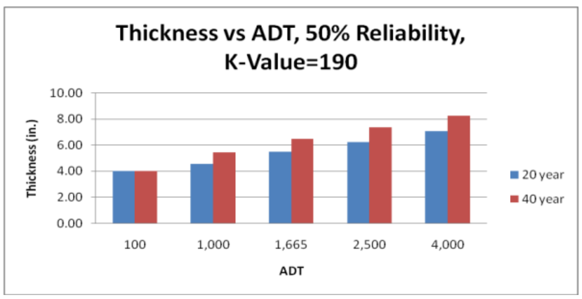
Appendix C-2.3 Concrete Pavement (20 years vs. 40 years)



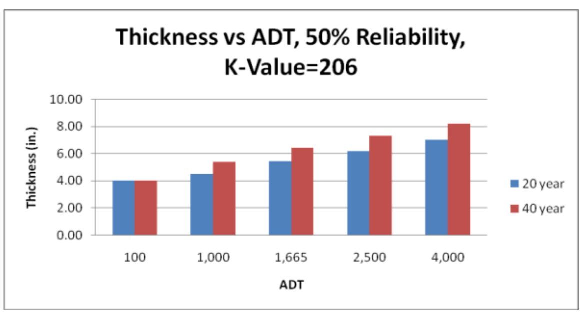
(a) k-value=97 (Reliability: 50%)



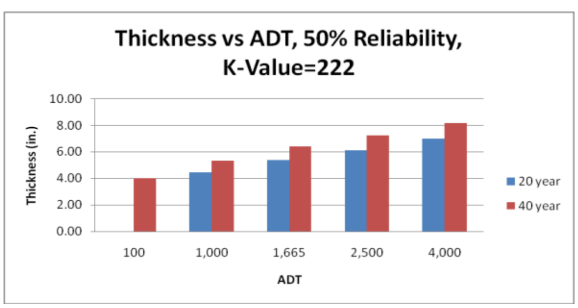
(b) k-value=146 (Reliability: 50%)



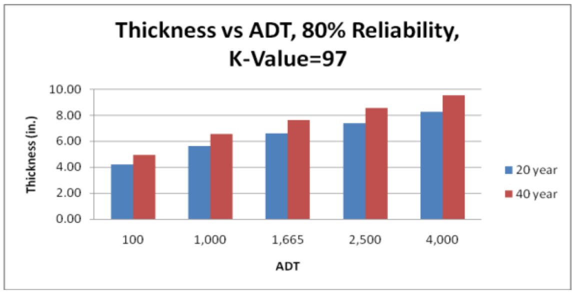
(c) k-value=190 (Reliability: 50%)



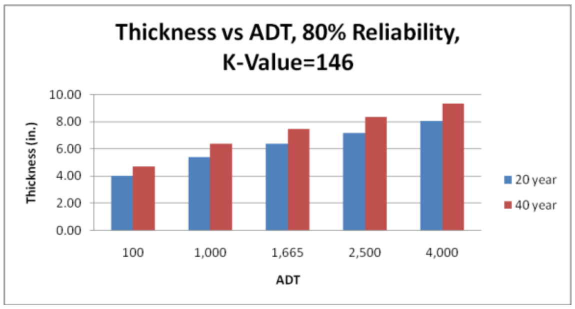
(d) k-value=206 (Reliability: 50%)



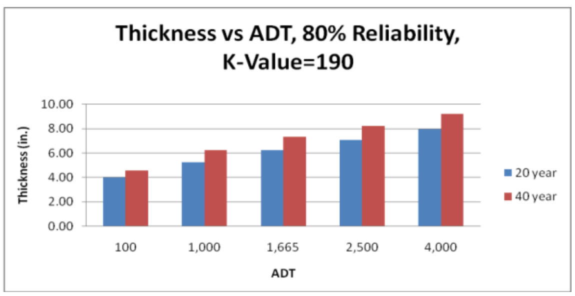
(e) k-value=222 (Reliability: 50%)



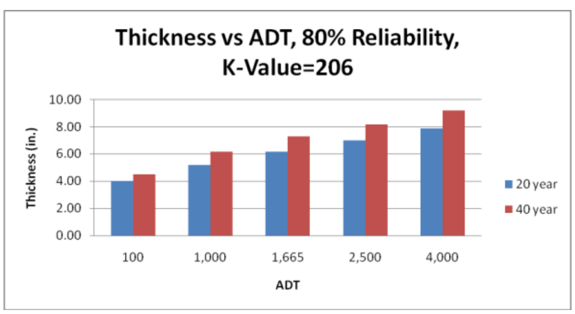
(f) k-value=97 (Reliability: 80%)



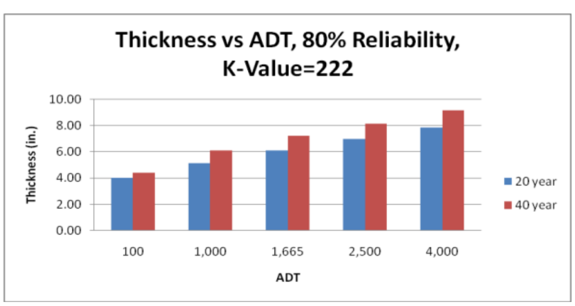
(g) k-value=146 (Reliability: 80%)



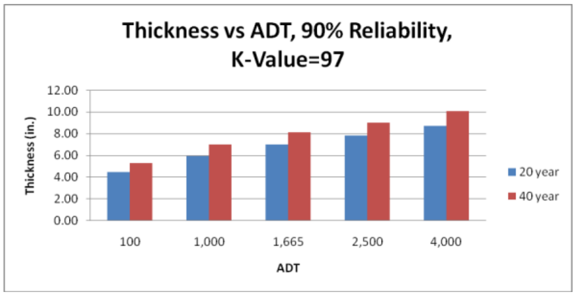
(h) k-value=190 (Reliability: 80%)



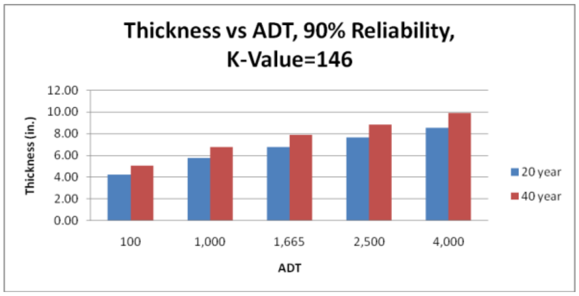
(i) k-value=206 (Reliability: 80%)



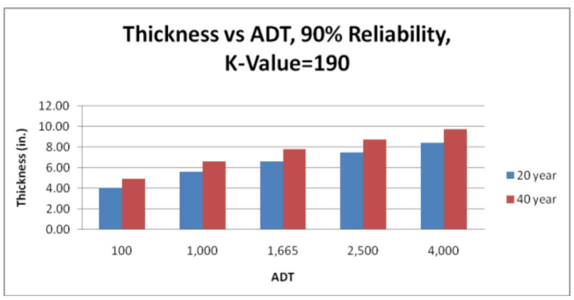
(j) k-value=222 (Reliability: 80%)



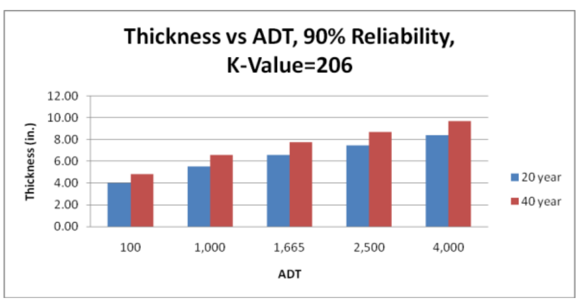
(k) k-value=97 (Reliability: 90%)



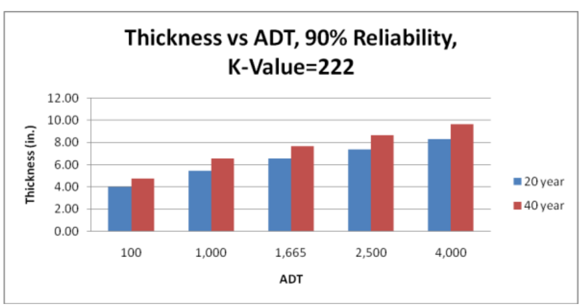
(l) k-value=146 (Reliability: 90%)



(n) k-value=190 (Reliability: 90%)

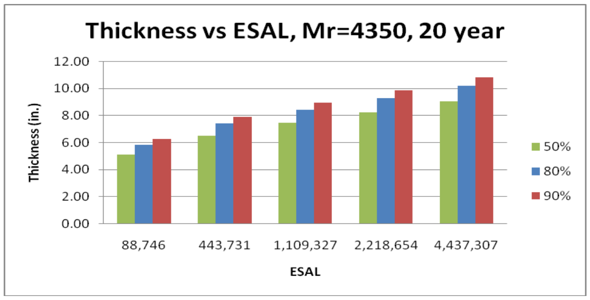


(m) k-value=206 (Reliability: 90%)

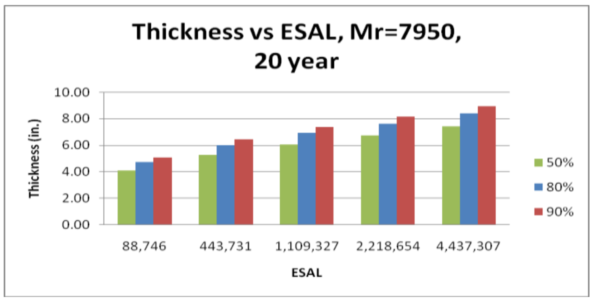


(o) k-value=222 (Reliability: 90%)

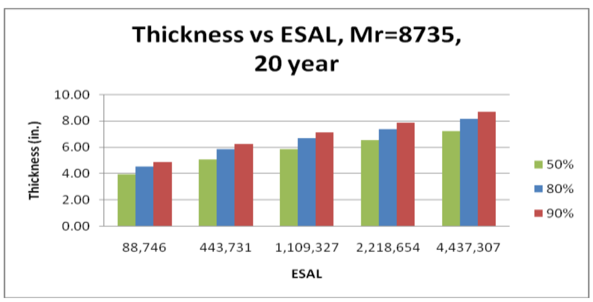
Appendix C-2.4 Asphalt Pavement (Design Life: 20 years)



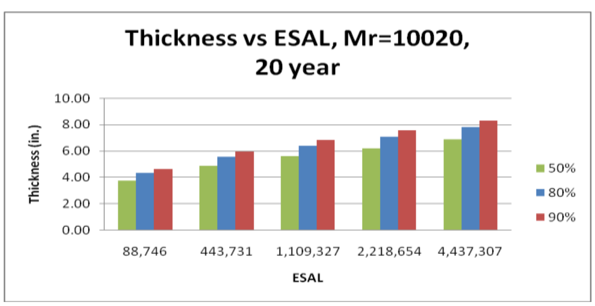
(a) Mr=4350



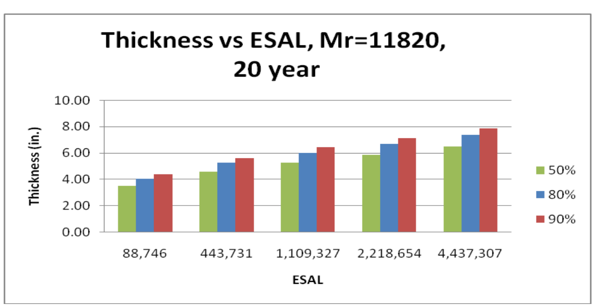
(b) Mr=7950



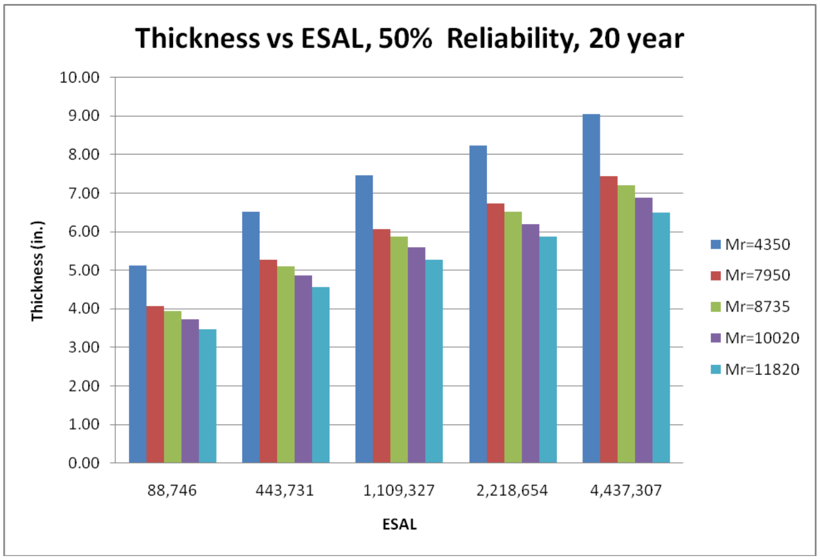
(c) Mr=8735



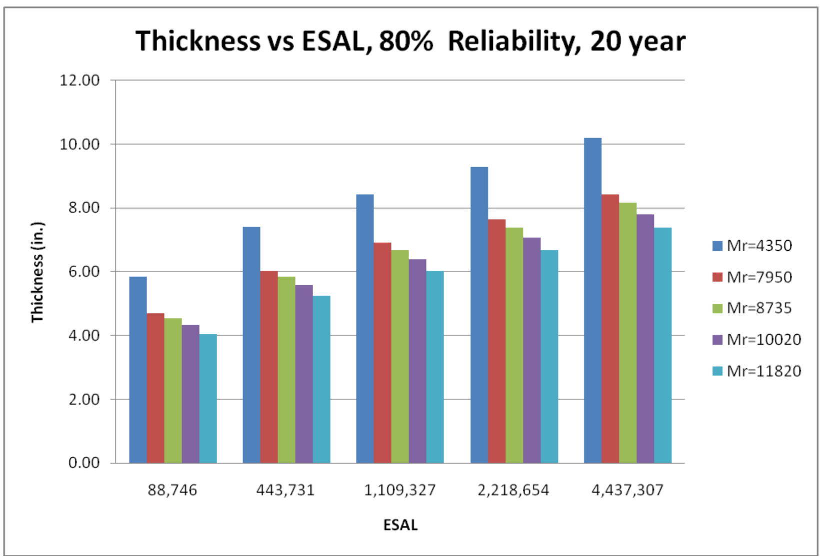
(d) Mr=10020



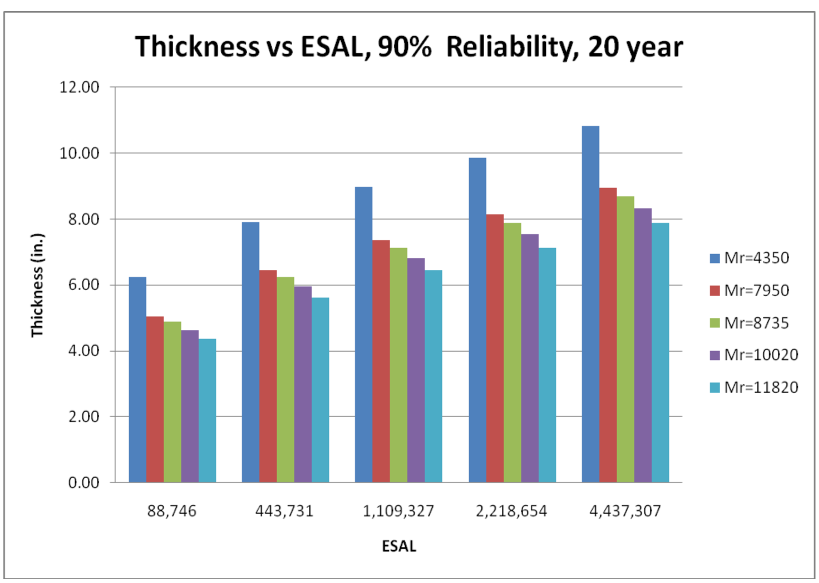
(e) Mr=11820



(f) Reliability: 50%

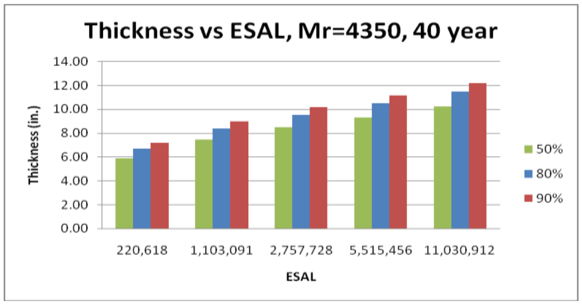


(g) Reliability: 80%

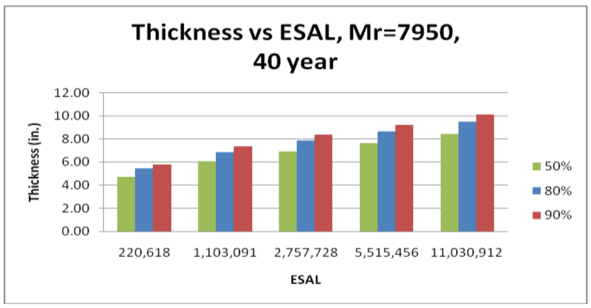


(h) Reliability: 90%

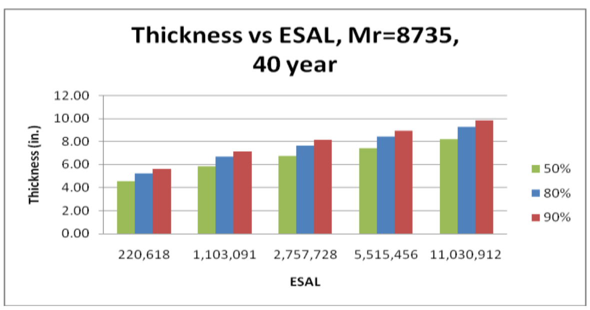
Appendix C-2.5 Asphalt Pavement (Design Life: 40 years)



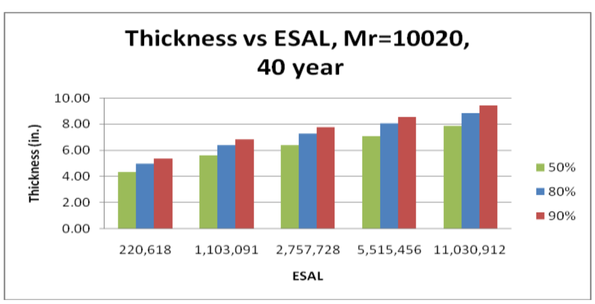
(a) Mr=4350



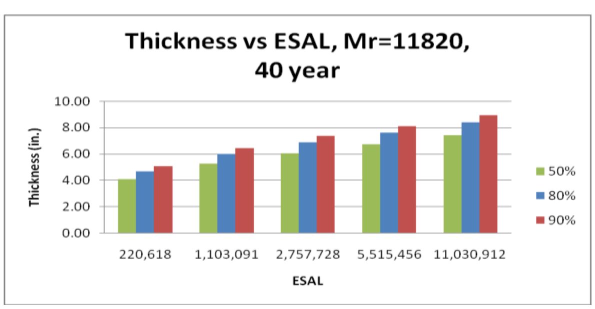
(b) Mr=7950



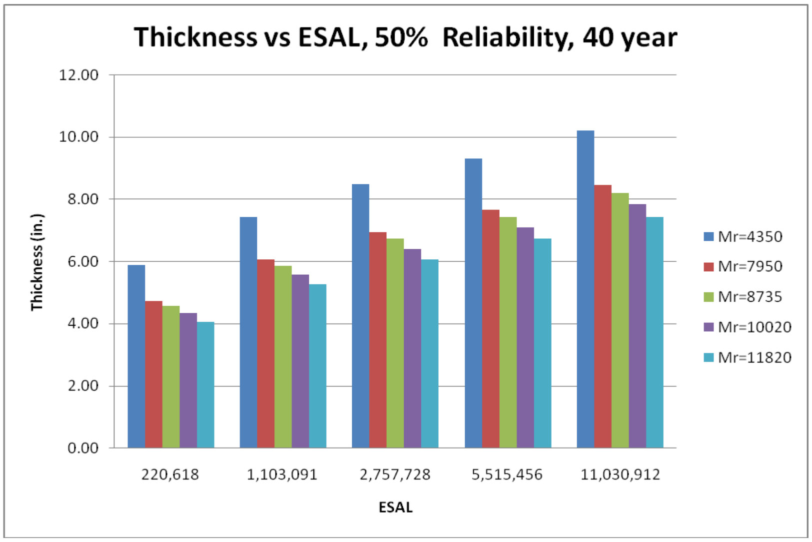
(c) Mr=8735



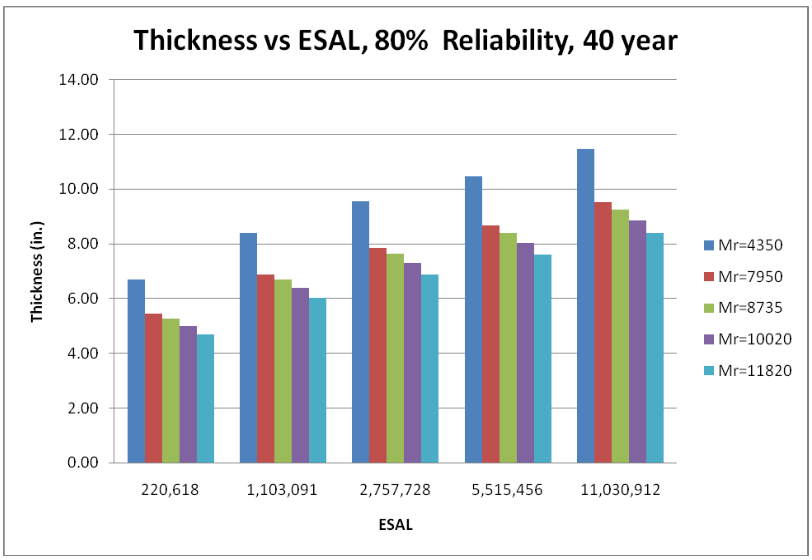
(d) Mr=10020



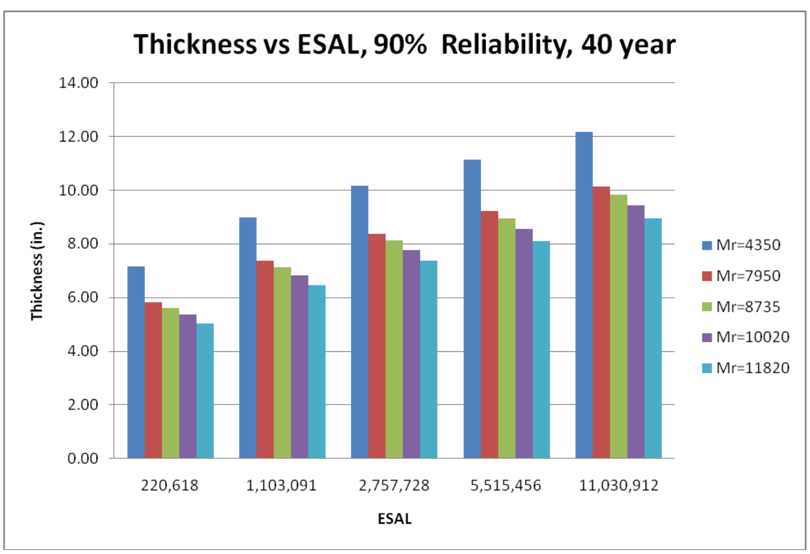
(e) Mr=11820



(f) Reliability: 50%

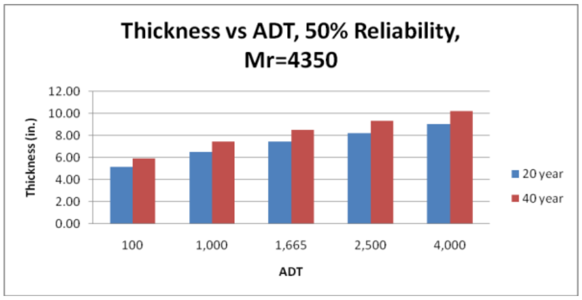


(g) Reliability: 80%

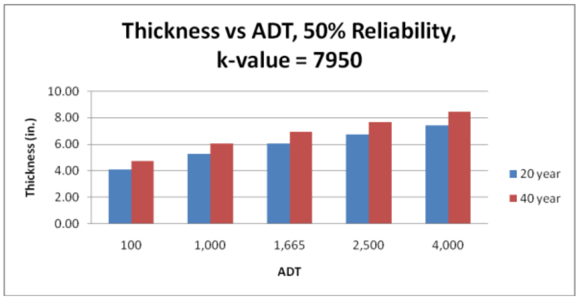


(h) Reliability: 90%

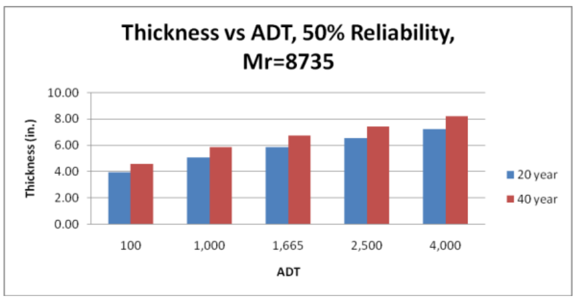
Appendix C-2.6 Asphalt Pavement (20 years vs. 40 years)



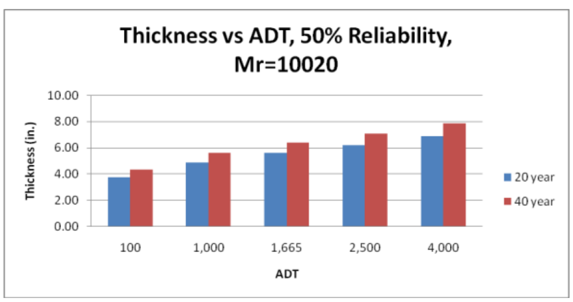
(a) Mr=4350 (Reliability: 50%)



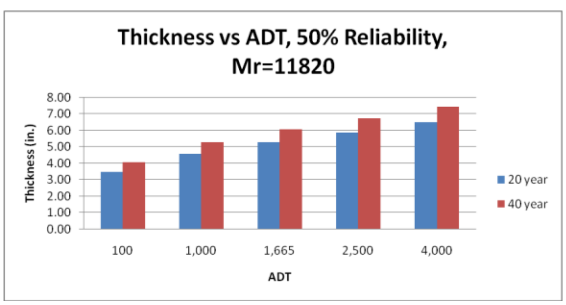
(b) Mr=7950 (Reliability: 50%)



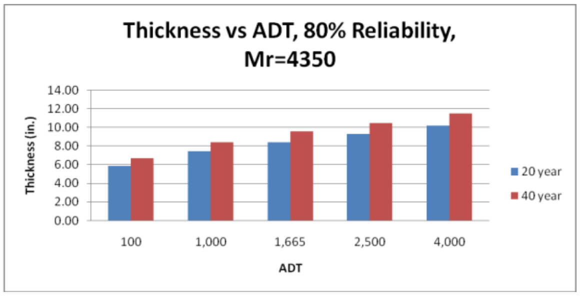
(c) Mr=8735 (Reliability: 50%)



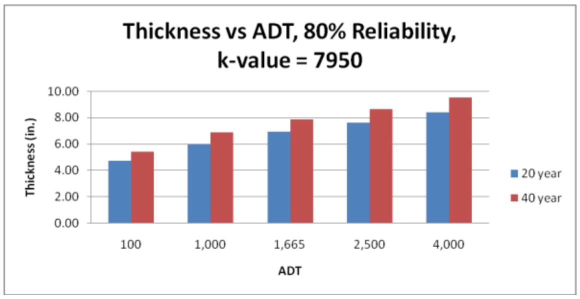
(d) Mr=10020 (Reliability: 50%)



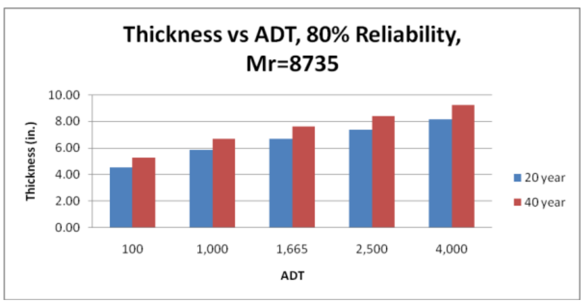
(e) Mr=11820 (Reliability: 50%)



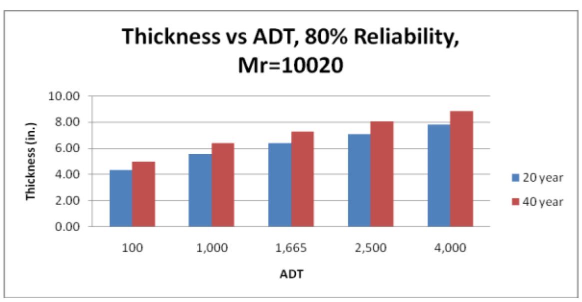
(f) Mr=4350 (Reliability: 80%)



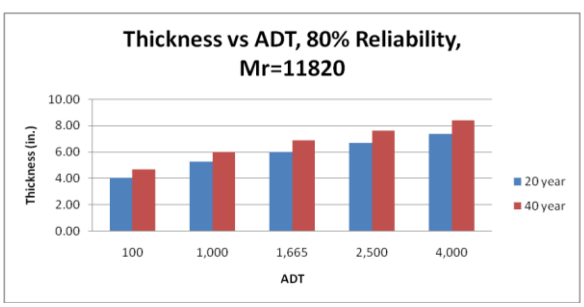
(g) Mr=7950 (Reliability: 80%)



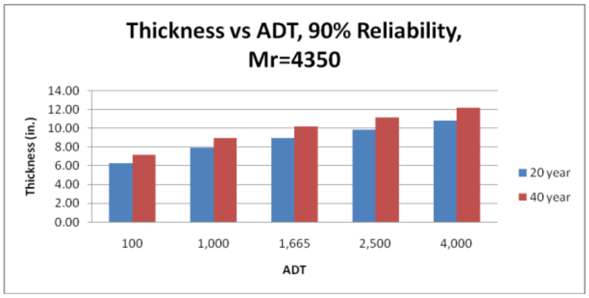
(h) Mr=8735 (Reliability: 80%)



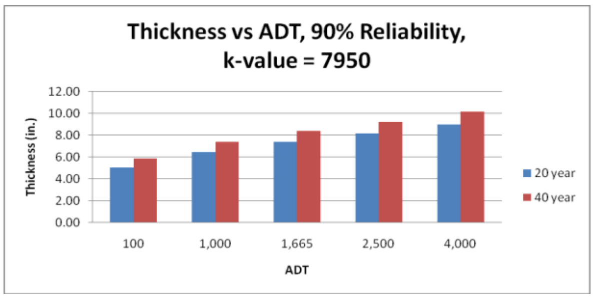
(i) Mr=10020 (Reliability: 80%)



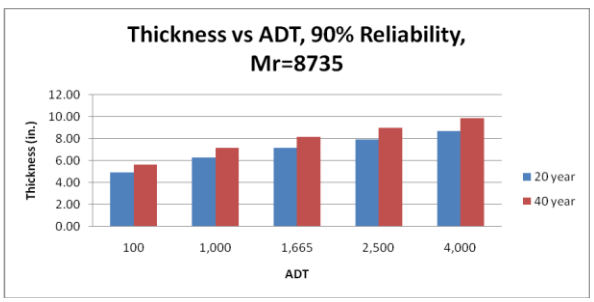
(j) Mr=11820 (Reliability: 80%)



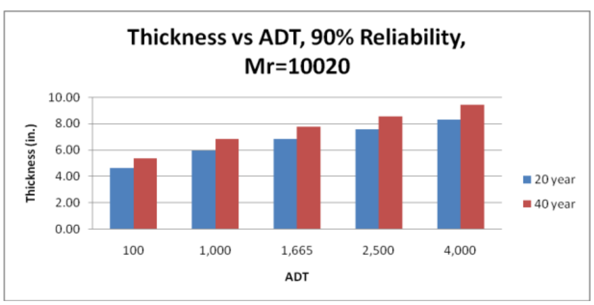
(k) Mr=4350 (Reliability: 90%)



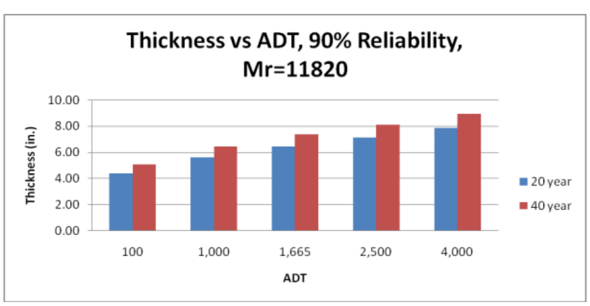
(l) Mr=7950 (Reliability: 90%)



(m) Mr=8735 (Reliability: 90%)



(n) Mr=10020 (Reliability: 90%)

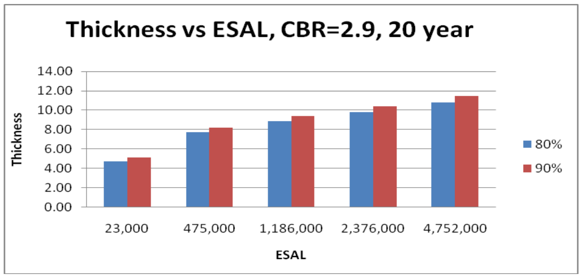


(o) Mr=11820 (Reliability: 90%)

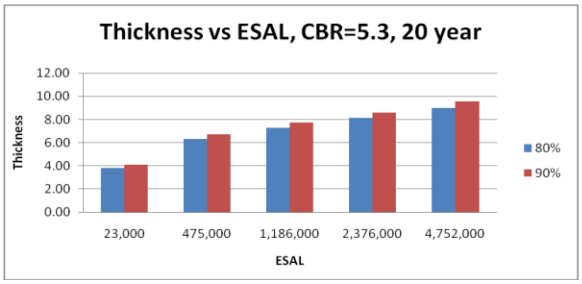
C-3 APAI Software

- C-3.1 Asphalt Pavement (Design Life: 20 years)
- C-3.2 Asphalt Pavement (Design Life: 40 years)
- C-3.3 Asphalt Pavement (20 years vs. 40 years)

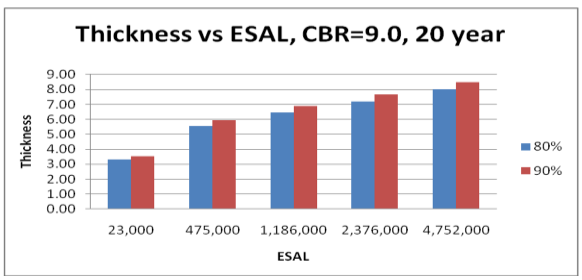
Appendix C-3.1 Asphalt Pavement (Design Life: 20 years)



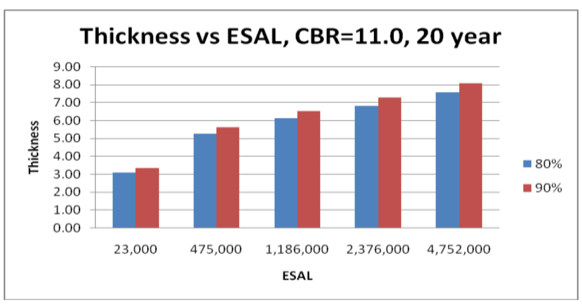
(a) CBR=2.9



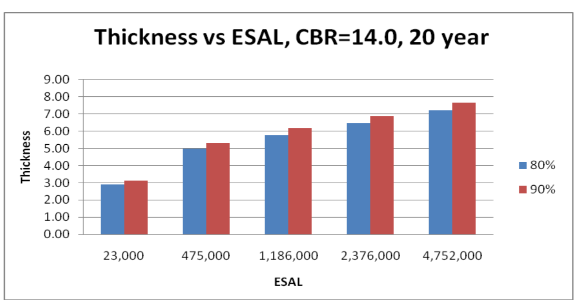
(b) CBR=5.3



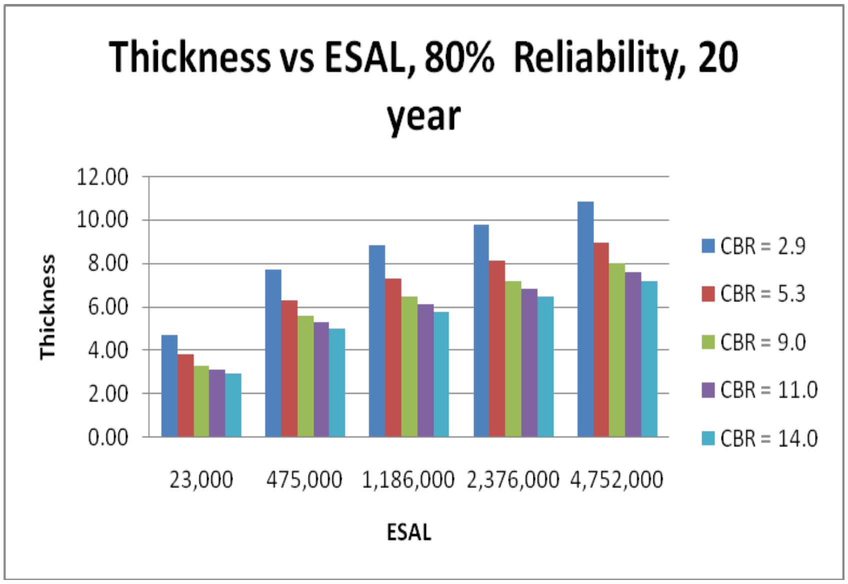
(c) CBR=9.0



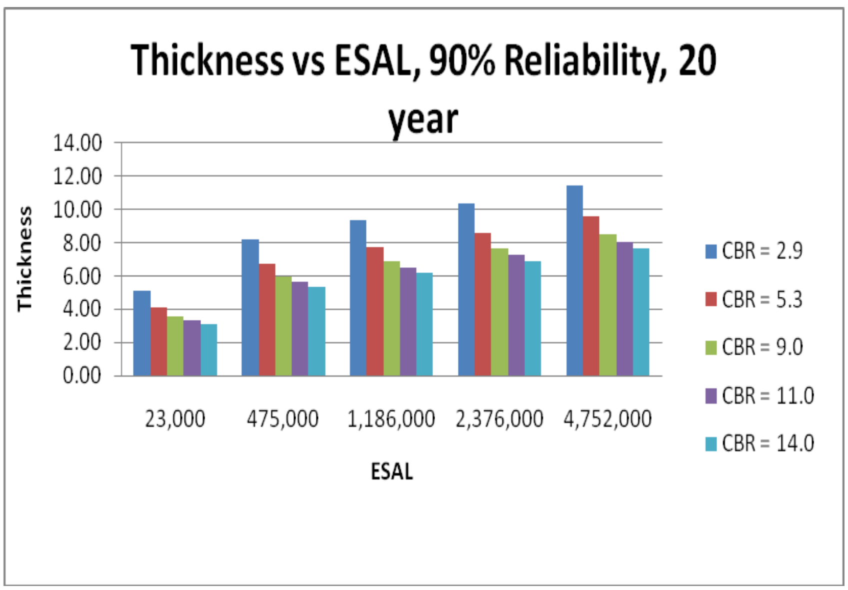
(d) CBR=11.0



(e) CBR=14.0

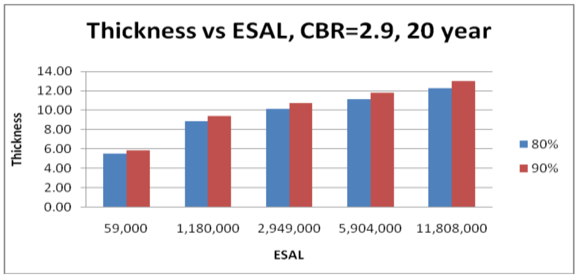


(f) Reliability: 80%

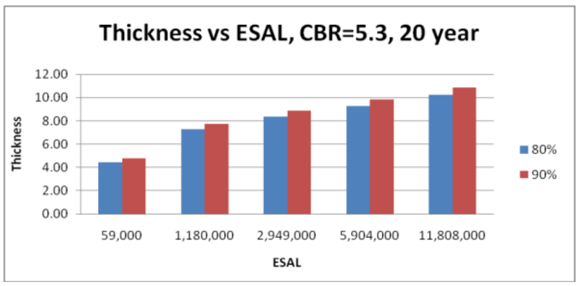


(g) Reliability: 90%

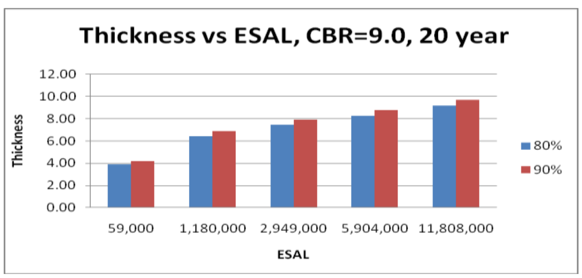
Appendix C-3.2 Asphalt Pavement (Design Life: 40 years)



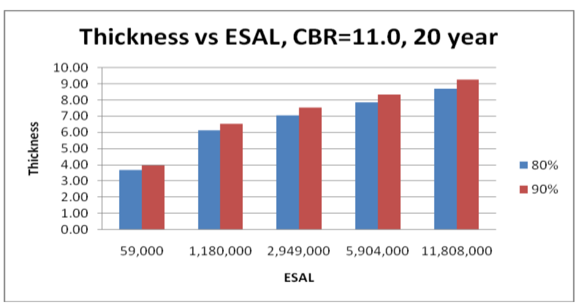
(a) CBR=2.9



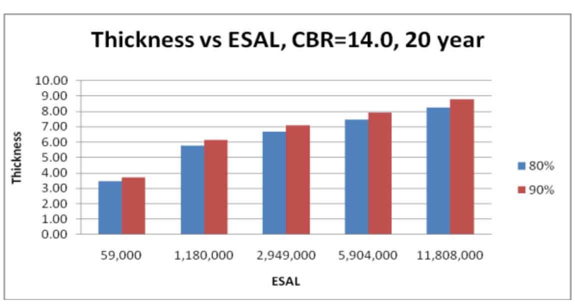
(b) CBR=5.3



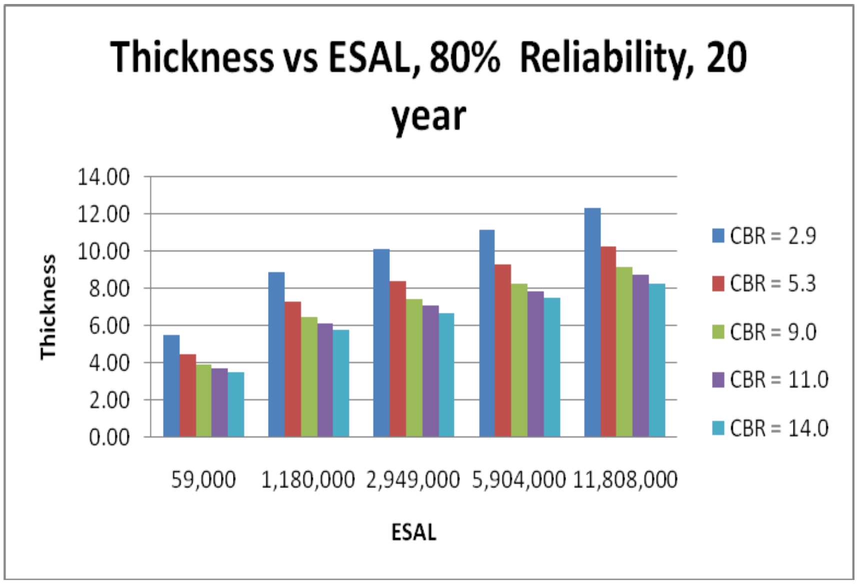
(c) CBR=9.0



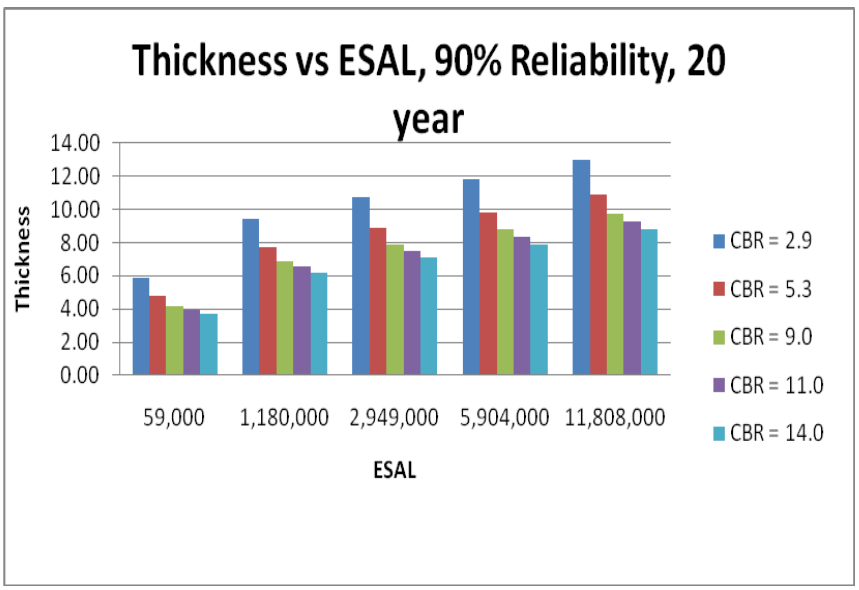
(d) CBR=11.0



(e) CBR=14.0

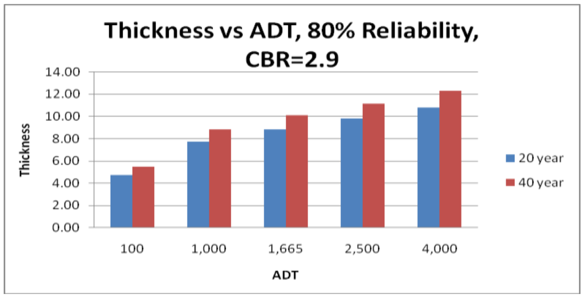


(f) Reliability: 80%

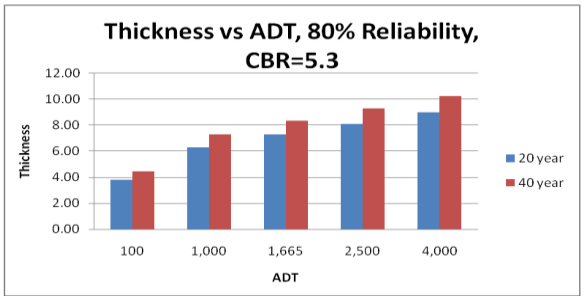


(g) Reliability: 90%

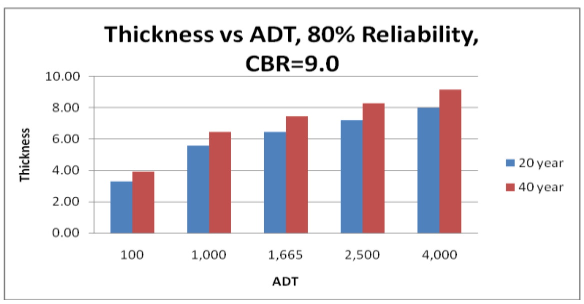
Appendix C-3.3 Asphalt Pavement (20 years vs. 40 years)



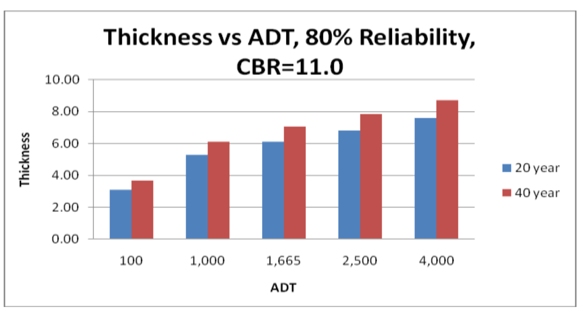
(a) CBR=6.0 (Reliability: 80%)



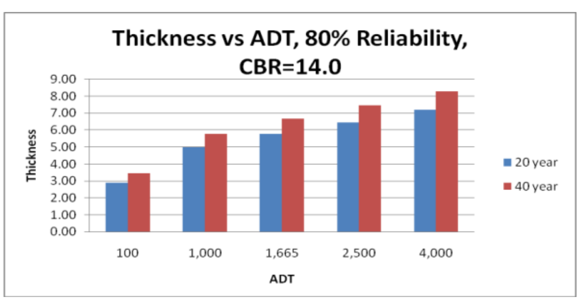
(b) CBR=8.0 (Reliability: 80%)



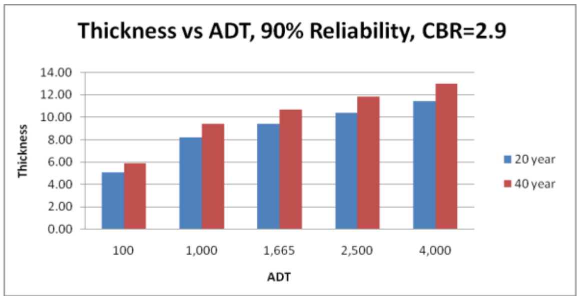
(c) CBR=11.0 (Reliability: 80%)



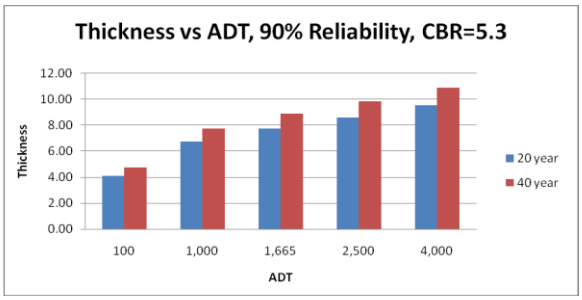
(d) CBR=13.0 (Reliability: 80%)



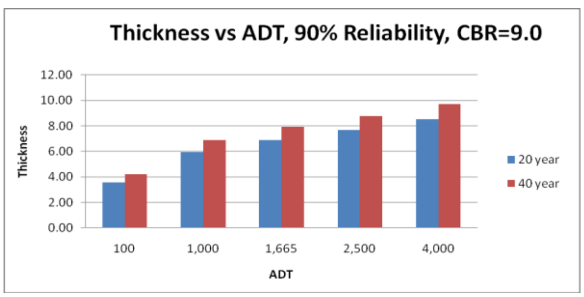
(e) CBR=16.0 (Reliability: 80%)



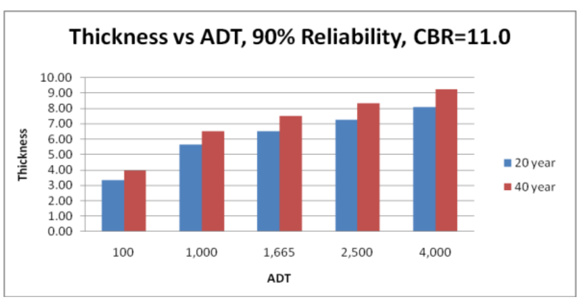
(f) CBR=6.0 (Reliability: 90%)



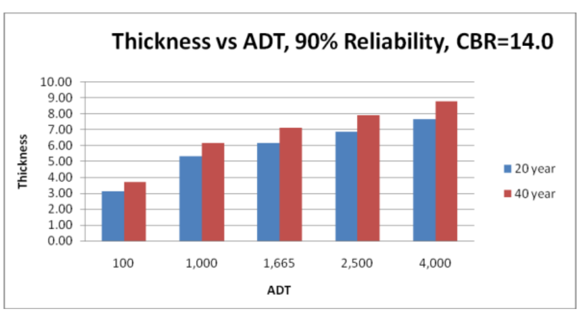
(g) CBR=8.0 (Reliability: 90%)



(h) CBR=11.0 (Reliability: 90%)



(i) CBR=13.0 (Reliability: 90%)

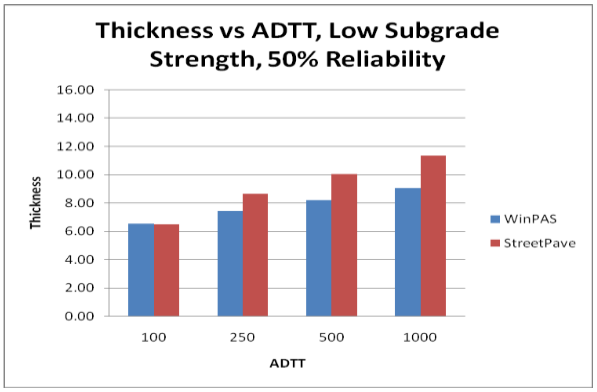


(j) CBR=16.0 (Reliability: 90%)

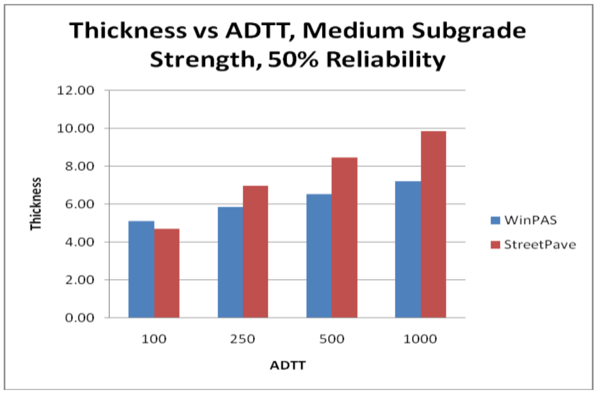
C-4 Comparison

- C-4.1 Asphalt Pavement (WinPas vs. StreetPave vs. APAI)
- C-4.2 Concrete Pavement (WinPas vs. StreetPave)

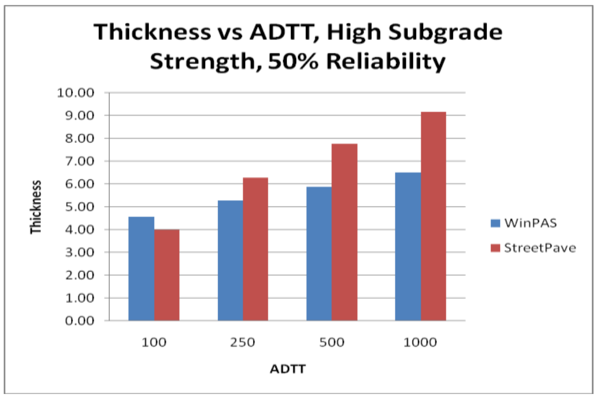
Appendix C-4.1 Comparison of Asphalt Pavement (WinPas vs. StreetPave vs. APAI)



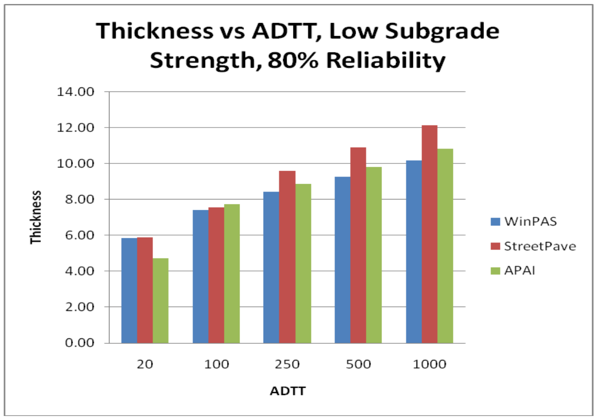
(a) Low subgrade (Reliability=50%)



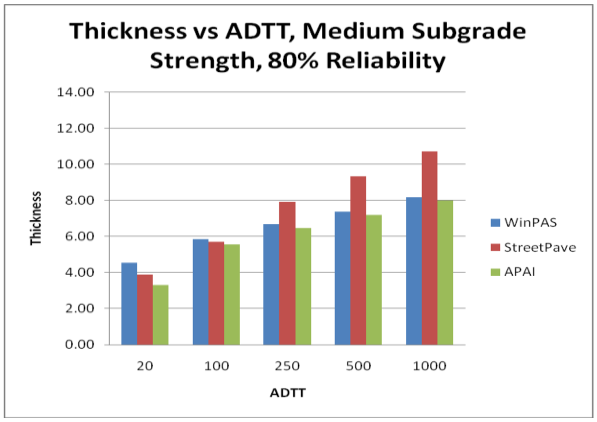
(b) Medium subgrade (Reliability=50%)



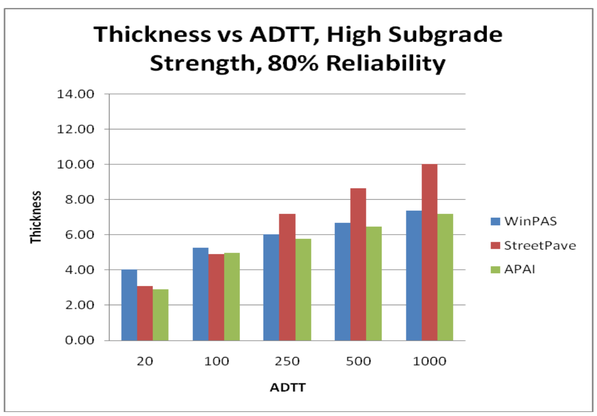
(c) High subgrade (Reliability=50%)



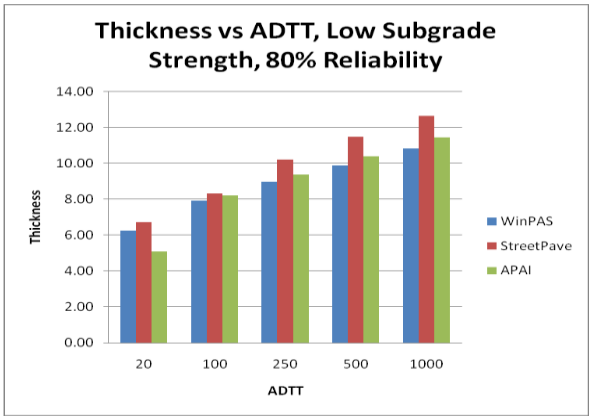
(d) Low subgrade (Reliability=80%)



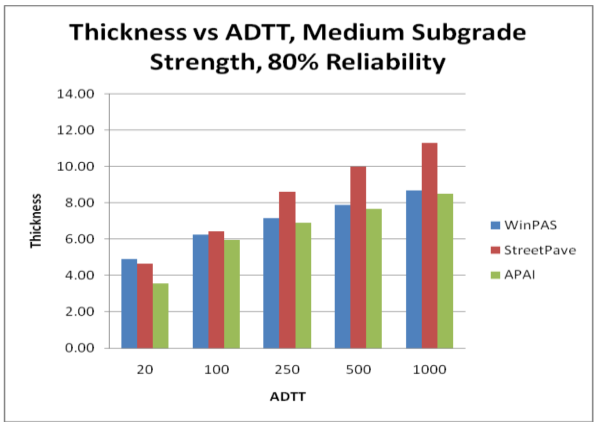
(e) Medium subgrade (Reliability=80%)



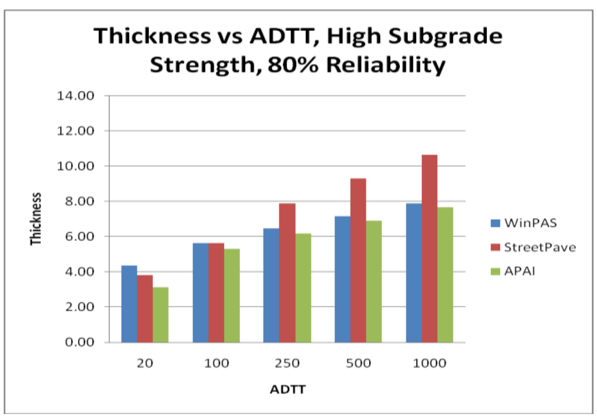
(f) High subgrade (Reliability=80%)



(g) Low subgrade (Reliability=90%)



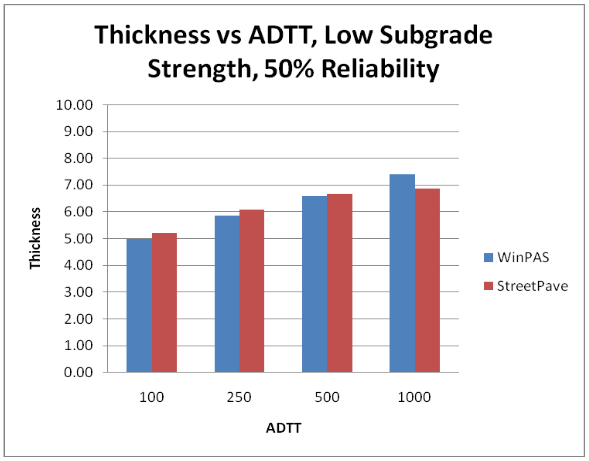
(h) Medium subgrade (Reliability=90%)



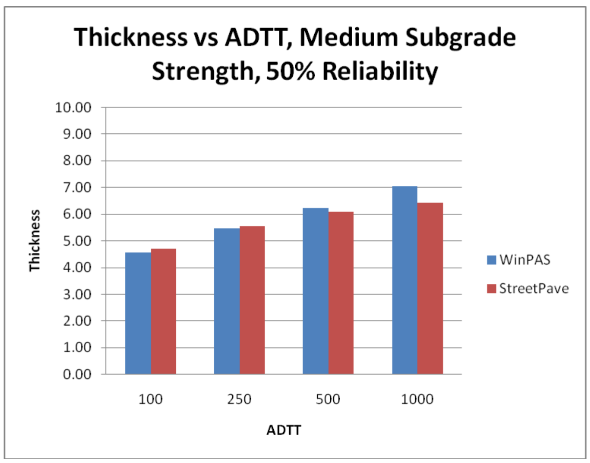
(i) High subgrade (Reliability=90%)

Appendix C-4.2 Comparison of Concrete Pavement

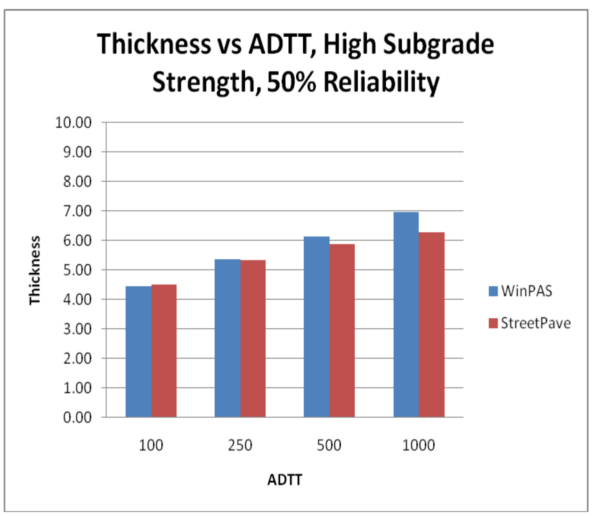
(WinPas vs. StreetPave)



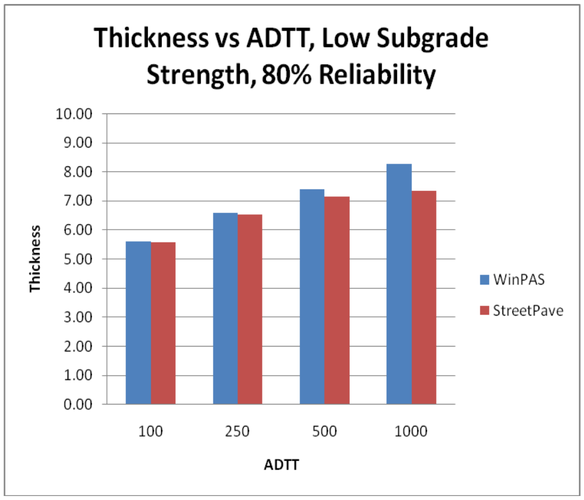
(a) Low subgrade (Reliability=50%)



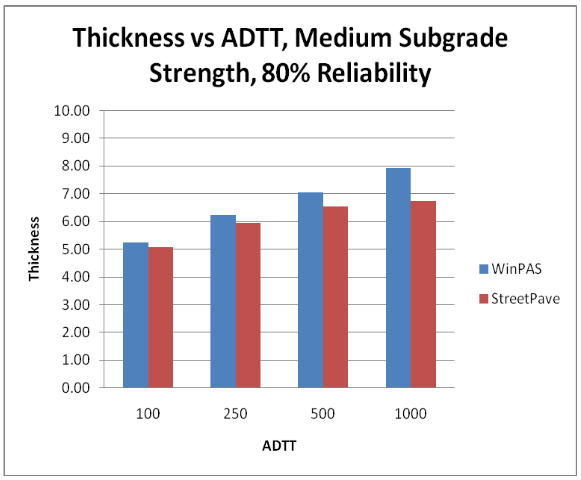
(b) Medium subgrade (Reliability=50%)



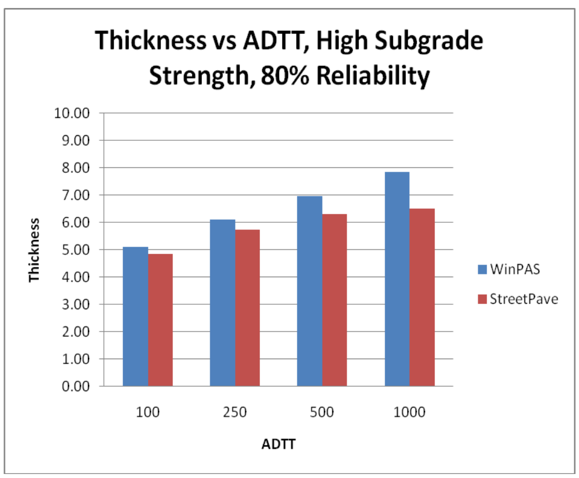
(c) High subgrade (Reliability=50%)



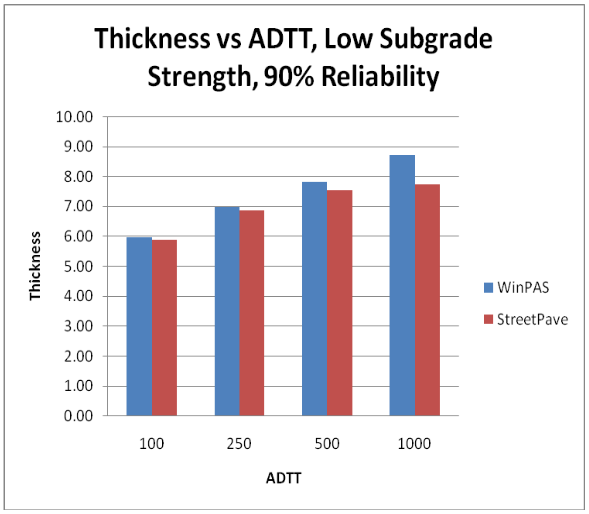
(d) Low subgrade (Reliability=80%)



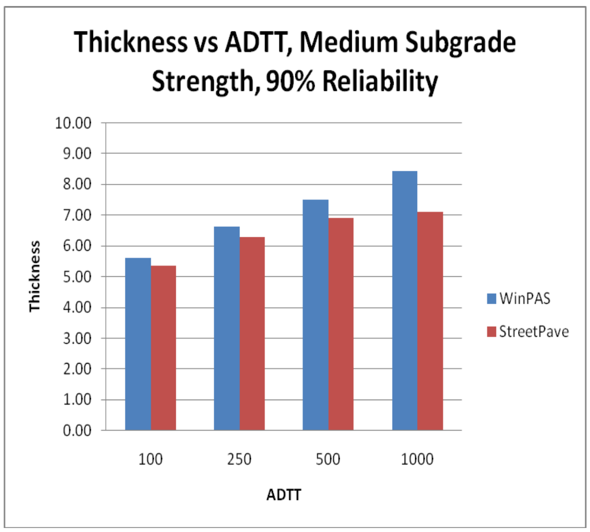
(e) Medium subgrade (Reliability=80%)



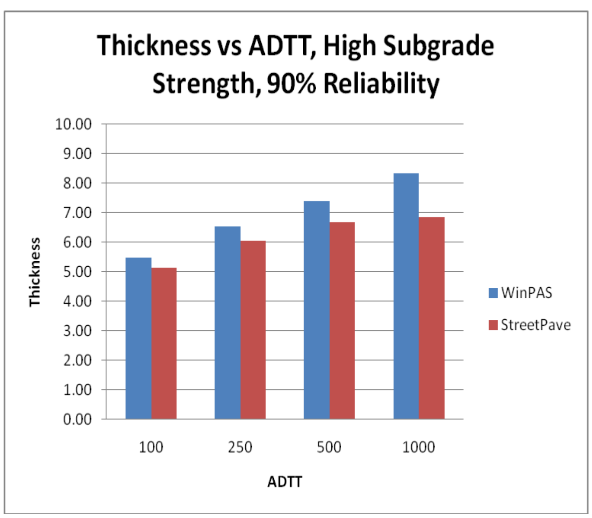
(f) High subgrade (Reliability=80%)



(g) Low subgrade (Reliability=90%)



(h) Medium subgrade (Reliability=90%)



(i) High subgrade (Reliability=90%)