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NEW METRIC FOR THE CALCULATION OF SENSITIVITY ANALYSIS INDEX OF FLEXIBLE PAVEMENT USING MECHANISTIC-EMPIRICAL APPROACH, TURKEY-CASE STUDY

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ABSTRACT: The application of new Mechanistic-Empirical Pavement Design Method (M-EDM) in Turkey needs a huge data about the materials properties under specific climate and traffic conditions. Sensitivity Analysis (SA) can reduce time, effort and cost required for the determination and collection of this data. One-At-a-Time (OAT) SA was conducted using different Quantitative and Qualitative methods. Graphical, Normalized Sensitivity Index NSI and Distance Sensitivity Index DSI were used to determine the most sensitive factors (property). DSI was used for the first time in this study to conduct SA for both continuous and categorical parameters using one equation. Two climate regions, three traffic categories and different types of asphalt were used. MnPave software was used to conduct Mechanistic-Empirical analysis. The results were important and many conclusions and recommendations were reported.

Keywords: *Mechanistic-Empirical Design Method, Sensitivity Analysis, Normalized Sensitivity Index, Premature deterioration, MnPave, Distance Sensitivity Index, Turkey*

1. INTRODUCTION

The application of new Mechanistic-Empirical Pavement Design Method (M-EDM) in Turkey needs a huge data about the materials properties under specific climate and traffic conditions. The collection of such a data is costly and time consuming. The Sensitivity Analysis (SA) can reduce time, effort and cost required for the determination and collection of this data by focusing on the most important (very sensitive and sensitive) properties that have a significant effect on pavement life and performance. So, one of the main objectives of this research is to conduct a SA of Typical Pavement Sections (TTS) in Turkey as a part of the implementation of M-EDM in Turkey.

The M-EDM analysis cannot be made by hand, so the MnPave design software developed by Minnesota Department of Transportation MDOT in the USA is used. The analysis is conducted using the Base and Base (+/-20%) of the property using One At a Time OAT analysis by changing one factor at a time which is called Local Sensitivity Analysis.

1.1. Objectives

One of the main objectives of this study are:

Starting the first steps towards the application of M-EDM in Turkey.

Determinations of Material, Traffic and Climate properties (Factors) that have a significant effect on pavement performance (pavement life). This can reduce the time and effort required for collection of data about less important.

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1.2. Sensitivity Metrics

One-At-a-Time (OAT) sensitivity analysis is the commonly used method to conduct SA. In OAT, each potentially sensitive design input is varied individually for a given base case or reference condition in order to assess qualitatively and quantitatively the local sensitivity of the predicted output (pavement life). There are two types of OAT:

1.1.1. Qualitative Sensitivity Analysis (Graphical Assessment Method)

In this method, the assessment of the importance of each factor is based on its range or span in the scheme. The higher span can be considered very sensitive and so on. The assessment of this method is highly dependent on human assessment so it's expected that its results would be less accurate.

1.1.2. Quantitative Sensitivity Analysis

This method is depends on mathematical evaluation, so it's expected that the results will be more accurate. Two methods are used:

1.1.1.1. Normalized Sensitivity Index NSI

The NSI always uses the design limit as the normalizing factor for the predicted design life as shown in Equation 1 for most design inputs. However, in some cases the design input can be categorical rather than continuous (e.g., binder grade). For these design inputs, a modified non-normalized NSI Equation 2is used:

$$NSI = \frac{\Delta y}{\Delta x} \times \frac{Xbase}{DL} \quad (1)$$

$$\mathrm{NSI} = \frac{\Delta \mathrm{y}}{\mathrm{DL}} \quad (2)$$

In which (Δy) is the change in pavement life (Fatigue or rutting life) caused by the change in property magnitude from the base (Δx) (e.g. changing base layer thickness +20% from base), (Xbase) is the base of the property and (DL) is the design life (assumed 20 years).

1.1.1.2. Distance Sensitivity Index DSI

It can be seen that NSI method needs two different equations to calculate NSI. It is prefer to find new method to solve this problem so that the results can be compared. Distance Sensitivity Index method is one of the results of this study and it can be used to conduct SA for both continuous and categorical parameters using one equation. The method is depends on the distance between the resulted Fatigue Life (FL) or Rutting Life (RL) at (Base+/- 20%) case and that at Base case. Figure 1. shows the scheme of this method.

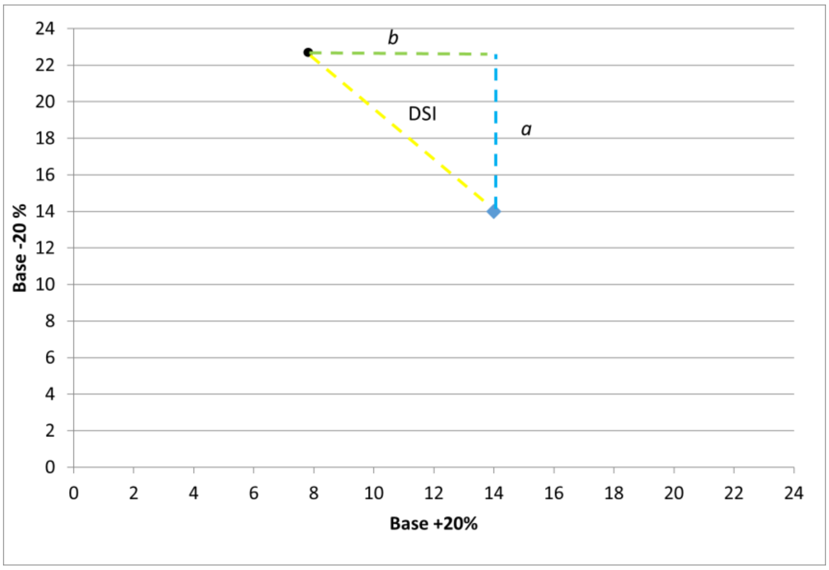

Figure 1. Scheme of DSI method

Equations 3 through 5 can be used for the calculation of DSI. These equations can be used for both categorical and continuous values.

$$DSI = \sqrt{a^2 + b^2} \quad (3)$$

a=(y_1-z_o) (4)

b=(x_1-z_o) (5)

where:

y1: the RL or FL (or distress) at (Base-20%)

x1: the RL or FL (or distress) at (Base+20%)

z_o: the RL or FL (or distress) at Base.

An example of the method can be shown Table 1 for FL.

Table 1. Example of the parameters used in the calculations of DSI.

Parameter	FL at Base (z_o)	FL at Base+20% (x_1)	FL at Base-20% (y_1)	DSI
Value	14	8	23	
Equation used for calculation	-	a=(x_1-z_o)=-6	a=(y_1-z_o)=9	$DSI = \sqrt{a^2 + b^2}$
				11.18

2. LITERATURE REVIEW

Traffic, material and climate data collection is one of the most Time and Effort-Consuming stage in the Implementation of M-EDM. Not all data at the same level of importance and have the same effect on the results of design, so it is important that the SA be conducted to shadow the light on the properties and factors that have a significant effect on the results of pavement performance [1-5].

Researchers and transportation authorities started the implementation plan of M-EDM by conducting SA to reduce the time and effort required for collection of data of less significance.

NCHRP Report 1-47 was the unique among the SA studies which reviewed recently SA researches and identified several main problems common to existing literature. Within the scope of this report Schwartz et al. undertook a detailed two-part SA involving an initial OAT analysis followed by a Global Sensitivity Analysis (GSA) [6].

Compared to OAT, the GSA allowed inputs to be varied simultaneously across their entire problem domain. This allows to look for interactions between design inputs. GSA is much more computationally intensive than a traditional OAT. Sensitivity results in NCHRP 1-47 were reported in terms of NSI.

The results of GSA revealed that [7]:

- HMA E* Alpha Parameter,
- HMA E* Delta Parameter and
- HMA Thickness.

were Hypersensitive, while :

- Base Resilient Modulus,
- HMA Poisson's Ratio,
- Subgrade Resilient Modulus,
- Base Thickness and
- Operational Speed. were Very sensitive.

In Florida state, SA were performed on material property inputs at different hierarchical levels using OAT. The flexible pavement consisted of four layer structure. An AADTT of 70,000, 20 year design period, and Orlando climatic input were used in the analyses. The M-EDM software was used for conducting SA by adjusting each input within an acceptable range. Variables with high sensitivity based on predicted performance were found to be:

- AC dynamic modulus,
- Layer thickness,
- Base modulus,
- Subgrade modulus,

It was found that the pavement with a higher AC modulus were perform better. The results provided information on how to proceed with establishing the input database [8].

The OAT SA of the M-EDM performance predictions to input parameters was studied in Maryland. Typical sections were selected. The studied parameters include: base and asphalt layer thickness, traffic loadings, design criteria, material properties, performance model parameters, and climate. The results showed that :

- Base thickness,
- Class 9 percentage trucks as the vehicle class,
- Temperature and precipitation,
- Binder grade and
- Asphalt concrete material properties.

were the most sensitive parameters [9].

Minnesota Department of Transportation MnDoT conducted SA for flexible pavements at 20 year design life and two different traffic levels, 10 and 1 million ESAL. SA was made by changing specific inputs within a reasonable range from the base values. For the 10 million ESAL analyses, longitudinal cracking was shown to be highly sensitive to:

- Asphalt concrete layer thickness and
- Soil type.

For transverse cracking the most sensitive parameters were found to be climate, asphalt concrete layer thickness, and asphalt concrete binder grade. While asphalt concrete layer thickness was found to be the only highly sensitive input for rutting and alligator cracking [10].

Focusing on traffic inputs, SA was performed using data from five LTPP sites in New Jersey. OAT analysis was conducted using M-EDM default values as a base values. It has been found that [11] :

- Rutting was highly sensitive to the monthly adjustment factor and number of axles per truck.
- Alligator cracking was found to be sensitive to the hourly distribution of truck traffic and number of axles per truck.
- Longitudinal cracking was also sensitive to hourly distribution of truck traffic and the monthly adjustment truck factor.

North Carolina utilized data from 27 LTPP sections to conduct SA. The pavement structures were divided by pavement type and climatic area. The SA was associated with materials and traffic inputs. The results of the study found that [12]:

- Alligator cracking was sensitive to air voids and dynamic modulus.
- Longitudinal cracking was sensitive to air voids, dynamic modulus, and surface shortwave absorptivity.
- Rutting was sensitive to the asphalt mixture dynamic modulus.

Table 2 below summarizes significant M-EDM inputs in some states in the USA according to SA [13].

Table 2. Results of SA in different states in the USA.

State	Inputs (Properties)
Florida	HMA Dynamic Modulus HMA Layer Thickness Base Modulus Subgrade Modulus Coefficient of Thermal Expansion Joint Spacing Dowel Bar Diameter PCC Compressive Strength
Maryland	HMA Layer Thickness Vehicle Class Distribution Climatic Location HMA Binder Content HMA Air Voids Subgrade Modulus
Minnesota	Soil Type Climatic Location HMA Binder Grade Traffic Volume Slab Thickness Base Thickness Coefficient of Thermal Expansion
New Jersey	Monthly Adjustment Factor Number of Axles Per Truck Hourly Distribution of Traffic
North Carolina	HMA Air Voids HMA Dynamic Modulus Surface Shortwave Absorptivity Coefficient of Thermal Expansion Thermal Conductivity Joint Spacing Dowel Bar Diameter

3. METHODOLOGY

As mentioned previously, the SA is conducted using OAT approach. NSI and DSI metrics were used. It is claimed that DSI is used in this work for the first time. Figure 2 shows the implementation plan used to conduct SA.

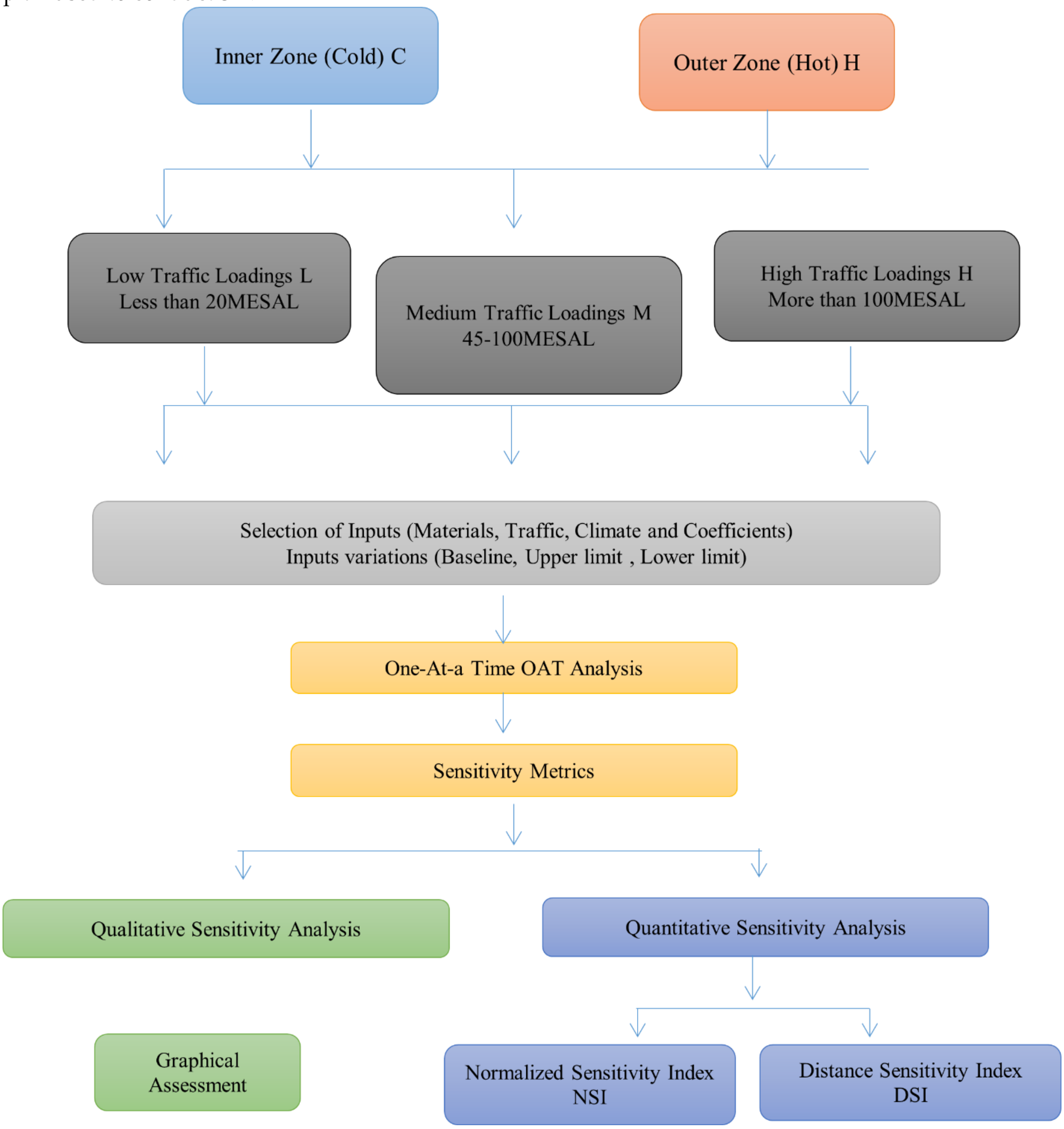

Figure 2. Methodology plan of SA

3.1. Inputs

The Inputs (variables) used in SA are collected from available resources (e.g. Turkish standards, specifications, manuals and literature). Inputs associated with climate, materials and traffic typical values of Turkey are used for SA. The value of each input is varied from the Base case by +/- 20% .

3.1.1. General Inputs

The general inputs are those still constant during conducting SA. Table 3 tabulates these inputs and their values.

Table 3. General inputs in SA

Input	Value	Unit
Design life	20	year
Confidence level	70	%

3.1.1.1. Climate Inputs

To show the effect of climate on SA of different variables, two climatic zones are selected:

1- The Inner Region (Cold). This region is denoted as Co. Afyon city in Turkey is selected to represents the Cold region.

2- The Outer Region (Hot). This region is denoted as Ho. Antalya city in Turkey is selected to represents the Cold region.

The climate inputs used in the SA under each climate and traffic condition are shown in Table 4.

Table 4. Climate Inputs and Ranges for M-EDM Sensitivity Analysis.

Inputs	Abbreviations	Values		
		-20%	Base	+20%
Depth (z) in Pavement Temperature Equation, (Ratio of (z))	ZD	1/5	1/3	1/2

3.1.1.2. Traffic Inputs

The traffic loadings of each climatic zone can be divided into the groups shown in Table 5. Traffic is represented by Million Equivalent Single Axle Loads (MESAL). Traffic loading is sub grouped into three different groups to represent High, Medium and Low traffic condition. This can identify the effect of traffic loading variation on SA results.

Table 5. Traffic Inputs and ranges for M-EDM Sensitivity Analysis for Cold and Hot regions.

Inputs	Abb.	Traffic Category								
		Low (L) 3-20 MESAL			Medium (M) 45-100 MESAL			High (H) 150-200 MESAL		
		-20%	Base	+20%	-20%	Base	+20%	-20%	Base	+20%
Traffic Loadings, MESAL	TRL	9.2	11.5	13.8	58	72.5	87	140	175	210
Speed, Km/h	SP	48	60	72	48	60	72	48	60	72
Tire Pressure, kpa	TP	442	552	662	442	552	662	442	552	662
Axle Weight, kN	AW	64	80	96	64	80	96	64	80	96
Growth Rate (Simple), %	GR	2.4	3	3.6	2.4	3	3.6	2.4	3	3.6

3.1.1.3. Materials Inputs

Materials inputs can be discussed in the following subsections.

3.1.1.3.1. Asphaltic Layers Inputs

The TTS consists of three asphaltic layers:

- Surface layer.
- Binder layer.
- Base layer.

Each layer is a HMA layer. The inputs of each layer under each climate region and traffic category are shown in Tables 6 through 9.

According to Flexible Pavement Design Catalogue of Turkey, asphalt types are the same for all traffic conditions. Therefore and for the Base cases, asphalt types used in SA are assumed to be fixed for all traffic conditions. At the same time the Performance Grade PG of each Base case is shifted one degree upward and downward from the Base case according to the catalogue.

Table 6. Inputs of Asphaltic layers and ranges for SA for H and C regions under All Traffic Categories.

Layer type	Inputs	Abbr.	Inputs values		
			-20%	Base	+20%
Surface layer	Percentage of binder, %	Pb	4.4	5.5	6.6
	Percentage passing sieve 3/4, %	P3/4-S	66.7	83.3	100
	Percentage passing sieve 3/8, %	P3/8-S	64.8	81	97.2
	Percentage passing sieve 1/2, %	P1/2-S	37.6	47	56.4
	Percentage passing sieve No.200, %	P200-S	4.4	5.5	6.6
Binder layer	Percentage of binder, %	Pb-B	4	5	6
	Percentage passing sieve 3/4, %	P3/4-B	66.7	83.3	100
	Percentage passing sieve 3/8, %	P3/8-B	47.2	59	70.8
	Percentage passing sieve 1/2, %	P1/2-B	32.8	41	49.2
	Percentage passing sieve No.200, %	P200-B	3.6	4.5	5.4
Base layer	Percentage of binder, %	Pb-Ba	2.8	3.5	4.2
	Percentage passing sieve 3/4, %	P3/4-Ba	66.7	83.3	100
	Percentage passing sieve 3/8, %	P3/8-Ba	60	75	90
	Percentage passing sieve 1/2, %	P1/2-Ba	45.2	56.5	67.8
	Percentage passing sieve No.200, %	P200-Ba	3.6	4.5	5.4
All layers	Asphalt type, PG[a] (for Hot Region)	PGH	PG 64-10	PG 70-10	PG 76-10
	Asphalt type, PG[a] (for Cold Region)	PGC	PG 58-28	PG 64-28	PG 70-28
	Air voids at bottom of HMA layer, %	AV	4.8	6	7.2
	Poisson ratio	PR	0.38	0.41	0.44
	Bulk specific gravity of aggregate.	Gbs	2.12	2.65	3.18

[a] Asphalt types are the same for all asphaltic layers (Surface, Binder and Base).

Table 7. Thicknesses of asphaltic layers and ranges for SA for Ho and Co regions under Low traffic category.

Layer type	Inputs	Abbr.	L (3-20) MESAL		
			Inputs values		
			-20%	Base	+20%
Surface layer	Layer thickness, cm	ASTH.	4	5	6
Binder layer	Layer thickness, cm	ABiTH.	5.6	7	8.4
Base layer	Layer thickness, cm	ABaTH.	6.4	8	9.6

Table 8. Asphaltic layers thicknesses and ranges for M-EDM SA for Ho and Co regions under Medium Traffic Category.

Layer type	Inputs	Abbreviations	M (45-100) MESAL Inputs values -20%	Base	+20%
Surface layer	Layer thickness, cm	ASTH.	4	5	6
Binder layer	Layer thickness, cm	ABiTH.	8	10	12
Base layer	Layer thickness, cm	ABaTH.	8.8	11	13.2

Table 9. Asphaltic Layers Thicknesses and ranges for M-EDM SA for Ho and Co regions under High traffic category.

Layer type	Inputs	Abbreviations	H (150-200) MESAL Inputs values -20%	Base	+20%
Surface layer	Layer thickness, cm	ASTH.	4	5	6
Binder layer	Layer thickness, cm	ABiTH.	9.6	12	14.4
Base layer	Layer thickness, cm	ABaTH.	11.2	14	16.8

3.1.1.3.2. Plant Mix Base PMB layer.

The properties of PMB layer used in the SA for all climate zones (Ho and Co) and under different traffic categories (H, M and L) are shown in Table 10.

Table 10. Plant Mix Base PMB layer properties and ranges for SA of Ho and Co regions under all traffic categories.

Layer type	Inputs	Abbreviations	All Traffic categories Inputs values -20%	Base	+20%
Plant Mix Base PMB layer	Layer thickness, cm	PMBTH.	16	20	24
	MR, Mpa	PMBMR	176.8	221	265.2
	Poisons ratio.	PMBPR.	0.29	0.36	0.43

3.1.1.3.3. Sub Base SB Layer

The properties of SB layer used in the SA for all climate zones (Ho and Co) and under different traffic categories (H, M and L) are shown in Table 11.

Table 11. Sub Base SB Layer Properties and ranges for M-EDM SA for Ho and Co regions for All Traffic Categories.

Layer type	Inputs	Abbreviations	All traffic categories Inputs values -20%	Base	+20%
Sub Base SB Layer	Layer thickness, cm	SBTH.	16	20	24
	MR, Mpa	SBMR	99.6	124.5	149.4
	Poisons ratio.	SBPR.	0.29	0.36	0.43

3.1.1.3.4. Sub Grade SG Layer

The properties of SG layer used in the SA for all climate zones (Ho and Co) and under different traffic categories (H, M and L) are shown in Table 12.

Table 12. Subgrade layer properties and ranges for M-EDM SA for Ho and Co regions for All Traffic Categories.

Layer type	Inputs	Abbreviations	All traffic categories		
			Inputs values		
			-20%	Base	+20%
Sub Base SB Layer	MR, Mpa	SGMR	48.8	61	73.2
	Poisons ratio.	SGPR.	0.26	0.32	0.38

4. RESULTS AND DISCUSSION

The results are discussed under each climate condition as in the following subsections.

4.1. Results of Cold Climate Condition

Afyon city was selected to represent cold climate condition in Turkey. MnPave design software was used for conducting the M-E analysis. The screenshot of the software is shown in Figure 3. MnPave software is used by the MDoT for the M-E design of flexile pavement. The M-EDM analysis is conducted using MnPave software for the determination of FL and RL of TTS under different traffic categories (L, M and H) for Base and Base +/-20% cases. Different methods are used to conduct SA as in the following subsections.

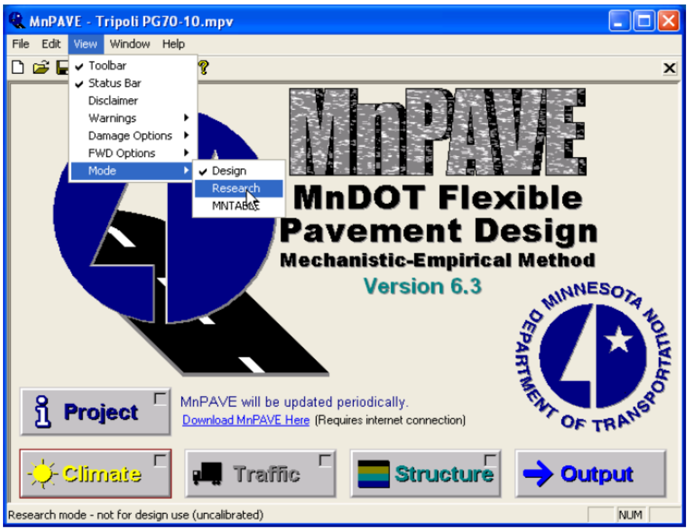

Figure 3. Screenshot of MnPave software.

4.1.1. Qualitative Sensitivity Analysis (Graphical Assessment Method)

The results of SA using graphical method under Light, Medium and High traffic conditions are shown in Figure 4 through 9.

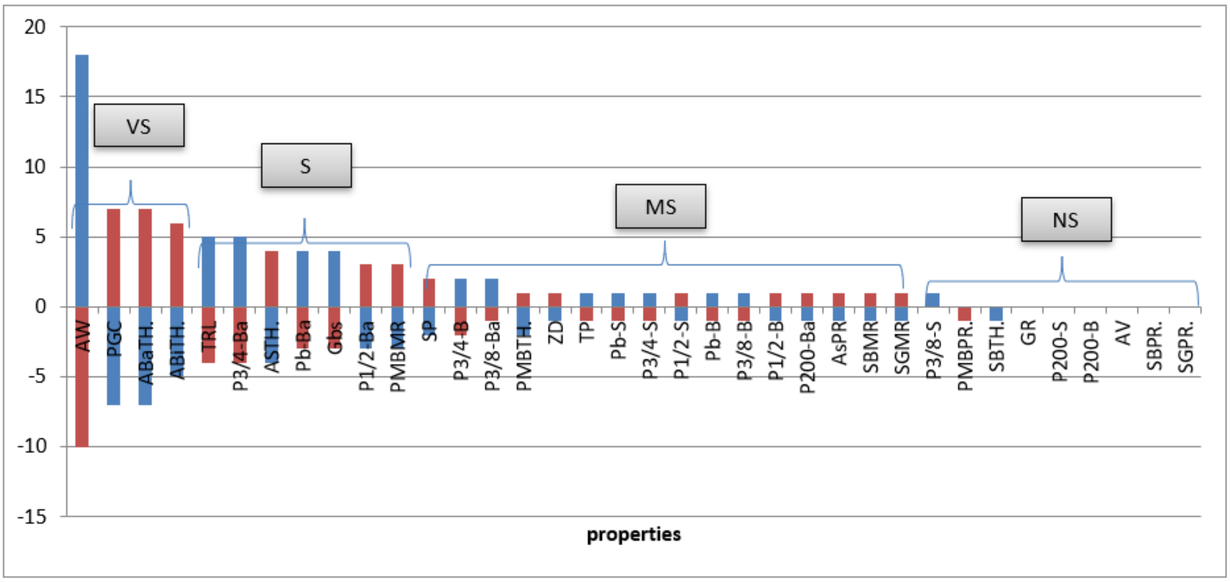

Figure 4. SA results under Light Traffic condition and Cold Climate for FL.

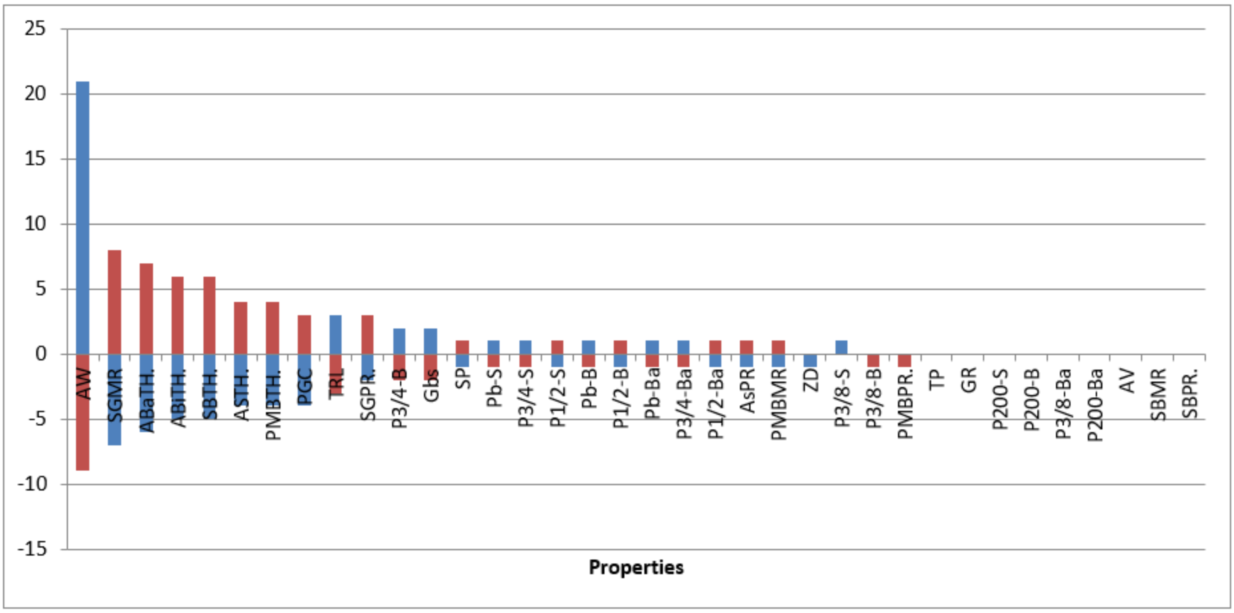

Figure 5. SA results under Light Traffic condition and Cold Climate for RL.

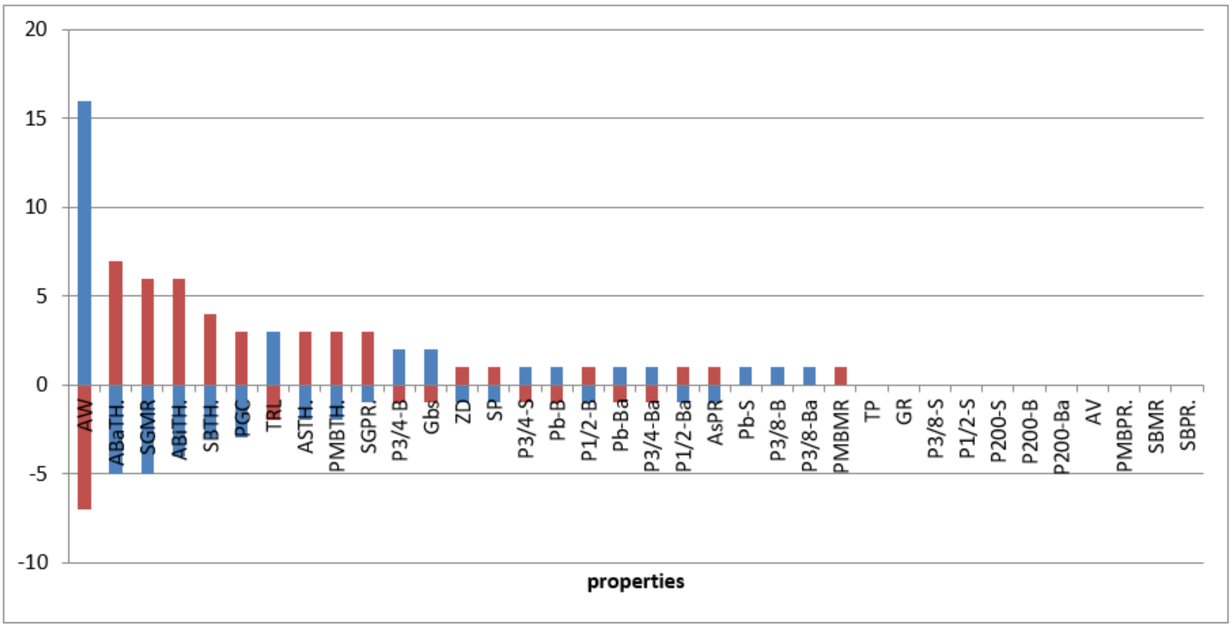

Figure 6. SA results under Medium Traffic condition and Cold Climate for RL.

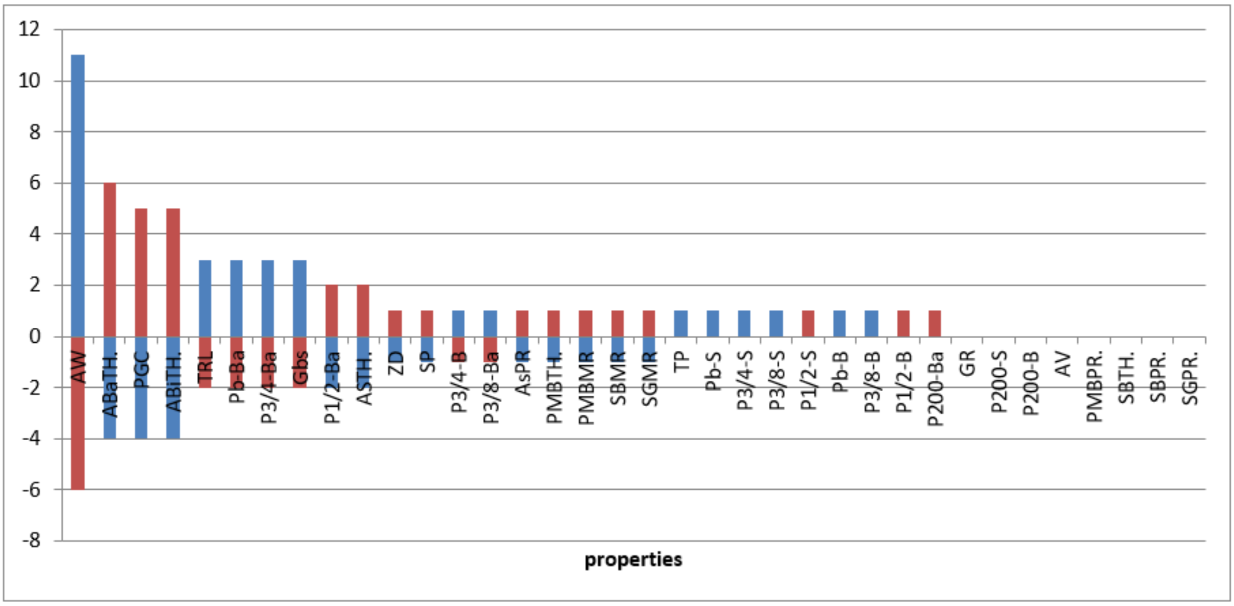

Figure 7. SA results under Medium Traffic condition and Cold Climate for FL.

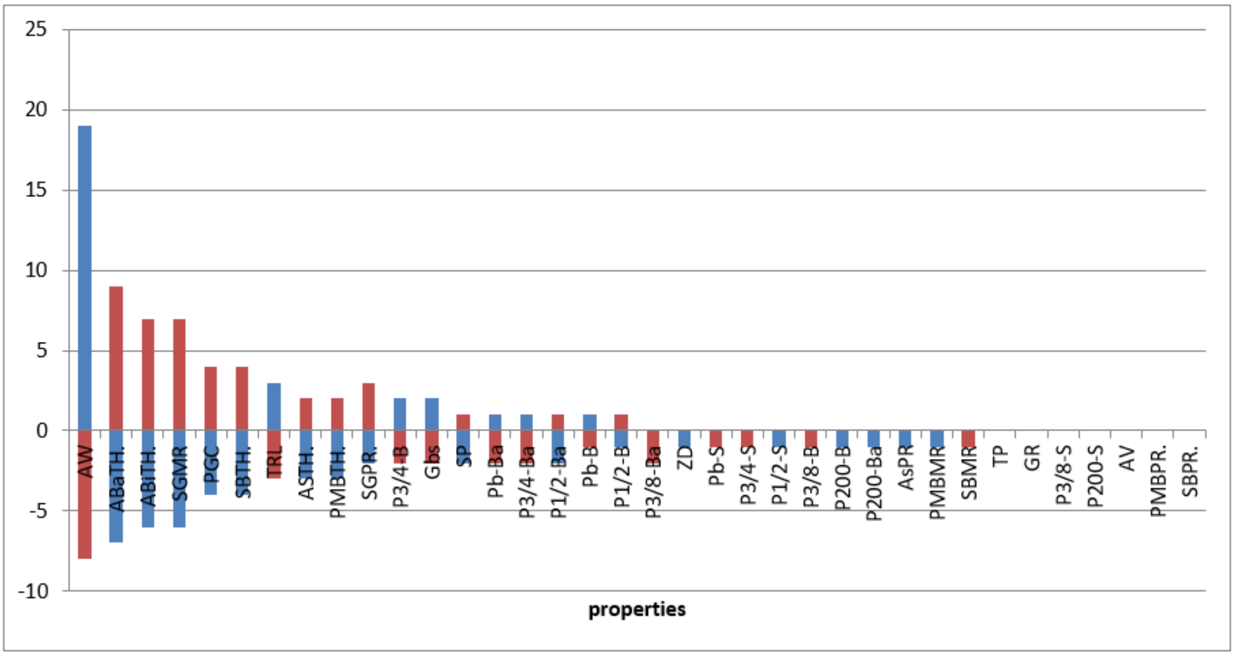

Figure 8. SA results under High Traffic condition and Cold Climate for RL.

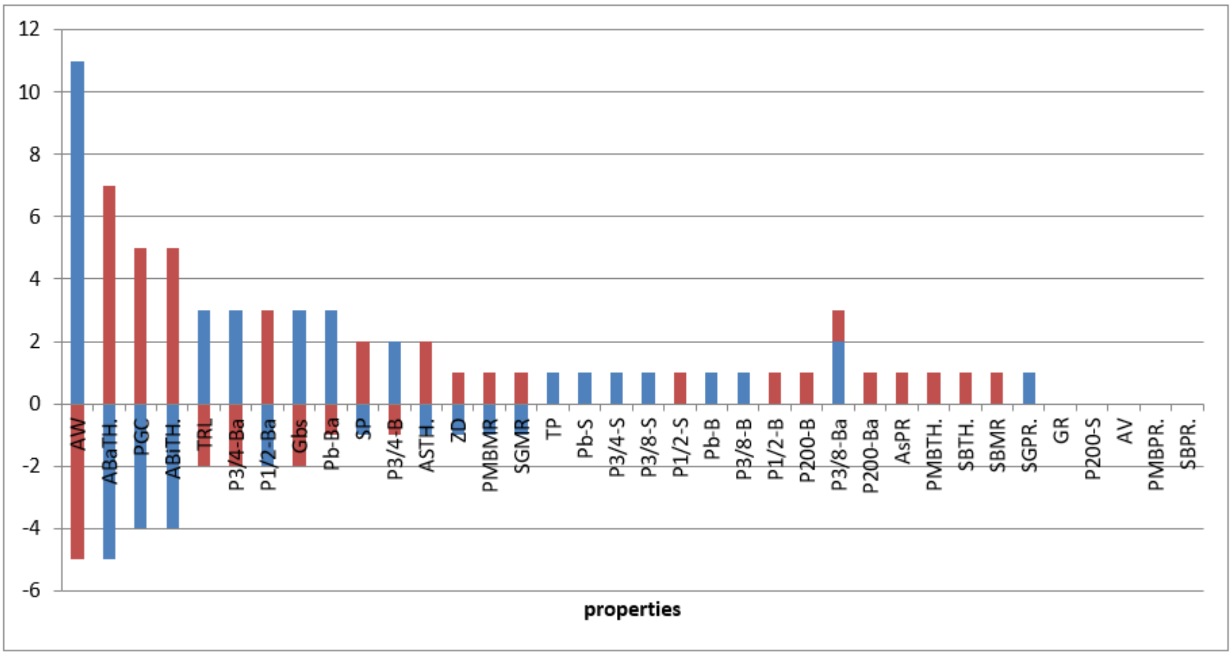

Figure 9. SA results under High Traffic condition and Cold Climate for FL.

The results of graphical method are classified graphically into, Very Sensitive (VS), Sensitive (S), Medium Sensitive (MS) and Non Sensitive (NS) as shown in Figure 4. To make a comparison between graphical method and other metrics of SA, the results are classified as shown in Tables 13 through 15.

Table 13. SA metrics of graphical method under Light traffic and Cold climate conditions for RL and FL

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
SGMR	VS	PGC	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	ABiTH.	VS
SBTH.	VS	TRL	S
ASTH.	S	P3/4-Ba	S
PMBTH.	S	ASTH.	S
PGC	S	Pb-Ba	S
TRL	S	Gbs	S
SGPR.	S	P1/2-Ba	S
P3/4-B	S	PMBMR	S
Gbs	S	SP	MS
SP	MS	P3/4-B	MS
Pb-S	MS	P3/8-Ba	MS
P3/4-S	MS	PMBTH.	MS
P1/2-S	MS	ZD	MS
Pb-B	MS	TP	MS
P1/2-B	MS	Pb-S	MS
Pb-Ba	MS	P3/4-S	MS
P3/4-Ba	MS	P1/2-S	MS
P1/2-Ba	MS	Pb-B	MS
AsPR	MS	P3/8-B	MS
PMBMR	MS	P1/2-B	MS
ZD	NS	P200-Ba	MS
P3/8-S	NS	AsPR	MS
P3/8-B	NS	SBMR	MS
PMBPR.	NS	SGMR	MS
TP	NS	P3/8-S	NS
GR	NS	PMBPR.	NS
P200-S	NS	SBTH.	NS
P200-B	NS	GR	NS
P3/8-Ba	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 14. SA metrics of graphical method under Medium traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
SGMR	VS	PGC	VS
ABiTH.	VS	ABiTH.	VS
SBTH.	VS	TRL	S
PGC	S	Pb-Ba	S
TRL	S	P3/4-Ba	S
ASTH.	S	Gbs	S
PMBTH.	S	P1/2-Ba	S
SGPR.	S	ASTH.	S
P3/4-B	S	ZD	MS
Gbs	S	SP	MS
ZD	MS	P3/4-B	MS
SP	MS	P3/8-Ba	MS
P3/4-S	MS	AsPR	MS
Pb-B	MS	PMBTH.	MS
P1/2-B	MS	PMBMR	MS
Pb-Ba	MS	SBMR	MS
P3/4-Ba	MS	SGMR	MS
P1/2-Ba	MS	TP	MS
AsPR	MS	Pb-S	MS
Pb-S	MS	P3/4-S	MS
P3/8-B	MS	P3/8-S	MS
P3/8-Ba	MS	P1/2-S	MS
PMBMR	MS	Pb-B	MS
TP	NS	P3/8-B	MS
GR	NS	P1/2-B	MS
P3/8-S	NS	P200-Ba	MS
P1/2-S	NS	GR	NS
P200-S	NS	P200-S	NS
P200-B	NS	P200-B	NS
P200-Ba	NS	AV	NS
AV	NS	PMBPR.	NS
PMBPR.	NS	SBTH.	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 15. SA metrics of graphical method under High traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	PGC	VS
SGMR	VS	ABiTH.	VS
PGC	S	TRL	S
SBTH.	S	P3/4-Ba	S
TRL	S	P1/2-Ba	S
ASTH.	S	Gbs	S
PMBTH.	S	Pb-Ba	S
SGPR.	S	SP	S
P3/4-B	S	P3/4-B	S
Gbs	S	ASTH.	S
SP	S	ZD	MS
Pb-Ba	S	PMBMR	MS
P3/4-Ba	S	SGMR	MS
P1/2-Ba	S	TP	MS
Pb-B	S	Pb-S	MS
P1/2-B	S	P3/4-S	MS
P3/8-Ba	S	P3/8-S	MS
ZD	MS	P1/2-S	MS
Pb-S	MS	Pb-B	MS
P3/4-S	MS	P3/8-B	MS
P1/2-S	MS	P1/2-B	MS
P3/8-B	MS	P200-B	MS
P200-B	MS	P3/8-Ba	MS
P200-Ba	NS	P200-Ba	MS
AsPR	NS	AsPR	MS
PMBMR	NS	PMBTH.	MS
SBMR	NS	SBTH.	MS
TP	NS	SBMR	MS
GR	NS	SGPR.	MS
P3/8-S	NS	GR	NS
P200-S	NS	P200-S	NS
AV	NS	AV	NS
PMBPR.	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

Under Low, Medium and High traffic conditions and according to the results of RL, SA metrics obtained from graphical method show that each of AW, ABaTH, ABiTH, SBTH and SGMR are VS and each one of them can alter the RL of pavement significantly. On the other hand, for the same traffic condition and for FL, results show that each of AW, ABaTH, ABiTH and PGC are VS and can change the FL of pavement dramatically.

The VS factors mentioned previously need to be considered carefully. Axle Weight AW can be controlled by reducing the number of overloaded axles passing the highway, while suitable selection of the thicknesses of Asphalt Base layer ABaTH, Asphaltic Binder layer ABiTH and Subbase layer SBTH is recommended when designing of pavement section. Subgrade Resilient Modulus SGMR is very important, so that it is recommended that laboratory tests should be conducted for determination of SGMR. The results show that asphalt grade PG is VS, so that asphalt type should be selected carefully using SuperPave tests.

Other properties such as TRL, ASTH, PMBTH, SGPR, Gbs and SP as well as the volumetric properties of asphaltic Base layer (e.g. P3/4-Ba and P1/2-Ba) can be considered S.

It is prefer to ensure that suitable method is used to conduct Traffic Survey for the determination of traffic loadings TRL. Subgrade Poisson Ratio SGPR is also S and it is recommended to be tested using triaxial test. The effect of vehicle speed SP is associated with high traffic loadings only and caused a considerable effect on RL and FL.

4.1.2. Quantitative Sensitivity Analysis

This method consists of two methods, NSI and DSI. The results of NSI and DSI are discussed in the following subsections.

4.1.2.1. Normalized Sensitivity Index NSI Results.

The results of SA using this method is based on mathematical solution rather than qualitative assessment, therefore it is expected that the results are more reasonable and comparable.

The results of SA using NSI metric and under Light, Medium and High traffic conditions are shown in Tables 16 through 18.

Table 16. Results of SA using NSI metric under Low traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
SGMR	VS	ABaTH.	VS
ABaTH.	VS	ABiTH.	VS
SBTH.	VS	P3/4-Ba	VS
ABiTH.	VS	TRL	VS
ASTH.	S	ASTH.	S
PMBTH.	S	Gbs	S
TRL	S	Pb-Ba	S
AsPR	S	PMBMR	S
SGPR.	S	P1/2-Ba	S
P3/4-B	S	PGC	S
Gbs	S	AsPR	S
PGC	MS	P3/4-B	S
P3/4-S	MS	SP	S
P3/4-Ba	MS	P3/8-Ba	MS
Pb-S	MS	PMBTH.	MS
P1/2-Ba	MS	TP	MS
PMBMR	MS	P3/4-S	MS
P1/2-S	MS	Pb-S	MS
SP	MS	P3/8-B	MS
Pb-B	MS	P1/2-S	MS
Pb-Ba	MS	Pb-B	MS
P1/2-B	MS	P200-Ba	MS
P3/8-S	MS	SBMR	MS
PMBPR.	MS	SGMR	MS
P3/8-B	MS	P1/2-B	MS
ZD	NS	P3/8-S	MS
TP	NS	PMBPR.	MS
GR	NS	SBTH.	MS
P200-S	NS	ZD	MS
P200-B	NS	GR	NS
P3/8-Ba	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 17. Results of SA using NSI metric under Medium traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
SGMR	VS	ABiTH.	VS
ABiTH.	VS	AsPR	S
SBTH.	S	P3/4-Ba	S
AsPR	S	TRL	S
TRL	S	Gbs	S
ASTH.	S	Pb-Ba	S
PMBTH.	S	P1/2-Ba	S
SGPR.	S	ASTH.	S
P3/4-B	MS	PGC	MS
Gbs	MS	P3/8-Ba	MS
PGC	MS	P3/4-B	MS
P3/4-S	MS	PMBMR	MS
P3/4-Ba	MS	SP	MS
P1/2-Ba	MS	PMBTH.	MS
SP	MS	SBMR	MS
Pb-B	MS	SGMR	MS
Pb-Ba	MS	P3/8-S	MS
P1/2-B	MS	TP	MS
P3/8-Ba	MS	P3/4-S	MS
Pb-S	MS	Pb-S	MS
P3/8-B	MS	P3/8-B	MS
PMBMR	MS	P1/2-S	MS
ZD	MS	Pb-B	MS
TP	NS	P200-Ba	MS
GR	NS	P1/2-B	MS
P3/8-S	NS	ZD	MS
P1/2-S	NS	GR	NS
P200-S	NS	P200-S	NS
P200-B	NS	P200-B	NS
P200-Ba	NS	AV	NS
AV	NS	PMBPR.	NS
PMBPR.	NS	SBTH.	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 18. Results of SA using NSI metric under High traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	ABiTH.	VS
SGMR	VS	P3/4-Ba	S
SBTH.	S	P1/2-Ba	S
TRL	S	TRL	S
SGPR.	S	Gbs	S
ASTH.	S	Pb-Ba	S
PMBTH.	S	PGC	MS
P3/4-B	S	P3/4-B	MS
Gbs	S	SP	MS
PGC	MS	ASTH.	MS
P3/4-Ba	MS	AsPR	MS
P1/2-Ba	MS	PMBMR	MS
SP	MS	SGMR	MS
Pb-Ba	MS	P3/8-S	MS
AsPR	MS	P3/8-Ba	MS
P3/8-Ba	MS	SGPR.	MS
Pb-B	MS	TP	MS
P1/2-B	MS	P3/4-S	MS
P3/4-S	MS	Pb-S	MS
Pb-S	MS	P3/8-B	MS
P3/8-B	MS	P1/2-S	MS
PMBMR	MS	Pb-B	MS
P1/2-S	MS	PMBTH.	MS
P200-B	MS	SBTH.	MS
P200-Ba	MS	P200-B	MS
SBMR	MS	P200-Ba	MS
ZD	NS	SBMR	MS
TP	NS	P1/2-B	MS
GR	NS	ZD	MS
P3/8-S	NS	GR	NS
P200-S	NS	P200-S	NS
AV	NS	AV	NS
PMBPR.	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

The results of NSI revealed that the RL is VS to ABaTH, ABiTH, SGMR and AW, while S to SBTH, TRL, SGPR, PMBTH, ASTH, PMBTH and some volumetric properties of Binder layer. FL was VS to ABaTH, ABiTH and AW especially at high traffic loading but it was S to SBTH, TRL, SGPR, PMBTH a some volumetric properties of Base layer. It was surprisingly that FL eas S to AsPR.

4.1.2.2. Distance Sensitivity Index DSI Results.

As in NSI metric, the results of SA using DSI metric are based on mathematical solution rather than qualitative assessment as explained previously. It is expected that the results are similar to NSI metric.

The results of SA using DSI metric under Light, Medium and High traffic conditions are shown in Tables 19 through 21.

Table 19. Results of SA using DSI metric under Low traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
SGMR	VS	PGC	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	ABiTH.	VS
SBTH.	VS	TRL	VS
ASTH.	VS	P3/4-Ba	VS
PMBTH.	VS	ASTH.	VS
PGC	S	Pb-Ba	S
TRL	S	Gbs	S
SGPR.	S	P1/2-Ba	S
P3/4-B	S	PMBMR	S
Gbs	S	SP	S
SP	MS	P3/4-B	S
Pb-S	MS	P3/8-Ba	S
P3/4-S	MS	PMBTH.	S
P1/2-S	MS	ZD	MS
Pb-B	MS	TP	MS
P1/2-B	MS	Pb-S	MS
Pb-Ba	MS	P3/4-S	MS
P3/4-Ba	MS	P1/2-S	MS
P1/2-Ba	MS	Pb-B	MS
AsPR	MS	P3/8-B	MS
PMBMR	MS	P1/2-B	MS
ZD	MS	P200-Ba	MS
P3/8-S	MS	AsPR	MS
P3/8-B	MS	SBMR	MS
PMBPR.	MS	SGMR	MS
TP	NS	P3/8-S	MS
GR	NS	PMBPR.	MS
P200-S	NS	SBTH.	MS
P200-B	NS	GR	NS
P3/8-Ba	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 20. Results of SA using DSI metric under Medium traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index RL	Property	Sensitivity index FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
SGMR	VS	PGC	VS
ABiTH.	VS	ABiTH.	VS
SBTH.	S	TRL	S
PGC	S	Pb-Ba	S
TRL	S	P3/4-Ba	S
ASTH.	S	Gbs	S
PMBTH.	S	P1/2-Ba	S
SGPR.	S	ASTH.	S
P3/4-B	S	ZD	MS
Gbs	S	SP	MS
ZD	MS	P3/4-B	MS
SP	MS	P3/8-Ba	MS
P3/4-S	MS	AsPR	MS
Pb-B	MS	PMBTH.	MS
P1/2-B	MS	PMBMR	MS
Pb-Ba	MS	SBMR	MS
P3/4-Ba	MS	SGMR	MS
P1/2-Ba	MS	TP	MS
AsPR	MS	Pb-S	MS
Pb	MS	P3/4-S	MS
P3/8-B	MS	P3/8-S	MS
P3/8-Ba	MS	P1/2-S	MS
PMBMR	MS	Pb-B	MS
TP	NS	P3/8-B	MS
GR	NS	P1/2-B	MS
P3/8-S	NS	P200-Ba	MS
P1/2-S	NS	GR	NS
P200-S	NS	P200-S	NS
P200-B	NS	P200-B	NS
P200-Ba	NS	AV	NS
AV	NS	PMBPR.	NS
PMBPR.	NS	SBTH.	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 21. Results of SA using DSI metric under High traffic and Cold climate conditions for RL and FL.

Property	Sensitivity index RL	Property	Sensitivity index FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	PGC	VS
SGMR	VS	ABiTH.	VS
PGC	VS	TRL	S
SBTH.	VS	P3/4-Ba	S
TRL	S	P1/2-Ba	S
ASTH.	S	Gbs	S
PMBTH.	S	Pb-Ba	S
SGPR.	S	SP	S
P3/4-B	S	P3/4-B	S
Gbs	S	P3/8-Ba	S
SP	S	ASTH.	S
Pb-Ba	S	ZD	MS
P3/4-Ba	S	PMBMR	MS
P1/2-Ba	S	SGMR	MS
P3/8-Ba	MS	TP	MS
Pb-B	MS	Pb-S	MS
P1/2-B	MS	P3/4-S	MS
ZD	MS	P3/8-S	MS
Pb-S	MS	P1/2-S	MS
P3/4-S	MS	Pb-B	MS
P1/2-S	MS	P3/8-B	MS
P3/8-B	MS	P1/2-B	MS
P200-B	MS	P200-B	MS
P200-Ba	MS	P200-Ba	MS
AsPR	MS	AsPR	MS
PMBMR	MS	PMBTH.	MS
SBMR	MS	SBTH.	MS
TP	NS	SBMR	MS
GR	NS	SGPR.	MS
P3/8-S	NS	GR	NS
P200-S	NS	P200-S	NS
AV	NS	AV	NS
PMBPR.	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

It can be noted that, DSI metric has the ability to differentiate between the effect of different traffic loading conditions on the results of SA. Under Low traffic loading and based on the results of RL, all layers thicknesses, AW and SGMR were VS. Asphalt grade PG and TRL were also VS according to FL results. When traffic loading is Medium, RL was VS to ABaTH, ABiTH, AW and SGMR, while it was S to PG, TRL, PMBTH, SBTH, SP and some volumetric properties of Binder layer. The results show that FL was VS to ABaTH, ABiTH, AW and PG.

On the other hand, FL was S to TRL and some volumetric properties of Base layer. Under High traffic condition and for RL, the result were similar to that of Medium traffic condition. Layers thicknesses, AW and SGMR were VS which is the same as in the case of Low traffic condition, while it was S to some of volumetric properties of Binder layer, PMBTH, TRL and ASTH. The results show that FL was VS to ABaTH, ABiTH, AW and PG while it was S to some of volumetric properties of Base layer, SP, TRL and ASTH.

Summary of the results:

The results of SA under cold climate condition and according to the results of RL can be summarized in the followings:

1- Under L and M traffic conditions:
   a) It can be seen that AW and Layers thicknesses (e.g. ABaTH and ABiTH) were S and VS. High AW and low thicknesses of layers due to poor design decreased the RL of pavement. There is a need for the improvement of flexible pavement design method and enhance the monitoring system of axel weight in highways.
   b) It is also found that RL is S to PG of asphalt. Higher PG can increase the RL significantly. A special consideration must be paid when selecting type of asphalt.
   c) RL is also S to TRL. Higher traffic loadings can increase the deterioration of pavement structure in the form of rutting.
   d) It was surprising that RL is S to Poisson Ratio PR of asphalt and Subgrade. This agreed with the findings of different researches in the literature. It could be associated with high flexibility of pavements layers thus low RL.
2- Under H traffic conditions:
   The result was similar to the results of L and M traffic loadings. It is also discovered that pavement RL is S to the properties of Base layer (e.g. P3/4-Ba and Pb-Ba). High traffic loadings can increase the vertical stresses on Base layer. That can increase the vertical stresses on the subgrade layer and can increase rutting potential.
3- It is found that the number of S and VS parameters using Graphical method is higher than that using NSI and DSI metrics. This can be due to the difficulty associated with graphical differentiation between the sensitivity of parameters.
4- The results revealed that the result using DSI metric was similar to NSI metric under L and M traffic conditions, while it was similar to the Graphical method under H traffic condition. It can be assumed that DSI metric can be considered the solution for the differences between graphical and NSI methods.

The results of SA under cold climate condition and according to FL can be summarized in the followings

1- Under H, M and L traffic conditions:
   a) It can be seen that AW and Layers thicknesses (e.g. ABaTH and ABiTH) were VS and S. High AW and low thicknesses of layers due to poor design decreased the RL of pavement. There is a need for the improvement of flexible pavement design method and enhance the monitoring system of axel weight in highways.
   b) It is also found that the pavement is S to the PG of asphalt. Higher PG can increase the FL significantly. A special consideration must be paid when selecting the appropriate type of asphalt that can decrease the tensile strain at the bottom of asphalt layer.
   c) Pavement was also S to TRL and the speed SP of vehicles. Higher traffic loadings with low traffic speed induce higher tensile strains at the bottom of asphalt layers. This can increase the deterioration of pavement structure in the form of fatigue cracking.
   d) The FL is also S to the properties of asphaltic Base layer (e.g. P3/4-Ba and Pb-Ba) where the tensile strains accrue.
   e) It was found that the FL is S to M_R of PMB. The PMB layer is the base of asphaltic layers where the tensile strains take place. The strength of this layer can increase the FL of pavement.

f) As expected, the FL of pavement was S to the thickness of asphalt layer ASTH. Sufficient thickness of asphaltic layer can increase the FL significantly. The selection of appropriate thickness is related to the design method that need to be enhanced.

2- It is found that the number of S and VS parameters found using different methods (i.e. Graphical, NSI and DSI methods) are different under different traffic conditions.

4.2. Results of Hot Climate Condition

Antalya city was selected to represent hot climate condition in Turkey. M-EDM analysis was conducted using MnPave software for the determination of FL and RL of TTS under different traffic categories (L, M and H) for Base and Base+/-20% cases. Different methods were used to conduct SA as in the following subsections.

4.2.1. Results of Qualitative (Graphical Assessment Method)

The results of SA using graphical method under Light, Medium and High traffic conditions are shown in Figures 10 through 15.

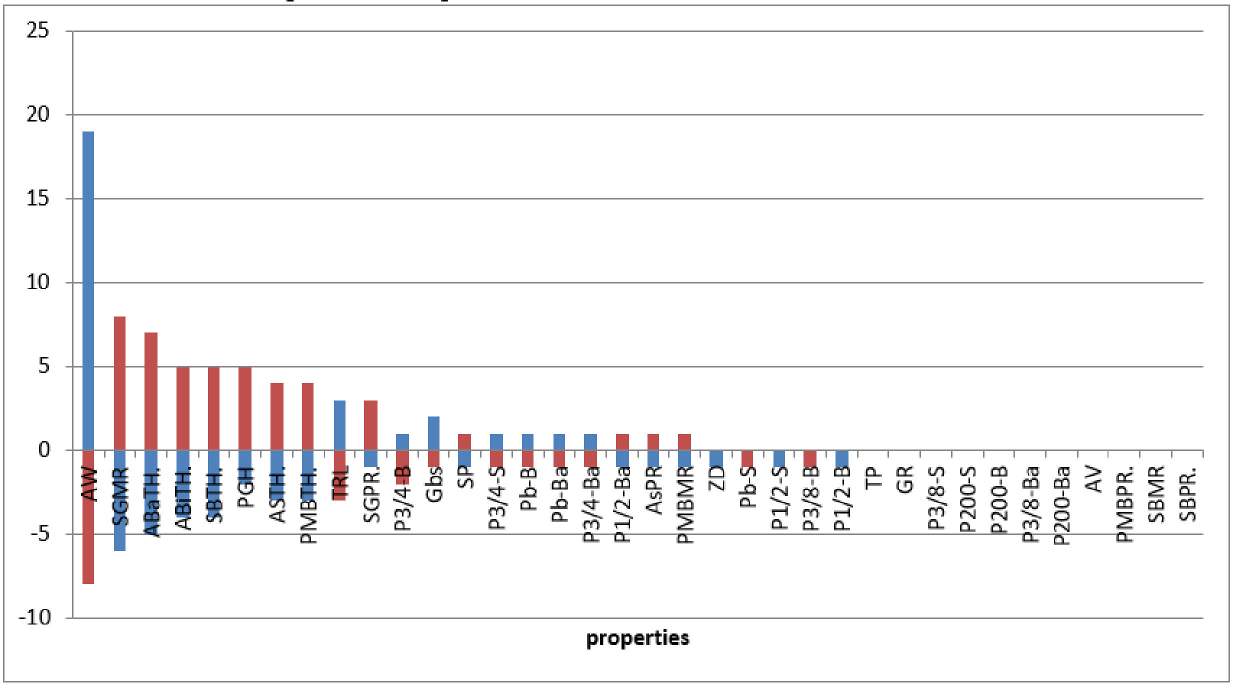

Figure 10. Results of SA under Low Traffic condition and Hot Climate using RL.

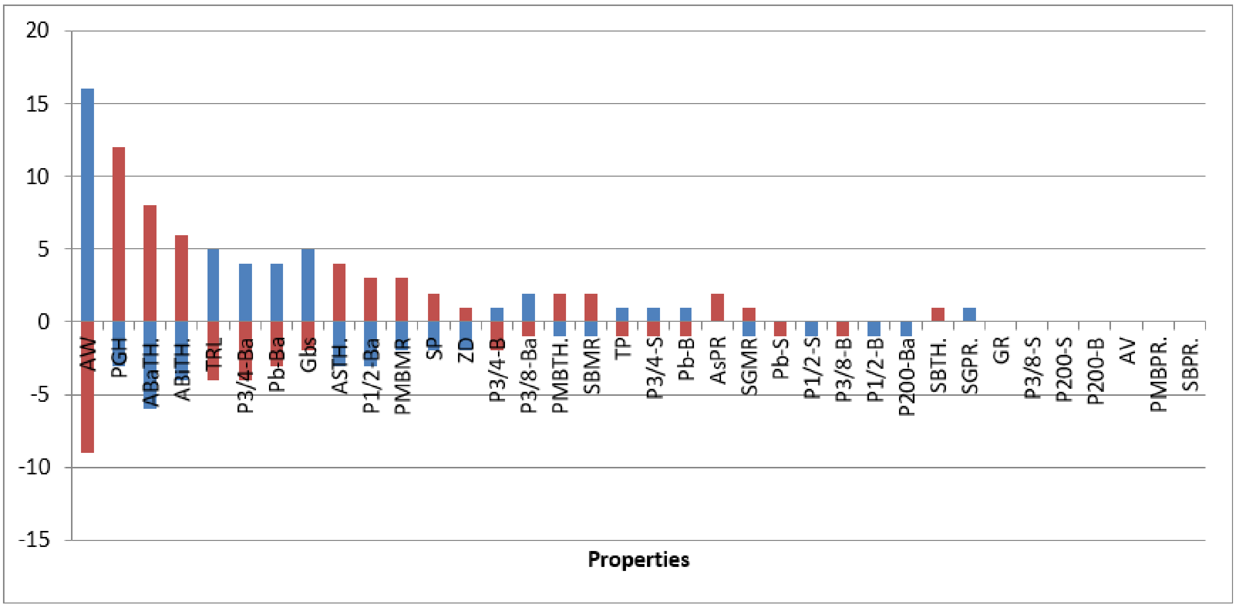

Figure 11. Results of SA under Low Traffic condition and Hot Climate using FL.

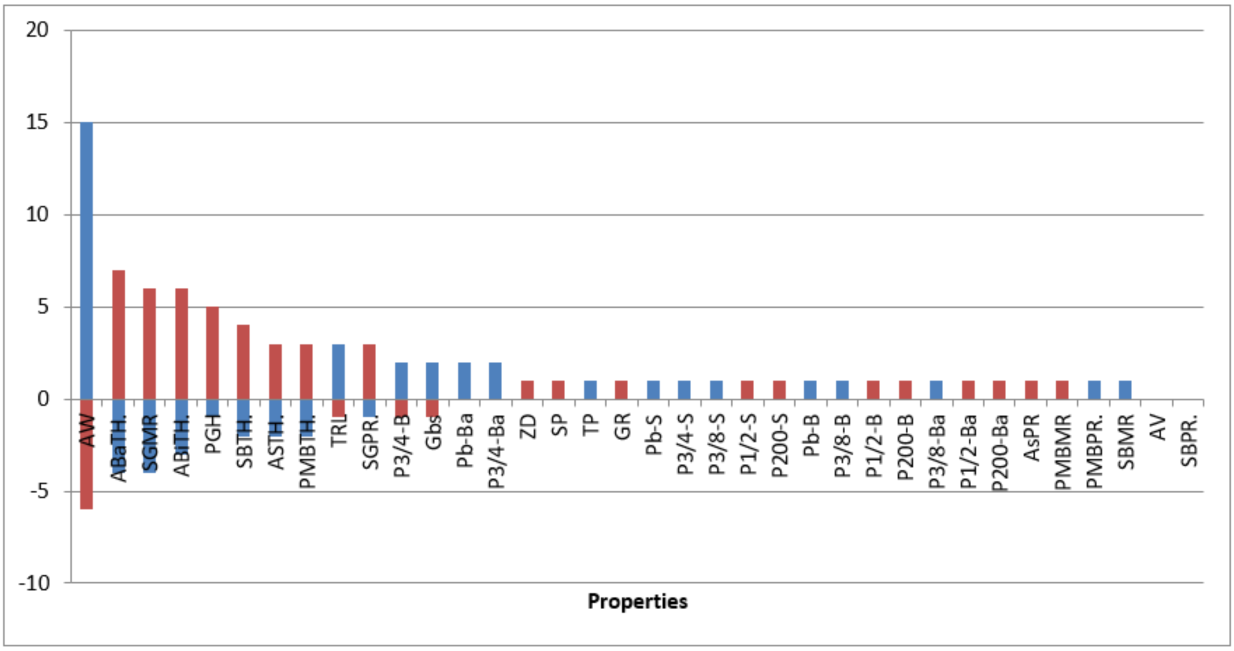

Figure 12. Results of SA under Medium Traffic condition and Hot Climate using RL.

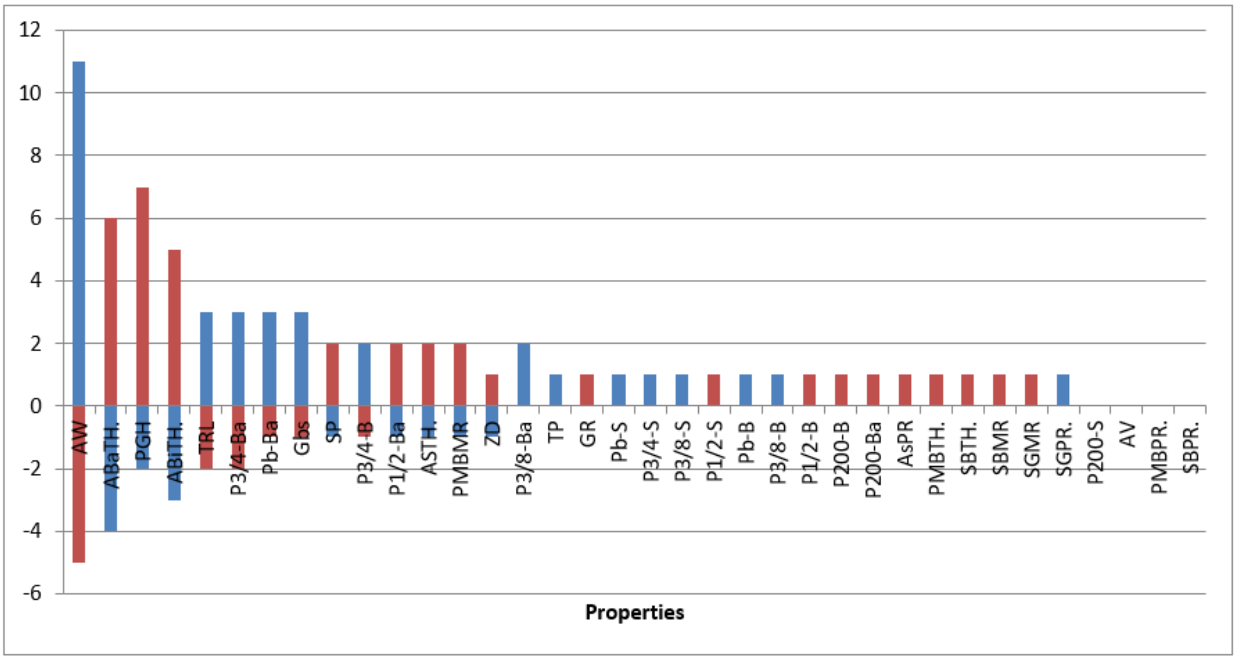

Figure 13. Results of SA under Medium Traffic condition and Hot Climate using FL.

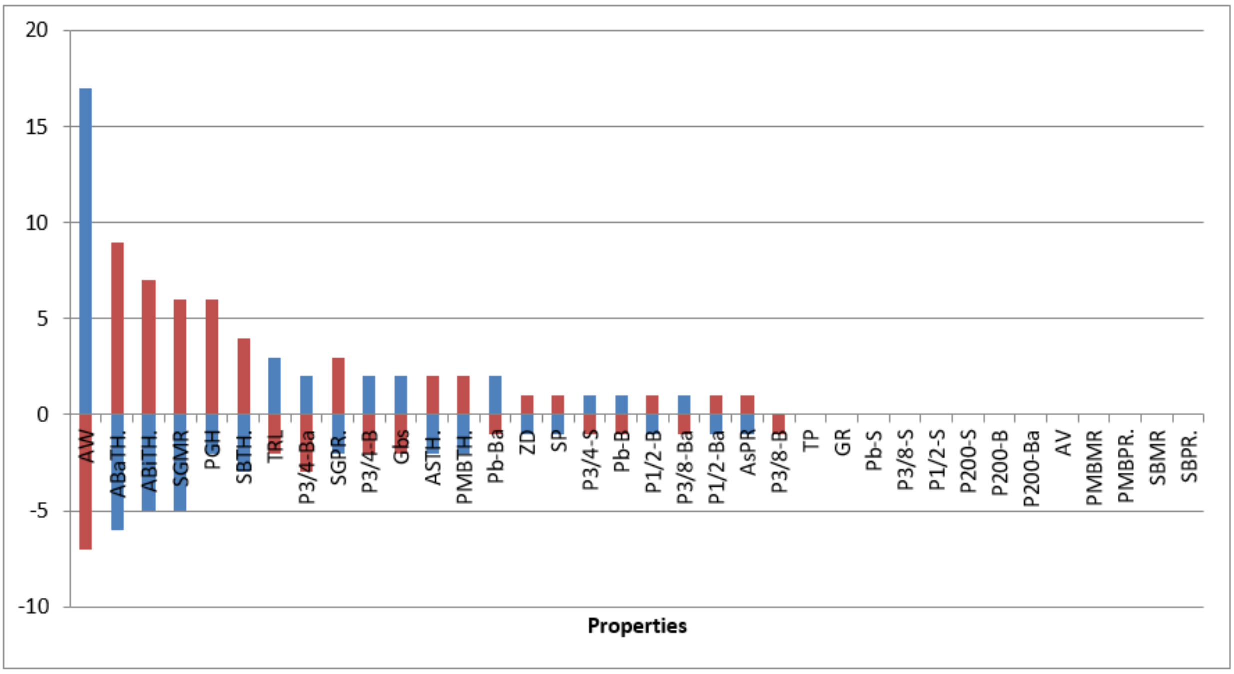

Figure 14. Results of SA under High Traffic condition and Hot Climate using RL.

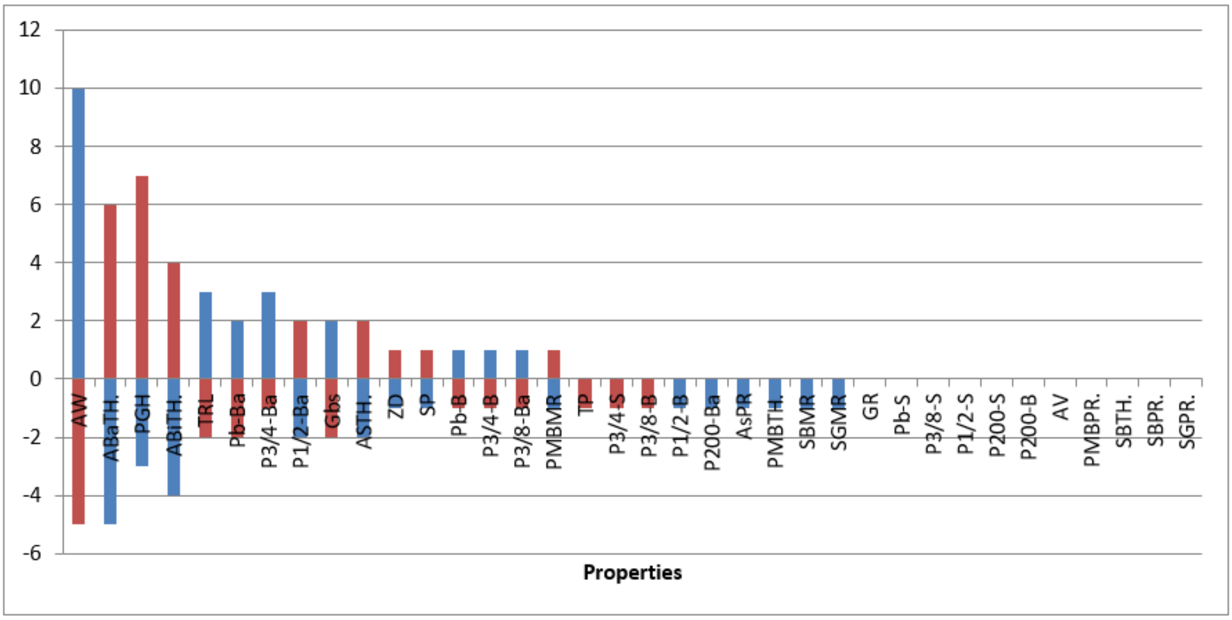

Figure 15. Results of SA under High Traffic condition and Hot Climate using FL.

To make a comparison between Graphical method and other NSI and DSI metrics, SA results of graphical method are classified under (VS, S, MS and NS) categories. The results are shown in Tables 22 through 24.

Table 22. SA results of graphical method under Light traffic and Hot climate conditions using RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
SGMR	VS	PGH	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	S	ABiTH.	VS
SBTH.	S	TRL	S
ASTH.	S	P3/4-Ba	S
PMBTH.	S	ASTH.	S
PGH	S	Pb-Ba	S
TRL	S	Gbs	S
SGPR.	MS	P1/2-Ba	S
P3/4-B	MS	PMBMR	S
Gbs	MS	SP	MS
SP	MS	P3/4-B	MS
Pb-S	MS	P3/8-Ba	MS
P3/4-S	MS	PMBTH.	MS
P1/2-S	MS	ZD	MS
Pb-B	MS	TP	MS
P1/2-B	MS	Pb-S	MS
Pb-Ba	MS	P3/4-S	NS
P3/4-Ba	MS	P1/2-S	NS
P1/2-Ba	MS	Pb-B	NS
AsPR	MS	P3/8-B	NS
PMBMR	MS	P1/2-B	NS
ZD	NS	P200-Ba	NS
P3/8-S	NS	AsPR	NS
P3/8-B	NS	SBMR	NS
PMBPR.	NS	SGMR	NS
TP	NS	P3/8-S	NS
GR	NS	PMBPR.	NS
P200-S	NS	SBTH.	NS
P200-B	NS	GR	NS
P3/8-Ba	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Table 23. SA results of graphical method under Medium traffic and Hot climate conditions using RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
SGMR	VS	PGH	VS
ABiTH.	VS	ABiTH.	VS
PGH	S	TRL	S
SBTH.	S	P3/4-Ba	S
ASTH.	S	Pb-Ba	S
PMBTH.	S	Gbs	S
TRL	MS	SP	MS
SGPR.	MS	P3/4-B	MS
P3/4-B	MS	P1/2-Ba	MS
Gbs	MS	ASTH.	MS
Pb-Ba	MS	PMBMR	MS
P3/4-Ba	MS	ZD	MS
ZD	MS	P3/8-Ba	MS
SP	NS	TP	NS
TP	NS	GR	NS
GR	NS	Pb-S	NS
Pb-S	NS	P3/4-S	NS
P3/4-S	NS	P3/8-S	NS
P3/8-S	NS	P1/2-S	NS
P1/2-S	NS	Pb-B	NS
P200-S	NS	P3/8-B	NS
Pb-B	NS	P1/2-B	NS
P3/8-B	NS	P200-B	NS
P1/2-B	NS	P200-Ba	NS
P200-B	NS	AsPR	NS
P3/8-Ba	NS	PMBTH.	NS
P1/2-Ba	NS	SBTH.	NS
P200-Ba	NS	SBMR	NS
AsPR	NS	SGMR	NS
PMBMR	NS	SGPR.	NS
PMBPR.	NS	P200-S	NS
SBMR	NS	AV	NS
AV	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

Table 24. SA results of graphical method under High traffic and Hot climate conditions using RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	PGH	VS
SGMR	VS	ABiTH.	VS
PGH	VS	TRL	S
SBTH.	VS	Pb-Ba	S
TRL	S	P3/4-Ba	S
P3/4-Ba	S	P1/2-Ba	S
SGPR.	S	Gbs	S
P3/4-B	S	ASTH.	S
Gbs	S	ZD	MS
ASTH.	S	SP	MS
PMBTH.	S	Pb-B	MS
Pb-Ba	MS	P3/4-B	MS
ZD	MS	P3/8-Ba	MS
SP	MS	PMBMR	MS
P3/4-S	MS	TP	NS
Pb-B	MS	P3/4-S	NS
P1/2-B	MS	P3/8-B	NS
P3/8-Ba	MS	P1/2-B	NS
P1/2-Ba	MS	P200-Ba	NS
AsPR	MS	AsPR	NS
P3/8-B	NS	PMBTH.	NS
TP	NS	SBMR	NS
GR	NS	SGMR	NS
Pb-S	NS	GR	NS
P3/8-S	NS	Pb-S	NS
P1/2-S	NS	P3/8-S	NS
P200-S	NS	P1/2-S	NS
P200-B	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
PMBMR	NS	PMBPR.	NS
PMBPR.	NS	SBTH.	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Under Low traffic conditions and according to the results of RL, SA metrics obtained from graphical method show that RL was VS to AW, ABaTH, ABiTH and SGMR. While it was S to ASTH, ABiTH, TRL, PMBTH and PGH. On the other hand, for the same traffic condition, FL was VS to AW, ABaTH, ABiTH and PGH. FL was S to ASTH, TRL, PMBMR and some volumetric properties of Base layer.

Under Medium traffic conditions, it can be noted that RL was VS to AW, ABaTH, ABiTH and SGMR. While it was S to ASTH, TRL, PMBTH and PGH. On the other hand, FL was VS to AW, ABaTH, ABiTH and PG. FL was S to TRL and some volumetric properties of Base layer.

Under High traffic conditions, RL was VS to AW, ABaTH, ABiTH, ASTH, PG and SGMR. While it was S to ASTH, SGPR, TRL, PMBTH and some volumetric properties of Base and Binder layers. On the other hand, for the same traffic condition, FL was VS to AW, ABaTH, ABiTH and PG. FL was S to ASTH and some volumetric properties of Base layer.

4.2.2. Quantitative Sensitivity Analysis

There are two metrics. NSI and DSI. The results are discussed in the following subsections.

4.2.2.1. Normalized Sensitivity Index NSI Results.

The results of SA using NSI metric and under Light, Medium and High traffic conditions are shown in Tables 25 through 27.

Table 25. Results of NSI under Low traffic and Hot climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
SGMR	VS	ABaTH.	VS
ABaTH.	VS	ABiTH.	VS
SBTH.	VS	TRL	VS
ABiTH.	VS	P3/4-Ba	VS
ASTH.	S	ASTH.	S
PMBTH.	S	Gbs	S
TRL	S	Pb-Ba	S
AsPR	S	P1/2-Ba	S
SGPR.	S	PGH	S
PGH	MS	AsPR	S
P3/4-B	MS	PMBMR	S
Gbs	MS	SP	S
P3/4-Ba	MS	P3/8-Ba	MS
P3/4-Ba	MS	P3/4-B	MS
P1/2-S	MS	PMBTH.	MS
PMBMR	MS	SBMR	MS
SP-B	MS	TP	MS
Pb-Ba	MS	P3/4-S	MS
Pb-S	MS	Pb-B	MS
Pb-B	MS	SGMR	MS
P3/8-S	MS	ZD	MS
P1/2-B	MS	SGPR.	MS
P1/2-Ba	NS	P3/8-B	MS
ZD	NS	Pb-S	MS
TP	NS	P1/2-S	MS
GR	NS	SBTH.	MS
P3/8-S	NS	P200-Ba	MS
P200-S	NS	P1/2-B	MS
P200-B	NS	PMBPR.	NS
P3/8-Ba	NS	SBPR.	NS
P200-Ba	NS	P200-S	NS
AV	NS	P200-B	NS
PMBPR.	NS	P3/8-S	NS
SBMR	NS	GR	NS
SBPR.	NS	AV	NS

Table 26. Results of NSI under Medium traffic and Hot climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
SGMR	VS	ABiTH.	VS
ABiTH.	VS	P3/4-Ba	S
SBTH.	S	TRL	S
ASTH.	S	Gbs	S
PMBTH.	S	Pb-Ba	S
SGPR.	S	PGH	MS
TRL	S	P3/4-B	MS
P3/4-B	MS	PMBMR	MS
Gbs	MS	P1/2-Ba	MS
AsPR	MS	SP	MS
PGH	MS	ASTH.	MS
P3/4-Ba	MS	AsPR	MS
Pb-Ba	MS	P3/8-Ba	MS
P3/8-S	MS	P3/8-S	MS
P3/8-Ba	MS	SGPR.	MS
PMBPR.	MS	TP	MS
TP	MS	P3/4-S	MS
P3/4-S	MS	Pb-S	MS
Pb-S	MS	P3/8-B	MS
P200-S	MS	P1/2-S	MS
P3/8-B	MS	Pb-B	MS
P1/2-Ba	MS	PMBTH.	MS
PMBMR	MS	SBTH.	MS
P1/2-S	MS	GR	MS
SP	MS	P200-B	MS
Pb-B	MS	P200-Ba	MS
GR	MS	SBMR	MS
P200-B	MS	SGMR	MS
P200-Ba	MS	P1/2-B	MS
SBMR	MS	ZD	MS
P1/2-B	MS	P200-S	NS
ZD	NS	AV	NS
AV	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

Table 27. Results of NSI under High traffic and Hot climate conditions for RL and FL.

Property	Sensitivity index RL	Property	Sensitivity index FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	ABiTH.	VS
SGMR	VS	TRL	S
SBTH.	S	P3/4-Ba	S
AsPR	S	P1/2-Ba	S
SGPR.	S	PGH	S
P3/4-Ba	S	Gbs	S
TRL	S	ASTH.	S
P3/4-B	S	Pb-Ba	S
Gbs	S	AsPR	MS
ASTH.	S	P3/8-Ba	MS
PMBTH.	S	P3/4-B	MS
PGH	MS	PMBMR	MS
Pb-Ba	MS	SP	MS
P3/8-Ba	MS	Pb-B	MS
P3/4-S	MS	TP	MS
P1/2-Ba	MS	P3/4-S	MS
SP	MS	P3/8-B	MS
Pb-B	MS	PMBTH.	MS
P1/2-B	MS	P200-Ba	MS
P3/8-B	MS	SBMR	MS
ZD	MS	SGMR	MS
TP	NS	P1/2-B	MS
GR	NS	ZD	MS
Pb-S	NS	GR	NS
P3/8-S	NS	Pb-S	NS
P1/2-S	NS	P3/8-S	NS
P200-S	NS	P1/2-S	NS
P200-B	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
PMBMR	NS	PMBPR.	NS
PMBPR.	NS	SBTH.	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Under Low and Medium traffic conditions, RL was VS to AW, ABaTH, ABiTH, SBTH and SGMR. While it was S to ASTH, SGPR, TRL, PMBTH and AsPR. On the other hand, for the same traffic condition, FL was VS to AW, ABaTH, ABiTH and TRL. FL was S to ASTH, SP, AsPR, PGH, PMBMR and some volumetric properties of Base layer. It can be noted that the results Under Medium traffic conditions were very similar to the results of Graphical method.

Under High traffic conditions, the results were also resembled to the results of Graphical method. Moreover, RL was S to AsPR and SGPR.

4.2.2.2. Results of Distance Sensitivity Index DSI.

The results of SA using DSI metric under Light, Medium and High traffic conditions are shown in Tables 28 through 30.

Table 28. Results of DSI under Low traffic and Hot climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
SGMR	VS	PGH	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	ABiTH.	VS
SBTH.	VS	TRL	VS
PGH	VS	P3/4-Ba	VS
ASTH.	S	Gbs	VS
PMBTH.	S	Pb-Ba	S
TRL	S	ASTH.	S
SGPR.	S	P1/2-Ba	S
P3/4-B	S	PMBMR	S
Gbs	S	SP	S
SP	MS	ZD	S
P3/4-S	MS	P3/4-B	S
Pb-B	MS	P3/8-Ba	S
Pb-Ba	MS	PMBTH.	S
P3/4-Ba	MS	SBMR	S
P1/2-Ba	MS	AsPR	MS
AsPR	MS	TP	MS
PMBMR	MS	P3/4-S	MS
ZD	MS	Pb-B	MS
Pb-S	MS	SGMR	MS
P1/2-S	MS	Pb-S	MS
P3/8-B	MS	P1/2-S	MS
P1/2-B	MS	P3/8-B	MS
TP	NS	P1/2-B	MS
GR	NS	P200-Ba	MS
P3/8-S	NS	SBTH.	MS
P200-S	NS	SGPR.	MS
P200-B	NS	GR	NS
P3/8-Ba	NS	P3/8-S	NS
P200-Ba	NS	P200-S	NS
AV	NS	P200-B	NS
PMBPR.	NS	AV	NS
SBMR	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

Table 29. Results of DSI under Medium traffic and Hot climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	PGH	VS
SGMR	VS	ABaTH.	VS
ABiTH.	VS	ABiTH.	VS
PGH	VS	TRL	S
SBTH.	S	P3/4-Ba	S
ASTH.	S	Pb-Ba	S
PMBTH.	S	Gbs	S
TRL	S	SP	S
SGPR.	S	P3/4-B	S
P3/4-B	S	P1/2-Ba	S
Gbs	S	ASTH.	S
Pb-Ba	MS	PMBMR	S
P3/4-Ba	MS	P3/8-Ba	MS
ZD	MS	ZD	MS
SP	MS	TP	MS
TP	MS	GR	MS
GR	MS	Pb-S	MS
Pb-S	MS	P3/4-S	MS
P3/4-S	MS	P3/8-S	MS
P3/8-S	MS	P1/2-S	MS
P1/2-S	MS	Pb-B	MS
P200-S	MS	P3/8-B	MS
Pb-B	MS	P1/2-B	MS
P3/8-B	MS	P200-B	MS
P1/2-B	MS	P200-Ba	MS
P200-B	MS	AsPR	MS
P3/8-Ba	MS	PMBTH.	MS
P1/2-Ba	MS	SBTH.	MS
P200-Ba	MS	SBMR	MS
AsPR	MS	SGMR	MS
PMBMR	MS	SGPR.	MS
PMBPR.	MS	P200-S	NS
SBMR	MS	AV	NS
AV	NS	PMBPR.	NS
SBPR.	NS	SBPR.	NS

Table 30. Results of DSI under High traffic and Hot climate conditions for RL and FL.

Property	Sensitivity index	Property	Sensitivity index
	RL		FL
AW	VS	AW	VS
ABaTH.	VS	ABaTH.	VS
ABiTH.	VS	PGH	VS
SGMR	VS	ABiTH.	VS
PGH	VS	TRL	S
SBTH.	S	P3/4-Ba	S
TRL	S	Pb-Ba	S
P3/4-Ba	S	P1/2-Ba	S
SGPR.	S	Gbs	S
P3/4-B	S	ASTH.	S
Gbs	S	ZD	MS
ASTH.	S	SP	MS
PMBTH.	S	Pb-B	MS
Pb-Ba	S	P3/4-B	MS
ZD	MS	P3/8	MS
SP	MS	PMBMR	MS
P3/4-S	MS	TP	MS
Pb-B	MS	P3/4-S	MS
P1/2-B	MS	P3/8-B	MS
P3/8-Ba	MS	P1/2-B	MS
P1/2-Ba	MS	P200-Ba	MS
AsPR	MS	AsPR	MS
P3/8-B	MS	PMBTH.	MS
TP	NS	SBMR	MS
GR	NS	SGMR	MS
Pb-S	NS	GR	NS
P3/8-S	NS	Pb-S	NS
P1/2-S	NS	P3/8-S	NS
P200-S	NS	P1/2-S	NS
P200-B	NS	P200-S	NS
P200-Ba	NS	P200-B	NS
AV	NS	AV	NS
PMBMR	NS	PMBPR.	NS
PMBPR.	NS	SBTH.	NS
SBMR	NS	SBPR.	NS
SBPR.	NS	SGPR.	NS

Under Low traffic conditions, the results of DSI metric were similar to that of NSI metric. Moreover, FL was S to SBMR and PMBMR.

Under Medium traffic conditions it can be noted that RL was VS to AW, ABaTH, ABiTH, PG and SGMR. While it was S to ASTH, ABiTH, TRL, PMBTH and PG. On the other hand, FL was VS to AW, ABaTH, ABiTH and PGH. While it was S to TRL, SP, ASTH, PMBMR and some volumetric properties of Base layer.

Under High traffic conditions , RL was VS to AW, ABaTH, ABiTH, PG and SGMR. While it was S to ASTH, TRL, PMBTH, SBTH, SGPR and some volumetric properties of Base layer. While, FL was VS to AW, ABaTH, ABiTH and PG. Where FL was S to ASTH, TRL, PMBMR and some volumetric properties of Base layer.

Summary of the results:

The results of SA under hot climate condition and according to the results of RL can be summarized in the followings:

1- Under L and M traffic conditions:
   a) It can be seen that AW and Layers thicknesses (e.g. ABath and ABith) were S and VS. High AW accompanied with insufficient design with low thicknesses of layers can decrease the RL of pavement. There is a need for the improvement of flexible pavement design method and enhance the monitoring system of axel weight in highways.
   b) It is found that RL is S to the PG of asphalt. Asphalt of high PG can increase the RL significantly. A special consideration must be paid when selection the appropriate type of asphalt.
   c) Pavement is also S to TRL. Higher traffic loadings can increase the deterioration of pavement structure in the form of rutting.
   d) It is discovered that the RL of pavement is S to the specification of SG (Poisson ratio and M_R). This agreed with the findings of different researches in the literature. High Poisson ratio is associated with high flexibility of pavements layers thus low RL. At the meantime, higher M_R of SG can significantly increase the RL.
2- Under H traffic conditions:
   The results are similar to the results of L and M traffic loadings. But it was found that RL is S to the properties of Base layer (e.g. P3/4-Ba and Pb-Ba). High traffic loadings can increase the vertical stresses on Base layer. This can increase the vertical stresses on the subgrade layer and increasing rutting potential.
3- It is discovered that the number of S and VS parameters found using DSI metric is higher than that using NSI and Graphical methods.

The results of SA under hot climate condition and according to FL can be summarized in the followings

1- Under H, M and L traffic conditions:
   a) It can be concluded that FL was VS and S to AW and Layers thicknesses. High AW accompanied with insufficient thicknesses of pavements layers due to poor design reduced the FL of pavement. There is a need for the improvement of flexible pavement design method and enhance the monitoring system of axel weight in highways.
   b) It is found that the FL was S to the PG of asphalt. Higher PG can increase the FL significantly. A special consideration must be paid when selection the appropriate type of asphalt that can decrease the tensile strain at the bottom of asphalt layer.
   c) FL was S to TRL and the speed of vehicles SP. Higher traffic loadings with low traffic speed induce higher tensile strains at the bottom of asphalt layers. This can increase the deterioration of pavement structure in the form of fatigue cracking.
   d) The FL is also S to the properties of asphaltic Base layer (e.g. P3/4-Ba and Pb-Ba) where the tensile strains accrue.
   e) It was found that the FL is S to M_R of PMB. The PMB layer is the base of asphaltic layers where the tensile strains take place. The strength of this layer can increase the FL of pavement significantly.
   f) As expected, the FL of pavement is S to the thickness of asphalt layer ASTH. Sufficient thickness of asphaltic layer can increase the FL significantly. The selection of appropriate thickness is related to the design method that need to be enhanced.
   g) It was surprising that the FL of pavement is S to Bulk specific gravity Gbs of aggregate. More investigation about the effect of this factor need to be conducted.
2- It is found that the number of S and VS parameters found using different metrics (i.e. Graphical, NSI and DSI) are different under different traffic conditions, but it was higher when using DSI.

5. CONCLUSIONS AND RECOMMENDATIONS

According to the results of M-EDM and SA of TTS for hot and cold regions in Turkey under H,M and L traffic conditions discussed previously, it can be concluded that:

1- It can be seen that AW and layers thicknesses were S and VS. High AW accompanied with insufficient design with low thicknesses of layers can decrease the RL of pavement. There is a need for the improvement of flexible pavement design method and enhance the monitoring system of axel weight in highways.
2- It is also found that the pavement is S to the PG of asphalt. Higher PG can increase the RL and FL significantly. A special consideration must be paid when selection the appropriate type of asphalt.
3- Pavement is also S to TRL. Higher traffic loadings can increase the deterioration of pavement structure in the form of rutting and fatigue cracks.
4- It is discovered that the RL of pavement is S to the specification of SG (Poisson ratio and M_R). This agreed with the findings of different researches in the literature. High Poisson ratio is associated with high flexibility of pavements layers thus low RL. At the meantime, higher M_R of SG can significantly increase the RL.
5- It is also discovered that pavement is S to the properties of Base layer (e.g. P3/4-Ba and Pb-Ba). High traffic loadings can increase the vertical stresses on Base layer. That can increase the vertical stresses on the subgrade layer causing rutting.
6- It was found that the pavement is S to M_R of PMB. The PMB layer is the base of asphaltic layers where the tensile strains take place. The strength of this layer can increase the FL of pavement.
7- As expected, the FL of pavement is S to the thickness of asphalt layer ASTH. Sufficient thickness of asphaltic layer can increase the FL significantly. The selection of appropriate thickness is related to the design method that need to be enhanced.
8- The new proposed DSI method for SA which based on mathematical approach can be considered better than graphical method and can be used to overcome the shortcoming of inability of NSI method for conducting SA on categorical parameters.

Declaration of Ethical Standards

Authors followed all ethical guidelines including authorship, citation, data reporting, and publishing original research.

Credit Authorship Contribution Statement

Saadoon Obaid Eyada developed the theoretical formalism, performed the analytic calculations and performed the numerical simulations. Both Osman Nuri ÇELİK and Nibras Y. Abdulla authors contributed to the final version of the manuscript. Osman Nuri ÇELİK supervised the project.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported.

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Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

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NEW METRIC FOR THE CALCULATION OF SENSITIVITY ANALYSIS INDEX OF FLEXIBLE PAVEMENT USING MECHANISTIC-EMPIRICAL APPROACH, TURKEY-CASE STUDY

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Highlights

- New metric for the conducting Sensitivity Analysis
- Turkiye- Case study
- MECHANISTIC-EMPIRICAL design parameters

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