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Automated Thickness Design and Sensitivity Analysis for Rigid Pavements (AASHTO and PCA)

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Abstract

Rigid pavements provide enhanced durability and reduced maintenance costs; however, their design according to AASHTO (1993) and PCA methodologies necessitates intricate manual computations that are susceptible to inaccuracies. This research initiative has resulted in the development of PCAA Pave software using Microsoft Visual Basic 2008 to facilitate the automation of thickness design for both methodologies. Validation against manual computations and the MULTI-PAVE software indicated a remarkable agreement, with thickness discrepancies remaining below 0.4 inches for AASHTO and fatigue as well as erosion damage estimations within ±1-5% for PCA. Sensitivity analysis employing a one-at-a-time method and Monte Carlo simulation (10,000 scenarios executed in Python) effectively quantified the influences of various parameters. In the context of AASHTO, the factors of Reliability (NSI = 0.254, +1.10 in) and Traffic (ESAL) (NSI = 0.210, +0.91 in) were found to be predominant, followed by the Drainage Coefficient (NSI = 0.185, -0.80 in) and the Load Transfer Coefficient (NSI = 0.150, +0.65 in). The influence of material properties was determined to be minimal. Regarding PCA, the Subgrade Modulus (NSI = 0.325, -0.41 in) and the Modulus of Rupture (NSI = 0.310, -0.39 in) were found to significantly dominate the analysis, with the Design Period and Traffic (ADT) displaying only a moderate level of influence. The Monte Carlo simulation confirmed the subgrade modulus as the paramount factor in PCA, exhibiting a sensitivity that is nearly fivefold greater than that of the traffic parameters. The comparative analysis explains fundamental philosophical distinctions: AASHTO is predominantly influenced by traffic and reliability, whereas PCA is primarily controlled by the support offered by subgrade and the inherent material strength. These insights empower engineers to execute method-specific data prioritization, facilitating accurate traffic predictions for AASHTO and careful subgrade characterization for PCA. The validated PCAA Pave software serves as a dependable and time-efficient design tool; however, it is advisable to consider future enhancements in the analysis of reinforcement and joint designs.

Keywords: Rigid Pavement, AASHTO 1993, PCA Method, Sensitivity Analysis, Monte Carlo Simulation, PCAA Pave Software

1. Introduction

Pavements offer a reliable, cost-efficient, and secure surface that can sustain extremely high traffic volumes with minimal difficulty, ensuring comfort and durability. Their extended lifespan and low upkeep further enhance their overall economic value.

In today's technological landscape, software has become integral across a wide range of disciplines. This reliance has grown in tandem with rapid advancements in computing, providing users with robust and portable devices such as laptops and desktops. These tools simplify complex processes, allowing for calculations that were once labor-intensive or unfeasible to be executed in a matter of seconds.

Engineering, in particular, has embraced software applications due to the frequent need for complicated and time-consuming calculations. Specifically, in rigid pavement design, determining the optimal slab thickness based on expected traffic loads, soil conditions, and environmental variables is crucial for reducing both initial construction and ongoing maintenance expenses.

As a result, specialized pavement design software plays a vital role in supporting the development of concrete surfaces. This research utilizes such tools to determine rigid pavement thickness and to analyze how variations in key input parameters affect the final design result.

Thus, the primary objective of this study is to conduct a sensitivity analysis on rigid pavement thickness using two foundational methodologies in pavement design: the AASHTO 1993 guidelines & PCA method.

2. Problem Statement

Rigid pavements are increasingly preferred worldwide due to their extended durability and lower maintenance demands compared to flexible pavement systems. Despite these advantages, their structural design remains mainly guided by the AASHTO 1993 and PCA methodologies, which involve complex, repetitive calculations to determine appropriate pavement thickness. Performing these calculations manually is not only laborious but also susceptible to errors, which may compromise the accuracy of design outcomes.

Both design approaches depend on a wide collection of input variables ranging from traffic patterns and material characteristics to climatic conditions yet the specific impact of each parameter on the resulting pavement thickness is seldom quantified in practice. This lack of clarity complicates data prioritization during the design process and covers critical differences between the AASHTO method, which is more responsive to operational factors, and the PCA approach, which emphasizes material and subgrade behavior.

Currently available tools do not offer built - in sensitivity analysis, compelling engineers to rely on experiential judgment rather than systematic, data-informed strategies. This underscores the pressing need for an integrated computational framework that can simplify thickness design for both methodologies, assess the influence of each input variable, and ensure consistency with established manual procedures.

3. Objectives

Develop computational tool for automated, sensitivity informed rigid pavement design using AASHTO and PCA design methods.

Specific Objectives:

- Automate thickness design & reporting.

- Quantify parameter and thickness relationships using both deterministic (one-at-a-time) and probabilistic (Monte Carlo) sensitivity analysis. And rank critical parameters both in AASHTO and PCA design methods.
- Compare and contrast the sensitivity profiles of the AASHTO and PCA methods to explain their fundamental design philosophies and provide method-specific guidance for data prioritization.

4. Literature Review

Rigid pavement design is largely governed by two dominant methodologies: the empirically based AASHTO 1993 Guide (American Association of State Highway and Transportation Officials, 1993) and the mechanistic PCA approach (Packard, 1984). These methods prioritize different performance criteria. AASHTO focuses on reliability - centered serviceability degradation, while PCA emphasizes stress-induced fatigue failure, resulting in distinct parameter sensitivities (Darter, Khazanovich, & Snyder, 1985). The AASHTO method primarily accounts for operational variables such as equivalent single axle loads (ESALs) and design reliability, whereas the PCA model gives precedence to material characteristics and subgrade resilience, creating diverging analytical profiles (Darter, Khazanovich, & Snyder, 1985). Comparative evaluations of these methods, such as those by Guell (1985), have highlighted their fundamental differences in design philosophy and output sensitivity.

Manual implementation of these iterative calculations is not only time-consuming but also vulnerable to human inaccuracies (Huang, 2004), thereby reinforcing the necessity for automated computational solutions. Although advanced tools such as AASHTOWare Pavement ME (Transportation Research Board, 2004) and StreetPave provide automated functionality tailored to their respective methods, they often lack integrated, built-in sensitivity analysis capabilities (Federal Highway Administration, 2006). Recognizing this gap, several researchers have developed specialized software. For instance, Kıcı and Tiğdemir (2017) created a user-friendly program for rigid pavement design, demonstrating the technical viability of such automation. However, these tools are typically focused on a single design method and do not facilitate direct comparative evaluations between AASHTO and PCA methodologies.

While previous attempts, such as computational platforms, have demonstrated the feasibility of automating pavement design, there remains no consolidated system that integrates both AASHTO & PCA methods while simultaneously quantifying how individual parameters influence thickness. This represents a critical gap, particularly in the context of growing interest in comprehensive, optimization -driven design strategies. The need for such integrated tools is underscored by research emphasizing the importance of understanding parameter interactions & their collective impact on pavement performance (Rao & Roesler, 2010).

Sensitivity analysis provides a systematic framework for understanding these parameter influences. Foundational texts on the subject, such as Saltelli et al. (2008), establish that methods like the one-at-a-time (OAT) technique are well-suited for deterministic systems such as pavement design, offering a upfront means of ranking parameter influence. More sophisticated approaches, including global sensitivity analysis, have been applied to pavement performance predictions (Schwartz et al., 2013), demonstrating value of probabilistic

methods in capturing parameter uncertainty & interactions.

Existing literature highlights distinct sensitivity patterns between the two design frameworks. AASHTO thickness predictions are most influenced by traffic loading and reliability inputs, as explored in studies of parameter sensitivity (Guclu & Ceylan, 2005). In contrast, PCA outputs are particularly sensitive to material properties, such as the modulus of rupture and subgrade reaction modulus (Norwood, 1999). The critical role of subgrade support in pavement behavior has long been recognized, with foundational work by Ioannides (1990) on Westergaard solutions providing theoretical underpinning for these sensitivity patterns. More recent investigations, including case studies applying semi-empirical methods (Oltean & Matei, 2021), continue to confirm the dominant influence of material & subgrade characteristics in rigid pavement design.

However, direct cross-method sensitivity comparisons expressed in terms of quantitative metrics such as change in thickness per unit change in input remain largely lacking in the literature. Most studies isolate their focus to either AASHTO or PCA, limiting actionable insights for engineers tasked with prioritizing data collection during the design process. This study addresses the identified gap by developing PCAA Pave Software, an integrated platform that automates both AASHTO and PCA thickness designs, applies one-at-a-time and Monte Carlo simulation sensitivity analysis, and generates benchmarked sensitivity indices to enable meaningful methodological comparison.

5. Methodology

This section describes a systematic methodology employed in this research, concentrating on the design of an automated tool for rigid pavement thickness design and sensitivity analysis, utilizing both the AASHTO (1993) and PCA methodologies. The technique is intended to guarantee robustness, precision, and practical significance. The research process is divided into two primary phases: Software Development and Validation and Sensitivity Analysis.

5.1 Theoretical Design Equations

The AASHTO 1993 rigid pavement thickness design is based on the empirical equation developed from the AASHO Road Test (American Association of State Highway and Transportation Officials, 1993) (Equation 1):

Where:

W18 = traffic carried in ESALs
ZR=standard normal deviation for desired reliability
So = overall standard deviation
D = slab thickness in inches
∆PSI = design change in serviceability in dex
S'c = flexural strength of the concrete (psi)
Cd = drainage coefficient
J = load transfer coefficient
Ec = modulus of elasticity of concrete (psi)
K = modulus in sub grade reaction psi/in

For the PCA method, thickness design follows the fatigue and erosion analysis procedures documented in Packard (1984). Fatigue damage is computed as the cumulative percentage of total fatigue life consumed by repeated load applications:

$$\mathrm{Df} = \sum \frac{\mathrm{ni}}{\mathrm{Ni}} * 100 \quad (2)$$

Where ni is the expected number of load applications at stress level *i*, and Ni is the allowable number of repetitions from the PCA fatigue curves.

Erosion damage is similarly calculated

based on corner deflections and allowable repetitions from erosion criteria. Complete design procedures, including stress analysis and design thickness, are provided in the PCAWIN program for jointed concrete pavement design (Lee & Carpenter, 2001).

$$\log W18 = ZR * So + 7.35 * \log(D+1) - 0.06 + \frac{\log\left(\frac{\Delta PSI}{4.5-1.5}\right)}{\left(1 + \frac{1.624 * 10^7}{(D+1)^{8.46}}\right)} + (4.22 - 0.32 * Pt) * \log[(Sc) * (Cd)(D^{0.75} - 1.132)/(215.63 * J * (D^{0.75} - \left(\frac{18.42}{\left(\frac{Ec}{K}\right)^{0.25}}\right)) \quad \text{(Eqn. 1)}$$

5.2. Software Development

The fundamental computational framework for this investigation was constructed as an organized Windows application utilizing Microsoft Visual Basic 2008 (VB 2008). This environment was chosen for its proficiency in developing executable software featuring a user-centric graphical interface capable of executing intricate, iterative computations. The VB 2008 application was accurately engineered to function as an integrated platform that fulfills three principal roles: it accepts all requisite input parameters for both design methodologies, implements the embedded AASHTO and PCA algorithms to ascertain the necessary pavement thickness, and distinctly conveys final design outcomes.

5.3. Software Validation

The precision and dependability of the developed software were validated through a comprehensive direct verification methodology. The application was employed to produce design outputs across a diverse array of input parameters. Each result generated by the software, encompassing final thickness values, was rigorously contrasted against independent, thorough manual calculations executed in accordance with the identical AASHTO and PCA equations. This rigorous point-by-point analysis substantiated the internal computational accuracy and algorithmic integrity of the programmed software, confirming that the automated tool produces results consistent with established manual procedures.

5.4. Sensitivity Analysis Procedure

A dual methodology of sensitivity analysis was executed to thoroughly assess the impact of input parameters on the resultant design thickness. Following the establishment of various baseline scenarios, the analysis advanced by employing two distinct computational instruments to exploit individual advantage.

Initially, a One-at-a-Time (OAT) analysis was performed utilizing Microsoft Excel, taking advantage of its clarity for organizing data and illustrating the exclusive effect of altering a single parameter while maintaining others in a constant state. This deterministic approach enabled the direct measurement of thickness change per unit change in each input parameter. Subsequently, to simulate parameter interaction & stochastic variability, a Monte Carlo simulation was conducted using Python programming. This probabilistic methodology enabled automated creation of 10,000 random input sets predicated on specified statistical distributions and evaluation of numerous design iterations simultaneously, capturing the combined effects of parameter uncertainty and interactions.

6. Application of the Software

PCAA pave software was developed by using Microsoft visual basic 2008. This software comprises of several tabs and forms. The software is developed based on one module and seven forms. There is a unique coding written for every form. After running the software, we get the front interface shown below.



Figure 1 PCAA Pave Window Interface

The window contains tabs in its upper left corner. These are the login and about tabs. The log in tab introduces Password is required to proceed to the next form. The purpose of the password is to ensure security or protection of the software and the about tab introduces briefly about the purpose of the software is to determine the thickness of concrete pavement and this software executes using the design methods AASHTO and PCA. PCAA pave software calculates the thickness of concrete pavement by using AASHTO and PCA design methods. And it introduce briefly about the software developers. After the user puts the user name and password and proceed to the next form.

6.1 PCAA Pave Form

This form consists of file, edit, performance analysis, compute design thickness tabs. The file tab consists of read data from file, save input data, save report as PDF, print report and exit tabs. The Edit tab consists of PCA pavement data, PCA traffic data, Axle load category, AASHTO traffic input, AASHTO axle load input. And performance analysis includes Fatigue, Erosion and Both.

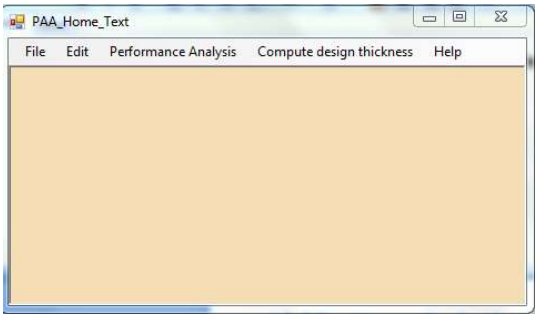


Figure 2 PCAA Pave Home Form

6.2 ESAL Calculation Form (AASHTO)

One basic parameters in pavement design is traffic. And in this form converts mixed traffic into ESAL according to AASHTO method. You can determine the design ESAL using ESAL by truck factor or ESAL by axle load data.

6.2.1 ESAL Calculation by Truck Factor (AASHTO)

In this form a designer puts the design period, growth rate, average annual daily traffic, percentage of truck, and truck factor. And select whether the traffic input is on the design lane or as total traffic.

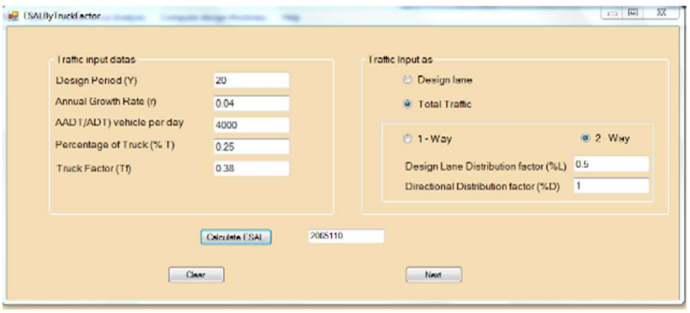


Figure 3 ESAL Calculations by Truck Factor Form

6.2.2 ESAL Calculation by Axle Load (AASHTO)

This form requires the following inputs;-

- Axle type (Single, tandem or tridem)
- Axle weight
- Number of axles for each axle type

And using the above inputs PCAA pave software calculates the equivalency factor and total ESAL over the design life for each combination of axle type and weight entered, and sums them at the bottom of the screen.

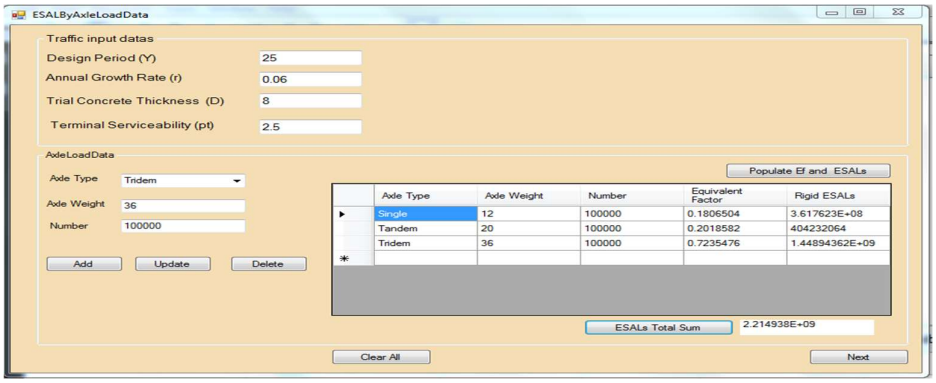


Figure 4 ESAL Calculations by Axle Load Data Form

6.3 Concrete Pavement Thickness analysis form (AASHTO)

This form displays and solves for the inputs in the AASHTO concrete pavement thickness (D). Information needed includes Reliability(R), over all standard deviation (So), 28-day mean flexural strength(f'c), 28-mean modulus of elasticity(Ec), load transfer coefficient(J), mean static modulus of subgrade reaction(K-value), drainage coefficient(Cd) and initial and terminal serviceability (Po and Pt) and total rigid ESAL input comes from ESAL calculation.

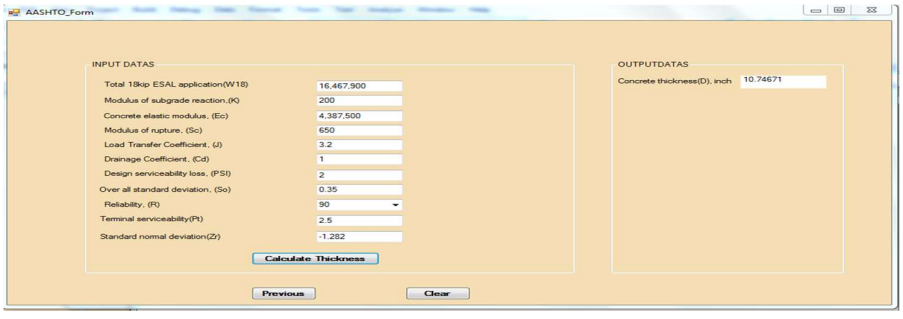


Figure 5 Concrete Pavement Thickness Calculation Form

6. 4 PCA Method – Pavement Data Input Form

This form shows input data for PCA method. In this form data required are as follows

- Trial thickness (H)
- Sub grade modulus(K)
- Modulus of rupture(So)
- Dowel / Aggregate inter lock joint
- Concrete shoulder/ No concrete shoulder

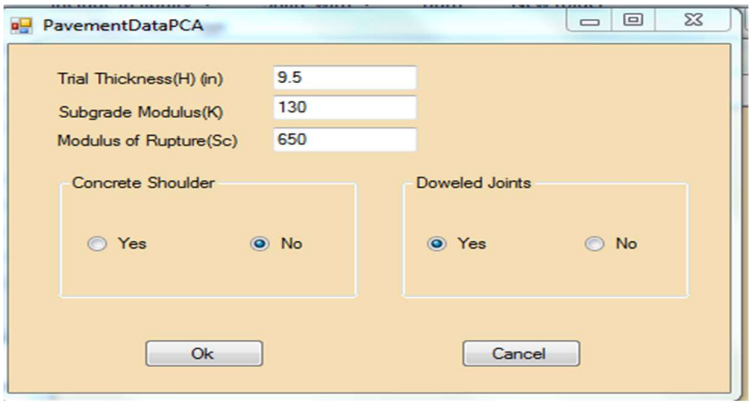


Figure 6 PCA Pavement Data Input Form

6.5 PCA Method – Traffic Data Input Form

Under this form the designer puts the traffic inputs for PCA method. These are

- Average daily truck traffic (ADTT)
- Proportion of trucks (%T)
- Annual growth rate(r)
- Design period(Y years)
- Directional and Lane distribution factor(D and L)

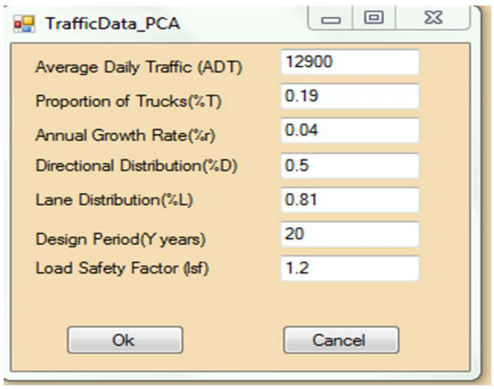


Figure 7 PCA Traffic Input Data Form

Finally, there are categories, erosion and fatigue analysis forms for PCA method.

7. Results and Discussions

This section presents the validation of the automated design tool, followed by a detailed sensitivity analysis of key input parameters affecting rigid pavement thickness using the AASHTO (1993) and PCA design methods. The analysis identifies critical parameters, compares methodological differences, and discusses practical implications for pavement design.

7.1 Software Validation

7.1.1 Validation Against Manual Calculations (AASHTO)

To ensure the reliability of the automated tool, the output thicknesses from the software were compared with manual calculations for several design scenarios. In contrast to manual and MULTI-PAVE software, the PCAA pave program (AASHTO) gives good results, and the below table shows how sensitive pavement thickness is to changes in design assumptions and proves that two calculation methods agree.

Table 1 Validation of PCAA Pave (AASHTO)

ESAL(W18) (Million)	5.1	**10**	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	**50**
Keff (pci)	72	72	**60**	72	72	72	72	72	72	72	72	**90**
Ec (psi)*10^6	5	5	5	**4**	5	5	5	5	5	5	5	**6**
Sc (psi)	650	650	650	650	**550**	650	650	650	650	650	650	**700**
J	3.2	3.2	3.2	3.2	3.2	**3.5**	3.2	3.2	3.2	3.2	3.2	**3**
Cd	1	1	1	1	1	1	**0.9**	1	1	1	1	**1.2**
PSI	1.7	1.7	1.7	1.7	1.7	1.7	1.7	**2**	1.7	1.7	1.7	**1.5**
Pt	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	**2**	2.5	2.5	**2.5**
R(%)	95	95	95	95	95	95	95	95	95	**90**	95	**99**
So	0.29	0.29	0.3	0.29	0.29	0.29	0.29	0.29	0.29	0.29	**0.4**	**0.2**
Thickness(inch)												
PCAA Pave Software (AASHTO)	9.69	10.7	9.8	9.61	10.6	10.2	10.2	9.46	9.7	9.34	10	11.7
MULTI-PAVE Software	10	11	10	10	11	10.5	10.5	9.5	10	9.5	11	12
Manual Calculation	10	11	10	10	11	10.5	10.5	9.5	10	9.5	11	12
Difference	0.31	0.3	0.2	0.39	0.4	0.3	0.3	0.04	0.3	0.16	1.0	0.3

The comparison of thickness predictions from all three methods is visualized in Figure 8, which illustrates the consistent agreement across twelve design cases.

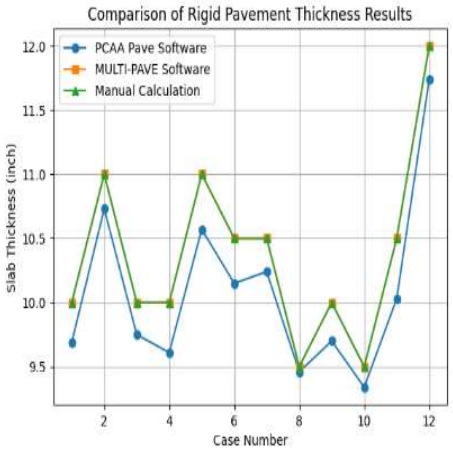


Figure 8 Comparison of Rigid Pavement Thickness from PCAA Pave, MULTI-PAVE, and Manual Calculation for Twelve Design Cases

The rigid pavement thicknesses for twelve design scenarios are compared in Figure 8 using manual AASHTO-based calculations, PCAA Pave Software, and MULTI-PAVE Software. The three methods results demonstrate a high degree of agreement. The accuracy and consistency of the manual design process are confirmed by the fact that the thickness estimated by the MULTI-PAVE software consistently matches the manual calculations. Overall, the comparison shows that the three approaches provide consistent and reliable thickness estimates, with only minor variations attributable to differences in computational algorithms and internal assumptions. The PCAA Pave software typically predicts slightly lower thickness values, as compared to the other methods. All methods exhibit similar trends with increasing traffic and design demands, especially at higher ESAL levels.

7.1.2 Validation Against Manual Calculations (PCA)

The accuracy of the PCAA Pave software for PCA design method was validated by comparing its fatigue and erosion damage

predictions with manual calculations. Table 2 presents this comparison for three trial thicknesses, showing agreement with minimal difference and confirming the reliability of the automated tool for PCA based pavement design.

Table 2 Comparison of Fatigue & Erosion Damage: Manual Calculation vs. PCAA Pave Software (PCA)

		Manual Solution		PCAA pave software		Difference (%)	
Trial	**Thickness(D) (in)**	**Fatigue (%)**	**Erosion (%)**	**Fatigue (%)**	**Erosion (%)**	**Fatigue (%)**	**Erosion (%)**
1	9	193.9	99.4	198.6	99.6	-4.7	-0.2
2	9.5	98.5	64.0	64.1	64.1	+0.1	-0.1
3	10	31.10	38.3	30.8	37.6	+0.3	+0.7

Table 2 presents a comparison of fatigue and erosion damage predicted using manual PCA based calculations and PCAA Pave software for three trial thicknesses.
At a thickness of 9 inch, both methods predicts fatigue damage well above the allowable 100% limit, indicating an inadequate pavement design despite erosion damage remaining close to the limiting value. Increasing the thickness to 9.5 inch significantly reduces fatigue damage to values at or below the allowable limit, with minor differences observed between the two methods. At 10 inch thickness, both fatigue and erosion damages are substantially lower than 100%, demonstrating a structurally adequate design. Overall, the differences between manual and PCAA predictions are small, generally within ±1% for erosion and within ±5% for fatigue, confirming good agreement between the manual and the developed software and validating the reliability of the PCAA software implementation.

Figure 9(a) compares the fatigue damage predictions from manual calculations and PCAA Pave software across three trial thicknesses, demonstrating close agreement between the two approaches.

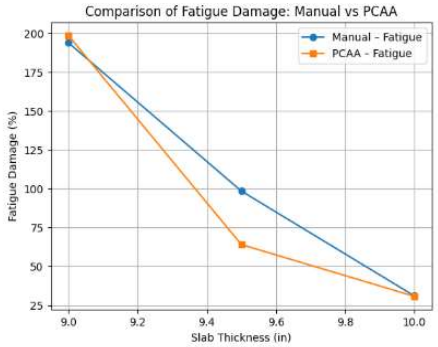


Figure 9 (a) Fatigue Damage Comparison: Manual and PCAA Pave (PCA Method)

Figure 9(b) presents the corresponding comparison for erosion damage, showing nearly identical predictions with differences of less than 1% for all trials.

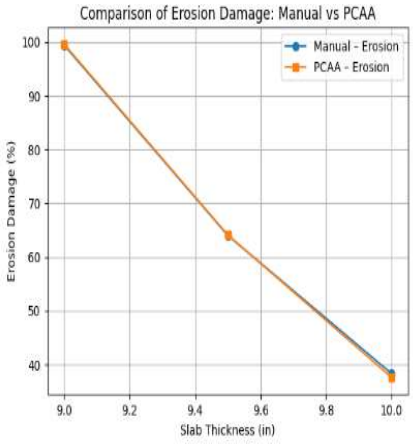


Figure 9 (b) Erosion Damage Comparison: Manual and PCAA Pave (PCA Method)

For changing thicknesses, Figures 9(a) and 9(b) compared the fatigue and erosion damage values obtained by PCAA Pave software and manual PCA based computations. As thickness increases, both methods consistently show a decrease in fatigue and erosion damage. At lower thickness levels, the PCAA software estimates slightly more fatigue damage; nevertheless, as thickness increases, results closely converge. For every trial, the two approaches predicts of erosion damage that is nearly the same, with ranges of less than 1%. Overall, the close agreement between the software based and manual results justifies the manual design process and indicates to the reliability of the PCAA pave implementation.

7.2 Sensitivity Analysis Using One at a Time Method

7.2.1 AASHTO Parameters

To conduct the sensitivity analysis of rigid pavement thickness, a baseline scenario was established using the following design inputs:

- Equivalent Single Axle Load (ESAL): 2×10^6
- Serviceability Loss (ΔPSI): 1.5
- Drainage Coefficient (Cd): 0.7
- Concrete Modulus of Elasticity (Ec): 4.2×10^6

These parameters served as the reference condition for evaluating how variations in input values affect pavement thickness. Table 3 summarizes all critical parameters used in the sensitivity analysis.

Table 3 List of Important Parameters for Sensitivity Analysis (AASHTO Method)

Number	In put parameters	Value	For sensitivity analysis
1	Traffic (In terms of ESAL)	2*10^6	Range (0.5*10^6 -100*10^6)
2	Effective modulus of subgrade reaction(K)	350	Range (100 - 500)
3	Reliability(R)	60%	Range (50 - 99.99%)
4	Standard deviation(So)	0.35	Range(0.2 - 0.6)
5	Design Serviceability loss(∆PSI)	1.5 (4.0-2.5)	-
6	Concrete elastic modulus(Ec)	4.2*10^6	Range(3*10^6 - 6*10^6)
7	Concrete modulus of rupture(Sc)	550	Range(550 - 800)
8	Load transfer coefficient(J)	3.2	Range(2.2 - 4.5)
9	Drainage Coefficient(Cd)	0.7	Range(0.6 -1.3)

The impact of individual parameters on rigid pavement thickness was evaluated by systematically varying one input while holding all others constant at baseline values and are shown the following figures.

Figure 10(a) illustrates the influence of material properties specifically modulus of rupture, elastic modulus, and subgrade modulus on required pavement thickness under the AASHTO method.

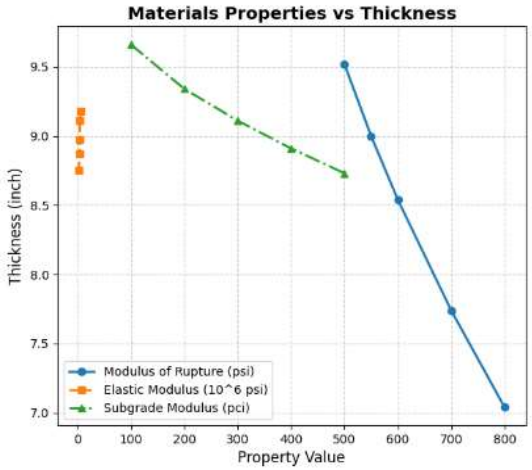


Figure 10(a) Influence of Modulus of Rupture, Elastic Modulus, and Subgrade Modulus on Pavement Thickness

The impact of traffic loading and reliability on pavement thickness is shown in Figure 10(b), revealing exponential sensitivity to ESAL levels and disproportionate effects at high reliability requirements.

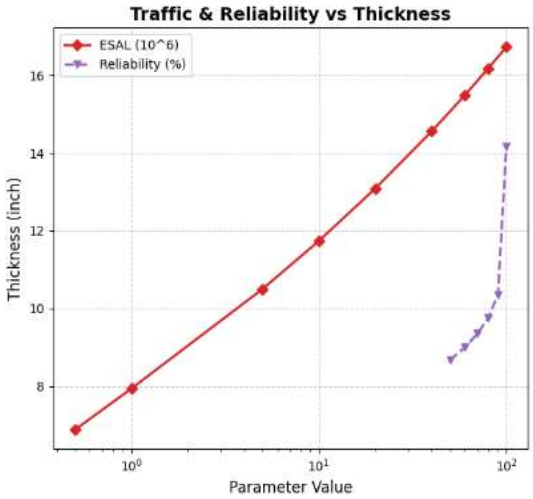


Figure 10(b) Influence of Traffic and Reliability on Pavement Thickness

Figure 10(c) presents the sensitivity of pavement thickness to design coefficients, including standard deviation, drainage coefficient, and load transfer coefficient.

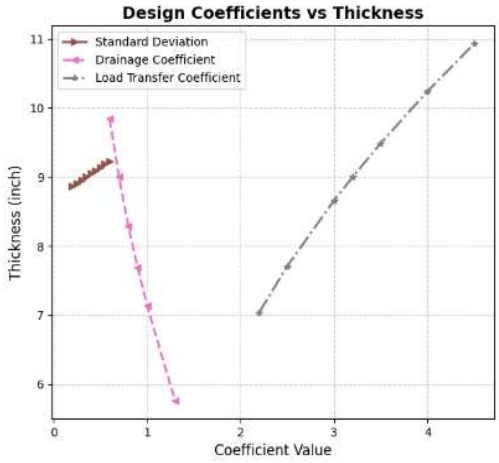


Figure 10(c) Influence of Standard Deviation, Drainage Coefficient, and Load Transfer Coefficient on Pavement Thickness

Three grouped analyses in Figures 10(a), 10(b), and 10(c) above show different AASHTO parameter sensitivities. Modulus of rupture is the most important element, according to material characteristics, with thickness decreasing as strength rises from 500 to 800 psi. Subgrade support has a small impact, while concrete stiffness displays unexpected positive association. Reliability requirements exhibit uneven thickness level, while traffic loading exhibit exponential sensitivity, with thickness growing across loading spectrum.

Design coefficients show that while material variation has little effect on thickness, drainage conditions and load transfer performance have a significant impact. When taken as a whole, these relationships show a balanced design philosophy that highlights the risk-based, multi-parameter optimization inherent in modern day pavement engineering. Traffic loading and material strength are the main factors determining thickness, drainage (environmental controls) provide significant improvement possibility, and statistical reliability requirements drive non-linear safety margins.

Table 4 Normalized Sensitivity Index (NSI) for AASHTO Parameters

Rank	Parameter	Avg. Thickness Change (in)	Absolute Value of Thickness Change (in)	NSI	Relative Influence
1	Reliability	+1.10	1.10	0.254	Very High
2	Traffic (ESAL)	+0.91	0.91	0.210	Very High
3	Drainage Coefficient	-0.80	0.80	0.185	High
4	Load Transfer Coefficient	+0.65	0.65	0.150	High
5	Modulus of Rupture(Sc)	-0.50	0.50	0.115	Moderate
6	Subgrade Modulus (k)	-0.23	0.23	0.053	Low
7	Concrete Elastic Modulus	+0.10	0.10	0.023	Very Low
8	Overall Std. Deviation	+0.045	0.045	0.010	Negligible
		D	4.335		

The sensitivity analysis ranks pavement design parameters according to their impact on required thickness in Table 4. The two most important variables are traffic load and reliability, which can cause thickness variations of more than 0.9 inches and necessitate careful selection. Potential thickness reductions of 0.65 to 0.80 inches are possible due to drainage quality and load transmission, which are also very important factors. Concrete stiffness and subgrade support result in negligible modifications (≤0.23 inches), although concrete strength has a substantial effect. Overall, since these four factors account for more than 80% of thickness variance, design optimization should give priority to precise dependability targets and traffic estimates before concentrating on drainage improvements.

To provide a visual ranking of parameter influence, Figure 5 presents a tornado chart showing the relative impact of each AASHTO design variable on pavement thickness.

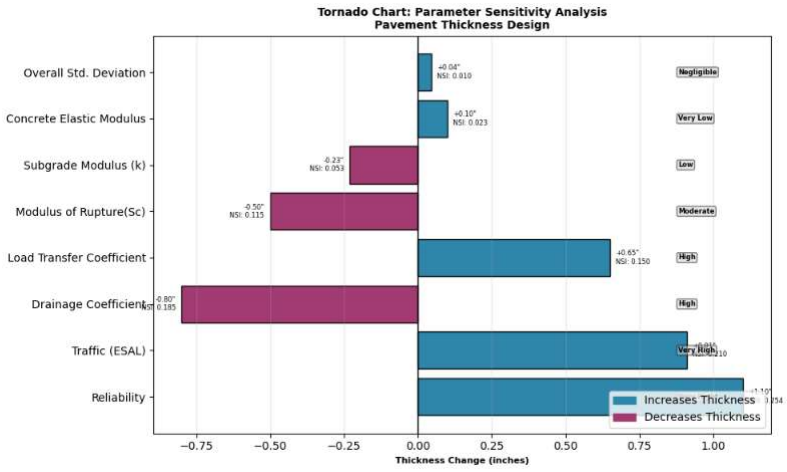


Figure 11 Tornado Chart Illustrating the Effect of Input Variables on Rigid Pavement Thickness Requirements (AASHTO)

With longer horizontal bars signifying greater sensitivity, the tornado chart in Figure 11 visually ranks design elements according to their effect on pavement thickness. The main causes of the greatest thickness differences are traffic and reliability (ESAL), which are followed by load transfer coefficients and drainage.

While subgrade support, concrete stiffness, and overall standard deviation have little to no effects, concrete strength has a considerable impact. Given that most thickness changes in pavement design are driven by dependability targets and traffic estimations, this picture makes it abundantly evident how important it is to concentrate on these factors.

7.2.2 PCA Parameters

To conduct sensitivity analysis of rigid pavement thickness using the PCA method, baseline scenario was established with the following design parameters:

- Annual Daily Traffic (ADT): 12,900
- Design Period: 20 years
- Load Safety Factor (LSF): 1.2
- Trial Thickness: 9.5 inches
- Joint Type: Dowelled

These parameters formed the reference condition for evaluating individual parameter sensitivity. Table 5 provides a comprehensive list of all parameters analyzed.

Table 5 List of Important Parameters for Sensitivity Analysis (PCA Method)

Number	Input parameters	Value	For sensitivity analysis
1	Average annual daily traffic (ADT)	12,900	Range (100-25,000)
2	Effective modulus of sub grade reaction(K)	130	Range (50-1000)
3	Trial thickness(H) inch	9.5	-
4	Proportion of trucks	19%	-
5	Design Period	20 yrs	Range(10-50)years
6	Lane distribution factor	81%	-
7	Concrete modulus of rupture(Sc)	650	Range(500-1000)
8	Directional distribution	50%	-
9	Concrete shoulder	No	-

Figure 12(a) demonstrates the inverse relationship between material properties concrete modulus of rupture and subgrade modulus and the required pavement thickness under the PCA method

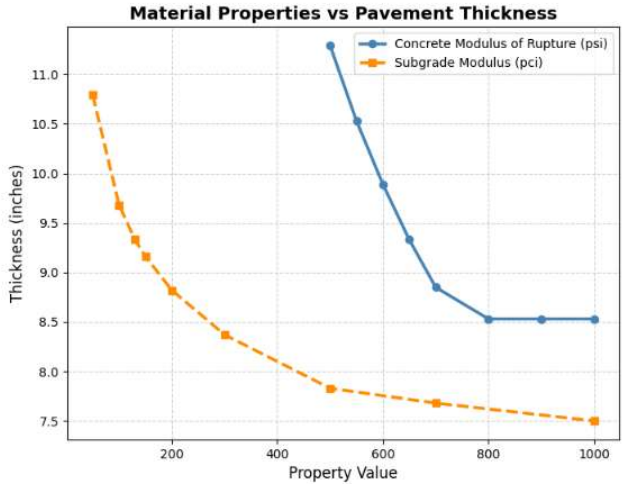


Figure 12(a) Influence of Concrete Modulus of Rupture & Subgrade Modulus on Pavement Thickness

Figure 12(a) illustrates the inverse relationship between key material properties and the required thickness of rigid pavement. As the concrete modulus of rupture which measures the flexural strength of the concrete increases, the required thickness decreases significantly. Similarly, when the subgrade modulus, which represents the support capacity of the underlying soil, improves, the pavement thickness can be reduced. This downward trending relationship demonstrates that using higher quality materials, such as stronger concrete or a more stable subgrade, creates a more efficient pavement system capable of distributing traffic loads effectively with a thinner section. Engineers can use this relationship to optimize pavement design by balancing material costs against construction thickness requirement.

The direct relationship between traffic demand, design life, and pavement thickness is illustrated in Figure 6(b), showing how increasing ADT and design period necessitate thicker pavement structure.

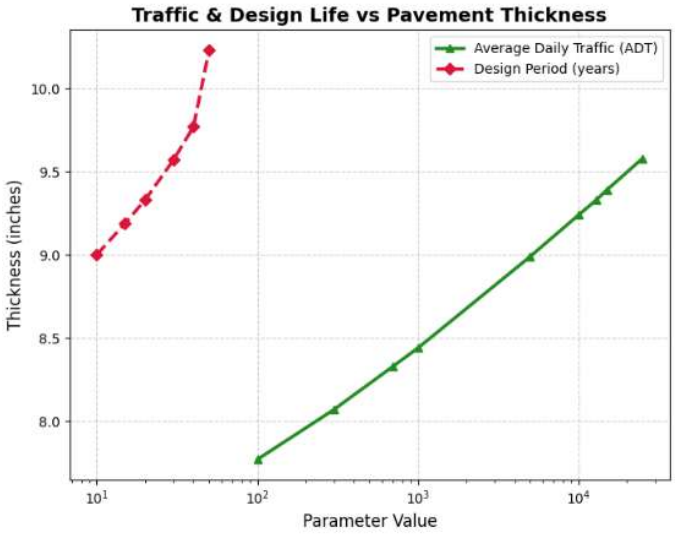


Figure 12(b) Influence of Average Daily Traffic and Design Period on Pavement Thickness

Figure 12(b) demonstrates the direct relationship between traffic demand, design life, and the required thickness of rigid pavement. As both the average daily traffic (ADT) and the design period increase, the necessary thickness also increases substantially. The x-axis spans a wide range of values using scientific notation, from 10 vehicles per day for low-volume roads to 10,000 vehicles per day for major highways, allowing comprehensive observation of traffic impacts on pavement design. The upward trending curves indicate that roads carrying heavier traffic volumes experience more load repetitions and accelerated fatigue damage, while longer design life requirements demand that the pavement withstand cumulative damage over extended timeframes. Together, these factors necessitate thicker, more durable slabs to ensure structural integrity throughout the intended service life of the pavement.

Table 6 Normalized Sensitivity Index (NSI) for PCA Parameters

Rank	Parameter	Avg. Thickness Change (in)	Absolute Value of Thickness Change(in)	NSI	Relative Influence
1	Subgrade Modulus(k)	-0.41	0.41	0.325	Very High
2	Modulus of Rupture(Sc)	-0.39	0.24	0.310	Very High
3	Design Period	+0.24	0.41	0.190	Moderate
4	Traffic (ADT)	+0.22	0.39	0.175	Moderate
		D	1.26		

Table 6 shows that for this particular pavement design scenario, the material properties of the **subgrade soil (k)** and the **concrete strength (Sc)** are the most critical factors, both having a Very High relative influence. A stiffer subgrade or stronger concrete significantly reduces the required pavement thickness, as indicated by the negative change values. In contrast, the **design period** and **traffic volume (ADT)** have a more moderate influence, increasing thickness as their values rise.

Therefore, to effectively control pavement cost and performance, the greatest focus should be placed on accurately assessing and improving the foundational soil support and specifying adequate concrete strength, as these material parameters drive the design outcome more than the projected traffic loadings or time horizon.

Figure 13 presents a tornado chart ranking the four key PCA parameters by their influence on pavement thickness, highlighting the dominance of subgrade modulus and concrete strength.

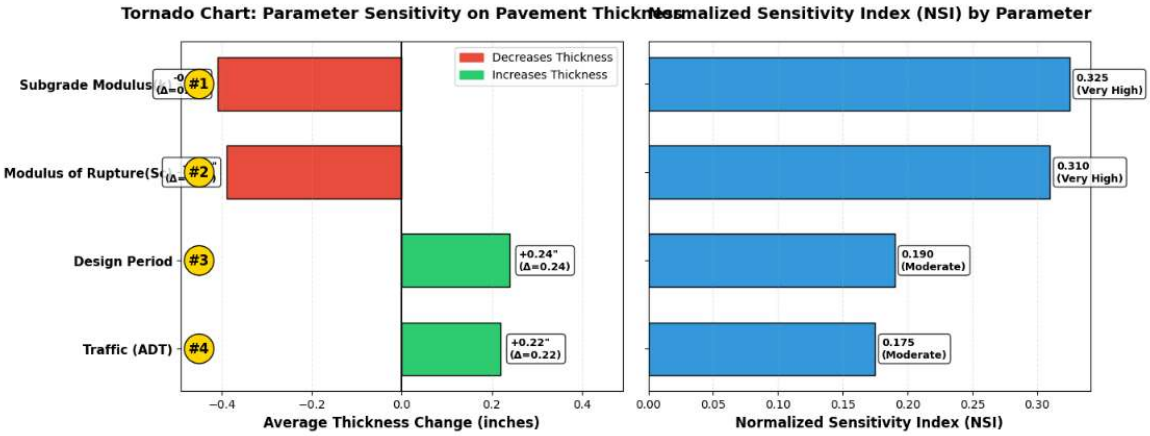


Figure 13 Tornado Chart Illustrating the Effect of Input Variables on Rigid575h Pavement Thickness Requirements (PCA)

Figure 7 presents a condensed sensitivity analysis, ranking four key parameters by their impact on pavement thickness. The subgrade modulus and concrete modulus of rupture (are the most influential factors, both classified as Very high and acting to decrease required thickness when improved. In contrast, extending the design period or increasing traffic volume (ADT) moderately increases the necessary thickness. Therefore, to optimize pavement design for cost and performance, primary attention should be given to enhancing soil support and concrete quality, as these material properties offer the greatest

potential to reduce thickness, whereas traffic and design life considerations have a lesser, opposing effect.

7.3 Sensitivity Analysis Using Monte Carlo Simulation Method

While the One-at-a-Time (OAT) method provides a useful ranking of individual parameter effects under controlled

conditions, it does not account for the inherent uncertainty and potential interactions among design inputs. To address this limitation and obtain a more realistic assessment of parameter sensitivity, a probabilistic approach using Monte Carlo simulation was conducted for both the AASHTO and PCA design methods.

7.3.1 AASHTO Parameters (Probabilistic)

To complement the deterministic One-at-a-Time (OAT) sensitivity analysis and to account for the inherent uncertainty and interactions among design inputs, a probabilistic sensitivity analysis was conducted using Monte Carlo simulation.

Using Python programming, 10,000 random scenarios were generated by simultaneously varying all AASHTO parameters within their typical ranges, allowing for a realistic assessment of their combined influence on rigid pavement thickness. From this simulation, sensitivity indices based on correlation coefficients were computed for each parameter, quantifying the strength and direction of their relationship with the predicted thickness. These indices, presented in Figure 8, provide a probabilistic ranking of parameter importance, offering deeper insight into which inputs contribute most to thickness variability under uncertainty.

The probabilistic sensitivity analysis results for the AASHTO method are presented in Figure 14, where the tornado chart ranks parameters by their correlation based sensitivity indices derived from 10,000 Monte Carlo simulations.

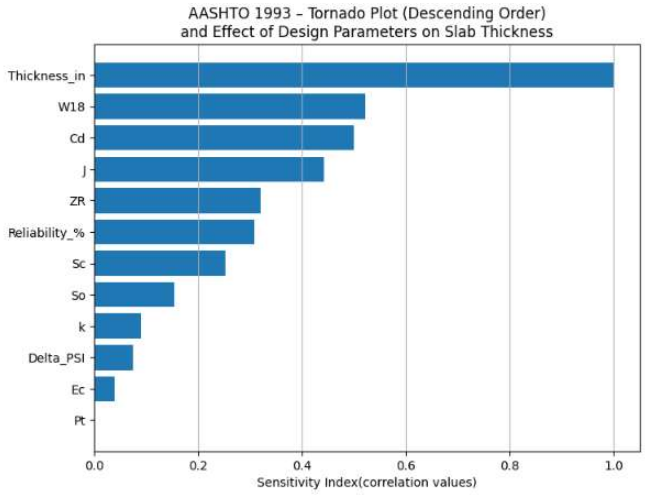


Figure 14 Tornado Chart Illustrating the Effect of Input Variables on Rigid Pavement Thickness Requirements (AASHTO)

Figure 14 plot from the Monte Carlo simulation reveals the relative influence of each AASHTO 1993 design parameter on predicted slab thickness, ranked in descending order of sensitivity. Traffic load (W18) is the most critical factor, meaning

even small uncertainties in traffic estimation cause the largest variation in required thickness. Drainage coefficient (Cd) and load transfer coefficient (J) also show high sensitivity, followed closely by reliability parameters (ZR and Reliability). Concrete strength (Sc) and overall standard deviation (So) have moderate influence, while subgrade modulus (k), change in serviceability (ΔPSI), concrete elastic modulus (Ec), and terminal serviceability (Pt) have comparatively minor impact. This hierarchy indicates that design accuracy depends most on precise traffic forecasting and proper accounting for drainage and load transfer, whereas parameters like Ec and Pt can be assigned typical values with minimal effect on thickness outcomes.

7.3.2 PCA Parameters (Probabilistic)

Following the same probabilistic approach applied to the AASHTO method, a Monte Carlo simulation was implemented in Python to assess parameter sensitivity within the PCA design framework. A total of 10,000 random design scenarios were generated by simultaneously sampling PCA input parameters including subgrade modulus (k), concrete modulus of rupture (Sc), average daily traffic (ADT), design period, truck proportion, and traffic growth rate from their respective probability distributions. For each scenario, the required pavement thickness was computed, and sensitivity indices based on correlation coefficients were derived to quantify the strength and direction of each parameter's influence under uncertainty.

The resulting tornado chart, presented in Figure 15, reveals a striking contrast to the AASHTO findings, subgrade modulus emerges as the single most critical factor, with a sensitivity index substantially higher than all other parameters, while traffic-related variables show minimal impact on thickness variability.
Figure 15 displays the Monte Carlo simulation results for the PCA method, revealing the overwhelming dominance of subgrade modulus and the negligible influence of traffic-related parameters on pavement thickness variability.

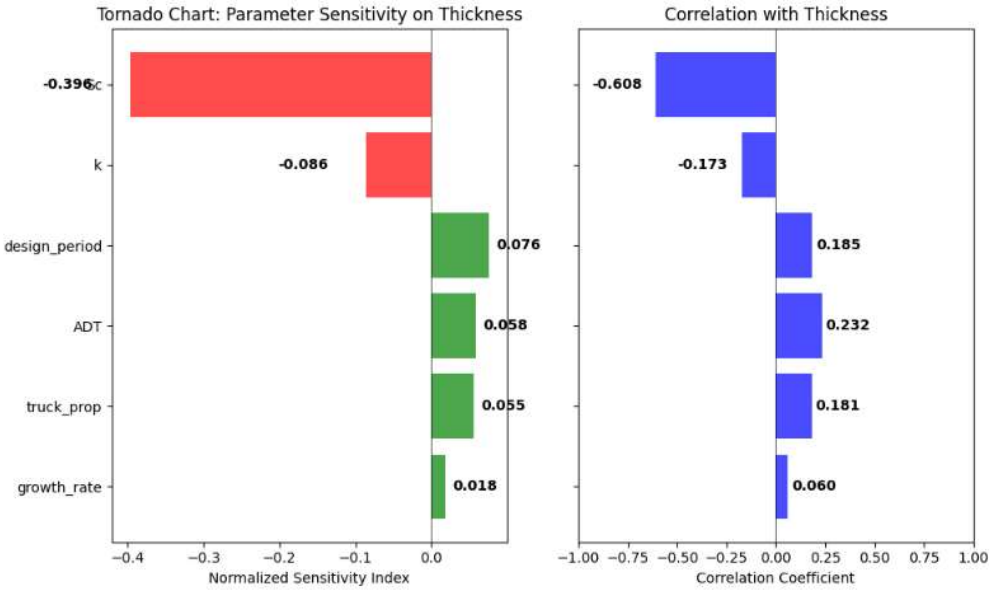


Figure 15 Tornado Chart Illustrating the Effect of Input Variables on Rigid Pavement Thickness Requirements (PCA)

Figure 15 the Monte Carlo simulation for the PCA design method reveals remarkably different sensitivity pattern compared to AASHTO 1993. Here, the subgrade modulus (k) completely dominates the analysis, with a sensitivity index nearly five times greater than any other parameter and a strong negative correlation. This means the stiffness of the underlying soil is the overwhelming, primary driver of pavement thickness in this method; a stronger subgrade directly and significantly reduces the required thickness. In contrast, all traffic-related parameters including design period, average daily traffic (ADT), truck proportion, and growth rate show negligible to very low sensitivity, indicating they have minimal influence on the thickness outcome.

Therefore, for a design using the PCA method, engineering resources and precision should be concentrated almost exclusively on accurately determining and improving the subgrade support, as uncertainties in traffic forecasting have little consequential impact.

7.4 Comparative Sensitivity Analysis

The sensitivity analysis employed both One-at-a-Time (OAT) and Monte Carlo simulation methods to evaluate the influence of design parameters on rigid pavement thickness for the AASHTO and PCA methods, revealing notable differences in parameter importance and methodology. Using the OAT approach with Normalized Sensitivity Index (NSI), the AASHTO method identified Reliability (NSI = 0.254) and Traffic (ESAL) (NSI = 0.210) as the most influential parameters, while material properties like Subgrade Modulus and Concrete Elastic Modulus showed relatively low influence. In contrast, the PCA method under OAT analysis ranked Subgrade Modulus (k) (NSI = 0.325) and Modulus of Rupture (Sc) (NSI = 0.310) as the dominant factors, with traffic-related parameters exhibiting only moderate influence. When subjected to Monte Carlo simulation, which accounts for parameter uncertainty and interaction, the sensitivity patterns diverged further. For AASHTO, traffic load (W18) emerged as the most critical factor, followed closely by drainage and load transfer coefficients, confirming that design accuracy depends heavily on precise traffic forecasting and environmental conditions. However, for the PCA method, Monte Carlo simulation revealed that Subgrade Modulus (k) overwhelmingly dominates the analysis, with a sensitivity index nearly five times greater than any other parameter, while traffic related parameters showed negligible influence. This comparative analysis demonstrates that while OAT provides a useful ranking of individual parameter effects under controlled conditions, Monte Carlo simulation offers a more realistic assessment by capturing parameter uncertainty and interactions. The results also highlight fundamental philosophical differences between the two design methods, AASHTO is predominantly traffic and reliability driven, whereas PCA is governed almost exclusively by subgrade support and material strength. These findings underscore the importance of selecting appropriate sensitivity methods and design frameworks based on project-specific priorities and data availability.

8. Conclusions and Recommendations

8.1 Conclusions

In order to automate rigid pavement thickness design for both AASHTO (1993) and PCA methods, PCAA Pave software was successfully developed using Microsoft Visual Basic 2008, simplifying intricate computations while reducing human error. The tool's accuracy and dependability for real-world engineering

applications were demonstrated by validation against manual calculations and MULTI-Pave software, which confirmed excellent agreement across multiple design scenarios with thickness differences below 0.4 inches for AASHTO and fatigue as well as erosion damage predictions within ±1–5% for PCA.

Both one-at-a-time and Monte Carlo simulation sensitivity analysis revealed different patterns of parameter influence between the two design methods. Material properties show low to negligible sensitivity, while the AASHTO method shows "Very High" influence from reliability (+1.10 inch, NSI = 0.254) and Traffic (ESAL) (+0.91 inch, NSI = 0.210), followed by drainage coefficient (-0.80 inch, NSI = 0.185) and load transfer coefficient (+0.65 inch, NSI = 0.150). The significance of precise traffic forecasting and reliable target selection in AASHTO based design is highlighted by the confirmation of traffic load as the most important factor under uncertainty by probabilistic analysis employing 10,000 Monte Carlo simulations in Python. Subgrade modulus (-0.41 inch, NSI = 0.325) and modulus rupture (-0.39 inch, NSI = 0.310) dominated the PCA method's sensitivity patterns, which were essentially different.

8.2 Recommendations

Based on these findings, several suggestions are made for future research and practice. Method – specific data prioritization is crucial for practicing engineers. For example, AASHTO designs should prioritize reliable target selection and accurate traffic forecasting, while PCA designs should concentrate on precise subgrade characterization and concrete strength testing. The validated PCAA Pave software should be used for quick and error-free design comparisons. Future software development improvements are needed for PCAA Pave, especially in the areas of reinforcement analysis, joint design and life-cycle cost analysis. Verify against software predictions against field performance data for upcoming studies, and adjust parameters for regional conditions in Ethiopia and other comparable areas. Finally, PCAA Pave ought to be incorporated into graduate and undergraduate pavement design courses for training and education purpose.

References

Aida Wee Sze Chia. (2006)."Software development for water pricing model" (Master's thesis). Universiti Teknologi Malaysia, Skudai.

American Association of State Highway and Transportation Officials. (1993)."Guide for design of pavement structures". Washington, DC: Author.

American Concrete Institute Committee 325. (2002). "Concrete pavement design and construction". American Concrete Institute.

Darter, M. I., Khazanovich, L., & Snyder, M. B. (1985)."Design and analysis of concrete pavements". University of Illinois.

Deitel, H. M., Deitel, P. J., & Nieto, T. R. (1999)."Visual Basic 6: How to program". Prentice Hall.

Duval, J. (2007).Debunking StreetPave's claim of an "equivalent" asphalt design Asphalt Institute.

Federal Highway Administration. (1997)."LTPP data analysis phase I: Validation of guidelines for k-value selection & concrete pavement performance prediction" (FHWA-RD-96-198). U.S. Department of Transportation.

Federal Highway Administration. (2006)."Concrete pavement design and analysis tools". U.S. Department of Transportation.

Guclu, A., & Ceylan, H. (2005, August). "Sensitivity analysis of rigid pavement systems using mechanistic–empirical

pavement design guide". In Proceedings of the Mid-Continent Transportation Research Symposium. Iowa State University.

Guell, D. L. (1985). "Comparison of two rigid pavement design methods". Journal of Transportation Engineering, 111(6), 607–617.

Hall, K. T., Darter, M. I., Hoerner, T. E., & Khazanovich, L. (1997)."LTPP data analysis phase I: Validation of guidelines for k-value selection and concrete pavement performance prediction". Federal Highway Administration.

Hall, K. T., Darter, M. I., & Beam, S. (2005)."Mechanistic-empirical pavement design guide: A manual of practice". Transportation Research Board.

Huang, Y. H. (2004)."Pavement analysis and design" (2nd ed.). Pearson Education.

Ioannides, A. M. (1990). "Westergaard solutions reconsidered." Transportation Research Record, 1286, 13–23.

Kıcı, A., & Tiğdemir, M. (2017). "A user friendly software for rigid pavement design. " International Journal of Engineering & Applied Sciences, 9(4), 1–16.

Khazanovich, L., Ioannides, A. M., & Korovesis, G. (1994). "Analysis of slab-on-grade pavement systems subjected to wheel loads." Journal of Transportation Engineering, 120(3), 466–487.

Oltean, G., & Matei, A. (2021). "Sensitivity analysis of rigid pavement design based on semi-empirical methods: Romanian case study." Materials, 14(2), 168.

Packard, R. G. (1984)." Thickness design for concrete highway and street pavements". Portland Cement Association.

Rao, C., & Roesler, J. R. (2010). Characterization of design inputs for jointed plain concrete pavements.*Journal of Transportation Engineering, 136*(4), 312–323.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008)." Global sensitivity analysis: The primer". Wiley.

Schwartz, C. W., Li, R., Ceylan, H., Kim, S., & Gopalakrishnan, K. (2013). "Global sensitivity analysis of mechanistic–empirical performance predictions for flexible pavements." Transportation Research Record: Journal of the Transportation Research Board, 2368, 12–23.

Transportation Research Board. (2004)."Guide for mechanistic-empirical design of new and rehabilitated pavement structures" (NCHRP 1-37A). National Research Council.

Ying-Haur Lee and Samuel H. Carpenter. PCAWIN Program for Jointed Concrete Pavement Design. *Tamkang Journal of Science and Engineering.* 2001. 4(4): 293-300.