QUALITY CONTROL, SENSITIVITY ANALYSIS, AND DEVELOPMENT OF TRAFFIC FACTORS FOR MECHANISTIC-EMPIRICAL PAVEMENT DESIGN

by

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Abstract

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is well-recognized as the next generation of pavement design. State transportation agencies across the U.S. are moving toward this method by implementing the MEPDG software, now known as DARWin-ME and made available through AASHTO. Compared to the AASHTO Pavement Design Guide of 1993, one of the major improvements in the MEPDG occurs in its characterization of traffic. Instead of converting all truck axles to 18,000 lb equivalent single axles (ESALs), the Mechanistic-Empirical Pavement Design Guide (MEPDG) simulates every truck axle, and the associated stresses and strains imposed on the pavement structure, from a wide range of vehicle class distributions (VCD) and axle load spectra (ALS). The MEPDG also enables pavement engineers to design pavements for various circumstances at different levels (among site/direction-specific, cluster-averaged, statewide, and nationwide) based on available traffic data. However, the recommendations of appropriate levels of traffic inputs in the MEPDG for local pavement design are currently an issue. The MEPDG community generally agreed to use quality control (QC), sensitivity analysis, and cluster analysis, to solve this problem, but subjective factors are currently involved. This dissertation developed objective procedures in QC, sensitivity analysis, and cluster analysis that also streamline the overall processes. As the first step of the overall procedure, an objective approach to QC of WIM data includes threshold checks that detect implausible values of individual variables in the truck weight records and rational checks that examine patterns in axle load distributions and relationships among the variables. Instead of using subjective visual comparisons of gross vehicle weight (GVW) distributions, the QC in this research implements a peak-range check, peak-shift check, and correlation analysis to quantify the ALS comparison process of rational checks. Following the QC procedure, sensitivity analysis was developed to examine the potential for implementation of various levels of traffic inputs. The changes of design pavement thicknesses due to variations of traffic factors are used as sensitivity indicators. The effects of traffic inputs on pavement design can be deemed practically significant when the thickness needed to maintain an acceptable level of pavement performance changed 0.5 inches or more from the baseline thickness developed from statewide traffic inputs. The third procedure presented a new clustering combination method, correlation-based clustering, that consider the effects of traffic inputs on pavement design thicknesses, so that determinations of the numbers of clusters and recommendations of data levels are made objectively. New procedures developed in this research have been implemented for 22 direction-specific WIM stations in Alabama, and the recommendations of data levels for use in the MEPDG were drawn.

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List of Abbreviations

AADT	Annual Average Daily Traffic
AADTT	Annual Average Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
AASHO	American Association of State Highway Officials
AC	Asphalt Concrete
AGPV	Axle Group per Vehicle
ALDOT	Alabama Department of Transportation
ALS	Axle Load Spectra
ASTM	American Society of Testing and Materials
ATR	Automatic Traffic Recorder
AVC	Automatic Vehicle Classifier
CRCP	Continuous Reinforced Concrete Pavement
DOT	Department of Transportation
ESAL	Equivalent Single Axle Load
F	Fail
FHWA	Federal Highway Administration
GFARG	Geographic/Functional Assignment of Roads to Groups
GVW	Gross Vehicle Weight
HDF	Hourly Distribution Factor
HMA	Hot mixed Asphalt
HRB	Highway Research Board
ID	Identification Number

IQR	Interquartile
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement
LTPP	Long-Term Pavement Performance
M-E	Mechanistic-Empirical
MDF	Monthly Distribution Factor
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
P	Pass
PG	Performance Grade
PSI	Present Serviceability Index
QC	Quality Control
SLINK	Single Linkage Clustering Method
SRFA	Same Road Factor Application
TADT	Truck Average Daily Traffic
TMG	Traffic Monitoring Guide
TxDOT	Texas Department of Transportation
USDOT	United States Department of Transportation
VC	Vehicle Classification
VCD	Vehicle Class Distribution
UPGMA	Unweighted Pair-group Method Using Arithmetic Averages
WIM	Weigh-in-Motion

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The pavement design system used until recently by transportation agencies followed the American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guide (AASHTO, 1993), which uses an empirical pavement design approach. The overall serviceability of the pavement in this approach is quantified by the present serviceability index (PSI), a composite performance measure combining cracking, patching, rutting, ride quality and other distresses. This approach requires a number of empirical data in order to obtain the relationships between input variables and outcomes. In the late 1950s, the American Association of State Highway Officials (AASHO) Road Test was performed for engineers to develop empirical relationships between pavement design and distresses under traffic loadings (HRB, 1962). In the AASHTO Pavement Design Guide of 1993, parameters for empirical equations were still derived from the AASHO Road Test. The pavement engineering community generally agrees that design procedures in the Design Guide of 1993 are insufficient for traffic, materials, and construction techniques today since the empirical equations derived from the AASHO Road Test used only one geographical location, one type of subgrade, one hot mix asphalt mixture and one Portland cement concrete mixture, two unbound bases, and 1 million axle load applications.

It is until now, a half century after the Road Test (HRB, 1962), that states are moving toward the new design approach that utilizes mechanistic-empirical (M-E) concepts to execute pavement design. In the M-E methods of pavement design, a number of failure criteria, each directed to a specific type of distress (such as cracking, rutting, International

Roughness Index or IRI, etc.), must be established. This is in contrast to the previous AASHTO method which uses the PSI. Principal types of distress measures include:

- Fatigue Cracking – the cracking of flexible pavement is based on the horizontal tensile strain at the bottom of the asphalt layer. Fatigue cracking of rigid pavement is most likely caused by the edge stress at the midslab.
- Rutting – this type of distress occurs only on flexible pavements, as indicated by the permanent deformation or rut depth along the wheelpaths.
- Thermal Cracking – the cracking occurs due to temperature. Low-temperature cracking is usually associated with flexible pavements in northern regions of the United States. Thermal fatigue cracking can occur in much milder regions when the asphalt becomes harder due to aging.
- IRI – the international roughness index (IRI) was developed so that different measures of roughness can be compared. The IRI summarizes the longitudinal surface profile in the wheelpath and is computed from surface elevation data collected by topographic survey.

On the mechanistic (M) aspect of the M-E approach, principles of engineering mechanics are applied to predict critical pavement responses (such as stresses and strains) on different pavement structures and material properties. On the empirical (E) aspect, transfer functions have been derived based on experiments (laboratory and field) that correlate pavement distresses to pavement responses. Miner's hypothesis (Miner, 1945) is then used to accumulate pavement damage over time. These M-E concepts are further applied in the Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A (ARA, 2004).

The benefits of M-E pavement design are well documented and generally agreed upon by the pavement engineering community. One of the major improvements in M-E pavement design occurs in its characterization of traffic. The program enables pavement engineers to design pavements for various circumstances at different levels based on available traffic data, and these levels are sorted in a hierarchical order as:

- Level 1 – Site and direction specific data.
- Level 2 – Statewide data.
- Level 3 – Nationwide data.

In order to collect traffic data for pavement design purposes using the old design guide or the MEPDG, state highway agencies have continuous count programs to help establish seasonal, daily, and hourly traffic characteristics. Within these programs, weigh-in-motion (WIM) stations have a unique function to collect axle load data. Depending on the extent of data usage (such as the use of data from only one collection site, or averaged data from multiple sites), 3 data levels are defined as aforementioned. Level 1 indicates that there is continuous traffic data collection near the design site, such as a nearby WIM station. Level 2 design uses statewide average data. Level 3 design uses the national average data developed from Long-Term Pavement Performance (LTPP) database; these are the default inputs of the MEPDG. In pavement design practices, local traffic characteristics can be hard to define when site-specific data are not available but statewide data are too general. For this reason, some researchers have divided Level 2 into 2A and 2B, where 2A represents group/cluster average data and 2B means statewide data. The Level 2A data are usually developed from similar traffic characteristics of WIM sites.

The MEPDG allows consideration of various vehicle classifications with multiple tires or axles. The FHWA vehicle classification scheme classifies buses and trucks from vehicle class (VC) 4 to VC 13 based on number of axles and tractor-trailer combinations. This vehicle classification scheme is shown in Figure 1.1. Instead of converting all VC 4 to VC 13 truck axles to ESALs as is the case with traditional methods of pavement design, the MEPDG simulates the pass of every truck axle from a wide range of axle load spectra (axle load distribution). Then, the damage of every single pass is calculated by M-E equations and accumulated based on Miner's hypothesis. The simulation will continue until the quantified damage of at least one type of distress measures (such as cracking, rutting, IRI, etc.) reach a pre-defined terminal threshold, and then the service life of the pavement is established.

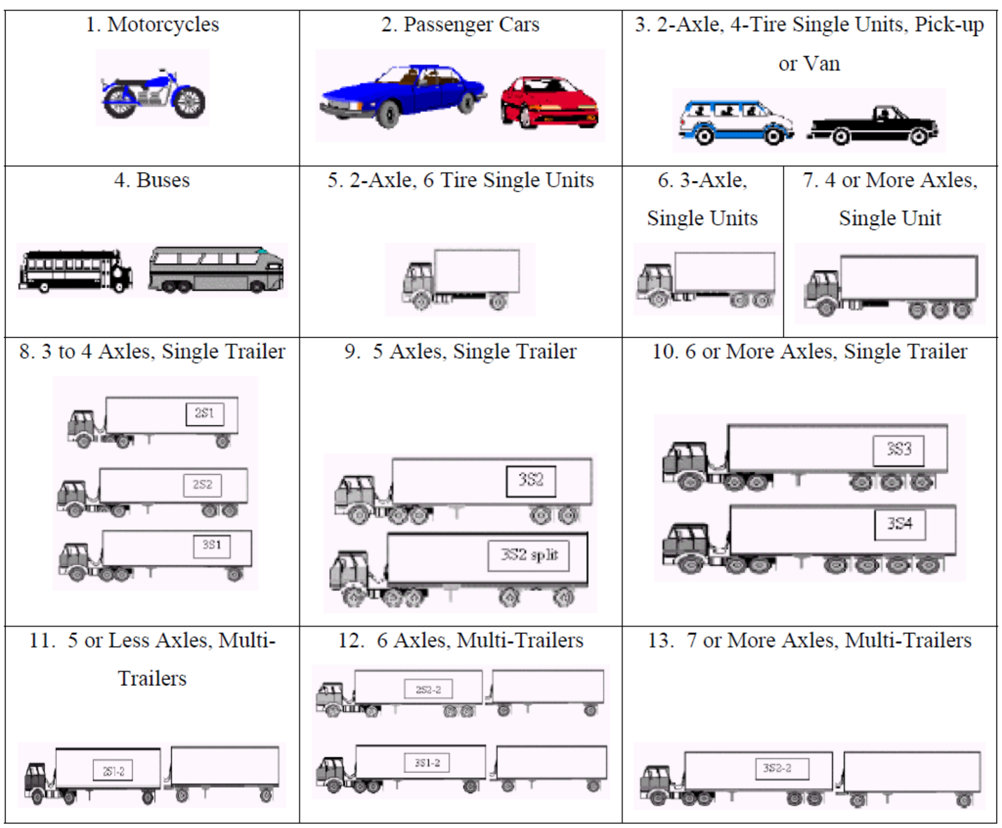

FIGURE 1.1 FHWA vehicle classifications (ASTM, 1994)

The MEPDG traffic inputs of all data levels include truck traffic by vehicle class distribution (VCD), hourly distribution factors (HDF), monthly adjustment factors (MDF), axle groups per vehicle factors (AGPV), and axle load spectra (ALS). There are four types of ALS based on four axle types (single, tandem, tridem and quad). As an example, Figure 1.2 illustrates the tandem ALS of Alabama's WIM station 961 in August 2007.

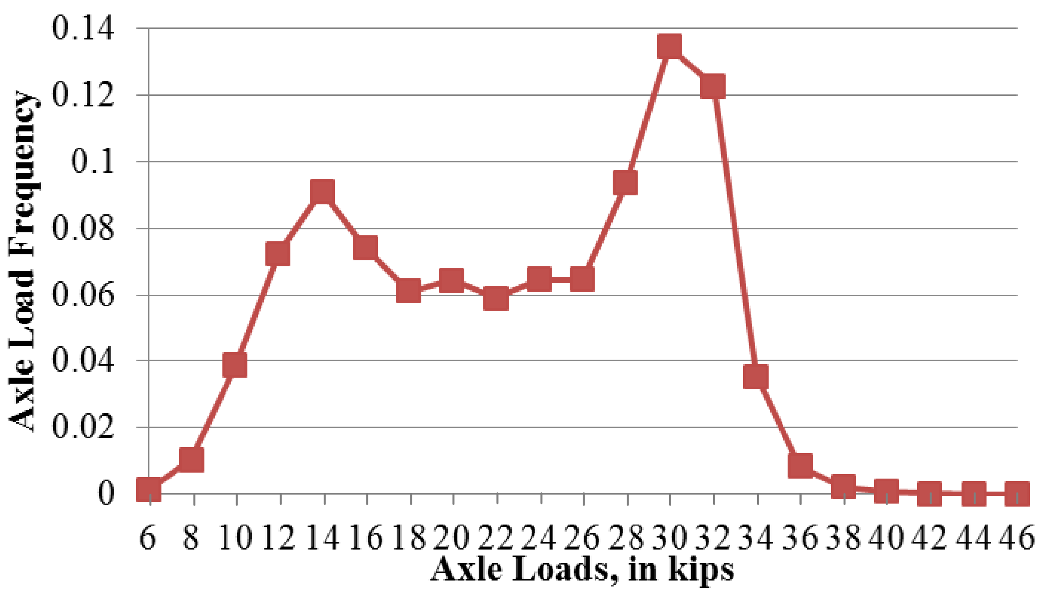

FIGURE 1.2 The tandem ALS of WIM Station 961 in August 2007

Since the range of traffic inputs required by the MEPDG is much more complex than that of the previously-used AASHTO ESALs method (AASHTO, 1993), the MEPDG has a higher requirement for traffic data, most of which is collected through weigh-in-motion (WIM) systems.

As state transportation agencies move toward adoption of the MEPDG, the Federal Highway Administration (FHWA) and many researchers have recommended that each state examine the potential for implementation of Level 1, Level 2A and Level 2B traffic inputs in an effort to minimize the risk of overdesign or underdesign of pavement structures. To develop and recommend appropriate levels of traffic data for transportation agencies, the overall process generally consists of quality control (QC), sensitivity analysis, and clustering of traffic data successively. The QC process examines the quality of WIM data prior to other analyses to avoid "garbage in, garbage out" situations. Sensitivity analysis tests the sensitivity of pavement performance to traffic inputs so that the needs for development of Level 2A data can be determined. Cluster analysis develops Level 2A data and recommends appropriate levels of traffic inputs.

1.2 OBJECTIVE

The dissertation herein includes processes of QC, sensitivity analysis, cluster analysis of traffic factors, and determination of input levels for the use in the MEPDG. A theme throughout the objectives was to create new approaches that could eliminate subjective decisions involved in current practices.

The first objective of this research was to create an unbiased approach to QC of WIM data. This QC procedure was intended not only for data users, but also to be integrated with daily data collection processes for rapid detection of systematic errors, and thus, identify the needs for WIM station calibration as soon as possible.

Secondly, due to different properties between pavement types, sensitivity analyses of flexible and rigid pavement were executed separately to compare the impact of traffic data of Level 1, Level 2B, and Level 3 on pavement thickness using the MEPDG.

When differences in pavement thicknesses based on Level 1 and Level 2B data were deemed sensitive, development of relevant Level 2A data were required. Thus, the third objective of this research was to develop and apply a new clustering process, correlation-based clustering, that considered the impacts of differences in data among different sites on pavement thicknesses to determine numbers of clusters.

Following the development of clusters, the fourth objective was to create a procedure to determine which level of data for each traffic input was recommended for pavement design in various circumstances.

1.3 SCOPE

In Alabama, data from 12 WIM stations from 2006 to 2008 were obtained for this research. A map (Figure 1.3) was developed to illustrate their locations. These data were utilized to validate new data development approaches created in this research.

The details of data used for different steps of the QC procedure were very different. Before examining the WIM data, file-size check firstly looked at the file size of monthly data file. Then, an out-of-range check inspected values of every row of data in these files. The ALS comparison module consisted of peak-range check, peak-shift check and correlation analysis, and they were looking at data at monthly basis. Finally, the number-of-axles check examined station-wide axle groups per vehicle (AGPV) inputs.

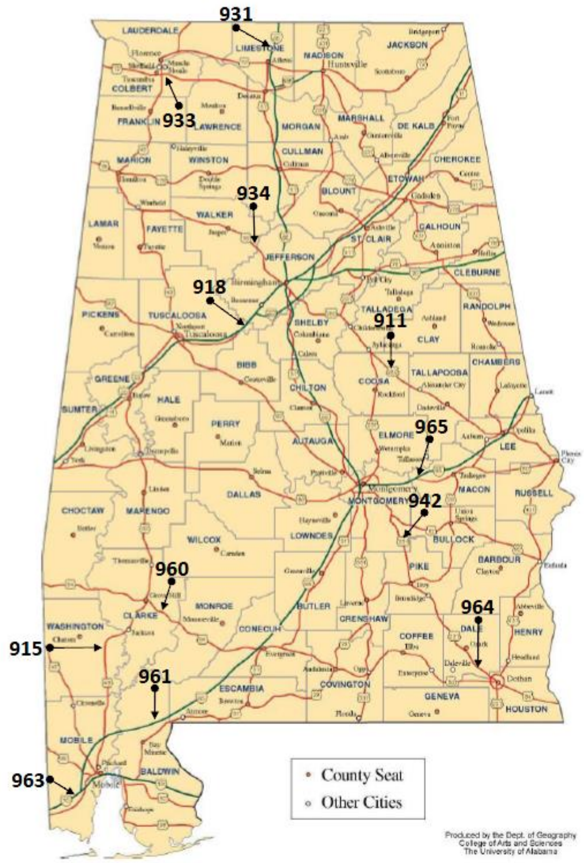

FIGURE 1.3 Locations of data collection sites in Alabama

In order to detect possible directional variations of traffic characteristics, these 12 WIM stations were subdivided into 24 directional stations. There were 13 types of traffic inputs, which include 1 HDF, 1 VCD, 4 AGPV (single, tandem, tridem and quad), 3 MDF (single unit, tractor trailer and multi-trailer) and 4 ALS (single, tandem, tridem and quad). These inputs were developed for sensitivity analysis. Since pavement thicknesses were used as sensitivity indicators, pavement thicknesses associated with relevant traffic inputs at different levels were developed through multiple iterations of the MEPDG. As a result, approximately 7,980 MEPDG program executions were used to accomplish the sensitivity analysis.

In development of Level 2A data, 13 cluster analyses were executed for 13 subdivided traffic inputs. Multiplying with sensitivity analyses for 3 types of traffic volumes, 39 clustering trees were formed, and cut locations of these trees were determined.

1.4 ORGANIZATION OF DISSERTATION

Chapter 2 serves as the literature review necessary to support the objectives of this dissertation. It documents the overall process for development of traffic factors for use in the M-E pavement design. Details of steps, such as QC, sensitivity analysis, and clustering, are also described. With the shortcoming of each step also discussed in Chapter 2, methodologies from Chapter 3 to Chapter 5 are created to improve currently used practices. Chapter 3 provides the QC methodology utilized to ensure the quality of WIM data objectively. Chapter 4 describes the method of sensitivity analysis that uses pavement thickness design as sensitivity indicator. Chapter 5 illustrates the correlation-based clustering processes. It depicts the integration of the sensitivity analysis with correlation-based clustering to determine number of traffic groups for each traffic input in an objective manner. This chapter also provides details on criteria to determine levels of traffic factors for the MEPDG as well as methods to identify traffic patterns. WIM data from Alabama were used, and performance of the methodologies are documented in Chapter 6. Lastly, Chapter 7 summarizes the findings of this dissertation and provides recommendations for the implementation of the traffic factor development procedures developed in this dissertation.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The processes to develop traffic factors for use in the MEPDG involve QC, sensitivity analysis, and clustering. The QC processes involve quality control of WIM data that attempts to eliminate random errors and systematic errors. WIM data errors can be categorized as random errors, which occur individually with no effect on other rows of data, and systematic errors, which can occur in a consecutive period of time and every record collected within that given period could possibly be affected. Therefore, data users' QC processes should include simple threshold checks that eliminate random errors and more data-driven rational checks that detect systematic errors. In the MEPDG, sensitivity analysis can be a broad concept that includes analyzing the impacts of design-related inputs (traffic, material, structure, environment data, etc.) on pavement performance (cracking, rutting, IRI, etc.). This research mainly focused on the effects of traffic inputs. Cluster analysis can be beneficial to the pavement design process when Level 1 data are preferred but not available. Past studies also used different clustering methods to quantify similarity of traffic characteristics. This chapter discussed different QC, sensitivity analysis, and clustering approaches taken by different researchers.

Ensuring the quality of WIM data is critical for traffic factor development. Thus, in terms of order for traffic data development processes, quality control is always the first step. After QC, the processes for traffic inputs development found in literature executed the cluster analysis prior to sensitivity analysis (Haider et al., 2011). This is because cluster analyses in recent studies solely considered the statistical similarity of traffic inputs, and then latter sensitivity analyses used traffic inputs of all levels (including cluster-averaged traffic inputs) to evaluate the sensitivity of pavement performance. Furthermore, since recent clustering practices might group WIM stations of different sensitivity analysis results into the same cluster, latter sensitivity analysis was needed to investigate the effect of cluster-averaged traffic inputs to pavement performance (Li et al., 2011). Overall, the processing orders for traffic factor development found in recent literature were QC, cluster analysis, and sensitivity analysis, respectively.

2.2 QUALITY CONTROL

For state transportation agencies, most continuous count programs collect traffic data using three types of traffic collection devices: automatic traffic recorders (ATR), automatic vehicle classifiers (AVC), and WIM stations (LTPP, 2012). While both ATR and AVC are not able to detect vehicle weight, WIM stations provide the most extensive traffic data, including volume, classification, speed, axle counts, and weight data. WIM devices measure transient tire forces that are applied on WIM sensors to determine static axle weights using computer algorithms. Bending plates, load cells, and piezo-quartz sensors are typical WIM types for continuous counts (ASTM, 2002). Each sensor technology has its own strengths and weaknesses. Data quality of any WIM system is dependent on environment and site conditions (Nguyen, 2010). Recently published research (Ban and Holguin-Veras, 2013; Gajda et al., 2012) has indicated that it is currently still a challenging issue to automatically and accurately classify vehicles, and some detectors might have an accuracy rate as low as 64% (Gajda et al., 2012).

Even though WIM calibration recommendations through the Long Term Pavement Performance (LTPP) Program suggest local government agencies or data collectors calibrate WIM stations regularly, it is suspected that WIM stations may not be routinely calibrated (LTPP, 2001). Furthermore, WIM calibration may not be able to address random errors which are common in WIM data. For example, a study focused on the relationship between speed and WIM system calibration factors found that a significant amount of speed errors were from random sources (Papagiannakis et al., 2008).

To better understand the relationship between systematic errors of WIM data and pavement designs, some prior studies have shifted the axle load distributions in different direction, and observed the changes in estimated pavement performance in the MEPDG (Prozzi et al., 2008; Haider et al., 2012). Both results have shown that MEPDG pavement life estimation is highly sensitive to WIM data. The study conducted by Prozzi et al. (2008) indicated that a ±1% axle load bias could create as much as 3% pavement life estimation error. The other study conducted by Haider et al. (2012) suggested that WIM stations should have a measurement bias limit of less than ±5% to ensure adequate design reliability. The effect of random errors has not been investigated, but it was anticipated that the combination of random and systematic bias could have a larger effect on pavement design (Li et al., 2011). To minimize the potential for a "garbage in and garbage out" problem in WIM data analysis, application of QC from data users' perspective is crucial.

ASTM E1318-02 (ASTM, 2002) specified standards for highway WIM systems and classifications (such as Type I, Type II and Type III) in North America to meet the needs of weight data in different circumstances. Type I classification has the highest data quality restriction. Under the Type-I requirement, WIM systems regardless of WIM sensor types should have the capability of producing WIM data that include:

- Date and Time
- Lane
- Speed
- Vehicle Classification
- Wheel Load
- Axle Load
- Axle Group Load
- GVW
- Individual Axle Spacing
- Vehicle Length
- Violation Code

Type I WIM systems should meet the performance requirement established by ASTM E1318-02 (2002). The specification of Type I performance requirement is shown in Table 2.1.

TABLE 2.1 Functional Performance Requirements for Type I WIM Systems (ASTM, 2002)

	Acceptable Tolerance at 95% Confidence Level					
Function	Wheel Load	Axle Load	Axle-Group	GVW	Speed	Axle-Spacing
Type I	$\pm$25%	$\pm$20%	$\pm$15%	$\pm$10%	$\pm$1 mph	$\pm$0.5 ft

To generate traffic inputs required by the MEPDG in an efficient way, the TrafLoad software was developed in 2004 as part of NCHRP Project 1-39 to serve as a principal source of traffic inputs for MEPDG (Wilkinson, 2005). In recent years, since little documentation has been published on QC procedures for WIM data, some WIM data users may rely on TrafLoad to perform QC on their data. However, this is risky because TrafLoad only performs rudimentary checks for valid site IDs and lanes and direction values, and does not provide a sophisticated QC procedure (Wilkinson, 2005).

There are a few WIM data QC procedures that have been introduced at the federal level. LTPP applies its QC procedure (LTPP, 2001) to SPS WIM sites before its annual publication (LTPP, 2012); the Traffic Monitoring Guide (USDOT, 2001) published by the Federal Highway Administration (FHWA) focuses on calibration of WIM systems during system installation and maintenance. FHWA Reports, “The Quality Control Procedure for Weigh-in-Motion Data” (Nichols et al., 2004), and “WIM Data Analyst’s Manual” (Quinley, 2009), introduce QC methods for agencies at different levels. These reports initially proposed the file-size checks, peak-range checks, and peak-shift checks but asked state agencies to define their QC ranges and thresholds. Studies conducted for state DOTs in North Carolina (Ramachandran et al., 2011), Kentucky (Southgate, 1990), Oregon (Pelphrey and Higgins, 2006) and Arkansas (Wang, 2009) detailed their QC procedures and criteria. In the 1990s, Southgate (1990) found a logarithmic relationship between steering axle load and the first axle spacing (longitudinal distance between steering axle and the next axle group) to adjust systematic errors of weight data, and data from the static weight station were used as the calibration target. However, this method was not widely adopted because the limitation of static weight data in many states. The Arkansas DOT QC process (Wang, 2009; Nguyen, 2010) followed the LTPP procedure (2001) that monitored peak patterns of tandem axles and percentages of overweight gross vehicle weight (GVW). The procedures of peak-range checks and peak-shift checks that were recommended by Traffic Data Editing Procedures (Flinner and Horsey, 2002) were illustrated using Arkansas WIM data (Nguyen, 2010). The front axle of VC9 was set to be between 8 and 12 kips; the tandem axle of a fully loaded VC9 was between 30 and 36 kips. Data that were out of these defined ranges were filtered out. As a result, more than 50% of data were filtered out. For the purpose of the current research, this QC procedure was considered not conservative enough and might impose bias on data. The study conducted for Oregon DOT (Pelphrey and Higgins, 2006) also illustrated the use of acceptable ranges to identify and remove errors, but it was observed that these range checks could not filter out replicate identical records, and it was necessary to use GVW distributions to manually look for visual distinctions such as repeated records, spurious outliers, and other inconsistencies. In the NCDOT QC procedures, the premise of rational checks was that GVW distributions of the same vehicle classification in different months maintain a very stable pattern. Then, manual checks, visual interpretation and local knowledge were used to identify abnormal patterns caused by systematic errors (Ramachandran et al., 2011). More than 7% of data were excluded during this process. ALS data were deleted only when they failed all the checks. This QC procedure was a conservative way to protect the original data. However, the process to identify abnormal patterns were visually based and had not been statistically quantified.

2.3 SENSITIVITY ANALYSIS

There are 5 major traffic inputs in MEPDG, such as hour distribution factor (HDF), vehicle class distribution (VCD), axle group per vehicle (AGPV), monthly distribution factor (MDF), and axle load spectra (ALS). However, past research (Haider et al., 2011) found that traffic data of different axle types and tractor-trailer combinations might have significantly different characteristics, and therefore, should be subdivided into 13 traffic inputs: 1 HDF, 1 VCD, 4 AGPV (single, tandem, tridem and quad), 3 MDF (single unit, tractor trailer and multi-trailer) and 4 ALS (single, tandem, tridem and quad).

Sensitivity analysis of pavement performance can be used to compare the effects of using Level 1 (direction-specific), Level 2B (statewide), and Level 3 (default values) critical traffic inputs. Past studies also used the results of sensitivity analysis to determine the levels of traffic inputs for use in the MEPDG. For example, in Arizona, a study examined the differences in input traffic data from two data sources (LTPP and Arizona DOT), and found large differences in predicted pavement distresses (Ahn et al. 2011). In Virginia, Smith and Diefenderfer (2010) recommended that site-specific ALS (if available) be used, and if site-specific data were not available, statewide was preferential to the default ALS provided in the MEPDG. Selection of VCD should also be site-specific if possible or otherwise statewide data should be used. A study conducted by Sayyady et al. (2011) using North Carolina data concluded that ALS, VCD, and MDF should be developed at the site-specific level, with a second choice of using regional distributions within the state. Research performed by Tran and Hall (2007) determined that statewide ALS and VCD are appropriate for use in Arkansas but that the MEPDG-provided MDF and HDF were sufficient. In Michigan, Haider et al. (2011) recommended development of cluster-averaged traffic inputs when site-specific data were not available.

Sensitivity analysis is based on the assumption of uniform pavement structures. Thus, determination of typical pavement designs is critical for sensitivity analysis; however, past studies used differing approaches in flexible and rigid pavements. For example, in flexible pavement analysis, Tran and Hall (2007) used only one asphalt concrete thickness for sensitivity analysis; the research performed by Li et al. (2009) used four AC thicknesses based on four soil types; the study conducted by Haider et al. (2011) used three surface thickness designs based on three levels of traffic volumes. In rigid pavement analysis, studies conducted by Hall et al. (2005) and Khanum et al. (2006) used one joint plaint concrete pavement (JPCP) section. Studies conducted by Guclu et al. (2009) used two JPCP sections and one continuous reinforced concrete pavement (CRCP) section that were selected from the Management Information System of the Iowa DOT. A similar study conducted by Haider et al. (2011) used three JPCP sections for three levels of traffic volumes.

Past studies of sensitivity analysis in both flexible and rigid pavement design also used various sensitivity indicators. For example, in sensitivity analysis of flexible pavements, studies conducted in Virginia (Smith and Diefenderfer 2010), Arkansas (Tran and Hall 2007), New York (Romanoschi et al. 2011), and Idaho (Bayomy et al., 2012) used rutting, cracking and IRI as sensitivity indicators, while a similar study conducted in Michigan used pavement life as the sensitivity indicator (Haider et al., 2011). For the analysis of rigid pavements, past studies (Hall et al., 2005, Khanum et al., 2006, Guclu et al., 2009) also use normalized pavement performance (such as faulting, cracking, and smoothness) as indicators, while a study conducted by Haider et al. (2011) used estimated pavement life to serve the purpose. The advantages of using rutting, cracking, IRI and pavement life as sensitivity indicators are the relative simplicity of experiment design pertaining to MEPDG iterations because they are direct outputs of the MEPDG. However, the disadvantage is that none of these indicators are directly related to pavement thickness, which is of the utmost importance in pavement design.

2.4 CLUSTERING OF TRAFFIC DATA

Development of regional traffic inputs (Level 2A traffic data) is crucial when site-specific data are not available, but statewide data are too general. To create inputs of this level, three approaches are recommended by the Federal Highway Administration (FHWA) Traffic Monitoring Guide (USDOT, 2001):

- Geographic/functional assignment of roads to groups (GFARG)
- Same road factor application (SRFA)
- Cluster Analysis

The GFARG method groups WIM sites by geographic location and functional classification of roads. The SRFA method applies local knowledge to group WIM sites with similar traffic characteristics, and thus engineering judgment is applied in this method. The cluster analysis approach tries to group WIM stations by their quantified extent of similarity.

Although cluster analysis is a more complex grouping method compared to the other two, this approach is widely used in WIM station grouping because it is relatively objective. However, in recent cluster analysis practices, there are still weaknesses and subjective decisions involved. Three general clustering techniques are widely used in scientific researches. They include optimization/partition cluster analysis, density or mode-seeking cluster analysis, and hierarchical cluster analysis (Strauss, 1973). Hierarchical cluster analysis is the most popular clustering technique, in which the classes themselves are classified into groups, with the process being repeated at different levels to form a tree (Everitt, 1993). It allows the data analyst to control and cease the clustering process at any point. One study found that the results of hierarchical cluster analysis had little differences compared to the other two clustering techniques (Wang et al., 2011a).

All clustering methods within the hierarchical clustering family begin with clustering the two most similar objects. However, once the first cluster is formed, latter clustering processes are significantly different among clustering methods (Romesburg, 1984). The current state of practice in using hierarchical clustering techniques for WIM data mainly use Euclidean distance based clustering combinations (Wang et al., 2011a; Lu and Harvey, 2006; Haider et al., 2011; Papagiannakis et al., 2006; Regehr, 2011; Sayyady et al., 2011; Wang et al., 2011b) combined with Ward's minimum variance method (Wang et al., 2011b; Haider et al., 2011; Papagiannakis et al., 2006; Regehr, 2011). In these approaches to clustering, a data set, such as a tandem axle load spectra derived from a particular WIM site, is viewed as one multi-dimensional point. The extent of similarity between two of these “points” is determined using Euclidean distance, and the combining of two separate points into one cluster is determined using Ward’s minimum variance method. This combination was shown as an example in the TMG (USDOT, 2001), and then detailed by Papagiannakis et al. (2006).

While past studies used very similar clustering methods, a variety of approaches have been taken. Papagiannakis et al. (2006) used the tandem axle spectra as the only representative axle type, and thus, single, tridem and quad axle clustering followed identified tandem axle clusters. In California (Lu and Harvey, 2006) and North Carolina (Sayyady et al., 2011) studies, cluster analyses were initially done on tandem axles. The identified clusters were then modified for single, tridem and quad axles using a GFARG method that required engineering judgment. In Michigan (Haider et al., 2011), it was found that traffic data of different axle types and tractor-trailer combinations had significantly different characteristics, and therefore, were subdivided into 13 traffic inputs: 1 HDF, 1 VCD, 4 AGPV (single, tandem, tridem and quad), 3 MDF (single unit, tractor trailer and multi-trailer) and 4 ALS (single, tandem, tridem and quad).

In current practice for clustering of WIM sites, one of the major disadvantages was the use of a Euclidean distance based measure to compute similarity for datasets that are in the form of distributions. To utilize the Euclidean distance measure, traffic distributions, such as axle load spectra, are viewed as multi-dimensional points. Linear distances between these points are used to represent the similarity between points. However, HDF, MDF, VCD and ALS are actually probability distributions, that when viewed as points, especially for tandem ALS that are seen as 39-dimension points (for 39 load bins), lose the inherent properties of a probability distribution in which all values sum to unity.

A second disadvantage is the lack of a bounded measurement for level of similarity. In the squared Euclidean distance resemblance matrix, one could not evaluate the extent of similarity between traffic distributions because the similarity limit was infinity. Thus, the cophenetic correlation coefficient test was then recommended (Romesburg, 1984) in squared Euclidean distance based clustering to standardize how similar distributions were to each other. However, recent practices, as described in the literature, had not implemented this post-clustering test to evaluate the level of similarity between traffic distributions and clusters.

A third disadvantage was the need for subjective decisions on where to cut clustering trees. This disadvantage is a consequence of the second disadvantage mentioned above. Without a bounded evaluation of similarity, subjective decisions were needed during clustering analysis to decide the location at which to "cut" the clustering trees (Papagiannakis et al., 2006). This decision is typically handled by specifying a certain number of clusters (USDOT, 2001; Papagiannakis et al., 2006). That is, a desired number of clusters were selected regardless of the level of similarity. Other researchers (Lu and Harvey, 2006; Sayyady et al., 2011; Wang et al., 2011b) used cubic clustering criterion, Pseudo T^2 statistic, Pseudo F statistic and other statistics to determine the number of clusters. However, these approaches did not allow for the number of clusters to be driven by pavement design related factors.

2.5 SUMMARY

In an effort to develop and recommend suitable level of traffic data for use in the MEPDG for state agencies, QC, sensitivity analysis, and cluster analysis are the three major steps.

The first step, QC, has drawn less attention in prior studies perhaps due to its data intensity. Past research have shown a range of QC procedures from liberal to conservative, and a significant portion of data errors were identified using either philosophy. Thus, QC should be considered prior to using the data for other purposes. For WIM data of different states, past researches recommended the establishment of their own QC parameters.

The literature review for sensitivity analysis presented in this chapter mainly focused on the impacts of traffic factors on pavement performance. Traffic factors in recent studies were subdivided into 13 categories. The performance measures used in past studies included cracking, rutting, IRI, pavement life, and user-defined thresholds of other statistic models. For sensitivity analysis of both flexible and rigid pavement, typical structures and baseline pavement thicknesses were developed, but they were very different across states.

For cluster analysis, researchers generally agreed on the use of hierarchical methods to quantify similarity of traffic characteristic. However, there are many approaches to choose from within the hierarchical methods and the most frequently used one was the combination of Euclidean distance and Ward's minimum variance. The disadvantages of this method include (1) the transformation of distribution curves to multi-dimensional points (as much as 39 dimensions) for similarity measurements, which loses the inherent properties of a probability distribution in which all values sum to unity; (2) the lack of a bounded measurement for level of similarity; and (3) subjective tree cut locations.

CHAPTER 3

METHODOLOGY OF QUALITY CONTROL

3.1 INTRODUCTION

Random and systematic errors commonly exist in WIM data. Literature reviewed in Chapter 2 indicated that a significant amount of errors were detected in various quality control (QC) procedures. Furthermore, data bias had strong influence on pavement designs. Thus, QC of WIM data is strongly recommended prior to using the data for further analysis.

One major objective of this dissertation is to develop an unbiased QC procedure. To meet this objective, major steps of the QC procedure include a data-file-size check, axle load spectra (ALS) comparisons and number-of-axles check. User-defined QC criteria were created in an objective manner.

3.2 OVERALL QUALITY CONTROL PROCESS

The QC process developed in this study consists of two types of approaches to ensuring data validity: threshold checks and rational checks. WIM data with implausibly low or high values can be readily identified, for example, a semi-trailer (Vehicle Class 9 or VC9) with speed over 120 mph could be considered implausible, and threshold checks are used to filter them out. However, some systematic errors cannot be observed merely by examining values for individual variables; to detect these errors, rational checks that examine axle load distributions and relationships among them are developed. The overall QC procedure is shown in Figure 3.1. In the first phase of the QC procedure, a file-size check is conducted on a monthly basis. Then, an out-of-range check inspects values in every row of data within these files. In the second phase, the axle load spectra (ALS) comparison module consists of a peak-range check, peak-shift check and correlation analysis, by looking at data on a monthly basis. Finally, the number-of-axles check examines station-wide axle groups per vehicle (AGPV) inputs. Each check is discussed in more detail in the following sections.

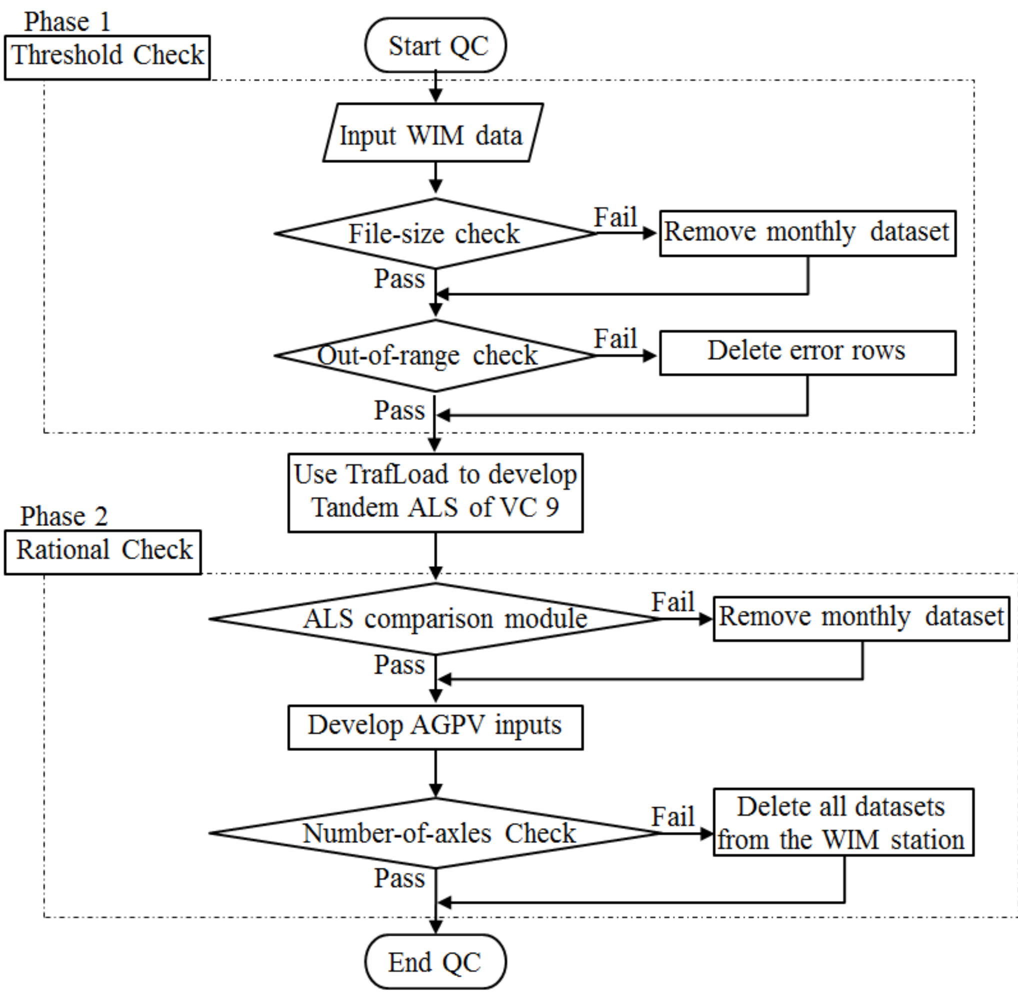

FIGURE 3.1 Overall QC process

3.3 THRESHOLD CHECKS

The threshold check phase consists of two steps: (1) eliminating dataset file-size outliers and (2) deleting out-of-range values. The file-size check is used to detect severe file size drops which represent substantial amounts of missing data. These drops might be due to

WIM system failure, road maintenance, rehabilitation and so on. However, regardless of the abnormal circumstances which lead to a file-size outlier, disrupted truck traffic counting and weighing should not be used for pavement design purposes. Therefore, monthly datasets with file-size outliers should be eliminated. In the second step of the threshold check, an out-of-range check is applied to detect and remove extreme values caused by random errors.

3.3.1 File-Size Check

A file-size check is recommended by the FHWA's *WIM Data Analyst's Manual* (Quinley, 2010); however, no detailed procedures are discussed. The file-size check developed herein assumes that file size has a positive linear relationship with the volume of truck traffic counted, and a file-size outlier indicates WIM system errors or abnormal circumstances occurred on the road.

The quartiles of a ranked set of data values are the three points that divide the data set into four groups. The first quartile is a specific sample value of a sample size's 25th percentile. The third quartile is the value of a sample size's 75th percentile. The difference between the first quartile and the third quartile is called the interquartile (IQR). Statistically, 1.5 times outside of the interquartile (1.5 IQR) is used to detect outliers in normal practice, while 3.0 IQR is used to define extreme outlier (Navidi, 2010). Regarding truck traffic data, it is reasonable to assume that monthly truck volumes do not change dramatically under normal circumstances. Thus, it was determined that file sizes beyond 1.5 IQR (but not 3.0 IQR) indicates severe data incompleteness during the monthly period. Therefore, a file-size outlier can be defined if its file size is out of the range shown in Equation 3.1. In Figure 3.2, WIM station 965 in Alabama is shown as an example of file-size check where minimum and maximum acceptable file size values are shown in the bottom-left corner. As a result, the September 2008 dataset was removed due to its abnormally low file size, indicating an unacceptable level of data incompleteness.

$$Q_1 - 1.5(Q_3 - Q_1) \; < R < \; Q_3 + 1.5(Q_3 - Q_1) \qquad (3.1)$$

Where,

R is the acceptable file size range
Q_1 is the first quartile of file sizes
Q_3 is the third quartile of file sizes
$(Q_3 - Q_1)$ is the interquartile (IQR)

WIM Station 965			
Years	2006	2007	2008
Month	File Size, in KBs		
Jan	11728	11744	12506
Feb	10775	11035	10036
Mar	12702	12708	12306
Apr	11621	11266	12225
May	13044	12196	12228
Jun	13986	13515	11549
Jul	11781	12893	11711
Aug	13725	10679	10014
Sep	12087	12246	4332
Oct	13098	9991	11594
Nov	11714	12508	9727
Dec	11138	11580	9337
1st Quartile	11086.5		
3rd Quartile	12507		
Lower Outlier	8955.75		
Higher Outlier	14637.75		

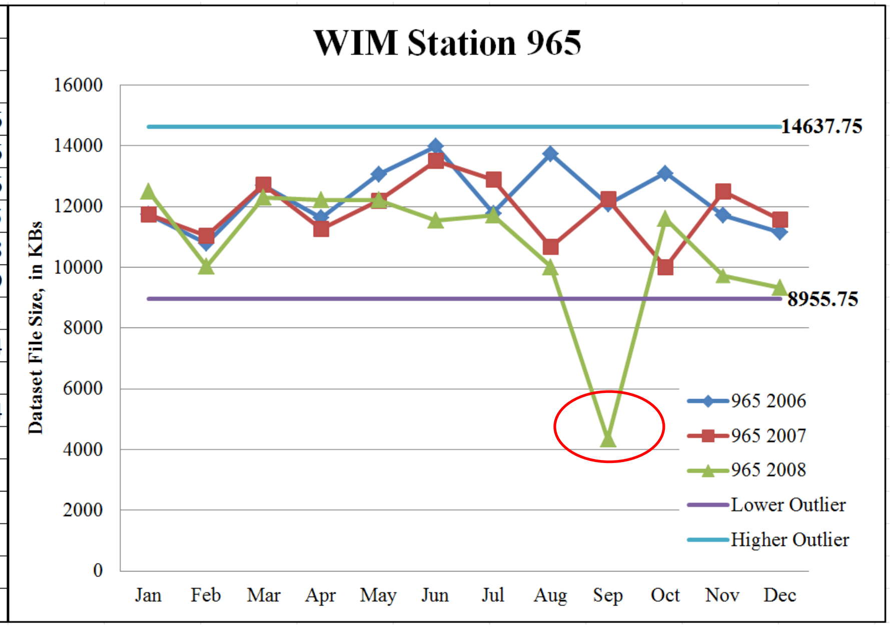

FIGURE 3.2 Identification of outlier at WIM Station 965

Note that commonly used statistics programs, such as SAS, Minitab and Excel, use different methods to calculate quartiles and outliers, and thus, results could be different depending on the program. SAS Method 5, which is the default method of SAS, is recommended in this file-size check. In this method, the value of a quartile is defined as the average value (point) between two samples that is closest to its quartile location. For example, in a ranked data set of 10 samples, the first quartile is the value of the 25[th] percentile, which in this case, means the value of the 2.5th sample. However, the 2.5th sample in a sample size of 10 does not exist. As a solution, according to the SAS Method 5, the average value of the 2nd sample and the 3rd sample are used as the first quartile. This quartile method is most commonly used in statistics and engineering (Navidi, 2010).

3.3.2 Out-of-Range Check

The *Traffic Monitoring Guide* (FHWA, 2001) and *WIM Data Analyst's Manual* (Quinley, 2010) suggest out-of-range checks for WIM data; however, no specific range value was assigned and local knowledge should be applied for these range values. Each row of WIM data indicated one truck pass. A unique truck ID was assigned when a truck pass a WIM station, and other information such as speed, vehicle class, number of axles, and respective axle loads were also record on the same row after the truck ID. In this study, a range for each field was set based on the literature review of QC practices presented and local knowledge. When any fields within a row had an out-of-range value, the entire record was deemed to have random error and therefore was filtered out. A list of the out-of-range check criteria implemented herein is shown in Table 3.1. Some criteria were set for data validation; while other criteria, such as speed and weight ranges, are designed to filter out extreme random errors.

The determination of weight ranges for different axle types is the most important part of the out-of-range check. If ranges are too narrow, the process may ignore the extent of overweight trucks and filter out too much valid data for vehicles that damage pavement the most. Underestimating overweight truck volume is a major reason of premature pavement failure (Turochy et al., 2005). The *FHWA WIM Data Analyst's Manual* (Quinley, 2010) indicates that the percentage of overweight trucks could be as high as 25% in certain parts of the United States. Furthermore, trucks can obtain an overweight permit and travel on the road legally. Therefore, weight ranges should be broad enough to include most overweight trucks. To be conservative in data deletion, the maximum weight ranges herein have increments of 20 metric tons (441,000 lb) from the weight ranges developed for the North Carolina DOT (Ramachandran et al., 2011) for different axle types.

TABLE 3.1 Out-of-range Criteria

Error Description	**Error Trigger Value**
Invalid axle type	Null or ≠ (1 – 6, or 21)
Invalid direction	Null or ≠ (1 – 8)
Invalid lane location	Null or ≠ (1 – 5)
Axle counts inconsistent with axle groups	# axles < # axle Groups
Steering axle weight is out of acceptable range	≠ (0.2 – 20.0 mton) or is null
Single axle weight is out of acceptable range	≠ (0.2 – 30.0 mton) or is null
Tandem axle weight is out of acceptable range	≠ (0.2 – 40.0 mton) or is null
Tridem axle weight is out of acceptable range	≠ (0.2 – 60.0 mton) or is null
Quad axle weight is out of acceptable range	≠ (0.2 – 80.0 mton) or is null
Penta axle weight is out of acceptable range	≠ (0.2 – 100.0 mton) or is null
Speed is out of acceptable range	over 192 km/h or is null
Invalid year	≠ (2006 – 2008)
Invalid month	≠ (1 – 12)
Invalid day	≠ (1 – 31)
Invalid hour	≠ (0 – 23)
Invalid state code (Alabama)	≠ 1 or is null
Invalid vehicle classification	≠ (4 – 13) or is null

3.4 RATIONAL CHECKS

Once a systematic error occurs, it may last indefinitely, or until the next scheduled calibration, and every record collected within that period could possibly be affected. Rational checks that consist of ALS comparison and number-of-axles checks were developed to detect systematic errors. TrafLoad was implemented in this process to develop ALS for curve comparisons. Since tandem axles of vehicle class (VC) 9 are the most frequently observed heavy vehicle axle types, only tandem ALS of VC 9 are developed for ALS comparison. Then, the last rational QC procedure is the number-of-axles check, which compares the average number-of-axles data with standard axle counts of its relevant vehicle class.

3.4.1 ALS Comparison Module

To quantify the extent of similarities between monthly datasets, an ALS comparison module that includes ALS peak-range check, ALS peak-shift check and ALS correlation analysis has been developed. Tandem ALS has the identical low peak and high peak that record loads of empty trucks and fully loaded trucks, respectively. The peak-range check examines load values of both peaks; the peak-shift check, as a second step, monitors abnormal shifting of peak loads; then, the ALS correlation analysis evaluates the similarity between ALS. Details of the ALS comparison module are shown in Figure 3.3. Since this module examines datasets on a monthly basis, a decision to filter out such a large amount of data at one time should be conservative to lower the risk of deleting valid data. For this reason, a dataset that passes any of these three sub-steps passes the ALS comparison module. Conversely, any dataset must fail all three sub-steps to be removed from further use.

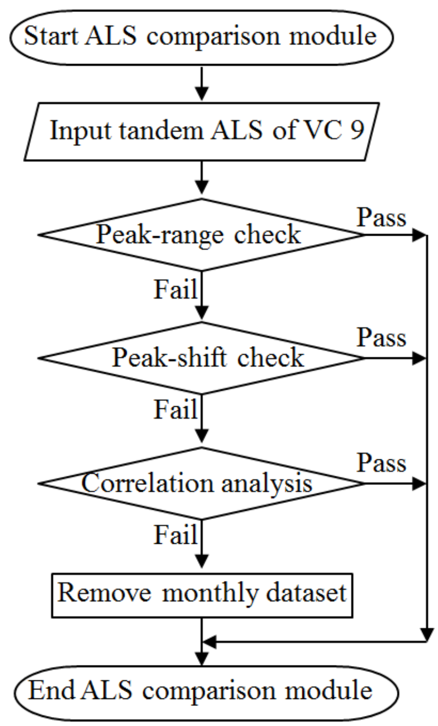

FIGURE 3.3 Sub-steps of ALS comparison module

The basic premise of this module is that the ALS curves from a particular WIM station for the same months from different years should be similar to each other. When systematic errors occur, it might affect subsequent months. Therefore, ALS comparison focuses on the same month of consecutive years instead of consecutive months in the same year. To identify potential erroneous datasets, at least three ALS curves are compared with each other. This requires at least 36 consecutive months of data that pass the first phase (threshold checks) of the QC procedure. The curve that is deemed statistically different from the other two curves is moved to the next sub-step of the module. Thus, for ALS comparison, if available, it is recommended that at least three years of WIM data are used.

The peak-range check focuses on load values of the low peak (when trucks are empty) and the high peak (when trucks are fully loaded). The report *Traffic Data Editing Procedure: Traffic Data Quality* (Flinner and Horsey, 2000) recommends the peak-range check and suggests peak ranges to be user defined and adapted to local traffic characteristics. According to the *Standard Data Release 26.0* of the LTPP (LTPP, 2012), Alabama has a low peak range of 14 to 16 kips and a high peak range of 32 to 38 kips for tandem ALS of VC 9 in Alabama. A monthly dataset will be identified as potentially erroneous and then subjected to peak-shift checks if either its low peak or high peak is out of its respective range.

The peak-shift check monitors peak patterns and compares the amount of peak shifting between datasets. While proposing this QC check, the LTPP (2001) also suggested state agencies to investigate local shifting values. In Alabama, the allowable peak-shift values are based on observations of peak shifting in the *Standard Data Release 26.0* of the LTPP for Alabama data (LTPP, 2012). To be considered as maintaining consistent peak patterns, the maximum acceptable shift for the low peak is 2 kips, and no more than 4 kips for high peaks. A third step, consisting of a correlation analysis, is applied to the dataset if either its low peak or high peak does not follow peak patterns.

Correlation analysis is implemented as a statistical method to quantify the similarity of two monthly ALS of different years. The advantage of correlation analysis is that it compares all data points on both ALS curves instead of comparing merely peak values and therefore provides a more sophisticated check. This analysis is intended as an objective approach to replace subjective visual comparisons used in some past QC studies.

The correlation coefficient r is the parameter to evaluate the similarity of two ALS curves; in that r ranges from -1 to 1. A coefficient of 1.00 indicates two ALS match perfectly while -1.00 indicates two ALS are inversely proportional. Generally, from a statistical perspective, a correlation value of less than 0.85 indicates that two datasets do not match acceptably well (Everitt, 1993). For the correlation analysis in this research, a value less than 0.85 was also selected to indicate that two ALS have significant differences. In this study, three years of data were obtained so that one dataset was compared with other two datasets of the same month. Since datasets subjected to correlation analysis have failed previous peak-range check and peak-shift check first, datasets with correlation coefficients less than 0.85 in both comparisons was considered to be erroneous, and were removed for further analysis.

As an example, the ALS comparisons of October and November datasets of WIM Station 961 from 2006 to 2008 are shown in Figure 3.4. Datasets of October 2008 and November 2008 were problematic; ALS of October 2008 has a high peak of 24 kips, and ALS of November 2008 has a low peak of 24 kips. These peak values fall outside respective ranges of peak-range checks. Considering the peak-shift checks, ALS of October 2008 exhibited a 6-kip shift, and that of November 2008 shifted 10 kips. They are considered to be not maintaining consistent peak patterns, and therefore are subject to the correlation analysis. Results of the correlation analysis are also shown in Figure 3.4. Since both ALS of 2008 have correlation coefficients less than 0.85 when compared to those of the same months in 2006 and 2007, datasets of October 2008 and November 2008 did not pass this phase of the QC procedure and were removed from further analysis.

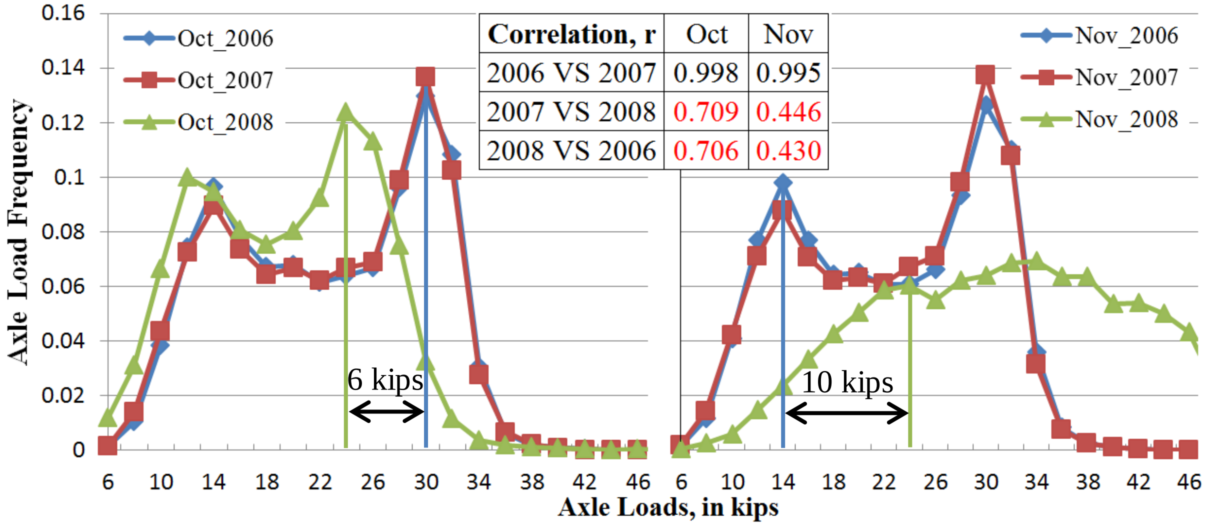

FIGURE 3.4 ALS comparisons for datasets of October and November of WIM Station 961

3.4.2 Number-of-Axles Check

The MEPDG software simulates pavement performance by modeling stresses and strain induced by each axle group on the pavement structure. Thus, the axle group per vehicle (AGPV) input is required in the program and is shown in Table 3.2. Note that some values in the AGPV table carry decimal places. This is because axle group configurations for vehicles in the same class might vary. For example, semi-trailer trucks with 5 axles are classified as VC9 (TxDOT, 2001), but their axle configuration could be three single axles with one tandem axle, one single axle with two tandem axles, or other combinations.

TABLE 3.2 The AGPV Input Table in the MEPDG for WIM Station 961

	Single	**Tandem**	**Tridem**	**Quad**
Class 4	1.60	0.40	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

Vehicles, especially buses and trucks from VC 4 to VC 9, are classified based on number of axles and tractor-trailer combinations (TxDOT, 2001). The number of axles of each vehicle class according to the FHWA standard is shown in Table 3.3. The number-of-axles check herein followed this FHWA standard. However, for VC4 and VC8 that allows two values of axles per axle group, the ranges of number of axles should be broadened. The number-of-axles ranges for QC purpose are shown in the third column of Table 3.3.

TABLE 3.3 FHWA Standard of Number of Axles and Its Range for QC Purpose

	Number of Axles	
Vehicle Class	FHWA Standard	Range for QC Purpose
Class 4	2 or 3	2 to 3
Class 5	2	2
Class 6	3	3
Class 7	4 or more	4 or more
Class 8	3 or 4	3 to 4
Class 9	5	5
Class 10	6 or more	6 or more
Class 11	5 or less	5 or less
Class 12	6	6
Class 13	7 or more	7 or more

Prior to the execution of the number-of-axles check, the average number of axles of each vehicle class must be calculated from the average AGPV table (Table 3.2). This conversion could be done because each single axle group has one axle, and so as two axles for tandem axle group, three axles for tridem axle group and four axles for quad axle group. For example, VC9 in Table 3.2 has an average of 1.13 single axles and 1.93 tandem axles. That is, for this station, vehicles in VC9 have an average of 5 axles $\approx 1.13 * 1 + 1.93 * 2 + 0 * 3 + 0 * 4 = 4.99$ axles.

Then, the number-of-axles of each WIM station is compared with the range for QC purpose shown in Table 3.3. If the number-of-axles data of any vehicle class are out of the determined range (as shown in the rightmost column of Table 3.3), it indicates the axle counting function of WIM sensor is problematic. Therefore, the data from the affected WIM station are then filtered out.

3.5 SUMMARY

This chapter served to describe the overall method utilized to develop an unbiased QC procedure. It was intended to eliminate random and systematic errors embedded in the WIM data. Threshold checks were developed to detect random errors. Steps within the threshold checks included file-size checks and out-of-range checks that were introduced in past studies. Alabama-specific QC parameters were developed to furnish these checks for QC of WIM data within the state. As another important part of the QC procedure, rational checks which examined relationship between data were used to detect systematic errors. Rational checks included ALS comparison module and number-of-axle checks. Correlation-analysis within the ALS comparison module and number-of-axle checks were introduced in this chapter to replace subjective visual-based inspections used by past studies.

Overall, QC of WIM data was the first step of this dissertation to ensure acceptable data quality for sensitivity analysis and cluster analysis in the following steps.

CHAPTER 4

METHODOLOGY OF SENSITIVITY ANALYSIS

4.1 INTRODUCTION TO SENSITIVITY ANALYSIS

As aforementioned in Chapter 1, traffic data for use in the MEPDG can be divided into four levels: Level 1, Level 2A, Level 2B, and Level 3. To recommend and develop a suitable level of traffic input for state agencies, two major steps were utilized after the quality control of WIM data in previous chapter: sensitivity analysis and cluster analysis. The role of a sensitivity analysis is to determine how much pavement performance changes based on changes in traffic inputs among Level 1, Level 2B, and Level 3. When pavement performance is deemed sensitive to traffic inputs, the cluster analysis is warranted as the next step to develop Level 2B data. This chapter mainly focused on the methodology of sensitivity analysis. The basic principle of the sensitivity analysis is to alter traffic input levels during the MEPDG iterations, and then pavement performance data established from the iterations were compared to determine sensitivity results. However, due to different practices of traffic input subdivisions, pavement structure designs, uses of sensitivity indicators, and determinations of sensitivity thresholds, past studies presented diverse and complex sensitivity analysis methods. Since pavement thickness is the critical output of the pavement design process, this chapter developed a straightforward sensitivity analysis method that uses pavement thickness as the sensitivity indicator to streamline the analysis process.

4.2 OVERALL SENSITIVITY ANALYSIS PROCESS

The order of sensitivity analysis and cluster analysis as executed in this research is different from past studies. This research integrated determination of the sensitivity of pavement thickness to traffic inputs with development of regional traffic inputs using cluster analysis so that the effects of Level 1 inputs on pavement performance are considered in the development of Level 2A traffic inputs. That is, the results of sensitivity analysis served as inputs to the cluster analysis. Therefore, the sensitivity analysis in this research was executed prior to the cluster analysis.

Due to different material properties and structural characteristics between rigid and flexible pavements, sensitivity analysis of different pavement types may show different results from the same set of traffic data. Therefore, the sensitivity analysis in this research was executed separately for both pavement types.

If a key objective of M-E pavement design is to produce a design that results in distress measures remaining below desired levels until the end of the pavement design life, then pavement thickness is a key parameter to be determined. For the sensitivity analysis of flexible and rigid pavement design to traffic inputs described herein, pavement thickness was used as the sensitivity indicator. The sensitivity analysis results can be obtained by changing baseline pavement thicknesses through successive simulations in the MEPDG program by an interval large enough to be deemed critical from a practical perspective. In this study, the effect of traffic input level on pavement design was deemed practically significant when pavement thickness deviated by one-half (0.5) inch or more from baseline intermediate layer thickness. A one-half inch difference was selected because it is not practical to design and build a pavement thickness to a finer level (Turochy et al., 2005).

4.3 TRAFFIC DATA PREPARATION

WIM data were collected from 12 WIM stations that used bending plate sensors in Alabama for a 3-year period (2006 through 2008). To expediently transfer WIM data into MEPDG recognized traffic inputs, TrafLoad developed in 2005 through NCHRP Project 1-39 (Wilkinson, 2005), was utilized.

Since traffic in different directions on the same road might have dissimilar characteristics, the 11 quality-checked WIM sites were further divided into 22 direction-specific WIM stations. TrafLoad was then utilized to develop Level 1 and Level 2B traffic inputs. In Michigan, a study conducted by Haider et al. (2011) found that traffic data of different axle types and tractor-trailer combinations had significantly different characteristics, and therefore, should be subdivided into 13 traffic inputs: 1 hour distribution factor (HDF), 1 vehicle class distribution (VCD), 4 axle group per vehicle (AGPV) (single, tandem, tridem and quad), 3 monthly distribution factor (MDF) (single unit, tractor trailer and multi-trailer) and 4 axle load spectra (ALS) (single, tandem, tridem and quad). The sensitivity analysis described herein followed these traffic inputs subdivisions.

The annual average daily truck traffic (AADTT) is also an important input of the MEPDG. Since equivalent single axle load (ESAL) was no longer used, axle passes in the MEPDG are simulated individually by assigning AADTT values proportionally into HDF, VCD, MDF, AGPV, and ALS. Based on AADTT values, roadways can be categorized as low-, median-, and high-volumes for pavement design purposes. To determine appropriate AADTT values for low-, median-, and high-volume roadways in Alabama, data from ALDOT’s traffic data website including the annual average daily traffic (AADT) and truck average daily traffic in percentage of AADT (TADT) information from 120 continuous traffic counting stations were obtained. AADTT values were then developed by multiplying AADT by TADT. Low, median and high truck traffic volumes were developed based on the 5^{th}, 50^{th} and 95^{th} percentile of the ranked AADTT per lane values at these 120 locations. These volumes are 110, 530, and 2440 heavy trucks per day respectively for low-, median-, and high-volume roadways respectively. According to the Alabama truck factor study in 2005, the State has an average truck factor of 0.8785 for flexible pavement design (Turochy et al., 2005). Assuming a 1% annual growth rate for truck traffic of 30 years on low- and median-volume roadways and no growth on high volume roadways, the ESAL levels for design of low-, median-, and high-volume roadways per design lane are 1.2, 6.0, and 24.0 million respectively.

4.4 SENSITIVITY ANALYSIS OF FLEXIBLE PAVEMENT

The typical pavement designs in a sensitivity analysis serve as baseline structures. For similar practices of different states, various typical pavement designs were created. For this study, typical pavement designs used in Alabama were created to test the sensitivity of pavement thickness to differences in traffic inputs at Levels 1, 2B, and 3.

Since traffic characteristics of low-, median- and high-volume roadways differ, each should have its own typical pavement structure. A representative pavement structure for high-volume roadways can be found at the National Center for Asphalt Technology (NCAT) test track located near Opelika, Alabama. A variety of mix designs on the 1.7-mile oval are installed in 200 ft test sections that facilitate meaningful field performance comparisons, and laboratory testing is conducted on plant-produced materials to facilitate comparisons with field performance. As shown in Table 4.1, the typical flexible pavement design for high-volume roadways in Alabama followed the design of NCAT Test Track section S-9. This section was used as a control section in the 2009-2011 research cycle to evaluate the performance of other test sections on the track.

TABLE 4.1 Typical Flexible Pavement Design for High-Volume Roadways

Layer/Detail	Binder Type/Elastic Modulus	Thickness (in.)
AC Surface	PG 76-22	2.0
AC Intermediate layer	PG 67-22	Variable
Crushed Aggregate Base	25,000 psi	10.0
Subgrade Soil A-4	8,000 psi	Semi-Infinite
Climate Location	Montgomery, AL	

The typical pavement designs for low- and median-volume traffic were developed in conjunction with the Alabama DOT, as shown in Table 4.2. Typical designs for low- and median-volume roadways in Alabama were similar, except for different thicknesses in asphalt concrete (AC) intermediate layers.

TABLE 4.2 Typical Flexible Pavement Design for Low- and Median-Volume Roadways

Layer/Detail	Binder Type/Elastic Modulus	Thickness (in.)
AC Surface	PG 67-22	1.5
AC Intermediate layer	PG 67-22	5.0 ≤ Variable
Crushed Aggregate Base	25,000 psi	6.0
Subgrade Soil A-4	8,000 psi	Semi-Infinite
Climate Location	Montgomery, AL	

For sensitivity analysis of pavement thickness to traffic inputs described herein, the design pavement life was set to be 30 years, and the climate location selected was Montgomery since it is in central Alabama. Note that the AC intermediate layer thicknesses in Table 4.1 and Table 4.2 are variable. Thickness designs of this layer were based on the effects of different levels of traffic inputs on pavement performance through MEPDG simulations.

The baseline intermediate layer thicknesses were developed from the Level 2B statewide traffic inputs. In sensitivity analysis for traffic inputs of Level 1 and Level 3, only one type of traffic input was changed in each MEPDG execution in order to isolate the effect of each input. Then, sensitivity analysis compared intermediate layer thicknesses developed from relevant traffic inputs (of Level 1 and Level 3) with baseline intermediate layer thicknesses.

Level 2B statewide traffic inputs were used to establish a basis to compare effects of traffic inputs at other levels on pavement thicknesses. Through MEPDG simulations, baseline pavement designs in Alabama required intermediate layer thicknesses of 6.1 inches, 11.2 inches and 24.3 inches for low-, median-, and high-volume roadways. These thicknesses, which resulted from using the default transfer function coefficients built into the MEPDG, may be considered excessively thick by many agencies. It is widely recognized that the MEPDG requires local calibration of the transfer function coefficients before it can be used in practice. However, for the purposes of this study, it was decided to utilize the built-in transfer functions since local calibration coefficients have not yet been developed for Alabama.

Due to the vast amount of MEPDG executions required to evaluate the effect of Level 1 traffic inputs of different WIM stations and of different levels of traffic volumes, the sensitivity analyses described herein did not try to identify specific intermediate layer thicknesses for relevant traffic inputs, but only to determine whether the intermediate layer thickness was sensitive to each Level 1 traffic input. Thus, the sensitivity analysis for Level 1 data was simplified to changing baseline pavement thicknesses by an interval deemed to be critical (½ inch) through successive iterations of the MEPDG program. Steps of this sensitivity analysis procedure included:

1. leave the intermediate layer thickness unchanged as the baseline thickness using statewide traffic inputs; change the type of traffic input that is being tested from statewide to direction-specific; run the MEPDG simulation;
2. if the pavement using baseline thickness is found to be sufficient enough to keep pavement distresses below terminal serviceability levels, change the intermediate layer thickness to 0.5 inch thinner; conversely, if pavement using baseline thickness is found to have premature failure, increase intermediate layer thickness by 0.5 inch. Then, run the MEPDG simulation again;
3. if results of simulations of Step 1 and 2 are the same, the pavement thickness is deemed sensitive to the type of traffic input being tested.

As an example of sensitivity analysis for Level 1 data, Table 4.3 shows sensitivity analysis results for the single ALS traffic input. The suffix of each direction-specific WIM site indicates its traffic direction, as 1=northbound, 3=eastbound, 5=southbound, and 7=westbound. The intermediate layer thicknesses of 6.1 inches, 11.2 inches and 24.3 inches were the baseline AC intermediate layer thicknesses for low-, median-, and high-volume roadways in Alabama as mentioned previously. Thicknesses of 5.6 inches and 6.6 inches were one-half inch away from the baseline intermediate layer thickness for low-volume roadways; thicknesses for median- and high-volume roadways were handled similarly. For the intermediate layer of high-volume roadways, the analysis began with the baseline thickness of 24.3 inches. A “P” (that stands for “pass”) was assigned to the Level 1 traffic input when pavement with baseline AC thickness of 24.3 inches was sufficient enough to control distress measures under desired levels, and intermediate layer thickness was changed to be one-half inch thinner (to 23.8 inches) to test its performance in the MEPDG again. On the contrary, an “F” (that stands for “fail”) was assigned to the directional traffic input when the pavement experienced premature failure in the MEPDG simulation, and the intermediate layer thickness was increased by ½ inch to test its performance again. Thus, for each WIM station at each traffic volume level, two MEPDG simulations were executed for two AC thicknesses at a one-half inch interval above or below the baseline thickness. When results of both simulations were the same (either both pass or both fail), the pavement thickness was deemed sensitive to the traffic input of the given WIM station being tested; these results are shaded in Table 4.3. By recording the results of MEPDG executions in this table, it can be shown that pavement thickness was sensitive to Level 1 single ALS input on high-volume roadways (at 9 of 22 sites), but was not sensitive to direction-specific single ALS on low- and median-volume roadways.

TABLE 4.3 Sensitivity Analysis of Flexible Pavement Design to Single ALS

Low-Volume Roadways				Median-Volume Roadways				High-Volume Roadways			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	Fail	Pass		911_3	F	P		911_3	P	P	
911_7	F	P		911_7	F	P		911_7	F	P	
915_1	F	P		915_1	F	P		915_1	P	P	
915_5		F	P	915_5		F	P	915_5		F	P
918_1	F	P		918_1	F	P		918_1		F	P
918_5	F	P		918_5	F	P		918_5		F	P
933_3	F	P		933_3	F	P		933_3		F	P
933_7	F	P		933_7	F	P		933_7	F	P	
934_3	F	P		934_3	F	P		934_3		F	P
934_7		F	P	934_7	F	P		934_7		F	F
942_1	F	P		942_1	F	P		942_1	P	P	
942_5		F	P	942_5	F	P		942_5		F	P
960_3		F	P	960_3		F	P	960_3		F	F
960_7		F	P	960_7	F	P		960_7		F	P
961_1	F	P		961_1	F	P		961_1	P	P	
961_5	F	P		961_5	F	P		961_5	P	P	
963_3		F	P	963_3		F	P	963_3		F	F
963_7		F	P	963_7	F	P		963_7		F	F
964_1	F	P		964_1	F	P		964_1	F	P	
964_5	F	P		964_5	F	P		964_5	F	P	
965_1	F	P		965_1	F	P		965_1	F	P	
965_5	F	P		965_5	F	P		965_5	F	P	

4.5 SENSITIVITY ANALYSIS OF RIGID PAVEMENT

The typical rigid pavement structures herein were also developed in conjunction with the Alabama Department of Transportation (ALDOT). Details of these designs are shown in Table 4.4. Jointed plain concrete pavement (JPCP) was chosen since it is the most popular rigid pavement type in the southeastern United States (Wielinski, 2007). Dowel bars were used in this design, and the diameter depended on JPCP thickness. The design pavement life was set to be 30 years, which is commonly used, and the climate location was assumed to be

Montgomery since it is near the center of Alabama. Rigid pavement design for low-volume roads was not considered per ALDOT practice.

The JPCP thicknesses (in Table 4.4) according to ALDOT practice are variable within a defined range, and the design of these thicknesses depends on the volume of truck traffic and other traffic factors. Pavement designs were developed separately for median and high truck traffic volumes. In the MEPDG simulation, based on the defined traffic volumes and the Level 2B statewide traffic inputs, typical rigid pavement designs required JPCP thicknesses of 7.1 and 8.6 inches for median- and high-volume roadways respectively, as shown in Table 4.4. It is noted that these JPCP thicknesses are thinner than the minimum practice of ALDOT and would be rounded up to 10 inches in pavement design practice. However, for the purposes of the sensitivity analysis, it was determined that the thicknesses of 7.1 and 8.6 inches would serve as a baseline to detect the sensitivity of JPCP thickness to Level 1 traffic inputs.

TABLE 4.4 Typical Rigid Pavement Design for Median- and High-Volume Roadways

Layer/Detail	Elastic Modulus/ Binder Type	Median-Volume Road Thickness (in)	High-Volume Road Thickness (in)
JPCP Thickness (ALDOT Standard)	4,500,000 psi	10.0 ≤ Variable ≤ 14.0	10.0 ≤ Variable ≤ 14.0
JPCP Thickness (Sensitivity Analysis)		7.1	8.6
Hot Mixed Asphalt	PG 67-22	6.0	6.0
Subgrade Soil A-4	8,000 psi	Semi-Infinite	Semi-Infinite
Joint Spacing	15 feet		
Dowel Bar Diameter	1.25 in (JPCP < 10 in), 1.5 in (≥ 10 in)		
Climate Location	Montgomery, AL		

Besides the differences of material properties and pavement structures for both pavement types, the sensitivity analysis process for rigid pavement is similar to that for flexible pavement. Details of the MEPDG iterations follow the 3 steps aforementioned in Section 4.4.

4.6 SUMMARY

Sensitivity analysis of pavement performance was used by state agencies to test the potential impacts of traffic data of different levels. Sensitivity analysis results were also the theoretical foundation for the needs of cluster analysis. Since pavement thickness is a direct and the most important design consideration in pavement design, the sensitivity analysis developed in this research used deviation of pavement thicknesses due to the influence of traffic inputs as sensitivity indicator. This chapter also determined traffic input subdivisions, design traffic volumes, and typical pavement structures for both pavement types. As an example, the sensitivity analysis of flexible pavement design to single ALS was shown in Table 6. This was a streamlined process that illustrated sensitivity results in one table. No other analytical models or artificial sensitivity thresholds needed to be determined.

As shown in the high-volume roadway section of Table 6, single ALS data in 9 out of 22 direction-specific WIM sites were deemed sensitivity. It is anticipated that other traffic inputs that had larger impacts on pavement designs based on past experiment would also be deemed sensitivity in this analysis. Once deemed sensitive, the uses of cluster analysis to develop Level 2A data are needed so that further comparison between Level 1 and Level 2A data can be done. Thus, the development of cluster analysis for this research in the next chapter is critical.

CHAPTER 5

METHODOLOGY OF CLUSTER ANALYSIS

5.1 INTRODUCTION TO CORRELATION-BASED CLUSTER ANALYSIS

In pavement design practice, the availability of Level 1 traffic inputs is questionable in many pavement design locations. A cluster analysis that develops Level 2A traffic inputs is warranted when the results of the sensitivity analysis indicated that the uses of Level 1 traffic input are significant to pavement designs. In this chapter, a new cluster analysis methodology is presented to use the results of the sensitivity analysis to determine numbers of clusters, and then derive Level 2A traffic inputs from cluster-averaged data. Furthermore, results of cluster analysis are used to determine a suitable level of traffic input so that the risk of overdesign or underdesign of pavement structures can be minimized.

There are two key steps in a cluster analysis: (1) erecting a resemblance matrix to evaluate similarity between datasets; and (2) grouping datasets together based on similarity. The cluster analysis developed in this research combined Pearson's correlation coefficient (Step 1) with unweighted pair-group method using arithmetic averages (UPGMA) method (Step 2). This new cluster analysis combination can be referred to as correlation-based clustering. By using a correlation-based clustering process that is integrated with traffic inputs sensitivity analysis, some of the disadvantages of recent practices found in the literature have been addressed. For example, the Pearson's correlation coefficient distance measure is more appropriate for comparing probability distributions than the squared Euclidean distance measure. The similarity measure is confined to a finite range, between +1 and -1, giving the analyst a sense of the extent of similarity. More importantly, when cutting clustering trees, decisions can be made based on the quantified similarity coefficient, instead of a pre-determined number of clusters.

Since clustering practices found in the literature might group WIM stations of different sensitivity analysis results into the same cluster, sensitivity analysis (after cluster analysis) was performed on both the Level 1 and Level 2A traffic inputs (Haider et al., 2011). In the recommended practice herein, for Level 2A inputs that are developed from cluster-averaged data, sensitivity analysis results are already known, and sensitivity analysis (after cluster analysis) for this level of traffic inputs is not needed again. This is because sensitivity analysis is performed prior to cluster analysis, and determinations of clusters in recommended practice are based on sensitivity analysis results of Level 1 traffic inputs. Thus, sensitivity analysis results of Level 2A traffic inputs must align with that of each Level 1 input within the same cluster.

5.2 DEVELOPMENT OF CORRELATION-BASED CLUSTERING

Correlation-based clustering is within the hierarchical clustering family. There are two major steps in hierarchical cluster analysis, which are (1) computing the resemblance matrix and (2) clustering. In each step, a few approaches must be chosen. Thus, hierarchical cluster analysis is not a fixed mathematical procedure, but combinations of choices in each step.

The first step of hierarchical clustering is to use the resemblance matrix to quantify similarity between datasets. Popular similarity measures for quantitative hierarchical cluster analysis are Euclidean distance (e_{jk}), squared Euclidean distance (d_{jk}) and Pearson's correlation coefficient (r_{jk}) (Romesburg, 1984). Table 5.1 shows a resemblance matrix, using Pearson's correlation coefficient, for single ALS in Alabama. For brevity, 10 of the 22 direction-specific sites are included in the table. A value of the coefficient r_{jk} close to 1.000 suggests a high degree of similarity between the pair of objects, while low r_{jk} values suggest differences between a pair of objects. For example, single ALS of Station 918_1 and 965_1 are most correlated with similarity coefficient of 0.997 (0.996608), and it is followed by Station 918_1 and 933_7 with coefficient of 0.997 (0.996563). The single axle load spectra of Station 911_3 and 934_7, with a coefficient of 0.650, are the least correlated among the sites addressed in Table 5.1.

TABLE 5.1 Pearson's Correlation Similarity Matrix of Single ALS; Selected 10 Sites

WIM Sites	911_3	911_7	915_5	915_1	918_5	918_1	933_7	933_3	934_7	965_1
911_3		0.925	0.974	0.913	0.907	0.866	0.872	0.831	0.650	0.850
911_7	0.925		0.966	0.988	0.995	0.981	0.984	0.973	0.868	0.974
915_5	0.974	0.966		0.949	0.952	0.923	0.928	0.904	0.764	0.907
915_1	0.913	0.988	0.949		0.977	0.952	0.958	0.947	0.865	0.941
918_5	0.907	0.995	0.952	0.977		0.993	0.994	0.985	0.887	0.986
918_1	0.866	0.981	0.923	0.952	0.993		0.997	0.994	0.898	0.997
933_7	0.872	0.984	0.928	0.958	0.994	0.997		0.993	0.900	0.994
933_3	0.831	0.973	0.904	0.947	0.985	0.994	0.993		0.930	0.990
934_7	0.650	0.868	0.764	0.865	0.887	0.898	0.900	0.930		0.888
965_1	0.850	0.974	0.907	0.941	0.986	0.997	0.994	0.990	0.888	

The second step is to cluster each entity based on the similarity on the resemblance matrix. Methods in this step are the core of cluster analysis. The most used methods are single linkage clustering method ("SLINK"), Ward's minimum variance method, and unweighted pair-group method using arithmetic averages (UPGMA) (Romesburg, 1984). To eliminate disadvantages of clustering approaches found in the literature, a correlation-based clustering that combines Pearson's correlation distance measure (to evaluate similarity) with UPGMA (to cluster WIM sites) is developed herein. This recommended clustering combination uses Pearson's correlation distance to compute the resemblance matrix. Pearson's correlation coefficient is widely used to measure the correlation between two datasets that measure the same properties (such as ALS), giving a value of +1 to -1 inclusively; a coefficient of 1.000 indicates two attributes match perfectly while -1 indicates they are inversely proportional. The following UPGMA method clusters WIM sites based on maximum average similarity values. In practice, the UPGMA method begins with clustering the pair of WIM sites that has the highest similarity values to form the first cluster. For following clustering steps, the UPGMA method keeps testing possible combinations with other WIM sites to find the next highest averaged similarity values. Since UPGMA uses the "average" approach while the similarity values developed by the Pearson's method are between +1 and -1 inclusively, the averaged similarity values regardless number of sites within one cluster, always keeps between +1 and -1 inclusively. This is the main reason that the UPGMA method is chosen as the second step of the correlation-based clustering. Theoretically, since some of degree of similarity, rather than dissimilarity, is expected between traffic data of different WIM stations, the range of values in this approach to quantifying similarity should be expected to range from zero to one.

It is noted that Pearson's correlation distance is not sensitive to proportional size change. This disadvantage could be ignored in clustering of traffic inputs such as HDF, MDF, VCD and ALS. This is because these traffic parameters are essentially probability distributions, and the accumulated values of each dataset must be 1. Thus, no proportional size change is possible in these traffic datasets. Furthermore, to measure similarity of distributions, Strauss et al. (Strauss, et al., 1973) found Pearson's correlation was more sensitive than the squared Euclidean distance measure so that it is easier to distinguish patterns between probability distributions.

5.3 DETERMINATION OF CUT LOCATION AND NUMBER OF CLUSTERS

As aforementioned in the sensitivity analysis, pavement thickness would be deemed sensitive to a given type of traffic input when it deviated ½ inch or more from the baseline pavement thickness. As an example, Table 5.2 shows the single ALS sensitivity analysis results for high-volume roadways. This table is the high-volume traffic portion of the single ALS sensitivity analysis results shown in Table 4.3. When traffic input of at least one WIM site was deemed sensitive, the entire type of traffic input was deemed sensitive to pavement thickness. In Table 4.3, single ALS in 9 out of 22 WIM sites were deemed sensitive, and therefore, single ALS were determined to have significant impacts on flexible pavement designs on high-volume roadways. According to the sensitivity analysis methodology in Chapter 4, this sensitivity analysis results also indicated that either Level 1 or Level 2A single ALS input are needed for pavement designs on high-volume roadways in Alabama.

Then, by using correlation-based clustering, a clustering strategy table was created for each traffic input. This strategy table shows every step of the clustering from grouping the most similar WIM stations to gathering all WIM stations as one cluster. Table 5.3 shows an example of the clustering strategy from clustering the first cluster in Step 1 to combining all 22 WIM sites in one cluster in Step 21. Based on Pearson correlation matrix of single ALS for 22 WIM stations (selected 10 stations are shown in Table 5.1), Station 965_1 and 918_1 formed the first cluster because single ALS of these two stations had the highest similarity coefficient of 0.997 (0.996608) in relevant Pearson correlation matrix; then, in Table 5.3, the clustering method of UPGMA was utilized from Step 2 to 21. In UPGMA, a new cluster was determined by the maximum pair-group average coefficient. For example, in Step 2 of Table 5.3, Station 965_1, 918_1, and 933_7 have relevant similarity coefficients of 0.997 (for

965_1 and 918_1), 0.997 (for 918_1 and 933_7) and 0.994 (for 933_7 and 965_1) to each other in Table 5.1; the average of these three coefficients was 0.996, which was the second highest similarity coefficient besides 0.997 in Step 1. According to the UPGMA method, combination of WIM sites with the next highest averaged similarity value would form a new cluster in the next step. Thus, these three stations (Station 965_1, 918_1, and 933_7) formed a new cluster in Step 2. This procedure repeated itself for a total of 21 steps (since there were 22 sites).

Before a decision can be made on the recommendation of either Level 1 or Level 2A data, it is necessary to determine the number of clusters to be formed, and cutting the cluster tree at different locations has a direct impact on the number of clusters. The hierarchical clustering to form a tree can be ceased at any point in the process. The tree cut location is then defined as the point where the clustering process is ceased. This research recommends the integration of sensitivity analysis with clustering to find the cut location. Thus, the cut location can be further defined as the value of the averaged similarity coefficient along its clustering strategy table at which two locations, or clusters of locations, are dissimilar, based on the results of the sensitivity analysis.

TABLE 5.2 Single ALS Sensitivity Analysis for High-Volume Traffic

Site	AC Intermediate Layer (in.)		
	23.8	24.3	24.8
911_3	Pass	P	
911_7	Fail	P	
915_1	P	P	
915_5		F	P
918_1		F	P
918_5		F	P
933_3		F	P
933_7	F	P	
934_3		F	P
934_7		F	F
942_1	P	P	
942_5		F	P
960_3		F	F
960_7		F	P
961_1	P	P	
961_5	P	P	
963_3		F	F
963_7		F	F
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

TABLE 5.3 Clustering Strategy for Single ALS

Cluster/Step	1st Item	2nd Item	Similarity
1	965_1	918_1	0.997
2	Cluster 1	933_7	0.996
3	918_5	911_7	0.995
4	963_7	934_7	0.994
5	934_3	933_3	0.993
6	961_5	911_3	0.991
7	965_5	964_5	0.990
8	Cluster 6	942_1	0.989
9	Cluster 5	Cluster 2	0.988
10	964_1	942_5	0.987
11	Cluster 10	Cluster 3	0.987
12	Cluster 7	960_7	0.987
13	Cluster 11	Cluster 9	0.975
14	Cluster 12	915_5	0.973
15	Cluster 8	915_1	0.970
16	963_3	960_3	0.959
17	Cluster 14	Cluster 13	0.957
18	Cluster 17	Cluster 15	0.915
19	Cluster 16	Cluster 4	0.845
20	Cluster 18	961_1	0.761
21	Cluster 20	Cluster 19	0.666

The cluster analysis herein used the results of the sensitivity analysis to determine cut locations of clustering trees and number of clusters. To find the cut location, each step of the clustering strategy table was compared with results of relevant sensitivity analysis. The cut location was determined once WIM stations (or WIM station clusters) of two different sensitivity criteria were clustered into one group. WIM stations that had been grouped into clusters prior to the cut location remained in the same clusters, and thus, the number of clusters was determined.

As an example, Figure 5.1 illustrates the process to integrate the clustering strategy with the sensitivity analysis table to find the cut location for clustering of WIM sites for a particular input (in this case, single ALS). In fact, the process shown in this figure compared every step of Table 5.3 with sensitivity results of Table 5.2 until stations with sensitive traffic inputs and stations with insensitive inputs were grouped into the same cluster. As shown in Figure 5.1, Step 1 of the clustering strategy combined Station 965_1 with 918_1; the sensitivity analysis results of both stations showed that pavement thickness differences between the uses of Level 1 and Level 2B data are less than ½ inch (and therefore, deemed insensitive). Step 2 combined three stations that had insensitive traffic inputs. Step 4 grouped two WIM stations that are both sensitive. It was not until the 18th step that WIM stations of different sensitivity criteria (resulting pavement thickness differences of more than ½ inch) were combined together. This step had a similarity coefficient of 0.915, which was then determined to be the tree cut location, as shown in Figure 5.2. As a result of the cut, five clusters were formed prior to the cut location. In this process, an objective, data-driven decision was made to determine the number of clusters.

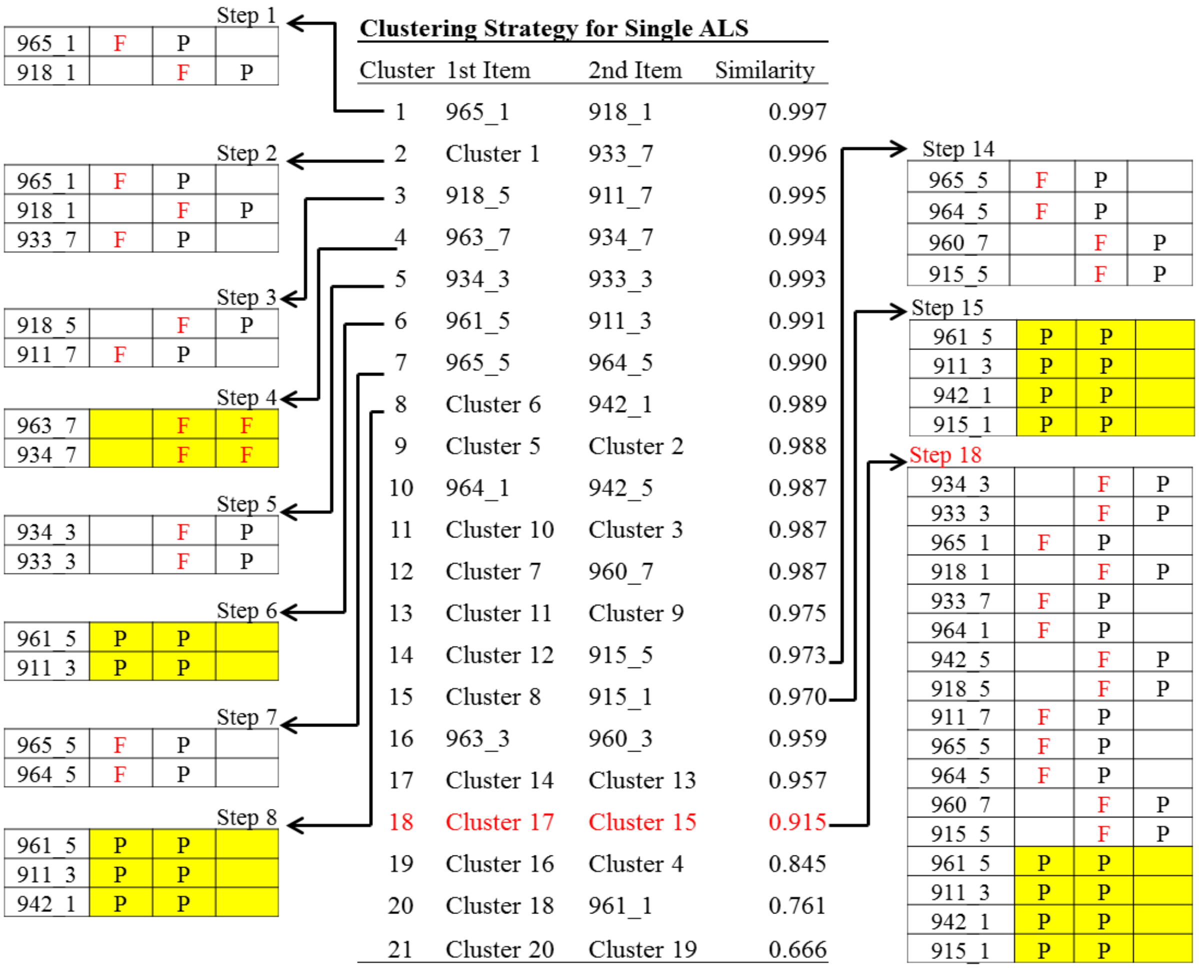

FIGURE 5.1 Process to find cut location for single ALS of high-volume roadways

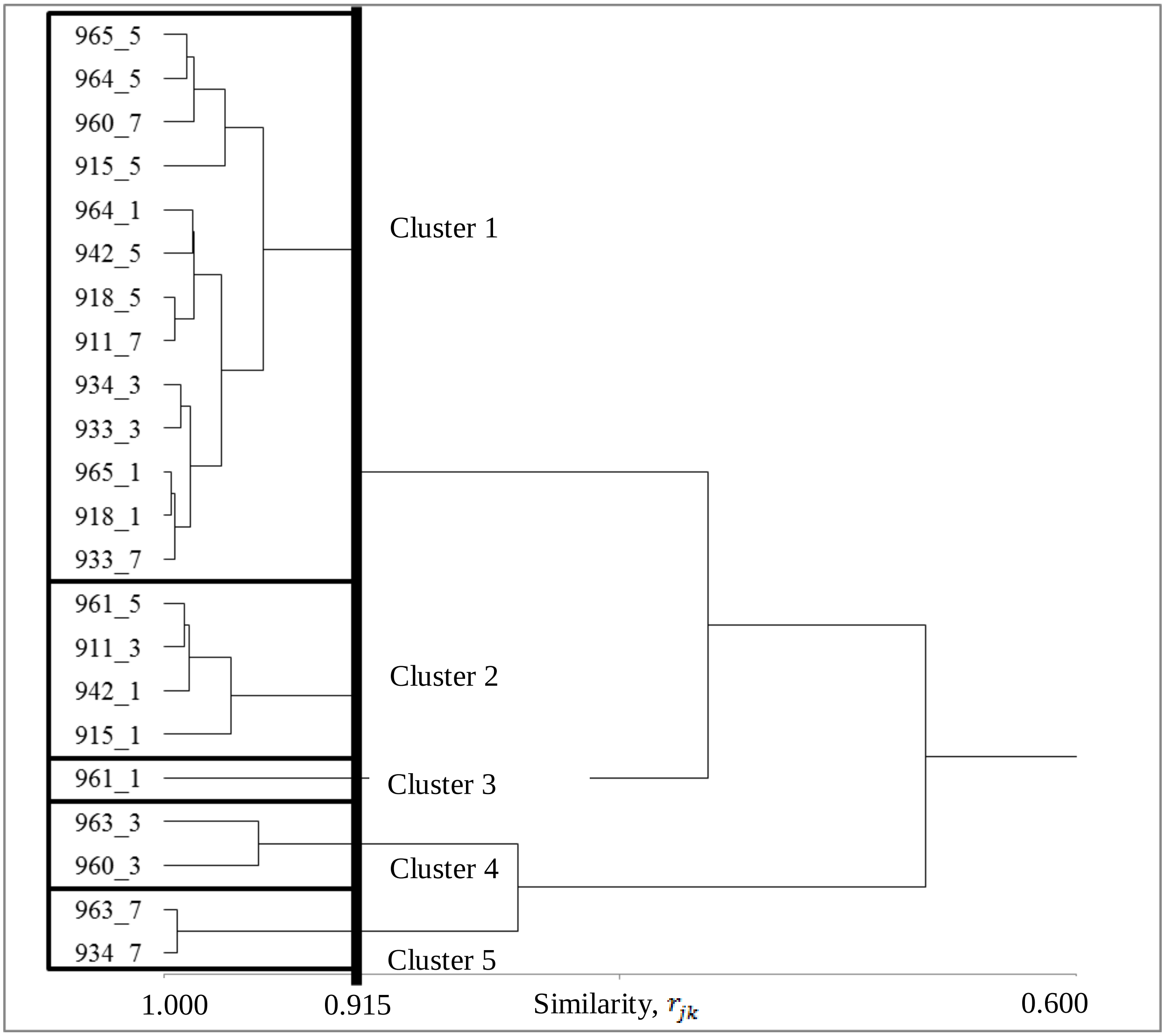

FIGURE 5.2 Cutting the clustering tree of single ALS for high-volume traffic

5.4 DETERMINATION OF DATA LEVELS FOR USE IN THE MEPDG

For the 13 traffic inputs required by the MEPDG, data of Level 1, Level 2A and Level 2B are developed by the methodologies above, and data of Level 3 are the default inputs of MEPDG. Note that Level 3 traffic inputs need not to be used in Alabama because statewide traffic inputs (Level 2B data) were developed in this research, and are more local than nationwide inputs. Therefore, the selection of data levels is among Level 1, Level 2A and Level 2B inputs.

Various circumstances could occur when clusters form: (1) only one cluster that includes all WIM sites is developed. This would indicate that pavement thickness is not sensitive to the given type of traffic input so that the use of Level 2B data is sufficient. (2) At the other extreme, a substantially large number of clusters are created and it burdens the determination of traffic patterns. In this case, pavement thickness is so sensitive to traffic input that the use of Level 1 data is recommended. (3) Between the first two scenarios above, there exists a third scenario that creates a manageable number of clusters. This indicates the use of Level 2B data is too general and the use of Level 2A data is most appropriate. Thus, in different circumstances, determinations of traffic input levels for use in MEPDG are important.

The determination of input levels for use in the MEPDG is based on numbers of clusters created by the integration process. For this research, it is determined that Level 2B input is recommended when only one cluster is created; Level 2A inputs are considered sufficient for pavement design when numbers of clusters are no more than the amount of site-specific WIM stations; otherwise, Level 1 inputs are needed. For example, there are 11 WIM sites in Alabama that are further subdivided into 22 directional WIM stations. Level 2B input is recommended when only one cluster is created; Level 2A inputs are used when there are no more than 11 clusters; if the numbers of clusters range from 12 to 22, Level 1 inputs are recommended.

5.5 IDENTIFICATION OF TRAFFIC PATTERNS

Another important step after the determination of clusters is to identify their patterns. Visual observations of distributions obtained from clusters can find apparent causes of distinct differences between their patterns. For example, Figure 5.3 shows cluster-averaged distributions of single ALS for the 5 clusters that were determined in the previous section. Clusters 1, 2, 3, and 4 were differentiated because the peaks of their ALS are about 1000 lb away from each other. Cluster 3 had the lightest peak load of 10,000 lb, and Cluster 4 had the heaviest peak value of 13,000 lb. Even though Cluster 1 and Cluster 5 had the same peak value of 12,000 lb, the distribution of Cluster 5 was more concentrated with a relatively low standard deviation. This figure indicated that pavement thicknesses were highly sensitive to axle loads and standard deviations of single ALS under high-volume traffic.

The TMG (USDOT, 2001) recommends the use of geographical location, functional classification and local knowledge to define each cluster. This is a practical way to relate clusters to their geographical locations and functional classifications in a closed-loop system so that Level 2A data can be implemented for any class of roads at any location. It gives pavement engineers the opportunity to design pavements when direction-specific data are not available but statewide data are too general.

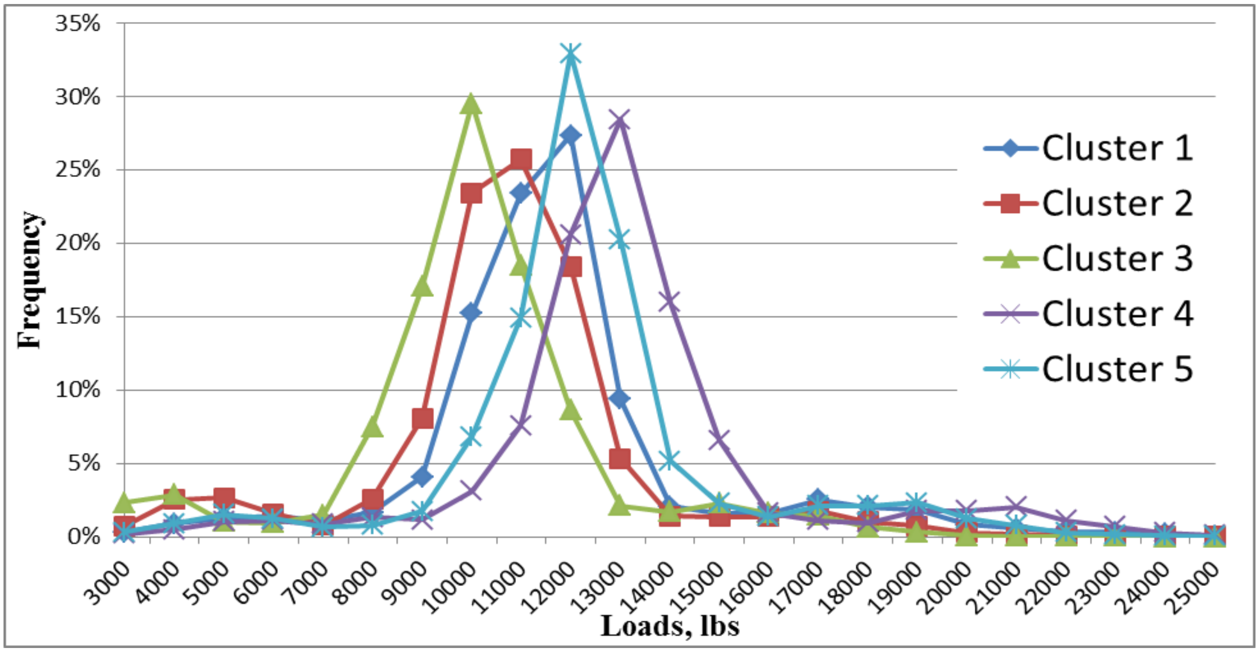

FIGURE 5.3 Frequency distributions for 5 clusters of single ALS for high-volume roadways

For the State of Alabama, the map shown in Figure 1.3 (of Chapter 1) was developed to illustrate locations of WIM stations and functional classifications of highways. WIM stations of each cluster were then linked to this map to identify traffic patterns. Engineering judgment and local knowledge were implemented in this process. To avoid inconsistent information in each cluster, WIM sites were grouped within relevant traffic volumes (USDOT, 2001). Note that Cluster 3 consisted of only one direction-specific station (Station 961_1), thus Level 2A cluster-averaged traffic inputs were effectively the same as Level 1 direction-specific traffic inputs at this location. The same road factor (USDOT, 2001) and local knowledge were applied to identify pattern of Cluster 3. For other clusters, relevant WIM stations were linked based on geography as shown in Figure 1.3. It is important to note that with only 22 directional stations in Alabama, clear definition of geographical patterns is difficult to obtain. Additional WIM installations would assist in this process. For single ALS for high-volume roadways, tentative traffic patterns associated with the clusters are defined as follows:

- Cluster 1: high-volume roads that have not been specified in other clusters.
- Cluster 2: southbound traffic on high-volume roads in southern Alabama;
- Cluster 3: northbound traffic along I-65 in southern Alabama;
- Cluster 4: eastbound traffic on high-volume roads in southwestern Alabama;
- Cluster 5: westbound traffic on high-volume roads in western Alabama.

Note that other geographical descriptions may also be appropriate. Cooperation with Division Traffic Engineers or other knowledgeable personnel within ALDOT may possibly improve the descriptions of traffic patterns for clusters.

5.6 STREAMLINE THE CLUSTERING OF NEW WIM SITES

This clustering approach allows for new WIM stations that may be installed in the future to be assigned to proper clusters based on these coefficients. For example, when the WIM station 931_1 was added in northern Alabama along I-65, correlation-based clustering of single ALS was executed again. Then, the new clustering tree that included the WIM station 931_1 was formed, and is shown in Figure 5.4. Comparing Figure 5.4 with Figure 5.2, the clustering structure of original WIM sites had not been changed statistically. The new WIM station (931_1) was then assigned to Cluster 3 based on the original similarity coefficient of 0.915, and thus no sensitivity analysis using data from this new station was needed. This indicated that similarity coefficients could streamline clustering processes for new WIM stations in the future, so that thee need to do pavement thickness sensitivity analysis for every new station can be avoided. Furthermore, the traffic pattern of Cluster 3 was further defined as “northbound traffic along I-65 in Alabama” due to the use of Station

931 in the analysis. This indicated that traffic patterns are better defined with additional WIM stations. Therefore, installation of more WIM stations is recommended in Alabama.

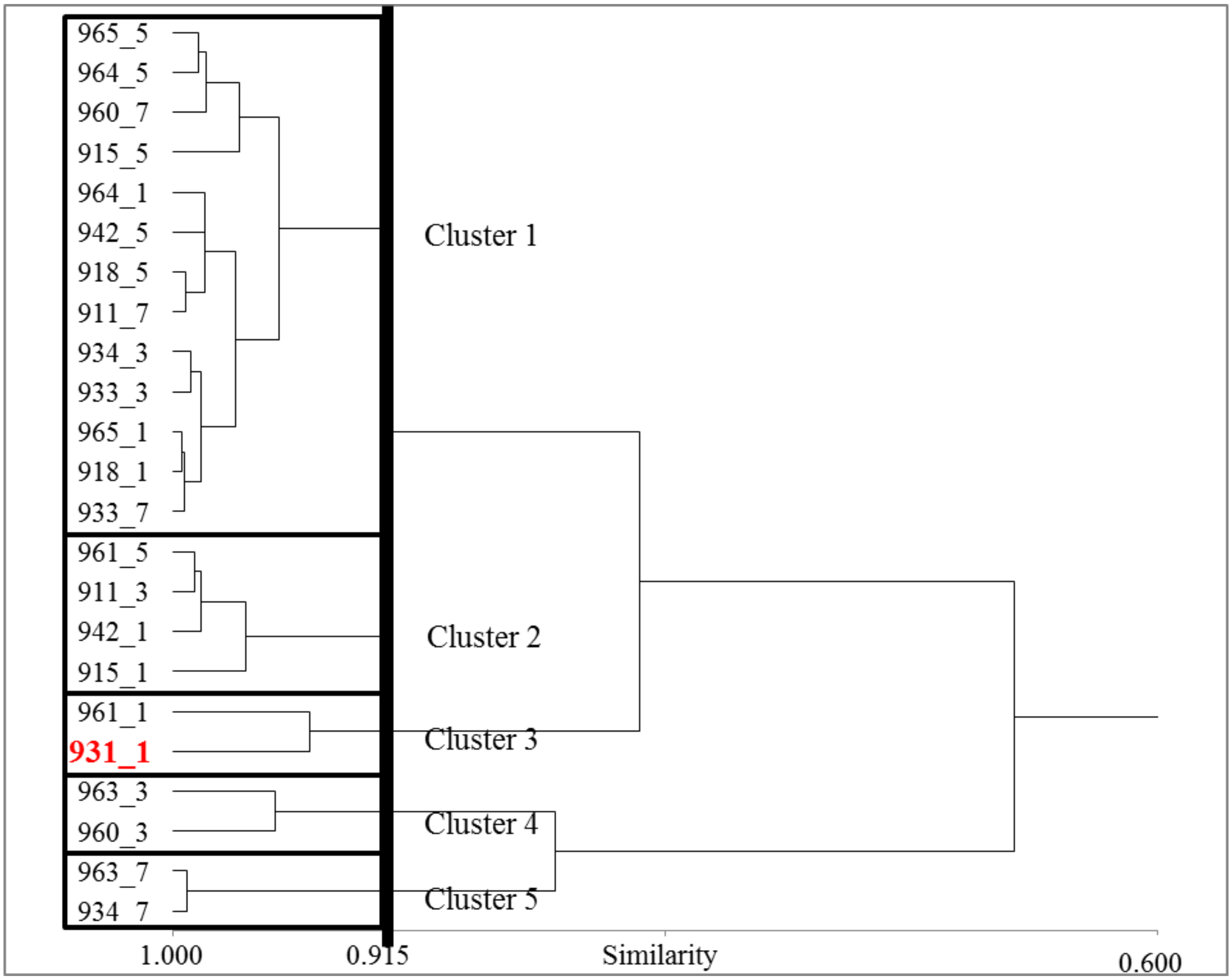

FIGURE 5.4 Assigning new WIM site (Station 931_1) to suitable cluster

5.7 SUMMARY

This chapter presented the development of correlation-based clustering that combined the Pearson's correlation similarity measure with unweighted pair-group method using arithmetic averages (UPGMA) method. Important advantages of this clustering method include (1) the confinement of averaged similarity coefficient between +1 and -1, which provides a sense of the extent of similarity within a bounded range of value; and (2) development of Level 2A regional data objectively.

To determine a tree cut location and number of clusters in an objective manner, sensitivity results was integrated with correlation-based clustering to find the tree cut location. Tree cut locations were defined once WIM sites of different sensitivity analysis results were grouped together. This method eliminates subjective decisions on number of clusters in past practices.

Furthermore, in this research, the recommendations of data levels for use in the MEPDG are based on the number of clusters created. Since this research uses an objective process to determine number of clusters, the recommendations of data levels also inherit this objective manner.

CHAPTER 6

IMPLEMENTATION AND PERFORMANCE

6.1 INTRODUCTION

The implementation of methodologies discussed in Chapter 3, 4, and 5 is presented in this chapter. Data used herein were collected from 12 WIM stations that use bending plate sensors in Alabama from 2006 to 2008. The quality control (QC) procedure described in Chapter 3 was applied to raw WIM datasets that contained 62,455,023 truck weight records, resulting in deletion of more than 23% of erroneous data. For sensitivity analysis and cluster analysis, quality-controlled WIM data were divided into direction-specific and were developed into 13 types of traffic inputs. In Chapter 4, a streamlined sensitivity analysis method that used differences of pavement thickness design as sensitivity indicator was developed. In Chapter 5, a new clustering method that develops Level 2A regional data in an objective manner was created. In Chapter 6 (this chapter), the following sections illustrate the implementation steps and results of these three processes.

6.2 QUALITY CONTROL

The literature review in Chapter 2 indicated that a significant amount of errors were typically detected in various QC procedures. Thus, for this research, QC of raw WIM data before sensitivity analysis and cluster analysis was critical. The QC process developed and implemented in this study consists of two types of approaches to ensuring data validity: threshold checks and rational checks. This process was designed to run the QC in an objective manner.

A total of 62,455,023 truck passes from the raw WIM data were examined using the QC procedure developed in this research. As an overall QC result, 23.82% of raw data were filtered out. Details of the QC results are depicted in Table 6.1. This table reports the number and percentage of total records that failed each step in the QC procedure.

TABLE 6.1 Overall QC Results

Total Truck Passes	Total Errors	Threshold Checks		Rational Checks	
		File-size Check	Out-of-range Check	ALS Comparison	Number-of-axles Check
62,455,023	14,874,908	1,411,484	9,872,507	1,077,862	2,513,055
100.00%	23.82%	2.26%	15.81%	1.73%	4.02%

File-size checks in this case focused on 36 consecutive months of WIM datasets for each WIM station at a time for three years of data collection (2006 through 2008). In the file-size check applied to the entire data set for 12 WIM stations, 42 monthly datasets among a total of 864 (36 monthly dataset per WIM site multiplied by 24 direction-specific WIM sites), that is, 4.86% of datasets were deemed potentially erroneous. However, since these 42 datasets tended to have relatively smaller file size, and fewer truck passes recorded, only 2.26% of the data were deemed out of acceptable file size ranges, and therefore were removed.

The out-of-range check criteria shown in Table 3.1 of Chapter 3 were applied, and as a result, 15.81% of records were filtered out as shown in Table 6.2. Note that most of the out-of-range errors appeared in the VC data. When a truck class is not recognized, the WIM software assigned it to VC 14, which is typically used as a category for vehicles which a detector is unable to classify. For this reason, 15.67% of truck passes in the Alabama WIM data had VC errors. Recently published research (Ban and Holguin-Veras, 2012; Gajda et al.,

2012) has indicated that it is currently still a challenging issue to automatically and accurately classify vehicles, and some detectors may have an accuracy rate as low as 64% (Gajda et al., 2012). Gajda et al. (2012) also observed that the errors of misclassifications tended to happen to trucks with complex axle configurations, and argued these errors could create bias on VC inputs of the MEPDG because less trucks were successfully classified, and thus, influence pavement designs. It is recommended that further improvements on VC technologies and algorithms are urgent for WIM systems.

Table 6.2 also indicates that 0.12% of records had speed errors that were over 192 km/h (120 mph) and therefore were deleted from further consideration. Another 6.75% of truck passes (not shown in Table 6.2) recorded a speed of 0 km/h (0 mph). However, without resources to investigate causes of the zero speed values, data with a speed of 0 km/h are flagged but not deleted from further use. This is an important concern as speed is an important calibration factor in axle loads. The NCHRP Synthesis Report *High Speed Weigh-in-Motion System Calibration Practice* (Papagiannakis, 2008) indicated that up to 67% of responding agencies report deriving speed-specific calibration factors in WIM systems. These speed errors could affect the accuracy of the axle load data.

TABLE 6.2 Details of Out-of-range Errors

Check Field	Number of Records Identified as Potentially Erroneous	Percentage of Total Record
Axle Type	0	0.00%
Direction	0	0.00%
Lane location	0	0.00%
# Axle vs. Axle Groups	153	0.00%
Steering Axle Weight	7,096	0.01%
Single Axle Weight	0	0.00%
Tandem Axle Weight	655	0.00%
Tridem Axle Weight	0	0.00%
Quad Axle Weight	2	0.00%
Penta Axle Weight	0	0.00%
Speed	75,524	0.12%
Station Year	71	0.00%
Station Month	0	0.00%
Station Day	0	0.00%
Station Hour	0	0.00%
State Code	0	0.00%
Vehicle Class	9,789,006	15.67%
All Out-of-range Errors	9,872,507	15.81%
Total Truck Passes	62,455,023	

In the ALS comparison module, a total of 5 monthly datasets from WIM station 931, 942 and 961 were deemed to have abnormal patterns, and therefore were removed. That is, 0.58% of datasets (5 out of 864 datasets) or 1.73% of truck passes were said to have systematic errors.

For the ALS comparison of WIM Station 961 as shown in Figure 3.4 of Chapter 3, besides the removal of datasets from October 2008 to November 2008, the dataset of December 2008 was also detected to have systematic errors by the module and therefore was removed. These removals of three consecutive datasets indicate that systematic errors could last for several months. Data collected between the occurrence of these systematic errors and the next scheduled system calibration could also be erroneous.

The out-of-range check in Table 6.2 also detected a significant amount of axle weight errors, especially in steering and tandem axles. Most of the steering axle errors appeared on Class 5 vehicles (VC5), while most of the tandem axle errors occurred on VC6 and VC8. Thus, the occurrences of steering axle and tandem axle weight errors did not appear on a same vehicle pass. Even though the direct cause of these errors is unknown, an observation of the connection between axle weight errors and abnormal patterns of ALS has found that 62.54% of the axle weight errors occurred within the 5 monthly datasets that were later deemed to have abnormal patterns. This correlation indicated that the occurrences of axle weight errors could be the forewarning of systematic errors in a WIM system.

In the number-of-axles check, all data from 11 WIM stations passed the criteria. However, one station (Station 931) did not. The number-of-axles check for this station is shown in Table 6.3. The AGPV values in this table were developed from data of Station 931 by TrafLoad. Then, the number of axles highlighted in this table was calculated from AGPV values using the conversion method aforementioned. For the number-of-axle check purpose, the numbers of axles were then compared with QC ranges. In Table 6.3, the average number of axles for vehicles in VC4, VC5, VC6, VC8, VC9, VC11 and VC12 exceeded the relevant QC ranges. This indicates that the axle counting function was faulty in this WIM system. As a result, all data collected from WIM station 931 were excluded from further analysis.

TABLE 6.3 The Number-of-axles Check for WIM Station 931

Sta 931	Average Axle Group Per Vehicle				Number-of-Axles Check		
Vehicle Class	Single	Tandem	Tridem	Quad	**Total Number of Axles**	Range for QC Purpose	Result
VC 4	3.38	0.62	0.00	0.00	**4.62**	2 to 3	Fail
VC 5	4.00	0.00	0.00	0.00	**4.00**	2	Fail
VC 6	1.99	1.99	0.01	0.00	**6.00**	3	Fail
VC 7	2.90	0.96	0.98	0.06	**8.00**	4 or more	Pass
VC 8	4.73	1.34	0.00	0.00	**7.41**	3 to 4	Fail
VC 9	2.80	3.60	0.00	0.00	**10.00**	5	Fail
VC 10	2.10	2.03	1.94	0.01	**11.99**	6 or more	Pass
VC 11	9.64	0.18	0.00	0.00	**10.00**	5 or less	Fail
VC 12	7.90	2.05	0.00	0.00	**12.00**	6	Fail
VC 13	4.66	2.79	1.27	0.63	**16.56**	7 or more	Pass

6.3 SENSITIVITY ANALYSIS

The sensitivity analysis focused on comparing the effect of nationwide traffic inputs and direction-specific traffic inputs with the effect of statewide inputs on pavement thickness design. The sensitivity analysis herein used the change in pavement thickness due to change in traffic input level as the sensitivity indicator. For both flexible and rigid pavement, the effect of traffic input level on pavement design was deemed practically significant when the pavement thickness deviated by 0.5 inches or more from baseline thickness based on statewide traffic inputs.

6.3.1 Sensitivity Analysis for Flexible Pavements

6.3.1.1 Sensitivity Analysis for Level 3 Nationwide Traffic Inputs

Prior to examining the impacts of each type of nationwide traffic inputs, the effect of overall traffic inputs on flexible pavement was tested to gain an overall sense of the data.

Table 6.4 shows the comparison of required intermediate layer thicknesses between statewide and nationwide traffic inputs. Use of nationwide traffic inputs (Level 3) resulted in intermediate layer thicknesses of 5.7 inches, 10.8 inches and 22.6 inches for low, median and high traffic volume roadways, respectively. Overall, the intermediate layer thicknesses based on Alabama statewide traffic inputs were greater than those based on nationwide traffic inputs. This indicated that truck traffic in Alabama, compared with nationwide averages, requires thicker pavement structures (if the effects of climate and soil conditions are ignored). For high-volume roadways, the required intermediate layer thickness for average truck traffic in Alabama was 1.7 inches thicker than that of nationwide. This thickness difference exceeded the sensitivity criterion of one-half (0.5) inch. Thus, flexible pavement thickness on Alabama high-volume roadways was deemed sensitive to differences between statewide and nationwide traffic inputs. The next step was to examine the impact of the differences between nationwide and statewide traffic inputs on pavement thickness of high-volume roadways.

TABLE 6.4 Comparisons of Pavement Thicknesses Influenced by Level 2B and Level 3 Data

Traffic Volume	AC intermediate layer Thickness (in.)		Thickness Differences (in.)
	Level 2B Statewide	Level 3 Nationwide	
Low	6.1	5.7	0.4
Median	11.2	10.8	0.4
High	24.3	22.6	**1.7**

Table 6.5 illustrates the sensitivity of pavement thickness on the high-volume roadways for each of 13 nationwide traffic inputs. Only the type of input that was being tested was changed from statewide to nationwide. As shown in bold type, the required pavement thickness of high-volume roadways was sensitive to the effects for 9 of the 13

categories of traffic inputs (specifically, single ALS, tandem ALS, tridem ALS, quad ALS, single AGPV, tridem AGPV, quad AGPV, MDF Tractor-Trailer, and VCD) because their resulting thickness differences equaled or exceeded the sensitivity criterion of one-half inch. All of these traffic inputs resulted in a thinner pavement structure using nationwide data, except for VCD, for which the nationwide level demands a thicker pavement structure.

TABLE 6.5 Sensitivity of Flexible Pavement on High-Volume Roadways to Nationwide Inputs

Traffic Inputs	AC Intermediate layer Thickness of Statewide Data (in.)	AC Intermediate layer Thickness of Nationwide Data (in.)	Thickness Differences (in.)
Single ALS	24.3	23.7	**0.6**
Tandem ALS		22.9	**1.4**
Tridem ALS		23.8	**0.5**
Quad ALS		23.8	**0.5**
Single AGPV		23.7	**0.6**
Tandem AGPV		24.7	-0.4
Tridem AGPV		23.8	**0.5**
Quad AGPV		23.8	**0.5**
HDF		24.3	0.0
MDF Single Unit		24.3	0.0
MDF Tractor-Trailer		23.8	**0.5**
MDF Multi-Trailer		23.9	0.4
VCD		25.4	**-1.1**

In the MEPDG, nationwide data are the default inputs of the program. The MEPDG only provides one set of values for most of these default inputs. However, for the VCD traffic input, there are 17 sets of truck traffic classifications (TTCs) to choose from in the default database to represent 17 different types of traffic characteristics for various functional classifications of roads. These TTCs are developed from clustering of LTPP WIM sites nationally (ARA 2004). TTC2 was chosen to generate nationwide inputs for this research because its percentage of tractor-trailer trucks (from VC8 to VC10) was nearest to that of Alabama statewide VCD; TTC2 has 75.60% of heavy vehicles in classes 8 through 10, while

Alabama VCD has 71.40% of these trucks. Figure 6.1 compares Alabama VCD with nationwide TTC2. Visual inspection found both distributions very similar with VC9 as the predominant heavy vehicles. However, by changing the statewide VCD to nationwide TTC2 in the MEPDG simulations, as shown in Table 6.4., it required the intermediate layer thickness to be 1.1 inches greater at the nationwide level. This indicates that the high-volume roadway pavement design was very sensitive to selection of VCD, especially the percentage of tractor-trailer trucks in the VCD.

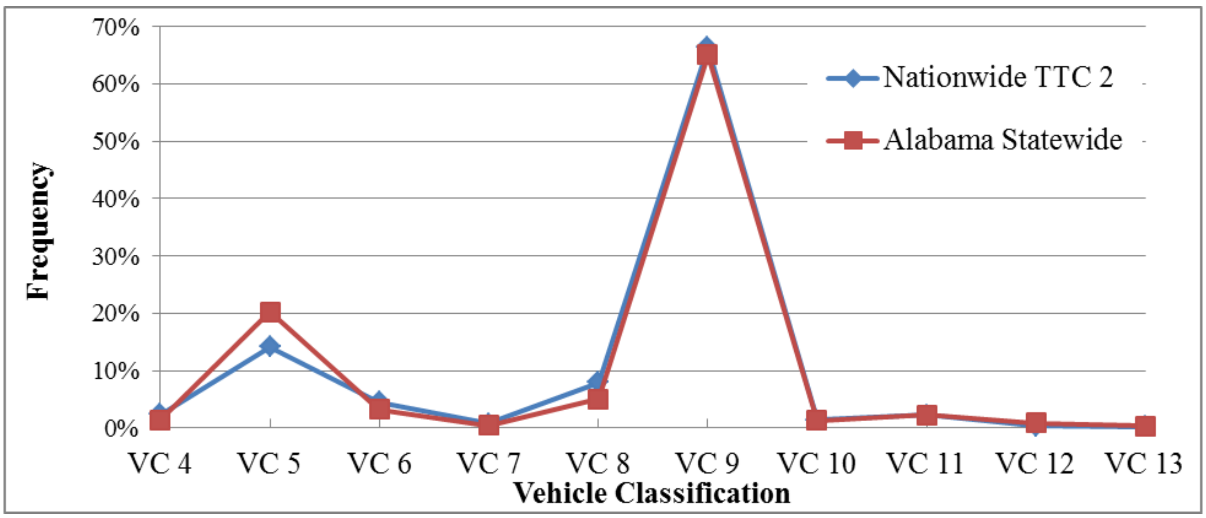

FIGURE 6.1 Statewide VCD vs. nationwide TTC2

In Table 6.5, the largest difference in required pavement thickness was associated with the tandem ALS traffic input. As shown, the required intermediate layer thickness when using the nationwide tandem ALS was 22.9 inches, which was 1.4 inches thinner than intermediate layer thickness of 24.3 inches based on statewide data. In general, VC9 is the dominant truck class on U.S. highways, and tandem axles are the most frequent axle type in VC9. Furthermore, in this research, the impacts of tandem ALS had resulted in the largest thickness difference between statewide and nationwide pavement thicknesses. Therefore, tandem ALS may be the most important traffic factor for pavement design in Alabama. Figure 6.2 depicts the comparison of statewide tandem ALS with nationwide tandem ALS in VC9. Both distributions have the typical double-peak shapes. The low peak (the peak with lower axle loads) is typical of axle loads for empty trucks, while the high peak (the peak with higher axle loads) is typical of axle loads for fully loaded trucks. As shown in this figure, statewide tandem ALS of Alabama has a roughly equal frequency of light and heavy tandem axle loads, while the nationwide tandem ALS had substantially more light tandem axles. This indicated the percentage of trucks in Alabama that are fully loaded is higher than the national average. Furthermore, while comparing axle loads at both peaks, even though the low peaks of both distributions had the same peak value of 14,000 lb, the statewide tandem ALS had a high peak value of 34,000 lb, which was 2,000 lb heavier than that of the nationwide. This indicated that fully-loaded tractor-trailer trucks that operate in Alabama were generally heavier than the national averages. As a result, the pavement design for high-volume roadways using Alabama data was thicker than that based on nationwide data.

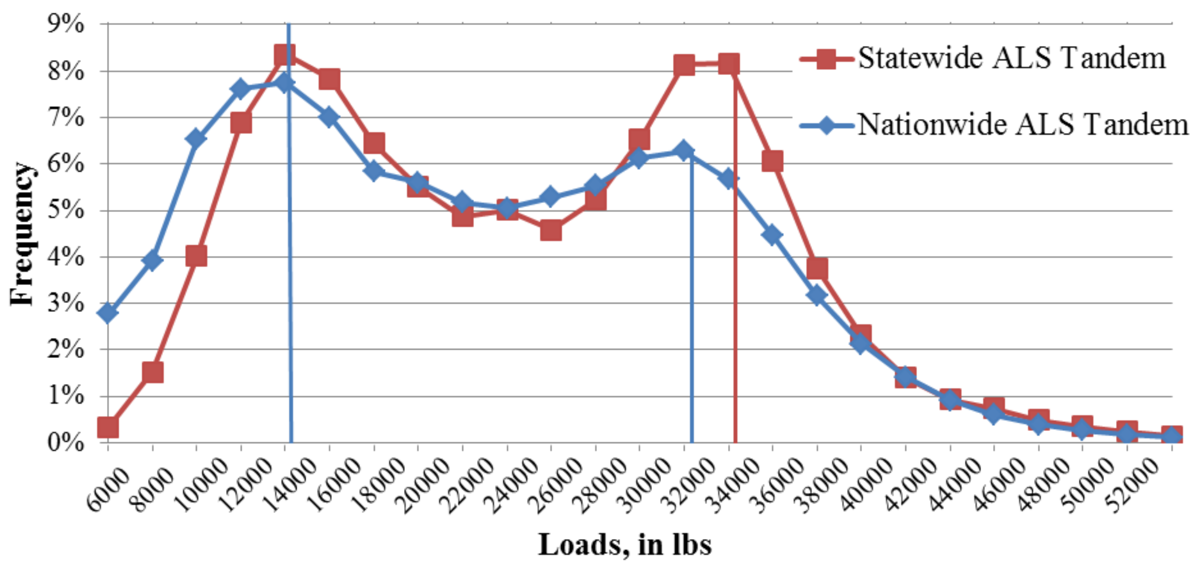

FIGURE 6.2 Statewide tandem ALS vs. nationwide tandem ALS in VC9

Overall, pavement thickness was found to be sensitive to differences between nationwide and Alabama statewide single ALS, tandem ALS, tridem ALS, quad ALS, single AGPV, tridem AGPV, quad AGPV, MDF Tractor-Trailer, and VCD. Therefore, these Level 3 inputs were found not suitable for pavement designs in Alabama. For other nationwide traffic inputs to which pavement thickness was not deemed sensitive, they are also not recommended to be used in Alabama because statewide traffic inputs developed within the state are more representative than nationwide inputs. Thus, statewide traffic inputs are preferential to nationwide inputs for the MEPDG in Alabama.

6.3.1.2 Sensitivity Analysis for Level 1 Direction-Specific Inputs

To test the sensitivity of flexible pavement thickness to a particular Level 1 traffic input in the MEPDG, traffic inputs other than the one being tested were based on statewide data. The sensitivity analysis herein did not examine the overall impact of a direction-specific WIM station on pavement thickness, but further focused on the effect of each traffic input. Details of sensitivity analysis procedures for Level 1 inputs were discussed in Chapter 4.

For sensitivity analysis of flexible pavement to 13 types of Level 1 traffic inputs in Alabama, Table 6.6 shows the summary of sensitivity results. For each type of Level 1 traffic input, 22 sets of inputs were developed from 22 direction-specific WIM sites. Once the impact of at least one of the 22 sets of direction-specific input was deemed sensitive, the impact of the type of traffic input was deemed sensitive on pavement designs at the respective traffic volume. Since sensitivity analyses were executed for 13 types of traffic inputs at three levels of traffic volumes, there are a total of 39 sensitivity analysis results shown in this table. The impacts of traffic inputs, such as single AGPV, tandem AGPV, quad AGPV, HDF, MDF Single Unit, and MDF Multi-Trailer on flexible pavement thicknesses were deemed insensitive at any levels of traffic volumes. On the contrary, flexible pavement thicknesses of high-volume roadways were sensitive to single ALS, tandem ALS, tridem ALS, quad ALS, tridem AGPV, MDF Tractor-Trailer and VCD. For low- and median-volume roadways, flexible pavements were sensitive to tandem ALS, MDF Tractor-Trailer, and VCD.

TABLE 6.6 Sensitivity Results of Flexible Pavement to Level 1 Inputs in Alabama

Traffic Inputs	Traffic Volume Levels		
	Low	Median	High
Single ALS	N (insensitive)	N	Y (sensitive)
Tandem ALS	Y	Y	Y
Tridem ALS	N	N	Y
Quad ALS	N	N	Y
Single AGPV	N	N	N
Tandem AGPV	N	N	N
Tridem AGPV	N	N	Y
Quad AGPV	N	N	N
HDF	N	N	N
MDF Single Unit	N	N	N
MDF Tractor-Trailer	Y	Y	Y
MDF Multi-Trailer	N	N	N
VCD	Y	Y	Y

6.3.2 Sensitivity Analysis for Rigid Pavements

Besides the differences of material properties and pavement structures aforementioned for both pavement types in Chapter 4, the sensitivity analysis process for rigid pavement was similar to that for flexible pavement. The first step was to test the overall effect of Level 3 nationwide traffic inputs on rigid pavements. As shown in Table 6.7, jointed plaint concrete pavement (JPCP) thicknesses required for nationwide traffic are 7.1 and 8.6 inches for median- and high-volume roadways, respectively. These thicknesses are in conformity with thicknesses for statewide traffic in Alabama. Thus, Table 6.7 indicates that, for both median- and high-volume roadway designs, rigid pavements are not sensitive to the differences between Alabama statewide and nationwide traffic inputs.

TABLE 6.7 Comparisons of Pavement Thicknesses Influenced by Level 2B and Level 3 Data

Traffic Volume	JPCP Thickness (in.)		Thickness Differences (in.)
	Level 2B Statewide	Level 3 Nationwide	
Median	7.1	7.1	0
High	8.6	8.6	0

In sensitivity analysis to Level 1 traffic inputs, the sensitivity of rigid pavement design was tested for 13 types of traffic inputs, 22 directional WIM sites, and 2 rigid pavement structures (for median and high traffic volumes). By executing 2 MEPDG interactions on thickness differences of ½ inch in each test, a total of 1144 MEPDG iterations were executed (1144 iterations = 13 inputs * 22 sites * 2 pavement types * 2 iterations for each scenario).

The analysis conducted to determine the sensitivity of rigid pavement thickness to differences in data levels in Alabama found that rigid pavement design was mostly not sensitive to traffic inputs except for tandem ALS, as shown in Table 6.8, in which rigid pavements of both median- and high-volume roadways were sensitive to tandem ALS.

TABLE 6.8 Sensitivity Results of Rigid Pavement to13 Level 1 Inputs in Alabama

Traffic Inputs	Traffic Volume Levels	
	Median	High
Single ALS	N	N
Tandem ALS	Y (sensitive)	Y
Tridem ALS	N	N
Quad ALS	N	N
Single AGPV	N	N
Tandem AGPV	N	N
Tridem AGPV	N	N
Quad AGPV	N	N
HDF	N	N
MDF Single Unit	N	N
MDF Tractor-Trailer	N	N
MDF Multi-Trailer	N	N
VCD	N	N

Details of the sensitivity analysis results for tandem ALS are shown in Table 6.9. Each single ALS of different WIM sites were tested twice using different pavement thicknesses at a ½ inch increment. A “Fail” or “F” indicates that pavement at specific thickness was not sufficient enough to support directional single ALS input indicated in the first column, while a “Pass” or “P” means pavement thicknesses are sufficient to handle provided traffic inputs. The results showed that data from 4 out of 22 directional WIM sites produced differences in pavement thickness that were greater than ½ inch and therefore deemed significant from a practical perspective.

TABLE 6.9 Sensitivity Analysis of Rigid Pavement Design to Single ALS

Tandem ALS							
Median-Volume Road				**High-Volume Road**			
Site	JPCP thickness (in.)			Site	JPCP thickness (in.)		
	6.6	7.1	7.6		6.6	7.1	7.6
911_3	Fail	Past		911_3	F	P	
911_7	F	P		911_7	F	P	
915_1	F	P		915_1	F	P	
915_5		F	P	915_5		F	P
918_1	F	P		918_1	F	P	
918_5	F	P		918_5	F	P	
933_3	F	P		933_3	F	P	
933_7	F	P		933_7	F	P	
934_3	F	P		934_3	F	P	
934_7	F	P		934_7	F	P	
942_1	P	P		942_1	P	P	
942_5	F	P		942_5	F	P	
960_3		F	F	960_3		F	F
960_7	F	P		960_7	F	P	
961_1	P	P		961_1	P	P	
961_5	P	P		961_5	P	P	
963_3	F	P		963_3		F	P
963_7	F	P		963_7	F	P	
964_1	F	P		964_1	F	P	
964_5	F	P		964_5	F	P	
965_1	F	P		965_1	F	P	
965_5	F	P		965_5	F	P	

6.3.3 Comparison of Sensitivity Analysis Results for Different Pavement Types

Due to the differences in material properties between rigid and flexible pavements, sensitivity analysis results of the same traffic input for different pavement types could be very different. In the sensitivity analyses above, since the same sets of traffic inputs were used in the simulations of both flexible and rigid pavements, the comparison of sensitivity analysis results between pavement types were used to illustrate the differences.

In comparing Table 6.6 with Table 6.8, it was found that flexible pavements were sensitive to 7 out of 13 types of traffic inputs in various degrees, while rigid pavements were only sensitive to one type of traffic input (tandem ALS). Table 6.10 compares details of tandem ALS sensitivity analysis results for both pavement types. If both test results of a WIM sites were the same, for example two “P” or two “F”, they indicate pavement designs were sensitive to tandem ALS of a WIM site, and therefore highlighted in yellow. In Table 6.10, while both pavement types were sensitive to the use of direction-specific tandem ALS, their degrees of sensitivity were different. It was found that flexible pavements on high-volume roadways were most sensitive; with 20 out of 22 direction-specific WIM sites are highlighted. In contrast, rigid pavements on median- and high-volume roadways were relatively less sensitive; with only 4 out of 22 WIM sites highlighted.

TABLE 6.10 Comparisons of Tandem ALS Sensitivity Analysis Results

Tandem ALS															
Flexible Pavement								Rigid Pavement							
Median-Volume Road				High-Volume Road				Median-Volume Road				High-Volume Road			
Site	Intermediate thickness (in.)			Site	Intermediate thickness (in.)			Site	JPCP thickness (in.)			Site	JPCP thickness (in.)		
	10.7	11.3	11.7		23.8	24.3	24.8		6.6	7.1	7.6		6.6	7.1	7.6
911_3	Past	P		911_3	P	P		911_3	F	P		911_3	F	P	
911_7	P	P		911_7	P	P		911_7	F	P		911_7	F	P	
915_1	Fail	P		915_1	P	P		915_1	F	P		915_1	F	P	
915_5		F	P	915_5		F	F	915_5		F	P	915_5		F	P
918_1	P	P		918_1	P	P		918_1	F	P		918_1	F	P	
918_5	P	P		918_5	P	P		918_5	F	P		918_5	F	P	
933_3	F	P		933_3	F	P		933_3	F	P		933_3	F	P	
933_7	P	P		933_7	P	P		933_7	F	P		933_7	F	P	
934_3	P	P		934_3	P	P		934_3	F	P		934_3	F	P	
934_7	P	P		934_7	P	P		934_7	F	P		934_7	F	P	
942_1	P	P		942_1	P	P		942_1	P	P		942_1	P	P	
942_5	F	P		942_5	F	P		942_5	F	P		942_5	F	P	
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961_1	P	P		961_1	P	P		961_1	P	P		961_1	P	P	
961_5	F	P		961_5	P	P		961_5	P	P		961_5	P	P	
963_3		F	P	963_3		F	F	963_3	F	P		963_3		F	P
963_7	F	P		963_7	P	P		963_7	F	P		963_7	F	P	
964_1	P	P		964_1	P	P		964_1	F	P		964_1	F	P	
964_5	P	P		964_5	P	P		964_5	F	P		964_5	F	P	
965_1	P	P		965_1	P	P		965_1	F	P		965_1	F	P	
965_5	P	P		965_5	P	P		965_5	F	P		965_5	F	P	

6.4 CORRELATION-BASED CLUSTERING AND COMPARISON OF DATA DEVELOPMENT FOR BOTH PAVEMENT TYPES

Correlation-based cluster analyses were executed for each of the 13 types of traffic inputs, and therefore, 13 pairs of clustering strategies and trees were formed. The development of the clustering strategy and tree for single ALS is shown in Table 5.3 and Figure 5.2 as an example. For the determination of proper data levels for use in MEPDG rigid pavement design, the integration of sensitivity analysis with correlation-based cluster analysis was used. An example of the integration process for single ALS on high-volume flexible roadways was also shown in Figure 5.1. As a result of that integration, 5 clusters were formed, and the use of Level 2A data was determined. For all 13 types of traffic inputs, the resulting number of clusters and determination of recommended traffic input data levels for flexible and rigid pavements were summarized in Table 6.11.

TABLE 6.11 Determination of Data Level for Flexible and Rigid Pavement Design

Traffic Input	Flexible Pavement Design			Rigid Pavement Design		
	Volume	Clusters	Determined Data Level	Volume	Clusters	Determined Data Level
Single AGPV	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
Tandem AGPV	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
Tridem AGPV	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
Quad AGPV	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
Single ALS	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	5	Level 2A	High	1	Level 2B
Tandem ALS	Low	20	Level 1	--	--	--
	Median	17	Level 1	Median	4	Level 2A
	High	17	Level 1	High	4	Level 2A
Tridem ALS	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	17	Level 1	High	1	Level 2B
Quad ALS	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
HDF	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
MDF Single Unit	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
MDF Tractor-trailer	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
MDF Multi-trailer	Low	1	Level 2B	--	--	--
	Median	1	Level 2B	Median	1	Level 2B
	High	1	Level 2B	High	1	Level 2B
VCD	Low	3	Level 2A	--	--	--
	Median	4	Level 2A	Median	1	Level 2B
	High	19	Level 1	High	1	Level 2B

For rigid pavement design, as shown on the right portion of Table 6.11, the clustering processes had created only one cluster (equivalent to the statewide average) for most traffic inputs. This aligned with the sensitivity analysis results shown in Table 6.8, that rigid pavements were mostly not sensitive to traffic inputs. The formation of only one cluster also indicated that the variances of most types of traffic inputs had no significant influence on rigid pavement design, and therefore, the use of Level 2B statewide traffic inputs would be sufficient. The tandem ALS was an exception. The sensitivity analysis in Table 6.8 demonstrated that rigid pavement design was sensitive to tandem ALS in 4 out of 22 directional WIM sites. Integration process of tandem ALS for rigid pavement design developed 4 clusters as shown in Table 6.11. Therefore, the use of Level 2A tandem ALS was recommended for rigid pavement design in Alabama.

For flexible pavement design, as shown on the left portion of Table 6.11, the clustering processes for the majority traffic inputs had formed only one cluster, and the uses of Level 2B data were determined. However, for single ALS on high-volume roadways, and VCD on low- and median-volume roadways, 5, 3, and 4 clusters were formed, respectively. Since the numbers of clusters formed fall between 2 to 11 per the data level scenarios indicated in Section 5.4, the use of Level 2A data (regional clusters) was recommended for these traffic inputs. For tandem ALS on all roadways, and tridem ALS and VCD on high-volume roadways, the numbers of clusters exceeded 11, which was more than half of the 22 sites. According to the methodology developed for determinations of data levels in Section 5.4, the uses of Level 1 data were recommended.

It is noted that the summarized sensitivity analysis results of flexible pavements in Table 6.6 did not completely align with the resulting number of clusters and determinations of data levels in Table 6.11. For example, for the traffic inputs of MDF Tractor-Trailer as shown in Table 6.6, flexible pavements were sensitive to them on roadways of all traffic-volume levels, however, Table 6.11 indicated only one cluster was formed, and the uses of Level 2B data were sufficient. The details of sensitivity analysis results of flexible pavement thickness to MDF Tractor-Trailer were shown in Table 6.12. While flexible pavement thickness was deemed sensitive to Level 1 MDF Tractor-Trailer at one of the 22 sites for low- and median-volume roadways, and 9 of the sites for high-volume roadways as shown, they all required a thinner pavement structure than that for Level 2B data. From a conservative perspective, it was determined that Level 2B statewide MDF Tractor-Trailer input would be appropriate. The same principle was applied to quad ALS and Tridem AGPV (detailed sensitivity analysis results of these inputs are shown in Appendix A for flexible pavement and Appendix B for rigid pavement), and thus the use of Level 2B data was recommended for these types of inputs.

TABLE 6.12 Sensitivity Analysis of Flexible Pavement Design to MDF Tractor-Trailer

MDF Tractor-Trailer											
Low-Volume Roadways				**Median-Volume Roadways**				**High-Volume Roadways**			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	Fail	Pass		911_3	F	P		911_3		F	P
911_7	P	P		911_7	P	P		911_7	P	P	
915_1		F	P	915_1	F	P		915_1		F	P
915_5	F	P		915_5	F	P		915_5		F	P
918_1		F	P	918_1	F	P		918_1		F	P
918_5		F	P	918_5	F	P		918_5		F	P
933_3		F	P	933_3	F	P		933_3		F	P
933_7		F	P	933_7	F	P		933_7		F	P
934_3	F	P		934_3	F	P		934_3	P	P	
934_7	F	P		934_7	F	P		934_7	P	P	
942_1	F	P		942_1	F	P		942_1	F	P	
942_5	F	P		942_5	F	P		942_5	F	P	
960_3	F	P		960_3	F	P		960_3		F	P
960_7	F	P		960_7	F	P		960_7		F	P
961_1		F	P	961_1	F	P		961_1		F	P
961_5		F	P	961_5		F	P	961_5		F	P
963_3	F	P		963_3	F	P		963_3	P	P	
963_7	F	P		963_7	F	P		963_7	P	P	
964_1	F	P		964_1	F	P		964_1	P	P	
964_5	F	P		964_5	F	P		964_5	P	P	
965_1	F	P		965_1	F	P		965_1	P	P	
965_5	F	P		965_5	F	P		965_5	P	P	

For both pavement types, in Table 6.11, the uses of Level 2B data were sufficient in most cases. Specifically, 31 out of 39 data scenarios for flexible pavement design and 24 out of 26 scenarios for rigid pavement design recommended Level 2B data.

At times when higher levels of data were required, it was found that flexible pavement design required more Level 1 and Level 2A data than rigid pavement design did. A further observation of Table 6.11 also found that when flexible pavement design required level 1 or Level 2A data in a certain type of traffic input, rigid pavement design generally required lower levels of data. For example, flexible pavement design required Level 1 tandem ALS but rigid pavement design only required Level 2A data. This observation found that rigid pavement designs, compared with flexible pavement designs in general, require a lower level of traffic inputs.

6.5 IDENTIFICATION OF TRAFFIC PATTERNS

The methodology of traffic patterns identification described in Section 5.5 was implemented to traffic inputs in which the uses of Level 2A data were required for pavement designs. As shown in Table 6.11, the uses of Level 2A data are required in single ALS for flexible pavement designs of high-volume roadways, VCD for flexible pavement design of low- and median-volume roadways, and tandem ALS for rigid pavement designs. For other traffic inputs that required either the uses of Level 1 or Level 2B data, patterns are self-explanatory, and the identification process was not needed.

6.5.1 Single ALS for Flexible Pavement Designs of High-Volume Roadways

The identification of traffic patterns for single ALS on high-volume roadways was shown as an example in Section 5.5. In summary, traffic patterns associated with the 5 clusters were possibly defined geographically as follows:

- Cluster 1: high-volume roads that have not been specified in other clusters.
- Cluster 2: southbound traffic on high-volume roads in southern Alabama;
- Cluster 3: northbound traffic along I-65 in southern Alabama;
- Cluster 4: eastbound traffic on high-volume roads in southwestern Alabama;
- Cluster 5: westbound traffic on high-volume roads in western Alabama.

6.5.2 VCD for Flexible Pavement Designs of Low-Volume Roadways

Three clusters were formed in the clustering of VCD for low-volume roadways, and their distributions of trucks by class are shown in Figures 6.3. Since VC5 and VC9 are the most common vehicle classes, they were used to identify VCD patterns. Hence:

- Cluster 1: slightly higher frequency of VC9 than VC5;
- Cluster 2: roughly equal frequencies of VC5 and VC9;
- Cluster 3: significantly higher frequency of VC9 than VC5.

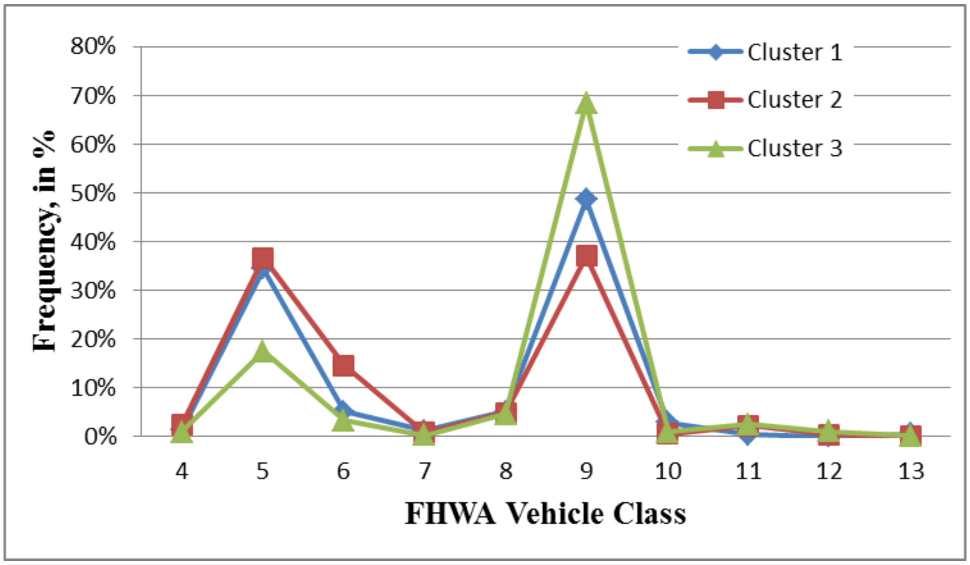

FIGURE 6.3 The three clusters of VCD for low-volume traffic

Observing VCD patterns geographically, it was found that VCDs in the region between I-85, I-65 and I-59 had significant directional variances; in that, traffic heading west had lower percentages of VC9. For interstates, VCDs did not vary despite changes of locations and directions. Hence:

- Cluster 1: eastbound, northbound and southbound traffic on highways (except interstates) in the region between I-85, I-65 and I-59;
- Cluster 2: westbound traffic on highways (except interstates) in the region between I-85, I-65 and I-59;

- Cluster 3: (1) all interstates in Alabama; and (2) roads of other functional classifications in the southeastern Alabama (divided by I-85 and I-65) and in northwest Alabama (divided by I-59).

6.5.3 VCD for Flexible Pavement Designs of Median-Volume Roadways

Four clusters were formed for VCD on median-volume roadways, and their distributions of trucks by class are shown in Figure 6.4. The clustering results for VCD on low- and median-volume roadways were very similar. In fact, Cluster 2 and 3 for VCD on low-volume roadways were the same as Cluster 3 and 4 for VCD on median-volume roadways, respectively. Thus, the geographical patterns of these clusters also reflected their uniformity. However, WIM Site 960_3, which originally belonged to Cluster 1 for VCD on low-volume roadways, was separated to form Cluster 2 for VCD on median-volume roadways. Geographical patterns for Cluster 1 and 2 were re-defined. Hence:

- Cluster 1: northbound and southbound traffic on highways (except interstates) in the region between I-85, I-65 and I-59;
- Cluster 2: eastbound traffic on highways (except interstates) in the region between I-85, I-65 and I-59;
- Cluster 3: westbound traffic on highways (except interstates) in the region between I-85, I-65 and I-59;
- Cluster 4: Cluster 3: (1) all interstates in Alabama; and (2) roads of other functional classifications in the southeastern Alabama (divided by I-85 and I-65) and in northwest Alabama (divided by I-59).

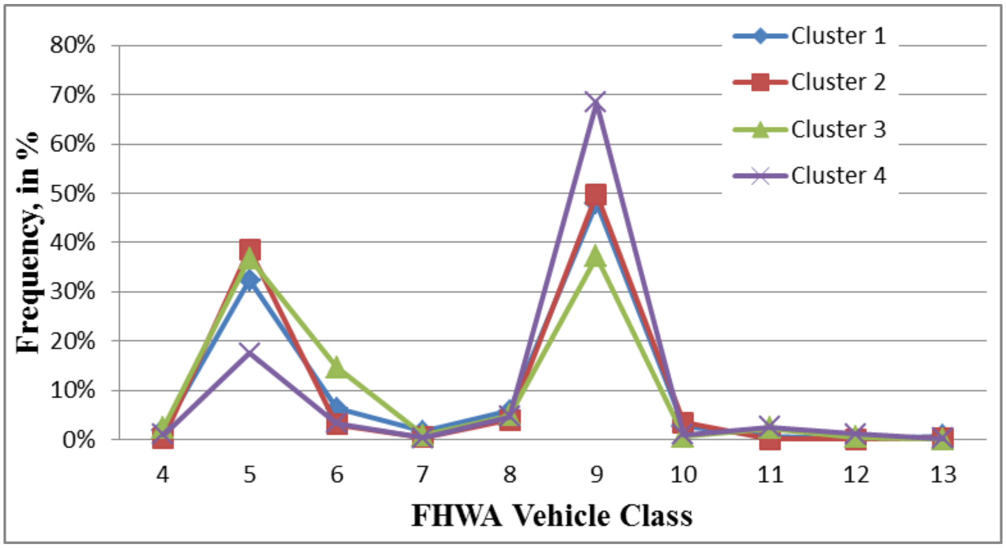

FIGURE 6.4 The four clusters of VCD for median-volume traffic

6.5.4 Tandem ALS Patterns for Rigid Pavement Designs

For rigid pavement design of both median and high-volume roadways, four tandem ALS clusters were formed. Level 2A tandem ALS developed from data of the four clusters are also shown in Figure 6.5. All tandem ALS have the typical double-peak shape. Clusters 1 and 2 have the same low peak value of 14,000 lbs, but their high peaks are 4,000 lbs away from each other. Cluster 3 has a dominant percentage of light or empty axles. Cluster 4 has significantly heavier axle loads due to heavy industries in that area. Based on locations of WIM sites within each cluster, possible traffic patterns of Level 2A tandem ALS was identified as:

- Cluster 1: traffic characteristics that have not been specified in other clusters;
- Cluster 2: traffic in both directions along I-65 in southern Alabama;
- Cluster 3: northbound traffic along U.S. 231 between the Troy and Montgomery;
- Cluster 4: eastbound traffic in southwestern Alabama

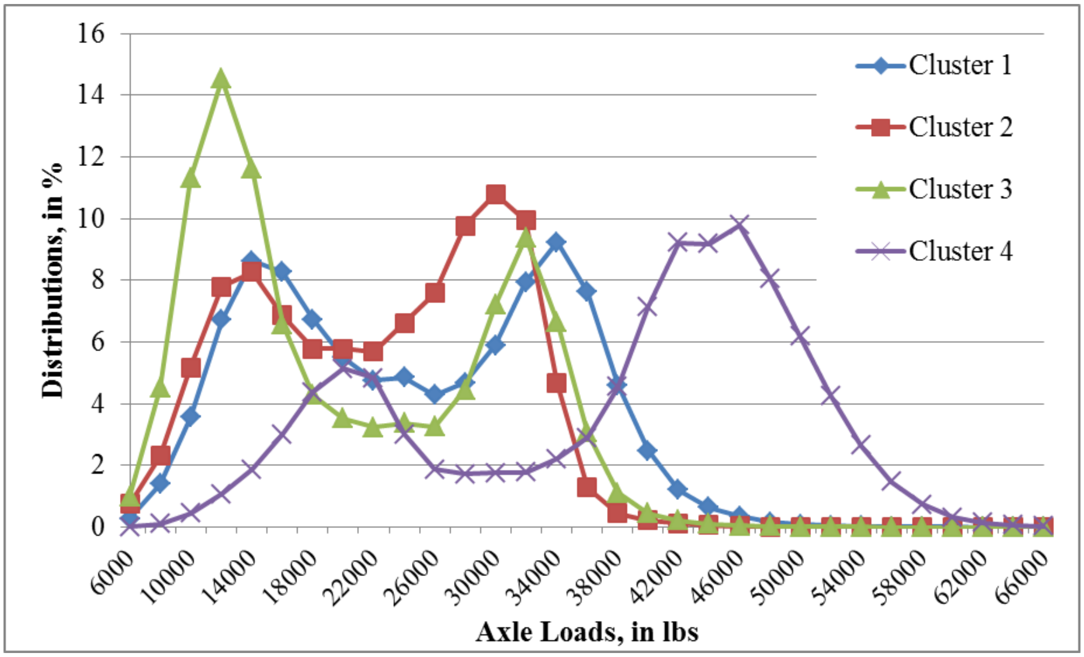

FIGURE 6.5 Distributions of Level 2A tandem ALS for rigid pavement design

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 SUMMARY AND CONCLUSION

The use of the mechanistic-empirical (M-E) approach to design and analysis of pavement distress is the trend of future pavement design. In the M-E methods of pavement design, a number of failure criteria, each directed to a specific type of distress (such as cracking, rutting, IRI, and etc.), must be established. On the mechanistic (M) aspect of the M-E approach, principles of engineering mechanics are applied to predict critical pavement responses (such as stresses and strains) on different pavement structures and material properties. On the empirical (E) aspect, equations have been derived based on experiments (in the labs and in the field) that estimate pavement performance using distress measures. State transportation agencies across the U.S. are moving toward this method by implementing the Mechanistic Empirical Pavement Design Guide (MEPDG) software, now known as DARWin-ME and made available through AASHTO. This dissertation aimed to create objective approaches to develop different levels of MEPDG traffic inputs among Level 1 (direction-specific), Level 2A (cluster-averaged), Level 2B (statewide), and Level 3 (nationwide) for state agencies. Furthermore, it was important to recommend appropriate levels of traffic inputs so that pavement thickness would not be overdesigned or underdesigned. From a pavement designer's standpoint, the main challenge in using traffic data is which level of data for each of the 13 traffic inputs is sufficient to design pavement in various circumstances. To solve this question objectively, (1) a quality control procedure that eliminates visual inspection of axle load data was developed; (2) a sensitivity analysis that uses the differences of pavement thicknesses as sensitivity indicator was designed to streamline the process; and (3) correlation-based clustering that integrates with results of sensitivity analysis was created to determine an appropriate number of clusters, and to recommend data levels for use in the MEPDG.

7.1.1 Quality Control

A sophisticated QC procedure that consists of threshold checks and rational checks was developed in this research. When applied to Alabama WIM data from 24 directional WIM stations, a large portion of data (23.8% of total records) that are possibly erroneous were filtered out. WIM data with implausibly low or high values can be readily identified, for example a semi-trailer (Vehicle Class 9) with speed over 120 mph, and threshold checks are used to filter them out. A series of threshold checks, especially an out-of-range check, detected most (66.4%) of the errors. Furthermore, observations have found that frequent occurrences of axle weight errors in monthly datasets detected by threshold checks could be the forewarning of systematic errors in a WIM station. Some systematic errors cannot be observed merely by examining their values; to detect these errors, rational checks that examine axle load distributions and relationships among them were developed. In the rational check phase of the QC procedure, an ALS comparison module was implemented to replace manual inspection of gross vehicle weight (GVW) distributions. This module successfully detected axle load spectra (ALS) errors in three WIM stations that lasted several consecutive months. The number-of-axles check was also created in this QC procedure, and it found miscounting of vehicle axles in one WIM station, and therefore, data of that WIM station were deleted from further use.

7.1.2 Sensitivity Analysis

For sensitivity analysis, this research illustrated an analysis of the sensitivity of pavement design thickness to traffic factors at various data levels for use in the MEPDG. Three typical flexible pavement structures and two typical rigid pavement structures were created based on Alabama DOT design practices. Level 2B statewide traffic inputs were used to establish baseline pavement thicknesses. Pavement performance based on Level 1 and Level 3 traffic inputs was evaluated and compared with baseline thicknesses. Pavement thickness was deemed sensitive to differences in traffic input levels when relevant intermediate layer thicknesses changed 0.5 inches or more from the baseline thicknesses.

In the sensitivity analysis of flexible pavement design thickness to Level 3 nationwide traffic inputs, it was found that pavement thickness was sensitive to differences between Level 3 nationwide traffic inputs and Level 2B statewide traffic inputs for high-volume roadways for 9 of the 13 traffic inputs tested. All of these traffic inputs resulted in a thinner pavement structure using nationwide data, except for vehicle class distribution (VCD), for which the nationwide level demands a thicker pavement structure. From the 17 default truck traffic classifications (TTCs) in the MEPDG, TTC2 was chosen to generate nationwide inputs for this research because its percentage of tractor-trailer trucks (from VC8 to VC10) was nearest to that of Alabama statewide VCD. By comparing traffic characteristics of Level 2B with that of Level 3, even though it was found that the percentage of tractor-trailer trucks at Level 2B was slightly less than that of Level 3 (at TTC 2), there was a substantially higher percentage of fully loaded tractor-trailer trucks in Alabama, and these trucks were generally heavier than the national average. Thus, in general, the MEPDG simulations indicated pavement designs in Alabama demanded thicker pavement structures than those based on national average traffic inputs.

In the sensitivity analysis of flexible pavement design thickness to Level 1 direction-specific data, due to the vast amount of MEPDG executions for traffic inputs of different WIM stations and of different levels of traffic volumes, the analysis procedure was streamlined to altering baseline pavement thicknesses by an interval of ½ inches through successive iterations. Traffic inputs developed from data of 22 directional WIM stations (the other 2 directional WIM stations were filtered out by the QC procedure due to miscounting of vehicle axles) were analyzed. Sensitivity analysis of flexible pavement results (as shown in Table 6.6) indicated that the impacts of 6 traffic inputs (single AGPV, tandem AGPV, quad AGPV, HDF, MDF Single Unit, and MDF Multi-Trailer) did not produce critical changes in required pavement thickness at any levels of traffic volumes. However, pavement thickness for high-volume roadways was sensitive to 4 types of traffic inputs (single ALS, tridem ALS, quad ALS and tridem AGPV), but not for low- or median-volume roadways. Sensitivity analysis results also indicated the impacts of tandem ALS, MDF Tractor-Trailer, and VCD are critical to pavement design thicknesses at all three levels of traffic volumes.

The analysis conducted to determine the sensitivity of rigid pavement thickness to differences in data levels in Alabama found that rigid pavement thickness was not sensitive to differences between Level 3 (nationwide) and Level 2 (statewide) traffic inputs. In the analysis to Level 1 inputs, it was found that rigid pavement was not sensitive to differences among most inputs except for tandem ALS, in which data from 4 out of 22 directional WIM sites produced differences in pavement thickness that were greater than ½ inch and therefore deemed significant from a practical perspective.

7.1.3 Cluster Analysis

Cluster analysis of traffic inputs is an important tool to develop Level 2A regional traffic inputs for use in the MEPDG. This research introduced a new hierarchical clustering approach, correlation-based clustering, that considered pavement thickness as the indicator of sensitivity of pavements to traffic inputs at differing geographical levels. In contrast to many other studies in this area, the cluster analysis in this research was executed after the sensitivity analysis because the results of sensitivity analysis were inputs of the cluster analysis. Pearson's correlation distance measure (to evaluate similarity) combined with UPGMA (to cluster WIM stations) were used in this approach to traffic inputs clustering. Similarity coefficients developed by this method range between +1 and -1 so that bounded measurements for level of similarity were created. To determine the number of clusters of WIM sites for use in pavement design, sensitivity analysis of pavement design thickness to traffic inputs was integrated with correlation-based clustering to determine the location at which a clustering tree should be cut and clusters formed. The similarity coefficients at the cut location were then used to assign new WIM stations to proper clusters without the need for further sensitivity analysis. Detailed clustering processes of single ALS for flexible and rigid pavements were illustrated. These examples demonstrate the use of objective measures at key decision points in the clustering process. Engineering judgment was needed only to identify geographical cluster patterns after determination of clusters. The cluster analysis process also determined data levels for use in the MEPDG based on number of clusters created: (1) Level 2B input is recommended when only one cluster is created. (2) Level 2A inputs are considered sufficient for pavement design when numbers of clusters are no more than the amount of site-specific WIM stations; (3) otherwise, Level 1 inputs are needed.

To test the streamlined process that assign new WIM sites to clusters, single ALS data from a new WIM site was used. Details of this test were described in Section 5.6. This process successfully assigned the station to a cluster, and the geographical traffic pattern of that cluster was better defined. The result of this test also indicated that the installation of more WIM stations can improve the accuracy of geographical traffic patterns identification.

In the cluster analysis for each of the 13 types of traffic inputs for flexible pavement design (results are shown in Table 6.11), only one cluster was formed for the majority traffic inputs, and the uses of Level 2B data were recommended. However, for single ALS on high-volume roadways, and VCD on low- and median-volume roadways, 5, 3, and 4 clusters were formed respectively, and the use of Level 2A data was recommended for these traffic inputs. For tandem ALS on all roadways, and tridem ALS and VCD on high-volume roadways, the numbers of clusters exceeded 11, and thus, the use of Level 1 data was recommended. In the cluster analysis of 13 types of traffic inputs for rigid pavement design, one cluster was created for 12 of the 13 types; however, 4 clusters were created for tandem ALS.

In the comparison of recommended data levels for use in design of both pavement types, it was found that (1) the uses of Level 2B data were sufficient in most cases; (2) flexible pavement design required more Level 1 and Level 2A data than rigid pavement design did; and (3) when flexible pavement design required Level 1 or Level 2A data, rigid pavement design generally required lower levels of data.

7.2 RECOMMENDATIONS

Based on findings of this research, important recommendations were drawn:

- Since WIM system calibration cannot address random errors, threshold checks that filter out these errors are recommended for data users regardless of the frequency of WIM system calibration. Using a series of rational checks, the ALS comparison module and the number-of-axles check module was able to detect systematic data errors. Thus, these rational checks are also recommended for future QC procedures. Overall, since a large portion (23.8%) of the WIM data that might create bias was filtered out, sophisticated QC of WIM data is strongly recommended toward having quality data available for engineering purposes.
- Statewide traffic inputs are preferential to nationwide inputs because statewide traffic inputs developed within the state are more representative than nationwide inputs. Furthermore, the MEPDG simulations indicated pavement thickness designs in using Alabama statewide data, compared with that in using nationwide data, demanded thicker pavement structures. It is recommended that statewide data be used for all traffic inputs in Alabama in lieu of nationwide inputs.
- Since pavement thickness is a key parameter to be determined in pavement designs, for the sensitivity analysis, pavement thickness is recommended as the sensitivity indicator.
- The correlation-based clustering approach described herein eliminates subjective predeterminations of the number of traffic data clusters, and streamlines the clustering process for new WIM stations. Therefore, this clustering process is recommended for development of regional traffic inputs.

- The streamlined clustering test of this research makes the need for additional traffic data collection or WIM sites in Alabama evident. Deployment of additional sites could also allow for clearer geographic definitions of clusters to be developed. This recommendation is similar to those made in studies conducted using data from other states.
- In the comparison of recommended data levels for use in designs for different pavement types, it was found that rigid pavement design in general requires traffic inputs of lower details (or broader scopes). For example, when flexible pavement designs require Level 1 site-specific tandem ALS inputs, rigid pavement designs of similar scenarios only require Level 2A regional traffic inputs. However, current MEPDG design practices use the same levels of traffic inputs for designs of both pavement types. When the rigid pavement designs might not require the same levels of data details as for flexible pavement design, it is recommended that data development procedures (sensitivity analysis and cluster analysis) that determine input levels in an objective manner are executed separately for different pavement types.
- For agencies in other states that have implemented previous clustering practices, investigation of the recommended clustering approach (in this research) may be useful. A comparison of clustering results between the method described in this paper and methods previously developed, for a set of WIM sites in other jurisdictions, and the resulting impacts on required pavement thicknesses, would allow quantification of the differences between these approaches.

- For the MEPDG pavement design in the State of Alabama, the recommended levels of traffic inputs separately for different pavement types are shown in Table 6.11 of Section 6.4. For the design scenarios that require Level 2A traffic inputs, geographical traffic patterns that guide to the uses of suitable cluster-averaged datasets are illustrated in Section 6.5.
- For flexible pavement design scenarios that require Level 1 traffic inputs but design locations are not adjacent to any WIM sites, future research that aims to create ALS and VCD models is warranted to develop direction-specific inputs. In the meanwhile, engineering judgment and local knowledge are needed to choose appropriate Level 1 inputs from WIM sites that have similar traffic characteristics to design sites.

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APPENDIX A

SENSITIVITY ANALYSIS OF FLEXIBLE PAVEMENT DESIGN

APPENDIX A.1 Sensitivity Analysis of Flexible Pavement Design to Single ALS

Low-Volume Roadways				**Median-Volume Roadways**				**High-Volume Roadways**			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	Fail	Pass		911_3	F	P		911_3	P	P	
911_7	F	P		911_7	F	P		911_7	F	P	
915_1	F	P		915_1	F	P		915_1	P	P	
915_5		F	P	915_5		F	P	915_5		F	P
918_1	F	P		918_1	F	P		918_1		F	P
918_5	F	P		918_5	F	P		918_5		F	P
933_3	F	P		933_3	F	P		933_3		F	P
933_7	F	P		933_7	F	P		933_7	F	P	
934_3	F	P		934_3	F	P		934_3		F	P
934_7		F	P	934_7	F	P		934_7		F	F
942_1	F	P		942_1	F	P		942_1	P	P	
942_5		F	P	942_5	F	P		942_5		F	P
960_3		F	P	960_3		F	P	960_3		F	F
960_7		F	P	960_7	F	P		960_7		F	P
961_1	F	P		961_1	F	P		961_1	P	P	
961_5	F	P		961_5	F	P		961_5	P	P	
963_3		F	P	963_3		F	P	963_3		F	F
963_7		F	P	963_7	F	P		963_7		F	F
964_1	F	P		964_1	F	P		964_1	F	P	
964_5	F	P		964_5	F	P		964_5	F	P	
965_1	F	P		965_1	F	P		965_1	F	P	
965_5	F	P		965_5	F	P		965_5	F	P	

APPENDIX A.2 Sensitivity Analysis of Flexible Pavement Design to Tandem ALS

Low-Volume Roadways			
Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6
911_3	P	P	
911_7	F	P	
915_1		F	P
915_5		F	P
918_1	P	P	
918_5	F	P	
933_3	F	P	
933_7	P	P	
934_3	F	P	
934_7	F	P	
942_1	P	P	
942_5	F	P	
960_3		F	F
960_7	F	P	
961_1	P	P	
961_5	P	P	
963_3		F	P
963_7	F	P	
964_1	F	P	
964_5	P	P	
965_1	F	P	
965_5	P	P	

Median-Volume Roadways			
Site	AC Intermediate layer (in.)		
	10.7	11.2	11.7
911_3	P	P	
911_7	P	P	
915_1	F	P	
915_5		F	P
918_1	P	P	
918_5	P	P	
933_3	F	P	
933_7	P	P	
934_3	P	P	
934_7	P	P	
942_1	P	P	
942_5	F	P	
960_3		F	F
960_7	F	P	
961_1	P	P	
961_5	F	P	
963_3		F	P
963_7	F	P	
964_1	P	P	
964_5	P	P	
965_1	P	P	
965_5	P	P	

High-Volume Roadways			
Site	AC Intermediate layer (in.)		
	23.8	24.3	24.8
911_3	P	P	
911_7	P	P	
915_1	P	P	
915_5		F	F
918_1	P	P	
918_5	P	P	
933_3	F	P	
933_7	P	P	
934_3	P	P	
934_7	P	P	
942_1	P	P	
942_5	F	P	
960_3		F	F
960_7	P	P	
961_1	P	P	
961_5	P	P	
963_3		F	F
963_7	P	P	
964_1	P	P	
964_5	P	P	
965_1	P	P	
965_5	P	P	

APPENDIX A.3 Sensitivity Analysis of Flexible Pavement Design to Tridem ALS

Low-Volume Roadways

Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5		F	P
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3		F	P
934_7		F	P
942_1	F	P	
942_5	F	P	
960_3		F	P
960_7		F	P
961_1	F	P	
961_5	F	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

Median-Volume Roadways

Site	AC Intermediate layer (in.)		
	10.7	11.2	11.7
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5		F	P
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3		F	P
934_7		F	P
942_1	F	P	
942_5	F	P	
960_3		F	P
960_7		F	P
961_1	F	P	
961_5	F	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

High-Volume Roadways

Site	AC Intermediate layer (in.)		
	23.8	24.3	24.8
911_3		F	P
911_7	P	P	
915_1	P	P	
915_5	P	P	
918_1	P	P	
918_5	P	P	
933_3	P	P	
933_7	P	P	
934_3		F	F
934_7		F	F
942_1	P	P	
942_5		F	P
960_3	P	P	
960_7	P	P	
961_1	P	P	
961_5	P	P	
963_3	F	P	
963_7	P	P	
964_1	P	P	
964_5	P	P	
965_1	P	P	
965_5	P	P	

APPENDIX A.4 Sensitivity Analysis of Flexible Pavement Design to Quad ALS

Low-Volume Roadways

Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6
911_3	F	P	
911_7		F	P
915_1	F	P	
915_5	F	P	
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3	F	P	
934_7	F	P	
942_1	F	P	
942_5	F	P	
960_3	F	P	
960_7	F	P	
961_1	F	P	
961_5	F	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

Median-Volume Roadways

Site	AC Intermediate layer (in.)		
	10.7	11.2	11.7
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5	F	P	
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3	F	P	
934_7	F	P	
942_1	F	P	
942_5	F	P	
960_3	F	P	
960_7	F	P	
961_1	F	P	
961_5	F	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

High-Volume Roadways

Site	AC Intermediate layer (in.)		
	23.8	24.3	24.8
911_3	F	P	
911_7		F	P
915_1	P	P	
915_5	P	P	
918_1		F	P
918_5		F	P
933_3	F	P	
933_7		F	P
934_3	F	P	
934_7		F	P
942_1	F	P	
942_5		F	P
960_3	P	P	
960_7	P	P	
961_1	P	P	
961_5	P	P	
963_3		F	P
963_7	F	P	
964_1	F	P	
964_5	P	P	
965_1	F	P	
965_5	P	P	

APPENDIX A.5 Sensitivity Analysis of Flexible Pavement Design to Single AGPV

Low-Volume Roadways

Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5	F	P	
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3	F	P	
934_7	F	P	
942_1	F	P	
942_5	F	P	
960_3	F	P	
960_7	F	P	
961_1	F	P	
961_5	F	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

Median-Volume Roadways

Site	AC Intermediate layer (in.)		
	10.7	11.2	11.7
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5	F	P	
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3	F	P	
934_7	F	P	
942_1	F	P	
942_5	F	P	
960_3	F	P	
960_7	F	P	
961_1	F	P	
961_5	F	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

High-Volume Roadways

Site	AC Intermediate layer (in.)		
	23.8	24.3	24.8
911_3	P	P	
911_7	P	P	
915_1	F	P	
915_5		F	P
918_1	F	P	
918_5	F	P	
933_3		F	P
933_7		F	P
934_3	F	P	
934_7	F	P	
942_1	F	P	
942_5		F	P
960_3	P	P	
960_7	F	P	
961_1	F	P	
961_5	F	P	
963_3		F	P
963_7	F	P	
964_1	P	P	
964_5	F	P	
965_1	P	P	
965_5	P	P	

APPENDIX A.6 Sensitivity Analysis of Flexible Pavement Design to Tandem AGPV

Low-Volume Roadways				Median-Volume Roadways				High-Volume Roadways			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3		F	P	911_3	F	P		911_3		F	P
911_7		F	P	911_7	F	P		911_7		F	P
915_1	F	P		915_1	F	P		915_1		F	P
915_5	F	P		915_5	F	P		915_5	F	P	
918_1	F	P		918_1	F	P		918_1		F	P
918_5	F	P		918_5	F	P		918_5		F	P
933_3	F	P		933_3	F	P		933_3	F	P	
933_7	F	P		933_7	F	P		933_7	F	P	
934_3		F	P	934_3	F	P		934_3		F	P
934_7		F	P	934_7	F	P		934_7		F	P
942_1	F	P		942_1	F	P		942_1		F	P
942_5	F	P		942_5	F	P		942_5	F	P	
960_3		F	P	960_3	F	P		960_3		F	P
960_7	F	P		960_7	F	P		960_7		F	P
961_1	F	P		961_1	F	P		961_1		F	P
961_5	F	P		961_5	F	P		961_5		F	P
963_3	F	P		963_3	F	P		963_3		F	P
963_7	F	P		963_7	F	P		963_7		F	P
964_1		F	P	964_1	F	P		964_1		F	P
964_5		F	P	964_5	F	P		964_5		F	P
965_1		F	P	965_1	F	P		965_1		F	P
965_5		F	P	965_5	F	P		965_5		F	P

APPENDIX A.7 Sensitivity Analysis of Flexible Pavement Design to Tridem AGPV

Low-Volume Roadways				**Median-Volume Roadways**				**High-Volume Roadways**			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	F	P		911_3	F	P		911_3	F	P	
911_7	F	P		911_7	F	P		911_7		F	P
915_1	F	P		915_1	F	P		915_1		F	P
915_5	F	P		915_5	F	P		915_5	F	P	
918_1	F	P		918_1	F	P		918_1		F	P
918_5	F	P		918_5	F	P		918_5		F	P
933_3	F	P		933_3	F	P		933_3		F	P
933_7	F	P		933_7	F	P		933_7		F	P
934_3	F	P		934_3	F	P		934_3	F	P	
934_7	F	P		934_7	F	P		934_7	F	P	
942_1	F	P		942_1	F	P		942_1	F	P	
942_5	F	P		942_5	F	P		942_5	F	P	
960_3	F	P		960_3	F	P		960_3		F	P
960_7	F	P		960_7	F	P		960_7	F	P	
961_1	F	P		961_1	F	P		961_1	F	P	
961_5	F	P		961_5	F	P		961_5	F	P	
963_3	F	P		963_3	F	P		963_3	F	P	
963_7	F	P		963_7	F	P		963_7	P	P	
964_1	F	P		964_1	F	P		964_1		F	P
964_5	F	P		964_5	F	P		964_5	F	P	
965_1	F	P		965_1	F	P		965_1	F	P	
965_5	F	P		965_5	F	P		965_5	F	P	

APPENDIX A.8 Sensitivity Analysis of Flexible Pavement Design to Quad AGPV

Low-Volume Roadways				**Median-Volume Roadways**				**High-Volume Roadways**			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3		F	P	911_3	F	P		911_3		F	P
911_7	F	P		911_7	F	P		911_7	F	P	
915_1	F	P		915_1	F	P		915_1		F	P
915_5	F	P		915_5	F	P		915_5		F	P
918_1	F	P		918_1	F	P		918_1	F	P	
918_5	F	P		918_5	F	P		918_5	F	P	
933_3	F	P		933_3	F	P		933_3	F	P	
933_7	F	P		933_7	F	P		933_7	F	P	
934_3	F	P		934_3	F	P		934_3	F	P	
934_7	F	P		934_7	F	P		934_7	F	P	
942_1	F	P		942_1	F	P		942_1	F	P	
942_5	F	P		942_5	F	P		942_5	F	P	P
960_3	F	P		960_3	F	P		960_3	F	P	
960_7	F	P		960_7	F	P		960_7		F	P
961_1	F	P		961_1	F	P		961_1	F	P	
961_5	F	P		961_5	F	P		961_5	F	P	
963_3	F	P		963_3	F	P		963_3	F	P	
963_7	F	P		963_7	F	P		963_7	F	P	
964_1	F	P		964_1	F	P		964_1	F	P	
964_5	F	P		964_5	F	P		964_5	F	P	
965_1	F	P		965_1	F	P		965_1	F	P	
965_5	F	P		965_5	F	P		965_5	F	P	

APPENDIX A.9 Sensitivity Analysis of Flexible Pavement Design to HDF

Low-Volume Roadways					Median-Volume Roadways					High-Volume Roadways			
Site	AC Intermediate layer (in.)				Site	AC Intermediate layer (in.)				Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6			10.7	11.2	11.7			23.8	24.3	24.8
911_3	F	P			911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P			965_5	F	P	

APPENDIX A.10 Sensitivity Analysis of Flexible Pavement Design to MDF Single Unit

Low-Volume Roadways				Median-Volume Roadways				High-Volume Roadways			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	F	P		911_3	F	P		911_3	F	P	
911_7	F	P		911_7	F	P		911_7	F	P	
915_1	F	P		915_1	F	P		915_1	F	P	
915_5	F	P		915_5	F	P		915_5	F	P	
918_1	F	P		918_1	F	P		918_1	F	P	
918_5	F	P		918_5	F	P		918_5	F	P	
933_3	F	P		933_3	F	P		933_3		F	P
933_7	F	P		933_7	F	P		933_7		F	P
934_3	F	P		934_3	F	P		934_3	F	P	
934_7	F	P		934_7	F	P		934_7	F	P	
942_1	F	P		942_1	F	P		942_1		F	P
942_5	F	P		942_5	F	P		942_5		F	P
960_3	F	P		960_3	F	P		960_3		F	P
960_7	F	P		960_7	F	P		960_7		F	P
961_1	F	P		961_1	F	P		961_1	F	P	
961_5	F	P		961_5	F	P		961_5	F	P	
963_3	F	P		963_3	F	P		963_3	F	P	
963_7	F	P		963_7	F	P		963_7	F	P	
964_1	F	P		964_1	F	P		964_1	F	P	
964_5	F	P		964_5	F	P		964_5	F	P	
965_1	F	P		965_1	F	P		965_1	F	P	
965_5	F	P		965_5	F	P		965_5	F	P	

APPENDIX A.11 Sensitivity Analysis of Flexible Pavement Design to MDF Tractor-Trailer

Low-Volume Roadways				**Median-Volume Roadways**				**High-Volume Roadways**			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	F	P		911_3	F	P		911_3		F	P
911_7	P	P		911_7	P	P		911_7	P	P	
915_1		F	P	915_1	F	P		915_1		F	P
915_5	F	P		915_5	F	P		915_5		F	P
918_1		F	P	918_1	F	P		918_1		F	P
918_5		F	P	918_5	F	P		918_5		F	P
933_3		F	P	933_3	F	P		933_3		F	P
933_7		F	P	933_7	F	P		933_7		F	P
934_3	F	P		934_3	F	P		934_3	P	P	
934_7	F	P		934_7	F	P		934_7	P	P	
942_1	F	P		942_1	F	P		942_1	F	P	
942_5	F	P		942_5	F	P		942_5	F	P	
960_3	F	P		960_3	F	P		960_3		F	P
960_7	F	P		960_7	F	P		960_7		F	P
961_1		F	P	961_1	F	P		961_1		F	P
961_5		F	P	961_5		F	P	961_5		F	P
963_3	F	P		963_3	F	P		963_3	P	P	
963_7	F	P		963_7	F	P		963_7	P	P	
964_1	F	P		964_1	F	P		964_1	P	P	
964_5	F	P		964_5	F	P		964_5	P	P	
965_1	F	P		965_1	F	P		965_1	P	P	
965_5	F	P		965_5	F	P		965_5	P	P	

APPENDIX A.12 Sensitivity Analysis of Flexible Pavement Design to MDF Multi-Trailer

Low-Volume Roadways					**Median-Volume Roadways**					**High-Volume Roadways**			
Site	AC Intermediate layer (in.)				Site	AC Intermediate layer (in.)				Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6			10.7	11.2	11.7			23.8	24.3	24.8
911_3	F	P			911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P			942_1		F	P
942_5	F	P			942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P			960_7		F	P
961_1	F	P			961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P			961_5		F	P
963_3	F	P			963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P			965_1		F	P
965_5	F	P			965_5	F	P			965_5	F	P	

APPENDIX A.13 Sensitivity Analysis of Flexible Pavement Design to VCD

Low-Volume Roadways				**Median-Volume Roadways**				**High-Volume Roadways**			
Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)			Site	AC Intermediate layer (in.)		
	5.6	6.1	6.6		10.7	11.2	11.7		23.8	24.3	24.8
911_3	F	P		911_3	F	P		911_3	P	P	
911_7	P	P		911_7	P	P		911_7	P	P	
915_1	F	P		915_1	F	P		915_1	P	P	
915_5		F	P	915_5		F	P	915_5		F	P
918_1		F	P	918_1		F	P	918_1		F	F
918_5		F	P	918_5		F	P	918_5		F	F
933_3		F	P	933_3	F	P		933_3		F	P
933_7	F	P		933_7	F	P		933_7	F	P	
934_3		F	P	934_3		F	P	934_3		F	F
934_7		F	P	934_7		F	P	934_7		F	F
942_1		F	P	942_1	F	P		942_1		F	P
942_5		F	P	942_5		F	P	942_5		F	F
960_3	F	P		960_3	P	P		960_3	P	P	
960_7		F	P	960_7	F	P		960_7	F	P	
961_1		F	P	961_1		F	P	961_1		F	F
961_5		F	P	961_5	F	P		961_5		F	P
963_3	F	P		963_3	F	P		963_3	P	P	
963_7	F	P		963_7	F	P		963_7	P	P	
964_1	F	P		964_1	F	P		964_1		F	P
964_5	F	P		964_5	F	P		964_5	P	P	
965_1		F	P	965_1	F	P		965_1		F	P
965_5	F	P		965_5	F	P		965_5	P	P	

APPENDIX B

SENSITIVITY ANALYSIS OF RIGID PAVEMENT DESIGN

APPENDIX B.1 Sensitivity Analysis of Rigid Pavement Design to Single ALS

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3		F	P		960_3	F	P	
960_7		F	P		960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.2 Sensitivity Analysis of Rigid Pavement Design to Tandem ALS

Median-Volume Roadways

Site	JPCP Thickness (in.)		
	6.6	7.1	7.7
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5		F	P
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3	F	P	
934_7	F	P	
942_1	P	P	
942_5	F	P	
960_3		F	F
960_7	F	P	
961_1	P	P	
961_5	P	P	
963_3	F	P	
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

High-Volume Roadways

Site	JPCP Thickness (in.)		
	8.1	8.6	9.1
911_3	F	P	
911_7	F	P	
915_1	F	P	
915_5		F	P
918_1	F	P	
918_5	F	P	
933_3	F	P	
933_7	F	P	
934_3	F	P	
934_7	F	P	
942_1	P	P	
942_5	F	P	
960_3		F	F
960_7	F	P	
961_1	P	P	
961_5	P	P	
963_3		F	P
963_7	F	P	
964_1	F	P	
964_5	F	P	
965_1	F	P	
965_5	F	P	

APPENDIX B.3 Sensitivity Analysis of Rigid Pavement Design to Tridem ALS

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.4 Sensitivity Analysis of Rigid Pavement Design to Quad ALS

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.5 Sensitivity Analysis of Rigid Pavement Design to Single AGPV

Median-Volume Roadways					**High-Volume Roadways**			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.6 Sensitivity Analysis of Rigid Pavement Design to Tandem AGPV

Median-Volume Roadways					**High-Volume Roadways**			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.7 Sensitivity Analysis of Rigid Pavement Design to Tridem AGPV

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.8 Sensitivity Analysis of Rigid Pavement Design to Quad AGPV

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.9 Sensitivity Analysis of Rigid Pavement Design to HDF

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1		F	P
918_5	F	P			918_5		F	P
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1		F	P
942_5	F	P			942_5		F	P
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7		F	P
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1		F	P
965_5	F	P			965_5		F	P

APPENDIX B.10 Sensitivity Analysis of Rigid Pavement Design to MDF Single Unit

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.11 Sensitivity Analysis of Rigid Pavement Design to MDF Tractor-Trailer

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5		F	P
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.12 Sensitivity Analysis of Rigid Pavement Design to MDF Multi-Trailer

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1	F	P	
918_5	F	P			918_5	F	P	
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3	F	P	
934_7	F	P			934_7	F	P	
942_1	F	P			942_1	F	P	
942_5	F	P			942_5	F	P	
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1	F	P	
961_5	F	P			961_5	F	P	
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1	F	P	
964_5	F	P			964_5	F	P	
965_1	F	P			965_1	F	P	
965_5	F	P			965_5	F	P	

APPENDIX B.13 Sensitivity Analysis of Rigid Pavement Design to VCD

Median-Volume Roadways					High-Volume Roadways			
Site	JPCP Thickness (in.)				Site	JPCP Thickness (in.)		
	6.6	7.1	7.7			8.1	8.6	9.1
911_3	F	P			911_3	F	P	
911_7	F	P			911_7	F	P	
915_1	F	P			915_1	F	P	
915_5	F	P			915_5	F	P	
918_1	F	P			918_1		F	P
918_5	F	P			918_5		F	P
933_3	F	P			933_3	F	P	
933_7	F	P			933_7	F	P	
934_3	F	P			934_3		F	P
934_7	F	P			934_7		F	P
942_1	F	P			942_1		F	P
942_5	F	P			942_5		F	P
960_3	F	P			960_3	F	P	
960_7	F	P			960_7	F	P	
961_1	F	P			961_1		F	P
961_5	F	P			961_5		F	P
963_3	F	P			963_3	F	P	
963_7	F	P			963_7	F	P	
964_1	F	P			964_1		F	P
964_5	F	P			964_5		F	P
965_1	F	P			965_1		F	P
965_5	F	P			965_5	F	P	