# FLEXIBLE PAVEMENT RUT DEPTH MODELING FOR DIFFERENT CLIMATE ZONES

by

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| Advisor | Date |
|---|---|

## DEDICATION

*To my parents,*

*To my brothers and sisters,*

*To my wife, and*

*To my children: Fatema, Hammza, Mosbah, and Alaa.*

*for their love, support, and encouragement……*

## ACKNOWLEDGEMENTS

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# CHAPTER 1 – INTRODUCTION

## 1.1 Background

Highways are one of the important infrastructure components that affect the economic and social development of countries. In major cities, a breakdown in the transportation system will paralyze the activities of the community; therefore, federal and local governments spend billions of dollars every year to build new pavements, and rehabilitate and maintain the existing pavements. Figure 1-1 shows the highway expenditures in the United States from 1957 to 2004. The expenditures have been increasing every year, which indicates a need for organized efforts to maximize the benefits of these investments.

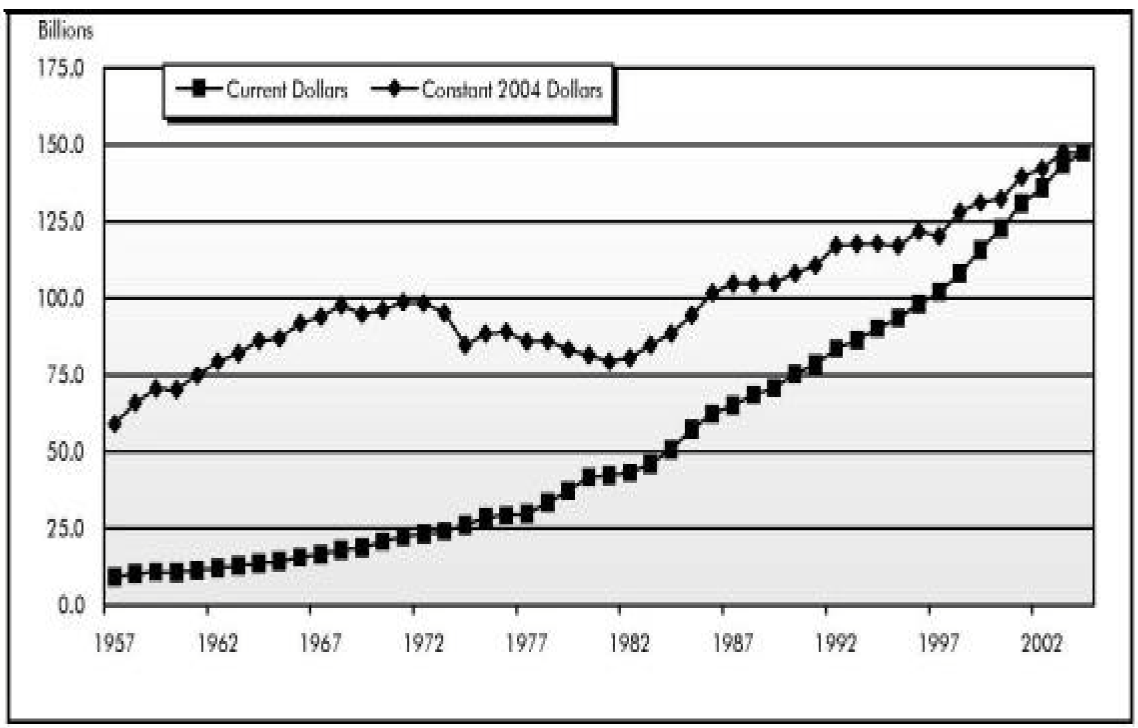


**Figure 1-1: Highway expenditures, 1957- 2004**

Source: (U.S.DOT, 2006)

State Highway Agencies (SHA's) use pavement management system (PMS) to assist decision makers to select the most cost- effective strategies for maintenance, rehabilitation, and reconstruction of pavements. Consequently, appropriate design, construction and maintenance of pavements, which reduce safe and efficient operational conditions, are important tasks in PMS (Zimmerman and Testa, 2008).

The pavement management concept was first conceived in the mid-1960s to organize the activities involved in achieving the best value possible for the obtainable funds (Karan and Haas, 1981). The American Association of State Highway and Transportation Officials (AASHTO) (1993) defines a pavement management system as " a set of tools or methods that assist decision makers in finding optimum strategies for providing, evaluating, and maintaining pavements in serviceable condition over a given period of time". Therefore, using a pavement management system helps maintain a highway network in a safe condition while working in a cost-effective manner.

Forecasting future deterioration of pavements through consideration of various factors is a crucial aspect of a pavement management system. Pavement condition surveys provide the most important data (in-service pavement data) for forecasting the future deterioration of a pavement, which yields models to predict pavement conditions throughout the pavement life.

There are many pavement deterioration prediction models, which have been developed using in- service pavements databases. The local agencies (e.g. state databases) provide somewhat limited information about pavements, but the Long-Term Pavement Performance (LTPP) database is the biggest pavement performance database in the world that provides extensive information about the pavements in different climates in the world, which can help develop efficient performance prediction models.

There are two types of pavements: flexible pavements and rigid pavements. Flexible pavements are those surfaced with soft/ flexible material, known as asphalt concrete pavements (AC). Rigid pavements, pavement surfaced with rigid material that do not deform under loading.

Flexible pavements are widely used in road constructions around the world. The body of the flexible pavements is usually composed of three layers: the surface course, the base course, and sub-base course as shown in Figure 1-2. Various types of deterioration can affect flexible pavements, including rutting, which affects the service quality of the road due to its poor operational conditions. Indeed, rutting can affect operation safety when it reaches critical depths (Ali, 2006).

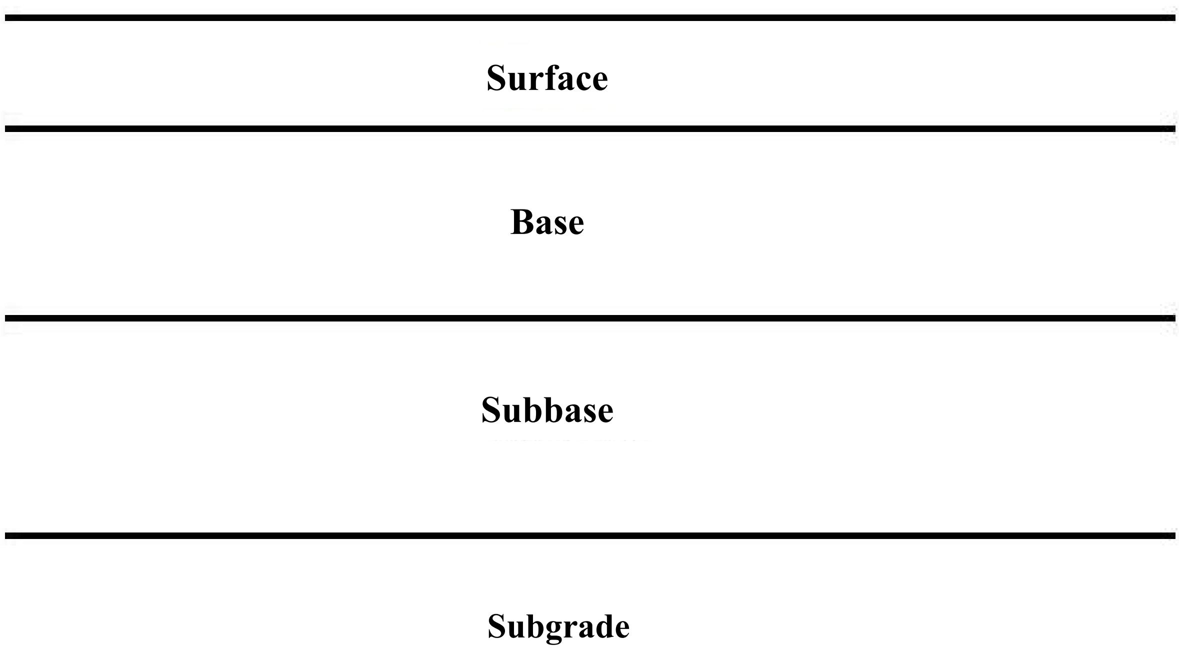


**Figure 1-2: Flexible pavement layers**

This dissertation focuses on the development of flexible pavement rutting prediction models for various climate zones using the Long Term Pavement Performance data. The developed models lead to a better understanding of the pavement rutting phenomena, and the major factors affecting it, which helps the decision makers, such as state and local transportation agencies, to select cost-effective strategies for maintenance, rehabilitation, and reconstruction of pavements.

## 1.2 Problem Statement

The presence of rutting on flexible pavement layers has always been and continues to be a problem adversely affecting the performance of pavements. Rutting not only reduces the life of pavement, but it also creates a safety hazard for the traffic.

Data from field experiments can assist in determining and recognizing the factors that affect pavement rutting. These factors can be used to develop prediction models that lead to improving and developing the existing design procedures.

There are many data sources available in different states, which have been developed in those states. The data collected by the states is different from state to state, because each state uses their own methods to collect the data, and to code and check the quality of the data. For example, pavement performance data collected in the State of Michigan is focused on the condition of the pavements in this state and uses a certain method to collect and check the quality of the data. Therefore, the rutting models that have been developed based on these data should be used only in Michigan or those other states that have the same climate zone and use the same method to collect and check the quality of the data. Therefore, the data collected in different states will have a large variation in quantity and quality. On the other hand, the LTPP data, which has been developed under controlled and uniform conditions, provides very large amounts of data for various climate zones in all of the states. The models developed based on these data could be used in a wide range of states or in other countries over the world that have similar climate.

## 1.3 Research Objectives

The objectives of this study are as follows:

1. Review and understand the Long Term Pavement Performance database contents and structure.
2. Identify the factors that may affect pavement rutting.
3. Develop empirical models to forecast the rutting of flexible pavement on granular base sections in various climate zones based on LTPP data. The developed models will assist better understanding of the pavement rutting phenomena, and factors that affect it; improve existing pavement design and rehabilitation methods; and further develop the PMS.

The following steps were preformed to achieve the objectives of this research:

1. Review the literature on pavement performance, pavement distress, and rut depth modeling.
2. Identify the pavement rutting indicators.
3. Extract the required data elements from the LTPP data
4. Construct the research database.
5. Identify abnormal and outlier data.
6. Identify the major factors that affect pavement rutting.
7. Conduct statistical analysis for models formulation, and validate the models.

## 1.4 Research Layout

Following the Introduction chapter (chapter 1), a comprehensive literature review of the pavement performance, pavement distress, pavement rutting, factors affect pavement rutting and empirical model for rutting is presented in chapter 2.

Chapter 3, methodology, covers the LTPP background, LTPP experiment, LTPP quality control, LTPP climate zones, initial selection of the models variables, site selection, research database development and data validation.

Chapter 4 presents formulation of the models. Wet freeze zone model, dry freeze zone model, wet no-freeze zone model, and dry no-freeze zone model are formulated and validated in this chapter.

Conclusion and recommendations chapter (chapter 5) presents research conclusion and recommendations.

Bibliographic sources used in this research are presented in the References section. It includes books, reports, papers, articles, online resources, and other type of resources.

Finally, this research includes two appendices. Appendix A contains the detailed LTPP information about the code of each state or province, while Appendix B presents the correlation matrix tables for all models.

# CHAPTER 2 - LITERATURE REVIEW

## 2.1 Pavement Performance

Pavement performance relates to the ability of a pavement to acceptably serve users over time. Serviceability is a measure of the ability of a pavement to serve the traffic that uses the facility. Combining both definitions will lead to understanding pavement performance, which can be viewed as the integration of the serviceability over time (Yoder and Witczak, 1975). The evaluation of pavement performance is an essential element of pavement design, rehabilitation, maintenance, and management. The evaluation of pavement performance includes evaluating pavement distress, roughness, friction, and structure (Huang, 2004).

## 2.2 Pavement Distress

Pavement distress is an indication of pavement layer deterioration. Environmental conditions, traffic loads, and pavement material are the principle factors that affect flexible pavement performance. Hasim, et al. (1994) indicate that the rate of deterioration is dependent on the quantity and variability of traffic loads. There are two types of distress for flexible pavements. The first type, structural distress, results in functional distress. Pavements with structural distress become incapacitated to carry traffic loads, needing immediate maintenance. The second type, functional distress, may or may not result from structural distress. Functional distress affects the ride quality and safety issues, and increase the maintenance cost.

Maintenance and rehabilitation engineers categorize the pavements distress by using the distress identification factors:

Distress Type – categorizing each type of distress as cracking, patching and potholes, surface deformation, and surface defects.

Distress Severity – identifying distress severity as high, medium, and low severity

Distress Amount – identifying the magnitude of each distress type characterized by severity level.

Bianchini (2007) describes pavement severity as “a qualitative measure of the degree of development of the deterioration over the pavement surface” and assigns severity levels of low, medium and high”.

Distress Identification Manual for the Long-Term Pavement Performance Project, Miller and Bellinger, (2003) classifies pavement distresses where each distress is described by its general mechanism, level of severity, and the measurement criteria. The distress types of flexible pavements classifies into five major categories of common pavement surfaces: pavement cracks, patching and potholes deterioration, surface deformations, surface defects, and miscellaneous distresses.

### 2.2.1 Pavement Cracks

Cracks are one of the main causes of pavement deterioration. In the past few decades, many studies showed the pavement alligator cracking as the principal type of pavement cracking (Ullidtz, 1987). Crack categories include alligator cracks, block cracks, transverse cracks, longitudinal cracks, and edge cracks. Miller and Bellinger (2003) describes pavement cracks as follows:

Alligator cracking

Alligator cracks: The phenomena of Alligator cracks, also known as fatigue cracks or crocodile cracks through the surface layer, are series of interconnected cracks.

Block cracking

Block cracks: Block cracks are an interconnected network of rectangular cracks that divided the pavement surface to rectangular pieces. The size of the cracks ranged between 1 $ft^2$ and 100 $ft^2$ (Miller and Bellinger, 2003).

Transverse cracking

Transverse cracks, also known as thermal cracks. are mainly perpendicular to the pavement centerline (Miller and Bellinger, 2003).

Longitudinal cracking

Longitudinal cracks are mainly parallel to the pavement centerline, and are caused by asphalt pavement surface fatigue, inadequate bonding during construction, or reflection cracks in underlying pavement. Longitudinal cracks in the wheel path are signs of fatigue failure from heavy vehicle loads.

Edge cracking

Edge cracking appears in pavements without paved shoulders as crescent-shaped or continuous cracks. Edge cracks are located in close proximity to the pavement shoulder within one to two feet of the outer pavement edge.

Hye, et al. (1992) illustrated different categories of pavement cracks, namely, alligator cracks, block cracks, transverse cracks, longitudinal cracks, and edge cracks, as shown in Figure 2-1.

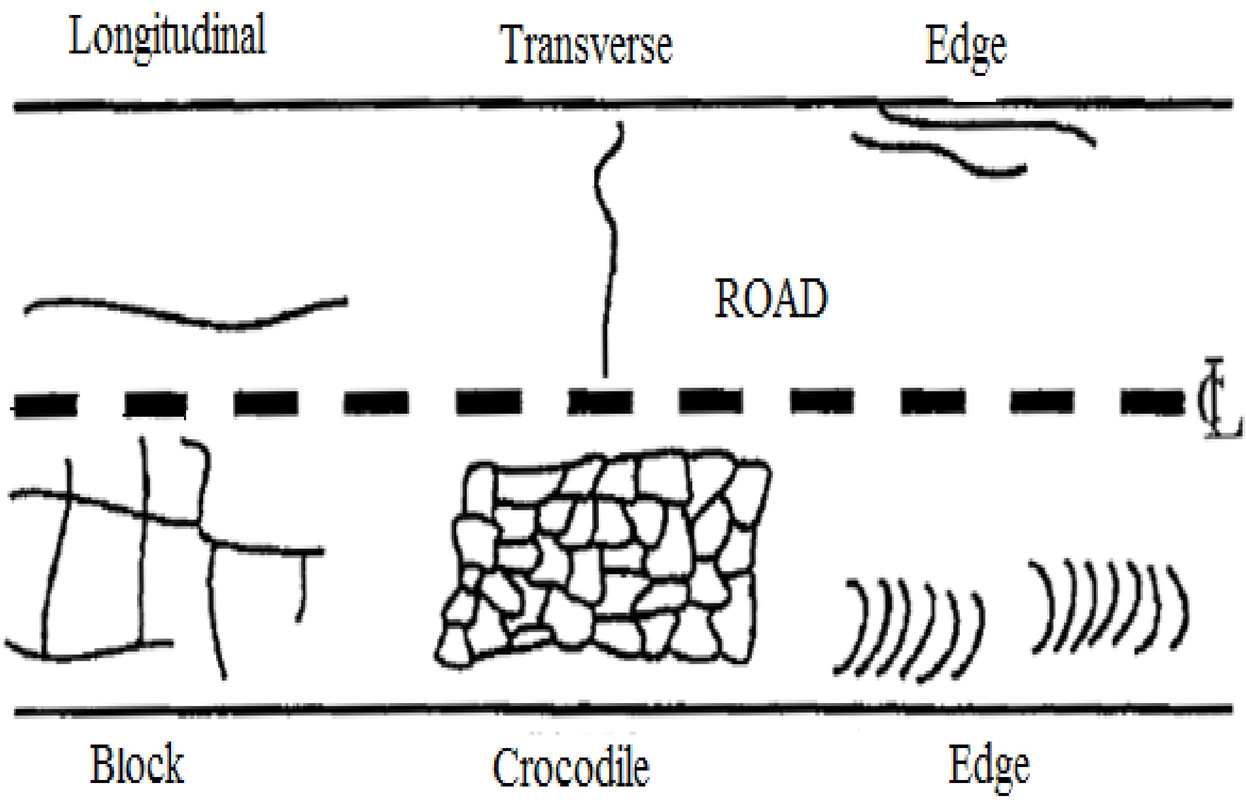


**Figure 2-1: Cracks categories**

Source: (Hye, et al., 1992)

### 2.2.2 Patching and Potholes Deterioration

Patch deterioration

Miller and Bellinger (2003) defined the patch deterioration as "portion of pavement surface, greater than 0.1 $m^2$, that has been removed and replaced or additional material applied to the pavement after original construction".

Potholes deterioration

The potholes deterioration are small bowl shaped holes of various sizes on the pavement surface.

Pavement patching and potholes deterioration are illustrated in Figure 2-2

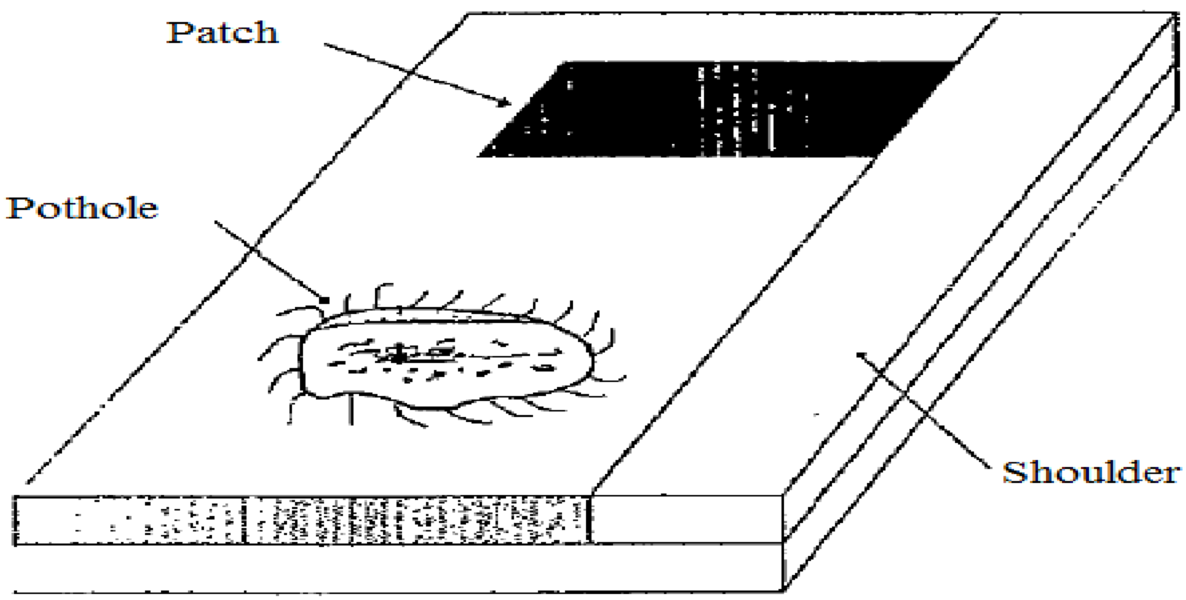


**Figure 2-2: Patching and potholes**

Source: (Hye, et al., 1992)

### 2.2.3 Surface Deformations

Rutting

Rutting, often referred to as permanent deformation of a pavement surface, causes longitudinal depressions creating channels in wheel paths. This is affected by the consolidation or lateral movement of material due to traffic loads, inadequate compaction during construction, unstable mixture, and failure of the lower layers of the pavement (Miller and Bellinger, 2003). The pavement rutting is described in more details later in sections 2.3 through 2.7.

Shoving

Shoving, also known as rippling is a form of plastic movement shaped by bulging of the road surface parallel to the direction of traffic caused by traffic pushing against the pavement (braking or accelerating vehicles). It usually occurs at the start and stop points of traffic and acceleration lanes (Miller and Bellinger, 2003).

Shafie (2007) explained the causes of surface deformation as follows: "pavement deformation takes place when road surface changes from its original constructed profile, possibly due to traffic or environmental influences as well as due to improper quality control during the construction. It will affect the riding quality and may lead to cracking problems. The possible causes of pavement deformation include inadequate pavement thickness, improper compaction, low stability of mix, settlement of layers, lack of bonding between layers, stopping at intersection stop lights or roundabout, etc".

The flexible pavement rutting and shoving are illustrated in Figure 2-3.

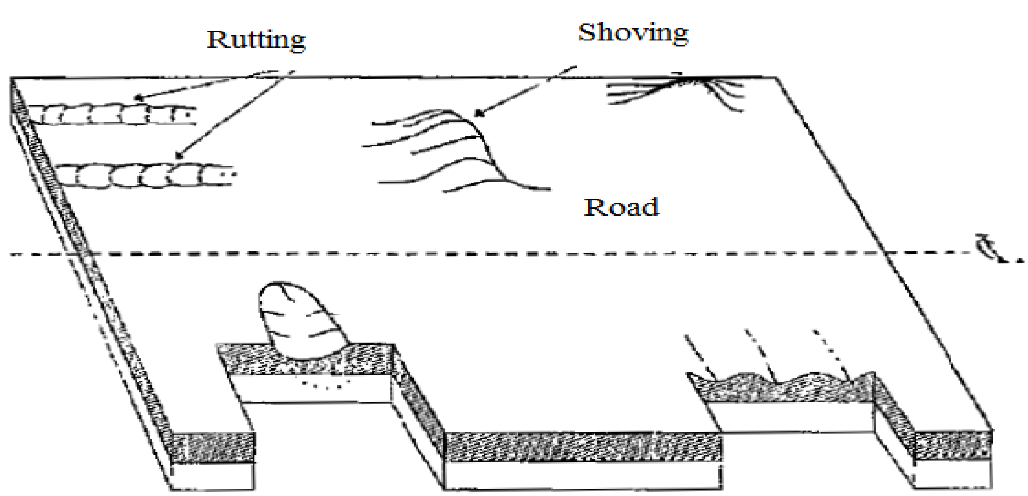


**Figure 2-3: Pavement deformations**

Source: (Hye, et al., 1992)

### 2.2.4 Surface Defects

Surface defects include bleeding, polishing, and raveling. These defects have great effects on the serviceability, ride quality, and safety issues. Miller and Bellinger (2003) explain the surface defect types as follows:

Bleeding

Miller and Bellinger (2003) identify the surface bleeding as "Excess bitumen binder occurring on the pavement surface, usually found in the wheel paths. May range from a surface discolored relative to the remainder of the pavement, to a surface that is losing surface texture because of excess asphalt, to a condition where the aggregate may be obscured by excess asphalt possibly with a shiny, glass-like, reflective surface that may be tacky to the touch".

Pavement Polishing

Pavement polishing occurs in both types of pavements, flexible pavement and rigid pavement. The main cause of the polishing is the low percentage of angular shaped aggregate in the mix. The polishing appears in pavement where there is a small or no angular aggregate. Repetition of traffic loads reduces surface friction.

Raveling

Raveling is caused by hardening of asphalt, insufficient asphalt content, loss of asphalt binder and aggregate particles, and insufficient compaction. Aggregate is dislodged from the mix creating surface deterioration.

Figure 2-4 illustrates the polishing, bleeding, and raveling phenomena.

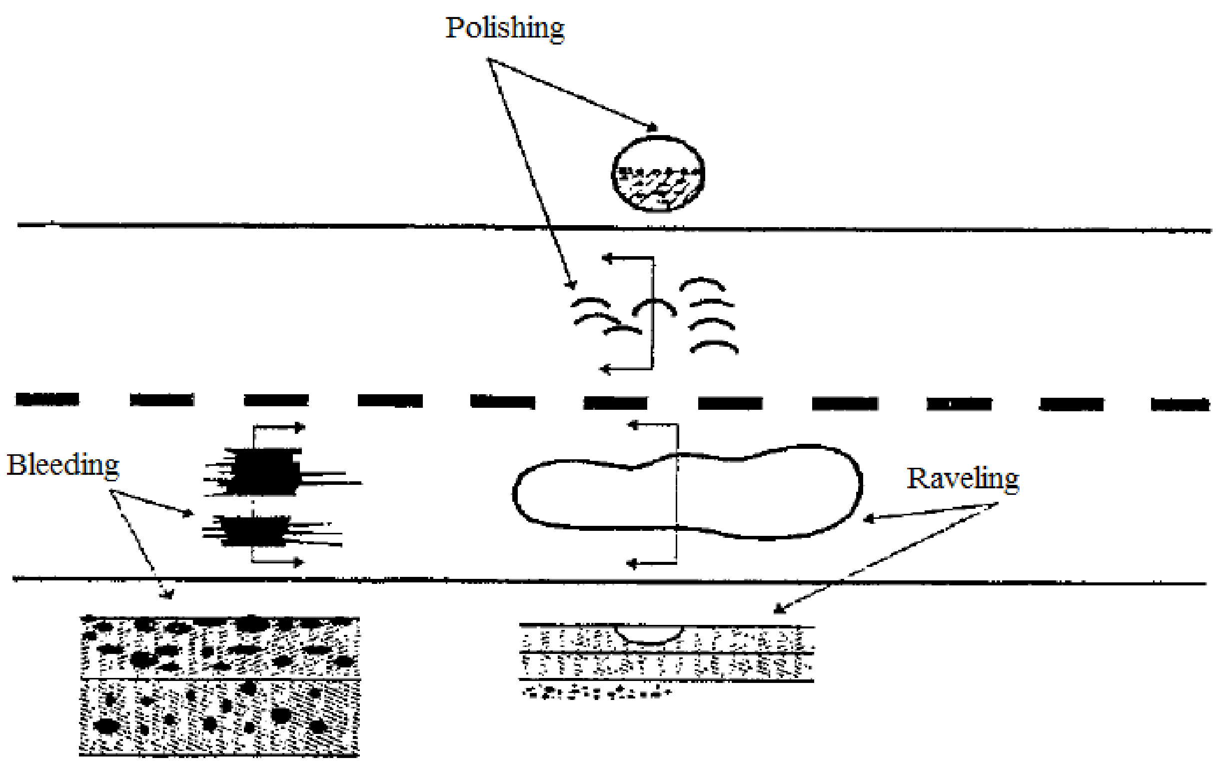


**Figure 2-4: Surface defects**

Source: (Hye, et al., 1992)

### 2.2.5 Miscellaneous Distresses

There are other flexible pavements distresses where asphalt pavement has been placed on the top of concrete pavement such as reflection cracking at joints, lane-to-shoulder drop-off, and water bleeding and pumping.

## 2.3 Rutting Overview

Various types of pavement deterioration can affect pavement including rutting which causes safety and service quality problems on the road. Pavement rutting is observed on roads and streets, especially at high-stress locations such as intersections, grades, and locations where heavy vehicles stop, start, turn or climb steep grades (Flexible Pavemet of Ohio, 2004). Indeed, the rutting may endanger safety when it reaches critical depths (Ali, 2006).

The increase in heavy traffic accelerates the beginning of rutting (Reddy and Veeraragavan, 1997). Deterioration of flexible pavement due to cracking and rutting is covered widely in the technical literature (Archilla and Madanat, 2000, Skok, et al., 2002, Zaniewski and Nallamothu, 2003, White, et al., 2005). Sousa, et al. (1991) and Archilla (2000) emphasized that rutting relates to many factors, such as the characteristics of pavement, the binder content, type and size of aggregates, and moisture in the lower layers.

Ashworth (2003) characterized the pavement rutting as follows:

- Subsidence of the surface layer over yielding lower layers. The surface layer over weak lower layers subsides due to heavy and repeated traffic. The surface layer endeavors to conform to the shape of the lower layers.
- Loss of material from the wheel paths due to the progressive loss of particle aggregates of the surface layer. A combination of traffic and the environment causes this type of rutting.
- Plastic shear deformation of the asphalt mixtures near the pavement surface is a material failure of the asphalt concrete. The mixture is displaced from under the tires and typically humps up outside the wheel paths. Plastic shear deformation is caused by the vertical load, when the pavement fails to resist the shear loads.

## 2.4 Rutting Mechanics

The flexible pavement rutting is the accumulation of the plastic flow in the surface layer or in other layers (Cebon, 1993). It is also thought by some researchers that the initial rutting is caused by the deformation of the pavement layers in wheel paths due to heavy and repetitive traffic loads (Archilla, 2000). Different mechanisms may be the bases of flexible pavement rutting (Sousa and Weissman, 1994). The deformation causes the pavement material to rise adjacent due to the accumulation of the material in between the side of the wheel paths caused by movement of material under the wheels; however, for well compacted pavements, the stress in the asphalt pavement shear layer is the primary mechanism of rutting (Bahuguna, et al., 2006).

Figure 2-5 shows the flexible pavement surface deformation induced by traffic loads.

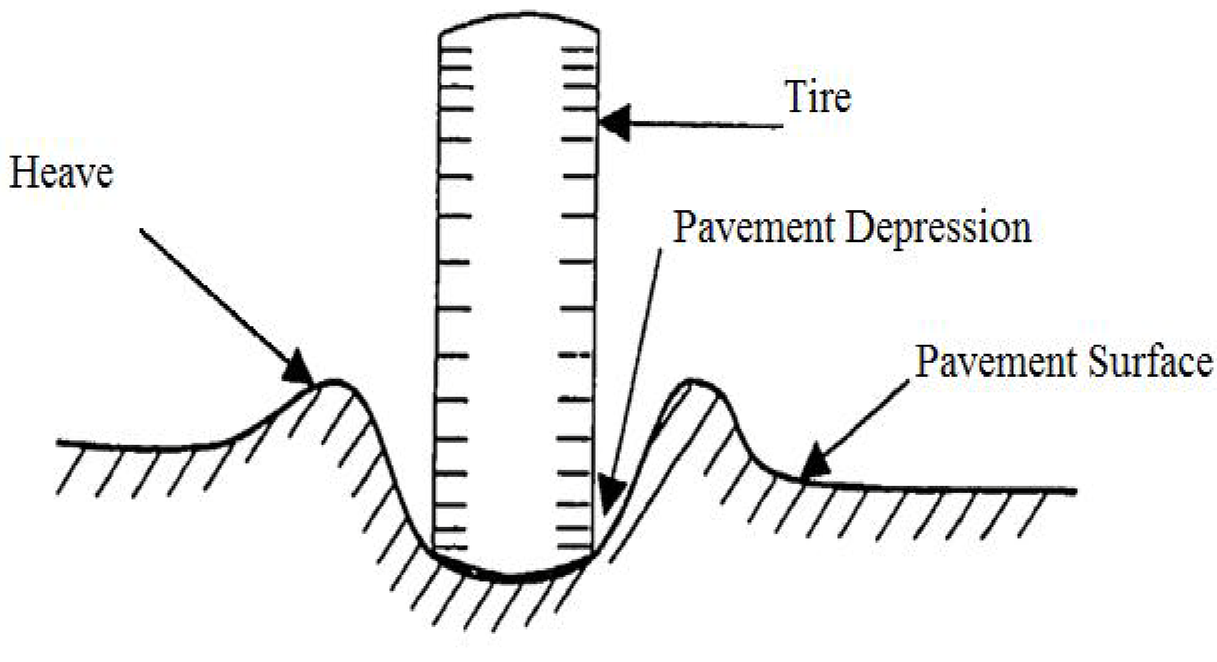


**Figure 2-5: Pavement surface deformation**

Source: (Archilla, 2000)

## 2.5 Types of Rutting

MTC (1986) classified pavement rutting into three categories based on severity (magnitude of depression): 1- Low: less than 1 in (13 to 25 mm), 2- Medium: between 1 and 2in (25 to 5o mm), and 3- High: equal to or greater than 2 in (> 50 mm).

Dawley, et al. (1990) classified flexible pavement rutting based on the causes of rutting into three types. These are as follows:

- Wear ruts: The main cause of this type of flexible pavement rutting is the progressive loss of particle aggregates of the surface layer, and other factors such as environmental and traffic loads.
- The rut instability: The main cause of this type of flexible pavement rutting is lateral displacement of material of layers.
- Structural rutting: The structural rutting is due to the permanent vertical deformation in lower layers.

Figure 2-6 illustrates the three types of flexible pavement rutting according to the main causes of rutting.

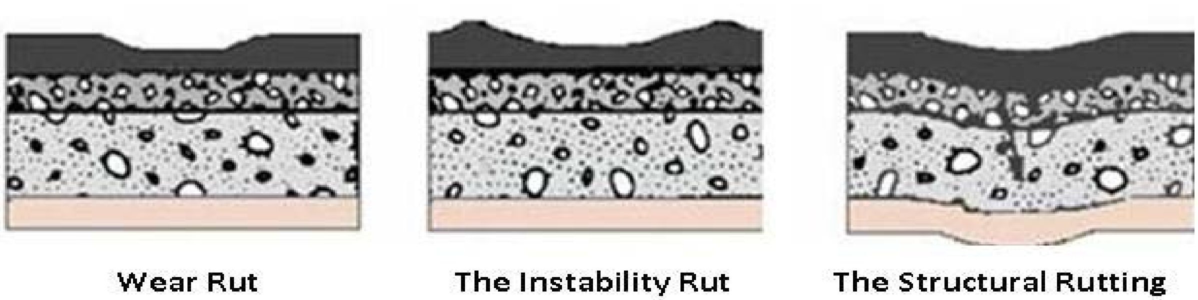


**Figure 2-6: flexible pavement rutting types based on the causes of rutting**

Source:(Ali, 2006)

## 2.6 Factors Affecting Pavement Rutting

There are several factors, which may influence the development of pavement rutting. Ali (2006) classified these factors into two categories: internal factors, such as material properties and pavements structure; and external factors, such as traffic and the environmental factors. These factors should be understood when designing or evaluating pavements in order to be able to forecast the pavement's functional and structural conditions over time.

### 2.6.1 Internal Factors

The internal factors that may affect flexible pavement rutting are material properties and pavement structure. These aspects are reviewed in the following sections.

#### 2.6.1.1 Asphalt Binder

Asphalt binder is a multiple origin material such as natural asphalt and asphalt from petroleum refining. ASTM D 8-02 (2003) defines asphalt as a dark brown to black cementation material, which can be found in nature, or obtained from petroleum refining.

The binder viscosity is the main factor affecting pavement rutting; therefore, asphalt binder grade has a significant effect on pavement rutting (Ali, 2006). The viscosity of asphalt varies from grade to grade at a specified temperature. The flexible pavement with harder and less temperature susceptible binder decreases the risk of flexible pavement rutting (Ali, 2006).

#### 2.6.1.2 Air Voids in Total Mix

The air voids content in the total mix (VTM) and excessive amount of the asphalt binder in the total mix (AC) are the most influenced properties of asphalt mixtures that may affect pavement rutting (Brown and Cross, 1989). AASHTO (1997) expressed the voids in the total mix as the percent of voids in the compacted mixture". The VTM content is one of the important characteristics that have a main effect on pavement performance under traffic loads. Mixtures perform well when there is an adequate air voids content and sufficient stability (Wagner, 1984).

#### 2.6.1.3 Layers Thickness

The stress level is one of the most important factors in the flexible pavement mechanism in a pavement; in addition, the level of stress depends on the pavement layers thickness and traffic loads (Gillespie, et al., 1993). Isa, et al. (2005) indicated that flexible pavement with thicker layers would distribute less amounts of loads to the subgrade and subsequently reduce vertical critical strain than thin layers. Ali (2006) showed that the surface layer thickness has effects on pavement rutting; therefore, the thin surface layer with poor distribution of traffic loads, produce pavement rutting due to high stresses in the layer, which lead to rutting instability.

#### 2.6.1.4 Voids in the Mineral Aggregate

Voids in the mineral aggregate (VMA) is the percentage of voids in the compacted asphalt mixture. Roberts, et al. (1996) defined and explained (VMA) as the intergranular void space that exists between the aggregate particles, which are occupied by asphalt and air in a compacted asphalt mixture. VMA includes air voids and the effective asphalt in the total mix; therefore, the volume of absorbed asphalt binder is not a part of VMA (Roberts, et al., 1996). The small voids space between the particles will lead to low VMA because the asphalt binder will not coat the individual particles; while, a mixture with excessive VMA will have low mixture stability. Therefore, the asphalt binder should coat the individual aggregate particles in the mixture to get an acceptable VMA and consequently an acceptable mixture (Rahman, 2006).

The following equation can be used to determine VMA:

$$\mathbf{VMA} = (\mathbf{100} - \mathbf{P_b})\mathbf{G_{mb}}/(\mathbf{S.G_{eff}}) \qquad 2\text{-}1$$

where**:**

- VMA: Voids in mineral aggregate.
- $P_b$: Percentage of asphalt content by total weight of mixture,
- $G_{mb}$: Bulk specific gravity of the compacted asphalt mixture,
- $S.G_{eff}$: Effective specific gravity of aggregates.

The gradation of aggregate in the pavement mixture may have a significant effect on the mixture. Therefore, changing in the gradation will affect VMA and VTM; consequently, durability, workability, stability of the mixture, and the surface skid resistance. For that reason, during the design of the mix, the gradation of aggregate should be selected to meet the design specification (Chadbourn, et al., 1999).

In the recent years, several studies have been carried out to evaluate the effect of VMA on pavement performance such as the study carried out in the University of Kansas in 1999 focused on evaluating the effects of aggregate gradation on performance of asphalt mixture. Two types of aggregate were used in the study; one with coarse gradation and another with fine gradation. The study concluded that increase in the aggregate size would lead to an increase in the VTM and VMA, and consequently, this would lead to increase in pavement rut (Cross, et al., 1999).

Roberts, et al. (1996) explained that the mixtures with elongated and flat particles tend to densify under traffic, which leads to pavement rutting due to low voids and plastic flow. In the other hand, the mixture with high quantities of crushed aggregates and more angular crushed aggregates will generally produce a higher VMA (Chadbourn, et al., 1999).

#### 2.6.1.5 Marshall Stiffness

In the late 1930's Bruce Marshall, who was an employee at the Mississippi Highway Department, originally developed the Marshall Mix Design Method. After that U.S. Army improved it, and it was used to some extent by about 38 states (White, 1985). There are two important measured values in this method; Marshall stability and Marshall flow. Engineers could select the amount of asphalt binder content in the mix at a desired density to achieve acceptable stability and flow (Kandhal and Koehler, 1985, Usmen, 1977).

Abukhettala (2006) defined Marshall stability as a measure of mass viscosity of the aggregate-asphalt cement mixture. This property is used to determine the performance of asphalt under loads and to evaluate the change in mix stability with increasing asphalt content to assist in selecting the optimum asphalt content. The angle of the friction of aggregate and the viscosity of the binder affect the stability of the mix (Abukhettala, 2006). A stable mixture is one that can carry traffic loads and resist the pavement deterioration for the design life of the mixture (Asphalt Institute, 2001). Therefore, a mixture with high Marshall stability is a stable mixture and it will resist pavement rutting.

Marshall flow is the vertical deformation of the specimen. It is measured at the same time with Marshall stability until the point where Marshall stability starts to decrease under loading. Brown and Cross (1989) suggested that Marshall flow appears to be a good indicator of rutting potential. In acceptable mix design and construction, Marshal flow should be around 16, and mixtures with Marshall flow exceeding 16 tend to a higher amount of rut (Abukhettala, 2006).

Marshall stiffness (MS), which is Marshall stability divided by Marshall flow, estimates load deformation characteristics of the mixture, and indicates the material resistance to pavement rutting (Asphalt Institute, 2001). A mixture with high Marshall stiffness is a stiffer mixture, and is resistant to pavement rutting (Abukhettala, 2006).

$$\text{Marshall stiffness} = \frac{\text{Marshall stability}}{\text{Marshall flow}}$$

#### 2.6.1.6 Subgrade Material Stiffness

Material stiffness, which is the ability of subgrade material to carry the repetition of traffic loads, material strength, and bearing capacity are the most common characterizations of subgrade material. The stiffness of the subgrade material should be sufficient to carry and distribute the applied traffic loads; therefore, the higher the subgrade material stiffness, the lower the pavement rut. California Bearing Ratio (CBR), resistance value (R- Value), and resilient modulus ($M_R$) are the most common characterizations of subgrade stiffness (WAPA, 2002).

In this research, the resilient modulus was used as characterization of subgrade material stiffness. Resilient modulus of subgrade material is a material stiffness test, and it is an assessment of modulus of elasticity of the subgrade material (WS. DOT, 2009).

#### 2.6.1.7 Pavement Structural Strength

Pavement structural strength is the ability of the roadbed layers to carry the repeated traffic loads as well as distribute the vertical deformation to the lowest layer. AASHTO method of pavement design uses structural number (SN), which depends on the thickness and type of surface, base, and subbase layers, and serves as a measure of pavement structural strength. In this research the SN was selected as the measure of pavement load carrying capacity.

The structural number is defined as follows (AASHTO, 1993):

$$SN = a1\,D1 + a2\,D2m2 + a3\,D3m3 \qquad 2\text{-}2$$

Where:

- D1, D2, and D3= The thickness (inch) of the surface, base, and subbase layers, respectively,
- $a_1$, $a_2$, and $a_3$ = The layer coefficients of the surface, base, and subbase layers, respectively,
- $m_2$ and $m_3$ = The drainage coefficients for the base and subbase layers, respectively.

### 2.6.2 External Factors

There are external factors that may have a significant effect on pavement rutting such as traffic loading and environmental conditions. The following sections will cover these factors.

#### 2.6.2.1 Traffic Loading

The repetitions of heavy traffic loads accelerate elastic deformation in layers of roadbeds, and cause permanent deformations. Therefore, the effect of traffic loads should be considered in the design process. According to the American Association of State Highway and Transportation Officials (1993) pavement rutting is directly related to the magnitude and frequency of the applied truck loading. Sebaaly and Tabatabaee (1989) showed that the deformation that is longitudinal to the base of the surface layer increases from 200 to 400% by increasing the load from 42 to 86 KN. The authors noted that the heavy trucks do not have the same effect on pavement because of the differences in the truck loads and the configuration of loads transmitted to the pavement layers. The design of pavement should depend on the loads of heavy trucks in the highways and some main street because pavement design depends on the passenger cars or light truck will fail to carry as well as distribute the heavy trucks loads. Pierre, et al (2003) explained that the loads of heavy vehicles are the main factor that leads to reduced life of flexible pavement. Various numbers of axles are applied on roadbed, which will deteriorate the pavement structure during the design life of the flexible pavements. It is difficult to calculate the total axle load because there are many factors related to traffic loads such as tire and axle load, contact pressure, axle and tire configuration, traffic speed, and the number of loading repetitions. Consequently, in the AASHTO design method, multiple axles are converted to a standard axle load (80- KN ESAL, Equivalent Single Axle Load) (Ali, 2006).

Equivalent single axle load is an expression developed from the data collected at the AASHO Road Test conducted from 1958-1960 in Ottawa, Illinois. The reference axle load is an 18,000-lb single axle with dual tires (Skorseth and Selim, 2000). According to AASHTO (1993) the following formula relates the ESAL's to Load Equivalent Factor (LEF), number of axle load groups, and the number of passes of the axle load.

$$\sum \mathbf{ESALs} = \mathbf{Traffic\ Factor} * \mathbf{Load\ Repetition} \qquad 2\text{-}3$$

$$\sum \mathbf{ESALs} = \mathbf{T_f\,.\,T.\,G.\,D.\,L.\,365\,.\,Y} \qquad 2\text{-}4$$

Where:

- $T_f$= Truck factor
- T= percentage of trucks in ADT (Average Daily Traffic).

- D= Directional distribution factor (percent of trucks in design direction).
- L= Lane distribution factors, (percent of trucks in design lane).
- Y= Design period in years (typically 20 years).
- G = Growth factor

$$\mathbf{T_f = \left(\sum_{i=1}^{m} P_i . F_i\right) A} \quad 2\text{-}5$$

Where:

- $p_i$ = Percentage of total repetitions for the *i*th load group.
- $F_i$ = Equivalent axle load factor for the *i*th load group.
- A = Average number of axles per truck.

$$\mathbf{G = \frac{(1+g)^n - 1}{g}} \quad 2\text{-}6$$

Where:

- g = Future projection, annual growth rate.
- n = Analysis period in years.

### 2.6.2.2 Environmental Factors

Environmental factors have a significant effect on pavement rutting, especially when the surface layer is subjected to high temperature, or when subgrade layer affected by seasonal climate variations. In other words, the rutting of underlying layers of pavements is affected by the low temperature: therefore, in low temperature the frost may lead to frost heave and reduce the bearing capacity of these layers during thawing (OECD, 1988). Asphalt binder is sensitive to temperature which makes the mixture stiffer during the winter season and softer during the summer season. For this reason, the pavement rutting risk will decrease during the winter season and will increase during the summer season (Archilla, 2000).

The moisture also has a significant effect on pavement layers. For example, existance of moisture would affect the material of base layer, which will lead to pavement rutting. Masada, et al. (2004) showed that the risk of pavement rutting would increase during the spring season due to the negative effect of moisture on the base layer material. Existance of moisture in the pavement layers would reduce dry density in the roadbed layers and would reduce the adhesion between the aggregate and asphalt binder, which will lead to pavement rutting. 5

## 2.7 Empirical Rutting Models

Over the years, designers have used the results obtained from road tests for efficient pavements design and for enhanced understanding of pavement performance. The most common relevant findings in the earlier road test help the designer to develop pavement design procedures.

In recent years, several models have been developed to forecast the rutting of flexible pavements. However, all developed models are not universally accepted (Xiao, 2006). Pavement rut depth models developed by several researchers such as HRB (1962), Hicks and Finn (1970), Maree, et al (1982), Paterson (1987), Epps, et al. (1997), Harvey, et al.(1999) and Brown et al. (2002) generated a concave curve of pavement rut depth. Therefore, the concave shape of rut depth with cumulative number of traffic loads repetitions is the key finding in the empirical literature (Archilla and Madanat, 2000, Archilla, 2000, Luo and Prozzi, 2008).

The most significant developed rutting models found in the literature are:

Thompson and Nauman Model

Pavement rutting rate developed by (Thompson and Nauman, 1993). The following equation was used to calculate the pavement rut rate.

$$\mathbf{R_R = \frac{RD}{N} = \frac{A}{N^B}} \qquad 2\text{-}7$$

Where:

- RR = Rutting rate
- RD = Rut depth, (in).
- N = The number of repeated load applications.
- A and B = Terms developed from field calibration data.

Archilla and Madanat Model

Archilla and Madanat developed a model depend on data from AASHO Road Test using a rut depth instead of a rutting rate which was used by Thompson and Nauman. The form of the model is as following(Archilla and Madanat, 2000):

$$\mathbf{RD_{it} = \beta_{i10} + a_i\, N_{it}^{bi}} \qquad 2\text{-}8$$

Where:

- $RD_{it}$ = Ruth depth (mm) for section i at time t.
- $\beta_{i10}$ = Ruth depth immediately after construction for pavement section i.
- $a_i$ and $b_i$ = Function of the characteristics of pavement I such as layer thickness, gradation, etc.

- $N_{it}$ = Variable representing the cumulative number of load repetitions applied to pavement section I up to time of period t.

Many pavement rutting models have been developed. Statistical analysis was performed where pavement rutting was used as dependent variables and the factors that affect the pavement rutting were used as independent variables. The rut depth is most widely used as rutting indicator (Wang, 2003).

The literature indicates that various studies have been carried out focusing on factors affecting pavement rutting including traffic loading, pavement material, pavement layers thickness, and environmental factors in specific climate zones (The study area in the North America have been divided into four climate zones which are dry freeze zone, wet freeze zone, dry no freeze zone, and wet no freeze zone which will defined later) due to unavailability and limitations of the data. For example, Senn, et al. (1997) developed rutting model using LTPP at dry freeze and dry no freeze zones. Archilla and Madanat (2000) also developed rutting prediction model based on data collected from AASHTO Road Test (wet freeze zone). Luo and Prozzi (2008) developed rutting prediction model using data collected from LTPP sections in State of Texas. Wang (2003) developed rutting prediction model using experimental data collected from all climate zones. These models should be used only in the states where it was developed. Therefore, more studies are still needed to create rutting prediction model for different climate zones.

This dissertation research developed pavement rutting prediction models for various climate zones of the U.S based on the LTPP data. However, the developed models could be also used in other parts of the world for similar climate to predict pavement rutting.

# CHAPTER 3 - METHODOLOGY

This chapter focuses on the process of developing new pavement rutting models based on the LTPP data. To develop a reliability-based methodology for pavement rutting prediction models, nine main steps were performed. These steps are shown in Figure 3-1. It includes reviewing previous studies - literature review, reviewing data sources of pavement performance, selecting the variables that may have effect pavement rutting, selecting the test sections at each climate zone, building the research database, verifying the data, analyzing the data, validating the models, and obtaining the final form of the models.

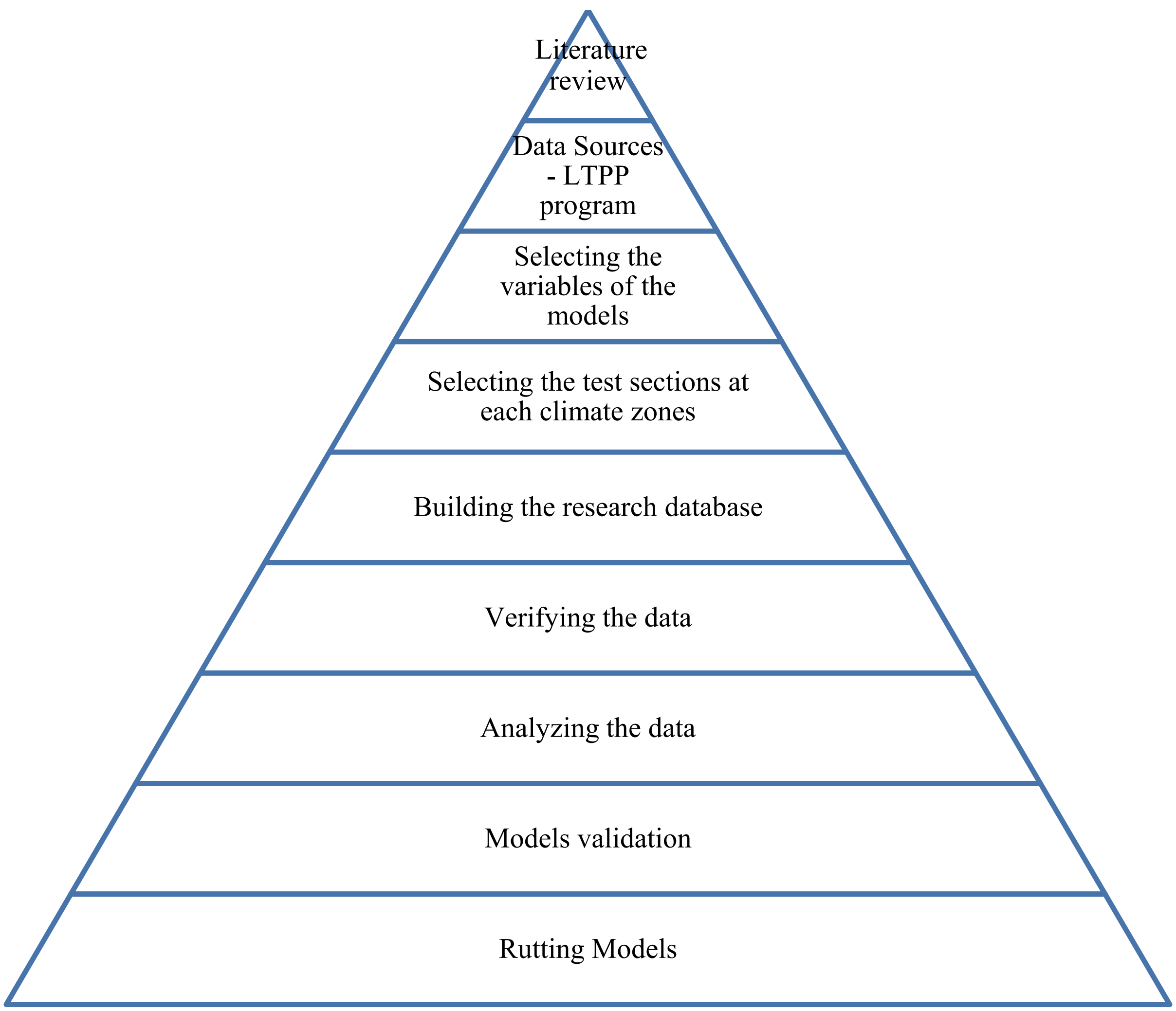


**Figure 3-1: Modeling methodology**

## 3.1 Review of the Literature

As mentioned in chapter two, in the recent years, several models have been developed to forecast the rutting of flexible pavements. However, all developed models are not universally accepted (Xiao, 2006). This step was covered in chapter two

## 3.2 Data Source

There are many in-service pavement performance databases such as Federal Highway Administration (FHWA), Accelerated Loading Facility (ALF), Long Term Pavement Performance Program (LTPP), United States Army Corps of Engineers (USACOE), Cold Regions Research and Engineering Laboratory (CRREL), WesTrack, MnROAD , and AASHTO Road Test. The LTPP database was used in this research because it is the largest pavement performance database in the world. The LTPP database includes extensive pavement performance data from different climate zones, which will help to develop efficient pavement rutting prediction models.

### 3.2.1 Historical Background of LTPP

The LTPP program encompasses field experiments and has more than 2400 in- service pavement test sections across the U.S. and Canada and aims to monitor pavement performance on these sections over a long time.

The LTPP program was designed as a 20-year program. In the late of 1980s, the Transportation Research Board (TRB) and the Federal Highway Administration (FHWA), with the corporation of the American Association of State Highway and Transportation Officials, conducted a study of the deterioration of the nation's highway and bridge infrastructure system to evaluate pavement performance and determine the factors that may have an effect on it (Rowshan, 1998). The study was described in Special Report 202, which is known as the Strategic Transportation Research Study (STRS) report and published by TRB. The study emphasized six research areas, one of which is the Long Term Pavement Performance program as one of the key research areas. Moreover, the objective of that study was to research and develop a national research program that would contribute to a better understanding of pavement performance and improve the existing pavement design procedures (Elkins, et al., 2009). The Strategic Highway Research Program (SHRP) took charge of the program from 1987 to 1992; then, FHWA has taken charge since 1992.

### 3.2.2 The LTPP Experiment

There are two types of experiments in the SHRP-LTPP program, the General Pavement Studies (GPS) and the Specific Pavement Studies (SPS), while the FHWA- LTPP included the Seasonal Monitoring Program (SMP) as an integral part of the LTPP program (Rowshan, 1998). The GPS test sections have used existing pavements while the SPS sections are multiple test sections that have different experimental treatments. The SPS section will be assigned as a GPS section when it is rehabilitated (Elkins, et al., 2009). Data that relate to the structural capacity and the seasonal variation of the material prosperities of existing pavements are included in the SMP (Salem, 2004). There are around 2400 test sections of the General Pavement Studies (GPS) and the Specific Pavement Studies (SPS) in the U.S and Canada.

#### 3.2.2.1 The General Pavement Studies

The GPS include 800 test sections. The objective of those tests is to investigate the pavement performance, which will help to develop efficient pavement design. The experiments numbers and experiment titles of GPS section are shown in Table 3:1.

**Table 3:1: List of GPS experiments**

Source: (Elkins, et al., 2009)

| Experiment | Experiment Title |
|---|---|
| GPS-1 | Asphalt Concrete (AC) Pavement on Granular Base |
| GPS-2 | AC Pavement on Bound Base |
| GPS-3 | Jointed Plain Concrete Pavement (JPCP) |
| GPS-4 | Jointed Reinforced Concrete Pavement (JRCP) |
| GPS-5 | Continuously Reinforced Concrete Pavement (CRCP) |
| GPS-6A | Existing AC Overlay of AC Pavement (existing at the start of the program) |
| GPS-6B | AC Overlay Using Conventional Asphalt of AC Pavement–No Milling |
| GPS-6C | AC Overlay Using Modified Asphalt of AC Pavement–No Milling |
| GPS-6D | AC Overlay on Previously Overlaid AC Pavement Using Conventional Asphalt |
| GPS-6S | AC Overlay of Milled AC Pavement Using Conventional or Modified Asphalt |
| GPS-7A | Existing AC Overlay on PCC Pavement |
| GPS-7B | AC Overlay Using Conventional Asphalt on PCC Pavement |
| GPS-7C | AC Overlay Using Modified Asphalt on PCC Pavement |
| GPS-7D | AC Overlay on Previously Overlaid PCC Pavement Using Conventional Asphalt |
| GPS-7F | AC Overlay Using Conventional or Modified Asphalt on Fractured PCC Pavement |
| GPS-7R | Concrete Pavement Restoration Treatments With No Overlay |
| GPS-7S | Second AC Overlay, Which Includes Milling or Geotextile Application, on PCC Pavement With Previous AC Overlay |
| GPS-9 | Unbounded PCC Overlay on PCC Pavement |

#### 3.2.2.2 The Specific Pavement Studies

There are around 1600 test sections in the LTPP program. The SPS objective is to understand how different experimental treatment and the particular features affect the pavement performance. Table 3:2 show the SPS section experiments.

**Table 3:2: List of SPS experiments**

Source: **(Elkins, et al., 2009)**

| Category | Experiment | Title |
|---|---|---|
| Pavement Structure Factors | SPS-1 | Strategic Study of Structural Factors for Flexible Pavements |
| | SPS- 2 | Strategic Study of Structural Factors for Rigid Pavements |
| Pavement Maintenance | SPS-3 | Preventive Maintenance Effectiveness of Flexible Pavements |
| | SPS-4 | Preventive Maintenance Effectiveness of Rigid Pavements |
| Pavement Rehabilitation` | SPS-5 | Rehabilitation of AC Pavements |
| | SPS-6 | Rehabilitation of jointed Portland Cement Concrete (JPCC) |
| | SPS-7 | Bounded PCC Overlays of Concrete Pavements |
| Environmental Effects | SPS-8 | Study of Environmental Effects in the Absence of Heavy Loads |
| Asphalt Aggregate Mixture Specifications | SPS-9 P | Validation and Refinements of Superpave Asphalt Specifications and Mix Design Process |
| | SPS-9 A | Superpave Asphalt Binder Study |

In this research, GPS-1 test sections, Asphalt Concrete (AC) on granular base, was selected because it is a commonly constructed pavement type. GPS-1 is a surface layer of dense-graded hot mix asphalt concrete. In Addition, pavement in these sections include asphalt concrete layer with or without other hot mix asphalt concrete (HMAC) layers (Elkins, et al., 2009).

### 3.2.3 LTPP Data

The LTPP data are available online and offline. The online LTPP data have been available to the public at http://www.datapave.com since March 2003 while the offline LTPP data are available annually to the public on DVD-ROM. This research used the LTPP Information Management System (IMS) Standard Data Release 23 released in January 2009.

The LTPP data is classified into the following modules as shown by Elkinse, et al. (2009):

- Administration (ADM): Tables of structure of the data and the master test section control are included in this module (Elkins, et al., 2009).
- Automated Weather Station (AWS): Data collected by the LTPP program from automated weather stations installed on some SPS projects are included in this module (Elkins, et al., 2009).
- Climate (CLM): Data collected from offsite weather stations that are used to compute a simulated virtual weather station for LTPP test sections or project sites are included in this module (Elkins, et al., 2009).
- Dynamic Load Response (DLR): This module includes dynamic load response instrumentation data from SPS test sections located in North Carolina and Ohio (Elkins, et al., 2009).

- Ground Penetrating Radar (GPR): Layer thickness data determined from ground penetrating radar measurements on SPS-1 and other selected SPS projects are included in this module (Elkins, et al., 2009).

- Inventory (INV): Inventory information for all GPS test sections and for SPS sections is included in this module (Elkins, et al., 2009).

- Maintenance (MNT): Information on maintenance-type treatments reported by a highway agency that were applied to a test section is included in this module (Elkins, et al., 2009).

- Mechanistic-Empirical Pavement Design Guide (MEPDG). All the computed parameters formatted for use as inputs to the Mechanistic-Empirical Guide for the Design of New and Rehabilitated Pavement Structures developed under NCHRP project 1-37A are included in this module (Elkins, et al., 2009).

- Monitoring (MON): Data of Pavement performance monitoring are included in this module. The Monitoring Module is the largest module in the LTPP data (Elkins, et al., 2009).

- Rehabilitation (RHB): This module contains the various applied rehabilitation treatments that result in changes to CONSTRUCTION_NO treatments (Elkins, et al., 2009).

- Seasonal Monitoring Program (SMP): This module contains data for moisture content, pavement subsurface temperature, onsite air temperature and precipitation, and frost-related measurements (Elkins, et al., 2009).

- Specific Pavement Studies (SPS): SPS-specific general and construction information are included in this module contains (Elkins, et al., 2009).

- Traffic (TRF): Traffic loads, classification, and volume data are included in this module (Elkins, et al., 2009).

- Test (TST): This module contains information about field and laboratory material testing (Elkins, et al., 2009).

As mentioned previously, the LTPP data has been distributed to the public since the early 1990's. The data were distributed in ASCII or Microsoft Excel file format, which can be transferred to Microsoft Access. It has become an accepted tool for analyzing the LTPP data that the LTPP program is now distributed in Access 2000® databases (Elkins, et al., 2009).

### 3.2.4 LTPP Quality Control

The LTPP program received data from different agencies in paper format, which needed additional effort to check and validate. In addition, the received data was routinely checked before loading to database and categorized in three levels according to quality control checks; level C, D, and E. (Elkins, et al., 2009).

Elkins, et al. (2009) explained the meaning of the level of quality control checks as follows:

- Record with level C means the quality check was to identify a null value in critical fields.

- Record with level D means the quality check was on the validity and reasonableness of filed values.

- The highest level of the quality control checks is level E where a wide range of checks are performed, compare the value in one field with another value in another field.

All the data was used in this research have a quality control of level E.

### 3.2.5 LTPP Climate Zones

In the LTPP data, the study area in North America (US and Canada) have been divided into four zones, depending on the freeze index and precipitation (Hadley, 1994). These are dry freeze zone, dry no-freeze zone, wet freeze zone, and wet no-freeze zone as shown in Figure 3-2.


**Figure 3-2: LTPP climate zones**

Source: (Hadley 1994)

Zone with freezing index exceeding 66 °C is considered freeze zone, while no-freeze zone is zone that has freezing index below 66 °C(Smith, et al., 2002) . Zone with greater than 508 mm precipitation per year is a wet zone. Dry zone is a zone with less than 508 mm precipitation per year (Smith, et al., 2002). Freezing Index and precipitation values for each climate zone are tabulated in Table 3:3.

**Table 3:3: Freezing Index and precipitation for each climate zone**

| Climate Zone | Freezing Index | Precipitation |
|---|---|---|
| Dry Freeze | > 66 °C-days / year | < 508mm/ year (20 in/ year) |
| Wet Freeze | > 66 °C- days / year | > 508mm/ year (20 in/ year) |
| Dry No- Freeze | < 66 °C- days / year | < 508mm/ year (20 in/ year) |
| Wet No- Freeze | < 66 °C- days / year | > 508mm/ year (20 in/ year) |

## 3.3 Initial Selection of Variables for the Models

The main objective of this research is to develop empirical models to forecast the rutting of flexible pavement on granular base sections in various climate zones. There are several factors, internal and external, which may influence the development of pavement rutting. These factors should be understood when designing or evaluating pavements to be able to forecast the pavement's functional and structural conditions over time.

The independent variables were initially selected based on structural, availability and limitation of the LTPP data, previous studies using the LTPP data, and engineering knowledge and judgment. Therefore, the main quantitative variables that were selected in the models were temperature (freeze, or no freeze) and moisture (dry, or wet). There were other factors selected in the development process of the models such as traffic loads, pavement strength (Structural Number), resilient modulus, asphalt content, voids in the mineral aggregate, air voids in the mix, Marshall stability, and Marshall flow. Table 3:4 contain the dependent variable and independent variables that were selected to develop the models. The table contains the name of the variables, field name, and its LTPP table name.

**Table 3:4: Models variables**

| Variable Name | LTPP- Field | LTPP Table |
|---|---|---|
| Rut depth (mm) | MAX_MEAN_DEPTH_1_8 | MON_T_PROF_INDEX _SECTION |
| Traffic loads (KESAL) | ANL_KESAL_LTPP_LN _YR | TRF_HIST_EST_ESAL &TRF_MON_EST_ESAL |
| Number of days maximum temperature > 32 °C (day) | DAYS_ABOVE_32_C_YR | CLM_VWS_TEMP_ANNUAL |
| Freeze Index (°C) | FREEZE_INDEX_YR | CLM_VWS_TEMP_ANNUAL |
| Total annual precipitation (mm) | TOTAL_ANN_PRECIP | CLM_VWS_PRECIP_ANNUA L |
| Resilient modulus (MPa) | RES_MOD_AVE | TST_UG07_SS07_WKSHT_S UM |
| Asphalt content in the mix (%) | ASPHALT_CONTENT_MEA N | INV_PMA_ORIG_MIX |
| Air voids in the mix (%) | PCT_AIR_VOIDS_MEAN | INV_PMA_ORIG_MIX |
| Voids in the mineral aggregate (%) | VOIDS_MINERAL_AGGR | INV_PMA_ORIG_MIX |
| Marshall stability (lb) | MARSHALL_STABILITY | INV_PMA_ORIG_MIX |
| Marshall flow (0.01 in) | MARSHALL_FLOW | INV_PMA_ORIG_MIX |
| Structural number | ESAL calculator software | ESAL calculator software |

### 3.3.1 Response Variable

Pavement rut depth was used as the dependent variable to develop the pavement rutting models. Rutting data are stored in MON_T_PROF_INDEX* tables in MON Module of the LTPP data. The rutting is characterized based on a variety of transverse profile distortion indices. Furthermore, there are two important ways to measures rut depth: 1.83-m (6-ft) straightedge method; and lane-width wireline reference method (Elkins, et al., 2009).

#### 3.3.1.1 The Straightedge Rut-Depth Method

Elkins, et al. (2009) explained that the straightedge rut-depth method is used to find the maximum displacement from the bottom of the straightedge to the top of the pavement surface by positioning the straightedge at various locations in each half of the lane, and there are three profile distortion indices in this method: maximum depth, offset from a lane edge to the point of maximum depth, and depression width for each half of the lane. These profile distortion indices are shown in Figure 3-3.

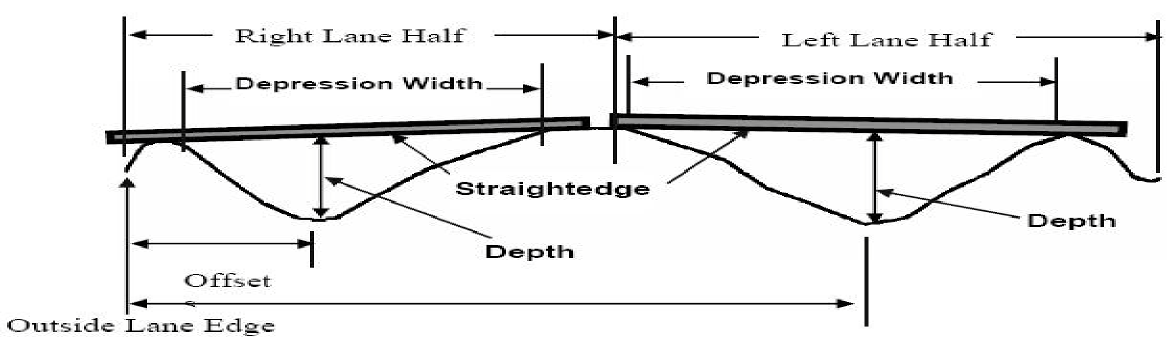


**Figure 3-3: LTPP transverse pavement distortion indices - 1.83 m straightedge method**

Source: (Elkins, et al., 2009)

#### 3.3.1.2 The Lane-Width Wireline Rut Depth Method

The objective of lane-width wireline rut as shown by Elkins, et al (2009) is to find the maximum displacement of rutting based on an imaginary wireline that is anchored at each lane edge. As shown in Figure 3-4, the peak elevation point is connected by the wire reference. There are three profile distortion indices: maximum depth, offset from a lane edge to the point of maximum depth, and depression width (Elkins, et al., 2009).

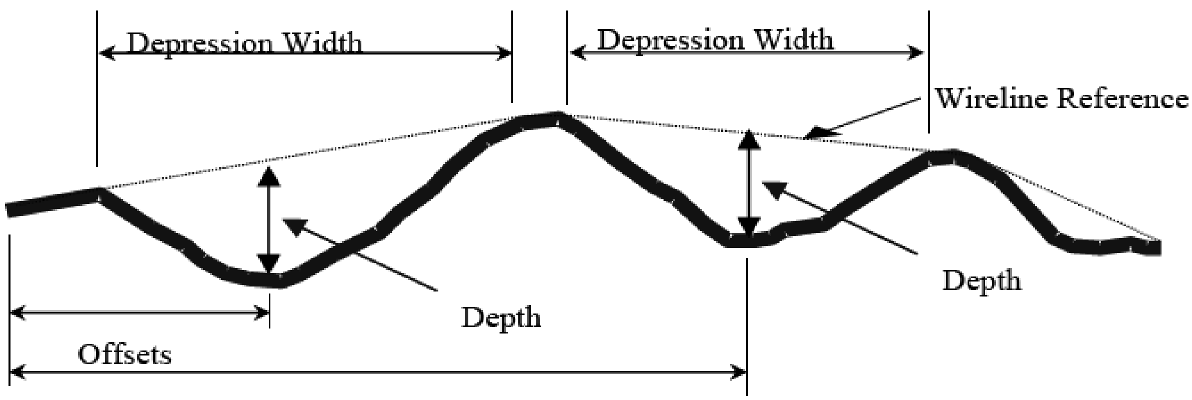


**Figure 3-4: LTPP transverse pavement distortion indices - lane-width wireline method**

Source: (Elkins, et al., 2009)

The rutting data in LTPP- IMS collected by straightedge method was used in this research. The maximum rut depth collected by this method (MAX_MEAN_DEPTH_WIRE_ REF) is located at Monitoring Module in MON_T_PROF_INDEX_SECTION.

### 3.3.2 Explanatory Variables

Based on structural, availability and limitation of the LTPP data, previous studies using the LTPP data, and engineering judgments, it is difficult to capture and address all the factors that affect rutting, which was discussed in section 2.6. Therefore, traffic loads, number of days when the maximum temperature is more than 32 C°, freeze index, total annual precipitation, resilient modulus, air voids in the mix, voids in the mineral aggregate, Marshall stability, Marshall flow, and structural number were selected as independent variables to build the models.

#### 3.3.2.1 Traffic Loads

There are two types of traffic data: historical traffic data and monitored traffic data. Historical traffic data provide traffic data for each year from the original construction date to 1990; while, the monitoring traffic data are annual estimates after 1990 provided by the participating highway agency or computed from raw data (Luo and Prozzi, 2008). Traffic loads were used in this research as main factors affecting flexible pavement rutting.

The field ANL_KESAL_LTPP_LN_YR in Table TRF_HIST_EST_ESAL includes the annual ESAL estimates from the original construction date to 1990. In addition, the field ANL_KESAL_LTPP_LN_YR in Table TRF_MON_EST_ESAL includes the annual estimates ESALs after 1990.

#### 3.3.2.2 Environmental Data

Traffic loads are the most important factors that lead to acceleration of pavement rutting; however, climate factors, temperature and precipitation, also have a significant effect on pavement rutting. In this research database development process, average annual precipitation (mm), average number of days above 32 $^{o}$C, and freezing index (FI) were extracted from the climate module tables.

The following equation is generally used to calculate the Freezing Index:

$$\mathbf{FI} = \sum_{i=1}^{n}(\mathbf{0} - \mathbf{Ti}) \qquad 3\text{-}1$$

where:

- FI= Freezing index, (ºC) degree-days.
- Ti= Average Daily air temperature on day i (ºC).
- n= Days in the specified period when average daily temperature is below freezing.
- i= Number of days below freezing.

The field FREEZE_INDEX_YR in Table CLM_VWS_TEM_ANNUAL includes the annual freezing indices of the test section. The number of days above 90 $^{o}$F (32 Cº) is stored in the field DAYS_ABOVE_32_C_YR. Field TOTAL_ANN_PRECIP in table CLM_VWS_ PRECIP_ ANNUAL includes the annual precipitation information.

#### 3.3.2.3 Subgrade Material Stiffness

As previously stated, material stiffness is the ability of subgrade material to carry the repetition of traffic loads, and material strength and bearing capacity are the most common characterizations of subgrade material. California Bearing Ratio (CBR), resistance value (R-Value), and resilient modulus ($M_R$) are the most common characterizations of subgrade stiffness (WAPA, 2002). In this research, the resilient modulus was used as characterization of subgrade material stiffness. Subgrade material resilient modulus data extracted from Material Test module. The resilient modulus field was saved as RES_MOD_AVE in TST_UG07_ SS07_ WKSHT _SUM table.

#### 3.3.2.4 Pavement Structural Strength

Pavement structural strength is the ability of the roadbed layers to carry the repeated traffic loads as well as distributing the vertical deformation to the lowest layer. The AASHTO method of pavement design uses structural number (SN), which depends on the thickness and type of surface, base, and subbase layers, and serves as a measure of pavement structural strength. The structural number data are not included in the LTPP data because it is not a value that could be directly measured in the laboratory. Equation 2-2 is the generally used to calculate the structural number.

In this research the SN was selected as the measure of pavement load carrying capacity. The SN values derived from ESAL calculator software, which are available online at the LTPP products online (LTPP Products Online, 2007).

#### 3.3.2.5 Air Voids and Asphalt Content Data

The air voids content in the total mix (VTM) and excessive amount of the asphalt binder in the total mix (AC) are the most influenced properties of asphalt mixtures that may affect pavement rutting (Brown and Cross, 1989). Therefore, air voids and asphalt content in the total mix were selected as independent variables in the development process of the models.

Data of air voids and asphalt content in the pavement mixture are included in the fields PCT_AIR_ VOIDS_MEAN and ASPHALT_CONTENT_MEAN respectively. These fields are located in INV_PMA_ORIG_MIX in Inventory Module tables.

#### 3.3.2.6 Voids in the Mineral Aggregate

Voids in the mineral aggregate (VMA) is the percentage of voids in the compacted asphalt mixture. Roberts, et al. (1996) defined and explained (VMA) as the intergranular void space that exists between the aggregate particles, which are occupied by asphalt and air in a compacted asphalt mixture.

The VMA data in the LTPP data is included in the field VOIDS_MINERAL_AGGR that saved in INV_PMA_ORIG_MIX Table.

#### 3.3.2.7 Marshall Stiffness

Marshall stiffness, which is Marshall stability divided by Marshall flow, estimates load deformation characteristics of the mixture, and indicates the material resistance to pavement rutting (Asphalt Institute, 2001). A mixture with high Marshall stiffness is a stiffer mixture, and is resistant to pavement rutting (Abukhettala, 2006).

Marshal stability and Marshall flow data in the LTPP program is included in Marshall_Stability and Marshall_Flow fields. These fields are saved in INV_PMA_ORIG_MIX table.

## 3.4 Selecting Sections at Each Climate Zones

There are four climate zones in study area of U.S and Canada in the LTPP data. These zones are dry freeze zone, dry no-freeze zone, wet freeze zone, and wet no-freeze zone. The zones categorized based on freeze index and precipitation. Each zone includes many states and each state includes many test sections, but the number of test sections is varied from state to state.

In the administration module, the experiment table includes the key fields that were used to build the research database. Table 3:5 illustrates these fields and the name of the LTPP tables that include the data of these fields.

**Table 3:5: Sites identification**

| Filed Name | LTPP Table |
|---|---|
| STATE_CODE | EXPERIMENT_SECTION |
| SHRP_ID | EXPERIMENT_SECTION |
| CONSTRUCTION_NO | EXPERIMENT_SECTION |
| GPS_SPS | EXPERIMENT_SECTION |
| EXPERIMENT_NO | EXPERIMENT_SECTION |

In the LTPP program, each state or province has a specific code of a two-digit number (STATE_CODE). For example, Michigan state code is 26. Therefore, test sections code start with 26 is located in state of Michigan. In addition, each test section in state or province has a unique code number (SHRP ID, four digit numbers) to identify its location. Table A: 1 in Appendix A shows the code of each state or province.

CONSTRUCTION_NO indicates to the number of rehabilitation and maintenance performed in the test section. The test section with CONSTRUCTION NO 1 means that this section is not rehabilitated or maintained. Therefore, when the test section maintained or rehabilitated the CONSTRUCTION NO will increase by 1. GPS and SPS experiments and the EXPERIMENT _NO were discussed in section 3.2.2.

In this research, the asphalt concrete pavement on granular base (GPS1) test sections was selected to develop the empirical models to forecast the rutting of flexible pavement at different climate zones. Therefore, based on availability of data, the GPS1 test sections on the LTPP data were initially selected at each climate zone. The number of test sections is given in Table 3:6.

**Table 3:6: Selected GPS1 test sections at each climate zone**

| GPS Experiment | Wet-Freeze | Dry-Freeze | Wet- No Freeze | Dry- No Freeze | Total Sections |
|---|---|---|---|---|---|
| GPS1 sections | 77 | 42 | 51 | 23 | 193 |

Table 3:6 illustrate the number of selected test sections at each climate zone. It is 77, 42, 51, 23 for wet freeze zone, dry freeze zone, wet no freeze zone, and dry no freeze zone respectively. Wet freeze zone has the highest number of test sections and the dry no freeze zone has the lowest number of test sections.

## 3.5 Constructing the Research Database

LTPP database is the largest pavement performance database in the world. It provides extensive information about the pavements in different climate zones in the world. There are 14 modules in the LTPP data, which include more than 400 tables. Therefore, it is important to create a research database to be able to study and analyze the data in a cohesive manner. The following flow chart, Figure 3-5, explains the steps that were used to build the research database.

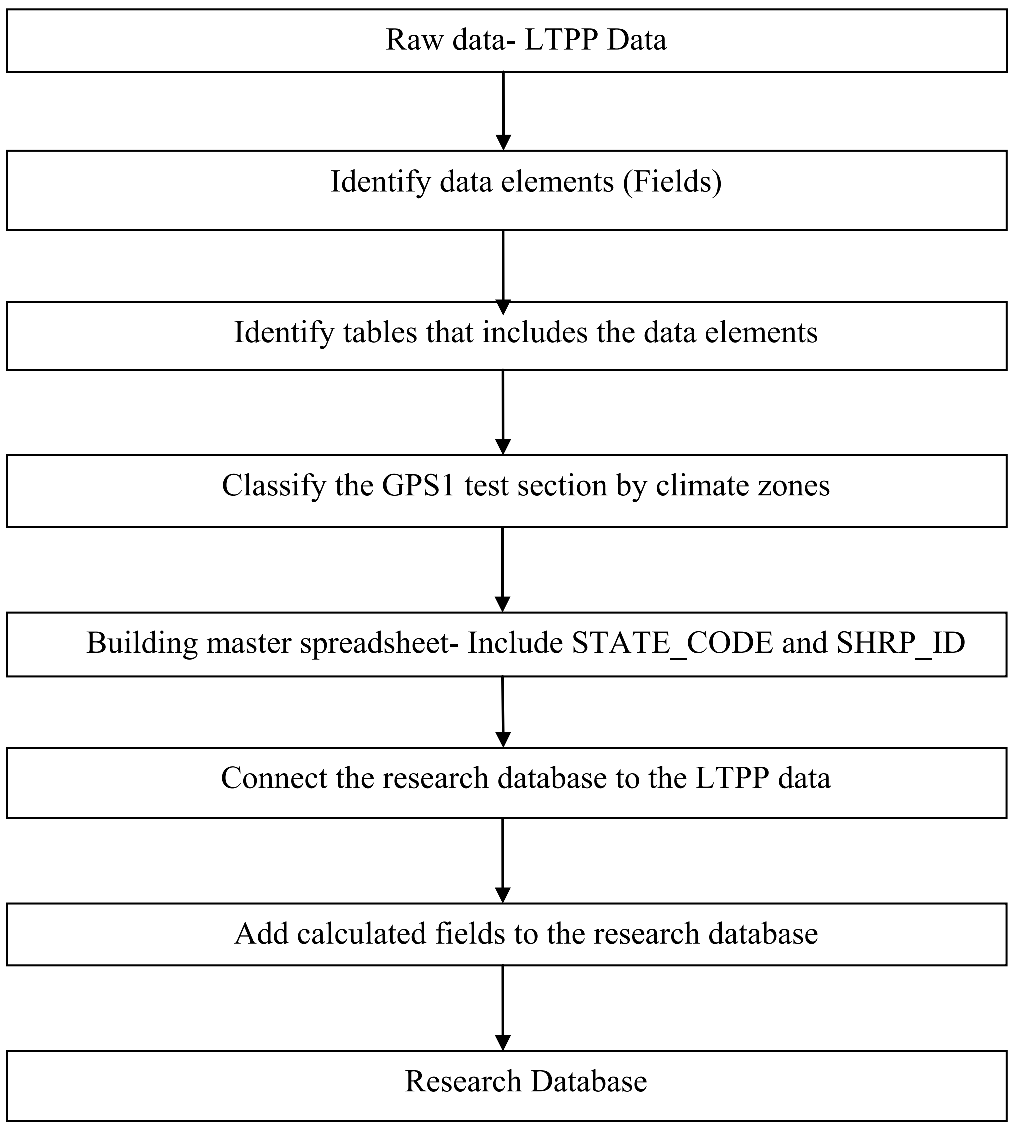


**Figure 3-5: Constructing the research database**

The flow chart illustrates the steps used to build the research database. The research data was derived from the LTPP raw data. The building process included the identification of the fields in the raw data and the fields that were calculated, such as SN. After determining the fields in the raw data, the tables where each field is located were identified. Then, a master spreadsheet was constructed. It included STATE_CODE and SHRP_ID. STATE_CODE and SHRP_ID used to connect the research database to the LTPP raw database to derive the efficient fields from the raw database. There are some factors such as SN that are not included in the LTPP data, but there are some fields in the raw database, which could be used to calculate these factors. Microsoft Access was used to construct the research database in this research project.

## 3.6 Data Validation

The main objective of this study is to develop empirical models to predict future pavement rutting in various climate zones. Statistical analyses were performed to establish a preliminary relationship between pavement rutting and the selected factors based on data pertaining to GPS-1 test sections.

The initially selected numbers of test sections were 193 to develop the rutting models. Pavement rutting data and selected independent variables data were incorporated in the analysis. The selection process of the independent variables was based on the construction of the LTPP data, availability of data in the LTPP set, and engineering knowledge of pavement design and performance.

There are many types of errors leading to outliers in data, but measurement errors and data entry errors, mechanical and technical errors, and incomplete historical data are the most important errors. Therefore, the raw data should be tested to identify any outliers.

The descriptive analysis is used to identify the missing values in the data. The graphical description, Scatter-plot and Box Plot methods, are used to identify any outlier in the raw data (Hinkle, et al., 2003). These methods were covered in the following sections.

### 3.6.1 Univariate Analysis

An exploratory analysis, univariate analysis, was performed to establish the descriptive data of rut depth and the independent variables. Univariate analysis individually investigates each variable in the data and gives a statistical summary such as number of cases at each field, minimum and maximum value of the field, mean, and standard deviation of each field.

Descriptive data of Wet Freeze zone, Dry Freeze zone, Wet No Freeze zone, and Dry No Freeze zone are tabulated in Table 3:7, Table 3:8, Table 3:9 and Figure 3-10 respectively. The univariate analysis was conducted before any exclusion of outlier or abnormal data.

**Table 3:7: Univariate analysis – wet freeze zone**

| Variables | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| Rut depth (mm) | 71 | 3 | 23 | 9.14 | 4.370 |
| Traffic loads (KESALs) | 70 | 11 | 357 | 119.27 | 77.842 |
| Days above 32 °C (day) | 68 | 0 | 68 | 11.13 | 15.303 |
| Freeze Index (°C) | 68 | 75 | 2270 | 630.77 | 477.833 |
| Precipitation (mm) | 68 | 451 | 2379 | 1040.47 | 318.135 |
| MR (MPa) | 66 | 45 | 85 | 65.47 | 12.403 |
| SN | 73 | 1.2 | 6.4 | 4.384 | 1.3371 |
| Asphalt content (%) | 69 | 3.6 | 6.9 | 5.252 | .8789 |
| VTM (%) | 72 | 1 | 11 | 4.22 | 2.043 |
| VMA (%) | 71 | 11 | 19 | 13.65 | 1.921 |
| MARSHALL STABILITY(lb) | 71 | 1295 | 2984 | 2094.00 | 249.349 |
| MARSHALL FLOW (0.01 in) | 71 | 6 | 21 | 12.04 | 2.226 |

**Table 3:8: Univariate analysis – dry freeze zone**

| Variables | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| Rut depth (mm) | 35 | 3 | 18 | 8.34 | 3.263 |
| Traffic loads (KESALs) | 42 | 3 | 1404 | 207.89 | 327.888 |
| Days above 32 °C (day) | 42 | 0 | 77 | 23.85 | 19.302 |
| Freeze Index (°C) | 42 | 30 | 1817 | 611.57 | 555.110 |
| Precipitation (mm) | 42 | 149 | 515 | 337.84 | 111.953 |
| MR (MPa) | 37 | 16 | 98 | 59.13 | 20.982 |
| SN | 42 | 1.6 | 6.7 | 3.771 | 1.1125 |
| Asphalt content (%) | 42 | 3.9 | 6.8 | 5.633 | .6083 |
| VTM (%) | 42 | 1.4 | 9.5 | 4.729 | 1.7934 |
| VMA (%) | 38 | 11.3 | 20.3 | 14.911 | 1.8873 |
| MARSHALL STABILITY (lb) | 37 | 654 | 2634 | 1705.49 | 527.851 |
| MARSHALL FLOW (0.01 in) | 38 | 7 | 16 | 10.55 | 2.044 |

**Table 3:9: Univariate analysis – wet no-freeze zone**

| Variables | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| Rut depth (mm) | 51 | 2 | 16 | 7.60 | 3.195 |
| Traffic loads (KESALs) | 49 | 2 | 2348 | 261.18 | 414.864 |
| Days above 32 °C (day) | 50 | 4 | 151 | 74.55 | 36.719 |
| Freeze Index (°C) | 50 | 0 | 84 | 15.04 | 19.749 |
| Precipitation (mm) | 50 | 437 | 1682 | 1203.65 | 322.358 |
| MR (MPa) | 51 | 21.5 | 184.3 | 86.382 | 34.1830 |
| SN | 51 | 1.1 | 7.3 | 4.118 | 1.5118 |
| Asphalt content (%) | 51 | 3.4 | 8.0 | 5.527 | 1.0446 |
| VTM (%) | 51 | 2.1 | 13.2 | 5.896 | 2.3950 |
| VMA (%) | 51 | 9.9 | 22.8 | 16.161 | 2.6128 |
| MARSHALL STABILITY (lb) | 51 | 1166 | 3401 | 2222.82 | 625.866 |
| MARSHALL FLOW (0.01 in) | 50 | 7 | 17 | 11.08 | 1.700 |

**Table 3:10: Univariate analysis – dry no-freeze zone**

| Variable | N | Minimum | Maximum | Mean | Std.Deviation |
|---|---|---|---|---|---|
| Rut depth (mm) | 20 | 4 | 21 | 8.65 | 4.886 |
| Traffic loads (KESALs) | 20 | 8 | 1415 | 413.65 | 467.686 |
| Days above 32 °C (day) | 20 | 57 | 191 | 101.25 | 43.783 |
| Freeze Index (°C) | 20 | 0 | 96 | 13.20 | 24.483 |
| Precipitation (mm) | 22 | 23 | 596 | 256.09 | 165.910 |
| MR (MPa) | 20 | 30 | 198 | 109.66 | 49.676 |
| SN | 23 | 2.9 | 6.4 | 4.030 | 1.0002 |
| Asphalt content (%) | 23 | 2.9 | 7.5 | 5.070 | .8652 |
| VTM (%) | 22 | 3.0 | 12.8 | 5.236 | 2.2152 |
| VMA (%) | 22 | 14.3 | 17.2 | 15.264 | .9011 |
| MARSHALL STABILITY (lb) | 4 | 1775 | 3752 | 2591.25 | 918.663 |
| MARSHALL FLOW (0.01 in) | 4 | 10 | 14 | 11.50 | 1.915 |

### 3.6.2 Identification of Missing and Abnormal Data

To develop a prediction model, the variables in the data were initially investigated to identify the missing, abnormal, and outliers of the data in each test section. There are many types of errors leading to outliers in data, but human errors, which are measurement errors and data entry errors, mechanical and technical errors, and missing of historical data are the most important errors. Therefore, the data were tested to identify any outliers. Scatter-plot and Box Plot methods were used to identify the outliers in the raw data.

#### 3.6.2.1 Missing and Abnormal Data in Rutting Data

Generally, the quality of the LTPP data varied from section to section. Therefore, the rutting data at each section was examined to identify any abnormal data. Section-by-section study, descriptive statistical analysis, and scatter-plot test were performed to evaluate the quality of the rutting data.

Descriptive statistics was performed to determine the missing value of rutting data. Table 3:11 include the valid, missing, and percentage of missing data at each climate zone.

**Table 3:11: Valid and missing values of rutting at each climate zones**

| Climate Zones | Wet Freeze | Dry Freeze | Wet No Freeze | Dry No Freeze |
|---|---|---|---|---|
| **Valid** | 71 | 35 | 51 | 20 |
| **Missing** | 3 | 7 | 0 | 3 |
| **%of missing** | 4.2 | 20.0 | 0.0 | 15.0 |

In this table, the dry freeze zone includes the highest percentage of missing rutting values (20%), while the wet no freeze zone does not include any missing values (0%).

Scatter-plot is a basic relationship between the dependent variable and independent variables, and the outlier points in a scatter plot-graph are the abnormal points that have very different values from the majority of the data (Hinkle, et al., 2003). The scatter-plot (X-Y) was used to identify the outliers in rutting data. In this method, the values of rutting were graphically displayed in scatter-plot against the pavement age.

Scatterplot test, which the rutting data at each section plotted against pavement age, was performed to determine the abnormal data. Figure 3-6 illustrates the relationship between the pavement rutting and pavement age. This figure gives an example of sections with a positive relationship between pavement rutting and time; pavement rutting increased with time, which is expected. Whereas, Figure 3-7 give an example of sections with a fluctuation in the relationship between the pavement rutting and pavement age, Figure 3-8 show a sudden increase or decrease in the pavement rutting with time. These sections were excluded from the data. Sections that have a negative relationship between rut and age, or in other words, the sections that have rut decreasing with time, were also excluded from the data. Figure 3-9 give an example of this relationship.

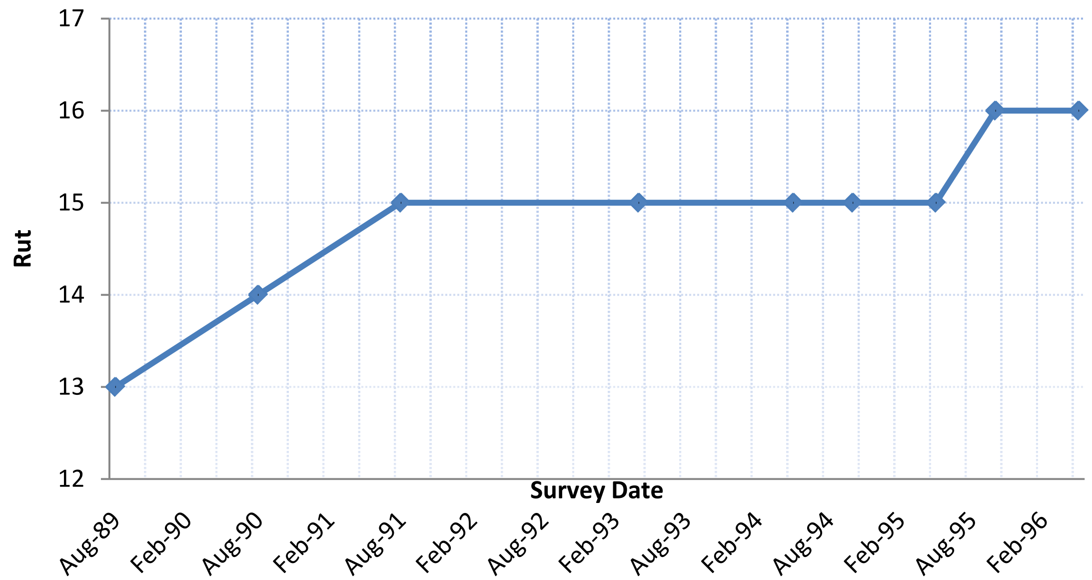


**Figure 3-6: Rut vs. survey date - section 231026**

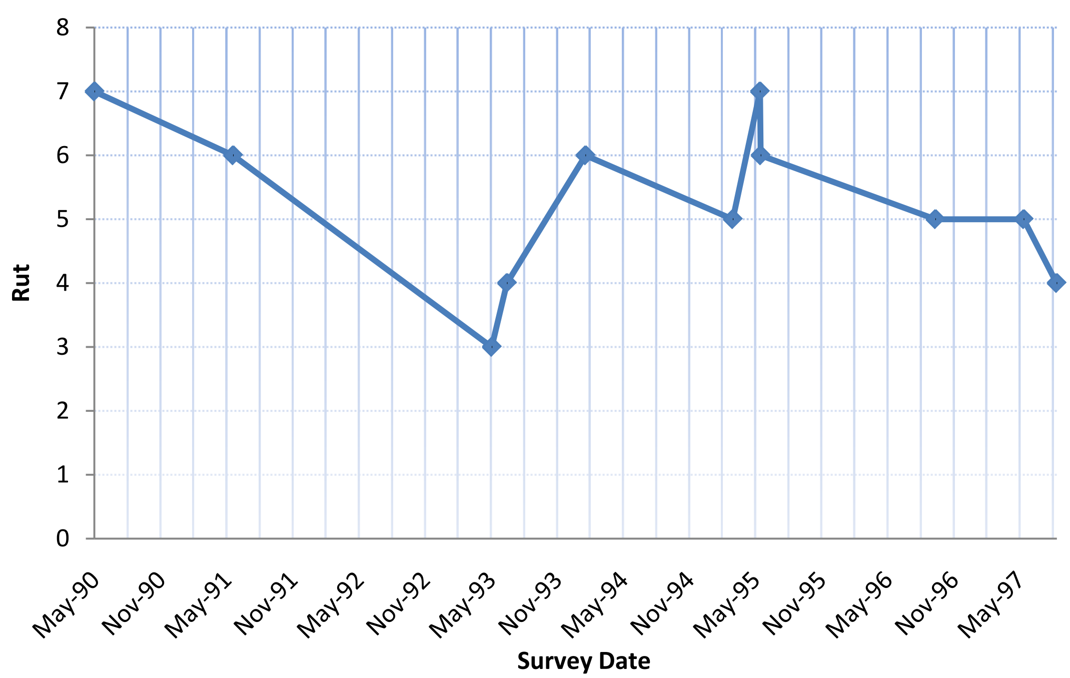


**Figure 3-7: Rut vs. survey date - section 276251**

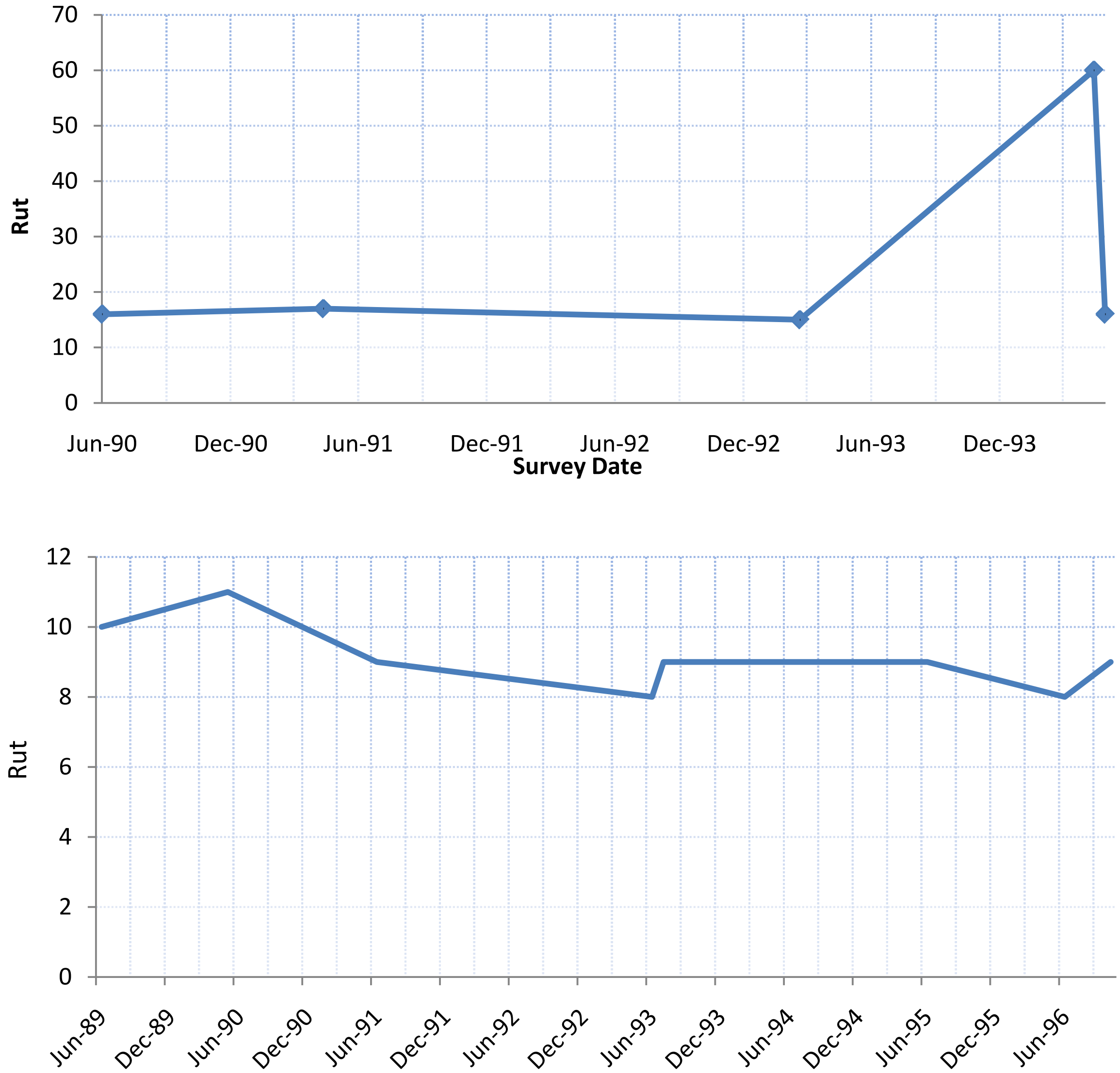


**Figure 3-9: Rut vs. survey date - section 271028**

### 3.6.2.2 Missing and Abnormal Data in Independent Variables

Independent variables were studied to evaluate the quality of data. Descriptive statistical analysis was conducted to determine the missing values in the independent variables. Table 3:12 and Table 3:13 include the variable name, valid values, missing values, and percentage of missing values at each climate zone.

**Table 3:12: Missing data of independent variables for wet and dry freeze zones**

| Independent Variables | Wet Freeze | | | Dry Freeze | | |
|---|---|---|---|---|---|---|
| | Valid | Missing | % of Missing | Valid | Missing | % of Missing |
| Traffic loads | 70 | 4 | 5.4 | 42 | 0 | 0.0 |
| Days above 32 °C | 68 | 6 | 8.1 | 42 | 0 | 0.0 |
| Freeze Index | 68 | 6 | 8.1 | 42 | 0 | 0.0 |
| Precipitation | 68 | 6 | 8.1 | 42 | 0 | 0.0 |
| MR | 66 | 8 | 10.8 | 37 | 5 | 11.9 |
| SN | 73 | 1 | 1.4 | 42 | 0 | 0.0 |
| AC | 69 | 5 | 6.8 | 42 | 0 | 0.0 |
| VTM | 72 | 2 | 2.7 | 42 | 0 | 0.0 |
| VMA | 71 | 3 | 4.1 | 38 | 4 | 9.5 |
| MARSHALL STABILITY | 71 | 3 | 4.1 | 37 | 5 | 11.9 |
| MARSHALL FLOW | 71 | 3 | 4.1 | 38 | 4 | 9.5 |

**Table 3:13: Missing data of independent variables for wet and dry no freeze zones**

| Independent Variables | Wet No Freeze | | | Dry No Freeze | | |
|---|---|---|---|---|---|---|
| | Valid | Missing | % of Missing | Valid | Missing | % of Missing |
| Traffic loads | 49 | 2 | 3.9 | 20 | 3 | 13.0 |
| Days above 32 °C | 50 | 1 | 2.0 | 20 | 3 | 13.0 |
| Freeze Index | 50 | 1 | 2.0 | 20 | 3 | 13.0 |
| Precipitation | 50 | 1 | 2.0 | 22 | 1 | 4.3 |
| MR | 51 | 0 | 0.0 | 20 | 3 | 13.0 |
| SN | 51 | 0 | 0.0 | 23 | 0 | 0.0 |
| AC | 51 | 0 | 0.0 | 23 | 0 | 0.0 |
| VTM | 51 | 0 | 0.0 | 22 | 1 | 4.3 |
| VMA | 51 | 0 | 0.0 | 22 | 1 | 4.3 |
| MARSHALL STABILITY | 51 | 0 | 0.0 | 4 | 19 | 82.6 |
| MARSHALL FLOW | 50 | 1 | 2.0 | 4 | 19 | 82.6 |

Marshall stability and Marshall flow at dry no freeze zone have the highest percentage of the missing values (82.6 %); whereas, the number of the valid values is 4 and the number of the missing values is 19. Therefore, Marshall stability and Marshall flow variables at dry no freeze zone were excluded from data that was used to build the model in dry no freeze zone. Dry no freeze zone includes the highest percentage of the missing values; while, the wet no freeze zone includes the lowest percentage of the missing values.

Missing data are not uncommon in many of the research studies reported in the literature. Missing values occur when some values of the data are not observed in the data, which will lead to incorrect results. Therefore, researchers always try to deal correctly with missing values or try to avoid it as much as possible (Adèr, et al., 2008). Little and Rubin (2002) exhibited the missing values patterns as follows:-

1. Univariate Non-response; this pattern exists where the missing values appear in single variables as shown in Figure 3-10- a.
2. Multivariate Tow Pattern; this pattern exists where the missing values appear in different variables but at the same cases as illustrated in Figure 3-10-b
3. Monotone; this type of pattern existed when the missing values have a monotone pattern as shown in Figure 3-10-c
4. General; this type of pattern existed when the missing values have a haphazard pattern as illustrated in Figure 3-10-d
5. File Matching; this pattern could exist when there is a large amount of data; wherefore, the likelihood that variables are never observed together arises as illustrated in Figure 3-10- e.

6. Factor Analysis; in this pattern, there are a completely missing variables as shown in Figure 3-10-f.

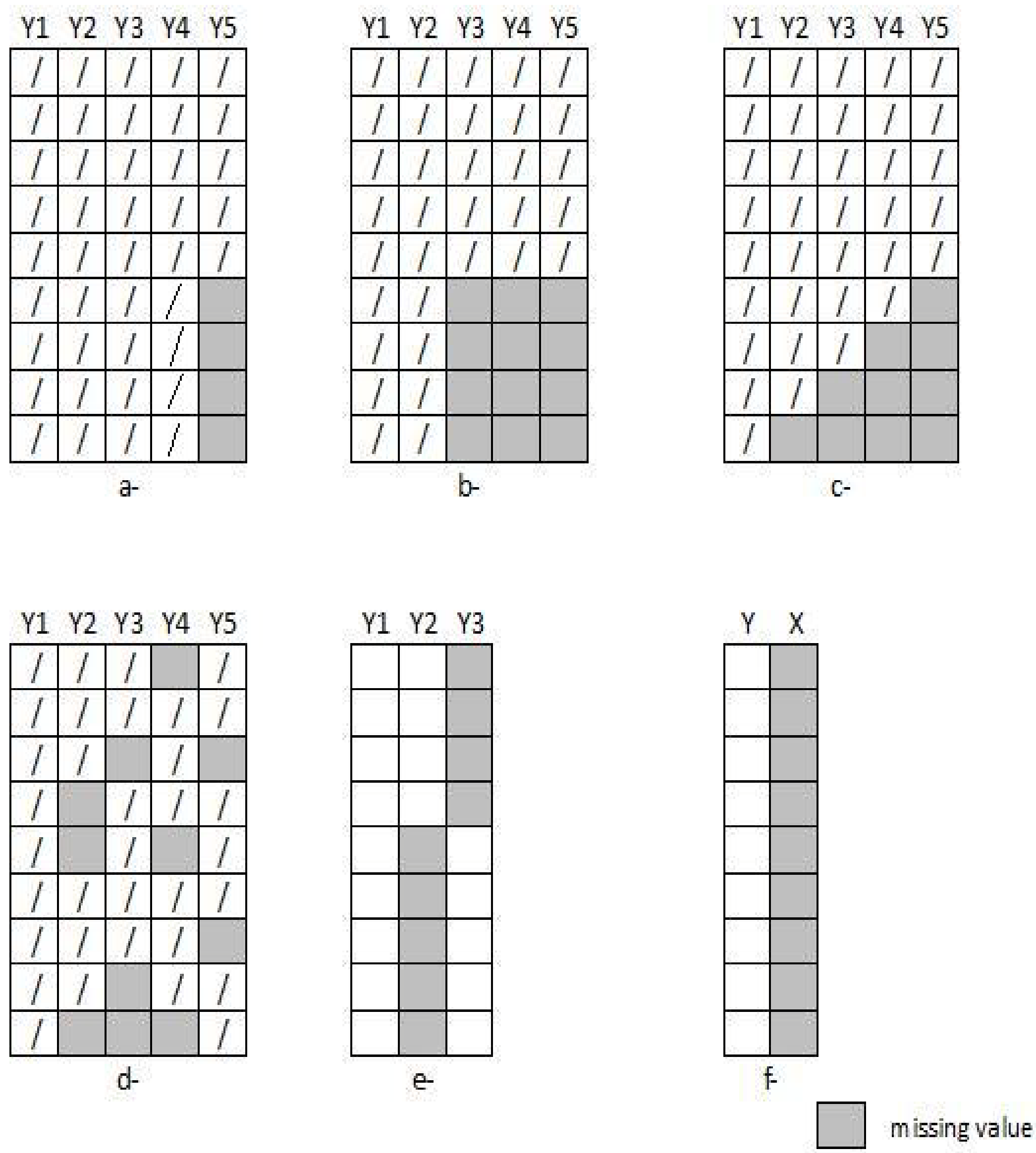


**Figure 3-10: Missing data patterns**

Source: (Little and Rubin, 2002)

In this research, the missing values could be classified as general pattern because the missing values have a haphazard pattern. These missing values are typically handled by imputation methods (Adèr, et al., 2008). Therefore, the imputation with mean method was used in this study.

As previously mentioned, the scatter-plot was used to identify the outliers in dependent variable data. Box plots method was used to determine the outlier and anomalous data in the independent variables.

Box plots method is a graphical method that displays the spread of scores in a distribution. Outlier points in the box plots methods are the points beyond the reasonable upper or lower boundary, but not less than 3 interquartile ranges from the box edge, and the extreme outlier point is the point with more than 3 interquartile range from the box edge (Montgomery, et al., 2001).

In this method, the median is used as the measure of the central tendency, while interquartile range (IQR) is used as a measure of dispersion, which is illustrated by the length of the box; therefore, the following five numbers are needed to graph the box plot (Hinkle, et al., 2003):

- Median
- Maximum value
- Minimum value
- $Q_3$ Third quartile (75 percentile)
- $Q_1$ First quartile (25 percentile)

The following equation is used to compute $Q_1$, and $Q_3$:

$$Px = ll + \left(\frac{np - cf}{fi}\right) * w \quad \textbf{3-2}$$

where:

- ll = Exact lower limit of the interval containing the percentile point.
- n = Total number of data.
- P = Proportion corresponding to the desired percentile.
- cf = Cumulative frequency of data below the interval containing the percentile point.
- fi = Frequency of data in the interval containing.
- w = Width of class interval.

IQR, the distance between the third percentile and first percentile, is computed as follows:

$$IQR = Q3 - Q1 \quad \textbf{3-3}$$

The following equation is generally used to compute the Reasonable Upper Boundary (RUP) and the Reasonable Lower Boundary (Hinkle, et al., 2003):

$$RUB = Q3 + 1.5(IQR) \quad \textbf{3-4}$$

and

$$RLB = Q1 - 1.5(IQR) \quad \textbf{3-5}$$

where

- IQR= Interquartile range

- RUB = Reasonable upper boundary.
- RLB = Reasonable lower boundary.
- $Q_3$= Third quartile (75 percentile).
- $Q_1$= First quartile (25 percentile).

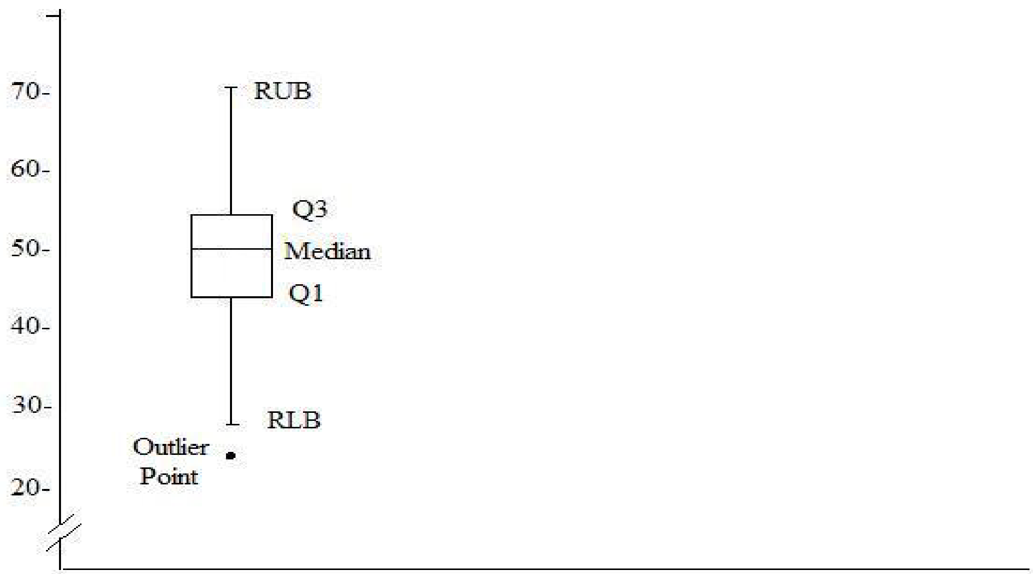


**Figure 3-11: Box plots**

Source: (Hinkle, et al., 2003)

Figure 3-11 shows the IQR, RUB, RLB, Median, $Q_3$, and $Q_1$. Outlier points are any points falling outside RUB or inside RLB (Jackson and Puccinelli, 2006).

Figure 3-12 and Figure 3-13 gives some examples about the outliers in the data. In Figure 3-12, there are no outlier points in asphalt content data. In Figure 3-13, there is one outlier value in structural number data at case number 7. In general, Predictive Analytics Software (PASW), which was used to analyze the data in this research, has good tools, which deal with outliers.

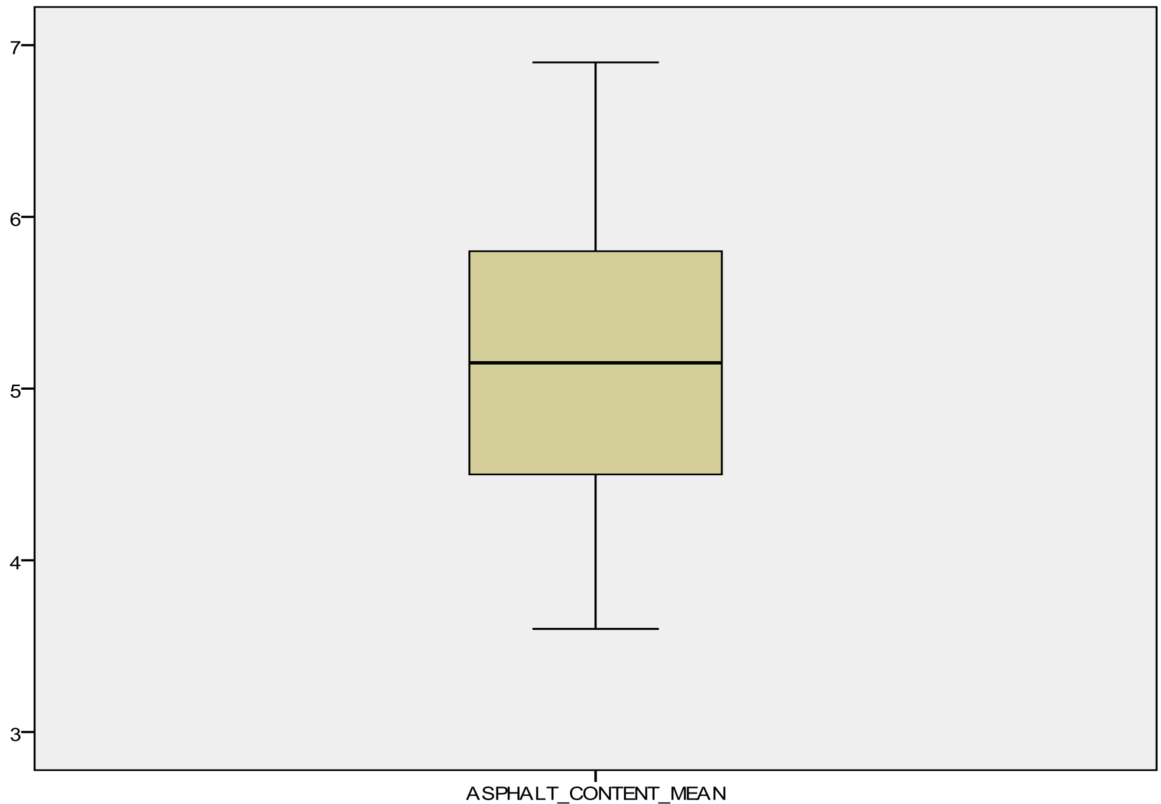


**Figure 3-12: Box plots method- asphalt content – wet freeze zone**

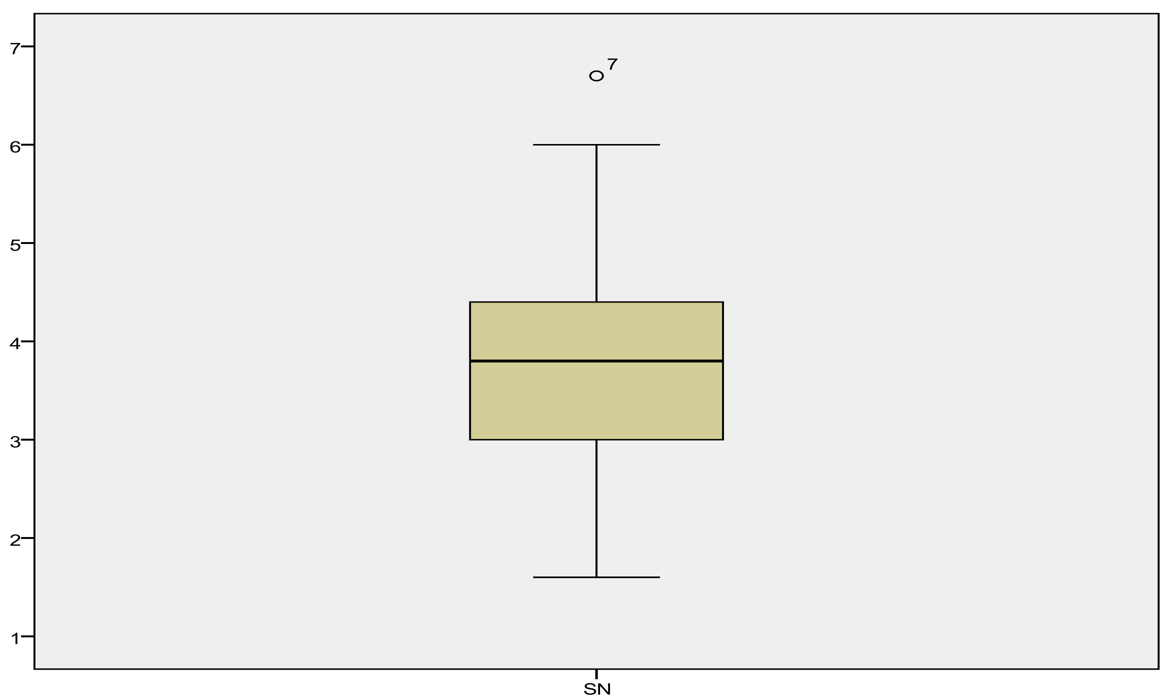


**Figure 3-13: Box plots method- SN – dry freeze zone**

### 3.6.3 Study of the Correlation between Variables

Multiple regression analysis is a regression analysis between one dependent variable (Y) and a number of independent variables (Xi). A model with too many independent variables can become a poor model, because increasing the number of independent variables does not improve $R^2$ (Rowshan, 1998). Consequently, it is very important to select the effective and efficient sets of predictor or independent variables in multiple regressions.

The selected independent variables should have high correlation with the dependent variable, and should be uncorrelated among themselves (Hinkle, et al., 2003). It is very important to avoid the collinearity, which is the high correlation among the independent variables to select effective and efficient sets of independent variables.

Collinearity occurs when one independent variable is highly correlated with two or more independent variables; for example, if there are two independent variables which have high correlation among themselves in the estimating equation, the variables will be not significant, so only one of the variables is needed (Elliott and Woodward, 2007).

The simple correlation matrix is one of the methods could be used to select the efficient number of independent variables. In this method, the correlation coefficient (r) used as a measure of the correlation between dependent variable and each independent variables or between independent variables themselves, which examine the correlation between the variables (U.S. DOT, 1967). Values of the correlation coefficient and their interpretation are shown in Table 3:14.

**Table 3:14: Correlation coefficient values and its interpretation**

Source: (Hinkle, et al., 2003)

| R | Interpretation |
|---|---|
| 0.9 – 1.0 | Very high correlation |
| 0.7 – 0.9 | High correlation |
| 0.5 – 0.7 | Moderate correlation |
| 0.3 – 0.5 | Low correlation |
| 0.0 – 0.3 | Little if any correlation |

**Table 3:15: Selected variables of the models**

| Variable Name | Abbreviated Symbols | LTPP- Field |
|---|---|---|
| Rut depth | $R_D$ | MAX_MEAN_DEPTH_1_8 |
| Traffic loads | KESAL | ANL_KESAL_LTPP_LN _YR |
| Number of days maximum temperature > 32 C° | D> 32 C° | DAYS_ABOVE_32_C_YR |
| Freeze Index | FI | FREEZE_INDEX_YR |
| Total annual precipitation (mm) | TAP | TOTAL_ANN_PRECIP |
| Resilient modulus | $M_R$ | RES_MOD_AVE |
| Asphalt content in the mix | AC% | ASPHALT_CONTENT_MEAN |
| Air voids in the mix | VTM% | PCT_AIR_VOIDS_MEAN |
| Voids in the mineral aggregate | VMA | VOIDS_MINERAL_AGGR |
| Marshall stiffness | MS | MARSHALL_STABILITY<br>MARSHALL_FLOW |
| Structural number | SN | ESAL calculator software |

The correlation test was conducted to test the correlation between each independent variable and rut depth, and between the independent variables themselves. Table B: 1, Table B: 2, Table B: 3, Table B: 4, and Table B: 5 include the correlation matrix between the variables in the wet freeze zone model, dry freeze zone model, wet no freeze zone model, dry no freeze zone model, and the model that developed based on combined data from different climate zones respectively. From these tables, the variables were selected and tabulated in Table 3:15. This table includes the name of the selected variables and its LTPP field that was used to build the models at each zone.

Marshall stability and Marshall flow variables were excluded from the wet no-freeze zone model due to the highest percentage of missing values in these variables (82.6%) as shown in Table 3:13.

# CHAPTER 4 – MODEL FORMULATION

Many pavement rutting models have been developed using pavement performance data since 1950's. Because the previous models have been developed based on pavement data from a specific climate zone, these models are not universally accepted (Xiao, 2006).

The next step that follows in the determination of independent variables is the model formulation. In this step multiple regression analysis was preformed to develop pavement rutting models for various climate zones.

The concave shape of rut depth with the cumulative number of traffic loads repetitions is the key finding in the literature covering empirical models (Archilla and Madanat, 2000, Archilla, 2000, Luo and Prozzi, 2008). Therefore, in this research the following form was used as a starting point for model formulation. In addition, some variables that may have a significant effect on pavement rutting were considered to build the prediction models for wet freeze zone, dry freeze zone, wet no-freeze zone, and dry no-freeze zone. The governing equation is as follows:

$$\ln R_D = \beta_0 + \beta_1 \ln N + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \ldots\ldots + \beta_n X_n \qquad 4\text{-}1$$

where:

- $R_D$ = Ruth depth;
- N= Annual KESAL on the LTPP sections;
- $\beta_0$,. $\beta_n$ = Estimated parameter; and
- $X_i$= Independent Variables.

The keeping with the main objective of this study which is developing empirical pavement rut models at various climate zones, regression analysis was performed to study the relationship between the rut depth as the dependent variable, and traffic loads, climate factors, resilient modulus, structural number, AC content, air voids in the total mix, voids in the mineral aggregate, and Marshall stiffness as independent variables. The selection process of the most significant independent variables based on the correlation matrix as stated in section 3.6.3. After the selection of the most significant independent variables, the regression analysis was performed using PASW by the stepwise method to develop the best model.

## 4.1 Model for Wet Freeze Zone

### 4.1.1 Model Formulation

There are 69 sections were selected in this zone to be analyzed. The regression analysis was performed by stepwise analysis at 0.05 significant level to create the model. The results of the regression analysis are shown in Table 4:1, Table 4:2, and Table 4:3

**Table 4:1: Model summary for wet freeze zone**

| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate |
|---|---|---|---|
| 0.774 | 0.600 | 0.568 | 0.30505 |

**Table 4:2: ANOVA for wet freeze zone**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 8.781 | 5 | 1.756 | 18.873 | 0.000 |
| Residual | 5.862 | 63 | 0.093 | | |
| Total | 14.643 | 68 | | | |

**Table 4:3: Coefficient for wet freeze zone**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| Constant | 1.659 | 0.489 | 3.390 | 0.001 |
| LN_KESAL | 0.131 | 0.050 | 2.637 | 0.011 |
| SN | -0.084 | 0.031 | -2.709 | 0.009 |
| VTM | 0.061 | 0.021 | 2.875 | 0.005 |
| VMA | 0.055 | 0.022 | 2.471 | 0.016 |
| MS | -0.004 | 0.001 | -3.882 | 0.000 |

Table 4:1 illustrates the models summary; correlation coefficient, multiple determination coefficient, adjusted determination coefficient, and the standard error of estimate for the developed model. Table 4:2 is the ANOVA table. The F test shows that the developed model is statistically significant at the 0.05 significance level. The regression coefficients, standard error, and t-test of predictors are shown in Table 4:3. This model has a high determination coefficient $R^2$ (0.600), significant standard error of estimate (0.30505), and statistically significant regression coefficients at the 0.05 significance level.

The model includes rut depth as response variable and traffic loads, structural number, air voids in the total mix, VMA in the total mix, and Marshall stiffness as the predictor variables. It is formulated as follows:

$$\mathbf{Ln\ R_D = 1.659 + 0.131\ (Ln\ KESAL) - 0.084\ (SN) + 0.061\ (VTM) + 0.055\ (VMA) - 0.004\ (MS)}$$

### 4.1.2 Model Validation

As stated in chapter three, the model validation is the final step in model development. Parameter estimates (regression coefficient), t-test, determination coefficient, and standard error of estimate were used to validate the models. These statistical measures are important indicators to illustrate that the developed models are suitable to predict pavement rutting.

#### 4.1.2.1 Multiple Determination Coefficient

Hinkle, et al. (2003) defined determination coefficient ($R^2$) as “the proportion of the total variance in Y that can be associated with the variance in X”. The values of $R^2$ range from 0 to 1. This coefficient is a measure of model fitting. The determination coefficient of this model is (0.60) which means that 60% of the variance in the rut depth can be associated with the variance in traffic loads, SN, air voids in the total mix, VMA in the total mix, and Marshall stiffness.

#### 4.1.2.2 Standard Error of Estimate

Standard error of estimate, measure of error of prediction, used to measure how the observed data is dispersed about the regression line (U.S. DOT, 1967). The small value of the SEE means less error in estimating the relationship in the model, large correlation between dependent variable and independent variables, and great the accuracy of prediction (Hinkle, et al., 2003). Therefore, the standard error of estimate in this model is considered small and significant (0.30505).

#### 4.1.2.3 Parameter Estimation

Parameter estimation, regression coefficient, illustrates the effect of the independent variables on pavement rutting. The parameter estimation of this model is +1.659, +0.131, -0.084, +0.061, +0.055, and -0.004, for intercept, traffic loads, SN, air voids in the total mix, VMA in the total mix, and Marshall stiffness respectively. The positive sign of traffic loads regression coefficient indicates that the rut depth will increase with increasing traffic loads, which are concurrent with engineering practice. The negative value of SN indicates that the rut depth will decrease when SN increases, which also agrees with engineering knowledge and practice. The equation shows that there is a positive correlation between air voids in the total mix and rut depth, which means the rut depth will increase when the air voids increase, which is as expected as well. The positive value of VMA indicates that the excessive amount of VMA will lead to increase rut depth, which again agrees with engineering practice. The negative value of Marshall stiffness, which is expected, indicates that the rut depth decreases when the Marshall Stiffness increases The parameter estimates indicate that traffic loads has the highest effect on pavement rutting, which is concur with the engineering knowledge and practice.

#### 4.1.2.4 t-test

Any parameter estimate of any independent variable that has insignificant t-test value should be eliminated from the model (U.S. DOT, 1967). The values of the t-test for the model are 3.390, 2.637, -2.709, 2.875, 2.471, and -3.882 for intercept, traffic loads, SN, air voids, VMA, and Marshall stiffness respectively. These values indicate that the parameter estimates are statistically significant at the 0.05 significance level.

## 4.2 Model for Dry Freeze Zone

### 4.2.1 Model Formulation

In this zone, 35 sections were selected to develop the model. The model was developed by using regression analysis, stepwise analysis at the 0.05 significance level. The results of the regression analysis are shown in Table 4:4, Table 4:5, and Table 4:6.

**Table 4:4: Model summary for dry freeze zone**

| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate |
|---|---|---|---|
| 0.854 | 0.729 | 0.703 | 0.21261 |

**Table 4:5: ANOVA for dry freeze zone**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 3.772 | 3 | 1.257 | 27.814 | 0.000 |
| Residual | 1.401 | 31 | 0.045 | | |
| Total | 5.173 | 34 | | | |

**Table 4:6: Coefficient for dry freeze zone**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| (Constant) | 2.075 | 0.379 | 5.479 | 0.000 |
| VMA | 0.059 | 0.023 | 2.582 | 0.015 |
| MS | -0.004 | 0.001 | -7.490 | 0.000 |
| FI | - 0.00028 | 0.000 | -4.148 | 0.000 |

Table 4:4 illustrate the models summary; correlation coefficient, multiple determination coefficient, adjusted determination coefficient, and the standard error of estimate. The model has a high $R^2$ (0.729). The F test in Table 4:5 show that the model is statistically significant at the 0.05 significance level.

The regression coefficients, standard error, and t-test of predictors are shown in Table 4:6. This model is initially selected because it has a high determination coefficient ($R^2$= 0.729), a small standard error of estimate (0.21261), and statistically significant regression coefficients at the 0.05 significance level. The final formulation of the model is as follows:

**$\ln R_D = 2.075 + 0.059\,(VMA) - 0.004\,(MS) - 0.00028\,(FI)$**

Even though the proposed model is statistically significant, it does not conform to engineering practice because it does not include traffic loads. There is a general believes that the traffic loads have a significant effect on pavement rutting, based on these believes, it is important to include traffic loads in the model even if it is not statistically significant. Consequently, traffic loads variable was added to analysis. Table 4:7, Table 4:8 and Table 4:9 show the results of the model that include traffic loads variable as one of the independent variables.

**Table 4:7: Model summary of selected model – dry freeze zone**

| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate |
|---|---|---|---|
| 0.856 | 0.733 | 0.697 | 0.21462 |

**Table 4:8: ANOVA for selected model- dry freeze zone**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 3.791 | 4 | 0.948 | 20.575 | 0.000 |
| Residual | 1.382 | 30 | 0.046 | | |
| Total | 5.173 | 34 | | | |

**Table 4:9: Coefficients for selected model- dry freeze zone**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| (Constant) | 1.878 | 0.489 | 3.842 | 0.001 |
| VMA | 0.063 | 0.024 | 2.639 | 0.013 |
| LN_KESAL | 0.028 | 0.043 | 0.648 | 0.522 |
| MS | -0.004 | 0.001 | -6.954 | 0.000 |
| FI | - 0.00029 | 0.000 | -4.160 | 0.000 |

Model summary; correlation coefficient, multiple determination coefficient, adjusted determination coefficient, and the standard error of estimate for the dry freeze zone model are tabulated in Table 4:7. The F-test in Table 4:8 show that the developed model is statistically significant at the 0.05 significance level. The regression coefficients, standard error, and t-test of predictors are tabulated in Table 4:9. This model has a high determination coefficient $R^2$ (0.733), significant standard error of estimate (0.21462), and statistically significant regression coefficients for voids in the mineral aggregate, Marshall stiffness, and freeze index at the 0.05 significance level.

The model includes rut depth as response variable and traffic loads, freeze index, VMA in the total mix, and Marshall stiffness as the predictor variables. It is formulated as follows:

$$\mathbf{Ln\ R_D = 1.878 + 0.063\ (VMA) + 0.028\ (Ln\ KESAL) - 0.004\ (MS) - 0.00029\ (FI)}$$

### 4.2.2 Model Validation

Validation of the selected model using statistical techniques is an important step in the development of the model. Therefore, the selected model was validated based on parameter estimates (regression coefficient), t test, determination coefficient, and standard error of estimate.

#### 4.2.2.1 Multiple Determination Coefficient

Multiple determination coefficient is a measure of model fitting. From Table 4:7, the determination coefficient of selected model is (0.733), a high determination coefficient, which means that 73.3 % of the variance in the rut depth can be associated with the variance in VMA in the total mix, traffic loads, Marshall stiffness, and freeze index.

#### 4.2.2.2 Standard Error of Estimate

This measure was used to measure the expected error in predicting pavement rutting depth from the independent variables. The standard error of estimate should be small to be statistically acceptable. In this model, the SEE is considered small and significant (0.21462) which mean less error in estimating the relationship in the model.

#### 4.2.2.3 Parameter Estimation

Regression coefficients illustrate the effect of each independent variable on the dependent variable. The parameter estimation of this model is +1.878, +0.063, +0.028, -0.004, and -0.00029 for intercept, VMA in the total mix, traffic loads, Marshall stiffness, and freeze index respectively. The regression coefficient of VMA (+ 0.63) indicates that the excessive amount of VMA will lead to increase in rut depth, which agrees with engineering practice. As expected, traffic loads have a positive value (+ 0.028), which indicates that the rut depth will increase with increasing traffic loads. The negative value of freeze index (- 0.00029) indicates that the rut depth will decrease with increasing in freeze index because bitumen material at low temperatures has good resistance to deformation. The negative value of Marshall stiffness indicates that the rut depth decreases when the Marshall Stiffness increases as expected and as pointed out by some researchers. The parameter estimates indicate that the VMA has the highest effect on the pavement rutting.

#### 4.2.2.4 t-test

In general, any parameter estimate of any independent variable that has insignificant value of t-test should be eliminating from the model. Nevertheless, traffic loads has an insignificant t-test value; it should be included in the model due to its significant effect on pavement rutting. The values of the t-test of the model are 3.842, 2.639, 0.648, - 6.954, and -4.160 for intercept, VMA in the total mix, traffic loads, Marshall stiffness, and freeze index respectively at the 0.05 significance level.

## 4.3 Model for Wet No Freeze Zone

### 4.3.1 Model Formulation

The regression analysis, stepwise method, was also performed to develop the model in the wet no freeze zone. In this zone, 48 sections were included in the analysis. Table 4:10, Table 4:11 and Table 4:12 illustrate the model summary, ANOVA table, and regression coefficients respectively.

**Table 4:10: Model summary for wet no freeze zone**

| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate |
|---|---|---|---|
| 0.736 | 0.541 | 0.510 | 0.28357 |

**Table 4:11: ANOVA for wet no freeze zone**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 4.176 | 3 | 1.392 | 17.310 | 0.000 |
| Residual | 3.538 | 44 | 0.080 | | |
| Total | 7.714 | 47 | | | |

**Table 4:12: Coefficient for wet no freeze zone**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| (Constant) | 0.900 | 0.330 | 2.726 | 0.009 |
| AC% | 0.190 | 0.044 | 4.298 | 0.000 |
| SN | -0.077 | 0.031 | -2.496 | 0.016 |
| LN_KESAL | 0.063 | 0.028 | 2.212 | 0.032 |

The wet no freeze zone's model summary; correlation coefficient, multiple determination coefficient, adjusted determination coefficient, and the standard error of estimate are shown in Table 4:10. The model has a high determination coefficient (0. 541). ANOVA results are shown in Table 4:11. The F test shows that the model is statistically significant at the 0.05 significance level. The regression coefficients, standard error, and t-test of predictors are shown in Table 4:12. This model was selected because it has a high determination coefficient, small standard error of estimate, and statistically significant regression coefficient at the 0.05 significance level.

The model includes rut depth as dependent variable and traffic loads, asphalt content, and structural number as independent variables. The model can be expressed as the following regression equation:

$$\mathbf{Ln\ R_D = 0.9 + 0.19\ (AC\ \%) - 0.077\ (SN) + 0.063\ (Ln\ KESAL)}$$

### 4.3.2 Model Validation

As in the previous models validations, this model was validated by using determination coefficient, standard error of estimate, parameter estimates (regression coefficient), and t-test. These statistical measures are important indicators to illustrate that the developed models are suitable to predict the pavement rutting.

#### 4.3.2.1 Multiple Determination Coefficient

The determination coefficient of this model is (0.541), high correlation, which means that 54.1% of the variance in the rut depth can be associated with the variance in asphalt content in the total mix, SN, and traffic loads.

#### 4.3.2.2 Standard Error of Estimate

The small value of the SEE means less error in estimating the relationship in the model. The standard error of estimate in this model is 0.28357, which considered small and statistically significant.

#### 4.3.2.3 Parameter Estimation

This model includes asphalt content in the total mix, structural number, and traffic loads as independent variables and rut depth as dependent variable. Regression coefficients were used to illustrate the effect of the independent variables on pavement rutting. The parameter estimations of this model are +0.90, +0.190, -0.077, and + 0.063 for the intercept, asphalt content in the total mix, structural number, and traffic loads respectively. Traffic loads has a positive sign (+ 0.063), which indicates that the rut depth will increase with increasing in the traffic loads, which agree with engineering knowledge and practices. The negative value of SN (-0.077) indicates that the rut depth will decrease when SN increase, which agrees with engineering knowledge and practices. The asphalt content in the total mix has a significant effect on pavement rutting. Moreover, the positive sign of regression coefficient of asphalt content in total mix (+0.190) indicates that the rut depth will increase possibly due to excessive percent of asphalt content in the total mix.

#### 4.3.2.4 t-test

The t-test is one of the statistical measures that were used in this research to validate the model. Therefore, any parameter estimate of any independent variable that does not meet the t-test should be eliminated from the model. The values of the t-test of the model are 2.726, 4.298, -2.496, and 2.212, for the intercept, asphalt content in the total mix, structural number, and traffic loads respectively. All the regression coefficients for this model are statistically significant at the 0.05 significance level.

## 4.4 Model for Dry No Freeze Zone

### 4.4.1 Model Formulation

Unfortunately, the number of sections available in dry no freeze zone were small (20 sections). All but one independent variable was included in the regression analysis. The Marshall stiffness excluded from the model because the percent of missing values of Marshall stability and flow is 82.6 % as shown in Table 3:13. The model was developed by using regression analysis, stepwise analysis, at the 0.05 significance level. The results are tabulated in Table 4:13, Table 4:14, and Table 4:15.

**Table 4:13: Model summary for dry no freeze zone**

| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate |
|---|---|---|---|
| 0.671 | 0.450 | 0.420 | 0.38289 |

**Table 4:14: ANOVA for dry no freeze zone**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 2.160 | 1 | 2.160 | 14.736 | 0.001 |
| Residual | 2.639 | 18 | 0.147 | | |
| Total | 4.799 | 19 | | | |

**Table 4:15: Coefficient for dry no freeze zone**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| (Constant) | 1.25 | 0.22 | 5.669 | 0.00 |
| D >32 ºC | 0.008 | 0.002 | 3.839 | 0.00 |

Table 4:13 illustrate the model summary, correlation coefficient, multiple determination coefficient, adjusted determination coefficient, and the standard error of estimate for the model. F test, in ANOVA table, shows that the model is statistically significant at the 0.05 significance level. The regression coefficients, standard error, and t-test of predictors are shown in Table 4:15. The model can be expressed as the following regression equation:

**Ln $R_D$= 1.250 + 0.008 (D >32 ºC)**

Even though, the proposed model is statistically significant, it does not meet the engineering practice because it does not include traffic loads. The traffic loads have a significant effect on pavement rutting; therefore, it is important to be included in the model even though it is not statistically significant in the proposed model. Consequently, traffic loads variable was introduced to analysis. Table 4:16, Table 4:17 and Table 4:18 show the result of the selected model.

**Table 4:16: Model summary of selected model for dry no freeze zone**

| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate |
|---|---|---|---|
| 0.754 | 0.569 | 0.518 | 0.34885 |

**Table 4:17: ANOVA for selected model for dry no freeze zone**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 2.730 | 2 | 1.365 | 11.218 | 0.001 |
| Residual | 2.069 | 17 | 0.122 | | |
| Total | 4.799 | 19 | | | |

**Table 4:18: Coefficients for selected model for dry no freeze zone**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| (Constant) | 0.681 | 0.331 | 2.056 | 0.055 |
| Ln_KESAL | 0.114 | 0.053 | 2.164 | 0.045 |
| D> 32 C° | 0.007 | 0.002 | 4.08 | 0.001 |

The final form of the selected model for dry no freeze zone is as follows:

$$\mathbf{Ln\ R_D = 0.681 + 0.114\ (Ln\ KESAL) + 0.007\ (D > 32\ C°)}$$

### 4.4.2 Model Validation

To ensure that the selected model is significant the model was validated based on parameter estimates (regression coefficient), t test, determination coefficient, and standard error of estimate.

#### 4.4.2.1 Multiple Determination Coefficient

The wet no freeze zone's model has a high determination coefficient ($R^2$= 0.569) as shown in Table 4:16, which mean that 56.9 % of the variance in the rut depth can be associated with the variance in traffic loads and days above 32 °C.

#### 4.4.2.2 Standard Error of Estimate

The standard error of estimate is preferred to be small to be acceptable. In this model, the SEE is considered small and statistically significant (0.34885), which mean less error in estimating the relationship between rut depth and independent variables.

#### 4.4.2.3 Parameter Estimation

The parameter estimates obtained from the regression analysis are presented in Table 4:18. It can be seen that the parameter estimation of this model is +0.681, +0.114, and +0.007 for intercept, traffic loads, and days above 32 °C respectively. The positive value of traffic loads parameter estimate indicates that the rut depth will increase with increasing traffic loads, as expected; likewise, the positive value of the parameter estimate of days above 32 °C indicates that the rut depth will increase with increasing daily temperature, which agrees with engineering knowledge and practice. The result indicates that the traffic loads (KESAL) were the most important factor that effects the pavement rutting, which agrees with engineering knowledge and practice.

#### 4.4.2.4 t-test

In general, any parameter estimate of any independent variable that does not meet the t-test should be eliminated from the model. The results of the -test are presented in Table 4:18. It can be noted that the t-test value for days above 32 °C obtain from the regression analysis are statistically significant (4.08), while the intercept (2.056) and traffic loads (2.164) has insignificant t-teat values. Nevertheless, traffic loads variable should be included in the model due to its significant effect on pavement rutting.

## 4.5 Model for Different Climate Zones Combined

### 4.5.1 Model Formulation

This model was developed based on combined data from wet freeze zone, dry freeze zone, wet no freeze zone, and dry no freeze zone. The total number sections were used in this analysis was 172 sections. The model was developed by using regression analysis, stepwise analysis, at the 0.05 significance level. The dependent variable in this model is rut depth, while traffic loads (ESAL), freeze index, total annual precipitation, number of days above 32 °C, structure number, resilient modulus, asphalt content in the total mix, air voids in the mix, and voids in the mineral aggregate. Table 4:19, Table 4:20 and Table 4:21 show the result of the regression analysis.

**Table 4:19: Model summary for different climate zones Combined**

| R | $R^2$ | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|
| .509 | .259 | .244 | .37738 |

**Table 4:20: ANOVA for different climate zones Combined**

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 7.375 | 3 | 2.458 | 17.262 | .000 |
| Residual | 21.077 | 148 | .142 | | |
| Total | 28.453 | 151 | | | |

**Table 4:21: Coefficients for different climate zones Combined**

| Model | Unstandardized Coefficients | | t | Sig. |
|---|---|---|---|---|
| | Reg Coeff | Std. Error | | |
| (Constant) | 1.216 | .271 | 4.480 | .000 |
| AC% | .122 | .037 | 3.316 | .001 |
| LN_KESAL | .111 | .028 | 3.928 | .000 |
| SN | -.085 | .024 | -3.584 | .000 |

The summary of this model; correlation coefficient, multiple determination coefficient, adjusted determination coefficient, and the standard error of estimate are tabulated in Table 4:19.

The model has a moderate determination coefficient ($R^2$ = 0.259). From analysis of variance (ANOVA), it is possible to identify that the model is statistically significant as shown in Table 4:20. The regression coefficients, standard error, and t-test of predictors are shown in Table 4:21.

It can be observed in Table 4:21 that this model includes pavement rutting as dependent variable and the percentage of asphalt content in the total mix, traffic loads, and structural number as the independent variables.

The statistical rutting model obtained is:

$$\textbf{Ln } \mathbf{R_D} \mathbf{= 1.216 + 0.122\ (AC\ \%) + 0.111\ (Ln\ KESAL) - 0.085\ (SN)}$$

### 4.5.2 Model Validation

The developed model was subjected to validation. The validation was performed to ensure that the model is statistically significant. The model was validated by using determination coefficient, standard error of estimate, parameter estimates (regression coefficient), and t-test.

#### 4.5.2.1 Multiple Determination Coefficient

The determination coefficient analysis allows ensuring that the statistical model obtained through regression analysis is efficient. The correlation coefficient (0.509) and determination coefficient (0.259) indicate a low to moderate correlation between rut depth and the independent variables, and 25.9 % of the variance in the rut depth can be associated with the variance in the percentage of asphalt content in the total mix, traffic loads, and structural number.

#### 4.5.2.2 Standard Error of Estimate

The standard error of estimate in this model is 0.37738. The small value of the SEE means less error in estimating the relationship in the model. Therefore, the standard error of estimate in this model considered small and statistically significant.

#### 4.5.2.3 Parameter Estimation

This model includes the percentage of asphalt content in the total mix, traffic loads, and structural number as independent variables. Parameter estimation was used to illustrate the effect of the independent variables on pavement rutting. The parameter estimation of this model is +1.216, + 0.122, + 0.111, and - 0.085 for the intercept, the percentage of asphalt content in the total mix, traffic loads, and structural number respectively.

In this model, traffic loads have positive value, which indicates that pavement rut will increase when the traffic loads increase, which agrees with engineering practice. From engineering knowledge of pavement design and performance, pavement rutting decreases when the structural number increases as found in this study. The positive sign of asphalt content indicates that the excessive amount of asphalt binder will lead to increase in the rut depth in the surface layer. The parameter estimation of the model of different climate zones shows that the percentage of asphalt binder content in the total mix is the most important factor that leads to increase the rut depth.

#### 4.5.2.4 t-test

The last step in model validation that used in this validation is the t-test. The values of the t-test of this model were 4.480, 3.316, 3.928, and -3.584 for intercept, the percentage of asphalt content in the total mix, traffic loads, and structural number respectively. All the regression coefficients for this model are statistically significant at the 0.05 significance level.

# CHAPTER 5- CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

One of the essential elements of pavement design is the understanding of the factors that may affect pavement performance. The objectives of this study are to review and understand the LTPP database contents and structure, identify the factors that may affect pavement rutting, and develop empirical models to forecast the rutting of flexible pavements with granular base sections in various climate zones based on LTPP data.

Five pavement rutting prediction models were developed. These models are pavement rutting model for wet freeze zone, pavement rutting model for dry freeze zone, pavement rutting model for wet no-freeze zone, pavement rutting model for dry no-freeze zone, and pavement rutting model for different climate zones combined.

In pavement rutting prediction model for wet freeze zone, the proposed model was developed based on the relationship between response variable, rut depth, and predictor variables, traffic loads, structural number, Marshall stiffness, air voids in the total mix, and VMA in the total mix. Traffic loads is one of the most important factors that have a significant effect in pavement rutting according to the existing literature and engineering knowledge and practice. In this model, traffic loads was the predominant factor that have a significant effect in pavement rutting which agree with existing literature and engineering knowledge and practice. Following the traffic loads, structural number was the most significant secondary factor followed by percent of voids in the total mix, voids in the mineral aggregate, and Marshall stiffness.

Pavement rutting prediction model for dry freeze zone was developed based on the relationship between rut depth as dependent variable and traffic loads, freeze index, voids in the total mix, and Marshall stiffness as independent variables. The important finding in this model is that traffic loads is not the most important factor which disagrees with existing literature and engineering knowledge due. Increasing in the voids in the mineral aggregate will increase the pavement rut. Voids in the mineral aggregate factor have the highest affect in pavement rutting in dry freeze zone. Marshall stiffness and freeze index has affect in pavement rutting. The negative value of freeze index (- 0.00029) indicates that the rut depth will increase with increasing in freeze index, as expected. Whereas, the rut depth should decrease with increase in freeze index because bitumen material at low temperatures has good resistance to deformation as found in this study.

Pavement rutting prediction model for wet no freeze zone includes rut depth as dependent variable, and traffic loads, asphalt content in the total mix, and structural number as independent variables. Asphalt content in the total mix has the highest effect in pavement rutting. The positive value parameter estimate of percent of asphalt binder content indicates that the rut depth will increase with increasing in the percent of asphalt content in the total mix which agree with the engineering judgment and practice. The second significant factor is structural number. The negative value of structural number indicates that the rut depth will decrease when structural number increase, which also agrees with engineering knowledge and practices.

Pavement rutting prediction model for dry no freeze zone was developed based on the rut depth as dependent variable and traffic loads and number of days above 32 °C as independent variables. Traffic loads fond as the significant factor effect the pavement rutting in dry no freeze zone. Number of days above 32 °C has affect on pavement rutting that the positive value of number of days above 32 °C indicates that rut depth will increase with increase in daily temperature, which agree with engineering knowledge and practice.

Pavement performance model for different climate zones combined was developed based on combined data from wet freeze zone, dry freeze zone, wet no freeze zone, and dry no freeze zone. This model includes rut depth as dependent variable and traffic loads, structural number and the percentage of asphalt content in the total mix as independent variables. In this model, percent of asphalt binder content in the total mix has the highest effect in pavement rutting. Rut depth will increase with increase in the percent of asphalt binder content in the total mix. Second significant factor that affects pavement rutting is traffic loads followed by structural number. The structural number effects the pavement rutting, whereas the rut depth decrease with increase in structural number.

## 5.2 Recommendations

Given the above conclusions, there are some recommendations to be made. These recommendations are:

1- The developed models in this study should be implemented in PMSs to assist decision makers, such as state and local transportation agencies, to select the most cost- effective strategies for maintenance, rehabilitation, and reconstruction of pavements.

2- Developed models can be used in a wide range of states or in other countries over the world that have similar climate.

3- The rutting prediction models have to be refined with increasing quantity and quality of data. Increasing the number of sections will increase the significant of the proposed model.

4- This study focused on GPS-1 which is asphalt concrete pavement on granular base at different climate zone and at combined climate zone; therefore, more studies are still needed to develop models by using another type of LTPP experiment.

5- In this study, traffic loads are not the most important factor in dry freeze zone, wet no freeze zone and different climate zones combined models which disagree with the existing literature and engineering knowledge. More studies should be focused on the effect of traffic loads on pavement rutting in different climate zones.

6- Future studies should develop models using field data from the LTPP database and from lab testing for the same section, and compare results between these models to determine if there are any incorrect data in the LTPP database.

# Appendix A - LTPP Information

**Table A: 1: State codes in LTPP database**

| Code | Description | Code | Description | Code | Description |
|---|---|---|---|---|---|
| 01 | Alabama | 30 | Montana | 67 | Belgium |
| 02 | Alaska | 31 | Nebraska | 68 | Austria |
| 04 | Arizona | 32 | Nevada | 69 | France |
| 05 | Arkansas | 33 | New Hampshire | 70 | Brazil |
| 06 | California | 34 | New Jersey | 71 | Italy |
| 08 | Colorado | 35 | New Mexico | 72 | Puerto Rico |
| 09 | Connecticut | 36 | New York | 73 | Chile |
| 10 | Delaware | 37 | North Carolina | 78 | Virgin Islands |
| 11 | District of Columbia | 38 | North Dakota | 81 | Alberta |
| 12 | Florida | 39 | Ohio | 82 | British Columbia |
| 13 | Georgia | 40 | Oklahoma | 83 | Manitoba |
| 15 | Hawaii | 41 | Oregon | 84 | New Brunswick |
| 16 | Idaho | 42 | Pennsylvania | 85 | Newfoundland |
| 17 | Illinois | 44 | Rhode Island | 86 | Nova Scotia |
| 18 | Indiana | 45 | South Carolina | 87 | Ontario |
| 19 | Iowa | 46 | South Dakota | 88 | Prince Edward Island |
| 20 | Kansas | 47 | Tennessee | 89 | Quebec |
| 21 | Kentucky | 48 | Texas | 90 | Saskatchewan |
| 22 | Louisiana | 49 | Utah | 91 | Australia |
| 23 | Maine | 50 | Vermont | 92 | Denmark |
| 24 | Maryland | 51 | Virginia | 93 | Finland |
| 25 | Massachusetts | 53 | Washington | 94 | Japan |
| 26 | Michigan | 54 | West Virginia | 95 | Netherlands |
| 27 | Minnesota | 55 | Wisconsin | 96 | Norway |
| 28 | Mississippi | 56 | Wyoming | | |
| 29 | Missouri | 66 | Guam | | |

# Appendix B- Correlation Matrix

**Table B: 1: Correlations matrix for wet freeze zone**

| | | Ln-$R_D$ | Ln-KESAL | DAYS > 32 °C | FI | PREC | MR | SN | AC | VTM | VMA | MS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LN_R D | r | 1 | .484** | -.104 | .111 | .159 | .058 | -.446** | .247* | .503** | .430** | -.480** |
| | Sig. (2-tailed) | | .000 | .396 | .366 | .191 | .635 | .000 | .041 | .000 | .000 | .000 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| LN_KESAL | r | .484** | 1 | -.104 | .077 | -.017 | -.149 | -.145 | .054 | .328** | .264* | -.228 |
| | Sig. (2-tailed) | .000 | | .397 | .528 | .889 | .222 | .234 | .659 | .006 | .029 | .059 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| DAYS > 32 °C | r | -.104 | -.104 | 1 | -.444** | -.214 | -.004 | .113 | -.208 | -.014 | -.165 | .031 |
| | Sig. (2-tailed) | .396 | .397 | | .000 | .077 | .974 | .356 | .086 | .908 | .175 | .798 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| FI | r | .111 | .077 | -.444** | 1 | -.345** | .129 | -.237 | -.116 | .176 | -.023 | .166 |
| | Sig. (2-tailed) | .366 | .528 | .000 | | .004 | .291 | .050 | .341 | .148 | .850 | .173 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| PREC | r | .159 | -.017 | -.214 | -.345** | 1 | .196 | -.046 | .224 | -.043 | .228 | -.394** |
| | Sig. (2-tailed) | .191 | .889 | .077 | .004 | | .107 | .705 | .064 | .728 | .060 | .001 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| MR | r | .058 | -.149 | -.004 | .129 | .196 | 1 | -.100 | .037 | .117 | -.279* | -.168 |
| | Sig. (2-tailed) | .635 | .222 | .974 | .291 | .107 | | .413 | .762 | .337 | .020 | .166 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| SN | r | -.446** | -.145 | .113 | -.237 | -.046 | -.100 | 1 | -.072 | -.405** | -.214 | .059 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sig. (2-tailed) | .000 | .234 | .356 | .050 | .705 | .413 | | .557 | .001 | .078 | .628 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| AC | r | .247* | .054 | -.208 | -.116 | .224 | .037 | -.072 | 1 | .008 | -.089 | -.239* |
| | Sig. (2-tailed) | .041 | .659 | .086 | .341 | .064 | .762 | .557 | | .947 | .469 | .048 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| VTM | r | .503** | .328** | -.014 | .176 | -.043 | .117 | -.405** | .008 | 1 | .098 | -.137 |
| | Sig. (2-tailed) | .000 | .006 | .908 | .148 | .728 | .337 | .001 | .947 | | .421 | .261 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| VMA | r | .430** | .264* | -.165 | -.023 | .228 | -.279* | -.214 | -.089 | .098 | 1 | -.242* |
| | Sig. (2-tailed) | .000 | .029 | .175 | .850 | .060 | .020 | .078 | .469 | .421 | | .045 |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |
| MS | r | -.480** | -.228 | .031 | .166 | -.394** | -.168 | .059 | -.239* | -.137 | -.242* | 1 |
| | Sig. (2-tailed) | .000 | .059 | .798 | .173 | .001 | .166 | .628 | .048 | .261 | .045 | |
| | N | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 | 69 |

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

**Table B: 2: Correlations matrix for dry freeze zone**

| | | Ln-$R_D$ | Ln-KESAL | DAYS > 32 °C | FI | PREC | MR | SN | AC | VTM | VMA | MS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LN_RD | r | 1 | .105 | .251 | -.340* | .097 | .000 | .142 | .106 | -.150 | .380* | -.706** |
| | Sig. (2-tailed) | | .549 | .146 | .046 | .578 | .998 | .415 | .543 | .390 | .024 | .000 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| LN_KESAL | r | .105 | 1 | -.107 | .202 | .369* | .237 | .222 | -.220 | -.258 | -.210 | -.252 |
| | Sig. (2-tailed) | .549 | | .540 | .244 | .029 | .170 | .200 | .204 | .134 | .225 | .144 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| DAYS > 32 °C | r | .251 | -.107 | 1 | -.621** | -.372* | -.153 | .211 | -.218 | -.213 | -.096 | -.035 |
| | Sig. (2-tailed) | .146 | .540 | | .000 | .028 | .379 | .223 | .209 | .220 | .584 | .842 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| FI | r | -.340* | .202 | -.621** | 1 | .332 | .119 | -.233 | -.029 | -.228 | -.090 | -.104 |
| | Sig. (2-tailed) | .046 | .244 | .000 | | .051 | .496 | .177 | .870 | .188 | .609 | .554 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| PREC | r | .097 | .369* | -.372* | .332 | 1 | .389* | -.179 | .073 | .216 | .141 | -.094 |
| | Sig. (2-tailed) | .578 | .029 | .028 | .051 | | .021 | .305 | .678 | .213 | .420 | .593 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| MR | r | .000 | .237 | -.153 | .119 | .389* | 1 | -.214 | -.115 | .111 | .068 | -.053 |
| | Sig. (2-tailed) | .998 | .170 | .379 | .496 | .021 | | .217 | .512 | .525 | .696 | .761 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| SN | r | .142 | .222 | .211 | -.233 | -.179 | -.214 | 1 | -.228 | -.307 | -.248 | .039 |
| | Sig. (2-tailed) | .415 | .200 | .223 | .177 | .305 | .217 | | .187 | .073 | .151 | .826 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AC | r | .106 | -.220 | -.218 | -.029 | .073 | -.115 | -.228 | 1 | .250 | .358* | .007 |
| | Sig. (2-tailed) | .543 | .204 | .209 | .870 | .678 | .512 | .187 | | .148 | .034 | .970 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| VTM | r | -.150 | -.258 | -.213 | -.228 | .216 | .111 | -.307 | .250 | 1 | .292 | .327 |
| | Sig. (2-tailed) | .390 | .134 | .220 | .188 | .213 | .525 | .073 | .148 | | .089 | .055 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| VMA | r | .380* | -.210 | -.096 | -.090 | .141 | .068 | -.248 | .358* | .292 | 1 | -.140 |
| | Sig. (2-tailed) | .024 | .225 | .584 | .609 | .420 | .696 | .151 | .034 | .089 | | .422 |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| MS | r | -.706** | -.252 | -.035 | -.104 | -.094 | -.053 | .039 | .007 | .327 | -.140 | 1 |
| | Sig. (2-tailed) | .000 | .144 | .842 | .554 | .593 | .761 | .826 | .970 | .055 | .422 | |
| | N | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

**Table B: 3: Correlations matrix for wet no freeze zone**

| | | Ln-$R_D$ | Ln-KESAL | DAYS > 32 °C | FI | PREC | MR | SN | AC | VTM | VMA | MS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LN_$R_D$ | r | 1 | .315* | .348* | .039 | -.264 | -.068 | -.505** | .657** | .122 | .152 | -.439** |
| | Sig. (2-tailed) | | .029 | .015 | .790 | .070 | .647 | .000 | .000 | .408 | .302 | .002 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| LN_KESAL | r | .315* | 1 | -.008 | -.063 | .309* | .122 | -.018 | .163 | .071 | .252 | -.204 |
| | Sig. (2-tailed) | .029 | | .956 | .668 | .032 | .407 | .905 | .269 | .631 | .084 | .165 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| DAYS > 32 °C | r | .348* | -.008 | 1 | -.443** | -.634** | .112 | -.223 | .273 | .032 | .073 | .014 |
| | Sig. (2-tailed) | .015 | .956 | | .002 | .000 | .447 | .128 | .060 | .831 | .624 | .927 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| FI | r | .039 | -.063 | -.443** | 1 | -.150 | -.169 | -.158 | -.035 | .359* | 025 | .031 |
| | Sig. (2-tailed) | .790 | .668 | .002 | | .310 | .252 | .284 | .813 | .012 | .866 | .837 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| PREC | r | -.264 | .309* | -.634** | -.150 | 1 | .040 | .225 | -.273 | -.240 | -.110 | -.129 |
| | Sig. (2-tailed) | .070 | .032 | .000 | .310 | | .789 | .125 | .061 | .100 | .459 | .383 |
| | N | 48 | 48 | 48 | 48 | 48 | 8 | 48 | 48 | 48 | 48 | 48 |
| MR | r | -.068 | .122 | .112 | -.169 | .040 | 1 | .037 | -.148 | -.095 | .027 | .329* |
| | Sig. (2-tailed) | .647 | .407 | .447 | .252 | .789 | | .803 | .316 | .519 | .855 | .023 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| SN | r | -.505** | -.018 | -.223 | -.158 | .225 | .037 | 1 | -.438** | -.177 | -.032 | .470** |
| | Sig. (2-tailed) | .000 | .905 | .128 | .284 | .125 | .803 | | .002 | .229 | .831 | .001 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| AC | r | .657** | .163 | .273 | -.035 | -.273 | -.148 | -.438** | 1 | .254 | .058 | -.482** |
| | Sig. (2-tailed) | .000 | .269 | .060 | .813 | .061 | .316 | .002 | | .081 | .697 | .001 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| VTM | r | .122 | .071 | .032 | .359* | -.240 | -.095 | -.177 | .254 | 1 | .273 | -.083 |
| | Sig. (2-tailed) | .408 | .631 | .831 | .012 | .100 | .519 | .229 | .081 | | .061 | .573 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| VMA | r | .152 | .252 | .073 | -.025 | -.110 | .027 | -.032 | .058 | .273 | 1 | -.242 |
| | Sig. (2-tailed) | .302 | .084 | .624 | .866 | .459 | .855 | .831 | .697 | .061 | | .097 |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| MS | r | -.439** | -.204 | .014 | .031 | -.129 | .329* | .470** | -.482** | -.083 | -.242 | 1 |
| | Sig. (2-tailed) | .002 | .165 | .927 | .837 | .383 | .023 | .001 | .001 | .573 | .097 | |
| | N | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

**Table B: 4: Correlation matrix for dry no freeze zone**

| | | Ln-$R_D$ | Ln-KESAL | DAYS > 32 °C | FI | PREC | MR | SN | AC | VTM | VMA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LN_$R_D$ | r | 1 | .383 | .671** | -.118 | -.320 | -.234 | .602** | .442 | -.368 | -.256 |
| | Sig. (2-tailed) | | .095 | .001 | .620 | .168 | .320 | .005 | .051 | .110 | .275 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| LN_KESAL | r | .383 | 1 | .058 | -.141 | -.472* | -.372 | .184 | .097 | -.235 | -.175 |
| | Sig. (2-tailed) | .095 | | .808 | .553 | .036 | .106 | .439 | .684 | .318 | .461 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| DAYS > 32 °C | r | .671** | .058 | 1 | -.290 | -.336 | -.218 | .386 | .374 | -.143 | .058 |
| | Sig. (2-tailed) | .001 | .808 | | .215 | .147 | .356 | .093 | .104 | .547 | .808 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| FI | r | -.118 | -.141 | -.290 | 1 | .186 | .348 | -.172 | .049 | .317 | -.139 |
| | Sig. (2-tailed) | .620 | .553 | .215 | | .432 | .132 | .467 | .838 | .174 | .560 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| PREC | r | -.320 | -.472* | -.336 | .186 | 1 | .376 | -.164 | .132 | .367 | -.005 |
| | Sig. (2-tailed) | .168 | .036 | .147 | .432 | | .103 | .489 | .579 | .112 | .982 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| MR | r | -.234 | -.372 | -.218 | .348 | .376 | 1 | -.066 | -.119 | .079 | .102 |
| | Sig. (2-tailed) | .320 | .106 | .356 | .132 | .103 | | .782 | .617 | .742 | .670 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| SN | r | .602** | .184 | .386 | -.172 | -.164 | -.066 | 1 | .176 | -.312 | -.291 |
| | Sig. (2-tailed) | .005 | .439 | .093 | .467 | .489 | .782 | | .459 | .180 | .213 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AC | r | .442 | .097 | .374 | .049 | .132 | -.119 | .176 | 1 | -.078 | -.002 |
| | Sig. (2-tailed) | .051 | .684 | .104 | .838 | .579 | .617 | .459 | | .744 | .993 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| VTM | r | -.368 | -.235 | -.143 | .317 | .367 | .079 | -.312 | -.078 | 1 | .414 |
| | Sig. (2-tailed) | .110 | .318 | .547 | .174 | .112 | .742 | .180 | .744 | | .069 |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| VMA | r | -.256 | -.175 | .058 | -.139 | -.005 | .102 | -.291 | -.002 | .414 | 1 |
| | Sig. (2-tailed) | .275 | .461 | .808 | .560 | .982 | .670 | .213 | .993 | .069 | |
| | N | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

**Table B: 5: Correlation matrix for different climate zones combined**

| | | Ln-$R_D$ | Ln-KESAL | DAYS > 32 °C | FI | PREC | MR | SN | AC | VTM | VMA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LN_$R_D$ | r | 1 | .327** | 0.068 | 0.071 | -0.053 | -0.098 | -.256** | .349** | 0.107 | .162* |
| | Sig. (2-tailed) | | 0 | 0.373 | 0.353 | 0.486 | 0.203 | 0.001 | 0 | 0.163 | 0.034 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| LN_KESAL | r | .327** | 1 | 0.102 | -0.016 | -0.021 | 0.048 | -0.027 | 0.065 | 0.075 | .169* |
| | Sig. (2-tailed) | 0 | | 0.183 | 0.836 | 0.78 | 0.53 | 0.724 | 0.397 | 0.328 | 0.027 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| DAYS > 32 °C | r | 0.068 | 0.102 | 1 | -.588** | -.211** | .348** | -0.082 | 0.069 | .200** | .308** |
| | Sig. (2-tailed) | 0.373 | 0.183 | | 0 | 0.006 | 0 | 0.287 | 0.366 | 0.009 | 0 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| FI | r | 0.071 | -0.016 | -.588** | 1 | -0.142 | -.243** | -0.097 | -0.044 | -.157* | -.277** |
| | Sig. (2-tailed) | 0.353 | 0.836 | 0 | | 0.062 | 0.001 | 0.205 | 0.562 | 0.039 | 0 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| PREC | r | -0.053 | -0.021 | -.211** | -0.142 | 1 | 0.078 | .165* | -0.021 | 0.009 | 0.015 |
| | Sig. (2-tailed) | 0.486 | 0.78 | 0.006 | 0.062 | | 0.308 | 0.031 | 0.781 | 0.909 | 0.848 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| MR | r | -0.098 | 0.048 | .348** | -.243** | 0.078 | 1 | -0.061 | -0.117 | 0.135 | 0.143 |
| | Sig. (2-tailed) | 0.203 | 0.53 | 0 | 0.001 | 0.308 | | 0.429 | 0.127 | 0.077 | 0.062 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| SN | r | -.256** | -0.027 | -0.082 | -0.097 | .165* | -0.061 | 1 | -.223** | -.296** | -.183* |
| | Sig. (2-tailed) | 0.001 | 0.724 | 0.287 | 0.205 | 0.031 | 0.429 | | 0.003 | 0 | 0.016 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AC | r | .349** | 0.065 | 0.069 | -0.044 | -0.021 | -0.117 | -.223** | 1 | 0.121 | 0.075 |
| | Sig. (2-tailed) | 0 | 0.397 | 0.366 | 0.562 | 0.781 | 0.127 | 0.003 | | 0.113 | 0.33 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| VTM | r | 0.107 | 0.075 | .200** | -.157* | 0.009 | 0.135 | -.296** | 0.121 | 1 | .321** |
| | Sig. (2-tailed) | 0.163 | 0.328 | 0.009 | 0.039 | 0.909 | 0.077 | 0 | 0.113 | | 0 |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |
| VMA | r | .162* | .169* | .308** | -.277** | 0.015 | 0.143 | -.183* | 0.075 | .321** | 1 |
| | Sig. (2-tailed) | 0.034 | 0.027 | 0 | 0 | 0.848 | 0.062 | 0.016 | 0.33 | 0 | |
| | N | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 | 172 |

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

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# ABSTRACT

## FLEXIBLE PAVEMENT RUT DEPTH MODELING FOR DIFFERENT CLIMATE ZONES

by

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Pavement rutting is one of the most important types of pavement distress that affect road safety and ride quality. Therefore, the primary objective of this study was to develop pavement rutting empirical models for different climate zones to predict pavement rutting on granular base based on LTPP data. Flexible pavements with granular base course were considered for this study. These models lead to better understanding of rutting phenomena and the factors that may have affect in pavement rutting. In addition, these models will help state and local transportation agencies make accurate decisions for maintenance, rehabilitation and reconstruction of pavement.

To develop a reliability-based methodology for pavement rutting prediction models, nine main steps were performed. These steps include reviewing previous studies, reviewing data sources of pavement performance, selecting the variables that may have effect pavement rutting, selecting the test sections at each climate zone, building the research database, verifying the data, analyzing the data, validating the models, and obtaining the final form of the models.

After the data were studied for missing and abnormal data, multiple regression analysis was performed to develop empirical models. Five models were developed based on the GPS-1 sections in wet freeze zone, dry freeze zone, wet no-freeze zone, dry no-freeze zone, and different climate zone combined.

The study indicated that traffic data was the most important factor in wet freeze zone model. The second significant factor in the model was SN followed by VTM, VMA, and Marshall stiffness. In dry freeze zone model, VMA is the most significant factor affecting pavement rutting. Traffic loads are the second significant factor affecting pavement rutting followed by Marshall stiffness and freeze index. The contributing factors in wet no-freeze zone model are VTM which is the most significant factor, SN, and traffic loads. In dry no-freeze zone, the developed model includes traffic loads as the most important factor that affect pavement rutting followed by number of days above 32 °C. As in wet no-freeze zone, VTM is the most significant factor that has affect in pavement rutting in the proposed model developed based on combined data from different climate zones. The model also includes traffic loads as the second significant factors affecting pavement rutting and SN.

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