Development of Traffic Data Input Resources for the Mechanistic Empirical Pavement Design Process

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Abstract

The Mechanistic-Empirical Pavement Design Guide (MEPDG) for New and Rehabilitated Pavement Structures uses nationally based data traffic inputs and recommends that state DOTs develop their own site-specific and regional values. To support the MEPDG NCDOT needs site-specific truck classification counts, truck axle load spectra, regional average seasonal adjustment factors, and forecasting methods for truck class volumes. This research proposal addresses these NCDOT traffic data and forecasting needs for implementing the MEPDG.

The research produced the following results: (1) software to process and clean WIM data; (2) database of high quality, clean NCDOT vehicle class counts and weight data; (3) simulation studies to guide the selection of sensitive traffic data and traffic count locations; (4) techniques for traffic data clustering and seasonal analysis of vehicle classification and truck axle loadings; (5) software to prepare datasets and sampling plans for Levels 1, 2, and 3 MEPDG requirements (Level 1 site specific, Level 2 seasonal groupings, and Level 3 statewide averages); (6) site specific, regional and statewide NC traffic data inputs for Levels 1, 2, and 3 in the MEPDG procedures for vehicle class distributions and axle load spectra including seasonality; (7) vehicle class forecasting methods for MEPDG procedures; (8) case study demonstrations and analyses; and (9) implementation and management plan for MEPDG traffic data.

Key Words **Pavement Design, Traffic Data, Traffic Data Analysis, Damage-based Sensitivity Analysis, Weight-in-Motion Data.**	Distribution Statement		
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ACRONYMS

Acronym	Meaning
AADTT	Annual Average Daily Truck Traffic
AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
ALDF	Axle Load Distribution Factors
APT	Axles per Truck
AASHTO	American Association of State Highway and Transportation Officials
BY	Base Year
CRCP	Continuously Reinforced Concrete Pavement
DOW	Day of Week
DDF	Directional Distribution Factor
FHWA	Federal Highway Administration
FC	Functional Class
FY	Future Year
HDF	Hourly Distribution Factors
HPMS	Highway Performance Monitoring System
IRD	International Road Dynamics
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement (JPCP)
LDF	Lane Distribution Factor
LTPP	Long Term Pavement Performance
MAF	Monthly Adjustment Factors
MADTT	Monthly Average Day-of-week Truck Traffic
MEPDG	Mechanistic Empirical Pavement Design Guide
MU	Multi-Unit Trucks (Vehicle Classes 8-13)
NCSU	North Carolina State University
PC	Principal Component
PCA	Principal Component Analysis
PDU	Pavement Design Unit
SU	Single-Unit Trucks (Vehicle Classes 4-7)
TFU	Traffic Forecasting Utility
TPB	Transportation Planning Branch
TPB/TF	Transportation Planning Branch/Traffic Forecast
TMG	Traffic Monitoring Guide
TSG	Traffic Survey Group
VCD	Vehicle Class Distribution
VTRIS	Vehicle Travel Information System
WIM	Weigh-in-Motion

EXECUTIVE SUMMARY

The Mechanistic Empirical Pavement Design Guide (MEPDG) requires specific types of traffic data to design new or rehabilitated pavement structures (*1*). Among the required data are axle load distribution factors (ALDF), monthly adjustment factors (MAF), hourly distribution factors (HDF), and vehicle class distributions (VCD). For each of these four factors depending on the level of design the MEPDG requires traffic distributions for each of 10 standard FHWA vehicle classes (4-13). The design levels are:

- Level 1: most accurate design level requiring site-specific weight and volume data collected at or near the project site.
- Level 2: intermediate accuracy design level with modest knowledge of traffic characteristics requiring regional weight data and site-specific volume data.
- Level 3: least accurate design level with knowledge only of statewide default weight and volume data.

Analyzing Level 1 data is straightforward. The difficulties lie in generating Level 2 data that pertain to roadways with limited traffic information. Level 3 analysis is an extension of the Level 2 analysis. Other states have also studied the problem of characterizing the truck traffic for Mechanistic-Empirical (M-E) pavement design [*Prozzi, 2005,Lu et al,. 2006, Papagiannakis (a),2006, Timm et a., 2006, Tran and Hall, 2007, Li et al., 2007, Swan et al., 2008, Lu et al., 2009*]. Table 1 shows the traffic data elements required for different design levels.

Table 1 Traffic Data Elements Required for the MEPDG

Traffic Data Element
Annual Average Daily Truck Traffic
Monthly Adjustment Factors by Vehicle Class
Hourly Distribution Factors
Vehicle Class Distribution Factors
Axle-Load Distribution Factors
Linear or Exponential Growth Rates
Directional Distribution Factors
Lane Distribution Factors
Lateral Traffic Wander
Number of Axles per Vehicle for Vehicle Classes 4-13
Axle Configurations
Wheelbase Distributions
Operational Speed

Figure 1 shows an Input-Process-Output model of this research project that concerns generating Level 2 MEPDG traffic inputs. NCDOT operates 44 WIM sites including 19 Long Term Pavement Performance (LTPP) stations. These WIM sites are located in three regions: the eastern coastal plain, central Piedmont, and western mountains. NCDOT provided twelve consecutive months of calibrated volume and weight data for each WIM site. Initially, the data were checked for completeness and anomalies using a quality control (QC) procedure. The quality control procedure confirmed that the data were reliable [*Ramachandran et al., 2010*].

WIM data
(W-cards and C-cards)

↓

NCSU*

- Developing WIM data quality control procedure (Ch 2)
- Developing traffic volume adjustment factors – VCD, MAF, and HDF (Chs 3 and 4)
- Developing general traffic inputs (Ch 4)
- Proposing traffic data forecasting procedure (Ch 5)
- Generating ALDF distributions (Ch 6)
- Developing axle load damage factors (Ch 7)
- Performing damage-based sensitivity analysis (Ch 8)
- Proposing seasonal sampling plan (Ch 9)
- Proposing locations to install future WIM stations (Ch 10)

↓

- WIM Data Quality Control Procedure
- SU/MU Seasonal Factors
- Seasonal Factor Decision Tree
- Hourly Distribution Factor (Table 4-1)
- Monthly Adjustment Factor (Table 4-2)
- Number of Axle per Vehicle Class (Table 4-3)
- Lateral Traffic Wander
- Axle Configurations (default)
- Axle Spacing (Table 4-4)
- Wheelbase Distribution
- Directional Distribution Factor (default)
- Lane Distribution Factor (default)
- Operational Speed (default)
- Recommendations regarding Traffic Forecasting
- ALDF Distributions
- ALDF Decision Tree
- Seasonal Sampling Procedure
- Recommendations regarding Locations of New WIM Stations

* A list of acronyms is included in Appendix 1.

Figure 1 Input-Process-Output Model of the Project

The cleaned data are then processed using computer programming to generate traffic factors including traffic volume adjustment factors (including VCD, HDF, and MAF), ALDF, and general traffic inputs.

Traffic Volume Adjustment Factors

The NC State University research team performed MEPDG damage-based sensitivity analysis to identify factors that affect North Carolina pavement performance measures (sensitive factors) and factors that do not (non-sensitive factors). Performance measures for flexible pavements are rutting, alligator cracking, longitudinal cracking, and the International Roughness Index (IRI). For rigid pavements, only Jointed Plain Concrete Pavement (JPCP) is considered because Continuously Reinforced Concrete Pavement (CRCP) is being phased out from use in the North Carolina road network. The performance measures for JPCP are faulting, percentage of slabs cracked, and the IRI. Structural and materials data were available only for LTPP sections. Representative LTPP sections were used in this sensitivity analysis.

Representative LTPP sections were used in this sensitivity analysis. To evaluate whether or not the effect of different traffic factors on pavement performance is significant, damage-based sensitivity criteria were developed in cooperation with the North Carolina Department of Transportation (NCDOT). These criteria suggest that an IRI of 14 inches/mile is the limit between being significant and insignificant for both flexible and rigid pavements. Similarly, the limits are 0.1 inch for rutting, 1% of the lane area for alligator cracking, 264 feet/mile for longitudinal cracking, 0.1 inch for JPCP faulting, and 3% for slabs cracked.

Table 2 shows the results of the sensitivity analysis. The results of the sensitivity analysis identified pavement performance to be sensitive to VCD. The VCD represents the percentage of each standard FHWA vehicle classes (class 4 buses through class 13 trucks). Table 3 lists the entire 13 standard FHWA vehicle classes. The proposed approach to generate VCD inputs is based on using the site-specific 48-hour vehicle classification counts plus a seasonal factoring procedure that accounts for day-of-week and seasonal variations in truck traffic volume. This simplified approach results in accurate VCD inputs because it incorporates site-specific knowledge of truck traffic.

Two types of traffic time distribution factors are needed as inputs. These factors are monthly adjustment factors (MAF) and hourly distribution factors (HDF). Monthly or seasonal distribution factors are used to adjust the Annual Average Daily Truck Traffic (AADTT) into monthly Average Daily Truck Traffic (ADTT) values/volumes, while the hourly distribution factor is used to distribute the monthly ADTT volumes by hour of the day. These time-dependent distribution factors are determined from detailed studies of WIM data. In addition, these factors are treated as constant throughout the pavement design life.

The monthly adjustment factor (MAF) is defined as the ratio of the monthly truck volume to the average monthly truck volume. MEPDG damage-based sensitivity analysis showed that pavement performance is not sensitive to NC site-specific and national default values of MAF, thus MAF statewide averages maybe used as input to MEPDG for Level 2 and Level 3 designs.

The hourly distribution factors (HDF) represent the percentage of the AADTT within each hour of the day. Based on the damage-based sensitivity analysis, flexible and rigid pavement performance was found to be relatively insensitive to different distributions of HDF. Thus, HDF statewide averages may be used for Level 2 design. Similar results are found when comparing the impact on pavement performance of national default values of HDF. This is a valuable finding that simplifies the design process. The pavement designer can use the HDF statewide averages for Level 2 and Level 3 designs.

Table 2 Sensitivity of Flexible and Rigid Pavements to Different Traffic Parameters

	Flexible Pavement				Rigid Pavement (JPCP)		
	Total Rut Depth (in)	Fatigue Cracking (%)	Longitudinal Cracking* (ft/mile)	IRI (in/mile)	Faulting (in)	Slabs Cracked (%)	IRI (in/mile)
HDF	×	×	×	×	×	×	×
MAF	×	×	✓	×	×	×	×
VCD	✓	✓	✓	✓	×	×	✓
ALDF	✓	✓	✓	✓	×	×	×

* The longitudinal cracking predictions obtained from the MEPDG are inaccurate, hence, the exclusion from the sensitivity study.

Table 3 FHWA Vehicle Classes

Vehicle Class Number.	**Standard FHWA Vehicle Classes**
1	Motorcycles
2	Passenger Cars
3	4-tire trucks
4	Buses
5	2-axle 6-tire trucks
6	3-axle trucks
7	4+ axle trucks
8	3-4 axle single-trailer combinations
9	5-axle single-trailer combinations
10	6+ axle single-trailer combinations
11	5-axle multi-trailer combinations
12	6-axle multi-trailer combinations
13	7+ axle multi-trailer combinations

Axle Load Distribution Factor

The ALDF represents the frequency of individual load intervals, known as load bins, for four axle types: single, tandem, tridem, and quad. The single load bins range from 2 – 41 kips at 1-kip interval, the tandem load bins range from 6 – 82 kips at 2- kip interval, and tridem and quad load bins range from 12 – 102 kip sat 3-kip interval. Flexible pavement performance was found to be sensitive to ALDF. After running the MEPDG for a 30-year design life for all rigid pavements, it was found that ALDF has an effect on % slabs cracked of rigid pavement from a "numbers point of view". However, from an "engineering point of view", this change is considered to be insignificant because of the following reason. Only one site out of four sites exhibited the effect of ALDF on % slabs cracked to be higher than the specified thresholds. When looking into the numbers, it was found that the predicted % slabs cracked for this particular site was 3.1% compared to the sensitivity criterion of 3.0%. Again, using engineering judgment, the team assumed that a 0.1% difference in % Slabs cracked is not enough to justify that ALDF significantly affects rigid pavements.

To develop ALDF inputs the NC State team followed the traditional approach based on inferring traffic data for roadway segments with data deficiencies from WIM data collected at other roads. Given the 44 NCDOT WIM databases available, investigating each database was not practical. Therefore, the team used a multidimensional clustering approach to cluster WIM sites that considers similarity of multiple attributes simultaneously and generates clusters for which their distinctions can be easily explained [*Sayyady et al., 2011*].

In order to decide what axle types and load combinations to include in multidimensional ALDF clustering, it is important to investigate the frequency and the effect of different axle types on pavement performance. MEPDG damage-based analysis showed that the contribution of tridem and quad axles to pavement damage is not appreciable in North Carolina (both less than 1%) while the effect of single and tandem axles is considerable (35% and 64%, respectively). Furthermore, single and tandem axles are more frequent (57.7% and 41.9%) and they are more representative of traffic on roadways compared to infrequent tridem and quad axles (0.3%, and 0.1%). More specifically, single and tandem axles are more frequent than tridem and quad axles. Given the aforementioned considerations, MEPDG damage analysis demonstrated that single and tandem axles are the two dimensions of the clustering analysis to use and to ignore infrequent tandems and quads.

Two-dimensional clustering analysis generates representative ALDF clusters that can be examined to identify explanatory traffic parameters for similar traffic patterns elsewhere on the highway system where design roads are located and for which there are only 48-hour counts. The traffic explanatory parameters define a decision tree to help the pavement engineer select the right ALDF input for the mechanistic-empirical pavement design at the design location. These parameters include 48-hour classification counts that specify design location AADTT and the percentage of class 5 and class 9 vehicles. The design engineer will also be familiar with local economic activities and the highway functional classification at the design location. The explanatory parameters are easy to acquire and result in a decision tree that is sound and straightforward to use.

General Traffic Inputs

Besides traffic volume adjustment factors and ALDF, there are some general traffic inputs to MEPDG software including lateral traffic wander, number of axles per truck for each vehicle class, axle configurations, and wheelbase.

National default values are recommended for lateral traffic wander input including mean wheel location (in inches from the lane marking), traffic wander standard deviation (in inches), and the design lane width (in feet). These factors were not evaluated in this research.

The NCSU team proposes using statewide average number of axles per truck as input to MEPDG. Since different types of vehicles with different axle configurations might be grouped under the same class, this can cause the average number of axle types per vehicle class to appear as a fraction.

Regarding axle configurations, the team recommends using national default inputs for average axle widths, dual tire spacing, and tire pressure. Statewide average axle spacing for tandem, tridem and quad axles are derived from available WIM data and are recommend to be used as input to MEPDG.

The wheelbase refers to the spacing between the steering and the drive axles of the truck-tractors or heavy single-units. Wheel base distribution information (average axle spacing and percentage of truck for short, medium and long axles) is required for JPCP top-down cracking considerations. National default inputs are recommended for wheelbase distribution information.

The generated traffic factors along with other data including climatic changes, material and soil properties, and pavement design features are used as input data for M-E pavement design.

Seasonal Sampling Plan

Resource and budget constraints may restrict department of transportation from collecting and reporting complete data. Technical problems may produce incomplete or intermittent Weigh-In-Motion (WIM) data. To address these issues WIM data sampling procedures are proposed. The proposed sampling schemes have two dimensions: the frequency (annual, semiannual, quarterly, and monthly) and the duration of samples (2-consecutive weekdays and 5-consecutive weekdays). As discussed above North Carolina pavement performance is sensitive to NC site-specific VCD and ALDF. The procedure to estimate VCD involves annualizing 48-hour counts using proper seasonal factors; hence, it is not necessary to investigate the effect of WIM data sampling plans on VCD estimates. This study focuses on axle load distributions and how effective the sampling procedures are to estimate the ALDF accurately. To evaluate the effectiveness of sampling schemes, the estimates of ALDF derived from WIM data collected over short periods of time are compared to estimates of ALDF derived from annual WIM data. Findings show that there is a direct correlation between seasonal variation of truck traffic and the accuracy of the sampling schemes. As expected, where truck traffic is stable (Piedmont region) all sampling schemes are attractive. Where truck traffic is not stable (coastal region) noticeable variations in truck traffic degrade annual-based sampling schemes because annually sampled data cannot sufficiently capture the seasonal variations of truck traffic. In such locations, semiannual and quarterly sampling schemes are required to capture ALDF seasonal variations. Findings also show that increasing the amount of sampled data does not necessarily reduce the error in estimating single and tandem ALDFs. There is relatively little improvement in estimation error as the sampling scheme changes from five consecutive weekdays per quarter (20 days), to two days per month (24 days), and to five days per month (60 days). This finding results because sampling five consecutive weekdays per quarter can efficiently capture the seasonal variation of truck traffic.

WIM Location Problem

Among the four major traffic inputs (HDF, MAF, VCD, and ALDF), generating ALDF and VCD factors involves averaging ALDF factors (seasonal factors) that belong to the same ALDF cluster (seasonal factor group). To rely on the averaged factors as robust statistics TMG recommends using reliability analysis. Reliability analysis determines the precision level of the statistics and identifies the required number of WIM sites to achieve a desired level of precision. NCDOT accepts 10% precision level for 95% confidence interval for seasonal factor groups of Single-Unit (SU) and Multi-Unit (MU) trucks, for ALDF clusters, however, the precision level are adjusted using MEPDG damage analysis. The damage factors are used to modify the precision level of 10% as well as prioritizing the candidate locations to receive new WIM sites.

The reliability analysis of seasonal factor groups and ALDF clusters showed that additional WIM sites are needed on some highways to reach the TMG desired levels of precision and confidence. On the other hand, related seasonal factor and ALDF analysis shows that TMG levels are exceeded for some factor groups/clusters. These WIM sites are candidates for abandonment depending on such factors as: pavement surrounding the WIM sensor, WIM equipment condition, urban/rural location, high/low truck volumes, and the expectation that the traffic pattern at a particular site is established or may change.

In summary, besides the 44 current WIM sites 21 additional WIM sites are required to achieve the preset precision levels of factor groups/clusters. The number of new sites could be adjusted depending on specific NCDOT needs, budget and timetable based on age of sensors in the field. The chosen WIM technology to install is also dependent on a tradeoff between using many low cost sensors to cover what is needed now versus fewer higher cost sensors that might last longer. Priority selections of new WIM locations can be made as a result of clustering analysis, ALDF ranking factors, and technical installation requirements [*TMG, 2001*].

New WIM data will help to improve the precision level of traffic factors derived from seasonal factor groups and ALDF clusters, as well as the statewide HDF, statewide MAF, and statewide number of axles per truck. Regardless of the number of WIMs added to the NC highway system, it is recommended that WIM sites are added in stages, evaluating where they fall in the groups/clusters, before moving on to the next stage and selecting new sites to install. The actual precision levels are evaluated as new WIM sites are installed and the process terminates when the desired level is achieved.

The reliability analysis showed that seven WIM sites are candidates for abandonment. These WIM sites may be prioritized based on their level of depreciation and also the level of truck traffic monitored by them. In general, WIM sites which are depreciated more and monitor fewer number of trucks have higher priority for abandonment.

Finally, a brief discussion on system wide monitoring of truck weights is relevant. The technique employed in traffic monitoring programs is to have a *continuous count* component and a *coverage count* component. The *continuous count* component is comprised of a limited number of sites where traffic is monitored continuously to provide detailed information on the types of traffic patterns and generate factors for short term counts. The *coverage count* component is comprised of many locations, enough to define system wide travel patterns, where short term counts are collected and annualized to provide monitoring of demand on the system. This is done for both volume and vehicle class data types as there are technologies available to collect both continuous and short term counts. This is not the case for truck weights. There is no viable technology to collect truck weights in short term sessions to support a *coverage* component for this data type. The 2009 AASHTO Guide for Traffic Data Programs Research has shown that these technologies (portable WIMs) are not reliable and that agencies should not use these technologies [*AASHTO 2009*]. The only method available to expand the knowledge of the system wide patterns as related to truck weights is technology used for the *continuous* component.

The NCSU team recommendation for NCDOT is to manage WIMs so that they meet the *continuous* component while supporting a process of expanding their knowledge of options for the *coverage* component. Such recommendation is supported with analysis, techniques, and guidelines presented in the research. The recommendation is to set up a dynamic program, where new WIM sites are added regularly (site selection), adequate data are collected (sampling), sites are discontinued after a short period (site abandonment), while the data needed for MEPDG input are maintained (reliability analysis). The collected data may not be "research quality" data, but they are valuable in expanding the knowledge of system characteristics at a slow and steady pace.

Implementation Plan

The overall recommended implementation plan for MEPDG in North Carolina is outlined in Figure 2. The user initially assumes a certain pavement design structure and input traffic data along with material specifications and climatic model. Then, the user performs damage analysis for the end of a design life and compares the predicted performance parameters to the criteria set by the agency. If the predicted performance parameters meet the specified criteria, the trial design structure becomes a candidate design. Otherwise, the trial pavement design structure is modified and the aforementioned steps are repeated.

The outcome of this research project provides the necessary traffic data for the implementation of MEPDG. The recommended process to generate Level 2 traffic input for MEPDG is illustrated in Figure 4. The details of the process are presented in the subsequent chapters of this report. The following subsections in this Executive Summary briefly explain how a user may collect, enter or import the required traffic data for a specific design. A comprehensive traffic data implementation plan is included in MEPDG NC User's Guide [*Kim and Jadoun, 2010*]. A summary of the guide is also presented in Appendix 6.

Vehicle Class Distribution and Annual Average Daily Traffic

TSG collects 48-classification counts for Project Count and Coverage Count Programs. TSG can then use the deliverables of this project including the seasonal factor decision tree and SU/MU seasonal factors to annualize the counts and to generate AADT, AADTT and VCD (or equivalently percentage vehicles by class). These annualized values represent base year traffic data for the subject highway section with no improvement. Based on historic traffic trends and engineering judgment traffic forecasters in the Transportation Planning Branch (TPB/TF) will adjust the base year AADT, AADTT, and VCD to estimate future year traffic values assuming no highway improvements occur. Then the traffic forecasters make additional base year and future adjustments assuming the anticipated highway improvement such as additional lanes, a parallel facility, or a bypass. The TPB/TF forecasters deliver the following information to the pavement designers in the Pavement Management Unit (PMU); AADT, AADTT, and VCD for the following cases: base year no improvement, base year improvement, future year no improvement, and future year improvement. .

To facilitate the process of generating VCD factors for a selected location, an Excel-based *VCD Generator and ALDF Cluster Selector* tool can generate VCD factors [*Kim and Jadoun, 2010*]. A screen shot of the tool is illustrated in Figure 3. The month and day of week seasonal factors (Table 3-8 and Table 3-12), single-unit and multi-unit decision trees (Figure 3-16 and Figure 3-29) are fundamental for the development of the tool. To generate VCD using the tool, the user (TSG) simply enters the 48-hour classification counts collected at the design road during typical weekdays (Tuesday-Thursday). The user also specifies whether the counts are collected on Interstate I-95 or not. TSG and TPB/TF can use the tool to generate the base year VCD factors. The pavement designer will manually enter the VCD values into the MEPDG software.

Hourly Distribution Factor

The pavement performance in North Carolina was found to be insensitive to site-specific HDF. Thus, statewide HDF averages may be used for North Carolina Levels 2 and 3 designs. Table 4-1is a summary of state-wide average HDF values that are recommended for use in the MEPDG. Users manually input HDF data to MEPDG.

Monthly Adjustment Factor

The pavement performance in North Carolina was found to be insensitive to site-specific MAF. Thus, statewide MAF averages may be used for North Carolina Level 2 and Level 3 designs. Table 4-2 is a summary of state-wide average MAF values that are recommended for use in the MEPDG. Users may either input MAF data manually or import them directly from the MAF file that is delivered to NCDOT.

Traffic Growth Factor

Traffic growth functions and rates are recommended to be supplied by the TPB/TF. CHAPTER 5 provides guidelines for developing growth rates for each vehicle class. The user can select to enter unique growth rates/functions for each vehicle class or a group of vehicle classes. For example if the user chooses to have a same growth rate/function for single-unit trucks, the same rate/function may be selected manually for vehicle classes 4 to 7.

Axle Load Distribution Factor

The 2-dimensional clustering analysis resulted in four representative ALDF clusters. Four ALDF files are generated that include the average ALDF of WIM sites forming four ALDF clusters. The ALDF files are delivered to NCDOT. A decision tree (Figure 6-18) is also developed that helps the designer select the proper ALDF input given percentage of class 5 and class 9 vehicles at design road as well as the road category: primary highways, secondary highways, collectors or local roads. The ALDF decision tree (Figure 6-18) and class 5% versus class 9% plot (Figure 6-11) are aggregated into the *VCD Generator and ALDF Cluster Selector* tool [*Kim and Jadoun, 2010*]. The user (pavement designer) initially inputs the base year 48-hour classification counts collected for the proposed project along with roadway category and the tool automatically suggests a representative ALDF cluster. The tool will automatically generate the base year VCD factors from the base year data. The existing VCD and AADTT values are sent to TPB to be adjusted if needed. TPB will provide the adjusted VCD and AADTT (base year VCD and AADTT values) to the pavement designer. The pavement designer will manually enter the adjusted values in the VCD table in the MEPDG software. Knowing the ALDF cluster, the user can import the associated ALDF file into MEPDG. There are cases for which the tool fails to suggest any representative ALDF clusters. These are cases that are poorly represented in the existing WIM data collection effort. It is suggested that users refer to Figure 6-11 and use their engineering judgment to select an ALDF cluster that has the closest class 5% and class 9% to those at the design road. Figure 6-11 is included in *VCD Generator and ALDF Cluster Selector* tool.

General Traffic Inputs

Here are the other traffic inputs that user will either manually update them or use the national default values:

- The number of axles per truck data; input the data provided in Table 4-3 manually.
- Axle spacing; input the data provided in Table 4-4 manually.
- Percent trucks in design lane; input the data provided in Table 4-4 manually.
- Average axle width, tire pressure, and dual tire spacing; use MEPDG national default values.
- Lateral traffic wander; use MEPDG national default values.
- Wheelbase distribution; use MEPDG national default values.
- Percent trucks in design direction; input the data provided in Table 4-4 manually.
- Operational speed; use MEPDG national default values.

Discussion on Terminology: Truck Percentages vs. Truck Distribution

A discussion on two terms used throughout this report is critical to avoid confusion. These terms are "truck percentages" and "truck distribution".

- Truck percentage (AADT-based): NCDOT, FHWA, the traffic monitoring profession, and most design processes, define truck percentages as the portion of the total traffic AADT (Classes 1 to 13) that are classified as truck types (Classes 4 to 13); i.e., $\frac{Number\ of\ Vehicle\ Classes\ 4\ to\ 13}{Number\ of\ Vehicle\ Classes\ 1\ to\ 13\ (AADT)}$).

Here, the truck percentages do not add to 100% because the base includes classes 1 to 3 as well.

- Truck distribution (AADTT-based): the MEPDG definition of truck distribution is related to vehicle class distribution (VCD). This is a VCD distribution of the total truck volumes AADTT (Class 4 to 13 only) into the individual truck classes. The sum of percentages of individual truck classes add up to 100 because no light weight vehicles are included, just trucks.

All of the discussions throughout this report relate to the AADTT–based VCD truck distributions except for Chapter 5 (Traffic Forecasts). Truck percentages (distributions) used in the report refer to AADTT-based values to be consistent with the MEPDG. Anywhere else when reference is made to the AADT-based truck percentages, a clear statement is made.

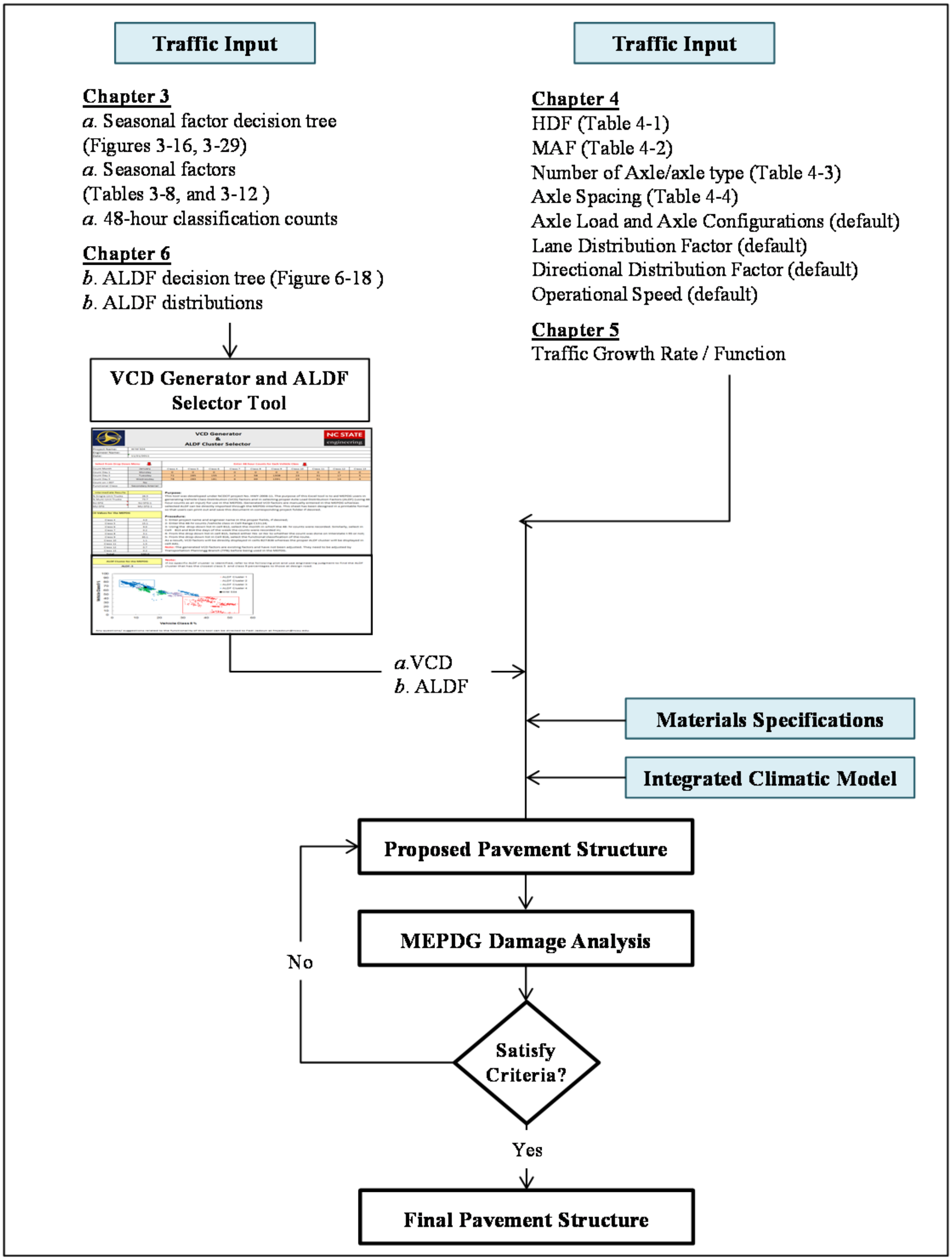


Figure 2 Overview of the MEPDG Implementation Procedure

VCD Generator
&
ALDF Cluster Selector

NC STATE engineering

Project Name:	WIM 504
Engineer Name:	
Date:	11/21/2011

Select from Drop Down Menu

Enter 48-hour Counts for Each Vehicle Class

		Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
Count Month	January										
Count Day 1	Monday	0	0	0	0	0	0	0	0	0	0
Count Day 2	Tuesday	72	285	155	2	58	1308	23	31	17	5
Count Day 3	Wednesday	78	283	181	6	69	1391	23	31	14	4
Count on I-95?	No										
Functional Class	Secondary Arterial										

Intermediate Results	
% Single-Unit Trucks	26.3
% Multi-Unit Trucks	73.7
SU-SFG	SU-SFG-1
MU-SFG	MU-SFG-1

CD Values for the MEPDG	
Class 4	4.0
Class 5	15.1
Class 6	9.0
Class 7	0.2
Class 8	3.1
Class 9	65.1
Class 10	1.1
Class 11	1.5
Class 12	0.7
Class 13	0.2
Total	**100.0**

Purpose

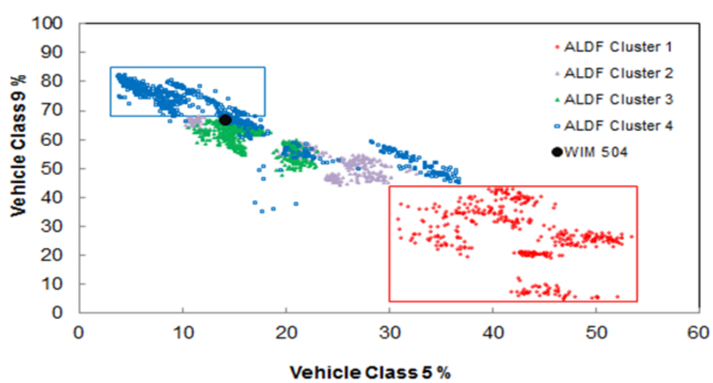
This tool was developed under NCDOT project No. HWY-2008-11. The purpose of this Excel tool is to aid MEPDG users in generating Vehicle Class Distribution (VCD) factors and in selecting proper Axle Load Distribution Factors (ALDF) (using 48-hour counts as an input) for use in the MEPDG. Generated VCD factors are manually entered in the MEPDG whereas selected ALDF can be directly imported through the MEPDG interface. This sheet has been designed in a printable format so that users can print out and save this document in corresponding project folder if desired.

Procedure:

1- Enter project name and engineer name in the proper fields, if desired;
2- Enter the 48-hr counts /vehicle class in Cell Range C13:L14;
3- Using the drop-down list In cell B12, select the month in which the 48- hr counts were recorded. Similarly, select in Cell B13 and B14 the days of the week the counts were recorded in;
4- From the drop down list in cell B15, Select either *Yes* or *No* to whether the count was done on Interstate I-95 or not;
5- From the drop-down list in Cell B16, select the functional classification of the route.
As a result, VCD factors will be directly displayed in cells B27:B36 whereas the proper ALDF cluster will be displayed in cell A41.
Note: The generated VCD factors are existing factors and have not been adjusted. They need to be adjusted by Transportation Planning Branch (TPB) before being used in the MEPDG.

ALDF Cluster for the MEPDG
ALDF-3

Note:
If no specific ALDF cluster is identified, refer to the following plot and use engineering judgment to find the ALDF cluster that has the closest class 5 and class 9 percentages to those at design road.



Any questions/ suggestions related to the functionality of this tool can be directed to Fadi Jadoun at fmjadoun@ncsu.edu.

Figure 3 Screen Shot of the VCD Generator and ALDF Cluster Selector Tool [*Kim and Jadoun, 2010*]

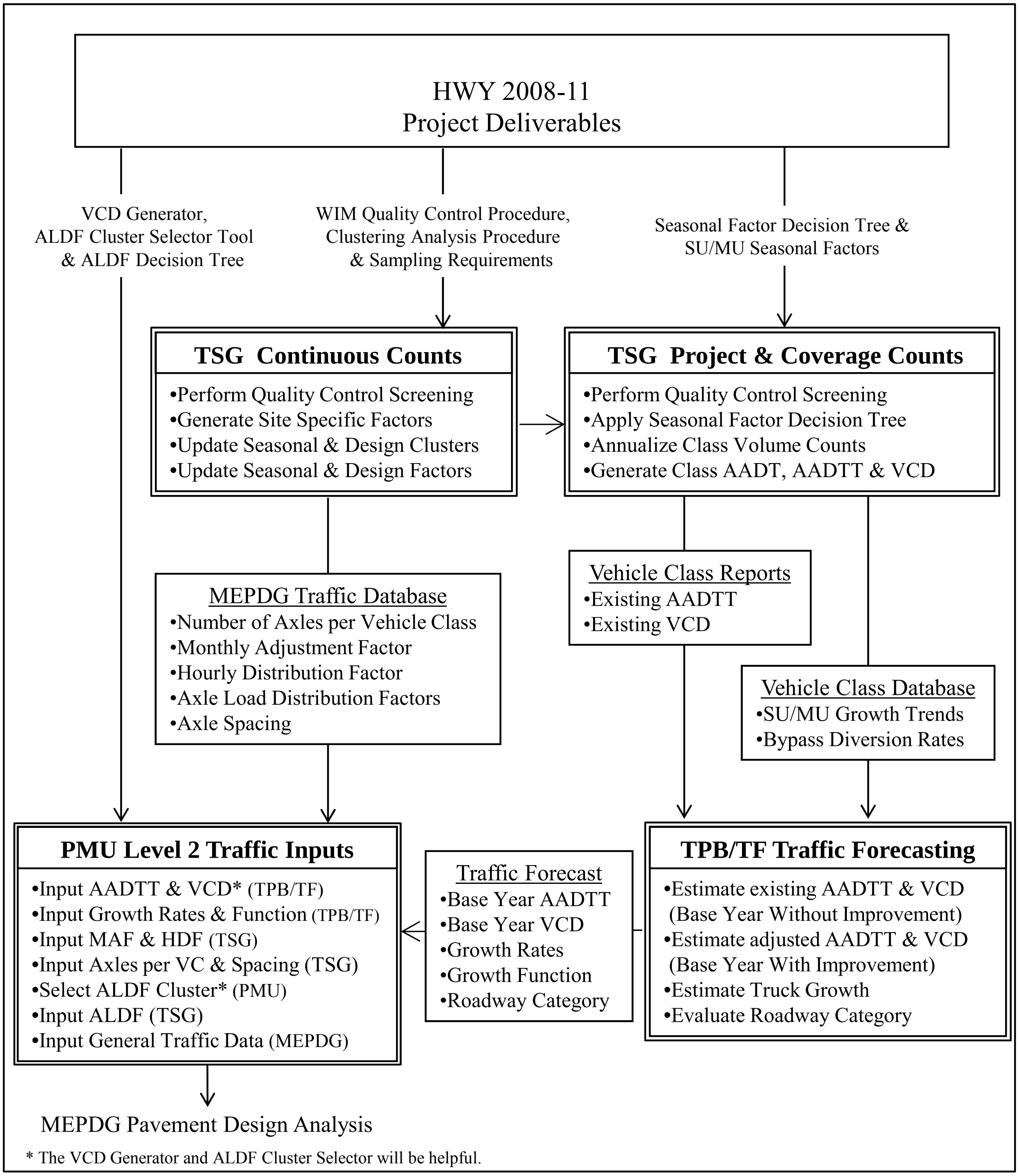


Figure 3 Recommended Process to Generate MEPDG Traffic Input (Level 2)

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CHAPTER 1. INTRODUCTION

This chapter of the report provides background information on the research project and how the traffic data prepared as a result of the research supports the use of the Mechanistic-Empirical Pavement Design Guide by NCDOT. The chapter describes the objectives of the research and the character of the data used for the research. Short summaries of subsequent chapters are provided. Of particular interest is a list of each of the research tasks and which of the report chapters address the tasks. The chapter ends with maps locating the NCDOT WIM stations and with tables that describe for each WIM station its identification numbers, the route it serves, the precise location, number of lanes monitored, installation date, and the county and town location.

1.1 Background

In 2002, the National Cooperative Highway Research Program released the Mechanistic-Empirical Design Guide (MEPDG) for New and Rehabilitated Pavement Structures [*NCHRP Project 1-37A,2004 and NCHRP Project 1-39, 2005*]. According to NCHRP Report 538, "…the 1-37A research provides engineers with practical and realistic pavement design procedures and software that use existing mechanistic-empirical principles. The mechanistic-based distress prediction models used in the MEPDG will require the input of specific data for each axle type and axle-load group. Project 1-39 research develops procedures and software for collecting and processing traffic data required by the Pavement Design Guide procedures."

NCHPR Projects 1-37A and 1-39 have consistent results except that NCHRP 1-39 stresses the need for using available DOT data resources and for developing statewide Level 3 data in place of national defaults. NCDOT will adopt the MEPDG procedures in the next few years; however, the models in the MEPDG contain design parameters based on limited national databases. For NCDOT, therefore, it is critical to calibrate the new design methods using NC design input data.

Four types of input data are required to use the MEPDG: structure, climate, material, and traffic data. The structure data are input by the user at the time of a pavement design. The climate data are automatically entered by the MEPDG software for the location of the design project. The material database for NC is under development in NCDOT project HWY-2007-07. Therefore, the final missing input data for the NC calibration of the MEPDG is the traffic data, the focus of this research. Briefly, the traffic data describe truck traffic volumes by class and axle load spectra, and future forecasts of the truck traffic.

1.2 Research Scope and Objectives

The research will develop a North Carolina database for Levels 1, 2 and 3 MEPDG traffic data and procedures, and it will identify the resources needed to collect the data including WIM sites, regional highway cluster sampling plans, seasonal analysis methods, and traffic forecasting methods. The research will follow the guidelines from NCHRP Project 1-39.

The specific objectives of the research are:

- Support the NCDOT MEPDG Implementation Plan.
- Develop resources, procedures, and guidelines for NCDOT traffic data needed for the MEPDG.
- Demonstrate the research findings in case study applications.
- Transfer the research findings to NCDOT.

1.3 Data Inventory

The traffic data used in this study were collected by NCDOT from 1997 to mid 2007 for 44 WIM Sites including 19 LTPP stations. NCDOT provided twelve consecutive months of calibrated volume and weight data for each WIM site. The data were checked for completeness and any anomalies which were corrected when found. The entire NCDOT WIM Data inventory is shown in Table 1-1.

The first column of Table 1-1 is the Station Identification Number (ID). It is generally a six digit number wherein the first two digits represent the State Code (37 for North Carolina). The second column identifies the Site ID, which is normally a three digit number representing the site at which the equipment for weight or classification purposes are setup. The third column shows the route at which the WIM sites are located. They are located on Interstate highways, US highways, North Carolina routes, and State Routes (SRs). The fourth column corresponds to the exact location at which the WIM site is located. Mile markers, exits or nearest landmarks/highways are used to identify the precise location of the site. The fifth column provides the number of lanes in the WIM site.

Two to four lanes are present in the sites and the direction is also specified along with the number of lanes. The sixth column represents the date at which the WIM site was first used for regular data collection purposes. The seventh column represents the county where the WIM site is located. The last column represents the nearest city/town to the location of WIM site.

44 WIM sites fall under three regions in North Carolina: Piedmont, mountainous or Coastal (east coastal and south coastal). Figure 1-1 to Figure 1-4 show the locations of the 44 WIM sites in these regions.

1.4 Report Organization

CHAPTER 1 of this report defines the NCDOT needs and issues related to the research problem and research scope, objectives and challenges. Chapter 1 also explains the data supplied by the TSG at NCDOT to support the project.

CHAPTER 2 of this report provides an overview of the quality control (QC) process as well as some examples of QC anomalies. It briefly discusses the application of local knowledge and provides some recommendations for future research.

CHAPTER 3 presents the process of developing seasonal factors for single-unit and multi-unit trucks that are used to annualize 48-hour counts collected at project locations. The annualized counts are the basis for developing vehicle class distribution (VCD) and Annual Average Daily Truck Traffic (AADTT) which are major traffic inputs to MEPDG.

CHAPTER 4 presents the approach for determining other traffic inputs including hourly distribution factors (HDF), monthly adjustment factors (MAF), and general traffic inputs. It also includes a discussion on sensitivity of pavement performance to HDF and MAF.

CHAPTER 5 specifically discusses these topics: NCDOT truck traffic forecasting procedures, truck traffic forecasting methods, truck traffic forecasting options in the M-E pavement design software, and MEPDG truck traffic forecasting guidelines for NCDOT.

CHAPTER 6 initially defines different axle type configurations that are dominant in NC. It then explains the process of developing axle load factors for four axle types (single, tandem, tridem, and quad). The chapter concludes with a decision tree that can help pavement engineers select the proper axle load factors (ALDF) as input to MEPDG.

CHAPTER 7 explains the process of developing axle load damage factors. These factors are multiplied by the actual axle load factors (ALDF) to identify axle types that have significant effects on pavement performance. The results show that the majority of pavement damage is caused by single and tandem axles. Thus, these two axle types form the basis for ALDF clustering analysis.

CHAPTER 8 explains the MEPDG sensitivity analysis including approach, sensitivity criteria, and results. The purpose of sensitivity analysis is to identify traffic factors that have effects on pavement performance and those that do not. Based on the damage-based sensitivity analysis, flexible and rigid pavement performances were found to be relatively insensitive to different distributions of HDF and MAF.

CHAPTER 9 provides guidelines for efficient and reliable data collection and sampling schemes when annual WIM data is not available. It proposes sampling schemes with different frequencies and different durations of sampled data. Also the relation between data sampling and seasonal variations in traffic was investigated and recommendations are provided.

CHAPTER 10 has a set of recommendations for locating new WIM sites to collect vehicle class counts and axle load data. It also provides recommendations for abandoning old WIM sites. The chapter covers the approach (reliability analysis combined with MEPDG damage-based analysis), the results, and the findings.

The following section includes explanations of tasks included in project proposal and where they are addressed in this document.

Task 1: Review research and US and state agency literature on MEPDG traffic analysis and implementation plans, and identify appropriate methods to consider for NCDOT and this research effort.

- There is no specific chapter to describe all the literature reviews for this research. Instead, each task (chapter) has its own literature review.

Task 2: Examine existing NCDOT traffic data resources to identify deficiencies.

- Fundamental to the conduct of this research is the availability of acceptable data. The data provided by NCDOT and discussed in Chapter 2 were very good; however, there were anomalies and exceptions that had to be screened before the research could begin. Thus, a significant, unanticipated task was the development of a Quality Control utility that could evaluate the NCDOT data (approximately 60 gigabytes) and facilitate identification of valid traffic data. The QC was done to capture a valid data set for each WIM. Edits were to one data set only which represented an exceptional case with unusual conditions
- In addition, Task 2 summarizes the data resources and collection technologies available to NCDOT. The complete technology assessment is included in 0 (Section 10.6).
- While the current resources for data collection are good, some are aging and will need to be replaced. Furthermore, there are "holes" in the data collection locations that must be filled. Thus, as part of this task the research team made recommendations for locating new WIM stations. This topic is covered in 0.

Task 3: Conduct MEPDG simulations of NC pavement designs to determine sensitive MEPDG traffic design parameters and pavement characteristics to guide the research.

- MEPDG Damaged Based Sensitivity Analysis – CHAPTER 8.

Task 4: Examine the effects of aggregating some or all the 10 FHWA vehicle classes 4-13, if possible, to simplify the MEPDG design process.

- Aggregation of VCD Clusters - CHAPTER 8 (Section 8.4)

Task 5: Analyze NC continuous vehicle classification and truck weight data and identify common patterns and seasonal groupings based on vehicle class and axle loadings.

- Vehicle Class Distributions – CHAPTER 3 (Section 3.3)
- Hourly Distribution Factors – CHAPTER 4 (Section 4.1)
- Monthly Adjustment Factors – CHAPTER 4 (Section 4.3)
- Axle Load Distribution – CHAPTER 6

Task 6: Validate the suitability of identified traffic data clusters or groupings and show that the groupings do not adversely affect the pavement design process.

- Aggregation of HDF Clusters – CHAPTER 4 (Section 4.1)
- Aggregation of MAF Clusters – CHAPTER 4 (Section 4.3)
- Aggregation of ALDF Clusters - CHAPTER 8 (Section 8.3)

Task 7: Generate Level 1, 2, and 3 NC traffic data inputs for the MEPDG and develop case study demonstrations to develop and use the traffic data.

- Monthly Adjustment Factors and Hourly Distribution Factors – CHAPTER 4
- Vehicle Class Distribution – CHAPTER 3
- General Traffic Input – CHAPTER 4
- Axle Load Distribution – CHAPTER 6

Task 8: Define a process to correlate and apply groupings to the highway system.

- Decision Tree of SU Seasonal Factor Groups – CHAPTER 3 (Section 3.5)
- Decision Tree of MU Seasonal Factor Groups – CHAPTER 3 (Section 3.7)
- Decision Tree of ALDF Clusters –CHAPTER 6 (Section 6.4)

Task 9: Develop a seasonal sampling plan for NC highway clusters and for vehicle classes and truck weights meeting AASHTO, FHWA and MEPDG standards.

- Seasonal Sampling Plan – CHAPTER 9

Task 10: Develop recommendations for truck traffic forecasting products to support the MEPDG.

- Traffic Forecasts for NCDOT M-E Pavement Designs – CHAPTER 5

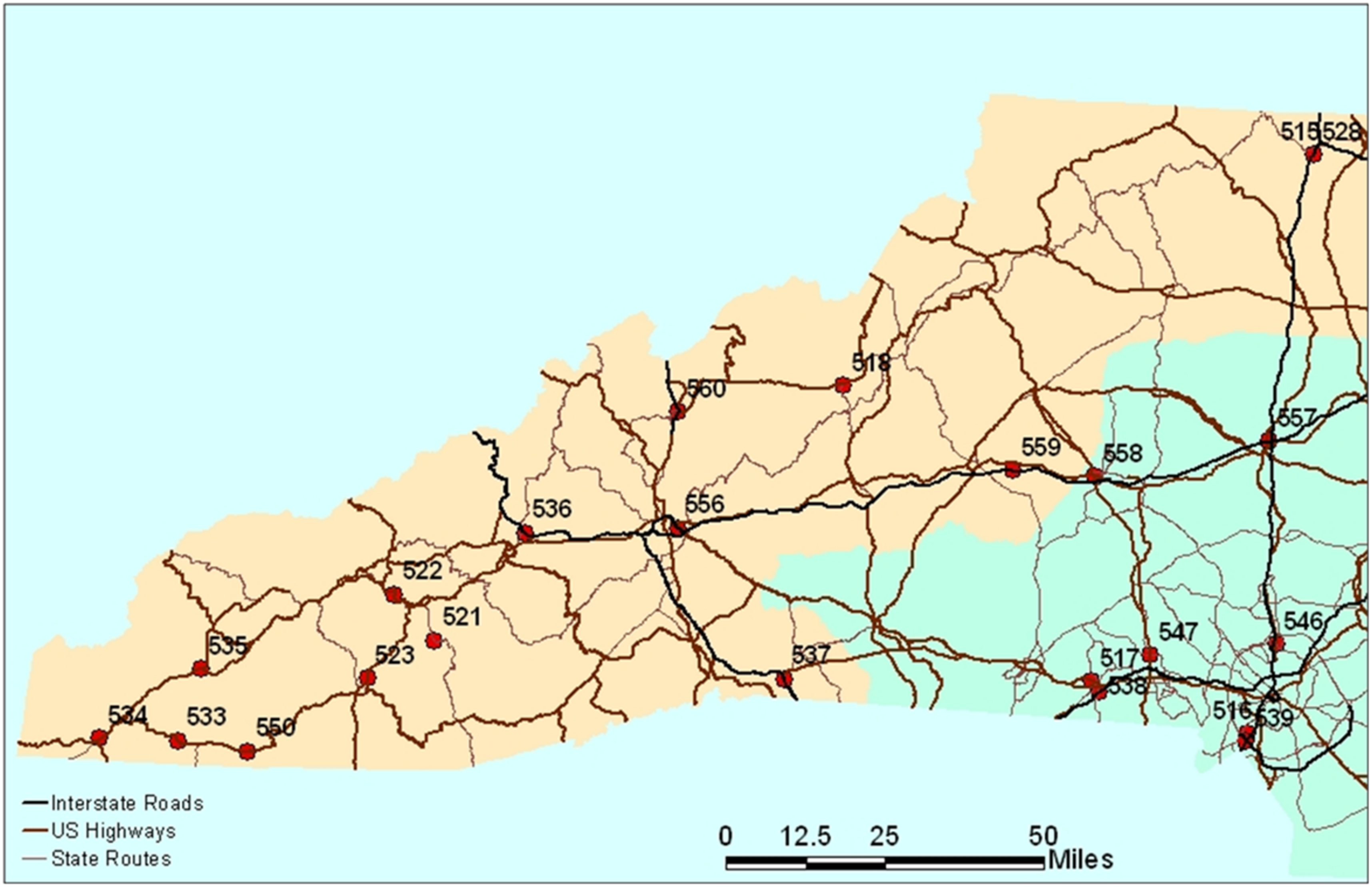


Figure 1-1 WIM Sites in the Mountainous Region of North Carolina

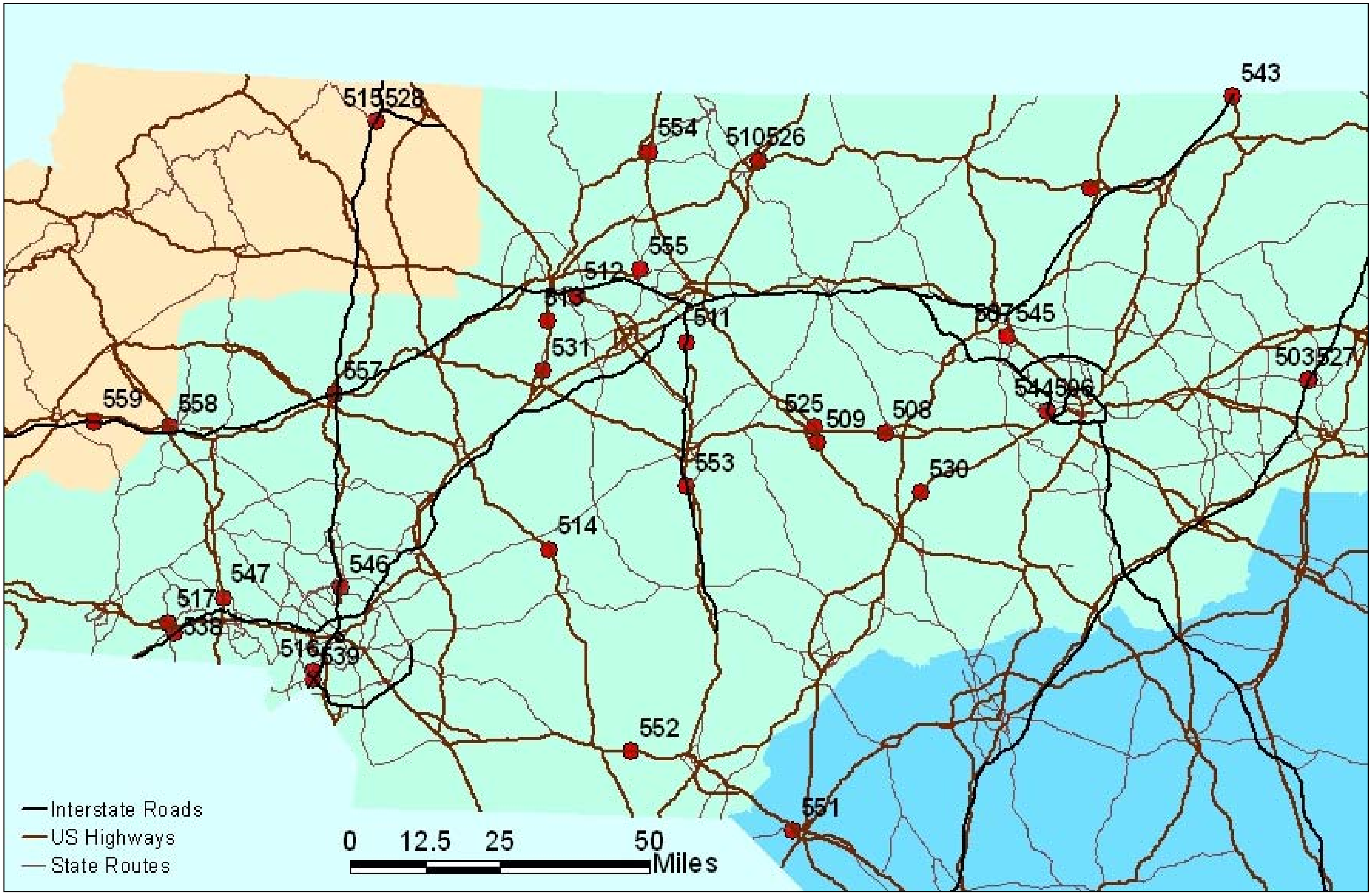


Figure 1-2 WIM Sites in the Piedmont Region of North Carolina

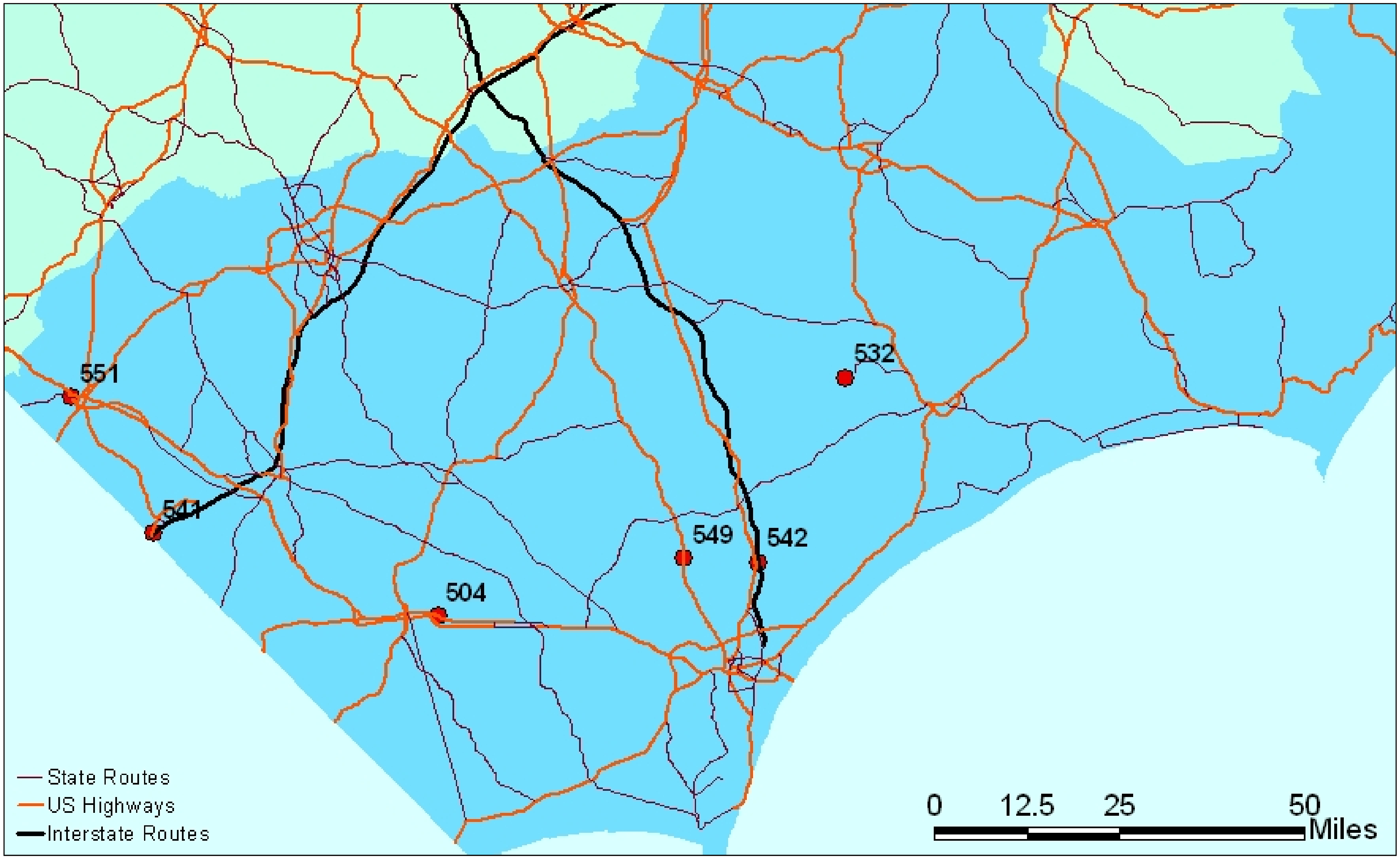


Figure 1-3 WIM Sites in the South Coastal Region of North Carolina

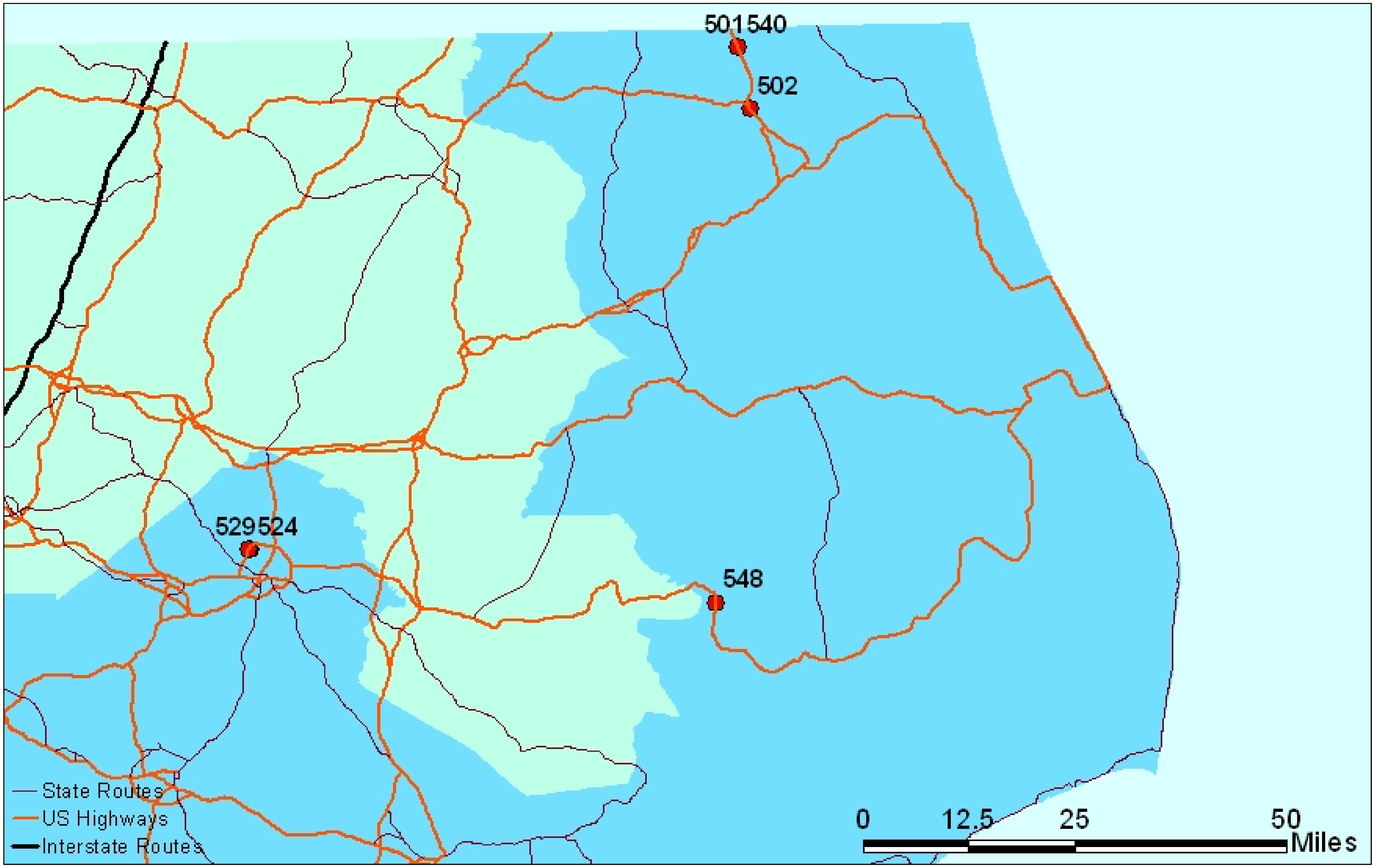


Figure 1-4 WIM Sites in the East Coastal Region of North Carolina

Table 1-1 Specification of WIM Sites in North Carolina

SHRP ID	Site ID	Route Name	Location	Lanes	Installation Date	County	Nearest City/Town
1 Site (Cabinet) at 1 Station							
371030	502	US 17	0.4 Miles South of US 158	2S, 2N.	18-Jun-04	Pasquotank	Elizabeth City
371645	504	US 74	1.9 Miles West of SR 1001	2W, 2E.	14-Apr-04	Columbus	Whiteville
371805	508	US 64	0.7 Miles West of US 15-501	2W, 2E.	24-Feb-03	Chatham	Pittsboro
372824	509	US 421	1.9 Miles South of US 64	2S, 2N.	3-Nov-03	Chatham	Siler City
372819	511	US 220	1.6 Miles North of NC 62	2S, 2N.	25-Feb-04	Guilford	Greensboro
371817	512	US 311	0.6 Miles East of SR 2698	2S.	29-Feb-04	Forsyth	Salem
375826	515	I-77	0.5 Miles North of SR 1345 (Mp 98)	2S, 2N.	3-Oct-03	Surry	Mount Airy
372825	516	SR 1138	0.7 Miles East of NC 49	2W, 2E.	6-Oct-03	Mecklenburg	Charlotte
375037	519	I-40	1.6 Miles West of SR 2838 (Mp 55)	2W.	16-Jun-03	Buncombe	Oteen
371801	520	I-40	1.3 Miles West of SR 2740	2W, 2E.	26-Jun-03	Buncombe	Swannanoa
371024	521	NC 107	0.3 Miles North of SR 1001	1N, 1S.	21-Jun-01	Jackson	Cullowhee
371803	522	US 74-441	0.2 Miles East of SR 1391	2W, 2E.	12-Oct-00	Jackson	Whittier
371814	523	US 23-441	0.2 Miles South of SR 1504	2S, 2N.	3-Jun-03	Macon	Franklin
371992	525	US 421	0.8 Miles North of US 64	2S, 2N.	30-Oct-03	Chatham	Siler City
377302	529	US 264	0.3 Miles West of NC 33	2W, 2E.	19-May-04	Pitt	Greenville
370900	530	US 1	0.1 Miles South of SR 1423	2S, 2N.	16-Nov-03	Lee	Sanford
370200	531	US 52	0.4 Miles North of US 64 (Mp 92)	2S, 2N.	11-Feb-04	Davidson	Lexington
370800	532	SR 1245	0.1 Miles North of SR 1209	1N, 1S.	31-May-00	Onslow	Jacksonville
372101	533	US 64	0.5 Miles East of SR 1304	1E, 1W.	7-Oct-99	Clay	Hayesville
371901	534	US 64	0.4 Miles East of US 19/129	2W, 2E.	21-Oct-99	Cherokee	Murphy
371902	535	US 74	0.3 Miles West of SR 1390	2W, 2E.	1-Nov-99	Cherokee	Andrews
374301	536	I-40	1.0 Miles West of US 19-23-74 Conn	2W, 2E.	18-Nov-99	Haywood	Clyde
377401	537	I-26	0.5 Miles East of US 74 (MP 67)	2W, 2E.	3-May-00	Polk	Columbus
372202	538	I-85	0.3 Miles East of NC 161 (MP 8)	2S, 2N.	29-Mar-00	Cleveland	Kings
375902	539	I-77	0.1 Miles South of I-485 (Mp 2)	3N, 3S.	1-Nov-00	Mecklenburg	Charlotte
377701	541	I-95	1.0 Miles South of NC 130 (Mp 1)	2S, 2N.	11-Jul-00	Robeson	McDonald
377001	542	I-40	0.3 Miles West of NC 210 (Mp 408)	2W, 2E.	14-May-04	Pender	Rocky Point
379201	543	I-85	0.2 Miles East of US 1 (Mp 233)	2S, 2N.	16-Aug-00	Warren	Wise
375903	546	NC 24	0.2 Miles East of US 21	2W, 2E.	21-Sep-03	Mecklenburg	Charlotte
373501	547	US 321	0.1 Miles South of NC 279	3S, 3N.	11-Sep-03	Gaston	Dallas
374701	548	US 264	0.1 Miles East of SR 1168	1W, 1E.	3-May-04	Hyde	Scranton
377002	549	US 421	0.2 Miles South of NC 210	2S, 2N.	20-Apr-04	Pender	Currie
378201	551	US 74	0.1 Miles East of NC 79	2W, 2E.	18-Apr-04	Scotland	Laurinburg
370301	552	US 74	0.1 Miles West of SR 1740	2W, 2E.	28-Mar-04	Anson	Lilesville
377501	553	US 220	0.1 Miles North of SR 1247	2S, 2N.	14-Feb-04	Randolph	Asheboro
377803	554	US 220	0.5 Miles South of SR 2150	2S, 2N.	17-Oct-03	Rockingham	Madison
374002	555	NC 68	0.5 Miles North of Bryan Blvd	2S, 2N.	4-Apr-04	Guilford	Greensboro
371003	556	I-240	0.5 Miles East of US 70 (Mp 8)	2E, 3W.	16-Jun-03	Buncombe	Asheville
374801	557	I-40	0.3 Miles West of US 21 (Mp 151)	2W, 2E.	24-Aug-03	Iredell	Statesville
371701	558	US 321	1.0 Miles North of I-40 (At US 70)	2S, 2N.	12-Aug-03	Catawba	Hickory
371101	559	I-40	0.3 Miles West of SR 1744 (Mp 109)	2W, 2E.	19-Aug-03	Burke	Valdese
375601	560	I-26	0.1 Miles West of US 19 (Mp 3)	2W, 2E.	27-Jul-03	Madison	Mars Hill

Table 1-1 Specification of WIM Sites in North Carolina (continued)

SHRP ID	Site ID	Route Name	Location	Lanes	Installation Date	County	Nearest City/Town
2 Sites (Cabinets) at 1 Station							
371028	501	US 17	0.7 Miles North of SR 1231	2N.	17-Jun-04	Camden	South Mills
371402	540			2S.	17-Jun-04	Camden	South Mills
373011	503	I-95	0.5 Miles South of SR 1745	2N.	24-Jun-04	Nash	Rocky Mount
376302	527			2S.	2-Jun-04	Nash	Rocky Mount
373102	545	NC 147	0.4 Miles North of SR 1940	2S.	23-Jun-04	Durham	Durham
373816	507			2N.	2-Aug-00	Durham	Durham
371006	506	I-40	0.8 Miles East of NC 54	2E.	15-Sep-00	Wake	Raleigh
379102	544			2W.	17-Oct-00	Wake	Raleigh
375827	510	US 29	1.8 Miles North of US 158	2S.	10-May-00	Rockingham	Reidsville
377802	526			2N.	4-Mar-97	Rockingham	Reidsville

CHAPTER 2. WEIGH-IN-MOTION DATA QUALITY CONTROL

This chapter discusses the development of a utility to clean and improve the quality of the NCDOT WIM data, if necessary. Overall the NCDOT WIM data is very good; however, there are a few anomalies and exceptions that had to be addressed. The utility is an MS Access/Excel based tool that examines each WIM station's data (44 stations representing about 60 gigabytes of data), identifies the problem data, and alerts the user. The user can then replace the data as needed. Quality control tests used guidelines for applying the utility, and sample results are provided in the chapter.

2.1 Background

At hundreds of WIM monitoring locations, State DOTs collect WIM data every year to meet Federal traffic reporting requirements [*LTPP, HPMS, and VTRIS*]. The large WIM datasets include date and time stamps for most vehicles crossing the WIM sensors, counts of each vehicle's axles, and measurements of the individual axle loads and spacing. The results provide statistics on the annual average daily traffic for each of the 13 FHWA vehicle classes (Figure 2-1), time histories of gross vehicle weights (GVW) by class, frequency distributions of the traffic by vehicle class, axle load spectra, and other important characteristics of the traffic flow at each WIM site.

The NCDOT uses WIM systems and procedures that are consistent with recommended industry practices as specified by the FHWA Long Term Pavement Performance Program [*LTPP, 2005*], the Traffic Monitoring Guide [*TMG, 2001*], and the American Association of State Highway and Transportation Officials [*AASHTO, 2009*]. The NCDOT collects class data for all types of vehicles, but weight measurements on truck vehicle classes only (Classes 4 – 13). The NCDOT WIM systems are designed to estimate static axle weights based on dynamic measurements. Site selection, pavement condition, system calibration, and system monitoring are as important as the sensor technology used to ensure collection of good quality weight measurements. Additionally, the measurements are affected by driver behavior such as weaving, accelerating and decelerating. Thus, data errors and poor quality data are captured regardless of the technology used, and a Quality Control (QC) process is an important part of all WIM data systems. Good quality WIM data can only be captured if a comprehensive quality control process is used, and the QC techniques developed in this research are a key component of that process.

The NCDOT requires that all data with quality issues (such as partial data, misclassified vehicles, and unacceptable axle weights and spacing) be excluded from datasets used for planning and design statistics. Thus, WIM data must undergo a series of sequential, well organized QC procedures to ensure that the data meets MEPDG requirements. This chapter documents the NCDOT WIMQC procedures. The results of the QC analysis provide reliable datasets for use in developing Levels 1, 2, and 3 traffic data inputs for the North Carolina MEPDG models [*MEPDG, 2002*].

2.2 Scope and Objectives

The scope of this chapter is limited to the development and application of QC methods for truck class and weight data from NCDOT WIM sites collected from 1997 to 2007. Twelve consecutive months of data were processed for each station and in most cases the date ranges span two calendar years. The date ranges were chosen based on the history of the equipment and sensors used at each station. Data collected immediately after installation, calibration, and validation of new sensors were selected to ensure use of the best quality data to support MEPDG development. However, in a few cases, due to operational or data quality issues, an entire month of vehicle class and weight data were replaced with data from another year. Although this created a discontinuity in those datasets, the requirements of the MEPDG design process are met. The quality control analysis was a joint effort where NCSU analyzed 32 of the WIM datasets and NCDOT analyzed 13 datasets.

The objective of this chapter is to explain the procedure used to perform the QC measures developed for NCDOT WIM data. A WIM data system must include a quality control process to exclude anomalous measurements inherent to them, to validate data used in the MEPDG process, and to provide a measure of the quality of the data collected. Many states are struggling with developing the data inputs for the MEPDG pavement design process, and the information provided herein will aid them in generating the traffic data component of those inputs. The database used for performing QC is called the NCDOT WIM QC Database and applies SQL queries in linked Access database tables and review of summary queries plotted in Excel workbooks.

2.3 Literature Review

There are a number of QC procedures that can be implemented for WIM data. The most recognized procedure is the LTPP procedure which guides many of the tests in the NCDOT WIM QC Database. Additionally, the TMG and AASHTO guides [*TMG 2001, AASHTO 2009*] are industry standards and emphasize the need for quality control measures in traffic monitoring programs. There are also state and project specific traffic data QC requirements, e.g., for traffic forecasting in Texas [*Qu et al., 1997; Lee et al., 1998*] and for truck axle spectra in Oregon [*Elkins et al., 2008*]. There is also a recent database application to support the MEPDG effort of the Arkansas State Highway and Transportation Department [*Wang, 2009*].

2.4 Methodology

After reviewing the literature and considering prototype procedures at NCDOT, the NCSU research team concluded that the most efficient method of performing the WIM QC included SQL queries in a front-end database system applied to raw data stored in live back-end databases. The resulting procedure for NCDOT is presented below. The QC technique uses a combination of rule based checks and manual audits of plots and reports. The rule based checks flag anomalous data that are improperly coded or have values that are out of range. The manual audits identify deviations in patterns that indicate equipment malfunction or invalid data sets.

Figure 2-2 shows a flowchart of the NCDOT WIMQC process. One year of class and weight data for each NCDOT WIM site was converted to fixed width ASCII text files in FHWA C (class) and W (weight) card formats. The data captured may be from twelve months within a year or 12 consecutive months over two years. The equipment vendor conversion utility generates an individual text file for each day of data for each data type. To ease the process of capturing the data into the QC applications, WIM data are aggregated into a single text file for each data type and then imported into the back end WIM Database developed by Neil Mastin (Figure 2-2). The WIM Database was developed for an earlier evaluation of the MEPDG design process and it is made more comprehensive by the NCDOT QC Database. The WIM Database is used as a capture utility, and during the import process it performs basic QC checks including exclusion of unclassified vehicles (Class 15 data) and invalid data types (e.g. text data in a number field) [*Mastin, 2009*]. The WIM Database is the back end for the more detailed QC analysis.

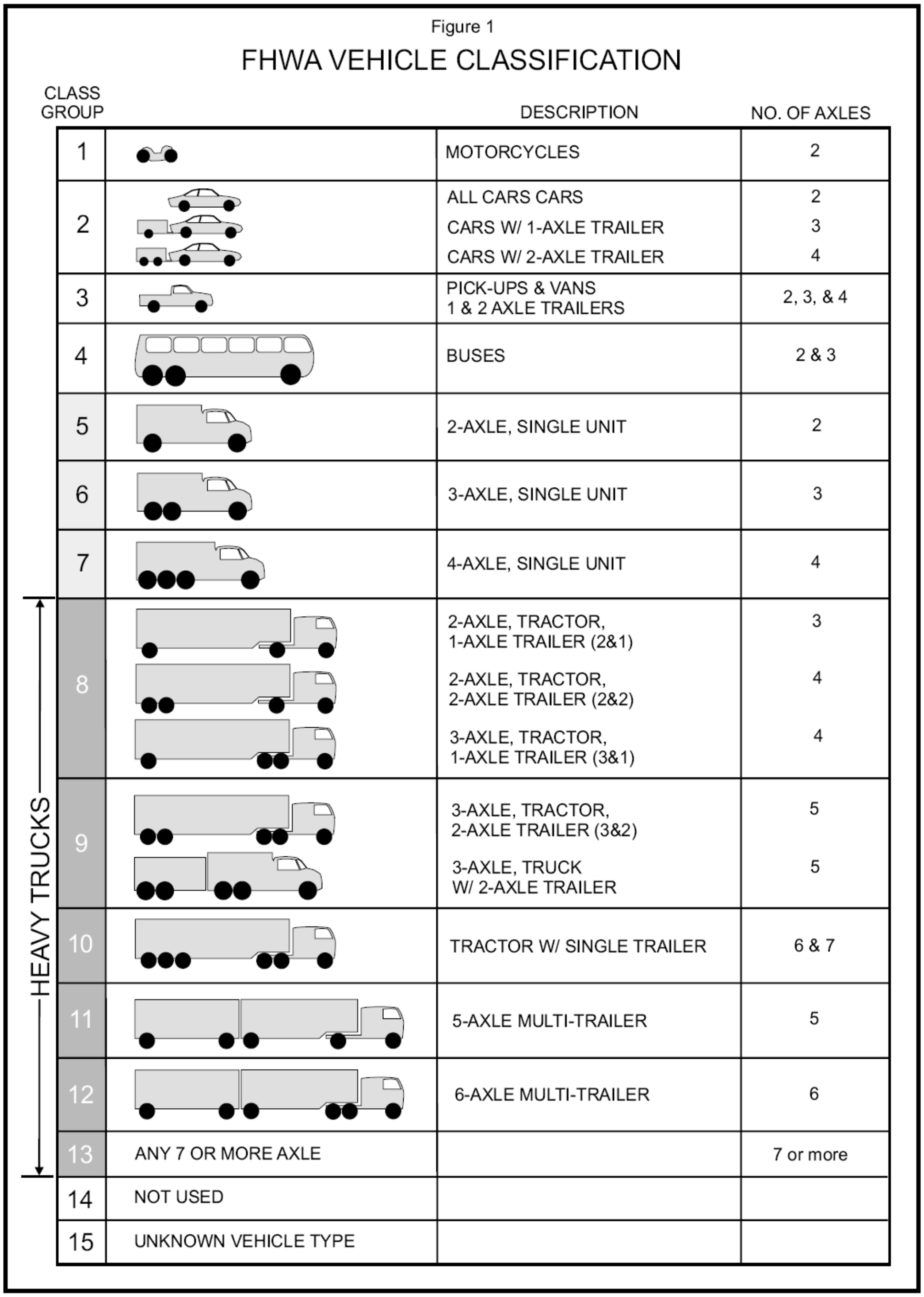


Figure 1

FHWA VEHICLE CLASSIFICATION

CLASS GROUP		DESCRIPTION	NO. OF AXLES
1		MOTORCYCLES	2
2		ALL CARS CARS CARS W/ 1-AXLE TRAILER CARS W/ 2-AXLE TRAILER	2 3 4
3		PICK-UPS & VANS 1 & 2 AXLE TRAILERS	2, 3, & 4
4		BUSES	2 & 3
5		2-AXLE, SINGLE UNIT	2
6		3-AXLE, SINGLE UNIT	3
7		4-AXLE, SINGLE UNIT	4
8		2-AXLE, TRACTOR, 1-AXLE TRAILER (2&1) 2-AXLE, TRACTOR, 2-AXLE TRAILER (2&2) 3-AXLE, TRACTOR, 1-AXLE TRAILER (3&1)	3 4 4
9		3-AXLE, TRACTOR, 2-AXLE TRAILER (3&2) 3-AXLE, TRUCK W/ 2-AXLE TRAILER	5 5
10		TRACTOR W/ SINGLE TRAILER	6 & 7
11		5-AXLE MULTI-TRAILER	5
12		6-AXLE MULTI-TRAILER	6
13	ANY 7 OR MORE AXLE		7 or more
14	NOT USED		
15	UNKNOWN VEHICLE TYPE		

HEAVY TRUCKS (classes 8–13)

Figure 2-1 FHWA Vehicle Classification [*Sarasota-Manatee MPO, 2009*]

2.5 Overview of the NCDOT QC Process

The following steps or guidelines should be followed to perform quality control checks for C and W card data.

1. Arrange and copy or aggregate data. The QC procedure has to be performed site-wise. Initially the data provided by NCDOT is arranged month-wise in separate folders. Data is copied for 12 months into one single folder. Using the MS-DOS copy command, data is aggregated into one single text file to simplify the import process.
2. Import aggregated data into the WIM Processor utility (WIM Database.mdb) and converted 2003 format (WIM Database_03.mde)
3. Always carry out QC checks including data exclusion or any modifications in a copy of the original WIM processor database with imported data.
4. It is recommended to perform all QC checks except for the Class Type Code check in Access 2003. The basic idea is use the queries in the WIM QC database (NCDOT_WIM_QC.mdb) and apply them to the data captured in the WIM Processor database by using the Linked Table Manager utility in Access.
5. Always keep track of the number of records excluded or flagged while executing QC checks. An Excel spreadsheet is available for this purpose.
6. There is no data deletion during the QC procedure. Flagged data are just removed to exclusion tables (by type) and not captured in the data sets used for MEPDG inputs As stated below, the data is captured into an Access table (one for class and one for weight) of excluded records and is not captured into the final tables used for the MEPDG input data development.

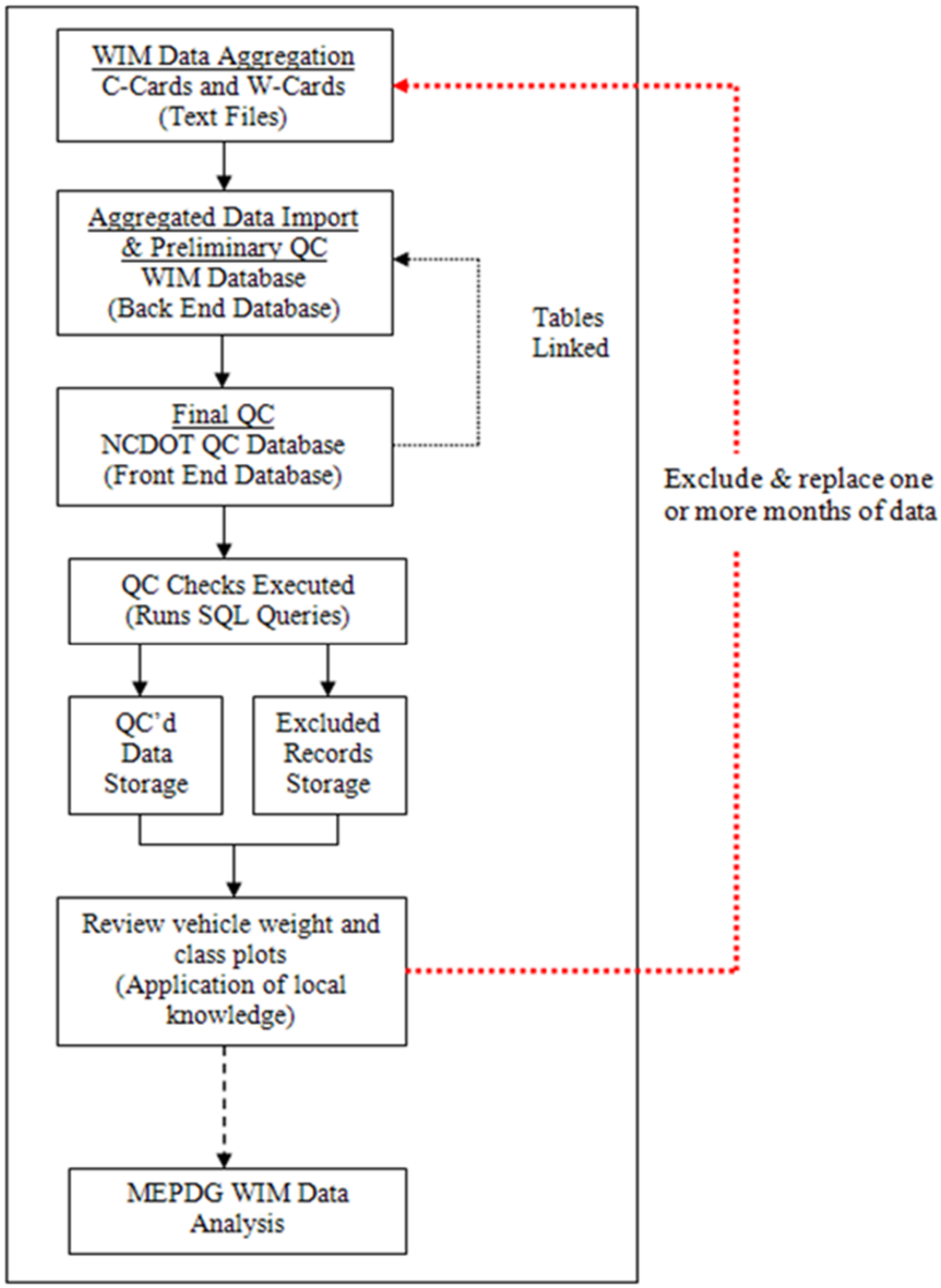


Figure 2-2 NCDOT WIM QC Flow Diagram.

The NCDOT WIM QC Database uses Microsoft Access to apply rule based checks, generate statistics, and prepare data for capture into Excel for generating summary plots. It is the front end for the QC process, is linked to the tables in the WIM Database, and extends its procedures. The output of the NCDOT WIM QC Database application are tables of accepted data for use in M-E pavement design and a table of excluded data for each data type. Some records may have QC issues that could cause multiple flags. However, once a record is flagged and excluded for failing a check, it is excluded from subsequent checks. The flag that causes a record to be excluded is documented in the exclusion tables.

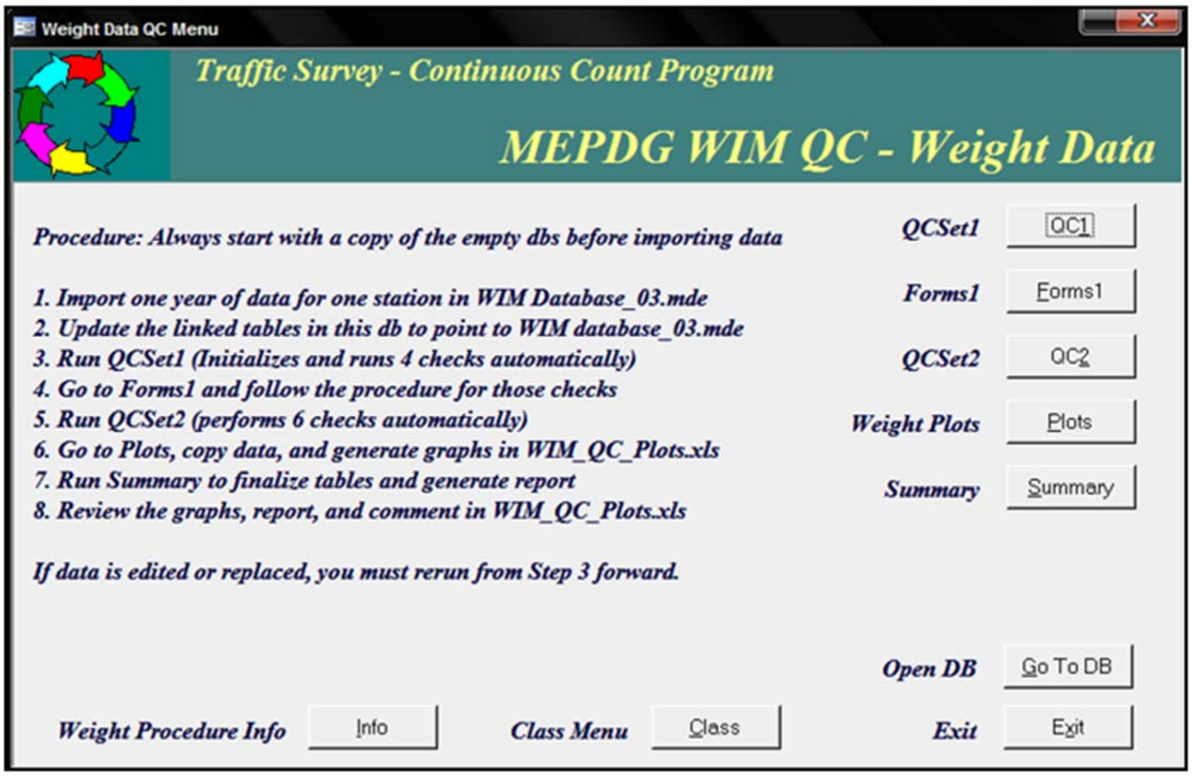


Figure 2-3 NCDOT WIM QC Checks Interface for Truck Weight Data

2.6 The NCDOT QC Process

The NCDOT WIM QC process consists of a combination of automated and manually applied procedures in a user friendly graphical user interface (GUI) as shown in Figure 2-3. The "QC Sets" are a collection of auto-applied rules (Table 2-1 and Table 2-2) that identify invalid entries for the fields checked and that automatically exclude flagged records into the exclusion tables. The QC process also consists of "Forms" (Table 2-1 and Table 2-2) which are a set of flags that alert the analyst to review the data displayed in the forms and manually exclude invalid data. In addition to the automated processes of the QC Sets and Forms, the QC process also utilizes plots and statistics to qualitatively assess the suitability of the data for the MEPDG process. Unusual patterns in the plots indicate that inconsistent data has been captured and that it may not be suitable. The process is applied sequentially where all steps for a data type are performed in order and weight QC is completed prior to evaluating class data. Weight QC is performed first as weight measurements are more complex, have many more sources of error, and are more likely to cause data to be excluded or replaced than class data.

A summary of all flagged records is generated and reported. The last feature of the QC function is generation of a table of records not flagged during the QC process. This will be the accepted dataset if the plots and report do not identify anomalous data. If inconsistent or invalid data are identified in the plots or report, the analyst returns to the start of the process, removes the text files in W/C card format for the month found to be anomalous, and replaces it with W/C card data for the same month from a different year. The entire QC process is rerun to ensure that the final datasets meet the requirements of the MEPDG process. Table 2-1 and Table 2-2 show the QC checks applied by the NCDOT WIM QC Database. During the review process, local knowledge of the site and traffic conditions is considered and any additional anomalous records are manually flagged.

Table 2-1 NCDOT QC Rule List for W-Cards [*LTPP QC Vol 1, 2001*]

Order	ID	Description	Criteria	Tool
1	W_NULL	Any field with a null value	Field Value ≠ Null	QCSet1
2	W12	Invalid hour	HOUR ≠ (0 - 23)	QCSet1
3	W10	Invalid month	MONTH ≠ (1 – 12)	QCSet1
4	W16	Invalid vehicle class code	VHCL_CLASS ≠ (4 - 13)	QCSet1
5	W14	Invalid FIPS Code	STATE_CD ≠ 37	Forms1
6	W6	Invalid station ID	STATION_ID ≠ Expected station identifier	Forms1
7	W8	Invalid direction for station	DRCTN_CD ≠ Valid values for station	Forms1
8	W7	Invalid lane number for station	TRVL_LN_NBR ≠ Valid values for station	Forms1
9	W9	Invalid year	YEAR ≠ Valid year for date range captured	Forms1
10	W11	Invalid day	DAY ≠ Valid date for the MONTH	Forms1
11	W13	Hour without any weight records. A full day of data may not be available for all lanes	Manual audit of hours without weight records	Forms1
12	W1	Axle count inconsistent with number of axle spacings	AXLE_COUNT ≠ (# of spacings +1)	QCSet2
13	W2	Axle count inconsistent with number of axle weights	AXLE_COUNT ≠ # of axle weights	QCSet2
14	W3	GVW is inconsistent with sum of axle weights	TOTAL_WGHT ≠ Sum of axle weights	QCSet2
15	W4	Axle weight is out of acceptable range	441 lb (200 kg) < (X)_WGHT < 44,100 lb (20,003.4 kg)	QCSet2
16	W5	Axle spacing is out of acceptable range	1.97 ft (0.6 m) < (X)_(Y)_SPACING < 49.2 ft (15 m)	QCSet2
17	W17	Sum of axle spacings exceeds maximum wheelbase	Sum of axle spacings > 98.2 ft (29.93 m)	QCSet2
18	WP1	Review Average DOW volumes by month for unusual patterns	A pattern deviates significantly from other months	Plots
19	WP2	Review GVW plots by class by month for unusual patterns	A pattern deviates significantly from other months	Plots

Table 2-2 NCDOT QC Rule List for Class Data [*LTPP QC Vol 1, 2001*]

Order	ID	Description	Criteria	Tool
1	C_NULL	Any field with a null value	Field Value = Null	QCSet3
2	C8	Invalid month	MONTH ≠ (1 – 12)	QCSet3
3	C10	Invalid hour	HOUR ≠ (0 – 23)	QCSet3
4	C1	Total lane volume exceeds max. limit	TOTAL_VOL > 3000	QCSet4
5	C11	Invalid FIPS Code	STATE_CD ≠ 37	Forms2
6	C4	Invalid station ID	STATION_ID ≠ Expected station identifier	Forms2
7	C6	Invalid direction for station	DRCTN_CD ≠ Valid values for station	Forms2
8	C5	Invalid lane number for station	TRVL_LN_NBR ≠ Valid values for station	Forms2
9	C7	Invalid year	YEAR ≠ Valid year for date range captured	Forms2
10	C9	Invalid day	DAY ≠ Valid date for the MONTH	Forms2
11	C3	A full day of data is not available for a day for all lanes	Manual audit of hours and days	Forms2
12	C2	Class volume exceeds maximum limit	CLS_CNT_## = TOTAL_VOL	Forms3
13	C13	1AM total lane volume exceeds 1PM total lane volume	HOUR(1) TOTAL_VOL > HOUR(13) TOTAL_VOL	Forms3
14	C14	Static total lane volume for four consecutive hours	HOUR(X) TOTAL_VOL = HOUR(X+1,+2,+3) TOTAL_VOL	Forms3
15	CP1	Review Avg. DOW volumes by month for unusual patterns	A pattern deviates significantly from other months	Plots
16	CP2	Review Class Distribution by month for unusual patterns	A pattern deviates significantly from other months	Plots
17	CP3	Review Class % Distributions for unusual patterns	The summary data exhibits an unusual pattern	Plots

2.7 Examples of QC Anomalies

Figure 2-4 and Figure 2-5 represent examples of replacing data to rectify an invalid data set identified by the QC. WIM site 510 (is located on US 29 in Rockingham County in the central Piedmont region (Figure 2-6). In this case, the class 9 GVW plot (Figure 2-4) shows invalid weight measurements where 10 months of data have shifted peaks to the left from what is normal (about 35,000 pounds empty and 75,000 pounds loaded). When the invalid data are replaced with data for a properly calibrated site, the peaks line up and the data is accepted (Figure 2-5).

As another example, consider WIM site 371902 located on US 74 in Cherokee County (western NC). In this example (Figure 2-7), NCDOT discovered that FHWA class 8 truck volumes drop to zero for a couple of months (September is used for this example) at this site. This anomaly was caused by an error in the class algorithm used at that time. NCDOT replaced this month with data from another year collected with a valid class algorithm and the class 8 volumes return to normal levels (Figure

2-8). The calibration example (Figure 2-4 and Figure 2-5) and class algorithm example (Figure 2-7and Figure 2-8) illustrate how data replacement resolves the QC problem.

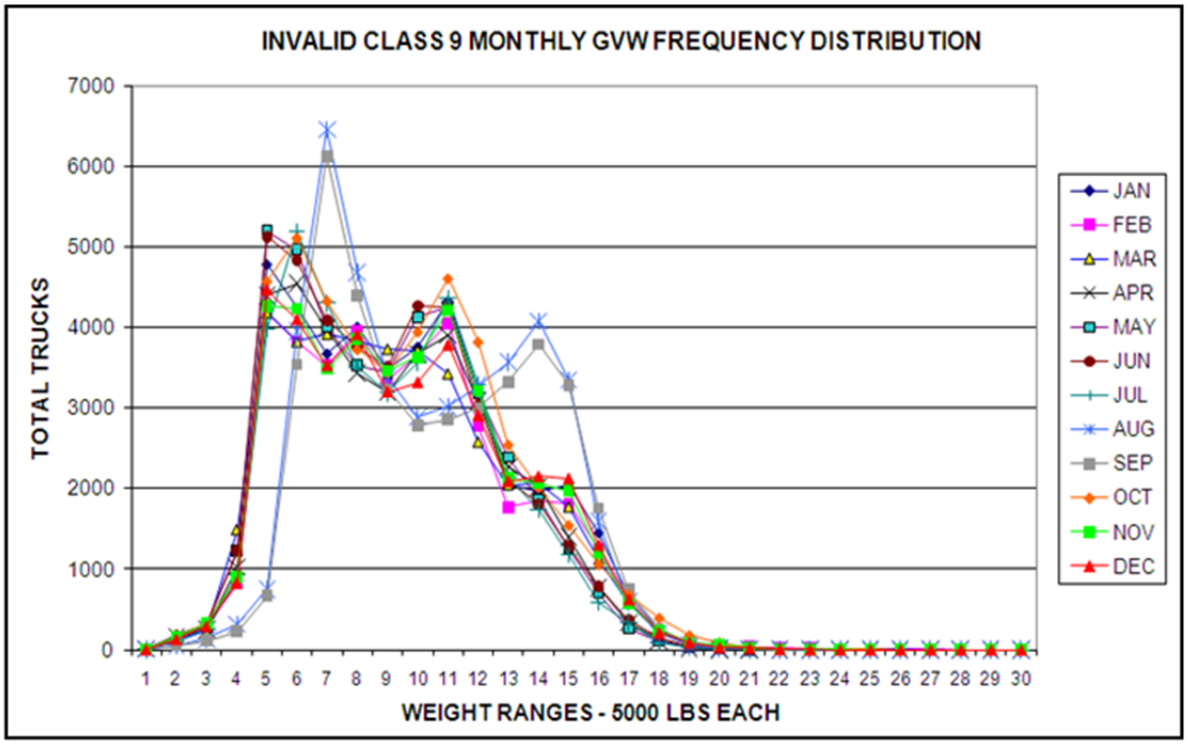


Figure 2-4 Invalid Class 9 GVW Plot for WIM Site 510

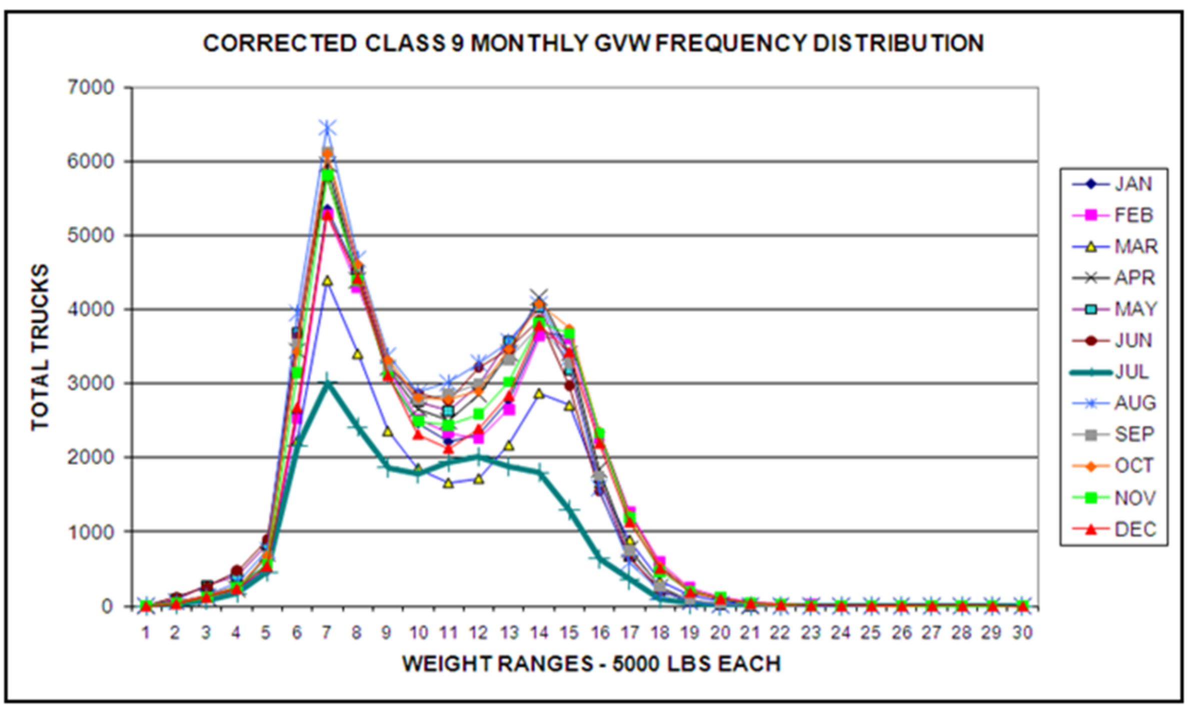


Figure 2-5 Corrected Class 9 GVW Plot for WIM Site 510

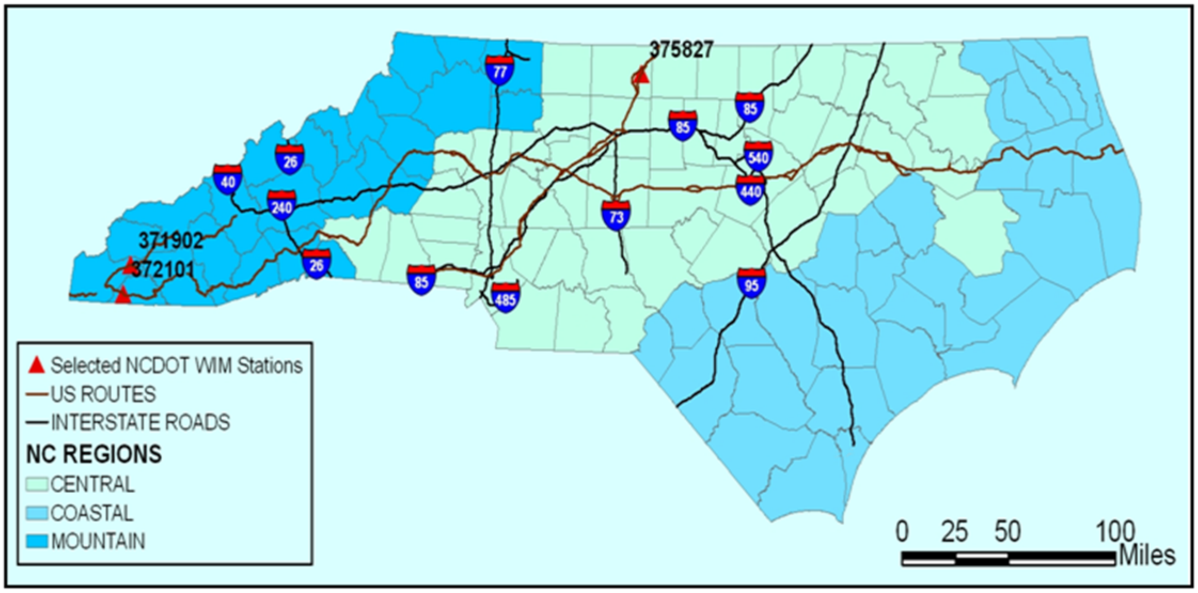


Figure 2-6 Selected NCDOT WIM Sites

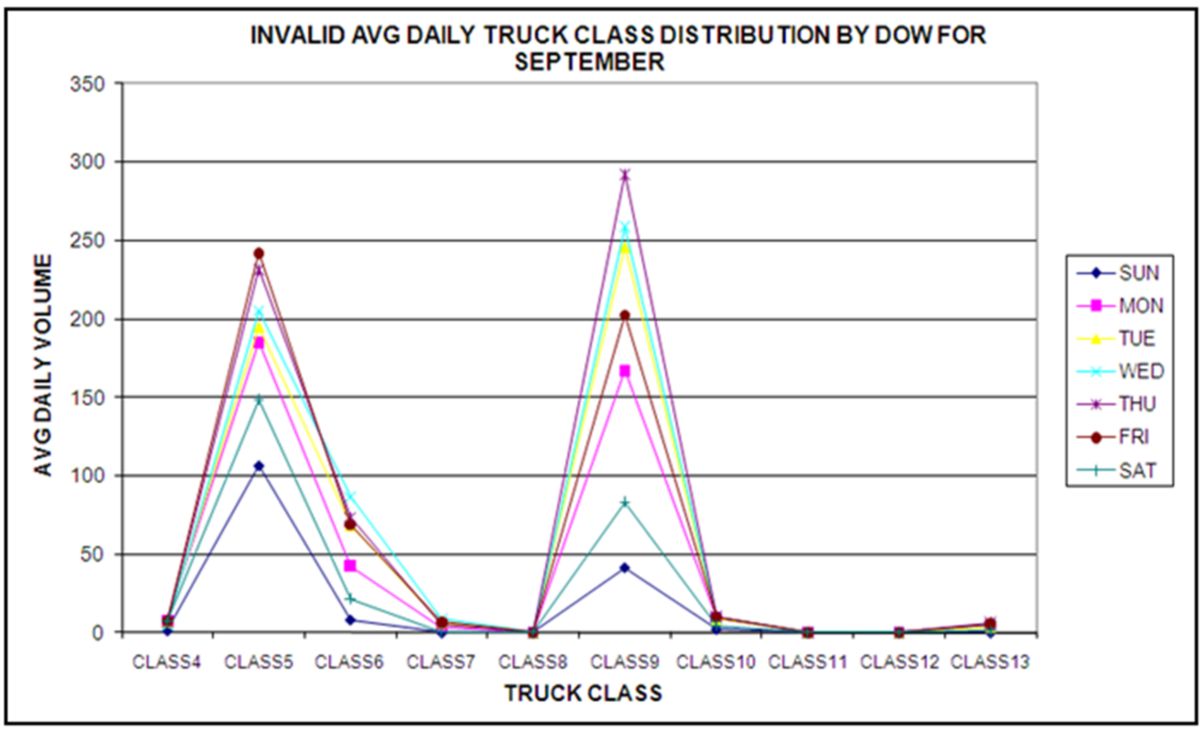


Figure 2-7 Invalid Average Daily Class Distribution by DOW for WIM Site 371902

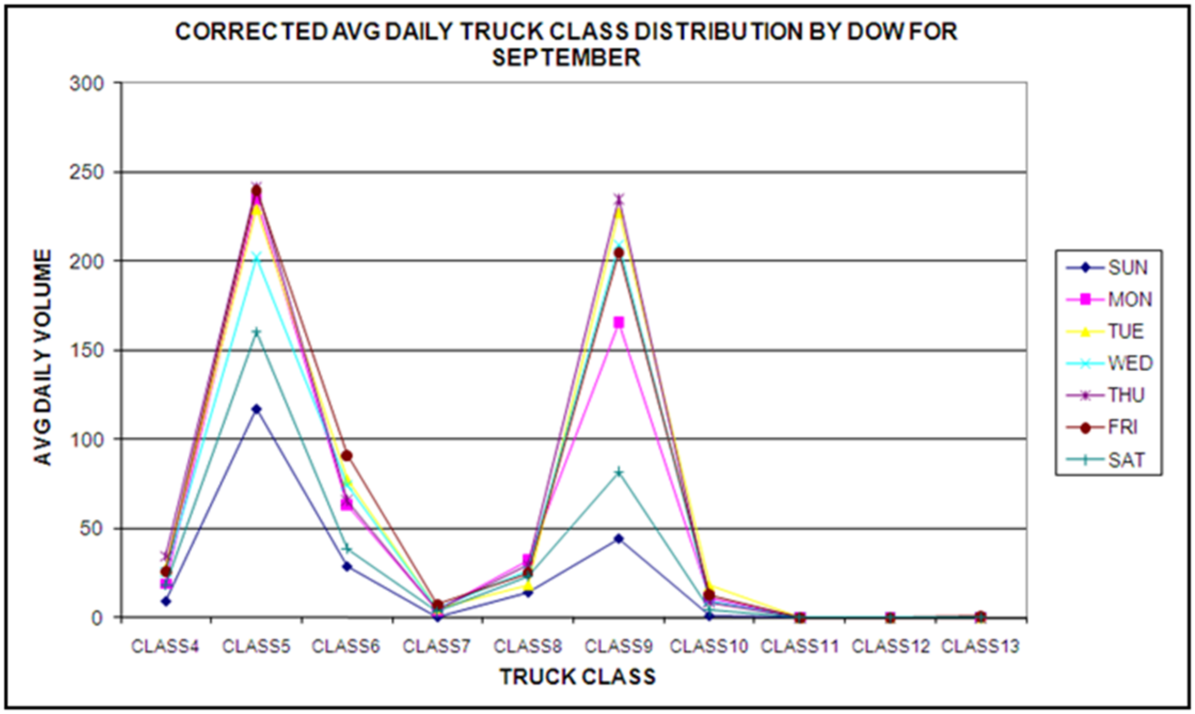


Figure 2-8 Corrected Average Daily Class Distribution by DOW for WIM Site510

2.8 Application of Local Knowledge

In addition to the automated and manual checks, the analyst must review weight plots generated for WP1 and WP2 in Table 2-1 and class plots generated for CP1, CP2, and CP3 in Table 2-2.

GVW plots sorted by Class 4 through 13 provide a graphical representation of how trucks are loaded. Typical plots with appropriate values have peaks at weight ranges that correspond to empty and fully loaded conditions for that truck class (Figure 2-5). Inconsistencies with expected peaks for a class, shown in Table 2-3, or deviations in peaks between months, are the basis for the GVW evaluation. By comparing the peaks in the GVW plots with the values in Table 2-3, unusual and potentially invalid values for weight measurements can be found and replaced if determined to be invalid.

Unusual values may be an indication of poor weight measurements (Figure 2-4) or patterns related to local conditions. Figure 2-9 shows a GVW plot for FHWA class 9 trucks at WIM site 372101 located on US 64 in Clay County. This is a good example of using local knowledge to accept unusual values. Although a class 9 GVW plot usually has two peaks corresponding to empty and loaded conditions, this plot is valid because WIM site 372101 is located in the mountainous western region of North Carolina (Figure 2-6). Local knowledge of truck traffic patterns confirms a significant reduction in loaded truck volumes because of the mountainous terrain and winding roads. The consistent pattern of the weight ranges for the unloaded peak validates the unusual measurements.

If the GVW pattern is inconsistent with the peaks for loaded and unloaded weights, and if the pattern cannot be justified by local knowledge, then the truck weight data for that time period should be excluded and replaced by data from another year.

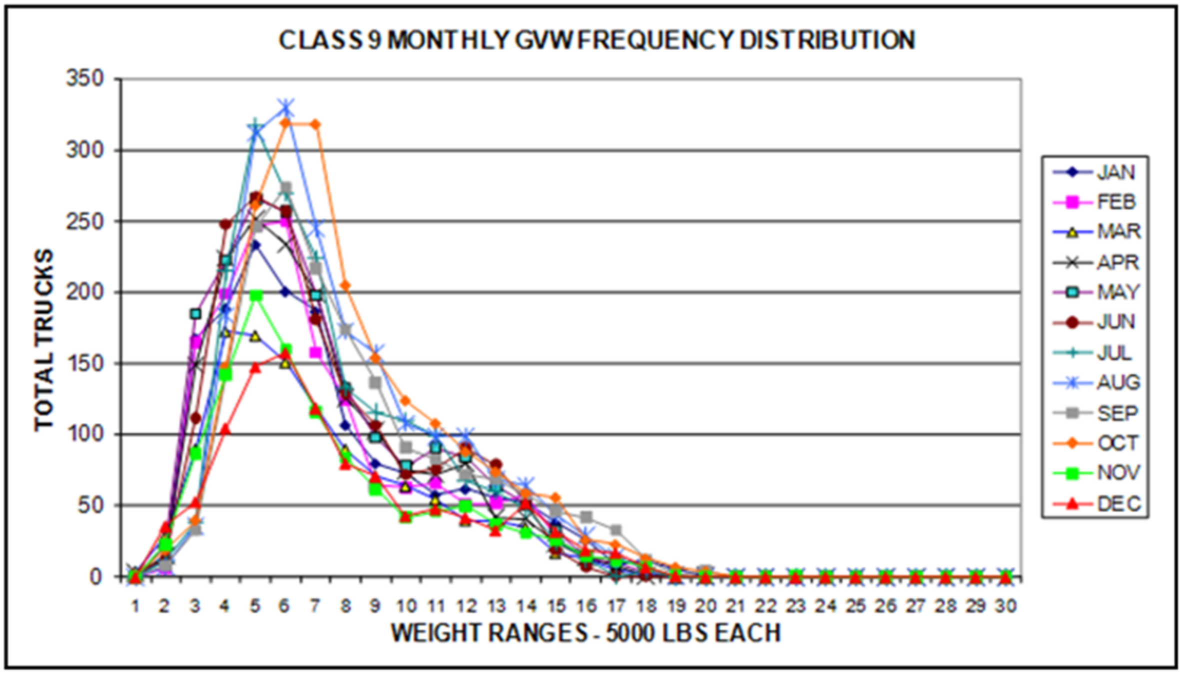


Figure 2-9 Class 9 GVW Plot by Month at WIM Site 372101

Table 2-3 GVWWeightRanges for Peaks

FHWA Vehicle Class	Typical Weight Ranges for Peaks (lbs)	Typical Weight Ranges for Peaks (kg)
4	One peak at 20,000	One peak at 9,072
5	One peak at 10,000	One peak at 4,536
6	One peak at 20,000 to 25,000 Other at 45,000 to 55,000	One peak at 9,072 to 11,340 Other at 20,411 to 24,948
7	One peak at 50,000 to 60,000	One peak at 22,680 to 27,216
8	One peak at 30,000 to 35,000	One peak at 13,608 to 15,876
9	One peak at 30,000 to 35,000 Other at 70,000 to 80,000	One peak at 13,608 to 15,876 Other at 31,751 to 36,287
10	One peak at 40,000 to 45,000 Other at 75,000 to 85,000	One peak at 18,144 to 20,412 Other at 34,019 to 38,555
11	One peak at 55,000 to 60,000	One peak at 24,948 to 27,216
12	One peak at 55,000 to 65,000	One peak at 24,948 to 29,484
13	Straight Line (Constant weight range with very low frequency of trucks)	Straight Line (Constant weight range with very low frequency of trucks)

2.9 An Important Consideration

The general QC procedure does not involve editing data but for the purpose of this research, we felt that it would be prudent to evaluate one of the sites. The site is 371024 on NC 107 in Jackson County (WIM 521). This site is located in an area with extensive recreational travel. The issue we saw was extreme seasonal variation in class 8 trucks. We know that there are a lot of recreational vehicles and boats that are towed by class 2 and 3 vehicles at this site. We also know that these are frequently misclassified as class 8 vehicles (an observed phenomena and well documented in the literature). This is a nominal issue for most sites but has an adverse impact for this site. The issue is evidenced by the high variability in class 8 volumes by month, the high class 8 volumes on weekends, and the low class 8 GVWs. We resolved the last issue by increasing the minimum GVW for class 8 and rescreening the data. This resulted in a significant reduction in class 8 weight records. However, the class 8 frequency captured in the class data is not addressed using this technique. To resolve the class data issue, we resorted to editing the class count data. This was done by adjusting each hourly class count for class 8 proportional to the number of weight records remaining after employing the higher class 8 GVW minimum. Specifically:

Adjusted Class 8 Hourly Volume = Counted Class 8 Hourly Volume x (Hourly count of Class 8 weight records after increased GVW minimum/Hourly count of Class 8 Records before increased GVW minimum)

This reduces the counted volume proportional to the reduction in class 8 trucks weighed for each hour. This supports generation of all statistics required including HDF using the adjusted values. Some consideration was given as to whether we should try to reclassify these records. We felt that the majority of these would fall in the class 2 and 3 categories, not needed for the MEPDG analysis. Once this edit was completed, both the class and weight data for class 8s exhibited travel patterns similar to class 9 vehicles at this location.

The NCDOT does not advocate editing data. These edits were made within the context of this research to expand our knowledge of truck travel. We are using the information generated in this research to develop a better class algorithm to minimize anomalous data measurements. As we use the same algorithm at all sites, this will not only minimize the problem at sites like this, but improve data quality at all sites.
The three plots that follow depict the problem at Site 371024 (Figure 2-10 – Figure 2-12).

High Class 8 Volume – The class 8 volumes are significantly higher in the summer months than winter months. This is a recreational pattern. They are much higher than class 9 vehicles also (not typical).

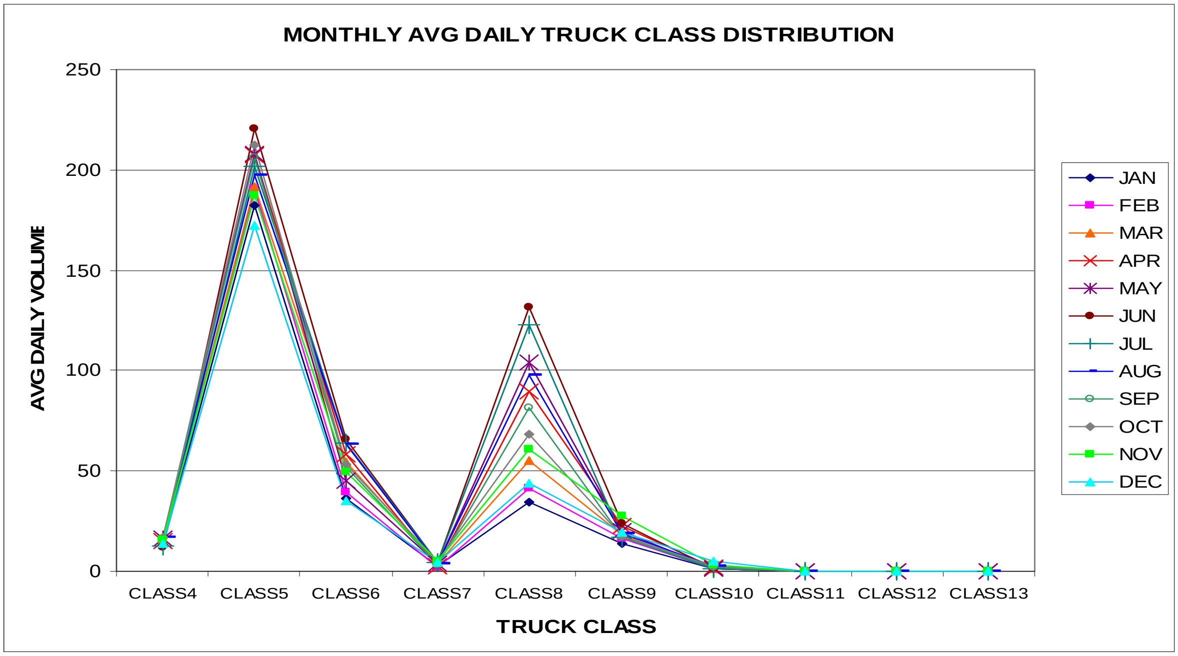


Figure 2-10 Monthly Average Daily Truck Class Distribution at site 371024

High Class 8 Volume – Not only are the class 8 volumes high in June, but they are highest on the weekend as seen in this graph. This is a recreational pattern.

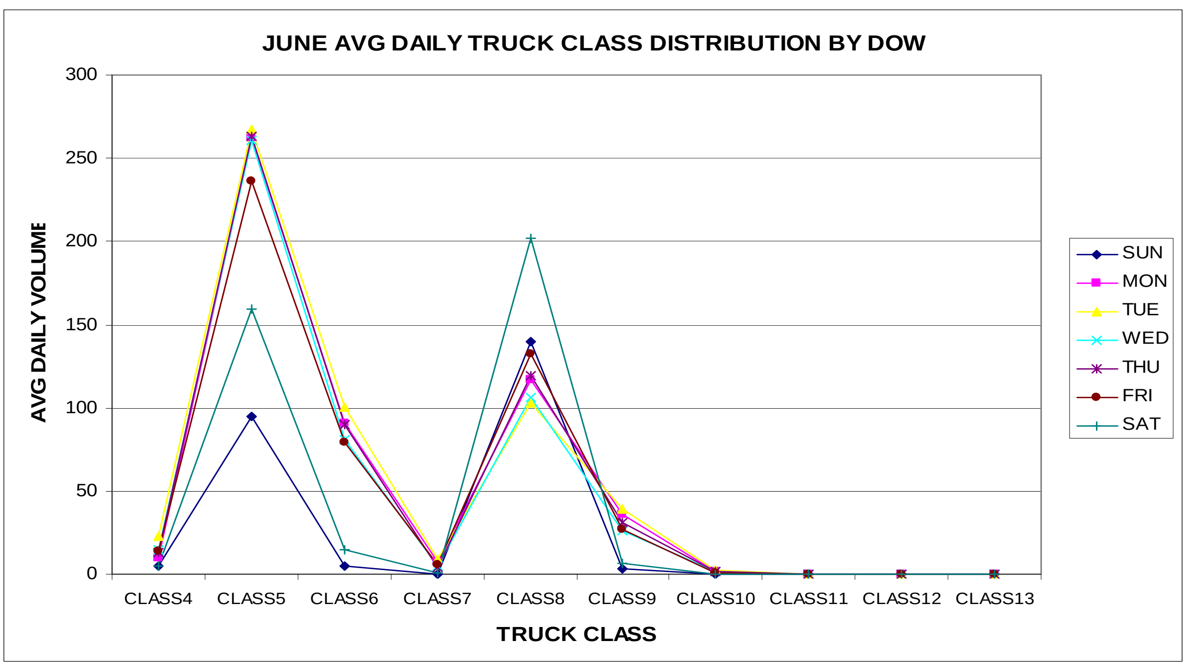


Figure 2-11 June Average Daily Truck Class Distribution at site 371024

Low Class 8 GVWs – The class 8 GVWs peak at a much lower weight than other WIM sites as shown below.

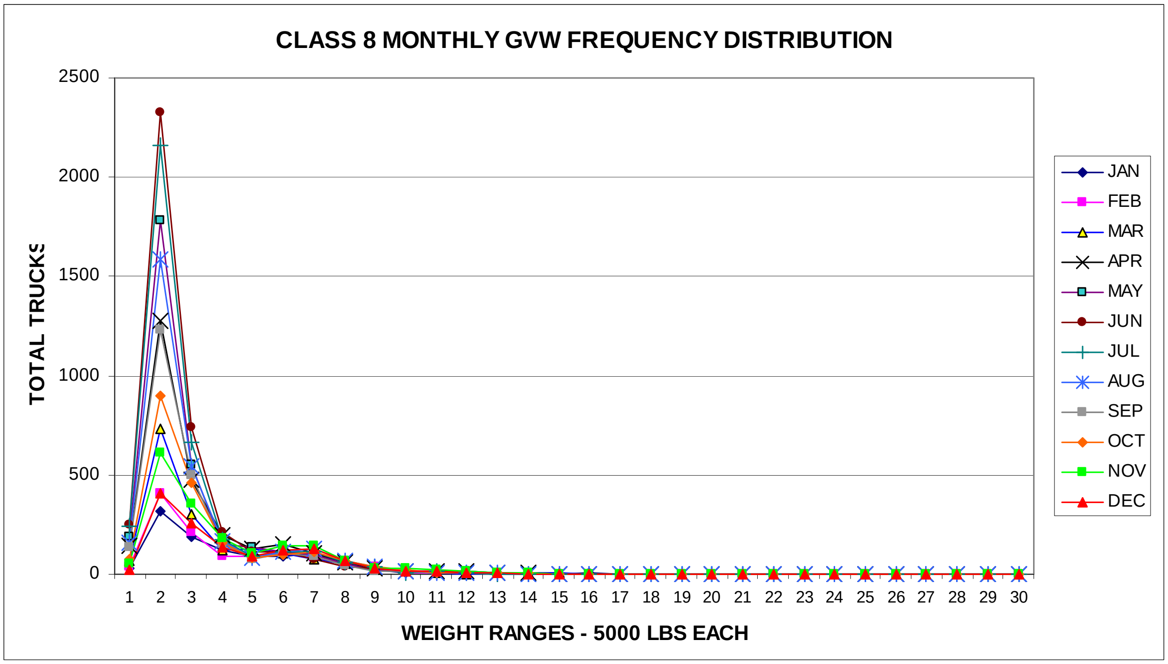


Figure 2-12 Class 8 Monthly GVW Frequency Distribution at site 371024

The following plots (Figure 2-13 – Figure 2-15) show the effect using a higher minimum GVW and adjusting volume. A minimum GVW of 19,000 lbs was used to screen class 8 weight records. Class 8 Monthly Distribution reflects a pattern similar to class 9 as shown in Figure 2-13.

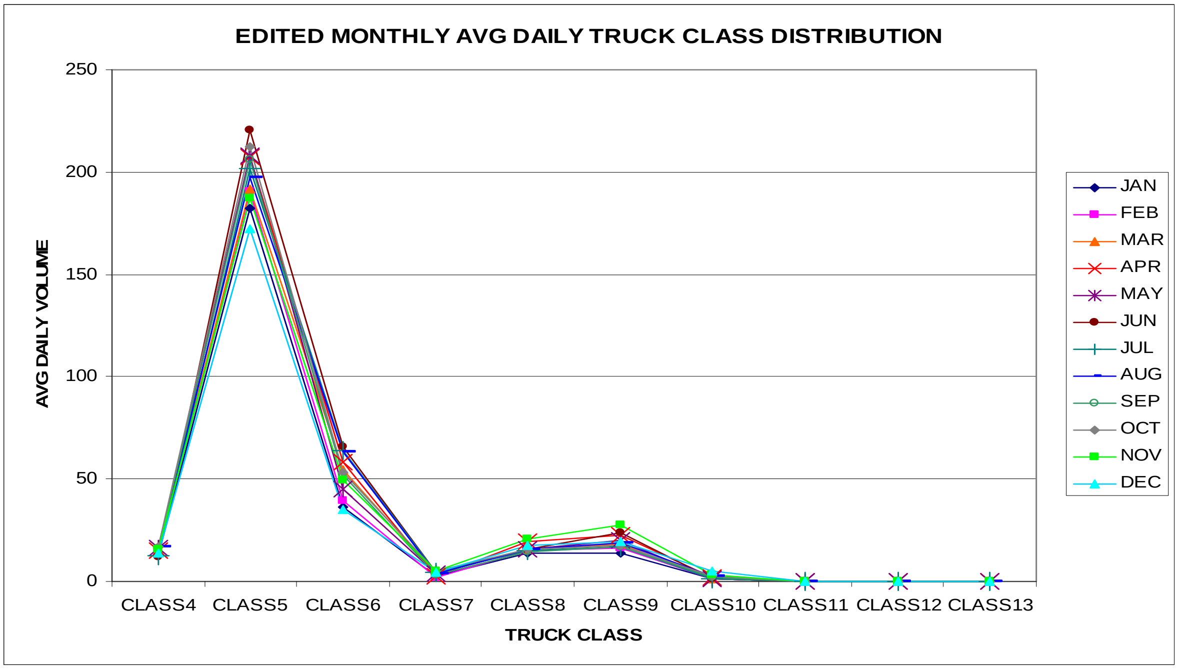


Figure 2-13 Edited Monthly Average Daily Truck Class Distribution at site 371024

Figure 2-14 shows the normalized Day of Week distribution; weekends have the lower volumes the same as other classes.

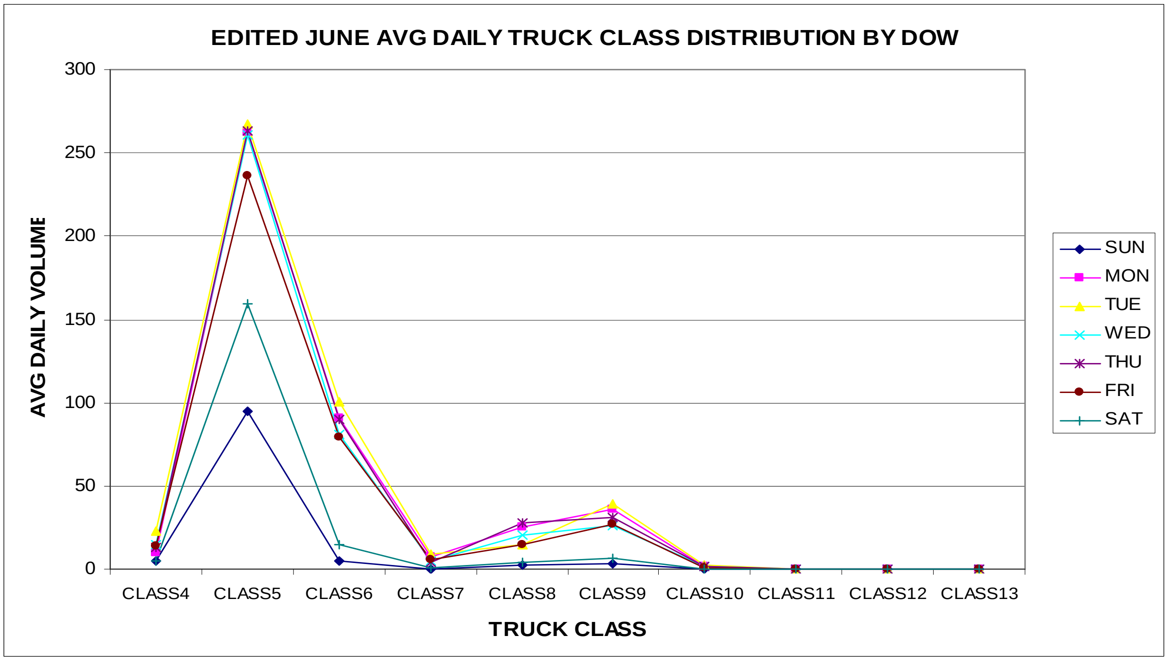


Figure 2-14 Edited June Average Daily Truck Class Distribution by DOW at site 371024

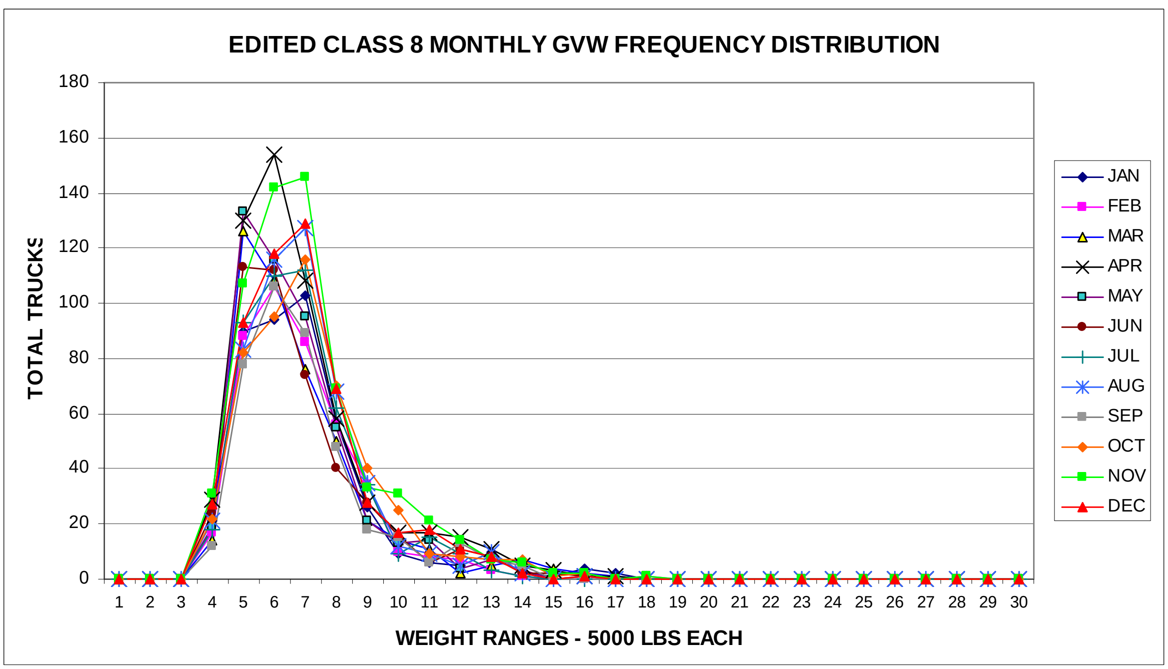


Figure 2-15 Edited June Average Daily Truck Class Distribution by DOW at site 371024

We excluded low GVW class 8 (not an edit). We edited the volume data to reflect the significant drop in class 8 volumes as reflected in the drop in class 8 weight records.

2.10 Recommendations for Future Research

Apart from a few sites with up to an entire month of data missing because of construction and other non-equipment problems, the WIM systems operated by the NCDOT provided valid weight and class data. When a month of data was excluded by the QC process, the NCDOT substituted equivalent data from the same month but from another year in order to develop complete datasets for MEPDG.

The following recommendations can be implemented to improve upon the existing quality control procedures implemented by the MEPDG research team at NC State University.

1. *Explore data sampling procedures to reduce the size of databases* - Weight data can result in extremely large databases, especially for sites with high vehicular volume like interstate routes. Statistically valid sampling methods should be explored to reduce the size of such datasets to a manageable extent. Sampling requirements must be based on the intended use of the data. For example, most LTPP GPS studies require only seven days of weight data per quarter.

2. *Consider quality control as part of a comprehensive process called quality assurance* - The quality assurance consists of various quality considerations which are made during data collection and after data summarization and reporting. Some of the quality assurance actions are listed in the following.
   - Develop effective equipment procurement procedure.
   - Establish inspection procedures for newly installed equipments.
   - Schedule periodic maintenance and calibration activities.
   - Develop automated quality control procedure to review and detect corrupt data.
   - Be in contact with the customer and ask for feedback [*Turner, 2007*].

   Considering such activities, recognize that the data quality control is restricted to identifying erroneous data and excluding them from the database is not an efficient practice in long term. The QC process shall be used as a diagnostic tool to identify the reasons behind poor data quality. The NC State research team has no direct control over the quality assurance process other than quality control. The results of the WIM data QC, however, may provide some insight for NCDOT in procuring data collection equipment and developing maintenance programs for equipment.

3. *Assign severity level to quality control rules* - Currently, the NCDOT QC Database simply excludes all the data which are rejected based on identified QC rules. In other words, a simple accept/reject decision is made for each rule. It will be more beneficial to assign a severity level to data which are not valid based on QC rules. Suggested severity levels are:
   - <u>High</u> – A high level of severity may happen because of equipment failure. For example, 24 consecutive zero values for volume in a single lane of a four-lane highway could be a serious equipment malfunction. There may be cases where one lane is closed by authorities for road maintenance activities, however identifying these reasons may be difficult in practice. The suggested action for data with high level of severity would be to exclude the data from further analysis.
   - <u>Medium</u> – Data with a medium level of severity are outside the acceptance range, however it is not very significant. In such cases some analysis is required to determine whether to accept or exclude the data. For example, volume level of one at 1:00 am compared to volume level of zero at 1:00 pm is considered an error based on rule number C13, but this case may often happen on low volume roads. Therefore, it is recommended to check the historical data (a few days before and after) to identify whether the trend is repeating or not. In summary, the

suggested action for data with medium level of severity is to perform more analysis based on local knowledge of traffic and site conditions at the WIM site.

- Low – Data with a low level of severity correspond to rules with boundary limits (maximum and minimum limits). Such data are usually inside the specified limits, however very close to boundaries. For example, a level of volume (2999 vehicles) which is less than 3000 vehicles is considered acceptable base on rule number C1. This volume may be excessive for the geometry of the highway cross section at some WIM sites. It is recommended to investigate such data further based on local knowledge of the WIM site to build more confidence on data quality [*Turner, 2007*].

4. *Long Term WIM Data Storage and Analysis* - While most research topics focus on collection and quality of data, there is little emphasis on the development of an integrated Database Management System (DBMS) to store and analyze traffic data. A Microsoft Access database or spreadsheet program can be used to analyze small datasets, but they are not feasible for analyzing a statewide WIM program. Therefore, the best way to effectively handle the tremendous amount of data generated by a WIM monitoring program is to upload it to a more robust relational database, such as Oracle or Microsoft SQL Server [*Nichols et.al, 2004*].

CHAPTER 3. VEHICLE CLASS DISTRIBUTION AND SEASONAL FACTOR ANALYSIS

This chapter begins with an introduction to the need for clustering analysis and then introduces the basic theory of clustering analysis and how it was applied in the research to WIM station data. Results are shown for VCD and how the results are applied in seasonal factor analysis. Initially, WIM sites are clustered by VCD in each month and those WIM sites that tend to remain in same cluster over the year (from January to December) form seasonal factor groups. Results for the seasonal factors are subsequently improved using principal component analysis. The next step of the factor analysis further refined the VCD WIM clusters by examining the ratio of Monthly Average Day-of-week Truck Traffic (MADTT) to Annual Average Daily Truck Traffic (AADTT) of: $MADTT_{SU}/AADTT_{SU}$ for single-unit (SU) factor groups and $MADTT_{MU}/AADTT_{MU}$ for multi-unit (MU) factor groups. Ultimately decision trees for SU and MU factor groups and related seasonal factors are developed for application by pavement designers who need to relate project sections with relatively little VCD information to similar WIM station locations with adequate information to allow the MEPDG design process to go forward. To expand the results of the analysis from the original 44 WIM stations the research team examined about 1000 locations in North Carolina which had 48-hour coverage counts. Results are summarized.

3.1 Importance of Clustering Analysis

To develop seasonal factor groups, a major task is to identify WIM sites with similar truck traffic pattern over the year. Analyzing a large amount of data (44 WIM sites ×12 months × 7 DOW) is not straightforward, thus, an easy-to-use technique is required to identify the similarities among WIM sites. There are numerous methods that can be used for this purpose including development of roadway group, regression analysis, and hierarchical clustering algorithm. Among these methods, clustering analysis has gained extensive attention by practitioners and researchers because of its simplicity and its capability to preserve the form of information available in data. It also does not require any prior knowledge of the traffic-related reasons for the existence of the clusters, which makes its application much easier. Clustering analysis relates to grouping a collection of objects (WIM sites here) into clusters (groups), such that those within each cluster are more closely related to one another than objects assigned to different clusters. Hierarchical clustering starts with *n* clusters (each containing a single object) and proceeds by a series of fusions of the *n* objects into groups.

3.2 VCD Clustering Analysis

The vehicle class distribution (VCD) represents the percentage of each truck vehicle class (class 4 through class 13). In order to study the current truck traffic patterns at current WIM locations, we clustered VCD factors for 44 WIM stations. An agglomerative clustering algorithm was implemented because of its simplicity and its capability to preserve the form of information available in data. The hierarchical clustering algorithm (1) begins with *n* clusters each consisting of exactly one WIM site; (2) compares the cluster of WIM sites based on the similarity of their attributes to produce individual clusters for VCD; (3) merges two clusters that result in the smallest increase in the value of an index *E*, called the sum of squares index, and reduces the number of clusters by one; and (4) performs steps (2) and (3) until the best partition that represents the natural structure of the data is found [*Anderberg 1973, Arabie, 1996*]. Index *E* quantifies the information loss associated with each merging. This means all possible combinations of two clusters are tested, the value of index *E* is calculated for each, and the one with the smallest value of *E* is selected. To find the best partitions that represent the natural structure of the data, the algorithm may stop to merge clusters further once a *significant* change in the homogeneity of clusters is observed. A metric, introduced by Mojena is used to explicitly define a *significant* change in the clustering criterion [*Mojena, 1977*].

For each possible set of clusters, E is calculated as follows. First, the mean of each cluster is calculated. The cluster mean is a virtual WIM site the VCD of which is the average of the axle load values for the WIM sites in the given cluster. Second, the difference between each WIM site in a given cluster and its cluster mean is calculated. For example, suppose a cluster contains three WIM sites, each described by 10vehicle classes (4 – 13). For the first WIM site, the difference in the values from it to its cluster mean values would be calculated, for each of the 10vehicle classes. The same computations would be performed for the second and third WIM sites, thus ending up with 3 × 10 differences for the cluster. Third, for each cluster the differences computed earlier would be squared. These values are added together for each cluster, thus providing a sum of the squares for each cluster.

The increase in the value of E resulting from merging clusters C_r and C_s into new cluster C_m is calculated as shown by the following equation:

$$\sum_{j}\left[\sum_{r=1}^{R}\left(x_{rj}-\bar{x}_{mj}\right)^{2}+\sum_{s=1}^{S}\left(x_{sj}-\bar{x}_{mj}\right)^{2}\right]$$

where,

$$\bar{x}_{mj}=\frac{1}{RS}\sum_{r=1}^{R}x_{rj}+\sum_{s=1}^{S}x_{sj}\ \forall j$$

x_{ij} denotes the percentage of vehicle class j at WIM site $i(i=1,\dots,n), \bar{x}_{ij}$ denotes the average vehicle class percentage, and R and S are numbers of WIM sites in clusters C_r and C_s, respectively.

The clustering analysis resulted in three representative VCD clusters with very distinct patterns (Figure 3-1). Cluster 1 WIM sites have similar percentages of Classes 5 and 9 vehicles because they are mostly in the Piedmont region where short and long haul trips, represented by class 5 and 9 vehicles, respectively, are frequent. In Cluster 2, however, the percentage of class 9 vehicles is dominant because Cluster 2 WIM sites are along Interstate highways (such as I-40, I-77, I-85, and I-95) and US highways. These highways have high AADTT (as high as 12,000) and serve long haul trips mostly. For Cluster 3 the percentage of class 5 vehicles is dominant, and it represents WIM sites in the mountains serving rural-recreational roads.

The representative VCD clusters (Figure 3-1) show distinct patterns but the range of VCD represented by each cluster is high, especially in Cluster 3. Therefore, we propose using site-specific VCD rather than average VCD to improve the accuracy of the M-E pavement design.

The accuracy of the three MEPDG design levels improves as more site-specific knowledge is incorporated in the design process. Level 2 design is set up to use AADTT as input and then to use the regional VCD to distribute the truck volumes to the different vehicle classes. In order to generate AADTT, NCDOT aggregates the classification counts collected for a specific site. Literally, the site-specific classification counts are annualized and aggregated to generate AADTT and then disaggregated using regional VCD. It seems reasonable to directly use annualized site-specific classification counts to generate VCD rather than using regional VCD.

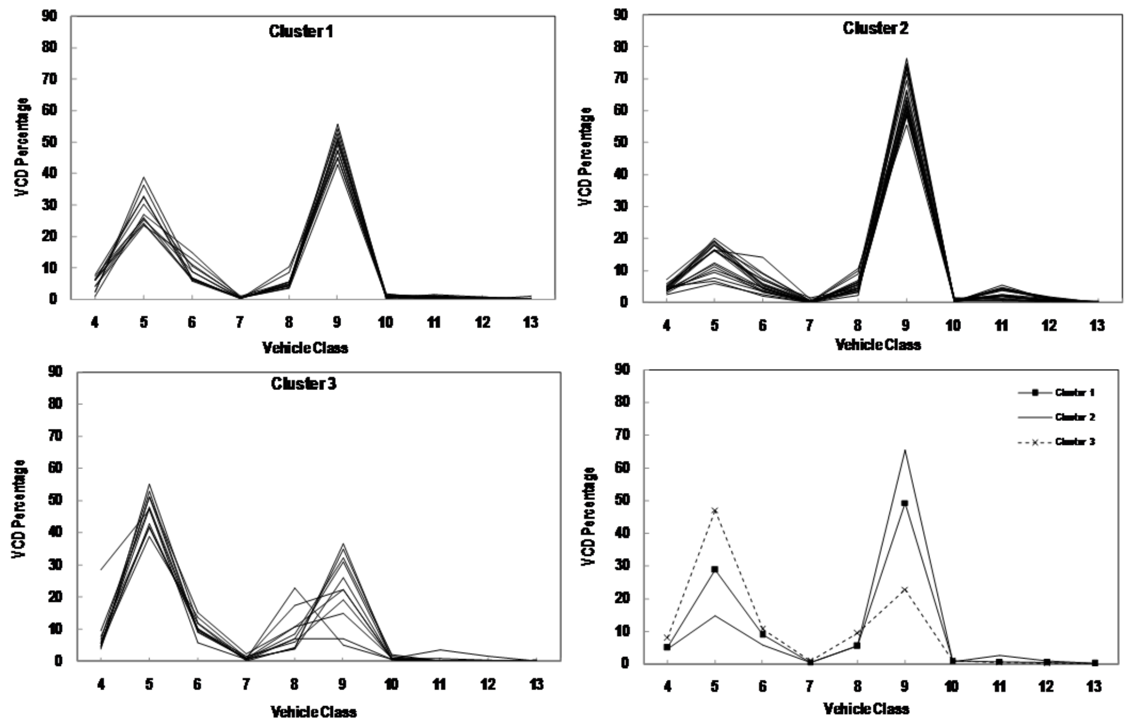


Figure 3-1 Vehicle Class Distribution for VCD Clusters: (a) Cluster 1, (b) Cluster 2, (c) Cluster 3, (d) Average Vehicle Class Distribution for VCD Clusters.

The Traffic Survey Group at NCDOT operates a Coverage Count Program with 45,000 locations monitored using portable traffic counters to support its Traffic Monitoring Program. The Program includes a statewide coverage of 3,000 locations where 48-hour classification counts are collected on state and locally maintained roadways.

Because truck travel patterns do not follow constant day-of-week and monthly patterns, the 48-hour counts need to be annualized [*Hallenbeck 1993, 1997*]. We used the high quality data collected at 44 WIM sites to capture the recurring patterns and to provide the seasonal factors to convert 48-hour classification counts to annual averages. These averages are used to generate site-specific VCD factors, which are more accurate than cluster averages.

<u>In the first step of seasonal factor analysis</u>, we used a variation of the traditional factoring procedure suggested by the TMG approach to generate the seasonal factors [*TMG, 2001*]. It is a three-step procedure for which data screening is the first step. The purpose of data screening is to distinguish typical and atypical traffic patterns. We used typical data to calculate the Monthly Averaged Day-of-week Truck Traffic (MADTT) and all data (both typical and atypical) to generate AADTT. The NCDOT Traffic Survey Group collects 48-hour counts on typical weekdays. Therefore, using typical weekday data (no holidays, adverse weather events, or other conditions that cause significant variations in travel) is consistent with how 48-hour counts are collected and provides more reliable estimates of VCD inputs.

<u>In the second step of seasonal factor analysis</u>, we developed the 84 seasonal factors (12 months × 7 DOW = 84). The TMG recommends developing month and day-of-week seasonal factors for several aggregated vehicle classes; single-unit trucks (including buses); single-unit combination trucks; and multi-trailer combination trucks. It also suggests combining the last two generalized groups into one

group in states located east of the Mississippi River if the states allow multi-trailer trucks. The State of North Carolina qualifies for the latter aggregation, therefore, the seasonal factors are generated for two generalized vehicle classes: single-unit trucks (SU) comprised of vehicle classes 4 to 7, and multi-unit trucks (MU) comprised of vehicle classes 8 to 13.

For each aggregated vehicle class (SU and MU), we developed separate sets of 84 month and day-of-week factors. The seasonal factors are computed as follows:

$$\text{Seasonal Factor}_{C,DOW,M} = AADTT_C / MADTT_{C,DOW,M}$$

where,

$AADTT_C$ = annual average daily truck traffic volume for an aggregated vehicle class (*c* is either SU or MU); and
$MADTT_{C,DOW,M}$ = monthly average day-of-week truck traffic volume for the month of M for an aggregated vehicle class (SU or MU).

The NCSU and NCDOT team generated one set of SU seasonal factors and one set of MU seasonal factors using 44 WIM databases. The 48-hour classification counts can be converted to an estimate of annual average counts by multiplying a48-hour count by an appropriate seasonal factor.

<u>In the third step of seasonal factor analysis</u>, we developed an objective procedure to select appropriate seasonal factors to convert the 48-hour counts obtained on specific roadways into annualized counts. The overall procedure distinguishes three categories of highway segments and uses a different assignment procedure for each:

Category 1: Highway segments that contain WIM sites;
Category 2: Highway segments located *near* Category 1 highway segments; and
Category 3: Other highway segments.

For each highway segment that contains WIM sites, the seasonal factors developed for that WIM site can be directly used to annualize the 48-hour counts for that highway. A Category 2 highway segment is the one that is on the same road as a Category 1 segment but several miles away from it. If the truck traffic characteristics of a nearby highway segment do not differ from that of the Category 1 segment, then the same seasonal factor may be used to annualize the 48-hour counts. Special care should be taken if the truck traffic pattern on a long highway changes because of changing economic activity, traffic generators, or intervening intersections. Determining whether or not a highway segment belongs to Category 2 requires local traffic knowledge. For urban areas Weinblatt (1996) assumes two highway segments are nearby segments if they are not more than a few miles apart. However, he says that on rural arterial segments which are 50 miles apart may still be considered nearby segments [*Weinblatt, 1996*].

For nearby highway segments with different truck traffic patterns, we use the objective assignment procedure developed for Category 3 highway segments to select an appropriate seasonal factor. For Category 3 highway segments, we need to identify factor groups including WIM sites with similar truck traffic patterns. We used a hierarchical clustering algorithm and the VCD_mas a similarity metric to cluster 44 WIM sites. Index *m* suggests that we identify factor groups for different *months* of the year because roads may possibly belong to one set of factor groups in January and another set of factors in February or March and so on.

3.3 Identifying WIM Sites with Similar Truck Traffic Pattern

The TMG seasonal factoring procedure involves categorizing WIM sites that have similar truck traffic patterns through the year. In order to do that, the team performed hierarchical clustering analysis using VCD in each month and identified those WIM sites that tend to remain in same cluster over the year (from January to December). For each month, there are ten variables (percentage of vehicle classes 4 to 13) that contribute to the variability of the data. The team performed Principal Component Analysis, in an attempt to reduce the dimensionality of the data set while retaining as much variability present in the data set as possible. This is achieved by transforming to a new set of variables, the principal components (PCs), which are uncorrelated, and ordered so that the first few components retain most of the variation present in all of the original variables.

3.3.1 Principal Component Analysis

Principal component analysis (PCA) can be used in selecting a subset of principal components to account for most of the variations in a data set. One approach is to select a cumulative percentage of total variation that the selected PCs contribute, say 80% or 90%. The smallest number of PCs for which this percentage exceeds 90%, for example, specifies the required number of PCs. The cumulative percentage of total variance is calculated as below:

Cumulative Percentage $$t_p = 100 \times \sum_{k=1}^{p} l_k \Big/ \sum_{k=1}^{10} l_k$$

Choosing a cut-off t^* between 80% or 90% and retaining p PCs, where p is the smallest integer for which the$t^* > t$ provides a rule which in practice contains most of the information in first p PCs [*Jolliffe, 2002*]. After selecting the important principal components, the next step is to select a variable that represents each of the retained PCs. The variable that has the highest weight on the principal component would be selected to represent that component, provided it has not been chosen to represent a PC with a larger variance. In that case, then the variable with the next largest weight would be chosen.

3.3.2 Principal Component Analysis Using VCD for the Month of January

The variation that is captured by each PC is presented in Table 3-1. Table 3-1 reveals that the first five PCs retain more than 99% of the variability that exists in the original database.

Table 3-1 Results of the Principal Component Analysis for the Month of January

Principal Component	Variance	Cumulative Variance
1	567.7038	0.9353
2	20.4030	0.9689
3	10.8677	0.9868
4	6.2745	0.9971
5	1.3167	0.9993
6	0.2323	0.9997
7	0.1279	0.9999
8	0.0451	0.9999
9	0.0354	1.0000
10	0.0000	1.0000

When the number of PCs (here p=5 $p = 5$) are selected the next step involves identifying a variable that represents each of the retained PCs. Formally, one variable is associated with each of the first p PCs: a variable that has the highest coefficient in absolute values in each successive PC and it is not already chosen. These p variables are retained and the remaining 10 p p are discarded from the clustering analysis. For the month of January, Table 3-2 shows that the Vehicle Classes 9, 4, 6, 8, and 11 are the first five principal components that retain more than 99% of the variability that exists in the original datasets.

Table 3-2 Latent Factor Derived from PCA of the Month of January

	Latent Vector									
	PC 1	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**	**PC 9**	**PC 10**
	0.092	-0.799	0.331	0.153	0.255	0.156	0.112	0.085	0.106	-0.316
	0.589	0.512	0.464	0.122	0.141	0.150	0.061	0.076	0.095	-0.316
	0.113	0.066	-0.743	0.431	0.165	0.267	0.145	0.095	0.133	-0.316
	0.016	-0.042	-0.050	0.043	-0.067	-0.033	-0.933	0.106	-0.077	-0.318
	0.029	0.016	-0.211	-0.864	0.256	0.146	0.058	0.090	0.099	-0.316
	-0.794	0.299	0.267	0.142	0.206	0.166	0.053	0.081	0.099	-0.316
	0.002	0.019	-0.063	0.051	0.109	-0.897	0.118	0.011	0.248	-0.317
	-0.035	-0.053	0.028	-0.066	-0.832	0.060	0.200	0.383	0.090	-0.318
	-0.011	-0.024	0.002	-0.026	-0.266	0.101	0.010	-0.897	0.125	-0.314
	-0.001	0.004	-0.025	0.015	0.035	-0.114	0.183	-0.041	-0.923	-0.314
Max Values	0.7936	0.7989	0.7427	0.8641	0.8317	-	-	-	-	-
Associated Veh Cls	9	4	6	8	11	-	-	-	-	-

Similar analysis is done using VCD for other months (February to December). The results are presented in Table 3-3. As results show the Vehicle Classes 4, 5, 6, 8, 9, and 11 (highlighted cells) retain more than 99% of the variability that exists in the original datasets.

Table 3-3 Important Variables (Vehicle Classes) for January to December

	Veh Cls 4	Veh Cls 5	Veh Cls 6	Veh Cls 7	Veh Cls 8	Veh Cls 9	Veh Cls 10	Veh Cls 11	Veh Cls 12	Veh Cls 13
Jan		■	■		■	■		■		
Feb		■	■		■	■		■		
Mar	■	■	■			■		■		
Apr	■	■	■			■		■		
May	■	■	■			■		■		
Jun	■	■			■	■		■		
Jul	■	■			■	■		■		
Aug	■	■	■			■		■		
Sep		■	■		■	■		■		
Oct		■	■		■	■		■		
Nov	■		■		■	■		■		
Dec	■		■		■	■		■		

A cursory examination for Table 3-3 suggests that the identified important vehicle classes generally seem reasonable.

- Class 5 vehicles are frequent users of highways especially in and near urban areas.
- Class 7 and 10 vehicles are not so frequent in NC; at most, they comprise 2% of trucks on roadways. Class 7 vehicles are mostly on US roads with low AADTT values (AADTT ≤ 2500).
- Class 9 tractor trailer vehicles are most frequent any time.
- Class 11 heavy load vehicles are frequent.
- Class 12 and 13 vehicles are practically non-existent in North Carolina.

3.3.3 Detection of Outliers Using Principal Components

There are situations where some of the observations are in some way different or inconsistent with the remainder of the data. The plot of the first few PCs may be used to detect outliers [*Jolliffe, 2002*]. The outliers that are detectable from the plot of the first few PCs are those which increase the variance that exists in the dataset. MATLAB software is used to perform the PCA analysis and generate the plots based on the first few PCs. Figure 3-2 shows the results of the principal component analysis for every month.

In order to test the data for the presence of outliers, we plotted the data sets (VCD in January) with respect to the first two PCs that account for 96% of the variability that exist in the dataset. As shown in Figure 3-2 WIM sites 516 and 521 are outliers compared to other data points. Similar results occurred when we repeated the analysis for VCD in other months of the year. Thus WIM 516 and 521 are discarded from the clustering analysis. In other words, the clustering analysis includes 42 WIM databases.

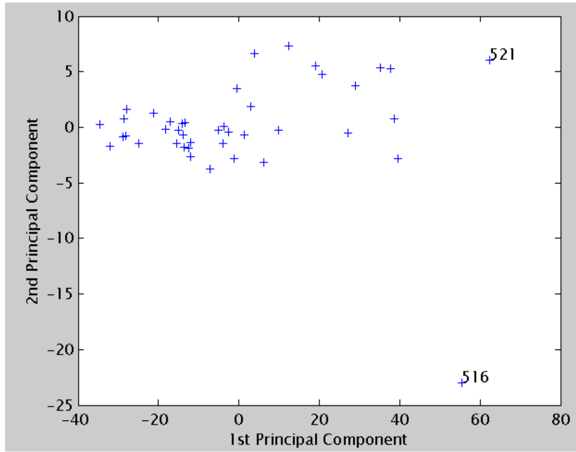


Figure 3-2 VCD for the Month of January, Plotted with Respect to Its PCs

The clustering analysis using the important vehicle classes in each month (for example, Vehicle Classes 5, 6, 8, 9, and 11) resulted in three clusters: Clusters, 1, 2, and 3. The research team repeated the clustering analysis 12 times for January to December. The results are presented in Table 3-4. As result show, there are WIM sites that tend to remain in a same cluster over the year. For example WIM sites 506/544, 508, 542, 555, and 558 belong to Cluster 2 in January through December. These five WIM sites form Cluster 2. There are some exceptions in Clusters 2 and 3 though. That is, some WIM site may change their cluster membership over the year. For example, WIM 551 is a member of Cluster 1 over the year except for the month April in which it belongs to Cluster 2. These exceptions are shadowed in Table 3-4. If a WIM site changes its membership to a specific cluster more than once, then it drops out of that cluster and remains unclassified, such as WIM 511 that dropped out of Cluster 2 four times in May, July, August, and September.

3.4 Identifying SU Factor Groups (Clusters)

Initial clustering analysis of 42WIM sites based on VCD for different months resulted in three major clusters (to be consistent with TMG terminology, we call the clusters Factor Groups). These initial factor groups are further refined based on a secondary similarity factor that is the ratio of $MADTT_{SU}/AADTT_{SU}$. To do so, the ratio of $MADTT_{SU}/AADTT_{SU}$ of the preliminary SU factor groups are plotted (Figure 3-3). As shown in Figure 3-3, there are WIM sites in SU Factor Groups 1 and 3 that have considerably different ratios of $MADTT_{SU}/AADTT_{SU}$ compared to other WIM sites in a same group. The $MADTT_{SU}/AADTT_{SU}$ distribution of these WIM sites is shown with dashed lines. These WIM sites are WIM sites 503/527, 541, 515, 536, 537, and 538 in SU Factor Group 1 and WIM sites 522 and 533 that belong to SU Factor Group 3.

WIM sites 503/527 and 541are both located on I-95 with different patterns compared to others. I-95 is a north-south highway in eastern NC that stretches from South Carolina to Virginia. It serves east coast recreational travel (SUs) and long haul trucks (MUs).

Table 3-4 Results of Clustering Analysis Based on VCD January to December

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Group
501/540	2	2	2	2	2	2	2	2	3	2	2	2	**Mixed Clusters (11 WIM Sites)**
502	3	2	2	2	2	2	2	2	3	2	2	2	
511	2	2	2	2	1	2	1	1	1	2	2	2	
530	2	2	2	2	2	2	1	1	2	2	2	2	
547	2	2	2	2	1	2	1	1	1	2	2	2	
548	2	2	2	2	1	2	1	1	1	2	2	2	
529	2	2	2	2	2	2	1	1	2	2	2	2	
539	2	2	2	2	1	2	1	1	1	2	2	1	
549	2	2	2	2	2	2	1	1	2	2	2	2	
554	1	1	1	2	1	1	1	1	1	1	1	1	
560	1	1	1	1	1	1	1	1	1	2	1	1	
504	1	1	1	1	1	1	1	1	1	1	1	1	**Cluster 1 (18 WIM Sites)**
509	1	1	1	1	1	1	1	1	1	1	1	1	
510/526	1	1	1	1	1	1	1	1	1	1	1	1	
520	1	1	1	1	1	1	1	1	1	1	1	1	
525	1	1	1	1	1	1	1	1	1	1	1	1	
531	1	1	1	1	1	1	1	1	1	1	1	1	
536	1	1	1	1	1	1	2	1	1	1	1	1	
537	1	1	1	1	1	1	2	1	1	1	1	1	
543	1	1	1	1	1	1	2	1	1	1	1	1	
551	1	1	1	2	1	1	1	1	1	1	1	1	
552	1	1	1	1	1	1	1	1	1	1	1	1	
553	1	1	1	1	1	1	1	1	1	1	1	1	
557	1	1	1	1	1	1	1	1	1	1	1	1	
559	1	1	1	1	1	1	1	1	1	1	1	1	
541	1	1	1	1	1	1	2	1	1	1	1	1	
503/527	1	1	1	1	1	1	2	1	1	1	1	1	
538	1	1	1	1	1	1	2	1	1	1	1	1	
515	1	1	1	1	1	1	2	1	1	1	1	1	
506/544	2	2	2	2	2	2	2	2	2	2	2	2	**Cluster 2 (5 WIM Sites)**
508	2	2	2	2	2	2	2	2	2	2	2	2	
542	2	2	2	2	2	2	2	2	2	2	2	2	
555	2	2	2	2	2	2	2	2	2	2	2	2	
558	2	2	2	2	2	2	2	2	2	2	2	2	
507/545	3	3	3	3	3	3	3	3	2	3	3	3	**Cluster 3 (8 WIM Sites)**
523	3	3	3	3	3	3	3	3	2	3	3	3	
534	3	3	3	3	3	3	3	3	3	3	3	3	
535	3	3	3	3	3	3	3	3	2	3	3	3	
546	3	3	3	3	3	3	3	3	3	3	3	3	
556	3	3	3	3	3	3	3	3	3	3	3	3	
522	3	3	3	3	3	3	3	3	3	3	3	3	
533	3	3	3	3	3	3	3	3	3	3	3	3	

WIM 515 is located on I-77, which is a north-south Interstate in central NC from Virginia to South Carolina. WIM 538 is located on I-85 which passes through the central Piedmont region of North Carolina. WIM 536 is located in the mountains on I-40, which is an east-west Interstate that stretches through the State. WIM 537 is located in the mountains on I-26, which stretches from South Carolina to Tennessee. The truck seasonal patterns of these four WIM sites are presented in Figure 3-4. WIM 515 is located in the mountains close to the Virginia border, and its traffic flow increases from September to November and drops in December and January. A similar pattern is observed for WIM sites 536 and 537. WIM 538 on I-85 in the Piedmont region shows a more stable seasonal pattern compared to others as trucks travel more consistently in the Piedmont region compared to mountain region.

In summary, the *preliminary* three SU factor groups are further disaggregated to form more homogenous groups with respect to seasonal variation ($MADTT_{SU}/AADTT_{SU}$) and the distribution of trucks (VCD). The *secondary* sets of SU factor groups including four groups are presented in Figure 3-5.

For each factor group, a set of SU seasonal factors is obtained as an average of the factors for each individual WIM in the factor group (Figure 3-6). The majority of WIM sites (32 out of 44) are grouped into either SU Group 1, 2, or 3. There are 13 WIM sites which form individual groups because of their specific traffic characteristics. They will be discussed later.

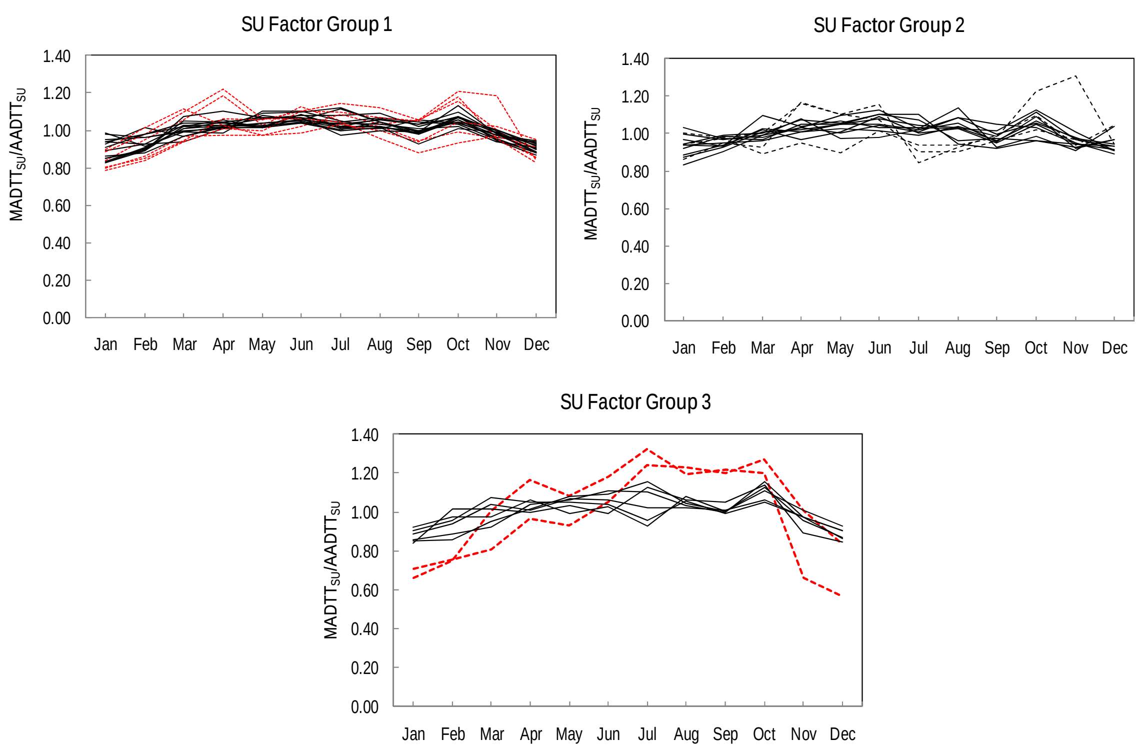


Figure 3-3 Ratio of $MADTT_{SU}/AADTT_{SU}$ of WIM Sites in Preliminary SU Factor Groups

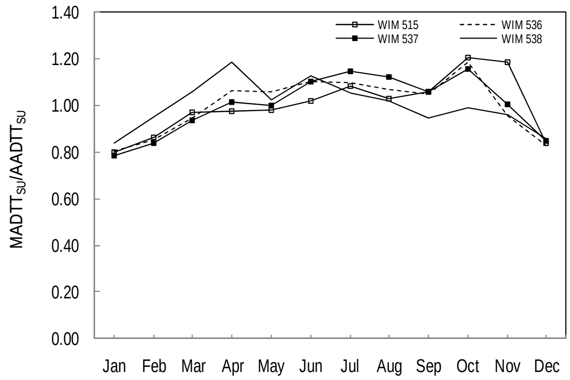


Figure 3-4 Seasonal Traffic Pattern ($MADTT_{SU}/AADTT_{SU}$)of WIM sites 515, 536, 537, and 538

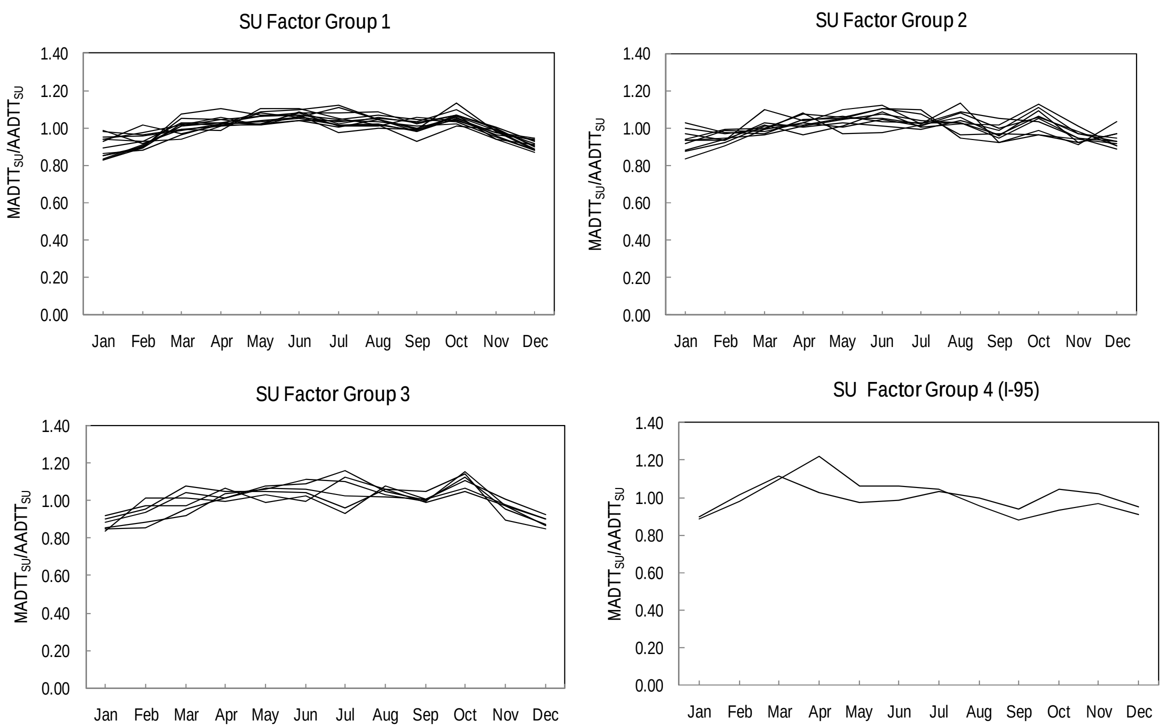


Figure 3-5 Ratio of $MADTT_{SU}/AADTT_{SU}$ of WIM Site in Secondary SU Factor Group

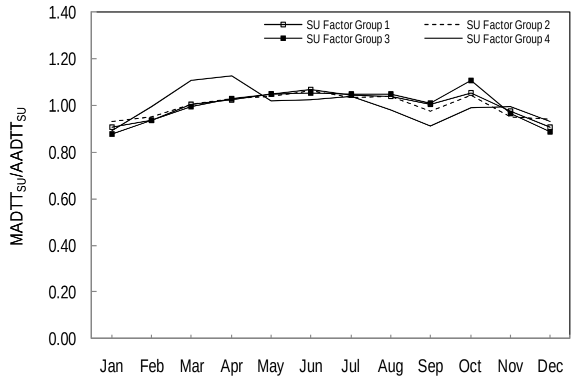


Figure 3-6 Average $MADTT_{SU}/AADTT_{SU}$ of Secondary SU Factors Groups

3.4.1 Stage 1 –Ratio of $MADTT_{SU}$ / $AADTT_{SU}$

3.4.1.1 SU Factor Group 1

In order to identify outliers in each factor group, we performed principal component analysis using the ratio of $MADTT_{SU}$ / $AADTT_{SU}$ for WIM sites that belong to each factor group. There are 16 WIM sites that belong to Factor Group 1. Looking at the plot of the ratio of $MADTT_{SU}$ / $AADTT_{SU}$ defined by the first two principal components will help in detecting the outliers. The PCA plot shows that there are five WIM sites that have different seasonal pattern compared to other WIM sites in Factor Group 1 (Figure 3-7):

- WIM 536 (a rural-recreational road, located on I-40 in the Mountain region),
- WIM 537 (a rural-recreational road, located on I-26 in the Mountain region),
- WIM 515 (a rural-recreational road, located on I-77 in the Mountain region),
- WIM 538 (a rural road, located on I-85 in the Mountain region),
- WIM 541 (located on I-95 in the Coastal region).

The first two principal components contain only 68% of the variability that exists among the original data. Thus, we refer to the original $MADTT_{SU}/AADTT_{SU}$ plot to see whether these patterns are shown as outliers or not. The $MADTT_{SU}/AADTT_{SU}$ plot also shows that these WIM sites have different seasonality compared to other WIM sites in Factor Group 1. There are two WIM sites (503 and 541) that are located on I-95. WIM 541 is located in the Coastal region and is detected as an outlier. However, WIM 503 located in the Piedmont region is not an outlier. For now, these two WIM sites are excluded from Factor Group 1 and form a separate Factor Group (Factor Group 4).

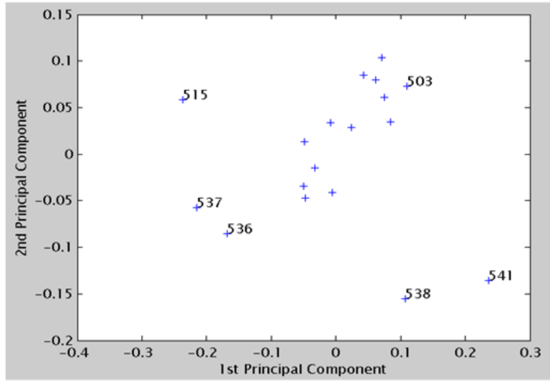
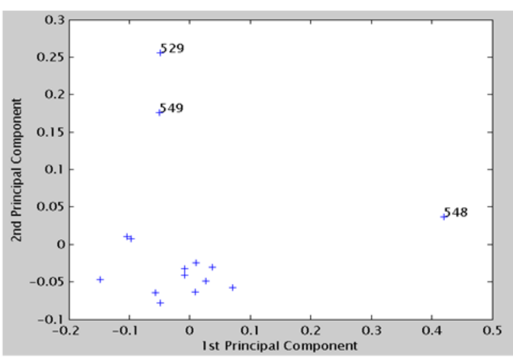


Figure 3-7 $MADTT_{SU}/AADTT_{SU}$ for the Factor Group 1, Plotted with Respect to Its PCs

3.4.1.2 SU Factor Group 2

Among 11 WIM sites that belong to different factor groups, there are nine WIM sites that belong to cluster 2 for most of the months. To examine the possibility of classifying these WIM sites as members of Factor Group 2, the team performed PCA on these WIM sites and the ones that are classified as cluster 2 in all months. The plot of the ratio $MADTT_{SU}/AADTT_{SU}$ defined by the first two principal components actually identifies WIM sites 529, 548, and 549 as outliers (Figure 3-8*a*). The plot of $MADTT_{SU}/AADTT_{SU}$ ratio in its original space also identifies these three WIM sites as outliers (dashed lines in Figure 3-8*b*). Thus, the total numbers of WIM sites that belong to Factor Group 2 are 10 WIM sites: 5 WIM sites that originally classified as cluster 2 and 5 WIM sites that belonged to mixed clusters.



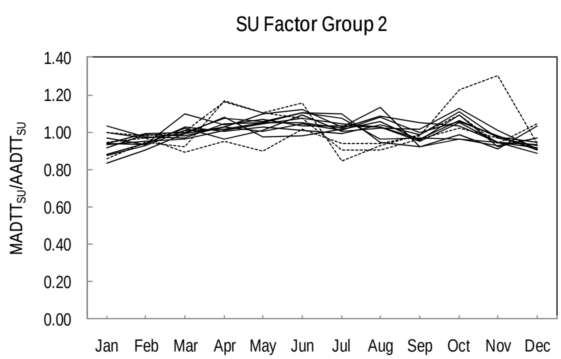


Figure 3-8 (a) The $MADTT_{SU}/AADTT_{SU}$ for the Factor Group 2, Plotted with Respect to its PCs, (b) The $MADTT_{SU}/AADTT_{SU}$ for the Factor Group 2

3.4.1.3 SU Factor Group 3

In order to detect the outliers in cluster 3, the team performed the PCA analysis using the ratio of $MADTT_{SU}/AADTT_{SU}$ defined by the first two principal components. The result of the PCA identifies WIM sites 522 and 533 as outliers (Figure 3-9*a*). The plot of the $MADTT_{SU}/AADTT_{SU}$ ratio in its original space also shows that these two WIM sites have different seasonality patterns compared to other WIM sites in Cluster 3 (Figure 3-9*b*). These two WIM sites are excluded from Cluster 3 and the remaining ones are classified as Factor Group 3.

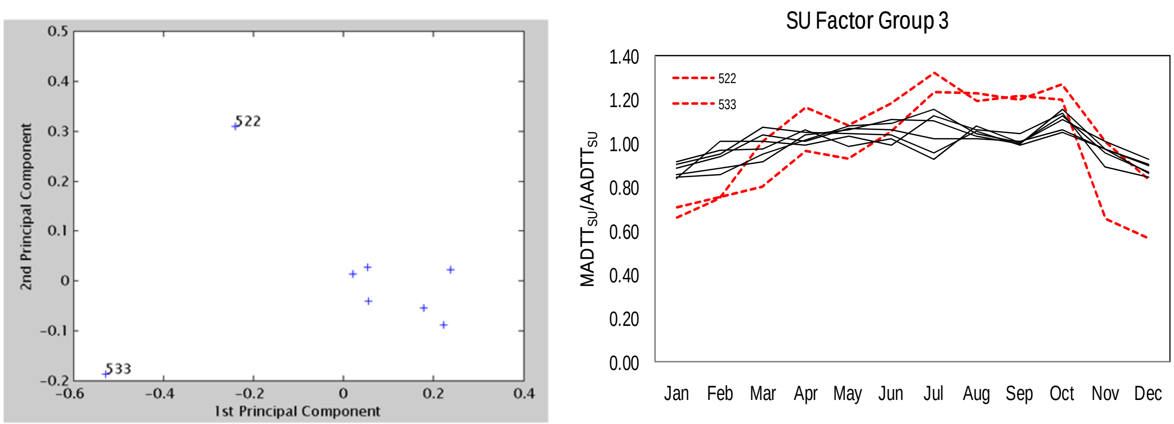


Figure 3-9 (a) The $MADTT_{SU}/AADTT_{SU}$ for the Factor Group 3 Plotted with Respect to PCs, (b) The $MADTT_{SU}/AADTT_{SU}$ for the Factor Group 3

3.4.2 Stage 2 – Confidence Interval of SU Factor Groups

The concept of confidence interval is used as a second measure to determine the variability of the factors within that group. If the group has reasonably homogenous factors then the group can be used for factor development. If the factors of the group are highly variable, the group needs to be modified. The precision of the factor group can be estimated within 95 percent confidence plus or minus Student's *t* value times the standard deviation divided by the square root of the number of WIM sites in the group. For each factor group of size *n*, the average is calculated as:

$$\bar{X} = \frac{X_1 + X_2 + \ \dots + \ X_n}{n}$$

where, $X_i$is the joint month and DOW seasonal factor of WIM site *i*. An approximate of the standard deviation (σ) is derived as:

$$\sigma \approx \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_1 - \bar{X})^2}$$

and then the confidence interval is calculated using

$$\bar{X} \pm t_{0.05,n-1}\frac{\sigma}{\sqrt{n}}$$

Those WIM sites for which their seasonal factor falls beyond the calculated confidence interval for most of the times are excluded from the factor group.

Figure 3-10 shows the individual SU seasonal adjustment factors for the month of January in Factor Group 1. Table 3-5 shows the same values as well as the mean, the standard deviation, and the confidence interval for each adjustment factor for all stations combined.

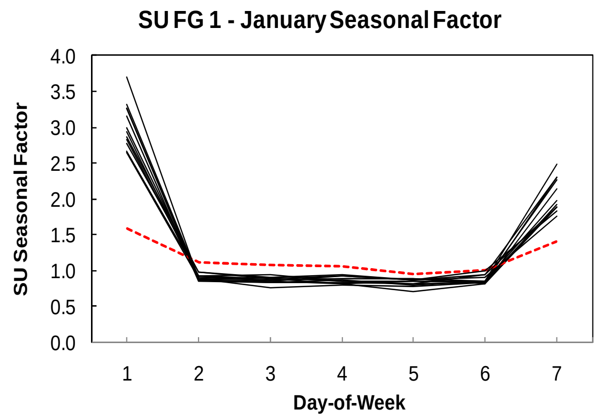


Figure 3-10 SU Seasonal Factor for the Month of January in Factor Group 1

Table 3-5 SU Seasonal Factors for the Month of January in Factor Group 1

Site ID	Road	Road Type	Region	AADTT	Jan						
					1	2	3	4	5	6	7
509	US 421	R	Piedmont	1,968	3.3	0.9	0.8	0.8	0.9	0.8	1.9
525	US 421	R	Piedmont	1,945	3.3	0.9	0.9	0.9	0.9	0.8	1.9
504	US 74	RR	Coastal	1,649	2.7	0.9	0.9	0.9	0.8	0.8	1.9
552	US 74	R	Piedmont	2,146	3.0	0.9	0.9	0.8	0.7	0.8	2.1
551	US 74	R	Coastal	2,401	2.9	0.9	0.9	0.9	0.9	0.8	2.3
553	US 220	R	Piedmont	2,652	3.1	0.9	0.8	0.9	0.8	0.8	2.5
531	US 52	R	Piedmont	3,039	3.7	0.9	0.8	0.8	0.8	0.8	2.3
510/526	US 29	R	piedmont	2,032	2.6	0.9	0.9	0.9	0.9	0.9	2.0
543	I-85	R	Piedmont	5,370	1.6	<u>1.1</u>	<u>1.1</u>	<u>1.1</u>	<u>1.0</u>	<u>1.0</u>	1.4
520	I-40	UR	Mountain	6,093	2.9	1.0	0.9	0.9	0.9	0.9	1.9
559	I-40	RR	Mountain	6,158	2.8	1.0	0.9	0.9	0.9	0.9	1.8
557	I-40	UR-	Piedmont	8,907	2.8	0.9	0.9	0.9	0.9	1.0	1.8
539	I-77	U	Piedmont	9,611	3.3	0.9	0.8	0.8	0.8	0.9	2.3
$\bar{X}$					2.9	0.9	0.9	0.9	0.8	0.9	2.0
σ					0.5	0.1	0.1	0.1	0.1	0.1	0.3
$\bar{X} + t_{0.05,12}\frac{\sigma}{\sqrt{n}} = \bar{X} + 2.179\frac{\sigma}{\sqrt{n}}$					3.2	1.0	0.9	0.9	0.9	0.9	2.2
$\bar{X} - t_{0.05,12}\frac{\sigma}{\sqrt{n}} = \bar{X} - 2.179\frac{\sigma}{\sqrt{n}}$					2.6	0.9	0.8	0.8	0.8	0.8	1.8

As illustrated in Figure 3-10, there are large differences between the seasonal factors of WIM site 543 (presented by dashed line) and the other WIM sites in SU Factor Group 1 (presented by the solid line). Table 3-5 also shows that the seasonal factors of WIM 543 (for the month January) fall beyond the calculated confidence interval for the entire weekdays (from Sunday to Friday). The same analysis was performed for the month of February through December, and it revealed that WIM 543 has seasonal factors which are very different (with respect to confidence interval) compared to other WIM sites. As a result, WIM 543 is excluded from SU Factor Group 1 to create a factor group that has a reasonably homogenous traffic pattern. The number of WIM sites in SU Factor Group 1 drops to 12.

The same analysis for other SU factor groups did not result in excluding any WIM site from the groups. Thus, the number of WIM sites in SU Factor Groups 2 and 3 remains 10 and 6, respectively.

3.5 Decision Tree Development for SU Seasonal Factor Groups

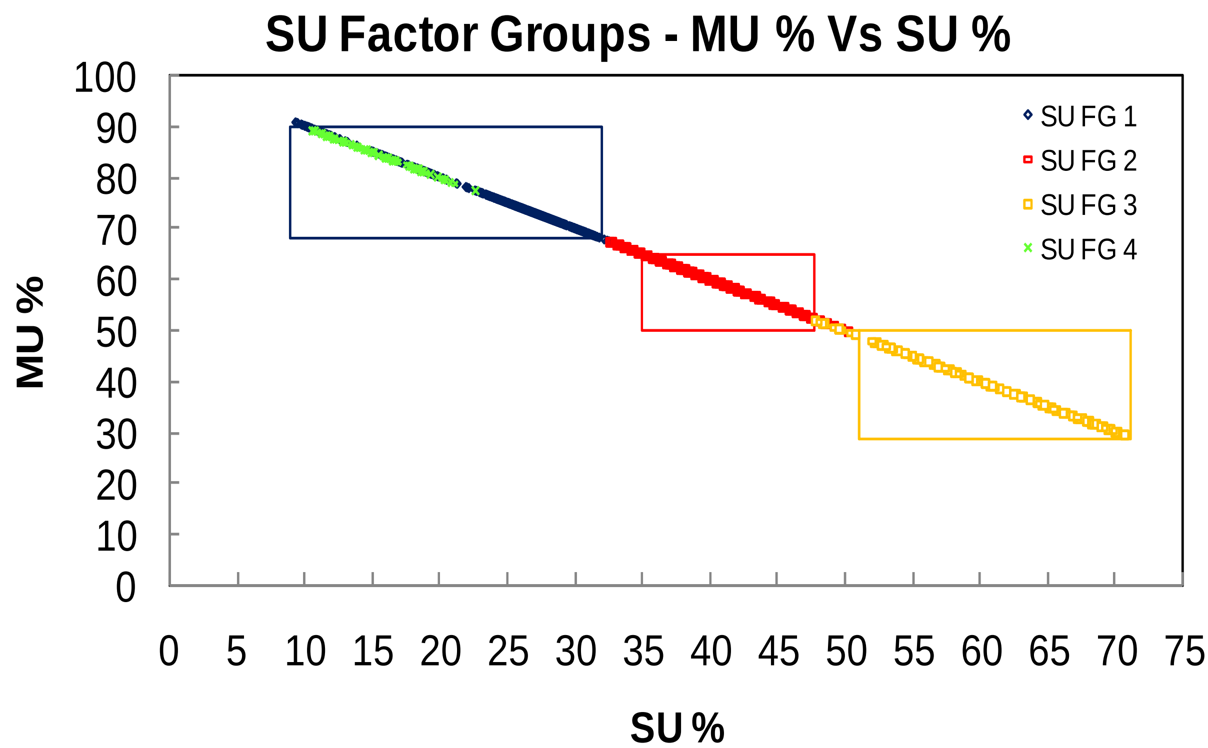
When the SU factor groups are identified, a decision tree is required to choose between several SU factor groups. Qualitative parameters and quantitative factors may be used to differentiate between SU factor groups. The qualitative factors include functional classification of road and the geographical location of the road. The quantitative parameters include the ratio of SU trucks to MU trucks obtainable from 48-hour classification counts. Qualitative parameters do not reveal discernible patterns to distinguish among SU factor groups. However, the quantitative parameters appear to distinguish factor groups. A discussion on how to generate the parameters and how to interpret them is presented below.

For a new pavement project (a new highway or widening), the 48-hour site-specific counts are the only available data to the pavement engineer. Thus, it is desired to have a decision tree that can benefit from the 48-hour data and lead the designer to select the right factor group. In order to associate the 48-hour count with the factor groups, we generated 48-hour data out of each WIM database using the following procedure:

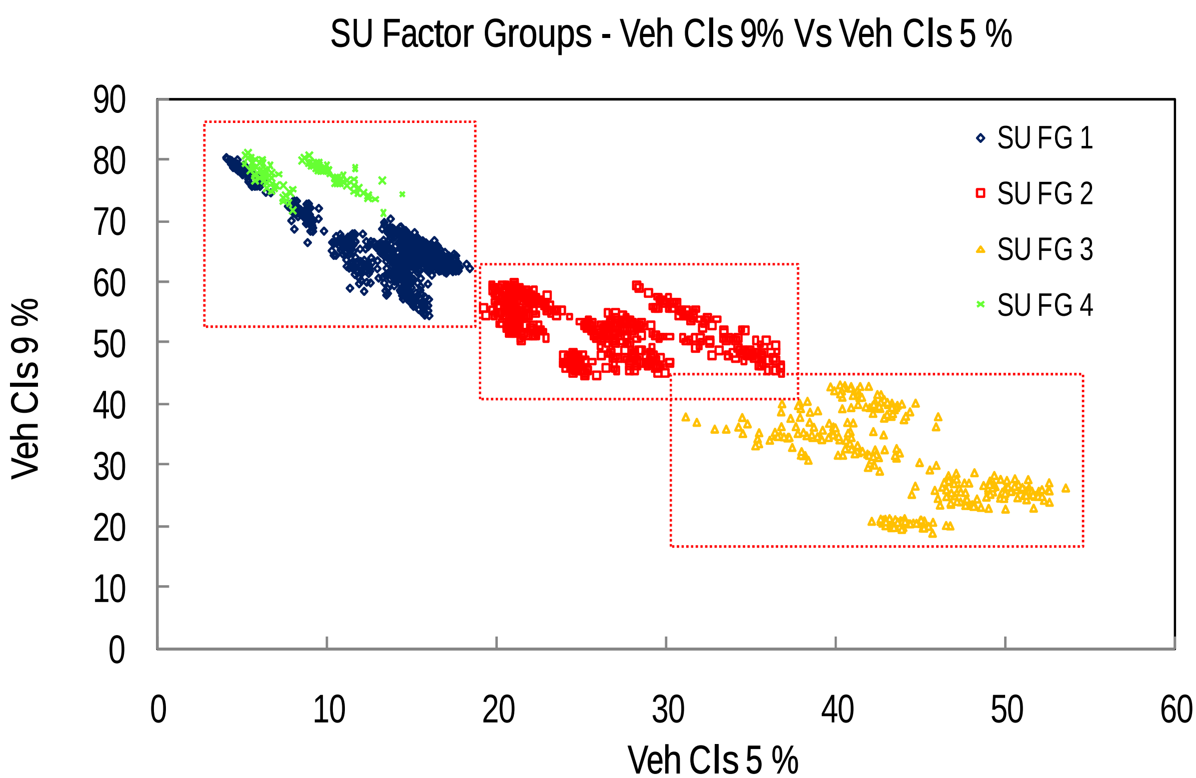
1. Exclude weekend data from the analysis. (Currently, NCDOT does not collect data during weekends, thus associating the week day data into factor groups is direct.)
2. Generate average traffic counts by vehicle class by Days of Week (DOW – Monday through Friday) by Month
   12 months × 5 DOW = 60 sets of average counts by vehicle classes,
3. Calculate vehicle class distribution (percentage of each vehicle class) by month by DOW
   12 months × 5 DOW = 60 sets of VCD,
4. Calculate the average VCD by month for every two consecutive DOW (Monday/Tuesday, Tuesday/Wednesday, Wednesday/Thursday, Thursday/Friday)
   12 months × 4 DOW = 48 sets of VCD_48,

Figure 3-11 shows the percentage of SU and MU trucks for WIM sites classified in Factor Groups 1, 2, 3, and 4. The figure shows that there exist distinct patterns for classifying WIM sites into Factor Groups. Here are some observations made from Figure 3-11*a*:

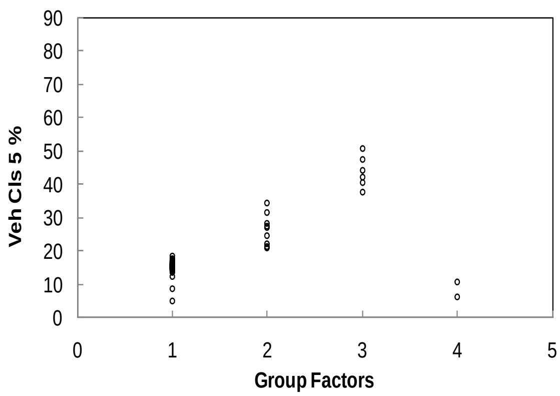
- WIM sites with $10 \le SU\% \le 31$ and $69 \le MU\% \le 90$ belong to Factor Group 1,
- WIM sites with $35 \le SU\% \le 49$ and $51 \le MU\% \le 65$ belong to Factor Group 2,
- WIM sites with $52 \le SU\% \le 70$ and $30 \le MU\% \le 48$ belong to Factor Group 3,
- WIM sites with $10 \le SU\% \le 23$ and $77 \le MU\% \le 90$ belong to Factor Group 4,


SU Factor Groups - MU % Vs SU %
MU %
SU %
SU FG 1
SU FG 2
SU FG 3
SU FG 4
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

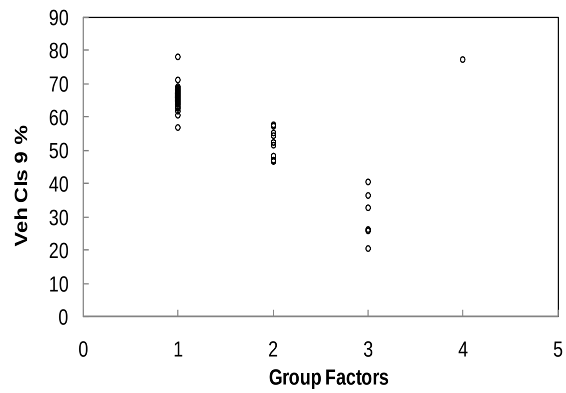
(a)


SU Factor Groups - Veh Cls 9% Vs Veh Cls 5 %
Veh Cls 9 %
Veh Cls 5 %
SU FG 1
SU FG 2
SU FG 3
SU FG 4
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60

(b)



(c)



(d)

Figure 3-11 (a) SU% versus MU% of 48-Hour Counts Generated from WIM Databases; (b) %Class 5 versus %Class 9 of 48-Hour Counts Generated from WIM Databases; (c) The %Class 5 of SU Factor Groups, and (d) The %Class 9of SU Factor Groups

As the above figures show, there are some areas where Factor Groups experience overlaps in plotted traffic parameters. The overlapping areas include:

- WIM sites with $31 \leq SU\% \leq 35$ and $65 \leq MU\% \leq 69$ belong to Factor Groups 1 and 2,
- WIM sites with $47 \leq SU\% \leq 51$ and $49 \leq MU\% \leq 53$ belong to Factor Groups 2 and 3,
- WIM sites with $10 \leq SU\% \leq 23$ and $77 \leq MU\% \leq 90$ belong to Factor Groups 1 and 4.

In order to distinguish between WIM sites in overlapping areas, we must look at the other attributes of the overlapping WIM sites. Initially, the team studied the association of the overlapping value with the months and DOW counts used to generate them.

3.5.1 Overlapping Area between SU Factor Groups 1 and 2

There are four WIM sites that contribute to the first overlapping between Factor Groups 1 and 2:

- WIM sites 551 in Factor Group 1 (a rural road, located on US 74 in Coastal region),
- WIM sites 558 in Factor Group 2 (an urban road, located on US 321 in Piedmont region),
- WIM sites 511 in Factor Group 2 (a rural road, located on US 220 in Piedmont region),
- WIM sites 547 in Factor Group 2 (a rural road, located on US 321 in Piedmont region),

Figure 3-12*a* shows the details of the overlapping area for these four WIM sites. The seasonality patterns of these WIM sites are presented in Figure 3-12*b*.

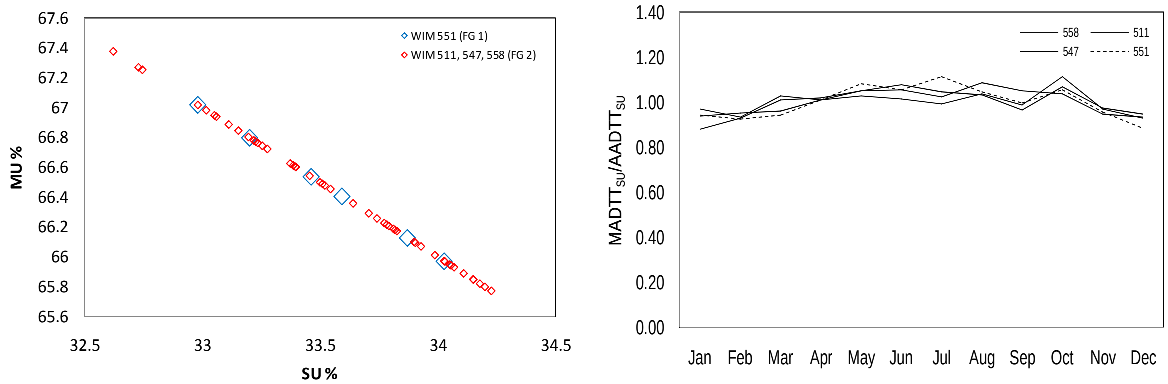


Figure 3-12 (a) The MU% versus SU% of the 1st Overlapping Area, (b) The Seasonality Patterns of the WIM sites in the 1stOverlapping Area

A close study of the months and DOW values reveals that, there are a few 48-hour counts from WIM 551 in Factor Group 1 that is attributed to the overlapping area. These counts belong to some days of week in May, June, July, August, and September (Table 3-6). The average truck volumes of WIM 515 during these months/DOWs and also other months/DOW are plotted in Figure 3-13. As it is shown in Figure 3-13, the average volume of class 6 vehicles is higher in the specified months/DOWs compared to other months/DOWs. The high volume of class 6 vehicles results in higher SU truck percentage which itself creates overlaps between SU factor groups 1 and 2.

Table 3-6 Months and DOWs Attributed to the Overlapping Area between SU Factor Groups 1 and 3 - WIM 551

Month	DOW
May	Mon-Tue
May	Thu-Fri
Jul	Mon-Tue
Jul	Tue-Wed
Jul	Wed-Thu
Aug	Thu-Fri

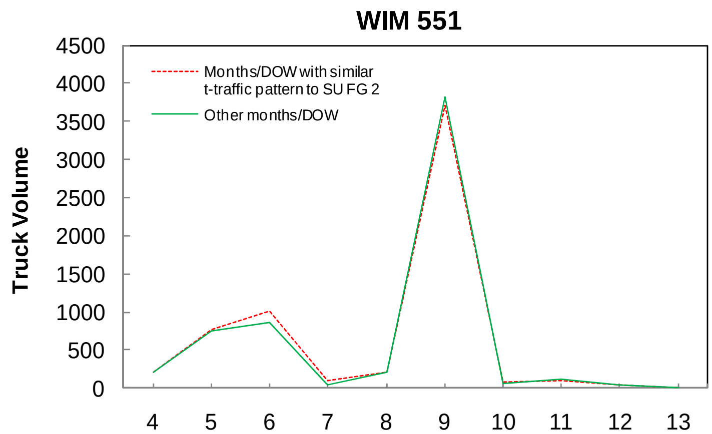


Figure 3-13 Vehicle Class Volume for WIM 551

3.5.2 Overlapping Area between SU Factor Groups 2 and 3

There are four WIM sites that contribute to the overlapping area between Factor Groups 2 and 3:

- WIM sites535 in SU Factor Group 3 (a rural-recreational road, located on US 74 in Mountain region),
- WIM sites502 in SU Factor Group 2 (a rural road, located on US 17 in Coastal region),
- WIM sites555 in SU Factor Group 2 (a urban road, located on NC 68 in Piedmont region),

Figure 3-14*a* shows the details of the overlapping area for these four WIM sites. The seasonality patterns of these WIM sites are presented in Figure 3-14.

A close study of the months and DOW values reveals that, there are a few 48-hour counts from WIM 535 in Factor Group 3 that are attributed to the overlapping area. These counts belong to some days of week in March, April, May and June (Table 3-7). As shown in Figure 3-15, the increase in MU trucks during these particular months/DOW has resulted in an increase in the percentage of MU trucks.

Table 3-7 Months and DOWs Attributed to the Overlapping Area between SU Factor Groups 1 and 3 - WIM 535

Month	DOW	Month	DOW
Mar	Mon-Tue	Apr	Thu-Fri
Mar	Tue-Wed	May	Mon-Tue
Mar	Wed-Thu	May	Wed-Thu
Mar	Thu-Fri	May	Thu-Fri
Apr	Mon-Tue	Jun	Mon-Tue
Apr	Tue-Wed	Jun	Tue-Wed
Apr	Wed-Thu	Jun	Thu-Fri

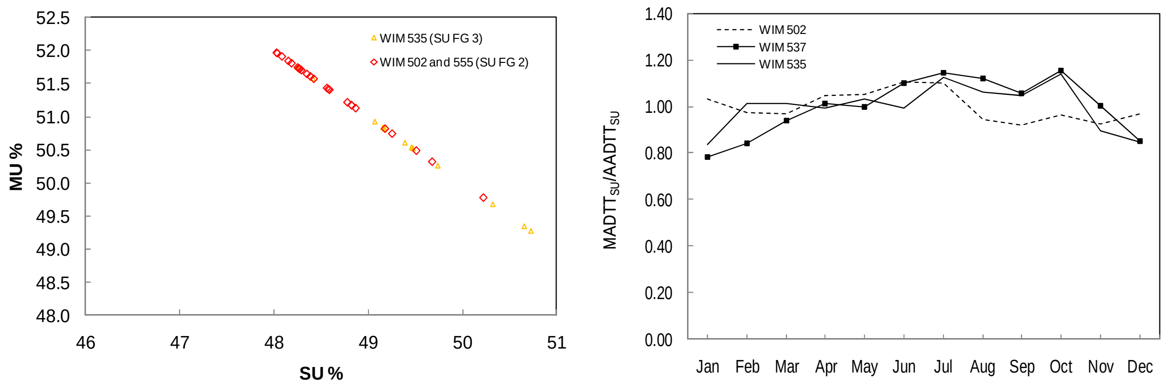


Figure 3-14 (a) The MU% versus SU% of the 2nd Overlapping Area, (b) The Seasonality Patterns of the WIM sites in the 2nd Overlapping Area

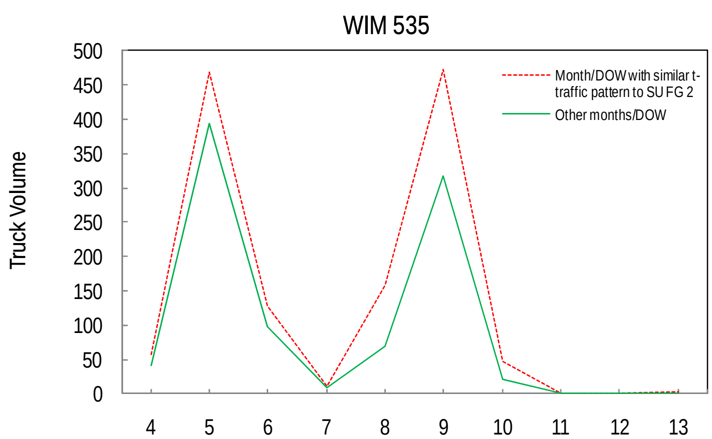


Figure 3-15 Vehicle Class Volume for WIM 535

The close study of the 48-hour classification counts in overlapping areas did not reveal any specific pattern to distinguish between factor groups. To resolve the issue, the research team met with NCDOT professionals and reviewed the results with them. As they suggested, the ranges of SU% and MU% may be extended equally for factor groups that share an overlapping area to cover the overlapping area. As a result of their suggestion the ranges of SU % and MU % associated to SU Factor Groups are revised. The following revised ranges help form a decision tree (Figure 3-16) that allows the traffic engineer to locate the correct seasonal factor to annualize the 48-hour counts. The seasonal factors are presented in Table 3-8.

- WIM sites with $9 \leq SU\% \leq 34$ and $66 \leq MU\% \leq 91$ belong to SU Factor Group 1
- WIM sites with $34 \leq SU\% \leq 50$ and $50 \leq MU\% \leq 66$ belong to SU Factor Group 2
- WIM sites with $50 \leq SU\% \leq 71$ and $29 \leq MU\% \leq 50$ belong to SU Factor Group 3
- WIM sites with $10 \leq SU\% \leq 23$ and $77 \leq MU\% \leq 90$ belong to SU Factor Group 4

The majority of WIM sites located in rural and rural-recreational area with AADTT ≥ 2000 belong to SU Factor Group 1. The roadways in this area mainly serve long haul trips (the % class 9 vehicles are higher than 70%). Similarly, WIM sites located in urban area with AADTT ≥ 9000 belong to SU Factor Group 1.

WIM sites located in rural and rural-recreational area with 1000 ≤ AADTT ≤ 2000 value belong to SU Factor Group 2. The roadways in this area have comparable combination of class 5 and class 9 vehicles, i.e., short haul and long haul trips are both frequent on these roads. WIM sites located in urban area in piedmont region with 2000 ≤ AADTT ≤ 7000 value belong to SU Factor Group 2.

WIM sites located in rural-recreational area in mountain region with AADTT ≤ 1000 value belong to SU Factor Group 3. The roadways in this area have high percentage of class 5 vehicles that are representatives of local and short haul trips (the percentage of class 5 vehicles are higher than 50%). Similarly, WIM sites located in urban area in piedmont region with AADTT ≤ 2000 value belong to SU Factor Group 3. These roadways are NC roads that serve local and short haul trips.

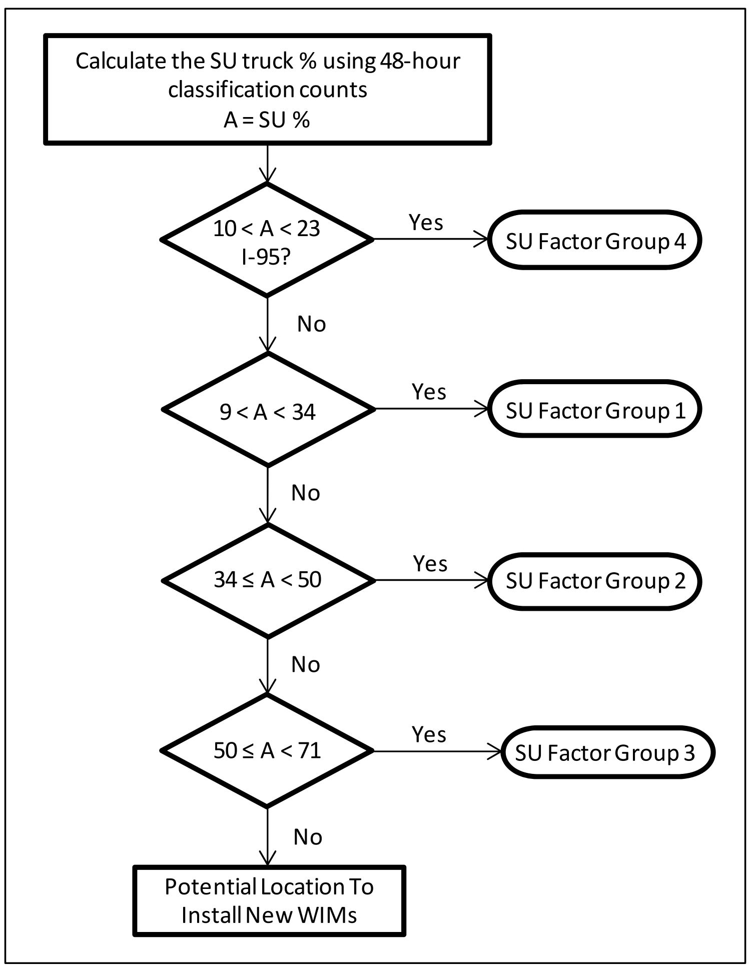


Figure 3-16 SU Seasonal Factor Decision Tree

Table 3-8 SU Month and DOW Seasonal Factors

	January							February						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
SU FG 1	3.0	0.9	0.9	0.9	0.8	0.9	2.1	2.8	0.9	0.9	0.8	0.9	0.8	1.8
SU FG 2	3.6	0.9	0.9	0.8	0.8	0.9	2.0	3.2	0.9	0.8	0.8	0.9	0.8	1.8
SU FG 3	3.9	1.0	0.9	0.9	0.9	0.9	2.0	3.5	0.9	0.9	0.9	0.9	0.9	1.9
SU FG 4	1.4	1.1	1.1	1.2	1.0	1.0	1.2	1.2	1.0	1.1	1.0	1.0	0.9	1.0

	March							April						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
SU FG 1	2.5	0.8	0.8	0.8	0.8	0.8	1.8	2.4	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 2	3.0	0.9	0.8	0.8	0.8	0.8	1.9	2.8	0.8	0.8	0.8	0.8	0.8	1.8
SU FG 3	3.4	0.8	0.8	0.8	0.8	0.8	1.9	3.0	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 4	1.0	0.9	1.0	1.0	0.8	0.8	0.9	1.0	1.0	1.0	1.0	0.8	0.8	0.8

	May							June						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
SU FG 1	2.3	0.8	0.8	0.8	0.8	0.8	1.7	2.2	0.8	0.8	0.8	0.8	0.8	1.6
SU FG 2	2.8	0.8	0.8	0.8	0.7	0.8	1.8	2.8	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 3	3.1	0.9	0.8	0.8	0.8	0.8	1.7	2.9	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 4	1.1	1.0	1.0	1.0	0.9	0.8	1.0	1.1	1.0	1.0	1.0	0.9	0.8	1.0

	July							August						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
SU FG 1	2.1	0.8	0.8	0.8	0.8	0.8	1.6	2.3	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 2	2.8	0.8	0.8	0.8	0.8	0.8	1.7	2.7	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 3	3.1	0.8	0.8	0.8	0.8	0.8	1.6	3.0	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 4	1.0	1.0	1.0	1.1	0.9	0.8	0.9	1.1	1.1	1.1	1.1	1.0	0.9	1.0

	September							October						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
SU FG 1	2.3	0.9	0.9	0.8	0.8	0.8	1.7	2.1	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 2	2.9	0.8	0.9	0.8	0.8	0.8	1.8	2.7	0.8	0.8	0.8	0.8	0.8	1.6
SU FG 3	3.1	0.9	0.8	0.8	0.8	0.8	1.7	2.8	0.8	0.8	0.8	0.7	0.7	1.5
SU FG 4	1.3	1.1	1.1	1.1	1.0	0.9	1.2	1.1	1.0	1.1	1.0	1.0	0.9	1.1

	November							December						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
SU FG 1	2.3	0.8	0.8	0.8	0.8	0.8	1.7	2.7	0.9	0.8	0.8	0.9	0.8	1.7
SU FG 2	2.9	0.8	0.8	0.9	0.8	0.8	1.8	3.1	0.8	0.8	0.8	0.8	0.8	1.7
SU FG 3	3.1	0.8	0.8	0.8	0.8	0.8	1.7	3.5	0.9	0.8	0.9	0.9	0.9	2.0
SU FG 4	1.1	1.0	1.0	1.0	0.9	0.9	1.1	1.4	1.1	1.1	1.1	1.0	1.0	1.1

3.5.3 Discussion on Annualizing Counts at Locations Identified as Outliers

So far we have identified some WIM sites as outliers to SU Factor Groups. These WIM sites are excluded from factor groups so a procedure is required to annualize 48-hour counts which are collected in the vicinity of these WIM locations. As explained earlier in Section 3.2 a highway segment that contains a WIM site is classified as a Category 1 highway, and a highway segment that is on the same road as a Category 1 segment but several miles away from it is Category 2 highway segment. If a 48-hour classification count is collected on a highway segment that happens to be a Category 1 or 2 highway segments, then the same seasonal factor of a WIM located on that highway may be used directly to annualize the counts. The specifications of the WIM sites identified as outliers are presented below:

- WIM 515 (rural principal arterial, located on I-77 in Mountain region, AADTT = 7092)
- WIM 536 (urban principal arterial, located on I-40 in the Mountain region, AADTT = 8142)
- WIM 537 (rural principal arterial, located on I-26 in the Mountain region, AADTT = 4426)
- WIM 538 (rural principal arterial, located on I-85 in Piedmont region, AADTT = 11503)
- WIM 529 (an urban road, located on US 264 in Coastal region, AADTT = 1467)
- WIM 548 (rural minor arterial, located on US 264 in Coastal region, AADTT = 4705)
- WIM 549 (rural minor arterial, located on US 421 in Coastal region, AADTT = 535)
- WIM 522 (rural principal arterial, located on US 74-441 in Mountain region, AADTT = 1155)
- WIM 533 (rural minor arterial, located on US 64 in Mountain region, AADTT = 354)
- WIM 560 (rural principal arterial, located on I-26 in Mountain region, AADTT = 1141)
- WIM 554 (rural principal arterial, located on US 220 in Piedmont region, AADTT = 2630)
- WIM 543 (rural principal arterial, located on I-85 in Piedmont region, AADTT = 5370)

3.6 Identifying MU Factor Groups

The TMG suggests generating factor groups for aggregated vehicle classes (single-unit and multi-unit trucks) especially in States with few multi-trailer trucks such as North Carolina to avoid the instability of factors that may result from low volume vehicle classes. In addition, calculating factor groups for each vehicle class complicates the seasonal factoring procedure without offering a considerable gain in separately annualizing low volume vehicle classes.

Figure 3-17 shows the seasonal patterns computed for 25 WIM sites. As expected, the two different aggregated vehicle classes (SU and MU) have different seasonal patterns. As Figure 3-17 shows, the seasonal patterns of SU trucks of these 25 WIM sites are similar while the seasonal patterns of MU trucks vary considerably. The fact that different factor groups are needed for different aggregated vehicle classes suggests that each WIM site (or road) may end up in multiple factor groups depending on what aggregated vehicle class is used for developing factor groups. Use of multiple groups may complicate the seasonal factoring procedure to some extent; however, it improves the accuracy of the factors developed.

As explained earlier, the initial clustering analysis of 42 WIM sites based on VCD in 12 months resulted in three homogenous clusters (18 WIM sites in Cluster 1, 5 WIM sites in Cluster 2, and 8 in Cluster 3) There are 11 WIM sites that belong to different clusters in different months. These WIM sites are analyzed further to identify the right cluster they belong to based on similarity of truck traffic patterns. These *preliminary* MU factor groups are further studied based on a secondary similarity factor that is the ratio of $MADTT_{MU}/AADTT_{MU}$. Figure 3-18 shows the $MADTT_{MU}/AADTT_{MU}$ ratio for WIM sites in the *preliminary* MU Factor Groups.

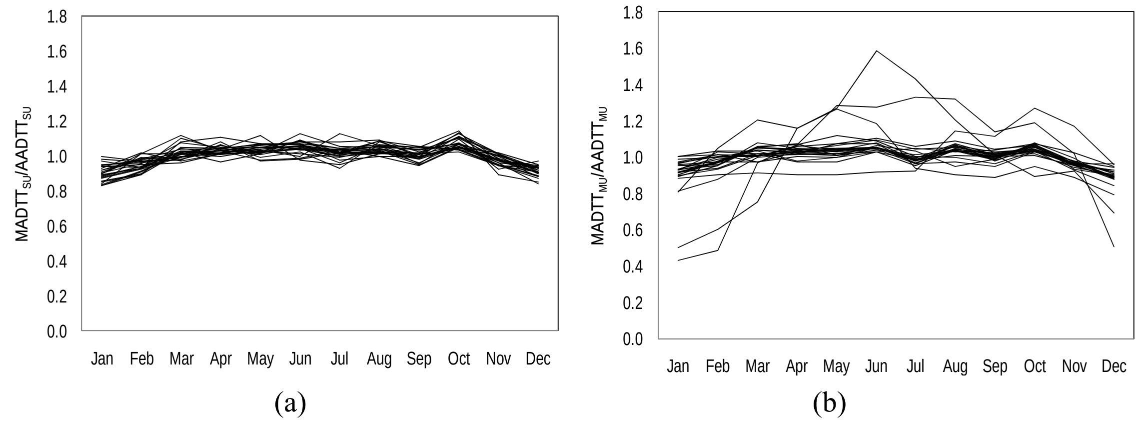


Figure 3-17 Seasonal Pattern of 25 WIM Sites by Aggregated Vehicle Classes (a) Single-Unit Trucks; (b) Multi-Unit Trucks

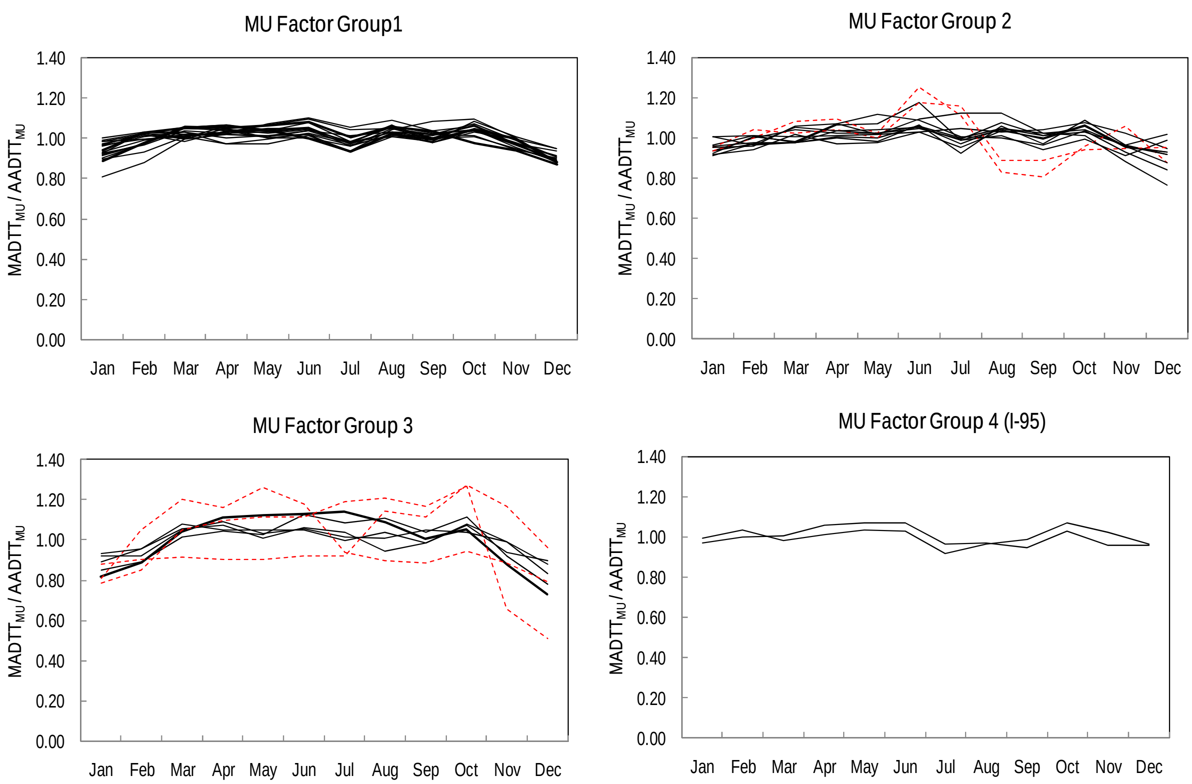


Figure 3-18 The Ratio of $MADTT_{MU}$/$AADTT_{MU}$ of Individual WIM Site in the *Preliminary* MU Factor Group

3.6.1 Stage 1 – The Ratio of $MADTT_{MU}$ / $AADTT_{MU}$

As shown in Figure 3-18, there are some WIM sites in MU Factor Groups 2 and 3 that have considerably different seasonal patterns compared to other WIM sites in the same group. We excluded these from group factors to form *secondary* MU factor groups that include WIM sites with consistent seasonal patterns. The truck seasonal patterns of *secondary* MU Factor Groups are presented in Figure 3-19.

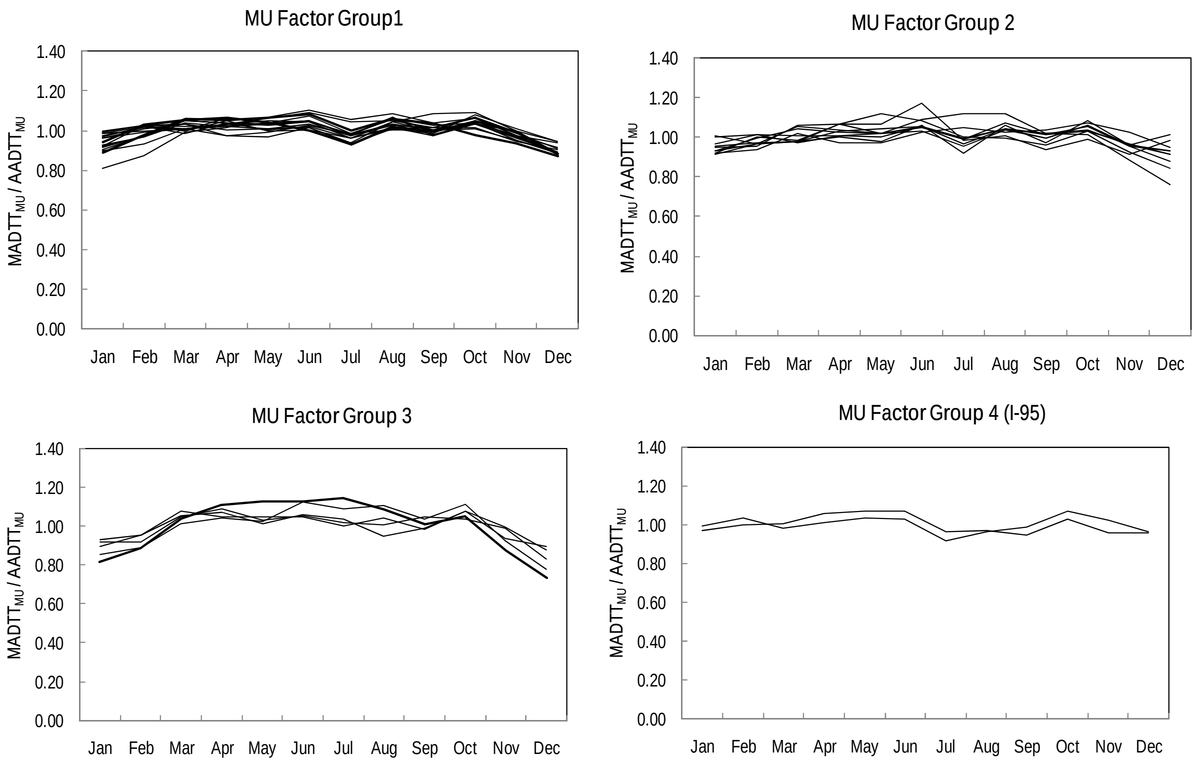


Figure 3-19 The Ratio of MADTT$_{MU}$/AADTT$_{MU}$ of Individual WIM Site in the *Secondary* MU Factor Group

The average ratios of MADTT$_{MU}$/AADTT$_{MU}$ of these four groups are presented in Figure 3-20. An important observation in Figure 3-20 is that the average MADTT$_{MU}$/AADTT$_{MU}$ ratios for the *secondary* MU Factor Groups 1 and 2 have very similar seasonal variation.

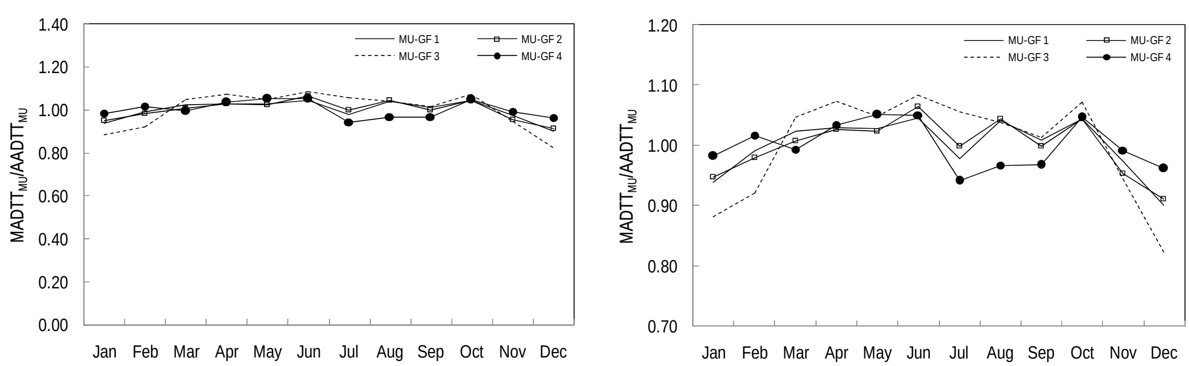


Figure 3-20 The Average Ratio of MADTT$_{MU}$/AADTT$_{MU}$ of MU Factor Groups 1, 2, 3, and 4 (The plots are different in the scale of Y-axis).

3.6.1.1 MU Factor Group 2

There are 10 WIM sites that belong to MU Factor Group 2. As Figure 3-18 shows there are two WIM sites with different seasonal traffic pattern compared to others. These WIM sites are excluded from the factor group. The specifications of these WIM sites follow:

- WIM 501/540 (a rural-recreational road, located on US 17 in coastal region),
- WIM 502 (a rural road, located on US 17 in coastal region),

Among 11 WIM sites that belong to different factor groups, there are nine WIM sites that belong to cluster 2 for most of the months. To examine the possibility of classifying these WIM sites as members of Factor Group 2, the team performed PCA on these WIM sites and the ones that are classified as cluster 2 in all months. The PCA analysis as well as the ratio $MADTT_{MU}/AADTT_{MU}$ identified WIM sites 529 and 549 as members of MU Factor Group 2. Thus, the total numbers of WIM sites that belong to Factor Group 2 are 10 WIM sites.

3.6.1.2 MU Factor Group 3

In order to detect the outliers in cluster 3, the team performed the PCA analysis using the ratio of $MADTT_{MU}/AADTT_{MU}$ defined by the first two principal components. The result of the PCA identifies WIM sites 533, 535, and 507/545 as outlier. The plot of the $MADTT_{MU}/AADTT_{MU}$ also shows WIM sites ratio in its original space also shows that these three WIM sites have different seasonality pattern compared to other WIM sites in Cluster 3 (Figure 3-21). These three WIM sites are excluded from Cluster 3 and the remaining ones are classified as Factor Group 3.

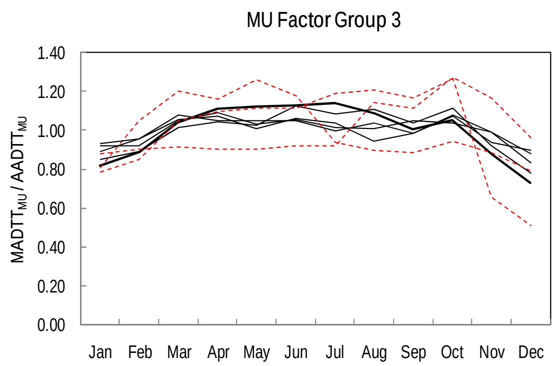


Figure 3-21 $MADTT_{MU}/AADTT_{MU}$ for the Factor Group 3

3.6.2 <u>Stage 2 – Confidence Interval of MU Factor Groups</u>

The concept of confidence interval is used as a second measure to determine the variability of the factors within that group. The confidence interval analysis revealed that the three MU Factor Groups have reasonably homogeneous traffic pattern. Thus the MU factor groups remain unchanged. The MU factor groups can be used to develop MU seasonal factors as presented in Table 3-12.

3.7 Decision Tree Development for MU Seasonal Factor Groups

The 48-hour site-specific counts are used to build a decision tree that helps the pavement designer select the right MU factor group.

Figure 3-22 shows the percentage of SU and MU trucks for WIM sites classified in MU Factor Groups 1, 2, 3, and 4. The figure shows that there exist distinct patterns for classifying WIM sites into Factor Groups. Here are some observations made from
Figure 3-22*a*:

- WIM sites with 8% ≤ SU% ≤ 33% and 66% ≤ MU% ≤ 92% belong to Factor Group 1,
- WIM sites with 31% ≤ SU% ≤ 50% and 50% ≤ MU% ≤ 68% belong to Factor Group 2,
- WIM sites with 47% ≤ SU% ≤ 70% and 30% ≤ MU% ≤ 52% belong to Factor Group 3,
- WIM sites with 10% ≤ SU% ≤ 22% and 77% ≤ MU% ≤ 90% belong to Factor Group 4,

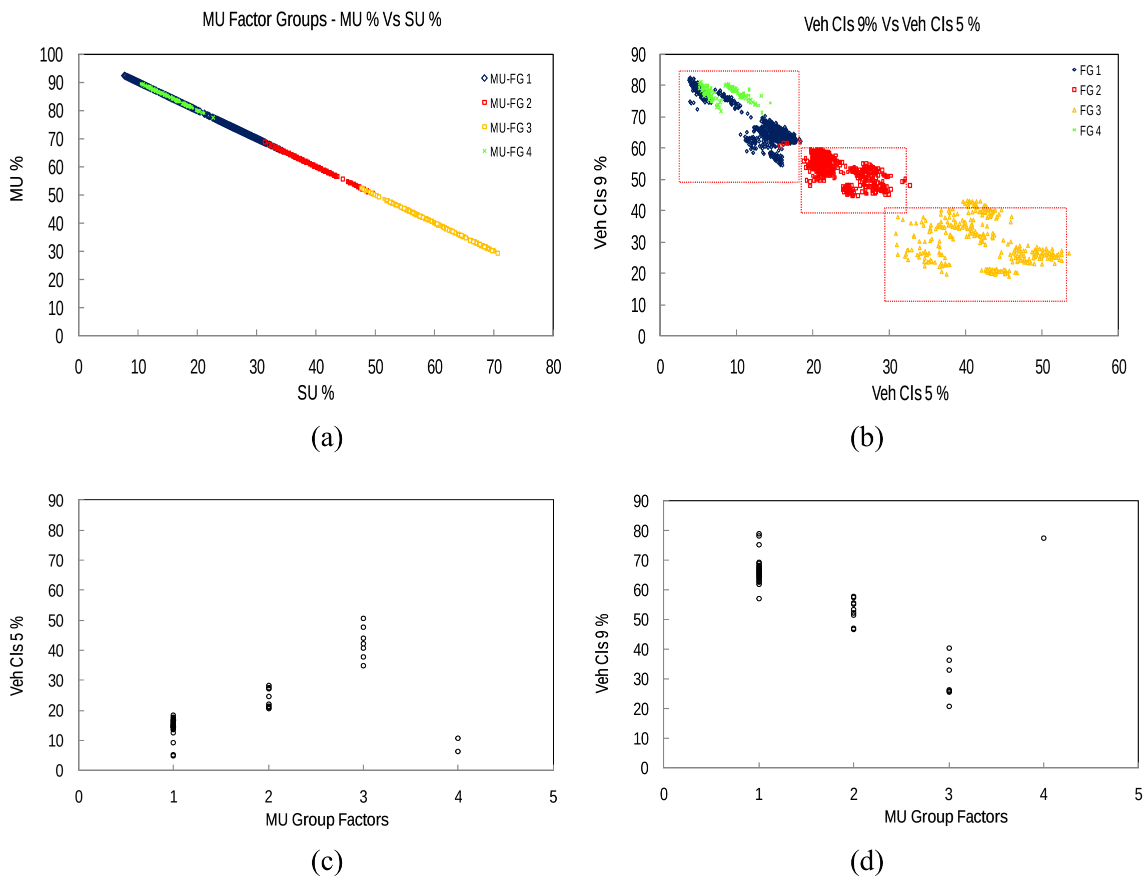


Figure 3-22 (a) SU% versus MU% of 48-Hour Counts Generated from WIM Databases; (b) %Class 5 versus %Class 9 of 48-Hour Counts Generated from WIM Databases; (c) The %Class 5 of MU Factor Groups, and (d) The %Class 9of MU Factor Groups

As
Figure 3-22*a* shows, there are some areas where MU Factor Groups experience overlaps in plotted traffic parameters.

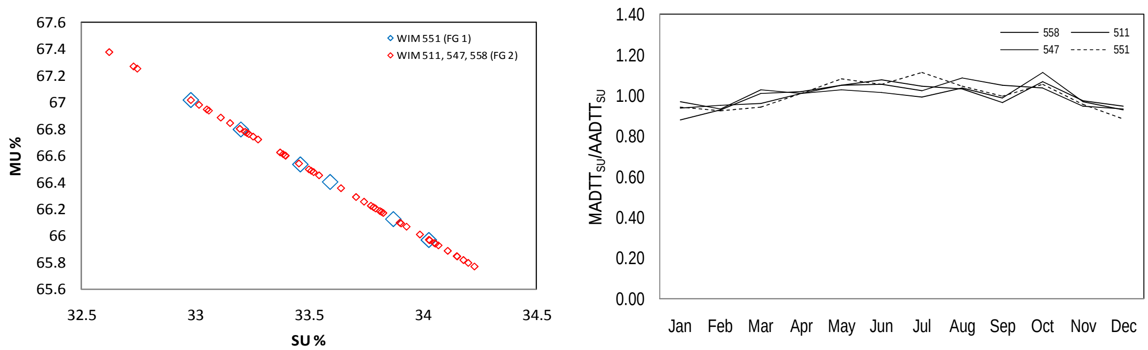
3.7.1 Overlapping Area between MU Factor Groups 1 and 2

There are seven WIM sites that contribute to the first overlapping area of Factor Groups 1 and 2:

- WIM sites 551 in Factor Group 1 (a rural road, located on US 74 in the Coastal region),

- WIM sites 552 in Factor Group 1 (a rural road, located on US 74 in the Piedmont region),
- WIM sites 558 in Factor Group 2 (an urban road, located on US 321 in the Piedmont region),
- WIM sites 511 in Factor Group 2 (a rural road, located on US 220 in the Piedmont region),
- WIM sites 547 in Factor Group 2 (a rural road, located on US 321 in the Piedmont region),
- WIM sites 549 in Factor Group 2 (a rural road, located on US 421 in the Coastal region),
- WIM sites 529 in Factor Group 2 (an urban loop located on US 264 in the Coastal region),

Figure 3-23 shows the details of the overlapping area for these four WIM sites. The seasonality patterns of these WIM sites are presented in Figure 3-23.



(a) (b)

Figure 3-23 MU% versus SU% of the Overlapping Area between MU Factor Groups 1 and 2, (b) The Seasonality Patterns of the WIM sites in the 1st Overlapping Area

A close study of the months and DOW values reveals that there are a few 48-hour counts from WIM 551 in Factor Group 1 that are attributed to the overlapping area. These counts belong to some days of the week in May, June, July, August, and September (Table 3-9). The average truck volumes of WIM 515 during these months/DOWs and also other months/DOW are plotted in Figure 3-24. As shown in Figure 3-24, the average volume of class 6 vehicles is higher in the specified months/DOWs compared to other months/DOWs. The high volume of class 6 vehicles results in higher SU truck percentage which itself creates overlaps between MU factor group 1 and 2. Similarly, as it is shown in Figure 3-25, the volume of class 6 Vehicles increases in May (Thu-Fri) and June (Thu-Fri) and results in increase in SU percentage. Thus, WIM 552, as well as WIM 551, contributes to the overlapping region between MU Factor Groups 1 and 2.

Table 3-9 Months and DOWs Attributed to the Overlapping Area between MU Factor Groups 1 and 2 - WIM 551

Month	DOW
Apr	Thu-Fri
May	Mon-Tue
May	Tue-Wed
May	Wed-Thu
May	Thu-Fri
Jun	Mon-Tue
Jun	Thu-Fri
Jul	Mon-Tue
Jul	Tue-Wed
Jul	Wed-Thu
Aug	Wed-Thu
Aug	Thu-Fri
Sep	Thu-Fri
Oct	Thu-Fri

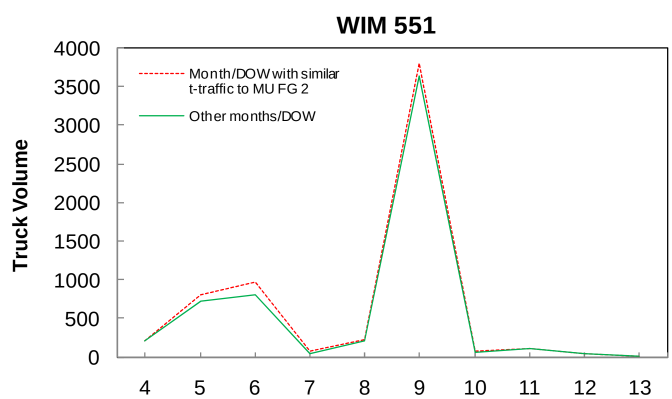


Figure 3-24 Vehicle Class Volume for WIM 551

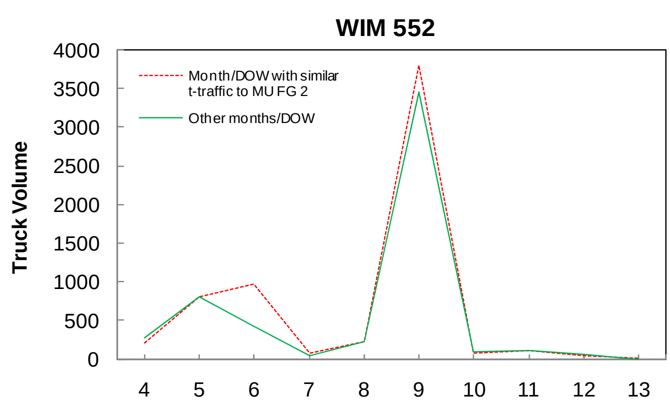


Figure 3-25 Vehicle Class Volume for WIM 552

3.7.2 Overlapping Area between MU Factor Groups 2 and 3

There are two WIM sites that contribute to the first overlapping between MU Factor Groups 2 and 3:

- WIM sites 535 in Factor Group 3 (a rural-recreational road, located on US 74 in Mountain region),
- WIM sites 555 in Factor Group 2 (a urban road, located on NC 68 in Piedmont region),

Figure 3-26 shows the details of the overlapping area for these WIM sites. A close study of the months and DOW values reveals that, there are a few 48-hour counts from WIM 535 in MU Factor Group 3 that is attributed to the overlapping area. These counts belong to some days of week in March, April, May and June (Table 3-10). Figure 3-27 shows the truck volume for these particular months and DOWs. As the figure shows, the increase in MU trucks results in increase in MU truck percentage which itself causes the overlaps between MU Factor Groups 2 and 3.

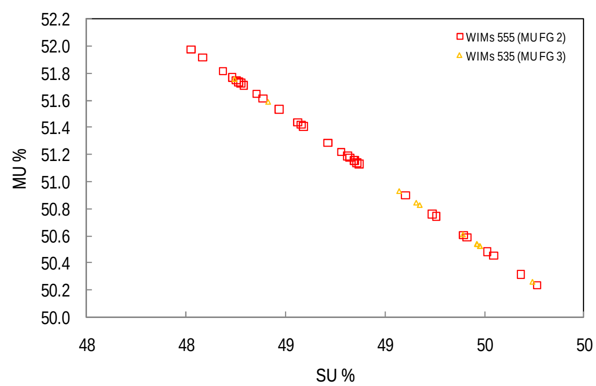


Figure 3-26 MU% versus SU% of the 2nd Overlapping Area between MU Factor Groups 2 and 3

Table 3-10 Months and DOWs Attributed to the Overlapping Area between MU Factor Groups 2 and 3 – WIM 535

Month	DOW
Mar	Tue-Wed
Mar	Wed-Thu
Apr	Mon-Tue
Apr	Tue-Wed
Apr	Wed-Thu
May	Mon-Tue
May	Wed-Thu
May	Thu-Fri
Jun	Mon-Tue
Jun	Tue-Wed
Jun	Thu-Fri

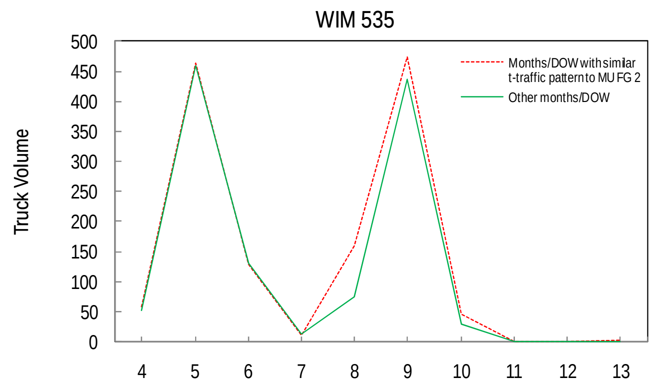


Figure 3-27 Vehicle Class Volume for WIM 535

Figure 3-28 shows the percentage of SU and MU trucks for WIM sites classified in MU Factor Groups 1, 2, 3, and 4. The figure shows that there exist distinct patterns for classifying WIM sites into Factor Groups.

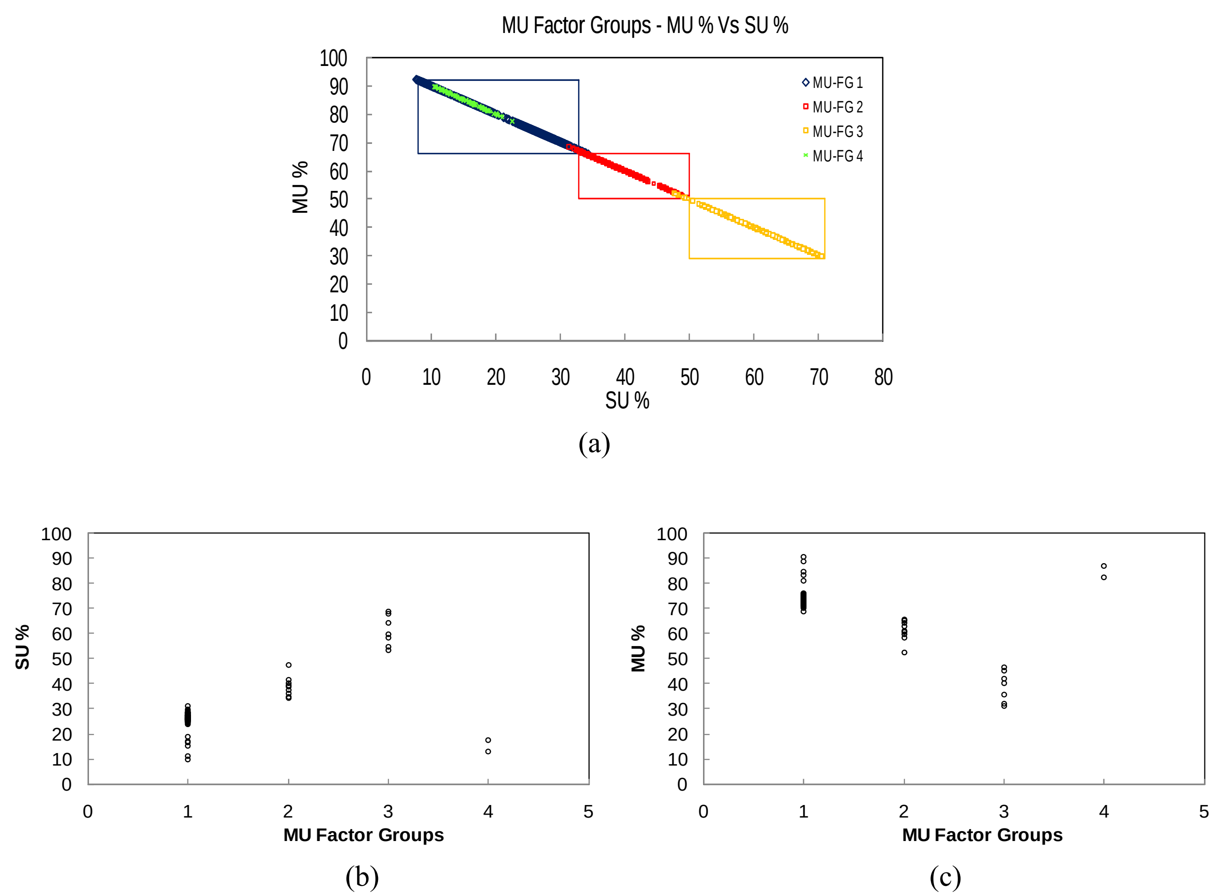


Figure 3-28 (a) The Percentage of SU Truck versus MU Trucks of 48-Hour Counts Generated from WIM Databases; (b) The Percentage of SU Truck of MU Factor Groups, and (c) The Percentage of SU Truck of MU Factor Groups

Similar to the SU factor group analysis, the close study of the 48-hour classification counts in overlapping areas did not reveal any specific pattern to distinguish between factor groups. As NCDOT professionals suggested, the ranges of SU% and MU% may be extended equally for factor groups that share an overlapping area to cover the overlapping area. As a result of their suggestion the ranges of SU % and MU % associated to MU Factor Groups are revised.

Figure 27 (a) shows the percentage of SU and MU trucks for WIM sites classified in MU Factor Groups 1, 2, 3, and 4. The figure shows that there exist distinct patterns for classifying WIM sites into Factor Groups. Here are some observations made from Figure 3-28 (a):

- WIM sites with 8 ≤ SU% ≤ 33 and 67 ≤ MU% ≤ 92 belong to MU Factor Group 1,
- WIM sites with 33 ≤ SU% ≤ 50 and 50 ≤ MU% ≤ 67 belong to MU Factor Group 2,
- WIM sites with 50 ≤ SU% ≤ 71 and 29 ≤ MU% ≤ 50 belong to MU Factor Group 3,
- WIM sites with 10 ≤ SU% ≤ 23 and 77 ≤ MU% ≤ 90 belong to MU Factor Group 4,

The above-mentioned observations form the basis of a decision tree that can be used to choose between several MU factor groups (Figure 3-29). WIM sites classified in each MU Factor Group are presented in Table 3-11. The month and DOW seasonal factors of four factor groups are also presented in Table 3-12.

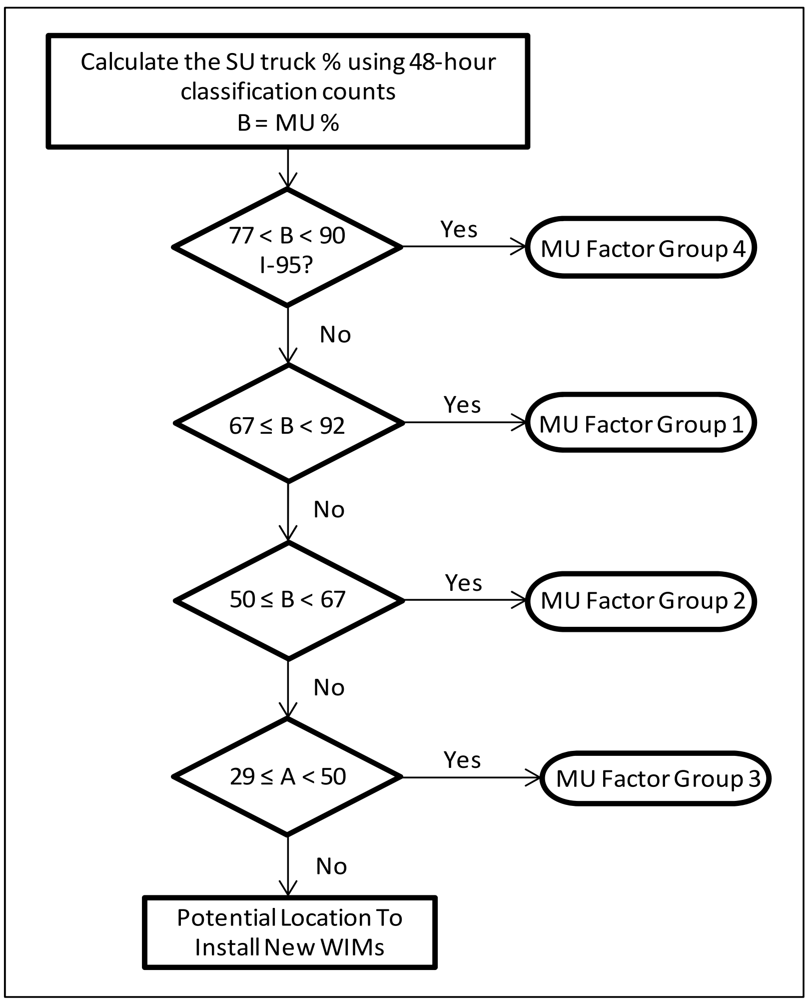


Figure 3-29 MU Seasonal Factor Decision Tree

Table 3-11 Specifications of WIM Sites Belonging to SU and MU Factor Groups

WIM ID	SHRP ID	Road	Road Type	Region	SU Factor Group	MU Factor Group	ADT_48
504	371645	US-74	RR	Coastal	1	1	2092
551	378201	US-74	R	Coastal	1	1	3081
510/526	375827	US-29	R	Piedmont	1	1	3056
525	371992	US-421	R	Piedmont	1	1	2472
509	372824	US-421	R	Piedmont	1	1	2538
552	370301	US-74	R	Piedmont	1	1	2751
554	377803	US-220	R	Piedmont	-	1	3312
553	377501	US-220	R	Piedmont	1	1	3483
531	370200	US-52	R	Piedmont	1	1	3846
537	377401	I-26	RR	Mountain	-	1	5451
520	371801	I-40	UR	Mountain	1	1	7349
559	371101	I-40	RR	Mountain	1	1	7575
515	375826	I-77	RR	Mountain	-	1	8413
536	374301	I-40	RR	Mountain	-	1	9749
538	372202	I-85	R	Piedmont	-	1	14362
543	379201	I-85	R	Piedmont	-	1	6459
557	374801	I-40	UR-	Piedmont	1	1	11156
539	375902	I-77	U	Piedmont	1	1	11974
542	377001	I-40	RR	Coastal	2	2	2129
506/544	371006	I-40	U	piedmont	2	2	8639
508	371805	US-64	R	Piedmont	2	2	1101
530	370900	US-1	R	Piedmont	2	2	2303
558	371701	US-321	U	Piedmont	2	2	3629
511	372819	US-220	U	Piedmont	2	2	3815
547	373501	US-321	U	Piedmont	2	2	5913
501/540	371028-371402	US-17	RR	Coastal	2	-	1159
502	371030	US-17	R	Coastal	2	-	1482
549	377002	US-421	R	Coastal	-	2	696
529	377302	US-264	Uloop	Coastal	-	2	1919
555	374002	NC 68	U	Piedmont	2	2	3056
556	371003	I-240	UR	Mountain	3	3	2052
535	371902	US-74	RR	Mountain	3	3	614
522	371803	US 74-441	RR	Mountain	-	3	1377
534	371901	US-64	RR	Mountain	3	3	895
523	371814	US-23-441	RR	Mountain	3	3	1287
546	375903	NC 24	U	Piedmont	3	3	2478
507/545	373816-373102	NC 147	U	piedmont	3	3	2655
541	377701	I-95	I-95	Coastal	4	4	8091
503/527	373011-376302	I-95	I-95	piedmont	4	4	9250
533	372101	US 64	RR	Mountain	-	-	439
560	375601	I-26	RR	Mountain	-	-	1403
548	374701	US-264	R	Coastal	-	-	5913
516	372825	SR 1138	U	Piedmont	Not Included in Analysis		774
521	371024	NC 107	RR^+	Mountain			439

Table 3-12 MU Month and DOW Seasonal Factors

	January							February						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
MU FG 1	3.1	0.9	0.8	0.8	0.8	0.9	2.4	2.9	0.9	0.8	0.8	0.8	0.9	2.3
MU FG 2	5.0	0.8	0.8	0.8	0.7	0.9	3.1	4.5	0.8	0.8	0.7	0.8	0.8	3.0
MU FG 3	4.5	1.0	0.9	0.9	0.8	0.9	2.6	4.2	0.9	0.8	0.9	0.8	0.9	2.4
MU FG 4	1.5	1.1	0.8	0.9	0.8	1.0	1.4	1.5	1.0	0.8	0.8	0.8	1.0	1.4

	March							April						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
MU FG 1	2.8	0.9	0.8	0.8	0.8	0.9	2.3	2.8	0.9	0.8	0.7	0.7	0.8	2.2
MU FG 2	4.4	0.8	0.8	0.8	0.8	0.8	3.0	4.5	0.8	0.7	0.7	0.7	0.8	3.1
MU FG 3	4.0	0.8	0.8	0.8	0.7	0.8	2.3	3.6	0.8	0.8	0.8	0.7	0.8	2.1
MU FG 4	1.5	1.1	0.8	0.8	0.8	1.0	1.5	1.4	1.0	0.8	0.8	0.8	1.0	1.4

	May							June						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
MU FG 1	2.7	0.8	0.8	0.7	0.7	0.8	2.2	2.7	0.8	0.8	0.7	0.7	0.8	2.1
MU FG 2	4.6	0.8	0.7	0.7	0.7	0.8	2.8	4.1	0.8	0.8	0.7	0.7	0.8	2.7
MU FG 3	3.7	0.8	0.7	0.8	0.7	0.8	2.2	3.3	0.8	0.7	0.8	0.7	0.8	2.1
MU FG 4	1.4	1.0	0.7	0.7	0.8	1.0	1.3	1.4	1.0	0.8	0.8	0.8	1.0	1.4

	July							August						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
MU FG 1	2.7	0.9	0.8	0.8	0.8	0.9	2.3	2.7	0.8	0.7	0.7	0.7	0.8	2.2
MU FG 2	4.5	0.8	0.8	0.8	0.7	0.8	2.9	4.4	0.8	0.7	0.7	0.7	0.8	2.7
MU FG 3	3.6	0.8	0.8	0.8	0.7	0.8	2.1	3.3	0.8	0.8	0.8	0.7	0.8	2.2
MU FG 4	1.5	1.1	0.9	0.8	0.9	1.0	1.6	1.6	1.1	0.8	0.8	0.9	1.0	1.6

	September							October						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
MU FG 1	2.8	0.8	0.8	0.7	0.7	0.8	2.2	2.7	0.9	0.7	0.7	0.7	0.8	2.2
MU FG 2	4.4	0.8	0.8	0.8	0.7	0.8	2.7	4.3	0.8	0.7	0.7	0.7	0.8	2.8
MU FG 3	3.5	0.9	0.8	0.8	0.7	0.8	2.1	3.3	0.8	0.8	0.8	0.7	0.8	2.1
MU FG 4	1.5	1.0	0.8	0.8	0.8	1.0	1.5	1.4	1.0	0.8	0.8	0.8	1.0	1.4

	November							December						
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat
MU FG 1	2.7	0.8	0.7	0.7	0.7	0.8	2.2	2.7	0.9	0.8	0.7	0.8	0.9	2.2
MU FG 2	4.2	0.8	0.8	0.8	0.8	0.8	3.0	4.5	0.8	0.8	0.8	0.8	0.8	2.8
MU FG 3	3.5	0.8	0.8	0.8	0.8	0.8	2.3	4.5	0.9	0.8	0.8	0.9	1.0	2.7
MU FG 4	1.4	1.0	0.8	0.7	0.8	1.0	1.3	1.4	1.0	0.7	0.7	0.8	1.0	1.4

3.8 Studying the Distribution of Trucks at 1000+ Coverage Count Locations

NCDOT staff has supplied 1106 48-hour classification counts to NCSU research team on December 18, 2009. Initially, the PCA analysis was performed to test the data for the presence of the outliers. Figure 3-30 is the plot of truck distribution with respect to the first two principal components that account for 97% of the variability that exist in dataset. As shown in Figure 3-30, there are eight coverage count locations that are outliers compared to other data points. These particular locations are discarded from the analysis.

The percentage of SU trucks versus MU trucks is plotted for the remaining data points (
Figure 3-31). These parameters form the basis for selecting the appropriate seasonal factor groups: the SU factor groups and the MU factor groups.

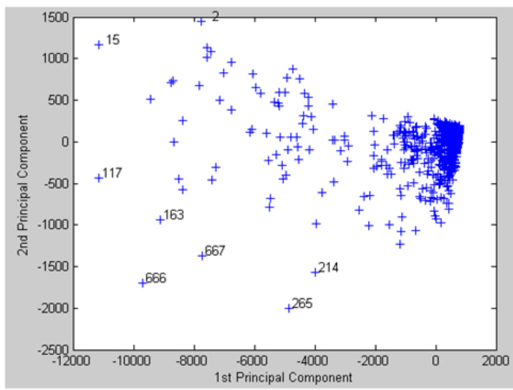


Figure 3-30 VCD for the 1106 Coverage Count Locations Plotted with Respect to PCs

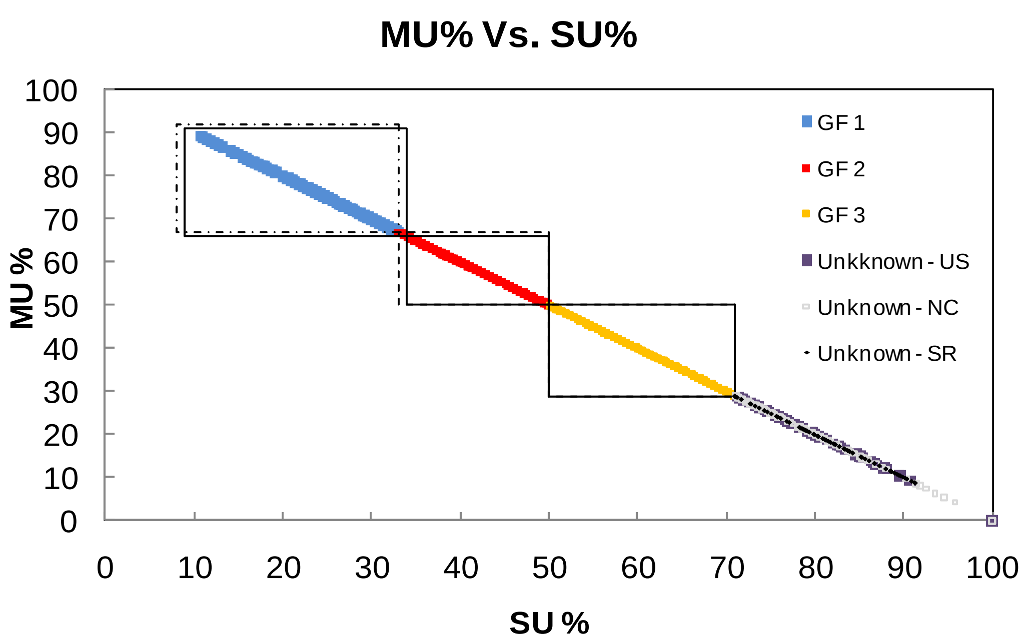


Figure 3-31 Percentage of SU Trucks versus MU Trucks for the 48-Hour Coverage Counts

(*The solid rectangles delimit the ranges of SU% and MU% for SU Factor Groups and the dashed rectangles delimit the ranges of SU% and MU% for MU Factor Groups.*)

The distribution of coverage count locations with respect to highway functional classification for each factor groups is presented in Table 3-13.

Table 3-13 Distribution of Coverage Count Locations with respect to Highway Functional Classification for each Factor Groups

Factor Groups	Hwy Functional Classification	Frequency
1	Interstate	66
1	US	87
1	NC	59
1	SR	2
1	**Total**	**214**
2	Interstate	10
2	US	128
2	NC	131
2	SR	3
2	**Total**	**272**
3	Interstate	5
3	US	131
3	NC	199
3	SR	19
3	**Total**	**354**
Unspecified	Interstate	0
	US	71
	NC	108
	SR	67
	Total	**246**

3.9 Results and Discussions

The TMG seasonal factoring procedure involves categorizing WIM sites that have similar truck traffic patterns through the year. To do so, the team performed hierarchical clustering analysis using VCD in each month and identified those WIM sites that tend to remain in same cluster over the year (from January to December). Before, performing the hierarchical clustering analysis, the team performed Principal Component Analysis to identify WIM sites with inconsistent traffic pattern with the remainder of the WIM sites. The result of PCA identified two WIM sites (WIM sites 516 and 521) as outliers. These outliers are removed from seasonal factoring analysis.

Initial clustering analysis of 42 WIM sites based on VCD for different months resulted in three major clusters (to be consistent with TMG terminology, we call the clusters Factor Groups). Each factor group includes WIM sites that tend to remain in same cluster over the year (from January to December). Initially, 31 WIM sites are categorized into either Factor Group 1, 2, or 3. There remain 12 WIM sites ungrouped. These initial factor groups are further refined based on a secondary similarity factor that is the ratio of $MADTT_x/AADTT_x$(x = SU or MU, as appropriate). The refining procedure may exclude some of the original WIM sites from the factor group or may include some of the ungrouped WIM sites into factor groups. Table 3-14 shows the final number of WIM sites that belong to different SU and MU factor groups.

A procedure is required to annualize 48-hour counts which are collected at the vicinity of ungrouped WIM locations. As explained earlier in Section 3.2, a highway segment that contains a WIM site is classified as a Category 1 highway and a highway segment that is on the same road as a Category 1 segment but several miles away from it is a Category 2 highway segment. If a 48-hour classification count is collected on a highway segment that happens to be a Category 1 or 2 highway segments, then the same seasonal factor of a WIM site located on that highway may be used directly to annualize the counts.

Table 3-14 Distribution of WIM Sites with Respect to SU and MU Factor Groups

	Number of WIM Sites SU FG	Number of WIM Sites MU FG
FG 1	12	18
FG 2	10	10
FG 3	6	7
FG 4	2	2
Ungrouped	12	5
Outliers	2	2
Total	44	44

When the SU factor groups are identified, a decision tree is required to choose between several SU factor groups. Qualitative parameters and quantitative factors may be used to differentiate between SU factor groups. The qualitative factors include functional classification of road and the geographical location of the road. The quantitative parameters include the ratio of SU trucks to MU trucks obtainable from 48-hour classification counts. A close study of qualitative parameters does not reveal discernible patterns to distinguish among SU factor groups. However, the quantitative parameters reasonably appear to distinguish factor groups though there are some overlaps between the ratio of SU and MU truck of factor groups. The close study of the 48-hour classification counts in overlapping areas did not reveal any specific pattern to distinguish between factor groups. To resolve the issue, the research team met with NCDOT professionals and reviewed the results with them. As they suggested, the ranges of SU% and MU% may be extended equally for factor groups that share an overlapping area to cover the overlapping area. As a result of their suggestion the ranges of SU % and MU % associated to SU and MU Factor Groups are revised. Based on the new ranges of SU% and MU%, a decision tree is developed that may be used for selecting the right seasonal factor for converting 48-hour classification counts of SU trucks and MU trucks into annual averages. The SU and MU seasonal factor decision tree are presented in Figure 3-16 and Figure 3-29, respectively.

As TMG emphasizes, the factoring process should be reviewed periodically to ensure that it is performing as intended [*TMG, 2001*]. For the first few years after initial development, these evaluations should be conducted every year. After that, the seasonal factoring procedure should be reviewed periodically every 3 years. When new WIM data is also available, they should be included in seasonal factoring analysis. New WIM data will help to improve the precision level of seasonal factor groups. This topic is discussed extensively in 0.

3.10 Implementation of VCD

To facilitate the process of generating vehicle class distribution factors for a selected location, an Excel-based “VCD Generator &ALDF Cluster Selector” tool was developed that can generate VCD factors [*Kim and Jadoun, 2010*]. A screen shot of the tool is illustrated in Figure 3 of the Executive Summary. The month and day of week seasonal factors (Table 3-8 and Table 3-12), single-unit and multi-unit decision trees (Figure 3-16 and Figure 3-29) are fundamental for the development of the tool. To generate VCD using the tool, the user simply enters the 48-hour classification counts collected at the design road during typical weekdays (Monday-Thursday). The user also specifies whether the counts are collected on Interstate I-95 or not. The tool will automatically generate the base year VCD factors. The base year VCD and AADTT values are sent to TPB to support AADT and truck traffic forecasts for the future year with and without the proposed project. TPB will provide the forecast VCD and AADTT (future year VCD and AADTT values) to the pavement designer. The designer will manually enter the values in the VCD table in the MEPDG software.

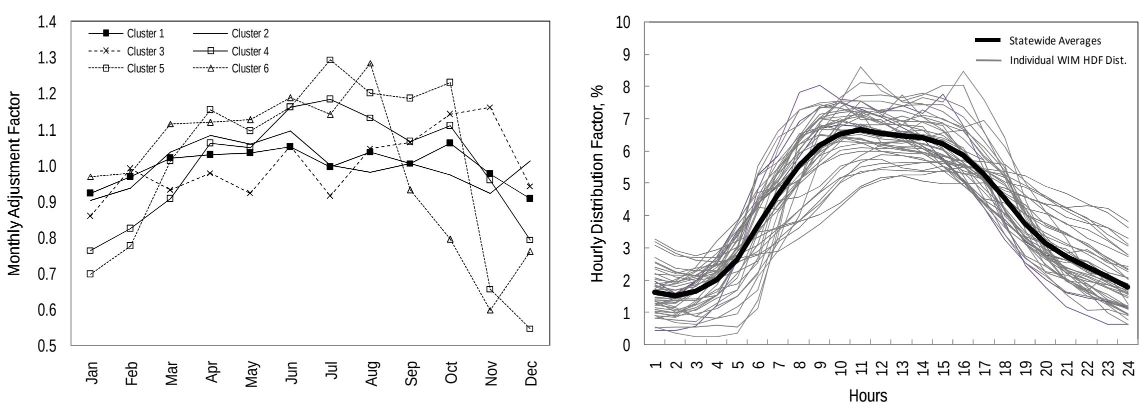
CHAPTER 4. OTHER TRAFFIC INPUTS

This chapter describes the development of hourly distribution factors (HDF) and monthly adjustment factors (MAF) and the analysis to determine if the factors affect pavement performance. Flexible and rigid pavement performance was found to be insensitive to site-specific HDF in North Carolina, and statewide averages for HDF may be used in the Mechanistic Empirical Pavement Design software for Levels 2 and 3 pavement design. Similarly, pavement performance in North Carolina was found to be insensitive to site-specific MAF, and statewide MAF averages may be used for North Carolina Levels 2 and 3 design. Using average HDF and MAF factors simplifies the pavement design process. Besides traffic volume adjustment factors (VCD, Chapter 3; HDF and MAF, Chapter 4; and ALDF, Chapter 7), other general traffic data are needed to characterize traffic patterns. These data items describe lateral traffic wander, axle configurations, axle spacing, wheelbase distribution, directional distribution factor, lane distribution factor, and operational speed. This chapter provides guidance on selecting these general traffic factors for pavement design.

4.1 Hourly Distribution Factor (HDF)

We used hierarchical clustering algorithm to identify representative clusters of HDF factors for 44 WIM sites (Figure 4-1*a*). The clustering analysis resulted in four representative clusters. To determine whether the HDF significantly affects the performance of representative NC pavement sections, the effect of the four HDF clusters on different performance measures for flexible and JPCP pavement sections was evaluated. Performance measures for flexible pavements are rutting, alligator cracking, longitudinal cracking, and the International Roughness Index (IRI). Performance measures for JPCP are faulting, percent slabs cracked, and IRI. Performance predicted by the MEPDG at the end of the design life was used in the analysis.

Pavement performance is considered to be insensitive to NC site-specific HDF if the biggest difference in predicted performance between any two HDF clusters does not exceed the sensitivity criteria (developed in cooperation with the NCDOT). Based on this approach, flexible and rigid pavement performance was found to be insensitive to HDF in NC. Therefore, the statewide HDF averages are recommended for use as input to Levels 2 and 3 pavement design (Figure 4-1*b* and Table 4-1). The approach simplifies the M-E pavement design process without losing accuracy. Similar results are found when comparing the effects on pavement performance of national default values of HDF.



(a) (b)

Figure 4-1 (a) Hourly Distribution Factor Averaged for HDF Clusters, (b) Hourly Distribution Factors for the 44 WIM Sites

Table 4-1 Statewide Average Hourly Truck Distribution Input

Midnight	1.63	**Noon**	6.48
1:00 AM	1.51	**1:00 PM**	6.41
2:00 AM	1.64	**2:00 PM**	6.23
3:00 AM	2.00	**3:00 PM**	5.87
4:00 AM	2.63	**4:00 PM**	5.30
5:00 AM	3.66	**5:00 PM**	4.55
6:00 AM	4.65	**6:00 PM**	3.74
7:00 AM	5.56	**7:00 PM**	3.15
8:00 AM	6.18	**8:00 PM**	2.73
9:00 AM	6.53	**9:00 PM**	2.42
10:00 AM	6.66	**10:00 PM**	2.12
11:00 AM	6.55	**11:00 PM**	1.79

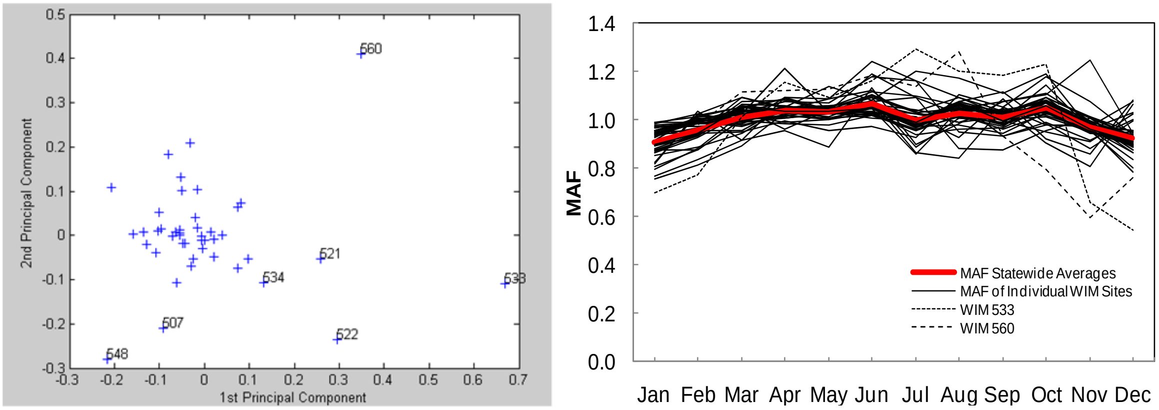
4.2 Implementation of HDF

The pavement performance in North Carolina was found to be insensitive to site-specific HDF, and statewide HDF averages may be used for North Carolina Levels 2 and 3 design. Table 4-1is a summary of state-wide average HDF values that are recommended for use in the MEPDG. Users manually input HDF data to MEPDG.

4.3 Monthly Adjustment Factor (MAF)

The monthly adjustment factor (MAF) is defined as the ratio of the monthly truck volume to the annual average monthly truck volume. Before we proceed with the analysis and result, it is important to identify and remove observations (WIM sites) that are inconsistent with the remainder of the data (i.e., outliers). Principal component analysis serves this purpose because it can be accomplished easily using statistical software including MATLAB. To test the data for the presence of the outliers, we plotted the data sets with respect to the first two PCs that account for 67% of the variability. The literature recommends retaining PCs that account for at least 70% of the total variability in data. The outliers detected from the plot of the first few PCs are those which inflate the variance that exists in the dataset and introduce bias in results, and these outliers need to be discarded. MATLAB software performs the PCA analysis and generates the plots based on the first two PCs. The results of the PCA are shown below in Figure 4-2 for the months of July and October. These two months are identified as the principal components because the variability of truck traffic is highest in these two months compared to other months at different WIM locations.

Figure 4-2*a* shows that WIM sites 533 and 560 are outliers compared to other data points. These two WIM sites are located on mountainous rural recreational routes. Figure 4-2*b* also verifies that the MAF at WIM sites 533 and 560 is appreciably different from MAF at other WIM locations. These two outliers are discarded, and the remaining 42 WIM sites are considered further in the clustering analysis.



(a) (b)

Figure 4-2 (a) Monthly Adjustment Factor Plotted with Respect to PCs, (b) Monthly Adjustment Factor for All WIM Sites.

The hierarchical clustering analysis based on MAF resulted in six clusters. Figure 4-3 shows the MAF for individual WIM site in each cluster as well as the average monthly adjustment factors (seasonal variation) of identified MAF clusters. The majority of the WIM sites (80%) are clustered either in Cluster 1, 2, or 4. WIM sites in these clusters have more stable seasonal variation compared to other clusters; the truck volume slightly decreases from November to February for WIM sites in Cluster 1. For WIM sites in Cluster 2, the truck traffic slightly drops at the end of the year (in November and December). WIM sites in Cluster 1, 2, and 4 are mainly located in the Piedmont region. Thus, the dominant seasonal variation in the Piedmont region is fairly stable through the year. The distribution of trucks in Cluster 4 is slightly higher in the first half of the year compared to Cluster 1. However, the truck volume decreases in the second half of the year. There are six WIM sites that do not follow the previous patterns and form separate clusters (Clusters 3, 5 and 6). For example, WIM sites 521 and 522 in Cluster 5 are located on rural-recreational roads in mountain region where truck trips drop in winter. Rural-recreational roads in mountains have higher truck traffic from April until October but the traffic drops to a very low level from November through February because the recreational travel declines significantly (as reflected in the drop in non-truck class volumes) at this time of year. The monthly variation of truck traffic at WIM site 501 and 502 (Cluster 6) is higher compared to other locations (high truck traffic in first half of the year followed by low truck traffic in the second half). The existence of farming industries (cotton, soybeans and corn) near the coast explains the higher number of trucks in June and July.

Pavement performance is considered to be insensitive to NC site-specific MAF if the biggest difference in predicted performance between any two MAF clusters does not exceed the sensitivity criteria (developed in cooperation with the NCDOT). Based on this approach, rigid pavement performance was found to be insensitive to MAF in NC. For flexible pavements, the average MAF for all sites and each of the clusters gave the same fatigue cracking (considering the criteria) which is the most important damage in NC. However, the longitudinal cracking fell beyond the acceptable sensitivity criteria defined by NCDOT. Since the longitudinal cracking model in MEPDG is not considered reliable (see Note below), using engineering judgment, the performance of flexible pavement is assumed to be insensitive to different distributions of MAF. Therefore, the statewide MAF averages are used as input to Levels 2 and 3 pavement design (Figure 4-2*b* and Table 4-2). The approach simplifies the M-E pavement design process without losing accuracy. Similar results are found when comparing the effects on pavement performance of national default values of MAF.

Note. The performance prediction model for longitudinal cracking that is embedded in version 1.0 of the MEPDG has problems and, therefore, predictions are not reliable and are ignored in the sensitivity study. In version 1.0, it is assumed that the number of cycles to failure (N_f) model can be used for alligator cracking as well as longitudinal cracking. This assumption is based on another assumption that the longitudinal cracking transfer function can handle the error inherent in the first assumption. Realizing that the N_f model currently embedded in the MEPDG was developed based on critical strain criteria, and knowing that longitudinal cracking is affected by thermal distresses and aging of the surface layers, it is clear that the longitudinal cracking predictions obtained from the MEPDG are questionable.

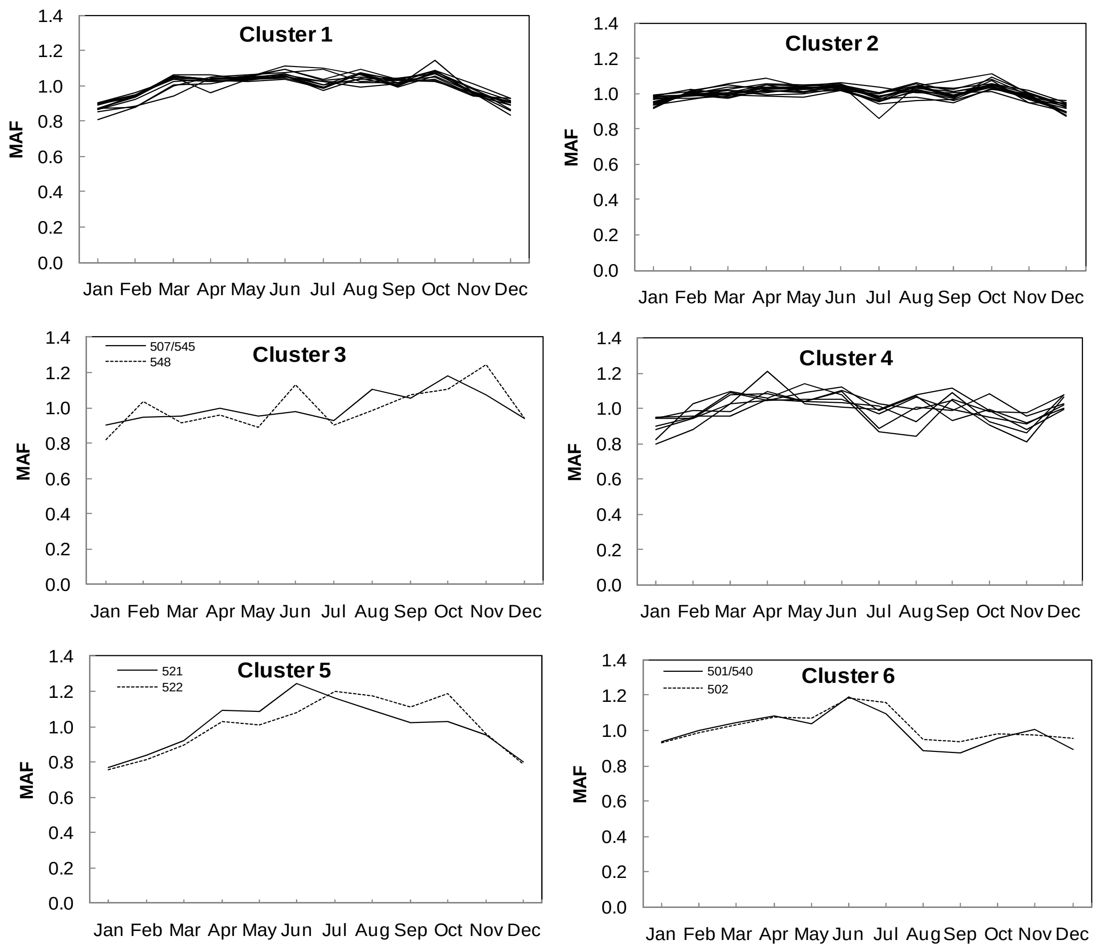


Figure 4-3 Monthly Adjustment Factor for MAF Clusters

Table 4-2 Statewide Average Monthly Adjustment Factor

Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
January	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

4.4 Implementation of MAF

The pavement performance in North Carolina was found to be insensitive to site-specific monthly adjustment factors (MAF), and statewide MAF averages may be used for North Carolina Levels 2 and 3 design. Table 4-2is a summary of state-wide average MAF values that are recommended for use in the MEPDG. Users may either input MAF data manually or import them directly from the MAF file that has been delivered to NCDOT.

4.5 General Traffic Input

Besides traffic volume adjustment factors (VCD, HDF, and MAF) and ALDF, MEPDG requires some general traffic data to fully characterize the traffic pattern for the design of new or rehabilitated pavement structures. The required traffic data are the same for designing either new or rehabilitated or for either flexible or rigid pavements. The following list identifies the typical required traffic data.

1. Loading details of the axle load and axle configuration. Default values or statewide average values might be used as input as stated below.

    a. Lateral traffic wander input including mean wheel location (in inches from the lane marking), traffic wander standard deviation (in), and the design lane width (ft) – National default values are provided.
    b. Average number of axles by axle type per vehicle classification – Statewide average values generated from 44 WIM databases are provided in Table 4-3. This statistic depends on the frequency of the axle configurations that occur in each vehicle class.
    c. Axle configurations including average axle width (ft), dual tire spacing (in), and tire pressure (psi) – National default values are provided depending on the axle load for single or dual usage.
    d. Axle spacing – Statewide average values are generated for three axle types using 44 WIM databases (tandem axle = 48.9 in, tridem axle = 52.7 in, and quad axle = 50.0 in).
    e. Wheelbase distribution – Wheelbase refers to the spacing between the steering and the first drive axles of the truck-tractor or heavy single-units - Default values are provided for short, medium and long axle spacing.

Table 4-3 Statewide Average Number of Axles by Axle Type per Vehicle Class

	Single	Tandem	Tridem	Quad
Class 4	1.77	0.23	0.00	0.00
Class 5	2.00	0.00	0.00	0.00
Class 6	1.12	0.93	0.00	0.00
Class 7	1.12	0.19	0.79	0.00
Class 8	2.44	0.57	0.00	0.00
Class 9	1.18	1.90	0.00	0.00
Class 10	1.04	1.25	0.52	0.15
Class 11	5.00	0.00	0.00	0.00
Class 12	3.82	0.96	0.00	0.00
Class 13	1.61	1.64	0.32	0.20

2. Other Traffic Factors: Default values for each of the following elements are provided for different types of highways. Once specified, these factors are treated as constants throughout the pavement design life.

a. Directional distribution factor – The directional distribution factors (DDF) account for the portion of total truck traffic in one direction. The national default value is 50%.

b. Lane distribution factor – The lane distribution factors account for the portion of the directional truck traffic traveling in the design lane. The following national default values which are based on the class 9 vehicle can be used:
   - Single-lane roadways in one direction = 100%
   - Two-lane roadways in one direction = 90%
   - Three-lane roadways in one direction = 60
   - Four-lane roadways in one direction = 45%

c. Operational speed – The national default value which is 60 mph can be used.

Table 4-4 identifies the sources of MEPDG traffic inputs. They may be developed from the available WIM data (which reaches back to weight and class counts), or from national defaults. Table 4-4 also shows the linkage or bridge between MEPDG traffic data and what is available from NCDOT traffic data sources with/without analysis.

4.6 Implementation of General Traffic Input

The user will either manually enter or update these data, or use the national default values.

- The number of axles by axle type per vehicle classification; input the data provided in Table 4-3 manually.
- Axle spacing; input the average statewide values provided in Table 4-4 manually.

For the following items use the MEPDG national default values provided in Table 4-4:

- Lateral traffic wander;
- Axle configurations (average axle width, dual tire spacing, and tire pressure);
- Wheelbase distribution;
- Lane distribution factor;
- Directional distribution factor;
- Operational speed

Table 4-4 MEPDG Traffic Input Requirements and Sources of Data

Traffic Input	Manual Input (Yes/No)	Provider	Level 1	Level 2	Level 3
Axle Load Distribution Factor (ALDF) – **Flexible Pavement**	No	TSG based on NC WIM weight data	ALDF files[1]	ALDF files[2] NC User's Guide	ALDF file[3]
Axle Load Distribution Factor (ALDF) – **Rigid Pavement (JPCP)**				ALDF file[3]	
Two Way AADTT	Yes	TPB	Appendix 2 (Table A2-1)	TPB uses the base year AADTT developed by TSG to estimate the future year AADTT	
Vehicle Class Distribution (VCD)	Yes	TPB	Appendix 2 (Table A2-2)	TPB uses the VCD developed by TSG to estimate the VCD for the future year	
Hourly Distribution Factors (HDF)	Yes	TSG based on NC WIM class data	Appendix 2 (Table A2-3)	Table 4-1 (Statewide Averages)	
Monthly Adjustment Factors (MAF)	Yes	TSG based on NC WIM class data	Appendix 2 (Table A2-4)	Table 4-2 (Statewide Averages)	
Number of Axles per Vehicle Class	Yes	TSG based on NC WIM weight data	Appendix 2 (Table A2-5, 6)	Table 4-3 (Statewide Averages)	
Traffic Growth Factor	Yes	Supplied by TPB/TF	Hierarchical levels does not apply		
Lateral Traffic Wander	Yes	MEPDG Default Values: Mean wheel location = 18 inches from the lane marking Traffic wander standard deviation = 10 inches Design lane width = 12 feet			
Axle Configuration	Yes	MEPDG Default Values: Average axle width = 8.5 feet Dual tire spacing = 12 inches Tire Pressure = 120 psi			
Axle Spacing	Yes	Supplied by TSG based on NC WIM weight data tandem axle = 48.9 inches tridem axle = 52.7 inches quad axle = 50.0 inches			
Wheelbase Distribution	Yes	MEPDG Default Values: Average axle spacing – Short (12 feet), Medium (15 feet), Long (18 feet) Percent of trucks – Short (33%), Medium (33%), Long (34%)			
Directional Distribution Factor (DDF)	Yes	MEPDG default values: Class 4, except for local or municipal routes = use 50% Class 4, for local or municipal routes = use 80%-100% Class 5, 6, 7 = use 62% Class 8, 9, 10 = use 55% Class 11, 12, 13 = use 50%			

Table 4-4 MEPDG Traffic Input Requirements and Sources of Data (cont.)

Traffic Input	Manual Input (Yes/No)	Provider
Lane Distribution Factor (LDF)[4]	Yes	MEPDG default values: Single-lane roadways in one direction = 100% Two-lane roadways in one direction, = 90% Three-lane roadways in one direction = 60% Four-lane roadways in one direction = 45% MEPDG default values is 95%
Operational Speed	Yes	Supplied by PMU (can be found in Highway Capacity Manual). If local data is not available use MEPDG default values (60 mph)

1. Axle Load Distribution Factor of all 44 WIM sites are delivered electronically in a format of ALDF files.
2. Level 2 ALDF files represent four ALDF clusters, and they are delivered to NCDOT electronically
3. Level 3 ALDF file is the statewide ALDF averages, and it is delivered to NCDOT electronically.
4. PMU Level 3 indicated that national defaults would be used for %Trucks in the design lane

CHAPTER 5. TRAFFIC FORECASTS FOR NCDOT M-E PAVEMENT DESIGN

Since traffic data inputs for MEPDG pavement design differ from those currently used in conventional pavement design, there is a need to provide clear information on truck traffic forecasting. The purpose of this chapter is to review procedures to forecast truck traffic for MEPDG. This chapter specifically discusses the following topics:

1. Truck traffic forecasting methods – MEPDG
2. NCDOT truck traffic forecasting procedures
3. Truck traffic forecasting options in the M-E pavement design software
4. MEPDG truck traffic forecasting guidelines for NCDOT

Note – A discussion on some terminologies used throughout this chapter is critical to avoid confusion. These terms are "truck percentages" and "truck distribution".

1. Truck percentage (AADT-based): NCDOT, FHWA, the traffic monitoring industry in general, as well as most design processes, define truck percentages as the portion of AADT (class 1 to 13) that are classified as truck types (class 4 to 13).
2. Truck distribution (AADTT-based): the MEPDG definition of truck percentages/distribution is related to VCD; this is a distribution of the total truck volumes AADTT (class 4 to 13 only) into the individual truck classes.

The truck percentages mentioned in this chapter refer to AADT-based truck percentages (definition 1 above).

5.1 Traffic Forecasting Procedures – MEPDG

The MEPDG requires forecasts of Annual Average Truck Traffic by truck class *i* ($AADTT_i$) over the design life of the pavement. The MEPDG software includes built-in linear and exponential procedures to forecast the rates of change by individual truck classes, groups of truck classes, or all trucks taken as one large group. A basic procedure is presented below for estimating rates of change in truck traffic volumes for the design lane and/or design direction at a project site.

<u>National Guidelines for MEPDG Traffic Forecasting Procedure</u>

In the basic procedure, the rates of change are referred to as "growth rates" to emphasize that for pavement design truck traffic growth is of primary interest. However, the procedure may also be applied to sites at which truck traffic is expected to decline.

The procedure consists of six steps [*NCHRP Project 1-39, 2005*]

1. *Distinguish two groups of vehicle classes: single-unit trucks and buses (Vehicle Classes 4–7); and combination trucks (Vehicle Classes 8–13)*. The distinction between the two groups permits the development of separate growth rates for single-unit trucks (which are used almost exclusively to serve local communities) and combination tractor trailer trucks (which serve regional and national markets).
2. *Identify all Level 1A sites for which estimates of AADTT have been developed for at least four years and that are believed to have historic rates of growth in the volume of heavy vehicles that are similar to those at the project site.* (Level 1A sites are sites for which continuous

data from an automatic vehicle classifier (AVC) are available for periods of at least one week for at least 12 consecutive months.

3. *Associate the project site with one or more Level 1A sites identified in Step 2.* Only Level 1A sites are used for this purpose because the $AADTT_i$ estimates developed for these sites are likely to achieve a much greater level of consistency over time than estimates developed for other sites.
4. *Use regression to estimate either linear growth rates or exponential growth rates for each Level 1A site for each vehicle class group.* In choosing between the two types of growth, a simple option is to choose the type that is believed to best describe expected future growth in truck traffic at the project site: linear growth if it is believed that the annual rate of increase in this traffic is not likely to grow significantly, and exponential growth if this annual rate of increase is expected to grow significantly. The Pavement Design Guide software has no provision for sites at which the annual increase is expected to decline over time. For such sites, linear growth should be assumed. If this option is used, the same type of growth should be assumed for the general vehicle groups (single-unit trucks and multi-unit trucks).

   A slightly more complex option is to choose the type of growth that best fits the historic data at the Level 1A sites and then to modify the type of growth in Step 6. If this option is used, the type of growth used in the regressions need not be limited to linear or exponential, and the regression for single-unit trucks can be one type of growth and that for combinations can use a different type of growth.
5. *For each vehicle class group, average the growth rates obtained in Step 4 for the associated Level 1A sites.*
6. *Judgmentally adjust the growth rates on the basis of a review of national and regional macroeconomic and local site-specific factors.* Macroeconomic factors include Gross Domestic Product (GDP), inflation, unemployment rates, etc. Site specific factors include land use, industrial development potential, and highway functional classification – Urban, Rural, Rural-Recreational, US Route, Interstate, etc.

The Step 6 review should consider any identifiable factors suggesting that future growth in heavy-vehicle traffic at the target site is likely to differ from past growth at the Level 1A sites. Factors to be considered include

- Expected changes in state or national macroeconomic trends (inflation, expansion, recession, etc.),
- Planned and recently completed facilities (industrial sites, distribution centers, ports, mines, quarries, commercial farms, etc.) that may affect the generation of truck trips, and
- Planned and recently completed highway projects that may affect truck routings.

This last category includes both new and upgraded feeder routes and new and upgraded parallel facilities.

More sophisticated forecasting procedures like multivariate linear regression, time series analysis, and travel demand models are discussed in Part 1, Appendix A of NCHRP Report 538 [*NCHRP Project 1-39, 2005*].

5.2 NCDOT Truck Traffic Forecasting Procedures

The material presented below describes current NCDOT truck traffic forecasting methods for site-specific projects. The material comes from NCDOT Report HWY 2004-11 [*Stone et.al, 2006*].

5.2.1 Current NCDOT Truck Traffic Forecasting Methods

NCDOT recognizes that total traffic and heavy truck volumes are critical factors in the design and maintenance of bridge structures, pavements, and highway lanes. Thus, NCDOT carefully prepares estimates of total traffic (AADT) forecasts for project design. NCDOT traffic forecasting approaches range from simple trend line analysis for project-level traffic forecasts to more complicated network-based methods for regional and statewide traffic forecasts. For project-level traffic forecasts NCDOT relies on the Traffic Forecasting Utility (TFU) spreadsheets to develop various trend line scenarios, which are used to inform decisions concerning the development of the forecast (Figure 5-1). These software tools apply linear, exponential and polynomial models to fit available traffic data to calculate a growth factor for total traffic for a highway project. However, NCDOT does not explicitly calculate a truck traffic growth factor for highway projects (as MEPDG requires). Rather, NCDOT typically assumes that the base year truck percentages of single-unit trucks (vehicle classes 4-7) and multi-unit trucks (vehicle classes 8-13) remain the same from the base year to the future year. Exceptions are made where there is local, specific knowledge that would indicate a change is warranted. Except for such ad hoc changes in the AADT-based truck percentages, NCDOT applies the base year truck percentages for two truck groups - single units (DUALs) and combination trucks (TTSTs) to the total traffic AADT forecast for the future highway segment in order to determine future truck volumes for the two groups. If the highway project is part of an urban network a model like TransCAD will likely be used to develop overall traffic which including truck traffic.

5.2.2 NCDOT Traffic Forecasting Utility

The most common NCDOT approach for project-level traffic forecasts is the TFU (previously called the Trend Program) to develop initial trend line information using linear and / or exponential functions. This tool utilizes ADT and/or AADT data provided by the Traffic Survey Group (TSG) and estimates a total traffic growth factor based on available historic years of data. The spreadsheet also accepts a user defined growth rate, which is based on the engineer's experience and judgment. The growth rate(s) calculated by the TFU is considered in conjunction with land use, anticipated land use, knowledge of the area, historic population trends, and transportation models (such as TransCAD) where available. Figure 5-1 describes the usual process for a traffic forecast conducted at NCDOT using the TFU. Percent "Duals" (single-unit trucks) and percent combinations TTSTs (multi-unit trucks) are typically obtained from project specific vehicle classification counts. Other resources include classification counts collected once every two years at automatic traffic recorder (ATR), HPMS sample locations, from coverage counts, or at sites similar to or near the project. In most NCDOT traffic forecasts, percent Duals and percent TTSTs of total traffic AADT are assumed to remain constant from the base year to the future year. Exceptions are made where there is local, specific knowledge that would indicate a change is warranted.

NCDOT research has also shown how to accommodate changes in percentages for Duals and TTSTs between the base year and current year, and how to use the results to predict future truck traffic [Stone et al, 2006]. The research of HWY 2004-11 describes how truck traffic forecasts may be calculated directly from historic NCDOT truck counts, VTRIS, and WIM data. This information is not currently incorporated into the typical project level traffic forecasting process.

5.2.3 Traffic Forecasting Utility (TFU) with WIM Data

WIM data contain consistent annualized truck traffic information for the period 1997-present for most years. WIM data are recorded at Weigh in Motion (WIM) stations and include truck weight information as well as classified vehicle classification counts. This data can be used directly for traffic forecasts. However, it is rare to have a project location near a WIM station because there are relatively few (44) such stations across the state. Data from WIM stations are currently utilized in traffic forecasts in the same manner as classification counts, ADT volumes and percent trucks (% Duals and % TTST) are provided to TPB/TF by TSG. With implementation of the MEPDG process, it is anticipated that if the project falls on a WIM station or in its vicinity, the WIM data can be directly used in the traffic forecasting process. (See the section entitled MEPDG Software Methods below for how MEPDG traffic input from WIM stations may be used for truck traffic forecasts.)

5.2.4 NCDOT Data Sources

The main data sources for forecasting truck traffic are regular coverage counts (48-hour ADT counts) throughout the state and continuously operating NCDOT WIM stations for vehicle classification counts. . In addition special sites may require turning movement counts usually taken over 48 hours. NCDOT data from WIM stations include continuous classified traffic counts, weight data by class, station numbers, and detailed descriptions of station locations (detailed description of WIM data is provided in Chapter 2).

The 48-hour classification counts are counted on typical days as Average Daily Traffic (ADT), and they are cleaned, and annualized (using seasonal factoring procedure explained in Chapter 3) to AADT to be used for trend analysis. Site-specific 48-hour counts should be converted to approximate annual values.

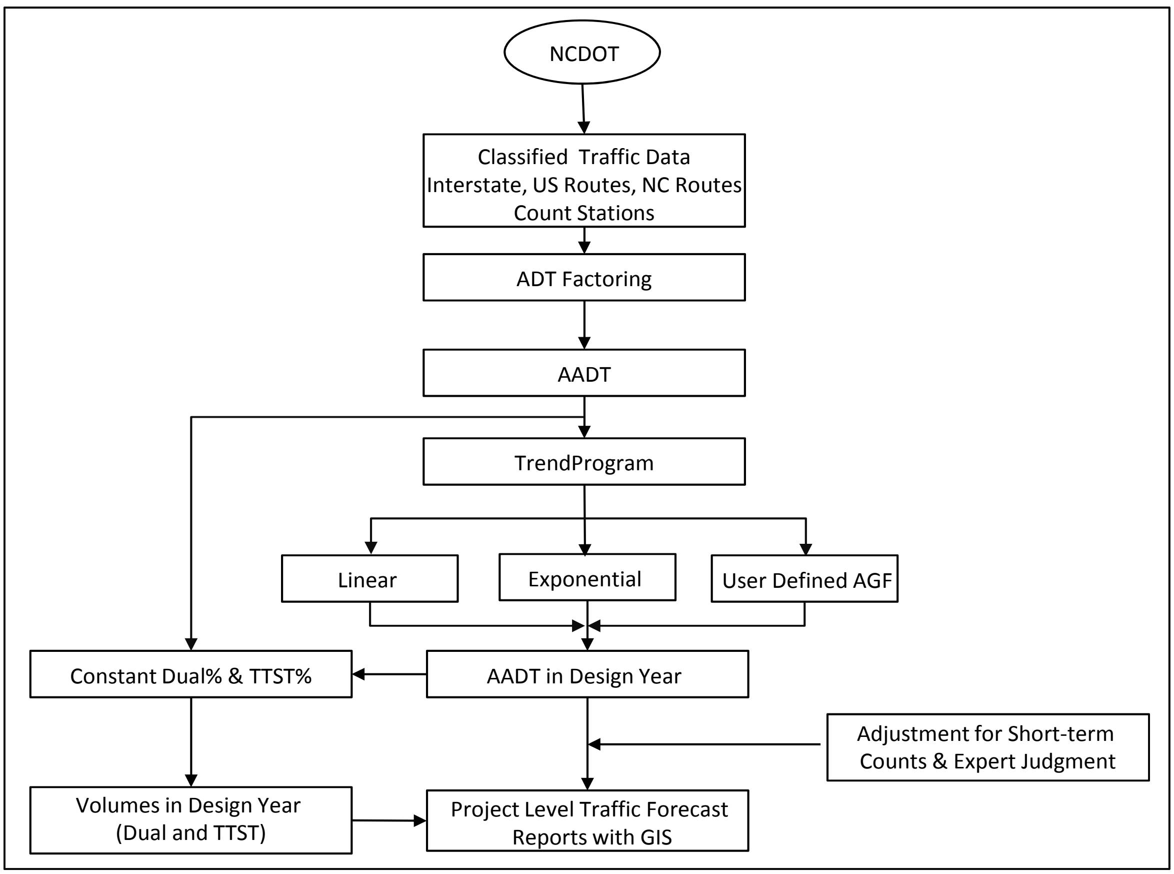


Figure 5-1 Forecasting Procedure using the NCDOT Traffic Forecasting Utility (previously called TrendProgram)

Source: NCDOT Report HWY 2004-11 [Stone et al., 2006]

5.3 MEPDG Software Traffic Forecasting Options

The Mechanistic-Empirical Pavement Design Guide (MEPDG) software allows users to choose one of three traffic growth functions to compute the growth in truck traffic over time. The three functions to estimate future truck traffic volumes are presented in Table 5-1.

Table 5-1 Function Used in Computing/Forecasting Truck Traffic Over Time.

Source: NCHRP 1-37A, MEPDG, Part 2, Chapter 4, 2004 [*NCHRP 1-37A, 2004*]

Function	Model
No Growth	$AADTT_{FY} = 1.0 \times AADTT_{BY}$
Linear Growth	$AADTT_{FY} = AADTT_{BY} + AADTT_{REF} \times GR \times t$
Compound Growth	$AADTT_{FY} = ADTT_{BY} \times (1+GR)^{t}$

In Table 5-1 $AADTT_{FY}$ is the annual average daily truck traffic at future year, *GR* is the chosen traffic growth rate in percentage, *t* is the forecast time period (FY – BY), $AADTT_{BY}$, $AADTT_{FY,}$ and $AADTT_{REF}$ are the annual average daily truck traffic at the base year, future year, and the reference year, respectively. Usually the base year equals the reference year. Separate growth factors for all truck classes (FHWA Vehicle Classes 4 – 13) can also be used in the MEPDG as shown in Figure 5-2.

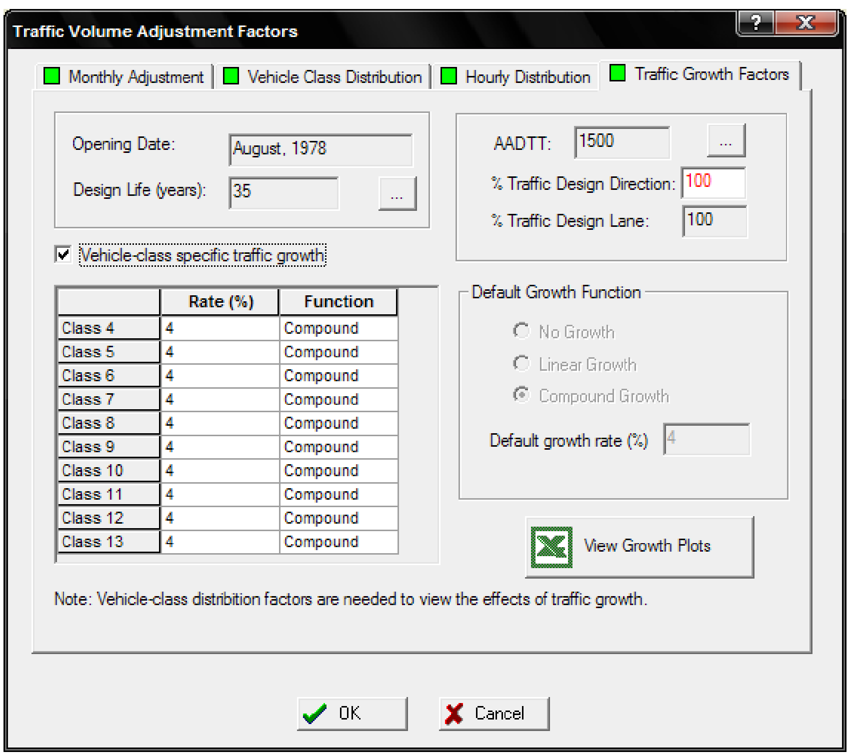


Figure 5-2 MEPDG Traffic Growth Factor Input Window

In addition to calculating the above mentioned traffic forecasts, the MEPDG software also has the option of generating growth plots in Excel. Figure 5-3 is an example of a growth plot generated from the MEPDG software.

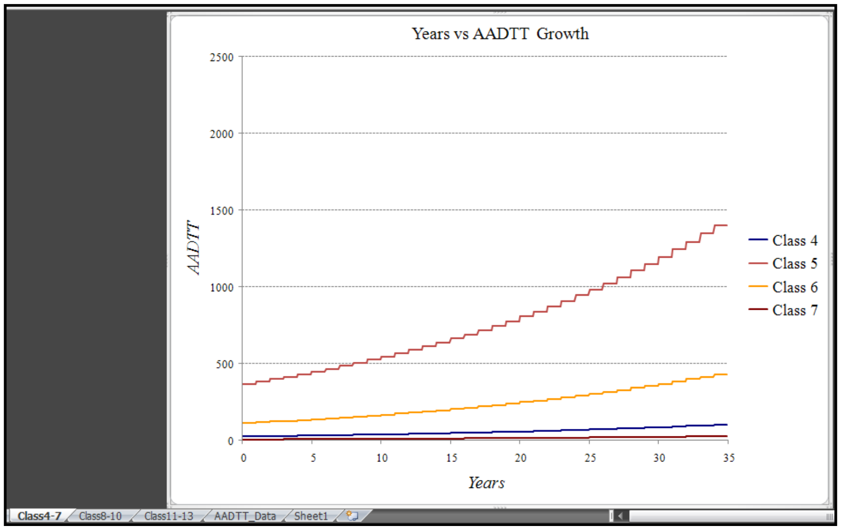


Figure 5-3 Traffic Growth Plot Generated by the MEPDG

The user can also specify the design life of the pavement, the construction month and year of the overlay pavement, existing pavement construction month and year, and the anticipated open-to-traffic month and year of the project. The type of design (New or Restoration) and overlay (Asphalt Concrete or Portland Cement Concrete) can also be specified in the MEPDG software (Figure 5-4).

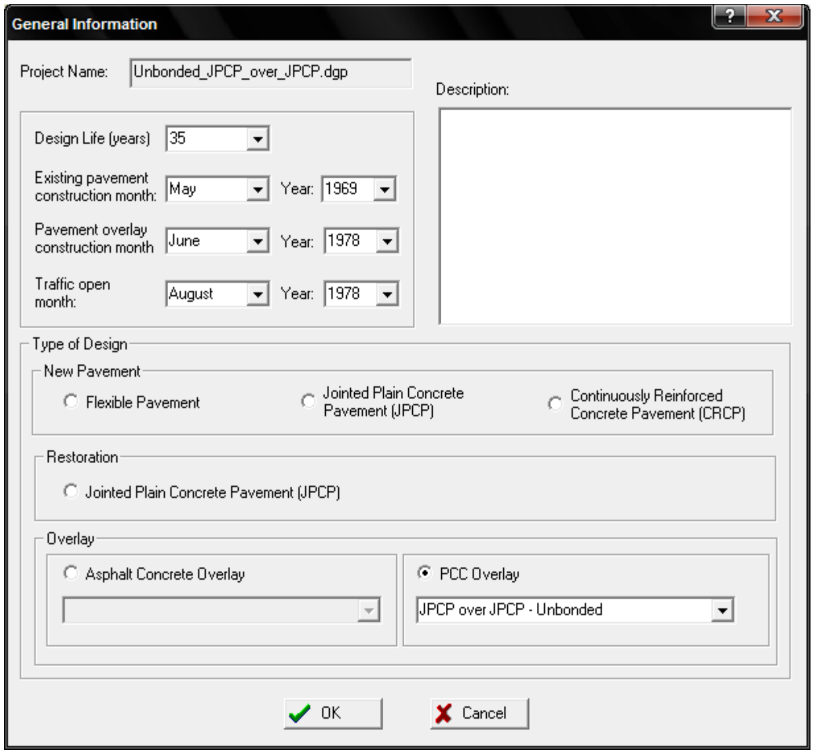


Figure 5-4 Traffic Growth Factor Customization Options in the MEPDG

In summary, NCHRP Reports 538 and 1-37A describe various methods for truck traffic forecasting including: linear growth models, compound growth models and more sophisticated multivariate linear regression and travel demand models. The methods, examples, and case studies in those reports can be used by NCDOT in MEPDG pavement design software. Subsequent case study examples in this report will demonstrate guidelines and applications for NCDOT,

The MEPDG software has built-in traffic forecasting functions including linear and exponential rates. In order to forecast and view the effects of traffic growth on the individual truck vehicle classes, previously identified truck input data are used for base year VCD factors. The software allows adjustments for specific vehicle class traffic growth and for type of pavement design - Flexible Pavement, Jointed Plain Concrete Pavement (JPCP), and Continuously Reinforced Concrete Pavement (CRCP).

5.4 MEPGD Traffic Forecasting Guidelines for NCDOT

The NCSU team held meetings with NCDOT staff to review and select truck traffic forecasting methods to apply to mechanistic-empirical pavement design. During the first meeting the NCSU research team described the general requirements for truck traffic forecasts in MEPDG software, and NCDOT staff described their desire for an easy-to-apply method. The second meeting reviewed options for MEPDG methods in more detail and compared the methods to those used by NCDOT for conventional traffic forecasts. The second meeting included sources for data to use in the MEPDG forecasts, recent NCDOT traffic forecasts for a rural project (R-4909), and further discussions regarding potential customized methods for NCDOT including use of the general characteristics of statewide highway functional class by vehicle class data. The guidelines are presented below.

The following guidelines were developed by NCSU and NCDOT staff. They provide a foundation for truck traffic forecasting for MEPDG pavement design in North Carolina. Appendix 3 applies the guidelines to an example bypass forecast.

1. For pavement design, light weight vehicle classes 1-3 are not a factor in pavement performance and are not included in MEPDG. However, these vehicles make up the majority of traffic volumes and will continue to be part of the NCDOT forecasts for use in other highway design processes.

2. Data analysis and traffic forecasts can be simplified by considering two aggregate truck classes: single-unit (SU) trucks corresponding to vehicle classes 4-7 and multi-unit (MU) trucks corresponding to vehicle classes 8-13. In the following notes SU and MU terminology will be equivalent to Duals and TTSTs, respectively. Please note that SU and MU percentages are AADT-based percentages of total traffic, not total truck traffic AADTT as explained earlier in this chapter.

3. AADT Characteristics:

   a. AADT increases as highway functional class (FC) increases in a highway system. This characteristic allows us to use Table 5-3 and Table 5-4 to infer growth characteristics for the classes represented.
   b. AADT increases as Rural Systems change to Urban Systems for the same FC. This characteristic allows us to use Table 5-3 and Table 5-4 to infer growth characteristics for the highway classes represented.
   c. As a highway corridor matures AADT increases, the number of lanes increases, access becomes more limited, and FC sometimes changes to a higher class as mobility increases.

4. Other Considerations:
   a. As an urban area expands, portions of corridors will shift from rural to urban systems. Thus, in growing fringe areas that mark the transition from rural to urban highway functional classes, the rural classification of a facility may be changed to urban during the life of the highway project. And truck traffic growth factors and distributions may have to be adjusted appropriately.
   b. Some highway improvements (widening, medians, and limited access) change the character of the route where they improve mobility.
   c. Other highway improvements (bridge replacements on lower FC) may not change the character of the route where they improve mobility.
   d. Higher order FC highways have higher design standards (speed, sight distance, intersection/signal spacing) that improve mobility.

5. General Character of SU Truck Traffic:
   a. SU trucks define the group containing Vehicle Classes 4-7 including Bus, 2ASU, 3ASU, and 4ASU (Figure 2-1).
   b. SU trucks, especially the predominant class 5 (2ASU) “box trucks”, are used primarily for local urban and rural deliveries. The range of class 5 percents of the total AADT on various urban and rural highway functional classes is narrow from about 3% to 6% (Table 5-3). This indicates that SU volumes are related to total traffic. SU trucks make local deliveries and use all highway classes for access to homes and businesses at levels proportional to total traffic. Variations in the percents depend on local land use type and intensity.

c. SU truck annual percent growth factors are likely to mirror AADT growth factors unless there are land use changes. SU truck traffic tends to be proportional to passenger vehicle traffic unless there are significant land use changes near the project.
d. The vehicle class 5 ranges of about 3% to 6% provides a good guide to check SU truck forecasts for pavement designs on facilities across NC. Note that these are AADT-based percentages.
e. As FC increases within the urban/rural systems, SU maintains relatively the same percentages (excluding Local FCs).
f. When a transition from rural to urban occurs, SU percentages drop moderately.
g. Inferences for SUs:
   - SU growth is very similar to AADT growth. Within a System, as AADT increases, SU volumes increase at a similar rate.
   - AADT increases at a slightly faster rate than SU for rural to urban transitions.
   - It appears improving mobility (improvements from lower to higher FC) has very little impact on changing SU growth.

6. General Character of MU Truck Traffic.
   a. MU trucks define the group containing Vehicle Classes 8-13 including 4AST, 5AST, 6AST, 6AMT, and 7AMT (Figure 2-1).
   b. MU trucks, especially the predominant class 9 (5AST) tractor trailer trucks, are used primarily for long-haul, through trips on higher functional class urban and rural highway facilities. Thus, the range of class 9 percents varies broadly across highway functional class (FC) with the greater percents occurring on arterial through routes and smaller percents on functional classes providing more local access (Table 5-3).
   c. The values of class 9 percents are much greater than the other vehicle classes in the MU category. Class 9 growth rate may be used to approximate the entire MU category (Classes 8-13).
   d. The values of class 9 percents for the various highway functional classes can serve as a guideline to check future MU truck traffic forecasts.
   e. For higher order FC, as FC increases within a System, the MU percentage increases significantly.
   f. For lower order FC, as FC increases within a System, MU maintains relatively the same percentage of AADT at very low values (including locals).
   g. When a transition from rural to urban occurs, MU percentage drops significantly.
      - For higher order FC, the significant jump in MU percentage may not be caused by growth. The long distances of MU trips and the higher mobility of higher FC concentrates MU trucks on these facilities and is probably the cause of the shift in percentages.
      - For lower order FC, within a System, MU volumes increase at a similar rate as AADT. The lower order systems serve the local portion of a long haul trip and growth is affected by the same factors that affect passenger vehicle and SU trucks.
      - AADT increases at a much faster rate than MU volumes for rural to urban transitions.
      - It appears improving mobility (improvements to raise FC) has a very significant impact on changing the basis for MU volume growth.

7. It is recommended that TPB continue to use current TPB traffic forecasting sheets showing vicinity maps, the local network of roads including the project main line, Y-line intersecting roads, project alternatives, base year traffic with and without the project alternatives, future traffic with and without the project alternatives, peak hour traffic direction and directional distribution

(D), AADT, and design hour volume, etc. The sheets will show the same type of data and forecasts for Dual (SU) and TTST (MU) trucks.

a. The peak hour directional distribution (D) which is mentioned above is different from directional distribution factor (DDF) required by MEPDG. The MEPDG definition of directional distribution factor is the portion of total truck traffic in design direction (the national default value is 50%).

b. In the new guidelines the custom of assuming constant SU and MU in the base and future years is no longer used, or appropriate as demonstrated by NCDOT Project HWY 2004-11. If different growth rates for total traffic, SU trucks, and MU trucks are used as suggested by these guidelines, there will be a change in the SU and MU percentages in the future year. This is not an issue for MEPDG as base year AADTT, VCD, and individual growth rates are input. However, it is a change from the custom of TPB/TF.

c. If the data supplied in the general forecast is to match the data provided for pavement design, then the truck percentages provided in the general forecast must be calculated after application of the individual growth rates to the volumes by class (AADT, SU, and MU). TPB/TF can no longer use base year values unless identical growth rates are used for all three.

8. TSG will provide the traffic characterization data (such as AADT, MAF, and HDF) to PMU. Traffic Survey will provide project specific data (annualized class counts) to TPB/TF to define base year traffic. TPB/TF will use the project specific data, as well as other resources and guidelines as discussed above, to generate a traffic forecast and provide forecast data to PMU. The forecast data include the AADTT, VCD, growth rates and growth functions for SU and MU trucks.

9. TSG will provide a variety of traffic characterization data to PMU (listed in Table 5-2). TSG will provide project specific annualized classification counts to TPB/TF. TPB/TF will then adjust the annualized counts as needed for impact and improvements to define base year traffic (AADTT and VCD). TPB/TF will use the project specific data, as well as other resources, to generate a traffic forecast and provide data listed in Table 5-2 to PMU.

Table 5-2 describes a preliminary recommendation of who provides what MEPDG information. Also see Figure 1.

Table 5-2 Selection of MEPDG Information

Traffic Input	Provider	Data Source
Hourly Distribution Factor	TSG	NC WIM Class Data
Monthly Adjustment Factor	TSG	NC WIM Class Data
Axle Load Distribution Factor	TSG	NC WIM Weight Data
Number of Axles Per Truck	TSG	NC WIM Weight Data
Axle Spacing	TSG	NC WIM Weight Data
Project-specific annualized class counts	TSG	48-hour classification counts
Base year AADTT	TPB	Annualized Class Counts*
Vehicle Class Distribution (class 4-13)	TPB	Annualized Class Counts*
Growth rate by individual or aggregate vehicle class (% per year)	TPB/TF	varies depending on what happens to traffic stream
Growth function by individual or aggregate vehicle class (linear or compound)	TPB/TF	varies depending on what happens to traffic stream

* Project-specific class count will be collected and annualized by TSG ; TPB will adjust as needed for impact and improvements.

10. TSG, TPB, and TPB/TF will need to work closely to provide the project specific data for a Level 2 design, which is the NCDOT selected level for MEPDG. Below, the NCSU team proposes a few recommendations that might improve the current practice at NCDOT.

    a. It is the expectation that TSG will annualize all class count data in 13 class distributions prior to delivery to the TPB/TF. This will give the forecaster project-specific VCD (the percentages generated from the annualized truck counts) and AADTT (the sum of the annualized truck counts).
    b. The expectations for TPB/TF follow.
        i. Specify base year VCD and AADTT – this may match the values generated from the TSG count data for many projects but will require some analysis for projects that cause a diversion in traffic (e.g. bypass, Appendix 3).
        ii. Check with TSG for any before and after counts for built projects to guide the selection of the truck diversion to the new facility (e.g. bypass). It is likely that widening will continue to have the same percent of SU and MU trucks as the original facility.
        iii. Specify the growth rate and function for each of the aggregate SU and MU categories. Generally:
            3. SU growth is not the same as MU growth.
            4. The growth for SU should be consistent across the individual classes (4-7).
            5. The growth for MU should be consistent across the individual classes (8-13).

            Note that TSG has very little to base truck growth on. TSG can reliably generate VCD and AADTT, and in some cases TSG can identify truck diversion to new facilities based on traffic data collected on existing routes. What is needed is a reliable way (a diversion database based on previous bypass projects for different sized cities) to generate truck growth input from current data. Table 5-3 and Table 5-4 provide insight when used with the SU and MU guidelines stated above.
        iv. In the absence of truck data resources for estimating SU and MU growth, AADT histories will be helpful. (NCDOT has a vast amount of AADT data.) As discussed previously,

some truck traffic growth patterns, especially SU traffic, will typically follow AADT growth on rural and urban facilities.

The foregoing are generalizations of what is common to many highways. However, there are always exceptions. Investigation of current conditions and anticipated development or changes affecting truck growth or routing need to be performed for each forecast. The forecaster needs to determine if these generalizations can be used or a deviation from what is typical will occur and modified estimates are needed.

Table 5-3 NCDOT 2008 HPMS Travel Activity by FHWA Highway Functional Class and Vehicle Class

FC	Functional Classification	MC	Cars	2A4T	Bus	2ASU	3ASU	4ASU	4AST	5AST	6AST	5AMT	6AMT	7AMT
1	Rural Principal Arterial – Interstate	0.4%	60.1%	13.7%	1.0%	2.9%	0.7%	0.1%	1.9%	17.6%	0.7%	0.5%	0.2%	0.1%
2	Rural Principal Arterial – Other	0.7%	66.8%	18.8%	0.8%	3.5%	1.2%	0.1%	1.3%	6.2%	0.3%	0.2%	0.1%	0.0%
6	Rural Minor Arterial	0.6%	66.8%	20.3%	0.9%	4.0%	1.2%	0.1%	1.3%	4.5%	0.2%	0.0%	0.0%	0.0%
7	Rural Major Collector	0.6%	72.3%	19.5%	0.5%	3.2%	1.1%	0.1%	0.8%	1.8%	0.1%	0.0%	0.0%	0.0%
8	Rural Minor Collector	0.7%	70.3%	20.8%	0.7%	4.2%	1.1%	0.1%	0.8%	1.1%	0.1%	0.0%	0.0%	0.0%
9	Rural Local System	1.1%	65.1%	22.7%	1.9%	5.7%	1.4%	0.1%	1.0%	0.8%	0.1%	0.0%	0.0%	0.0%
11	Urban Principal Arterial – Interstate	0.5%	66.8%	13.8%	0.9%	2.8%	1.0%	0.0%	1.5%	11.8%	0.3%	0.3%	0.1%	0.1%
12	Urban Principal Arterial – Other Freeways or Expressways	0.3%	71.3%	16.0%	0.7%	2.8%	0.9%	0.1%	1.3%	6.2%	0.2%	0.1%	0.0%	0.0%
14	Urban Principal Arterial – Other	0.6%	74.5%	17.0%	0.5%	2.9%	0.9%	0.1%	0.9%	2.4%	0.2%	0.0%	0.0%	0.0%
16	Urban Minor Arterial	0.6%	78.2%	15.7%	0.5%	2.8%	0.7%	0.1%	0.6%	0.6%	0.1%	0.0%	0.0%	0.0%
17	Urban Collector	0.8%	78.3%	16.2%	0.5%	2.6%	0.9%	0.0%	0.4%	0.2%	0.0%	0.0%	0.0%	0.0%
19	Urban Local System	1.0%	72.4%	18.4%	2.3%	3.6%	0.9%	0.0%	0.5%	0.6%	0.1%	0.0%	0.0%	0.0%

Table 5-4 Aggregated NCDOT 2008 HPMS Travel Activity by FHWA Highway Functional Class and Vehicle Class

System	FC	Functional Classification	PV	SU	MU
Rural	1	Rural Principal Arterial – Interstate	74%	5%	21%
	2	Rural Principal Arterial – Other	86%	6%	8%
	6	Rural Minor Arterial	88%	6%	6%
	7	Rural Major Collector	92%	5%	3%
	8	Rural Minor Collector	92%	6%	2%
	9	Rural Local System	89%	9%	2%
Urban	11	Urban Principal Arterial – Interstate	81%	5%	14%
	12	Urban Principal Arterial – Other Freeways or Expressways	88%	4%	8%
	14	Urban Principal Arterial – Other	92%	4%	3%
	16	Urban Minor Arterial	95%	4%	1%
	17	Urban Collector	95%	4%	1%
	19	Urban Local System	92%	7%	1%

CHAPTER 6. AXLE LOAD DISTRIBUTION FACTOR ANALYSIS

This chapter describes the development of axle load distribution (frequency) factors (ALDF) for use in MEPDG design. Different axle types and axle loads affect pavement damage differently. .Axle types include single, tandem, tridem, and quad with different spacing between axles. .Different axle loads occur depending on the product or commodity carried by the truck and how it is loaded on the truck. The frequencies of different loads per axle by axle configuration describe the loads for which the pavement must be designed. To simplify the selection of appropriate ALDF for pavement design, this chapter defines procedures to categorize (cluster) ALDF by axle type, WIM location, 48-hour traffic classification counts (percent class 5 and percent class 9 trucks), and roadway type (primary arterial, secondary arterial, and collector). Results are summarized in an easy to apply decision tree that helps the designer select the proper ALDF input.

6.1 Identifying Axle Types

The ALDF represents the frequency of individual load intervals, known as load bins, for four axle types: single, tandem, tridem, and quad. Thus, identifying axle types is required for generating ALDF. We derived axle type definitions from LTPP functional specifications; however, the definitions are adjusted to comply with the prevalent axle configurations in NC (Table 6-1). The data quality control rule for the minimum axle spacing is 24 inches, so there are cases that will not be encountered (the shaded cells in the table). For example, three axles cannot be classified as a single axle because the minimum axle spacing between three axles will be at least 24 × 2 = 48 inches which is greater than 39 inches. Instead the three axles would be classified as Tandem with 3 axles (Tandem-3).

Table 6-1 Axle Type Definitions Reflecting the NCDOT Data Characteristics

	Axle Spacing (inches)				
Axle Count	**24-39**	**40-96**	**97-150**	**118-192**	**193+**
1	Single	Single	Single	Single	Single
2	Single-2	Tandem-2	2 Singles	2 Singles	2 Singles
3		Tandem-3	Tridem	Tridem	2 or 3 config.
4		Tandem-4	Tridem-4*	Quad-4	Quad to 288
5		Tandem-5	Tridem-5*	Quad-5	Quad to 384
6			Tridem-6*	Quad-6	Quad to 480

** Quad axle types takes precedence over these configurations for spans ≥ 118 inches*

ASTM E 1572-93 procedure was used to identify the axle types [*ASTM, 1994*]. Details of the automated procedure follow:

1. Exclude all trucks with front axle spacing ≤ *96* inches.
2. Perform NCDOT truck configuration validation to eliminate invalid axle types.
3. Process all 2-axle trucks into two single axles.
4. Process trucks with three or more axles as follows:
    - 4.1. Evaluate axles in sequence from front to back of the truck.
    - 4.2. Use spacing criteria (96 inches) to determine if the current axle should be grouped with previous axle(s).
    - 4.3. Apply one of the following scenarios based on the result from the spacing evaluation:

Scenario 1 – Start new axle type
A – Evaluate spacing: *spacing > 96 or spacing > average spacing + 24 inches*
B – Create new axle type and place the current axle in new axle type
C – Identify the type of the previous axle type using Table 6-1
Scenario 2 – Add to previous axle type
A – Evaluate spacing: *(spacing ≤ 96 and |spacing – average spacing| ≤ 24 inches) or (previous axle type has only 1 axle)*
B – Add axle to previous axle type
Scenario 3 –Split previous axle type
A – Evaluate spacing: *spacing ≤ 96 and spacing < average spacing – 24 inches*
B – Create a new axle type and remove the last axle from previous axle type and combine with current axle
C – Identify the type of the previous axle type using Table 6-1

5. Process axle weights into axle type weights.

6.2 Multidimensional Clustering

Multidimensional clustering is a tool for data mining. One application of multidimensional clustering in the context of axle load analysis is to cluster simultaneously the four different axle types – single, tandem, tridem and quad. Instead of analyzing different types of axle clusters acquired from different runs of individual axle clustering, multidimensional clustering produces a unique set of clusters by simultaneously considering all axle types.

In multidimensional clustering analysis, special caution should be entertained to have all dimensions contribute reasonably to final clusters. If the variability of one dimension is considerably high compared to other dimensions, then this dimension will mask the effect of other dimensions. As a result, the final clusters would represent the variability of the dominant dimension not all dimensions. Thus, deciding what factors form the dimensions of the clustering analysis is an important issue to address before pursuing clustering analysis.

In order to identify the axle types (dimensions) to be included in clustering analysis, the damage analysis is performed. Using damage analysis, we identified the percent contribution of each axle type in pavement performance. Those axle types that are responsible for the high percentage of damage on pavement are considered in multidimensional clustering and the rest are discarded.

6.2.1 Damage Analysis to Identify Clustering Dimensions

Different axle configurations and axle loads affect pavement damage differently. For example, a single pass of a very heavy tandem axle might cause more damage to the pavement than multiple passes of lighter axles of the same axle type. For this reason, the research team developed a "damage factor" analysis that considers the effect of different axle configurations and axle loads on pavement damage. The detailed explanation of damage factor analysis is presented in Chapter 7.

First, we present the following useful definitions:

- The damage factor for any axle type-load combination is defined as the ratio of the "total pavement damage caused by that combination" to the "pavement damage caused by a standard 18-kip ESAL". Or

  Total damage caused by any axle type-load combination = (Damage Factor for that axle-type-Load combination) x (Damage caused by18-kip ESAL) (Equivalent Single Axle Load).

- The <u>axle load distribution factor</u> (ALDF) is the normalized frequency of individual load intervals, known as load bins, for four axle types: single, tandem, tridem, and quad.
- The <u>axle frequency</u> is the frequency of individual load intervals, known as load bins, for four axle types: single, tandem, tridem, and quad.

To quantify the effect of different axle types on pavement performance at 44 WIM locations, the axle frequency for a specific load bin is multiplied by its damage factor. The results are normalized to show the relative significance of each load bin on pavement performance. The following equations are used to calculate the percent of damage caused by each axle type:

Damage Caused by Single Axles
$=\sum_{L=3}^{41} \text{Axle Frequency}_{\text{L}} \times \text{Damage Factor}_{\text{L}} \sum_{\text{L}=3}^{41} \text{AxleFrequency}_{\text{L}} \times \text{DamageFactor}_{\text{L}}$
Damage Caused by Tandem Axles = $\sum_{L=6}^{82} \text{Axle Frequency}_{\text{L}} \times \text{Damage Factor}_{\text{L}}$
Damage Caused by Tridem or Quad Axles =
$\sum_{L=12}^{102} \text{Axle Frequency}_{\text{L}} \times \text{Damage Factor}_{\text{L}} \sum_{\text{L}=12}^{102} \text{AxleFrequency}_{\text{L}} \times \text{DamageFactor}_{\text{L}}$

Table 6-2 shows the percent of damage caused by each axle type at 44 WIM locations. The results are also shown graphically in Figure 6-1. As the results show, Single and Tandem axles on average account for 35% and 63% of damage on pavement, respectively. Although tridem and quad axles are heavier than tandem and single axles, they are less frequent than single and tandem clusters. Thus, their contribution in pavement damage is much less than the contribution of single and tandem axles. The damage analysis of tridem and quad axles showed that in most locations (nearly 80%) these heavy axles cause at most two percent of pavement damage. Given the negligible effect of tridem and quad axles on pavement, these axles are not included in multidimensional clustering analysis. As a result, the multidimensional clustering analysis reduces to two-dimensional clustering analysis with single and tandem axles as its two dimensions.

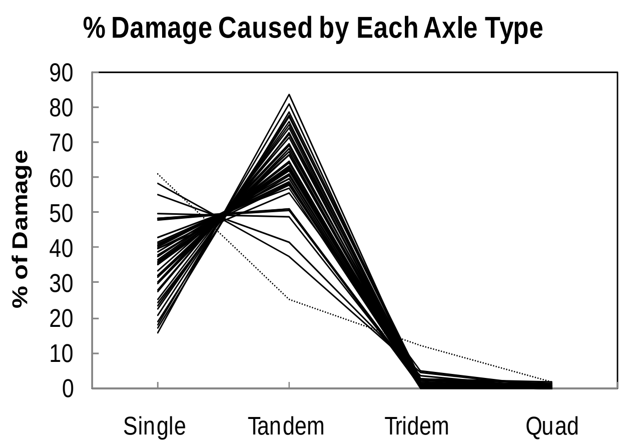


Figure 6-1 Percent of Damage Caused by Each Axle Type

Now that single and tandem axles are identified as the dimensions of clustering analysis, the damage analysis is repeated within each axle type (single and tandem) to identify those load bins that have high effects on pavement damage (higher than 1%) compared to other load bins. We set two rules for that purpose and discard bins that follow both rules from clustering analysis:
Rule 1: the percent of axles that falls within a specific load bin is less than 1% among all other axle type – load combination.

Rule 2: the percent of damage caused by axles in a specific load bin is less than 1% among all other axle type – load combination.

Figure 6-2 shows the single, tandem, tridem, and quad ALDF for 44 WIM sites. As the figure shows, all tridem and quad load bins follow Rule 1.

Figure 6-3 shows the normalized (Axle Frequency × Damage Factor) of 44 WIM Sites. Again, for all WIM sites (except WIM 516) all tridem and quad load bins follow Rule 2. With respect to single and tandem axles, there are also some load bins that follow both Rules 1 and 2. We discarded these load bins, as well as tridem and quad axles from clustering analysis.

WIM 516, mentioned as exception, is located on SR 1134 which has a low number of trucks (AADTT is 600). Vehicle Classes 4 and 5 are dominant on this road and they comprise 75% of all trucks that travel on this road. In all locations the relatively high frequency of single and tandem axles dominates the low frequency of tridem axles. This is not the case for WIM 516 for which the single and tandem axles are not so frequent. Thus, we observe a different pattern in this location compared to others (tridem axles do not follow Rule 2).

Table 6-3 shows the load bins that do not follow either one of the above mentioned rules, so they are further considered in clustering analysis.

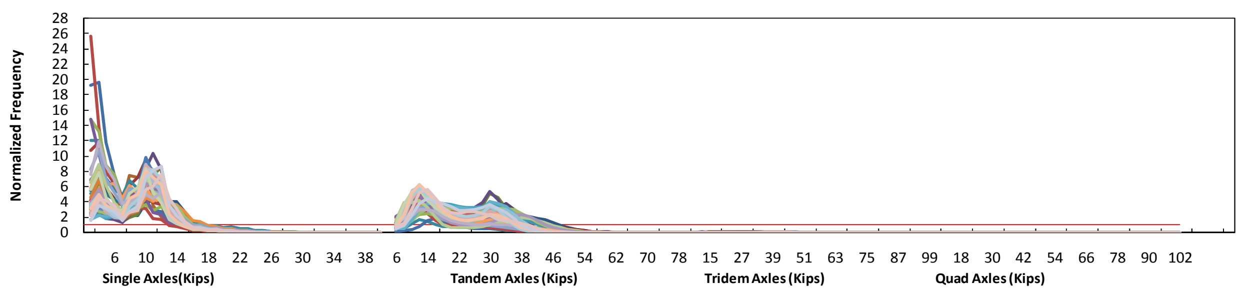


Figure 6-2 Single, Tandem, Tridem, and Quad ALDF of 44 WIM Sites

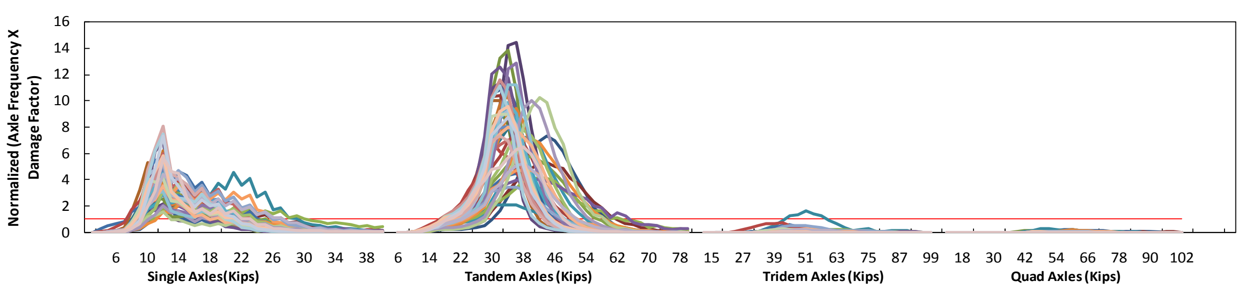


Figure 6-3 Normalized (Axle Frequency × Damage Factor) of 44 WIM Sites

Table 6-2 Percent of Damage Caused by Each Axle Type

	% Damage Caused by Axle Types			
WIM ID	**Single**	**Tandem**	**Tridem**	**Quad**
501/540	32	67	1	0
502	35	63	1	0
503/527	37	62	0	0
504	18	81	1	0
506/544	41	58	1	0
508	37	62	1	0
509	17	79	3	2
510/526	30	70	0	0
511	19	77	3	1
515	42	58	0	0
516	61	25	12	2
520	36	63	1	0
521	55	41	4	0
522	35	62	3	0
523	32	67	1	0
525	22	76	1	1
529	36	63	1	0
530	32	66	1	1
531	43	57	0	0
533	40	55	5	0
534	40	58	2	0
535	30	68	2	0
536	27	72	0	0
537	25	74	0	0
538	40	59	0	0
539	48	51	1	0
541	33	67	0	0
542	28	71	1	0
543	35	65	0	0
545/507	48	51	1	0
546	58	37	4	0
547	30	69	1	0
548	16	83	1	0
549	21	78	2	0
551	23	75	1	0
552	25	73	2	1
553	38	60	1	1
554	50	49	1	0
555	32	67	1	0
556	48	51	1	0
557	41	59	0	0
558	35	64	1	0
559	40	60	0	0
560	39	61	0	0
Average	**35**	**63**	**1**	**0**

Table 6-3 Load Bins Included in Two-Dimensional Clustering Analysis

Single	Tandem	Tridem	Quad
3 Kips- 21 Kips	6 Kips – 50 Kips	None	None

6.2.2 Two-Dimensional Clustering Analysis

We propose the two-dimensional clustering algorithm to generate representative ALDF clusters (single and tandem axles are the two dimensions). We identify clusters of WIM sites based on the similarity of their attributes: values in the 3 – 21 kip load bins (at 1-kip intervals) of the normalized axle load distribution of single axles and 6 – 50 kip load bins (at 2-kip intervals) of the normalized axle load distribution of tandem axles. The procedure of the two-dimensional hierarchical clustering algorithm (Ward's method) is outlined below.

Step 1. Form *n* clusters each consisting of exactly one WIM site;
Step 2. Merge two clusters that result in the smallest increase in the value of an index *E*, called the sum of squares index, and reduce the number of clusters by one. Index *E* quantifies the information loss associated with each merging. This means all possible combinations of two clusters are tested, the value of index *E* is calculated for each, and the one with the smallest value of *E* is selected
Step 3. Repeat Step 2 until the number of clusters equals one.

For each possible set of clusters, *E* is calculated as follows. First, the mean of each cluster is calculated. The cluster mean is a virtual WIM site whose axle load bin values are the average of the axle load values for the WIM sites in the given cluster. Second, the difference between each WIM site in a given cluster and its cluster mean is calculated. For example, suppose a cluster contains three WIM sites, each described by 42 load bins (3 – 21 kip single load bins at 1-kip interval and 6 – 50 kip tandem load bins at 2-kip interval). For the first WIM site, the difference in the values from it to its cluster mean values would be calculated, for each of the 42 load bins. The same computations would be performed for the second and third WIM sites, thus ending up with 3 × 42 differences for the cluster. Third, for each cluster the differences computed earlier would be squared. These values are added together for each cluster, thus providing a sum of the squares for each cluster.

The increase in the value of E resulting from merging clusters C_r and C_s into new cluster C_m is calculated as shown by the following equation:

$$\sum_{j_t}\left[\sum_{r=1}^{R}\left(x_{rj_t}-\bar{x}_{mj_t}\right)^2+\sum_{s=1}^{S}\left(x_{sj_t}-\bar{x}_{mj_t}\right)^2\right]$$

where,

$$\bar{x}_{mj_t}=\frac{1}{RS}\sum_{r=1}^{R}x_{rj_t}+\sum_{s=1}^{S}x_{sj_t}\;\forall j_t$$

x_{ij_t} denotes the axle frequency percentage taken by the load bin j for axle type t (for a single axle: j = 3 – 21 kip at 1-kip interval and for a tandem axle: j = 6 – 50 kip at 2-kip interval) at WIM site $i(i=1,\dots,n)$, $\bar{x}_{ij_t}$ denotes the average axle frequency percentage, and R and S are numbers of WIM sites in clusters C_r and C_s, respectively.

To find the best partitions that represent the natural structure of the data, the algorithm may stop to merge clusters further once a *significant* change in the homogeneity of clusters is observed. A metric, introduced by Mojena is used to explicitly define a *significant* change in the clustering criterion [*Mojena, 1977*].

6.2.3 Detection of Outliers Using Principal Components

There are situations where some of the observations are in some way different or inconsistent with the remainder of the data. The plot of the first few PCs may be used to detect outliers [*Jolliffe, 2002*]. The outliers that are detectable from the plot of the first few PCs are those which increase the variance that exist in the dataset. MATLAB software is used to perform the PCA analysis and generate the plots based on the first few PCs. The results of the principal component analysis are shown below for the joint single-tandem axle load distribution.

In order to test the data for the presence of the outliers, we plotted the data sets (single-tandem ALDF) with respect to the first two PCs that account for 87% of the variability that exist in dataset. As shown in Figure 6-4 WIM sites 521 and 533 are outliers compared to other data points. Thus WIM 521 and 533 are discarded from the clustering analysis. The clustering analysis is performed using 42 WIM databases.

- WIM sites521 is located a rural-recreational road on US 64 in Mountain region; AADTT = 354,
- WIM sites533 is located a rural-recreational road on NC 107 in Mountain region; AADTT = 367.

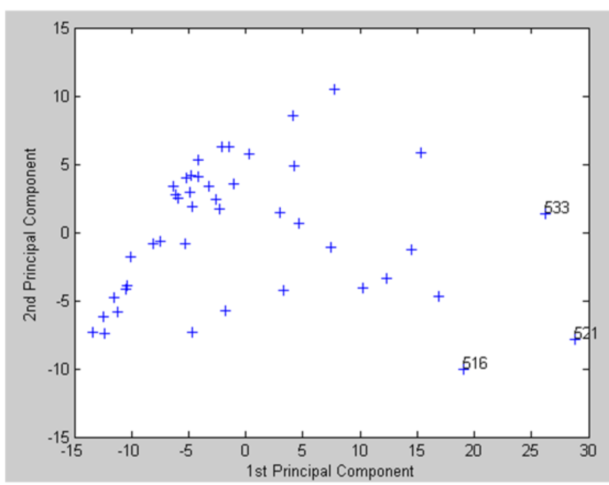


Figure 6-4 Single – Tandem ALDF, Plotted with Respect to Its PCs

Principal component analysis can be used in selecting a subset of variables that account for most of the variations in data set. One approach is to select a cumulative percentage of total variation that the selected PCs contribute, say 80% or 90%. The smallest number of PCs for which this percentage exceeds specifies the required number of PCs. The cumulative percentage of total variance is calculated as below:

Cumulative Percentage $t_p = 100 \times \sum_{k=1}^{p} l_k \Big/ \sum_{k=1}^{10} l_k$

Choosing a cut-off t^* between 80% or 90% and retaining p PCs where p is the smallest integer for which the $t^* > t$, provides a rule which in practice contains most of the information in first p PCs [*Jolliffe, 2002*]. After selecting the important principal components, the next step is to select a variable that represents each of the retained PCs. The variable that has the highest weight on the principal component would be selected to represent that component, provided it has not been chosen to present a PC with a larger variance. In that case, then the variable with the next largest weight would be chosen.

6.2.4 Identifying Aggregated Load Bins Using Principal Component Analysis

Table 6-3 shows the load bins that are included in clustering analysis. To reduce the effect of minor variations in individual load bins, the load bins are aggregated. The aggregated load bins do not necessarily include an equal number of original bins. The decision of selecting load bins to be aggregated into larger bins is mainly derived by the effect of axle types on pavement performance. Tandem axles account for 63% percent of damage on pavement while single axles account for 35%. Thus, it is desired to have aggregated bins that resemble the relative importance of these two axle types in clustering analysis. Principal Component Analysis is a technique used to evaluate different sets of aggregating bins.

The final set of aggregated bins is presented in Table 6-4. Tandem bins are aggregated into two large bins: heavy Tandem (22-50 Kips) and light Tandem (6-20 Kips), and single load bins are aggregated into four large bins: Single (11-20 Kips), Single (6-10 Kips), Single (5 Kips), Single (4 Kips), and Single (3 Kips)

The variation that is captured by each aggregated bin is presented in Table 6-4. The results show that the first four aggregated bins retain more than 99% variability that exists in the original database.

Table 6-4 Results of the Principal Component Analysis for Single-Tandem ALDF

Principal Component	Aggregated Load Bin	Variance	Cumulative Variance
1	Heavy Tandem (22-50 Kips)	74.82	0.65
2	Light Tandem (6-20 Kips)	24.10	0.86
3	Single(11-20 Kips)	8.83	0.94
4	Single (6-10 Kips)	5.59	0.99
5	Single (3 Kips)	1.42	1.00
6	Single (4 Kips)	0.15	1.00
7	Single (5 Kips)	0.03	1.00

When the variance of each principal component is calculated the next step is to select a variable that represents each of the PCs. Formally, one variable is associated with each of the PCs: a variable that has the highest coefficient in absolute values in each successive PC and it is not already chosen. As the results of Table 6-5 shows, heavy and light tandem ALDFs are the first two PCs that contribute the most to the clustering analysis. Next are the heavy, light, and lighter single ALDFs that contribute to the clustering analysis.

Table 6-5 Latent Factor Derived from PCA of Single-Tandem ALDF

	Latent Vector						
	PC 1	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**
	0.316	-0.132	-0.044	0.507	-0.675	0.164	0.376
	0.319	-0.114	0.099	0.202	0.387	-0.706	0.432
	0.190	-0.137	0.096	0.102	0.561	0.687	0.373
	0.397	0.268	-0.451	-0.656	-0.132	0.024	0.345
	-0.335	-0.527	0.435	-0.469	-0.227	-0.028	0.386
	-0.271	0.774	0.437	0.054	-0.062	0.016	0.360
	-0.648	-0.048	-0.629	0.196	0.088	-0.044	0.368
Max Values	0.648	0.774	0.451	0.656	0.675	0.706	0.373
Associated Load Category	Tandem (22-50 Kips)	Tandem (6-20 Kips)	Single (11-20 Kips)	Single (6-10 Kips)	Single (3 Kips)	Single (4 Kips)	Single (5 Kips)

6.3 Identifying Two-Dimensional ALDF Clusters

Initial clustering analysis of 42 WIM sites based on aggregated load bins of single-tandem axles resulted in four major clusters: ALDF Clusters 1, 2, 3, and 4. The specifications of WIM sites in two-dimensional ALDF Clusters are presented in Table 6-6.

Figure 6-5 shows the Single and Tandem ALDF of *individual* WIM sites grouped in two-dimensional ALDF Clusters. Figure 6-6 shows the *average* Single and Tandem ALDF for two-dimensional ALDF Clusters. Figure 6-7 shows the *average aggregated* Single and Tandem ALDF for two-dimensional ALDF Clusters.

The following observations are made from patterns illustrated in Figure 6-7:

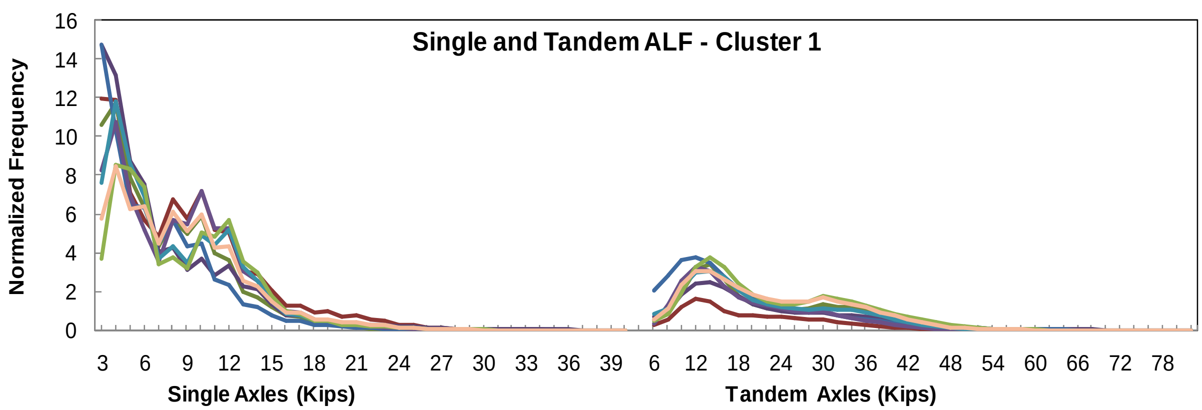
- WIM sites in ALDF Cluster 1 have the highest percentage of light single axles and the lowest percentage of heavy tandem axles. WIM sites in this cluster mostly serve local short haul trips.
- WIM sites in ALDF Cluster 4 have the lowest percentage of light single axles and the highest percentage of heavy tandem axles. WIM sites in this cluster are mostly located on Interstate highways that serve long haul trips.
- The percentage of light single axles and heavy tandem axles of WIM sites in ALDF Clusters 2 and 3 falls between the extreme ranges of those of WIM sites in ALDF Clusters 1 and 4.

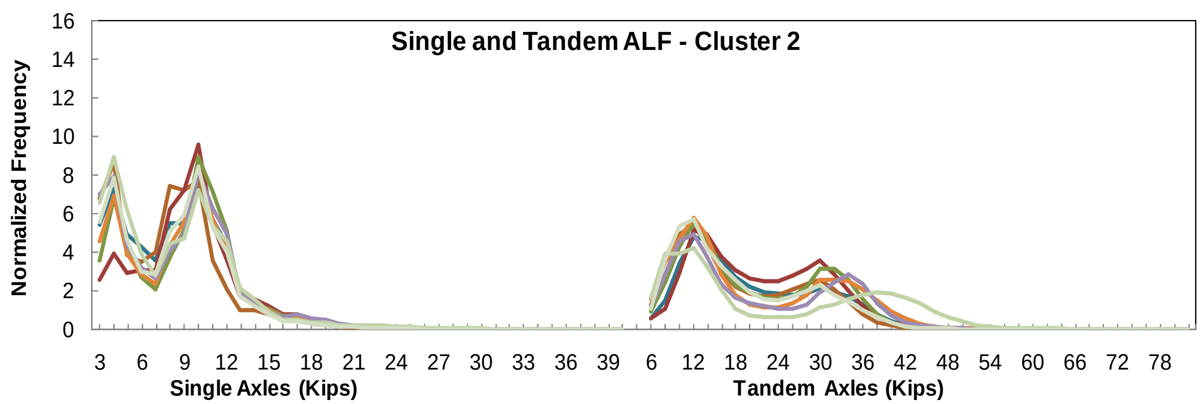
Table 6-6 Specifications of WIM sites in Two-Dimensional ALDF Clusters

WIM ID	SHRP ID	Road	Road Type	Region	ALDF Cluster	AADTT
545/507	373816/373102	NC 147	U	Piedmont	1	2219
546	375903	NC 24	U	Piedmont	1	1922
556	371003	I-240	UR	Mountain	1	1643
516	372825	SR 1138	U	Piedmont	1	604
523	371814	US 23-441	RR	Mountain	1	1039
534	371901	US 64	RR	Mountain	1	760
535	371902	US 74	RR	Mountain	1	507
522	371803	US 74-441	RR	Mountain	1	1155
555	374002	NC 68	U	Piedmont	2	2393
506/544	371006/379102	I-40 (EXIT 291)	U	Piedmont	2	6959
542	377001	I-40	RR	Coastal	2	1710
508	371805	US 64	R	Piedmont	2	839
510/526	375827/377802	US 29	R	Piedmont	2	2032
548	374701	US 264	R	Coastal	2	4705
511	372819	US 220	U	Piedmont	2	2969
530	370900	US 1	R	Piedmont	2	1736
558	371701	US 321	U	Piedmont	3	2835
554	377803	US 220	R	Piedmont	3	2630
552	370301	US 74	R	Piedmont	3	2146
547	373501	US 321	U	Piedmont	3	4716
531	370200	US 52	R	Piedmont	3	3039
553	377501	US 220	R	Piedmont	3	2652
509	372824	US 421	R	Piedmont	3	1968
525	371992	US 421	R	Piedmont	3	1945
504	371645	US 74	RR	Coastal	3	1649
551	378201	US 74	R	Coastal	3	2401
529	377302	US 264	Uloop	Coastal	3	1467
539	375902	I-77	U	Piedmont	3	9611
557	374801	I-40	UR-	Piedmont	3	8907
502	371030	US 17	R	Coastal	4	1175
549	377002	US 421	R	Coastal	4	535
501/540	371028/371402	US 17	RR	Coastal	4	942
538	372202	I-85	R	Piedmont	4	11583
543	379201	I-85	R	Piedmont	4	5370
560	375601	I-26	RR	Mountain	4	1141
520	371801	I-40	UR	Mountain	4	6093
559	371101	I-40	RR	Mountain	4	6158
536	374301	I-40	RR	Mountain	4	8142
537	377401	I-26	RR	Mountain	4	4428
541	377701	I-95	Unique/Rec	Coastal	4	8027
503/527	373011/376302	I-95	Unique/Rec	Piedmont	4	7300
515	375826	I-77	RR	Mountain	4	7092

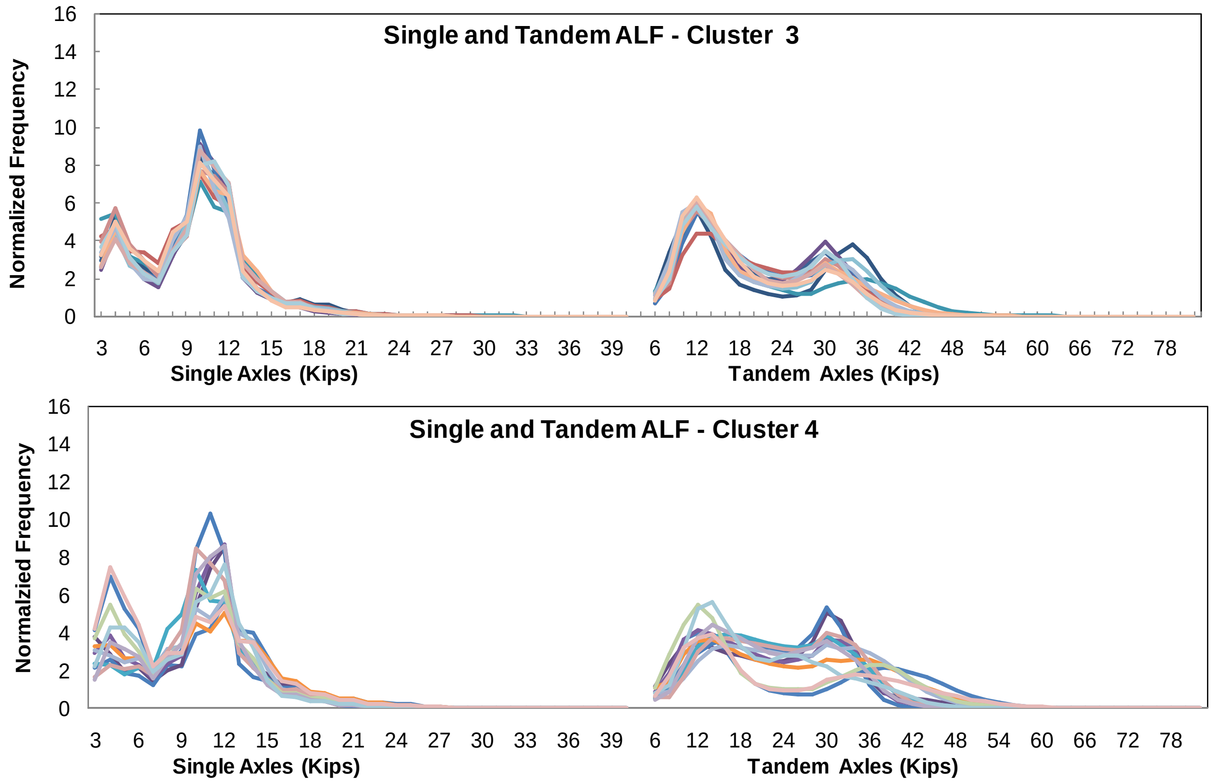
To gain some knowledge about the characteristics of WIM locations classified in different ALDF Clusters, initially, we plotted the annual average vehicle class distribution (Figure 6-8) as well as the AADTT of ALDF Clusters (Figure 6-9).
Here are some important observations regarding ALDF clusters:

- WIM sites in ALDF Cluster 1 have relatively low AADTT values; vehicle class 5 is the dominant vehicle class; and WIM sites are located on local roads that serve local trips.
- WIM sites in ALDF Cluster 4 have relatively high AADTT values; vehicle class 9 is the dominant vehicle class; WIM sites are located on roads that long haul trips; and the majority of WIM sites in this cluster (10 out of 13) are located on Interstate highways. There are three WIM sites located on US roads that belong to ALDF Cluster 4. Two of these WIM sites are located on US 17 (a major roadway in eastern part of the state that runs from north to south from Virginia border to South Carolina border). As there exists no nearby Interstate highway, this roadway mainly serves long haul trips in eastern part of NC (i.e. it functions as an Interstate road).
- WIM sites in ALDF Cluster 3 have moderate AADTT values; vehicle class 9 is the dominant vehicle class; the WIM sites are mostly located on urban US roadways in Piedmont region; and these roads mainly function as secondary arterials for truck traffic.
- WIM sites in ALDF Cluster 2 have moderate AADTT values; vehicle class 9 is the dominant vehicle class; the WIM sites are mostly located on rural-recreational US roadways in mountain region; and these roads mainly function as collectors.





Cluster 1: Roads Serving Local Trips Cluster 2: Collector and Recreational Highways



Cluster 3: Secondary Arterials Cluster 4: Highways Serving Interstate Travel

Figure 6-5 Single and Tandem ALDF of Individual WIM Sites in Two-dimensional ALDF Clusters

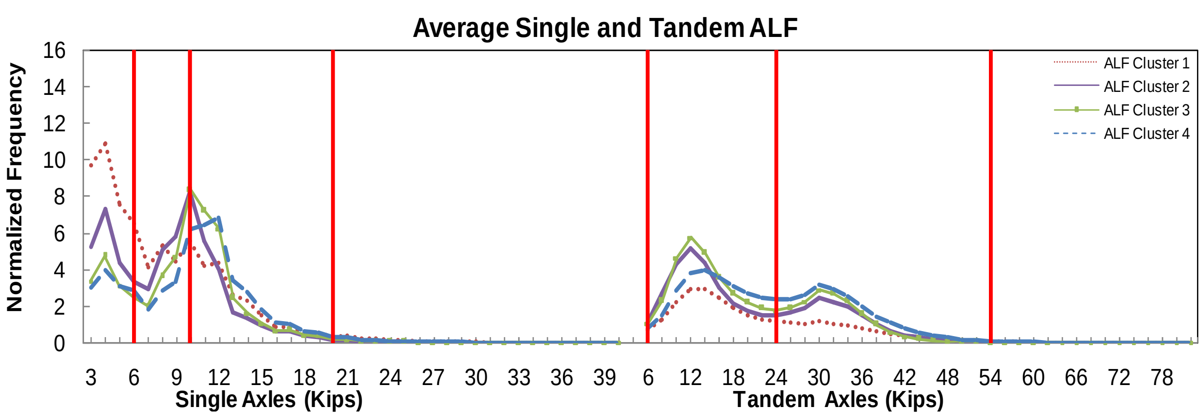


Figure 6-6 Average Single Tandem ALDF for Two-Dimensional ALDF Clusters

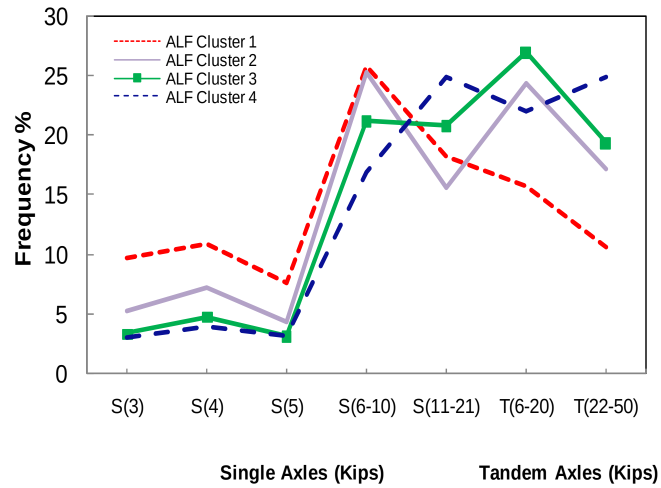


Figure 6-7 Average Aggregated Single-Tandem ALDF for Two-Dimensional ALDF Clusters

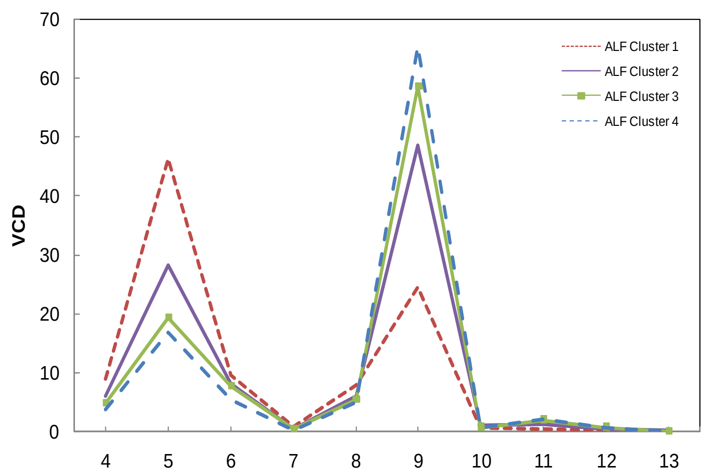


Figure 6-8 Average Vehicle Class Distribution for Two-Dimensional ALDF Clusters

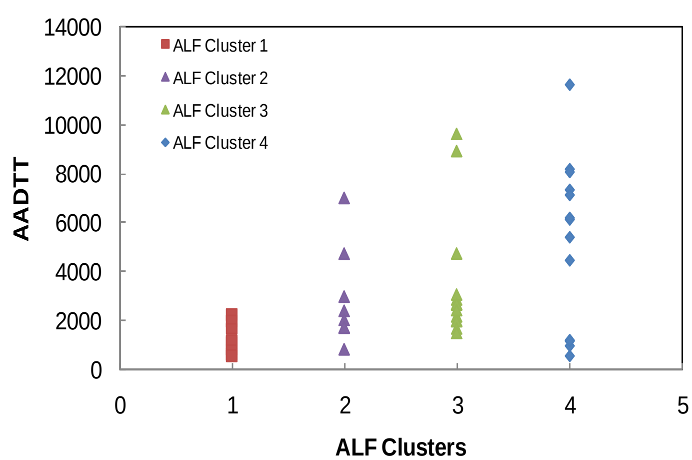


Figure 6-9 AADTT Values for Two-Dimensional ALDF Clusters

6.4 Decision Tree Development for Two-Dimensional ALDF Clusters

After identifying the two-dimensional ALDF clusters, a decision tree is required to choose between several clusters. Qualitative parameters such as functional classification of road, the geographical location of road along with some quantitative parameters such as the percentage of vehicle class 9 versus vehicle class 5 can be used to differentiate between two-dimensional ALDF clusters.

For a new pavement project (a new design or widening), the 48-hour site-specific classification counts are the only available data to the pavement engineer. Thus, it is desired to have a decision tree that can benefit from the 48-hour class data and lead the designer select the appropriate factor group. In order to associate the 48-hour data with the factor groups, we generated 48-hour data out of each WIM database using the following procedure:

- Exclude weekend data from analysis (currently, NCDOT does not collect data during weekends, thus associating the week day data into factor groups is direct.),
- Screen the weekday data to exclude atypical patterns (the NCDOT does not collect data on holidays, during adverse weather, or other events that cause unusual travel patterns)
- Generate average traffic counts by vehicle class by Days of Week (DOW – Monday through Friday) by Month,
- 12 months × 5 DOW = 60 sets of average counts by vehicle classes,
- Calculate vehicle class distribution (percentage of each vehicle class) by month by DOW
  12 months × 5 DOW = 60 sets of VCD,
- Calculate the average VCD by month for every two consecutive DOW (Monday/Tuesday, Tuesday/Wednesday, Wednesday/Thursday, Thursday/Friday)
  12 months× 4DOW = 48 sets of VCD_48.

The annual average percentage of vehicle class 9 versus vehicle class 5 as well as the percentage of vehicle class 9 versus vehicle class 5 obtained from 48-hour counts are plotted in Figure 6-10and Figure 6-11.

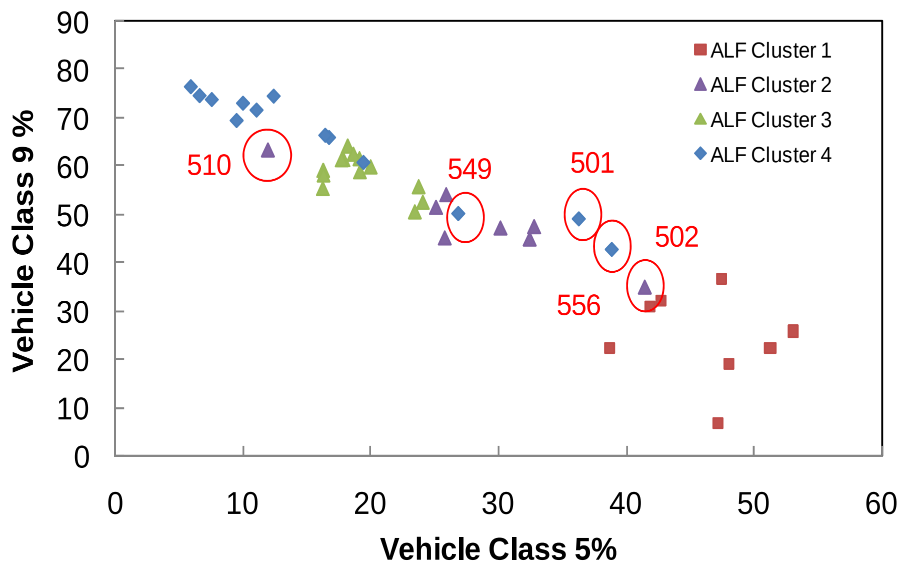


Figure 6-10 Annual Average Vehicle Class 9 % versus Class 5 % for Two-Dimensional ALDF Clusters

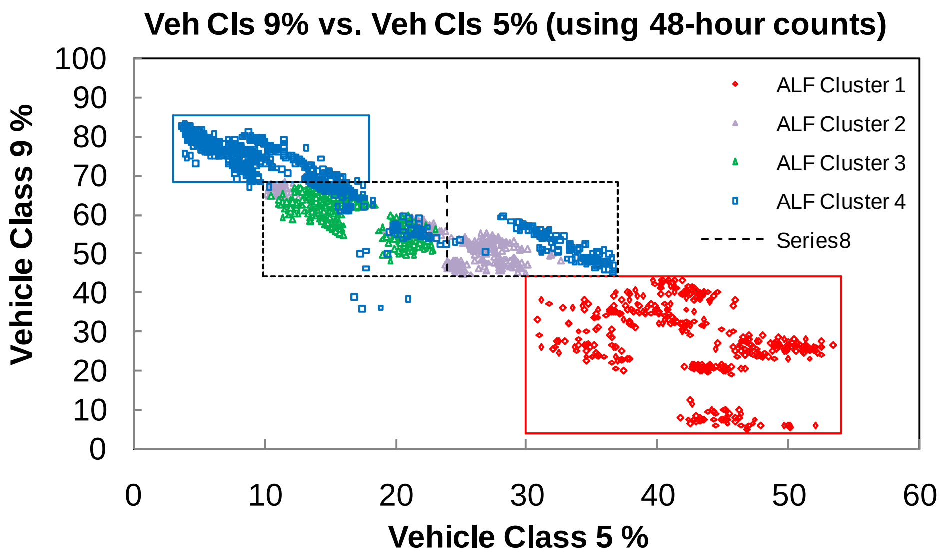


Figure 6-11 Vehicle Class 9% versus Vehicle Class 5% using 48-hour Counts Extracted from WIM Databases for Two-dimensional ALDF Clusters

ALDF clusters 1 and 3 are well contained on Figure 6-10 and Figure 6-11. However, ALDF clusters 2 and 4 range over most of the plot. It emphasizes that an exclusive quantitative analysis does not reveal discernible patterns to distinguish among all ALDF clusters. Thus, the designer must apply his/her judgment to distinguish ALDF clusters for the particular design case.

The following observations are made from Figure 6-11:

- WIM sites with 30% ≤ class 5% ≤ 54% and 4% ≤ class 9% ≤ 44% belong to ALDF Cluster 1,
- WIM sites with 3% ≤ class 5% ≤ 18% and 68% ≤ class 9% ≤ 85% belong to ALDF Cluster 4,
- WIM sites with 10% ≤ class 5% ≤ 37% and 44% ≤ class 9% ≤ 68% belong to either ALDF Cluster 2, 3, or 4,

As Figure 6-10and Figure 6-11show, there are some areas where ALDF clusters experience overlaps in plotted traffic parameters. The overlapping areas occur where 10% ≤ class 5% ≤ 37% and 44% ≤ class 9% ≤ 68%.

In order to distinguish between WIM sites in overlapping areas, it is required to look at other attributes of the WIM sites in this area. To identify those attributes, the team closely studied the traffic pattern on a few WIM sites in ALDF Clusters 2, 3, and 4 that do not follow the general traffic pattern that pertains to those clusters.

6.4.1 WIM 510/526 in Two-Dimensional ALDF Cluster 2

The team studied the truck traffic patterns and the load distributions of trucks to show that WIM 510/526 is properly grouped in AFL Cluster 2. This fact is verified when the vehicle class distribution and axle load distribution of WIM sites in ALDF Cluster 2 are plotted (Figure 6-12and Figure 6-13).

Figure 6-12 shows that the percentage of class 5 vehicles in WIM location 510 is much lower than that in other locations. It can also be seen from the figure that, the percentage of class 9 vehicles at this location is higher than that in other locations.

Figure 6-13 shows the axle load distribution of WIM sites in ALDF Cluster 2. Although the distribution of trucks in WIM 510 is different from those in other WIM sites in ALDF Cluster 2, its axle load distribution falls within the range of those in other WIM sites.

Such an observation shows that WIM 510 is properly classified as ALDF Cluster 2, it also substantiates that quantitative traffic parameters such as the percentage of vehicle classes are not sufficient to address the membership of WIM sites to a specific ALDF cluster.

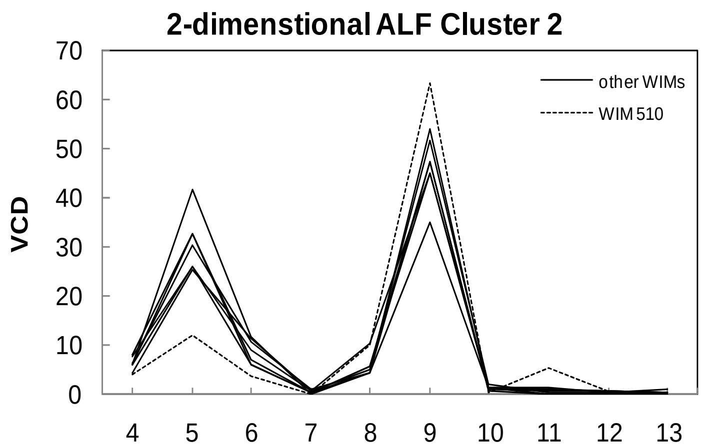


Figure 6-12 Vehicle Class Distribution of WIM Sites in Two-dimensional ALDF Cluster 2

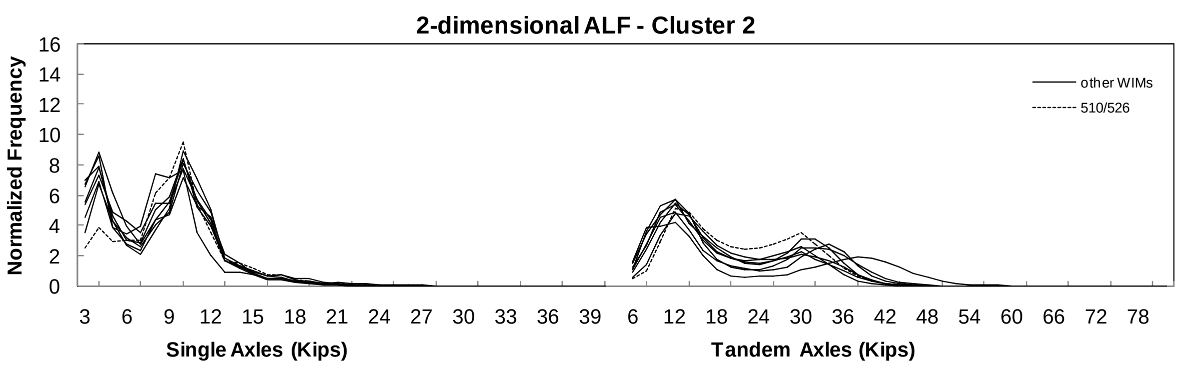


Figure 6-13 Single and Tandem ALDF in Two-dimensional ALDF Cluster 2

Another study showed WIM sites with similar truck distribution (VCD) may be categorized differently with respect to axle load classification. For that purpose, we plotted the vehicle class distribution of WIM sites 510/526 and 538.

- WIM sites510/526 in two-dimensional ALDF Cluster 2 (a rural road, located on US 29 in Piedmont region, AADTT = 2032),

- WIM sites 538 in two-dimensional ALDF Cluster 4 (a rural road, located on I-85 in Piedmont region, AADTT = 11583),

Figure 6-14 shows that these two WIM sites have very similar vehicle class distribution (VCD). However, their axle load patterns differs slightly (Figure 6-15). Figure 6-15 shows that heavy tandems are more frequent in vicinity of WIM 538 located on I-85 compared to WIM 501/526 located on US 29. Such an observation is well-matched with the characteristic of Interstate highways in which heavy long haul trucks are travelling.

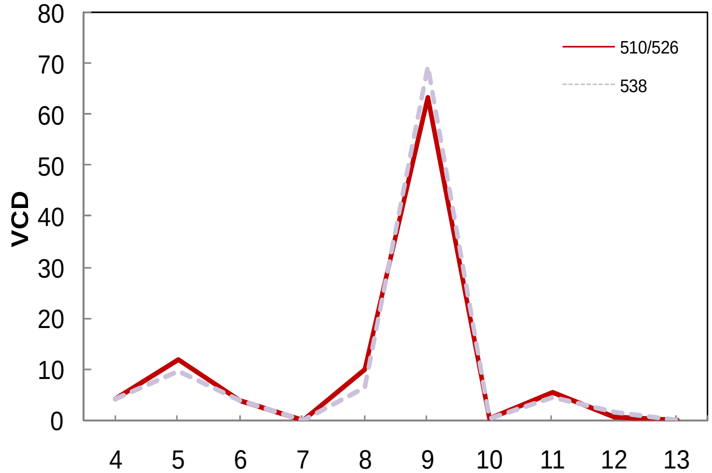


Figure 6-14 Vehicle Class Distribution of WIM 510/526 (ALDF Cluster 2) and WIM 538 (ALDF Cluster 4)

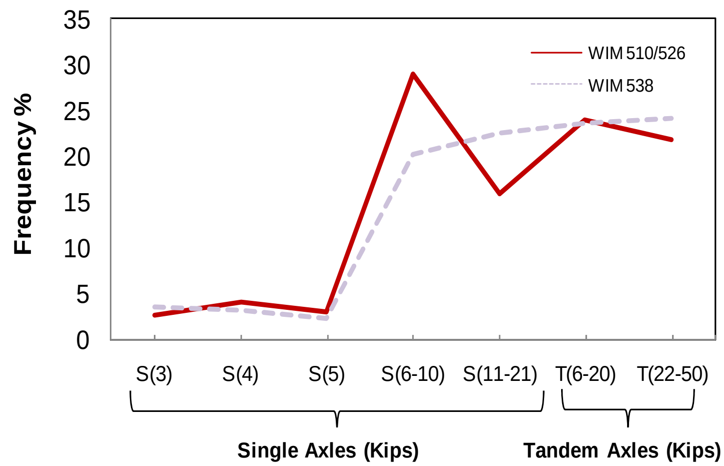


Figure 6-15 Aggregated ALDF of WIM 510/526 (ALDF Cluster 2) and WIM 538 (ALDF Cluster 4)

6.4.2 WIM 501/526, 502, 549 in Two-Dimensional ALDF Cluster 4

As already mentioned, WIM sites that belong to ALDF Cluster 4 are mostly located on primary arterials (including interstate highways and US roads): 10 WIM sites are located on Interstate highways and 3 are located on US roadways. Three WIM sites located on US roads marked on Figure 6-10 cause overlap between ALDF Clusters 2 and 4.

The specification of these WIM sites on US roads follows:

- WIM sites501/540 (located on US 17 in the Coastal region, a rural-recreational road, AADTT = 942),
- WIM 502 (located on US 17 in the Coastal region, a rural road, AADTT = 1175),
- WIM 549 (located on US 421 in the Coastal region, a rural road, AADTT = 535),

Figure 6-16 shows the vehicle class distribution of WIM sites in ALDF Cluster 4. Figure 6-17 shows the aggregated ALDF of WIM sites in ALDF Cluster 4. As it is shown in Figure 6-16, there exists an evident difference between vehicle class distribution of WIM sites on US roads and WIM sites on Interstate highways (that explains why these WIM sites are causing an overlap with ALDF Cluster 2).

Although, the truck distribution on these three locations differ from the truck distribution on Interstate roads, their axle load distributions are similar to axle load distributions on Intestate roads (see Figure 6-17). That explains why these WIM sites are all grouped as ALDF Cluster 4 though their truck distributions vary.

WIM sites 501/540 and 502 are both located on US 17. US 17 is a north-south US highway in eastern part of NC that runs from the Virginia border to the South Carolina border. As there is no nearby Interstate road to serve the long haul trips in the eastern part of the state, this US road is mainly used for that purpose. That explains the high frequency of heavy trucks on this road though such a pattern is usually expected on Interstate roads.

Again such an observation substantiates the need for the pavement designer to include his/her engineering judgment of what grouping or cluster should be applied to the design road.

6.4.3 WIM 548 in two-dimensional ALDF Cluster 2

Here we present another example to emphasize that the pavement designer need to make a decision based on engineering judgment when the traffic attributes of road fail to suggest a specific ALDF Cluster (the traffic attribute falls within the overlap zone).

WIM 548 is located in the coastal region on US 264, a rural road with relatively high AADTT of 4705. Although, WIM 548 is located on a US roadway, it does not belong to ALDF Cluster 3 to which most of the US WIM sites belong. Based on NC functional classification of roads, US 264 is classified as a rural minor arterial (FC Code 6). As Figure 6-13 shows, the percentage of class 5 vehicles is high compared to other WIM sites in ALDF Cluster 2. However, the axle load distribution at WIM 548 is very similar to other WIM sites in ALDF Cluster 2 (see Figure 6-17). Thus WIM 548 is grouped with other WIM sites in ALDF Cluster 2 which mostly include roadways that serve as collectors.

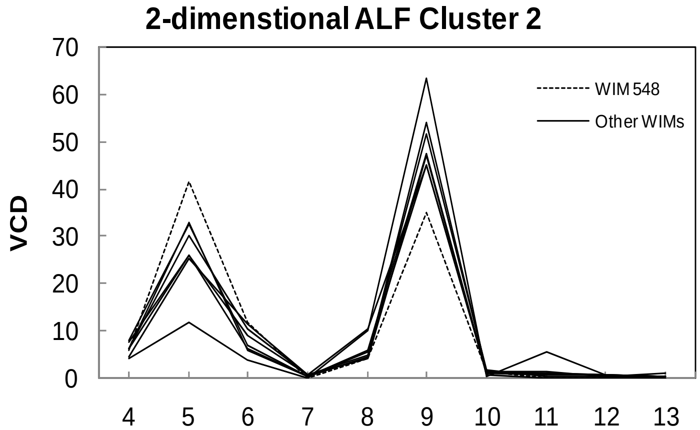


Figure 6-16 Vehicle Class Distribution of Two-Dimensional ALDF Cluster 2

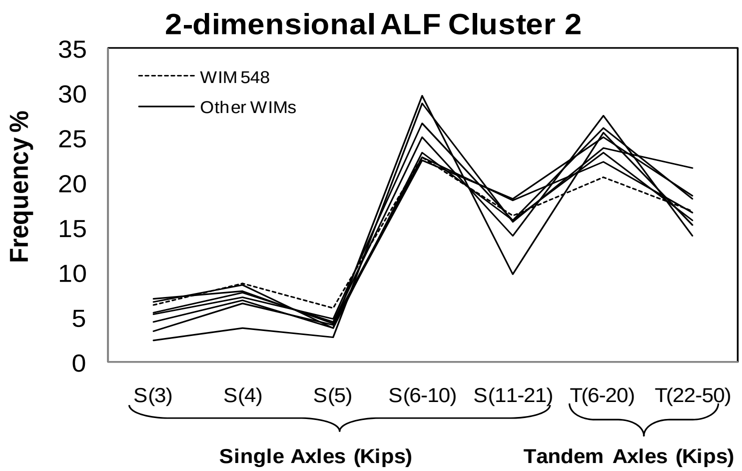


Figure 6-17 Aggregated ALDF of Two-Dimensional ALDF Cluster 2

6.4.4 ALDF Decision Tree

Qualitative and quantitative explanatory parameters define a decision tree that helps the pavement designer select the right ALDF input for the M-E pavement design. The quantitative parameters include the percentage of vehicle class 9 and 5 calculated from 48-hour classification counts. The qualitative parameters include local knowledge of the design road (including the geographical location of the road as well as the functionality of the road).

The observations made earlier in Section 1.3 help form a decision tree (Figure 6-18) that allows the pavement designer to locate the correct ALDF cluster for Level 2 design. For the Level 3 ALDF, we use the average statewide ALDF of 42 WIM sites (excluding WIM sites 521 and 533 that are identified as outliers).

To generate decision tree input parameters, 48-hour classification counts are needed. The NCDOT Traffic Survey Group collects 48-hour counts on typical weekdays on design roads and provides the counts to the traffic forecaster and pavement designer. Thus these classification counts may be used for that purpose.

As mentioned earlier, traffic parameters derived from 48-hour classification counts form the building blocks of the decision tree. Thus, it is important that NCDOT collect reliable 48-hour counts for the design road. The following recommendations will improve the reliability of the 48-hour counts:

- Collect counts on typical days. Exclude holidays, adverse weather events, and other conditions that cause significant variations in travel.

- Compare one day's hourly traffic counts against the second day's counts to check for any abnormal patterns in truck traffic. If a significant difference exists between two days' traffic, then collect additional counts.

- In most WIM locations, ALDF of single and tandem axles do not vary significantly from month to month (Figure 6-19 and Figure 6-20). However, there are a few WIM locations for which the ALDF patterns vary in some specific months. For example, the ALDF pattern in July is different from the ALDF pattern in other months for WIM sites 502,549, 507/545, and 510/526 (Figures 6-21 to Figure 6-24). The ALDF pattern is also different in August for WIM site 536 (Figure 6-25). Consequently, it is recommended that NCDOT avoid these specific months (July and August) while collecting short duration counts.

6.5 Results and Discussions

Other researchers and practitioners have used one-dimensional clustering analysis to generate clusters of similar ALDF data for different axle types one at a time. Although, the resulting clusters are very distinct with respect to one axle type, it is usually difficult to associate them with a specific traffic pattern because the information about the other axle types is missing. Previous post-clustering efforts that attempted to explain the variation among clusters have resulted in complicated decision trees that were difficult to implement. To address these issues, this chapter presents multidimensional clustering analysis, characterized by simplicity and accuracy, to develop MEPDG ALDF inputs. The dimensions of the clustering analysis are selected with caution to avoid inclusion of factors that introduce bias in clustering without providing additional information. For that purpose, axle types that are prevalent on NC roads and that also have a large effect on pavement performance are included. Specifically, single and tandem axles are selected because they comprise 57.7% and 41.9% of the axles in NC and they account for 35% and 63% of the pavement damage, respectively, based on MEPDG damage analysis. Two-dimensional hierarchical clustering analysis resulted in ALDF clusters of variations in the frequencies of light-weight and heavy-weight single and tandem axles. Post-clustering analysis that incorporates local knowledge of the design road and easy-to-obtain traffic parameters found that a strong relation exists between two-dimensional ALDF clusters and the roadway category (primary arterials, secondary arterials, collectors, and local roads). This approach leads to a simple and easy-to-use decision tree that facilitates the design process.

6.6 Implementation Plan

The 2-dimensional clustering analysis resulted in four representative ALDF clusters. Four ALDF files are generated that include the average ALDF of WIM sites forming four ALDF clusters. The

ALDF files were delivered to NCDOT. A decision tree (Figure 6-18) is also developed that helps the designer select the proper ALDF input given percentage of class 5 and class 9 vehicles at the design road as well as the road category: primary arterials, secondary arterials, collectors or local roads. The ALDF decision tree (Figure 6-18) and class 5% versus class 9% plot (Figure 6-11) are aggregated into the "VCD Generator and ALDF Cluster Selector" tool [*Kim and Jadoun, 2010*]. The user initially inputs the 48-hour classification counts collected at design road along with roadway category and the tool automatically suggests a representative ALDF cluster. Knowing the ALDF cluster, the user can import the associated ALDF file into MEPDG. There are cases for which the tool fails to suggest any representative ALDF clusters. These are cases that are poorly represented in the existing WIM data collection effort. It is suggested that users refer to Figure 6-11 (Vehicle class 9% versus Vehicle class 5% using 48-hour Counts Extracted from WIM Databases for Two-dimensional ALDF Clusters) and use their engineering judgment to select an ALDF cluster that has the closest class 5% and class 9% to those at the design road.

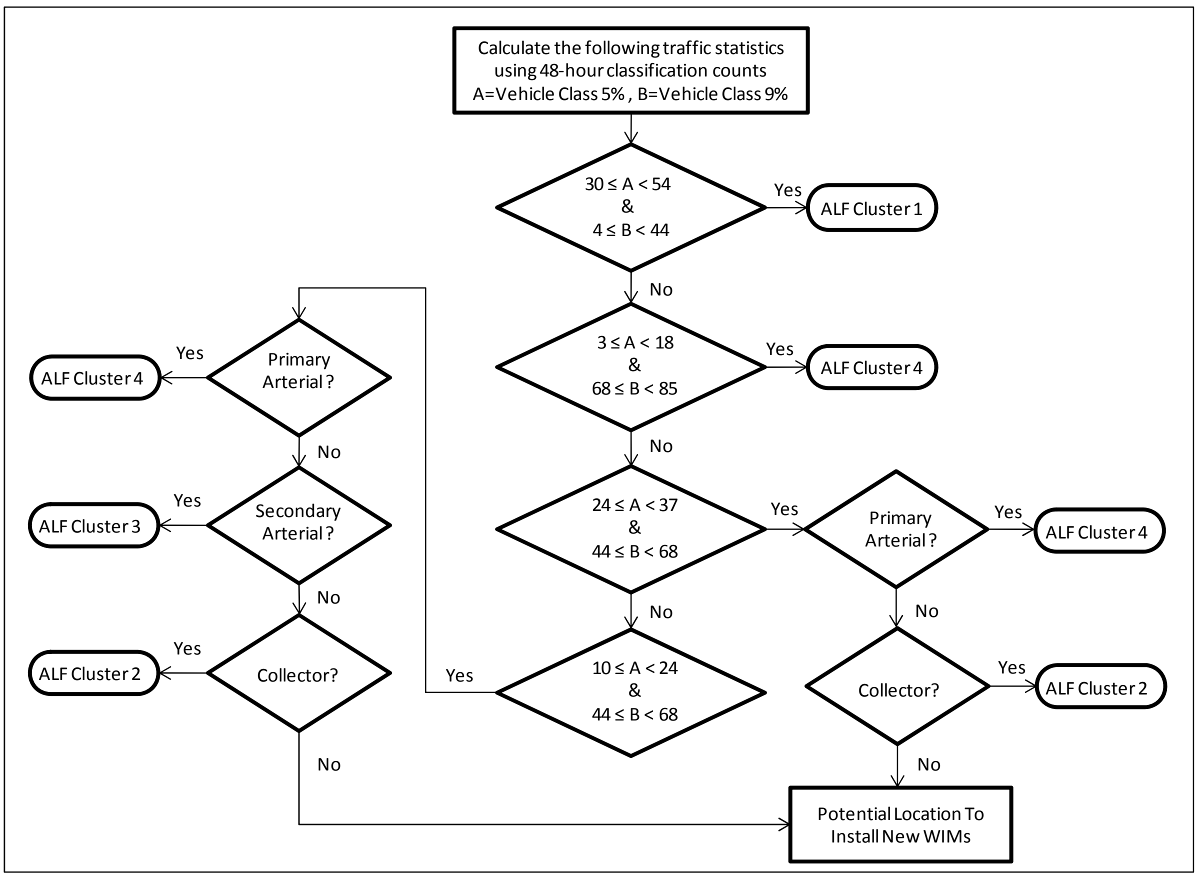


Figure 6-18 Decision Tree to Identify the Representative Two-Dimensional ALDF Cluster

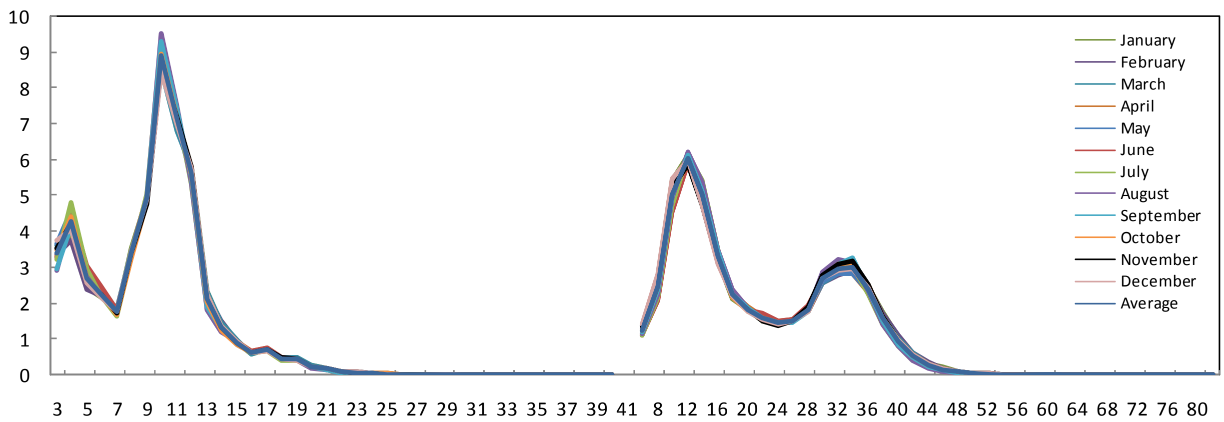


Figure 6-19 Single and Tandem ALDF in WIM 551 Located on US 74 in Coastal Region

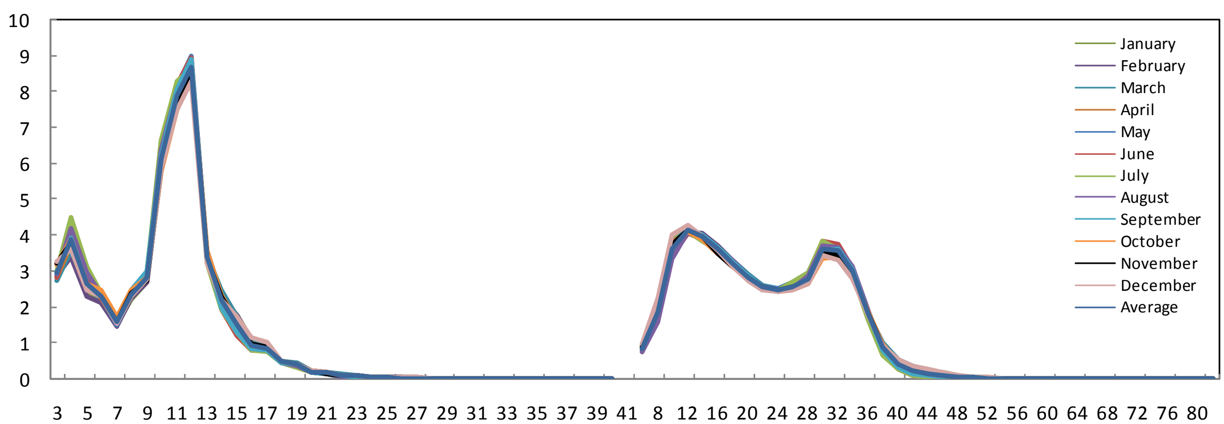


Figure 6-20 Single and Tandem ALDF in WIM 520 Located on I-40 in Mountain Region

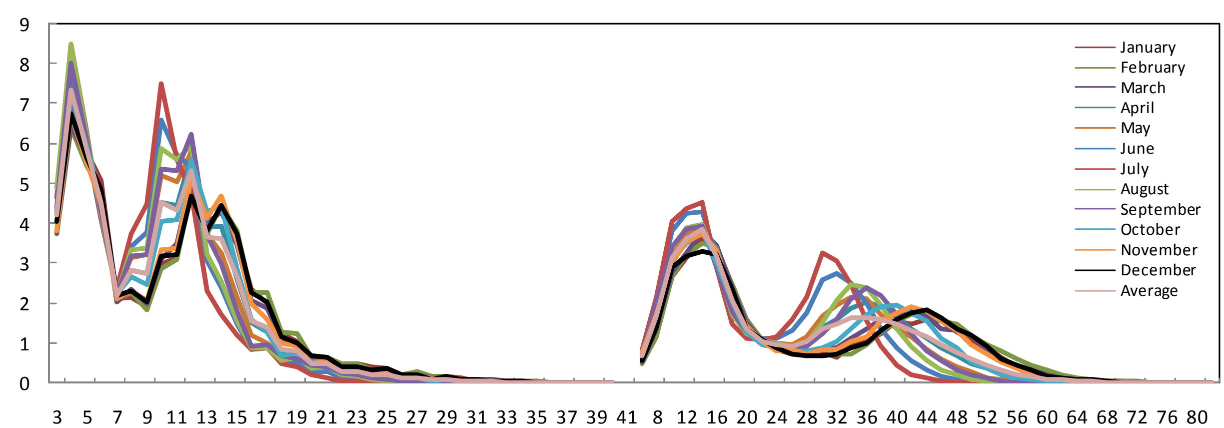


Figure 6-21 Single and Tandem ALDF in WIM 502 Located on US 17 in Coastal Region

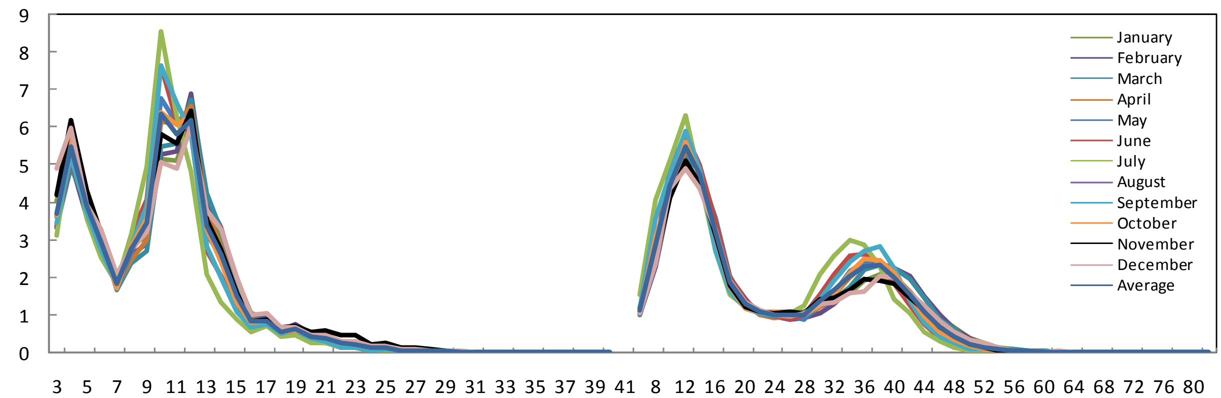


Figure 6-22 Single and Tandem ALDF in WIM 549 Located on US 421 in Coastal Region

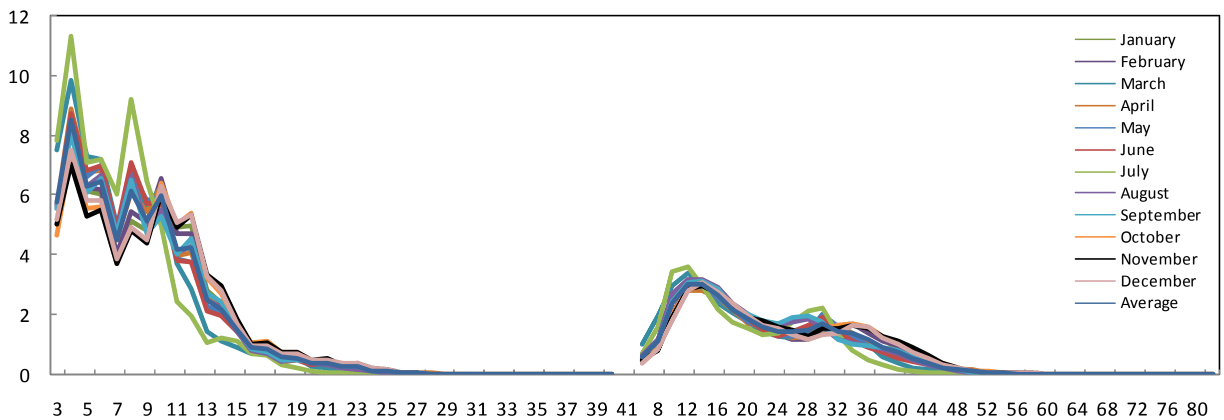


Figure 6-23 Single and Tandem ALDF in WIM 507/545 Located on NC 147 in Piedmont Region

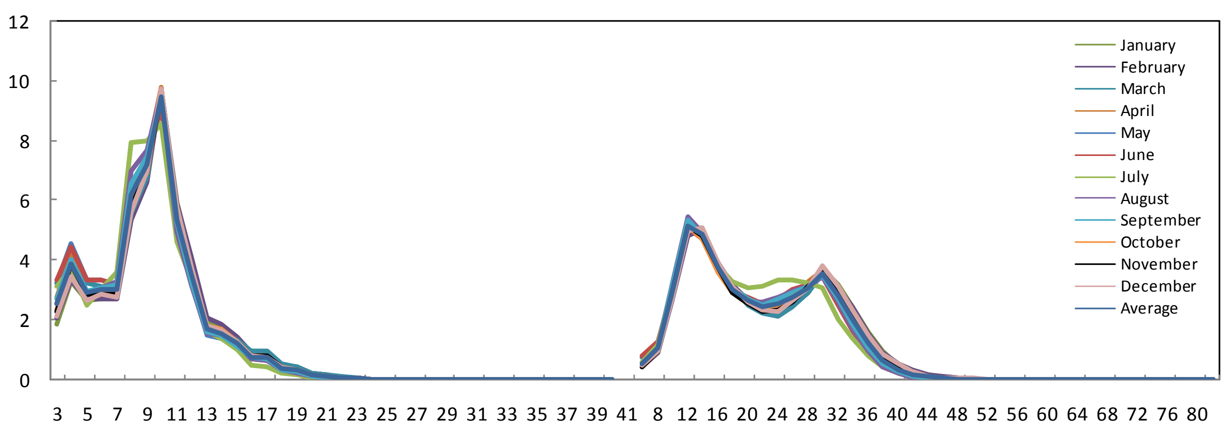


Figure 6-24 Single and Tandem ALDF in WIM 510/526 Located on US 29 in Piedmont Region

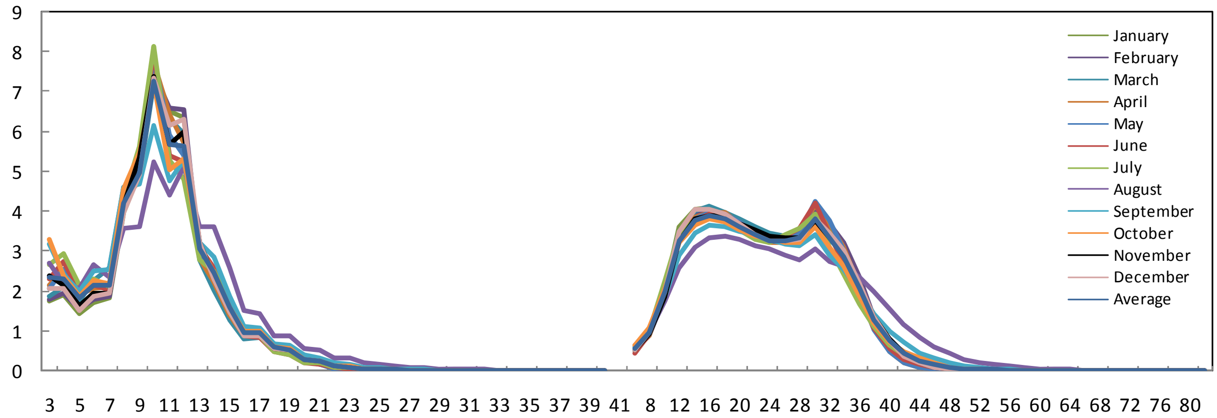


Figure 6-25 Single and Tandem ALDF in WIM 536 Located on I-40 in Mountain Region

CHAPTER 7. DEVELOPMENT OF AXLE LOAD DAMAGE FACTORS

Damage factors play a vital role in linking pavement performance to truck axle loading and geometry. In this chapter, damage factors are developed and used with clustering analysis to guide the development of ALDF clusters for use in the MEPDG. Damage factors ultimately modify the percentages of different axle type-load combinations in order to reflect their contribution to pavement damage. In this study, axle type-load combinations that cause more damage to pavements are given more weight than those combinations that have a smaller effect on pavement performance. Furthermore, frequency and damage factors, both of which depend on axle type, are considered together in identifying their effects on pavement performance. The damage factors presented in this chapter are based on bottom-up fatigue damage as the reference criterion. Fatigue damage was selected, in cooperation with the NCDOT, as the reference criterion because fatigue is the major cause of pavement failure in North Carolina.

7.1 Damage Factor Definition

A *damage factor* (DF) for any axle type-load combination is defined as the ratio of the fatigue damage caused by that axle type-load combination to the fatigue damage caused by a standard 18-kip Equivalent Single Axle Load (ESAL). Equation (1) presents the definition of *damage factor*. This study summarizes the development of damage factors for flexible pavements. There are two reasons that only flexible pavements are considered: first, flexible pavements comprise about 90% of the total road network in North Carolina; second, rigid pavements were found to be insensitive to ALDF input variations for NC traffic [*Sayyady et al., 2009*].

$$DF_{ij} = \frac{D_{f,ij}}{D_{ESAL}} \qquad (1)$$

where

DF_{ij} = Damage factor for axle type i and axle load j;

i = axle type (single, tandem, tridem, or quad);

$$j = \text{axle load} = \begin{bmatrix} \text{single} = 3\text{ kip}, 4, 5, \cdots\cdots 41\text{ kip} \\ \text{tandem} = 6\text{ kip}, 8, 10, \cdots\cdots 82\text{ kip} \\ \text{tridem} = 12\text{ kip}, 15, 18, \cdots\cdots 102\text{ kip} \\ \text{quad} = 12\text{ kip}, 15, 18, \cdots\cdots 102\text{ kip} \end{bmatrix}$$

$D_{f,ij}$ = bottom-up fatigue damage caused by axle i and axle load j; and

D_{ESAL} = bottom-up fatigue damage caused by an 18-kip ESAL.

7.2 Approach

A total of 44 pavement sections are included in this study. Only 36 of the sections are flexible pavements and 8 are rigid pavements. Because the analysis in this research specifically targets flexible pavements, the 8 available rigid pavements were converted to equivalent flexible pavements using their site-specific traffic, environment, and location information. The NCDOT's current AASHTO pavement design method was used to carry out this conversion [*NCHRP, 1993*].

The proposed development of ALDF damage factors is a two-step process. The first step runs the MEPDG for each axle type-load combination (a total of 140) and for each available pavement section (a total of 44), and records the predicted fatigue damage at the end of the design life (20 years). The second step is the normalization of fatigue damage predicted for each of the axle type-load combinations with respect to the fatigue damage predicted using an 18-kip ESAL. In order for this approach to be implemented, some of the traffic inputs within the MEPDG must be adjusted to force the MEPDG to apply only a certain axle type-load combination throughout the design life. This process was repeated for each of the combinations, i.e., 140 times. A detailed explanation of this process is presented in the following section.

7.3 Traffic Input Adjustment within the MEPDG

The four traffic inputs required by the MEPDG that must be adjusted in order for the MEPDG to apply a certain axle type and load combination on a pavement structure are: the Average Annual Daily Truck Traffic (AADTT), the Vehicle Class Distribution (VCD), the number of Axles per Truck (APT), and the Axle Load Factor (ALDF). The following steps provide an example of the way that this adjustment procedure works using a 12-kip tandem axle for 500 initial passes with a 4% annual compound growth rate. Note that although some of the numbers entered do not make sense, the final output fulfills the intended goal.

1. To force the MEPDG to consider an initial number of 500 trucks, Figure 7-1*a* suggests that users should enter the number 1000 in the *AADTT* field, 2 in the *number of lanes in the design direction* field, 50 in the *percent of trucks in design direction* field, and 100 in *percent of trucks in design lane* field. The outcome of this array of numbers yields 500 trucks.

2. To distribute the AADTT by vehicle class, i.e., FHWA vehicle classes 4 through 13, users can select any of the vehicle classes to contribute 100% to the overall truck traffic. Figure 7-1*b* shows that vehicle class 9 was selected in this task. In other words, the MEPDG will consider 500 vehicles in class 9 as the only traffic.

3. To calculate the total number of each axle type applied to the pavement, the MEPDG allows users to enter the number of each type of axle for each vehicle class. Figure 7-1*c* is a screen shot of the *number of axles per truck* table. In this table, each vehicle class from 4 through 13 is shown to have one axle from each axle type. For example, vehicle class 4 is shown to have one single axle, one tandem, one tridem and one quad axle, which is applicable to all vehicle classes. Again, one axle from each axle type is not realistic for some of the vehicle classes; however, the numbers are assumed as part of the overall process to achieve the aforementioned goal. Now, the total number of axles that can be applied on the pavement is 2000, that is, 500 single axles, 500 tandem axles, 500 tridem axles and 500 quad axles.

4. To ensure that only 500 tandem axles that are 12 kip each in weight are applied to the pavement, users must consult the ALDF table, a screen shot of which is shown in Figure 7-1*d*. The numbers in the ALDF table represent the contribution of a certain axle type and load combination from a certain vehicle class in a certain month. For example, the highlighted field in Figure 7-1*d* indicates that for each day in the month of January, the contribution of class 5 vehicles to the total number of tandem axles for all vehicles is determined only through the 12-kip axles. In other words, no other tandem axles are class 5 vehicles on that day. However, the output of step 4 suggests that no class 5 vehicles are in the traffic stream, which means that class 5 vehicles do not contribute at all to any of the axle types. On the other hand, class 9 vehicles contribute 500 12-kip tandem axles. To ensure that class 9 contributes only tandem axles, all fields in the single, tridem, and quad axle tables are populated with the number zero, indicating that even class 9 makes zero contribution to any axle type other than tandem.

Steps 1 through 4 suggest that any desired axle type-load combination can be achieved through changes to the ALDF tables, and that all other traffic inputs, i.e., the AADTT, VCD, and APT, remain unchanged. The procedure above was applied 140 times for one of the WIM sites and 27 times for each of the other 43 sites included in this study.

7.4 Full versus Partial Factorial

In order to consider the aforementioned full factorial analysis, the MEPDG must be executed 6,160 times, that is, 44 pavement sections × 140 axle loads. The execution and analysis of 6,160 runs requires a substantial amount of time and effort. Therefore, the authors adopted an alternative approach that simplifies the process. In the alternative approach, the MEPDG is executed 1301 times. The simplified approach calls for executing the MEPDG for full factorial, i.e., 140 axle loads, for one pavement section only. Results are then used to develop a regression model. Once a successful model is developed, the MEPDG is executed for only a partial factorial, i.e., 27 axle loads, and the model can be used to interpolate fatigue damage that corresponds to other axle loads. Axle loads that are included in the partial factorial are: 3, 9, 18, 27, 36, and 41 kips for the single axle; 6, 18, 30, 42, 54, 66, and 82 kips for the tandem axle; and 12, 27, 42, 57, 72, 87, and 102 kips for the tridem and quad axles.

7.5 Analysis of MEPDG Runs

Analysis results suggest that a bilinear function in the log-log space is a model that accurately explains the fatigue damage development with an increasing axle load. Figure 7-2*a* shows an example of the predicted fatigue damage at WIM Site 525 for the partial factorial, i.e., for the 27 axle-type load combinations. Figure 7-2*b* shows that the proposed bilinear function fits the predicted fatigue data well with a coefficient of determination of 1.0. In addition to the 27 fatigue damage values obtained through MEPDG runs, Figure 7-2*c* contains 113 additional fatigue damage values that were interpolated using bilinear functions whose coefficients were determined from the 27 fatigue damage values obtained from the MEPDG runs. For pavement sections at each WIM site, there are four different bilinear functions, one for each axle type.

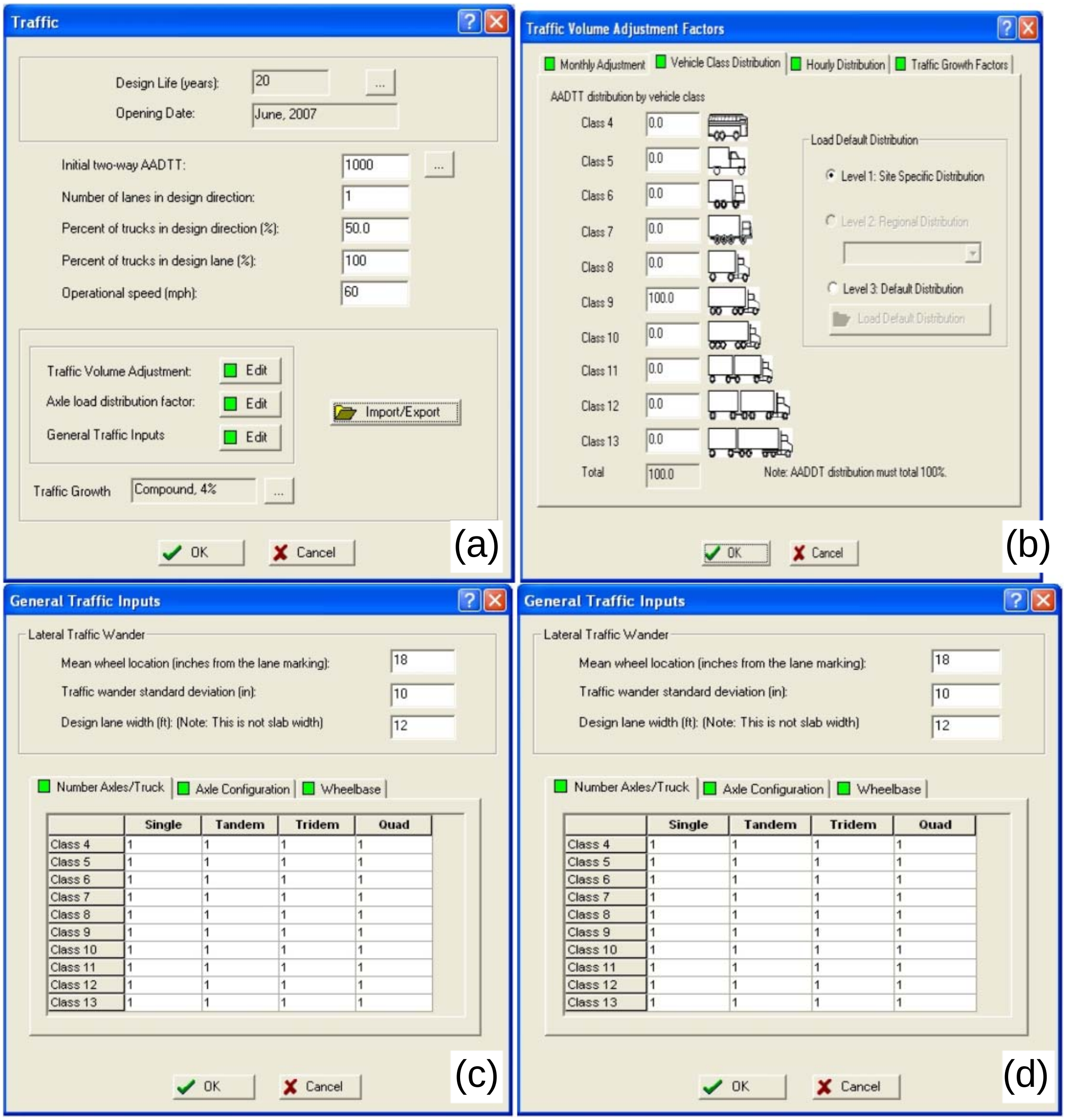


Figure 7-1 Traffic Input Adjustments to (a) AADTT, (b) VCD, (c) APT, and (d) ALDF

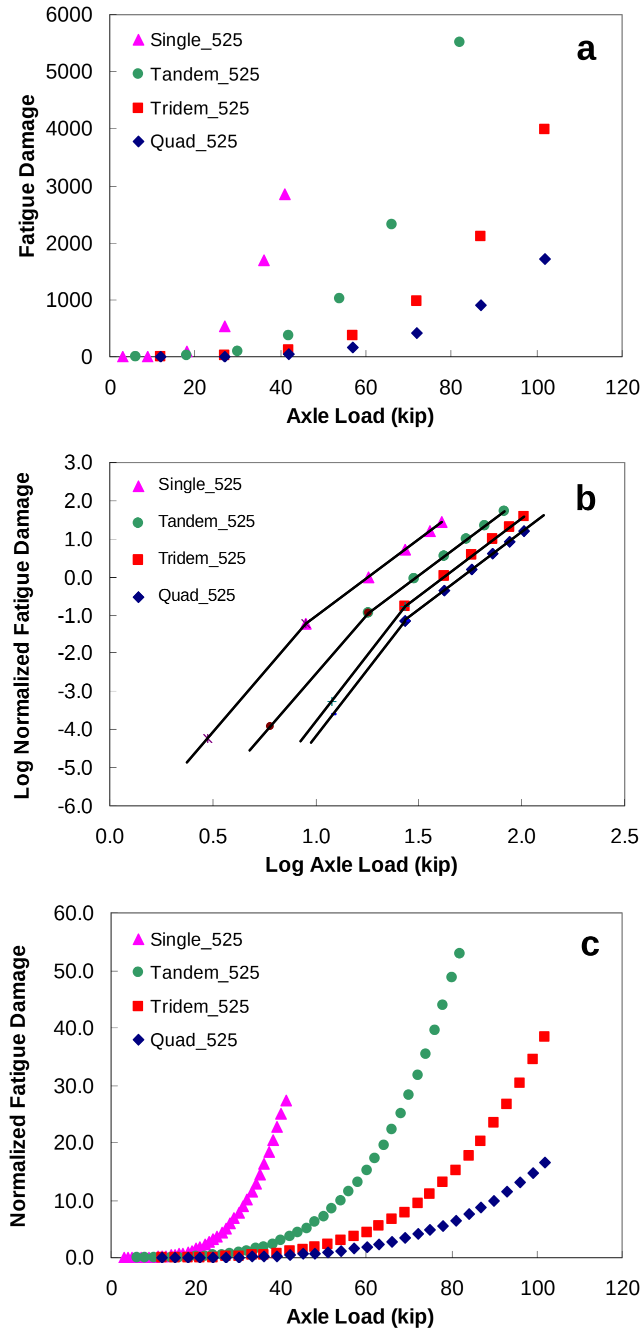


Figure 7-2 Damage Factors: (A) Results of Actual MEPDG Runs; (B) Bilinear Fitting Function; and (C) Complete Set of Damage Factors

Table 7-1 summarizes the statistics of the slope and intercept for linear functions that represent light axle loads (3 kips to 9 kips for the single axle, 6 kips to 18 kips for the tandem axle, 12 kips to 27 kips for the tridem and quad axles) and heavy axle loads (10 kips to 41 kips for the single axle, 20 kips to 82 kips for the tandem axle, and 30 kips to 102 kips for the tridem and quad axles).

Table 7-1 Statistics of the Slope and Intercept for Linear Functions Representing Light and Heavy Axles

Light Axle Weights								
Axle Type	Single		Tandem		Tridem		Quad	
Valid Load Range	3 kips - 9 kips		6 kips - 18 kips		12 kips - 27 kips		12 kips - 27 kips	
Statistics	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
Avg.	6.25	-7.20	6.24	-8.94	6.25	-7.20	6.24	-8.94
Min.	6.24	-7.20	6.23	-9.12	6.24	-7.20	6.23	-9.12
Max.	6.25	-7.20	6.24	-8.62	6.25	-7.20	6.24	-8.62
Std. Dev.	0.001	0.001	0.002	0.143	0.001	0.001	0.002	0.143
% Std. Dev. From Avg.	0.02	0.02	0.03	1.59	0.02	0.02	0.03	1.59

Heavy Axle Weights								
Axle Type	Single		Tandem		Tridem		Quad	
Valid Load Range	10 kips - 41 kips		19 kips - 82 kips		28 kips - 102 kips		28 kips - 102 kips	
Statistics	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
Avg.	4.07	-5.11	4.06	-6.21	4.07	-5.11	4.06	-6.21
Min.	4.06	-5.12	4.06	-6.39	4.06	-5.12	4.06	-6.39
Max.	4.07	-5.11	4.07	-5.89	4.07	-5.11	4.07	-5.89
Std. Dev.	0.001	0.001	0.001	0.143	0.001	0.001	0.001	0.143
% Std. Dev. From Avg.	0.03	0.03	0.03	2.30	0.03	0.03	0.03	2.30

Equation (2) is a group of linear functions representing light axle loads for each axle type. Similarly, Equation (3) shows a group of linear functions that represent heavy axle loads for each axle type. The coefficients of these linear functions are the average slope and intercept values presented in Table 7-1. For any axle type-load combination, Equations (2) and (3) can be applied to calculate damage factor for that combination.

$$\begin{bmatrix} \log(DF_{SH}) & = & -5.11 + 4.07\log(L_1), & L_1 = 10kips - 41kips \\ \log(DF_{TH}) & = & -6.21 + 4.06\log(L_2), & L_2 = 19kips - 82kips \\ \log(DF_{TrH}) & = & -6.75 + 4.07\log(L_3), & L_3 = 28kips - 102kips \\ \log(DF_{QH}) & = & -7.13 + 4.07\log(L_4), & L_4 = 28kips - 102kips \end{bmatrix} \quad (2)$$

where,

DF_{SH} = damage factor single heavy load,
DF_{TH} = damage factor tandem heavy load,
DF_{TrH} = damage factor tridem heavy load, and
DF_{QH} = damage factor quad heavy load,

$$\begin{bmatrix} \log(DF_{SL}) & = & -7.20 + 6.25\log(L_1), & L_1 = 3kips - 9kips \\ \log(DF_{TL}) & = & -8.94 + 6.24\log(L_2), & L_2 = 6kips - 18kips \\ \log(DF_{TrL}) & = & -11.01 + 7.05\log(L_3), & L_3 = 12kips - 27kips \\ \log(DF_{QL}) & = & -11.39 + 7.05\log(L_4), & L_4 = 12kips - 27kips \end{bmatrix} \quad (3)$$

where,

DF_{SL} = damage factor single light load,

DF_{TL} = damage factor tandem light load,

DF_{TrL} = damage factor tridem light load, and

DF_{QL} = damage factor quad light load.

7.6 Results and Discussion

Figure 7-3 shows averaged damage factors developed using data from all 44 WIM sites and normalized based on the 18-kip ESAL. Table 7-2 is an example summary of damage factors developed for pavement structure at WIM Site 525. The highlighted field in Table 7-2 suggests that a single pass of 40-kip tandem axle will cause 191% more fatigue damage to the pavement than a single pass of an 18-kip single axle. Furthermore, Figure 7-3 and Table 7-2 both suggest that damage factors increase with an increasing axle load. This finding is expected because heavier loads on the same axle type will develop larger stresses in pavement structure and, hence, have a larger damage potential than lighter loads. Figure 7-3 and Table 7-2 also suggest that for the same axle load, damage factors decrease as the number of axles increase, e.g., from single to quad axle. This finding also makes sense because when the same load is distributed over multiple axles, each axle will support a smaller amount of load and, hence, will develop smaller stresses and less damage than it would on a single axle or fewer axles. Because each of the 44 pavement sites included in this study has different pavement structures and environmental conditions, the developed ALDF damage factors are site-dependent, i.e., each site has unique ALDF damage factors.

Appendix 4 includes Tables 4A-1through 4A-8that summarize the damage factors developed for all 4 axle types; single, tandem, tridem, and quad. The numbers in the tables are all normalized to ESAL, which is; 18-kip Equivalent Single Axle Load. Table 4A-1for example suggests that a 22-kip single axle load will cause 2.22 more damage (alligator cracking) on the pavement section located at WIM 502, compared to damage caused by 18-kip single axle load at that location. All other tables can be interpreted in the same manner.

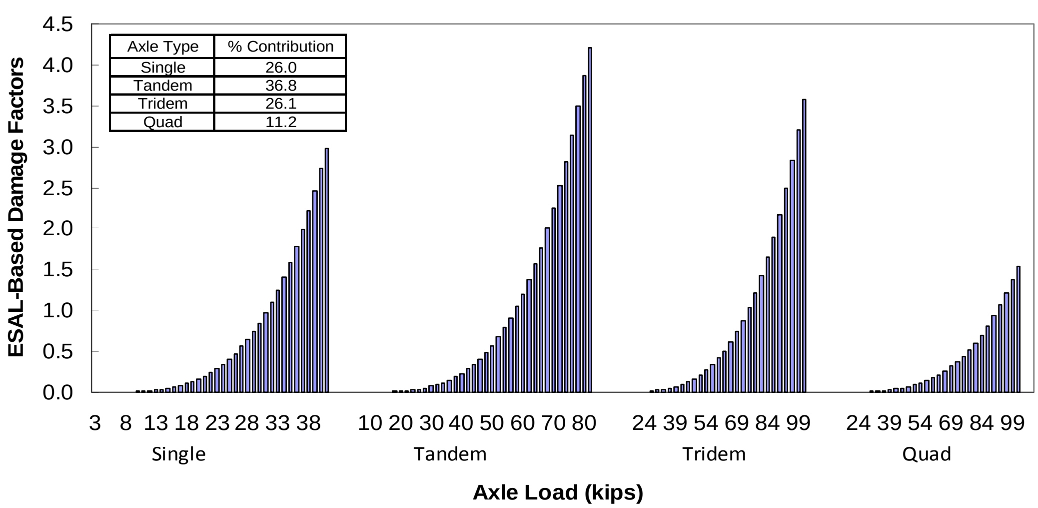


Figure 7-3 ESAL-Based Damage Factors Developed using the MEPDG.

Table 7-2 Example Summary of Damage Factors Developed for WIM Site 525

Axle Type							
Single		Tandem		Tridem		Quad	
Load (Kip)	DF	Load (Kip)	DF	Load (Kip)	DF	Load (Kip)	DF
3	0.00	**6**	0.00	**12**	0.00	**12**	0.00
4	0.00	**8**	0.00	**15**	0.00	**15**	0.00
5	0.00	**10**	0.00	**18**	0.01	**18**	0.00
6	0.00	**12**	0.01	**21**	0.03	**21**	0.01
7	0.01	**14**	0.02	**24**	0.07	**24**	0.03
8	0.03	**16**	0.05	**27**	0.17	**27**	0.07
9	0.06	**18**	0.11	**30**	0.27	**30**	0.11
10	0.09	**20**	0.17	**33**	0.39	**33**	0.17
11	0.13	**22**	0.26	**36**	0.56	**36**	0.24
12	0.19	**24**	0.36	**39**	0.77	**39**	0.33
13	0.26	**26**	0.51	**42**	1.06	**42**	0.45
14	0.35	**28**	0.68	**45**	1.38	**45**	0.59
15	0.47	**30**	0.92	**48**	1.80	**48**	0.77
16	0.61	**32**	1.17	**51**	2.31	**51**	0.99
17	0.77	**34**	1.50	**54**	2.91	**54**	1.25
18	1.00	**36**	1.90	**57**	3.67	**57**	1.58
19	1.22	**38**	2.36	**60**	4.47	**60**	1.91
20	1.50	**40**	2.91	**63**	5.45	**63**	2.34
21	1.83	**42**	3.60	**66**	6.59	**66**	2.82
22	2.21	**44**	4.28	**69**	7.90	**69**	3.38
23	2.65	**46**	5.13	**72**	9.44	**72**	4.04
24	3.15	**48**	6.10	**75**	11.10	**75**	4.75
25	3.71	**50**	7.20	**78**	13.02	**78**	5.58
26	4.36	**52**	8.45	**81**	15.19	**81**	6.50
27	5.13	**54**	9.90	**84**	17.62	**84**	7.54
28	5.89	**56**	11.42	**87**	20.29	**87**	8.66
29	6.79	**58**	13.17	**90**	23.33	**90**	9.99
30	7.79	**60**	15.11	**93**	26.67	**93**	11.41
31	8.91	**62**	17.26	**96**	30.35	**96**	12.99
32	10.13	**64**	19.64	**99**	34.41	**99**	14.72
33	11.48	**66**	22.21	**102**	38.37	**102**	16.44
34	12.96	**68**	25.13				
35	14.59	**70**	28.27				
36	16.25	**72**	31.70				
37	18.28	**74**	35.43				
38	20.38	**76**	39.48				
39	22.65	**78**	43.88				
40	25.10	**80**	48.63				
41	27.40	**82**	52.98				

CHAPTER 8. MEPDG DAMAGE-BASED SENSITIVITY ANALYSIS

In this chapter a damage-based sensitivity analysis is conducted to predict pavement distresses for different traffic parameters. There are two major goals of the sensitivity study; first is to determine how different clusters for different traffic parameters affect the predicted performance of flexible and rigid pavements in the MEPDG, i.e., to check the sensitivity of pavement predicted distresses to different traffic parameter clusters. Second, is to simplify the design process by attempting to aggregate different clusters. It is worth of mentioning that ALDF is the only traffic parameter from which clusters will be selected based on traffic data collected from all 44 WIM stations available in this project. The selection of appropriate ALDF clusters will be based on a decision tree that was presented in Chapter 6. For MAF, HDF and Number of axles per truck, state-wide averages will be used. As for VCD, annualized 48-hour vehicle classification data will be used.

8.1 Sensitivity Criteria

The sensitivity criteria provide threshold values for each of the performance measures. These threshold values are the basis for deciding whether different clusters of different traffic parameters, i.e., HDF, MAF, VCD, and ALDF, result in different predicted performance. This information is necessary for aggregating different clusters from the same traffic factors, if possible, to simplify the pavement design process.

Considering the precision of MEPDG predicted performance and the best available precision with which NCDOT survey teams can measure distresses of flexible and rigid pavements in the field, the research team in cooperation with the NCDOT Pavement Management Unit (PMU) developed sensitivity criteria that were used in all damage-based sensitivity work done in this project.. The final sensitivity criteria for flexible and Jointed Plain Concrete Pavement (JPCP) are shown in Table 8-1. The Continuously Reinforced Concrete Pavements (CRCP) have been discontinued from use in NC road network and are excluded from the analysis.

Table 8-1 Sensitivity Criteria for Flexible and JPCP Pavements

Pavement Type	Performance Measures	Measuring Unit	Failure Point (Maintenance Trigger)	Sensitivity	
				% of Failure Point	Threshold
Asphalt Concrete	IRI	inch/mile	140	10	14
	Total Rutting	Inch	0.5	20	0.1
	Alligator Cracking	% lane area	10	10	1
	Longitudinal Cracking*	feet/mile	2640 (50% of Section Length)	10	264
JPCP	IRI	inch/mile	140	10	14
	Faulting	Inch	0.5	20	0.1
	Slabs Cracked	%	15	20	3

8.2 Sensitivity Analysis Results

MEPDG simulations that are required to determine the sensitivity of flexible and rigid pavements to different traffic factor clusters include HDF, MAF,VCD, and ALDF. Figure 8-1 through Figure 8-4 present the maximum differences in predicted performance in flexible pavements when different clusters are used. Figure 8-5 and Figure 8-6 present corresponding differences in JPCP pavements. The interpretation of Figure 8-2 will be presented in the following paragraph. The Interpretation for all other figures follows basically the same logic.

Figure 8-2 suggests that all MAF clusters (a total of 6 clusters), when individually implemented in the MEPDG, would result in a total rut depth and IRI that can be considered to be similar based on the threshold values shown in Table 8-1 and presented as solid lines in all the sensitivity figures. In other words, the maximum difference between predicted total rut depths and IRI when any 2 MAF clusters were used was found to be below the threshold value of 0.1 inch and 14 inches/mile respectively. On the other hand, the differences in predicted alligator cracking and longitudinal cracking were found to be larger than the threshold values presented in Table 8-1. There are at least 2 MAF clusters that result in significant differences in predicted alligator cracking and longitudinal cracking.

While developing the sensitivity criteria in cooperation with NCDOT, it was decided that the criteria should consider not only the max differences in predicted distresses using any two traffic parameter clusters, but also the *amount* of predicted distresses at a particular site. For example, the average predicted alligator cracking, from all MAF clusters, at site 520 was found to be 25.7 percent of lane area, compared to only 1.6 percent at site 506. Furthermore, the maximum difference in predicted alligator cracking, due to any 2 MAF clusters, at site 520 was found to be 1.7 percent (which makes it fail the criteria shown in Table 8-1) compared to 0.2 percent (which makes it pass the criteria) for site 506.

It is generally agreed upon that the higher the predicted distress values (27.5 percent at site 520), the larger the expected differences between these distresses (1.7 percent at site 520). To account for this fact about expected differences, the research team agreed with NCDOT that the sensitivity criteria presented in Table 8-1 can be modified to account for the amount of predicted distresses at a particular site. A value of 10 percent has been adopted for this tolerance. In other words, the alligator cracking sensitivity criterion at site 520 can be modified from its original value of 1.0 percent, as shown in Table 8-1, to become approximately 2.6 percent (that is 27.5 x 10 percent). The alligator cracking criterion at site 506 stays at 1.0 percent because 10 percent of the average predicted alligator cracking (1.6 percent) is already less than the unmodified 1.0 percent criterion. Using the updated criteria, it can be concluded that all MAF clusters would result in predicted alligator cracking values that are insignificantly different.

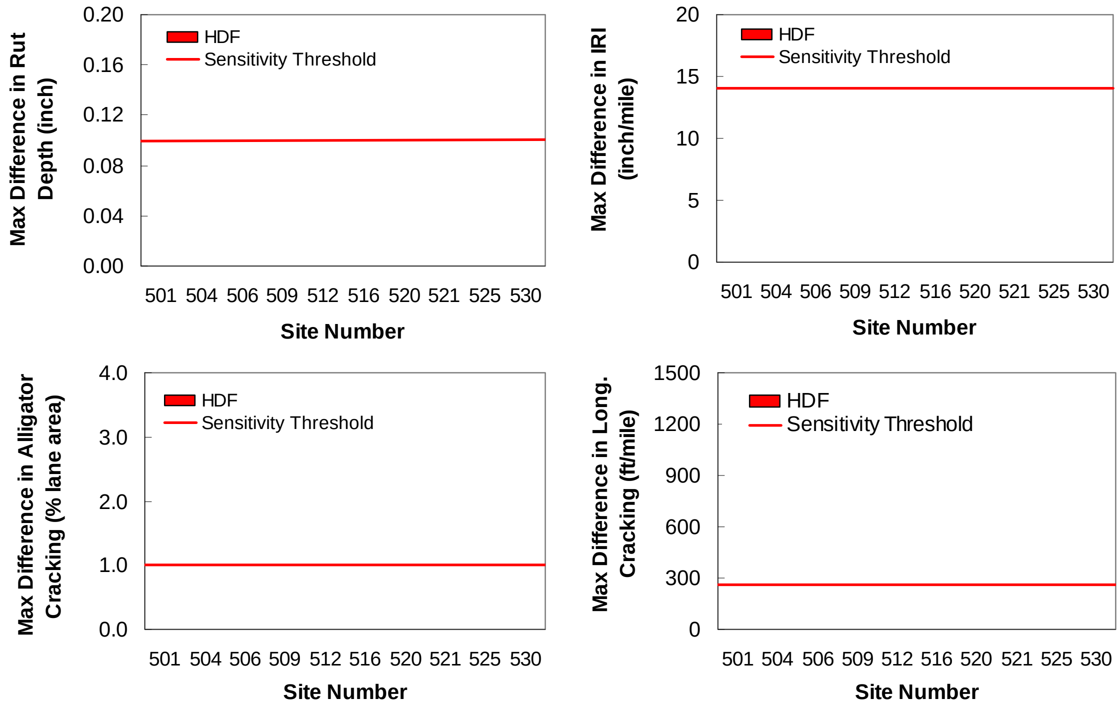


Figure 8-1 Maximum Difference in HMA Predicted Performance Using Different HDF Clusters

Note that the y-axes in Figure 8-1 refer to the differences not the actual predicted distresses.The graphs simply mean that changing HDF clusters has no effect on alligator cracking.

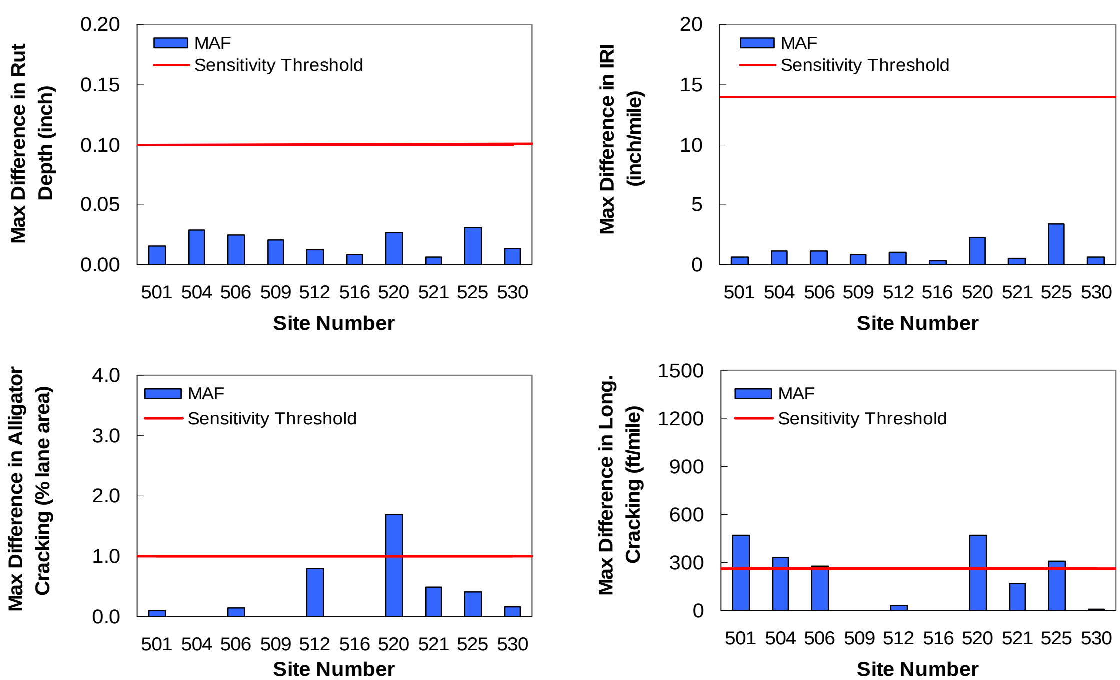


Figure 8-2 Maximum Difference in HMA Predicted Performance Using Different MAF Clusters

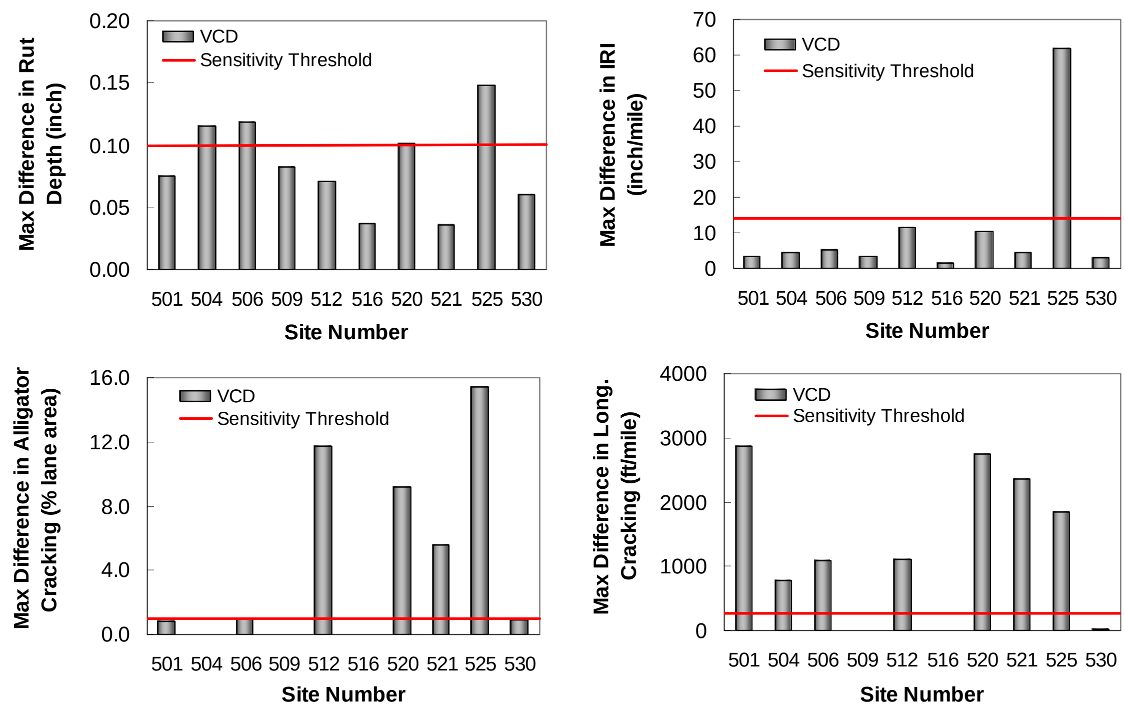


Figure 8-3 Maximum Difference in HMA Predicted Performance Using Different VCD Clusters

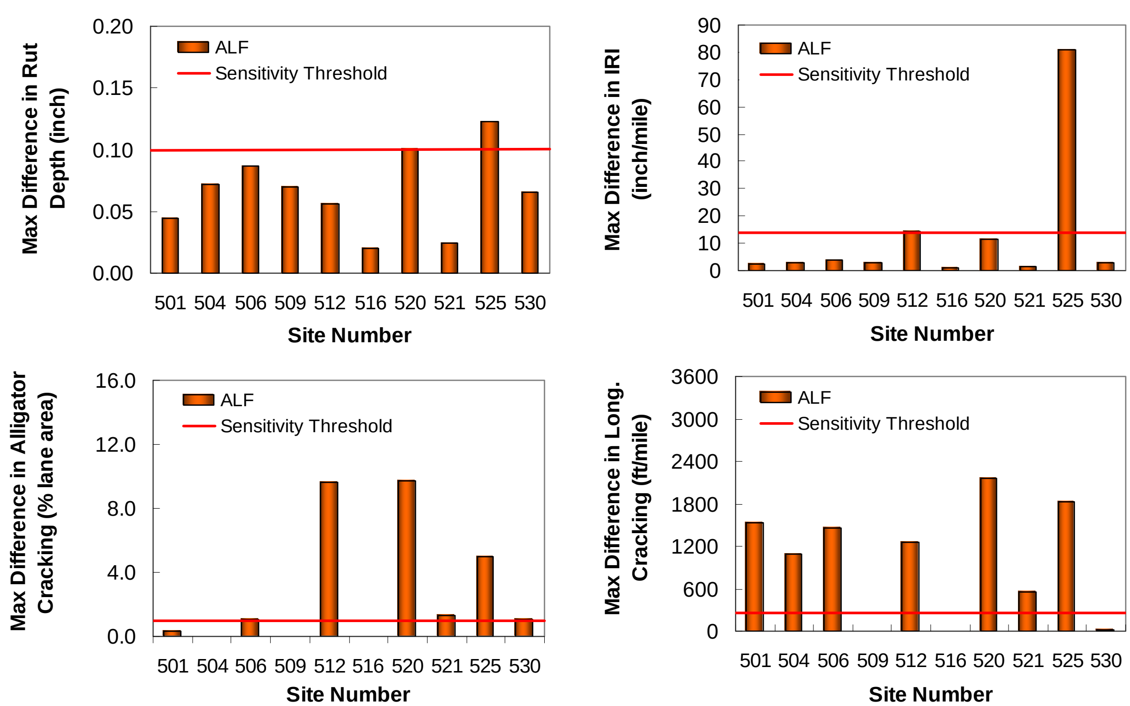


Figure 8-4 Maximum Difference in HMA Predicted Performance Using Different ALDF Clusters

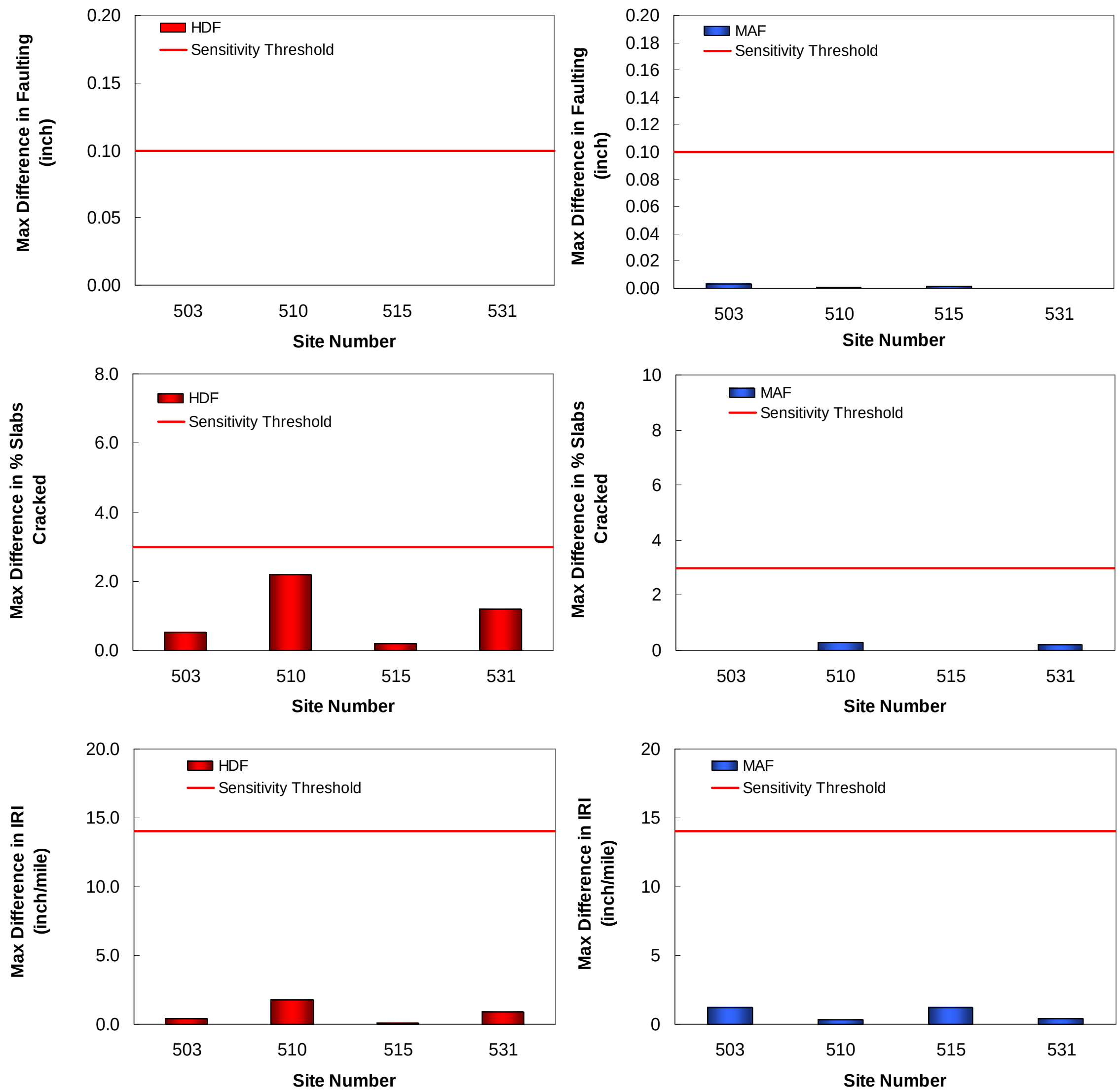


Figure 8-5 Maximum Difference in JPCP Predicted Performance Using Different HDF and MAF Clusters

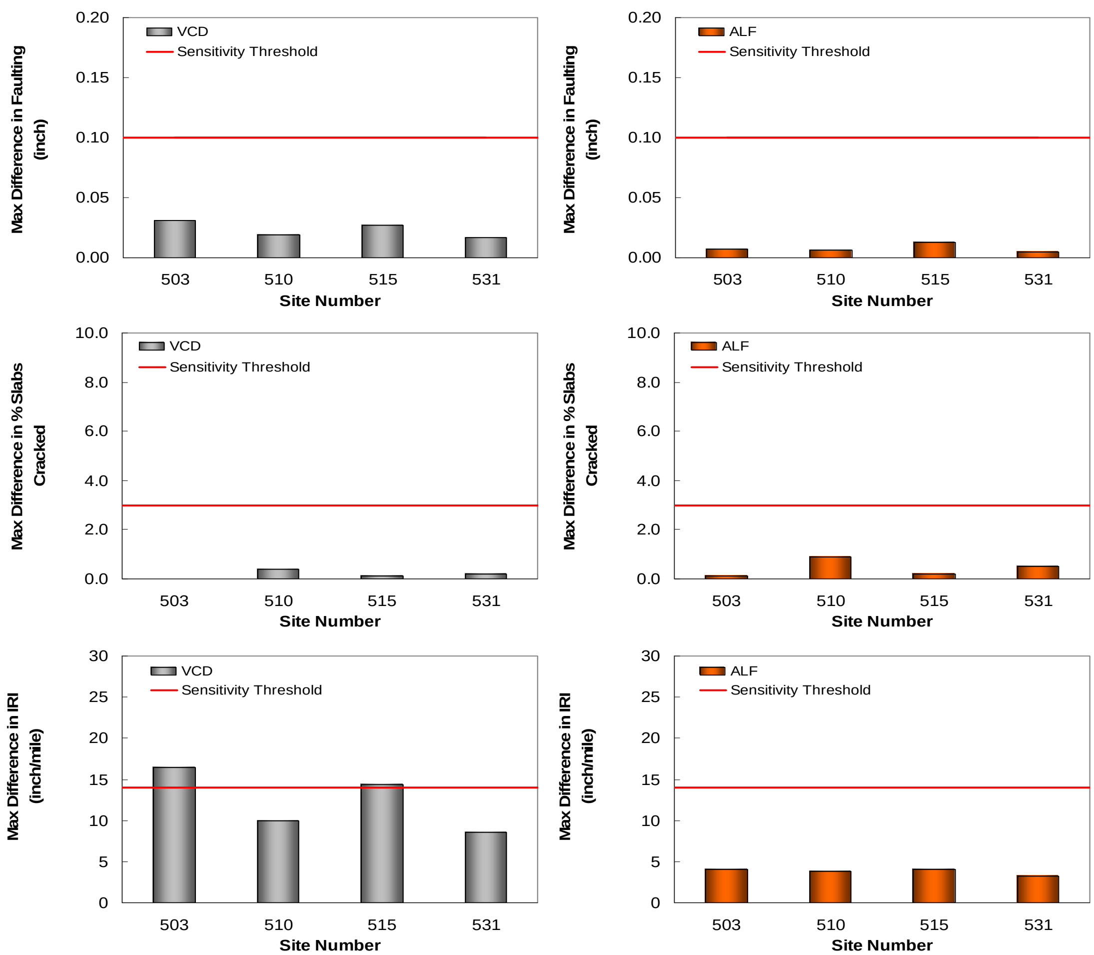


Figure 8-6 Maximum Difference in JPCP Predicted Performance Using Different VCD and ALDF Clusters

Table 8-2 summarizes the sensitivity of flexible and JPCP pavements to different traffic parameters. A check mark (✓) means sensitive whereas an (×) means insensitive in relation to the sensitivity criteria shown in Table 8-1.

Table 8-2 Sensitivity of Flexible and Rigid Pavements to Different Traffic Parameters

	Flexible Pavement				Rigid Pavement (JPCP)		
	Total Rut Depth (in)	Fatigue Cracking (%)	Longitudinal Cracking* (ft/mile)	IRI (in/mile)	Faulting (in)	Slabs Cracked (%)	IRI (in/mile)
HDF	×	×	×	×	×	×	×
MAF	×	×	✓	×	×	×	×
VCD	✓	✓	✓	✓	×	×	✓
ALDF	✓	✓	✓	✓	×	×	×

* The longitudinal cracking predictions obtained from the MEPDG are inaccurate, hence, the exclusion from the sensitivity study.

Table 8-2 suggests that using different HDF clusters for a particular design project in the MEPDG results in predicted distresses that are insignificantly different in both pavement types, i.e. flexible and JPCP. When distress predictions are compared for different MAF clusters, it was found that with the exception of longitudinal cracking in flexible pavements, all other predicted distresses are insignificantly different.

The performance prediction model of longitudinal cracking that is embedded in the MEPDG has problems and therefore, has been ignored from sensitivity results. In version 0.9of the MEPDG, the version that was exclusively used in this project, it was assumed that the number of cycles to failure (N_f) model can be used for alligator cracking as well as longitudinal cracking. This assumption was based on another assumption that the longitudinal cracking transfer function can handle the error inherent in the first assumption. Realizing that the N_f model currently embedded in the MEPDG has been developed based on critical strain criterion and knowing that longitudinal cracking is affected mainly by thermal distresses and aging of the surface layers, it becomes clear that the longitudinal cracking predictions obtained from the MEPDG are inaccurate, hence, the exclusion from the sensitivity study.

Table 8-2 shows that VCD clusters, on the other hand, resulted in predicted distresses that are significantly different for flexible pavements. For JPCP however, different VCD clusters resulted in predicted faulting that is insignificantly different and also a predicted percent slabs cracked that is insignificantly different. In contrast, different VCD clusters were found to have different effects on predicted IRI. The difference in IRI was significant because of factors other than faulting and slabs cracked. In fact IRI for JPCP is a function of faulting, percent slabs cracked, both of which were found to be insensitive, and also a function of spalling (not considered in this project), and site factor. So even though the 2 distress types considered in this project for JPCP were found to be insensitive to different VCD clusters, IRI was still found to be sensitive as it is highly affected by the site factor.

Finally, Table 8-2 shows that different ALDF clusters were found to result in predicted flexible pavement distresses are significantly different. On the other hand, different ALDF clusters resulted in JPCP distresses that are insignificantly different.

8.3 Aggregation of ALDF Clusters

8.3.1 Background

The aggregation process will only be carried out on ALDF since it is the only traffic parameter that will be derived from the sensitivity analysis results rather than the 48-hour counts. Considering ALDF, Table 8-2 shows that flexible pavement performance is sensitive to ALDF whereas rigid pavement performance is insensitive to ALDF. In other words, the aggregation of ALDF clusters should be driven by flexible pavement distresses and not by JPCP distresses.

The proposed approach for aggregating clusters is mainly dependent on the performance measures that were found to be sensitive, longitudinal cracking excluded. Table 8-2 suggests that for flexible pavements, these measures are: total rut depth, alligator cracking, and IRI with respect to ALDF clusters.

Table 8-3 summarizes the sites for which predicted performance was found to be sensitive to at least two ALDF clusters. Table 8-3 shows that with respect to ALDF, a total of 2 sites were found to be sensitive to total rut depth, 6 sites were found to be sensitive to alligator cracking, 7 sites were found to be sensitive to longitudinal cracking, and 2 sites were found to be sensitive to IRI.

Table 8-3 List of Sensitive Flexible Pavement Sections

Flexible Sections(10 Total) WIM Sites Sensitive to ALDF			
Total Rut Depth	Alligator Cracking	Longitudinal Cracking	IRI
520	506	501	512
525	512	504	525
	520	506	
	521	512	
	525	520	
	530	521	
		525	

8.3.2 Aggregation Approach

Aggregating ALDF clusters is investigated based on all 3 sensitive performance parameters for flexible pavements; total rut depth, IRI, and alligator cracking. The steps for aggregating ALDF clusters starts from *Step 1* by listing the predicted total rut depth (in) for the two sites that showed sensitivity in Table 8-3, and for every ALDF cluster. In *Step 2*, the predicted total rut depth is then sorted in an ascending order starting from the lowest to the largest. *Step 3* is a matrix representation of the differences in predicted total rut depth between each of the clusters and all other clusters.

A vital consideration when aggregating different clusters is to find the lowest possible number of cluster groups (final number of clusters) based on pavement performance predictions. The smaller the number of cluster groups, the simpler the design process will be. With this in mind, Step 3 suggests that when only one site is considered, the ALDF clusters can be aggregated into two cluster groups: for example, Cluster Group 1 contains C1, and C2; Cluster Group 2 contains C3, and C4. Same cluster groups are identified when predicted IRI is considered for the same WIM site. However, for other sites none of the ALDF clusters can be aggregated based on IRI. Following the same approach for aggregating ALDF clusters, the results suggest that ALDF clusters cannot be aggregated and should be considered separately. Therefore, it is recommended to include all four ALDF clusters into the final decision tree being developed.

8.4 Aggregation of Vehicle Classes

8.4.1 Background

One of the traffic input parameters required by the MEPDG is the VCD factor. MEPDG requires that the percentage or the contribution of every vehicle class into the truck traffic stream be entered. In the current design practice, NCDOT considers only two groups of vehicles; single-unit (SU) trucks (class 4 through 7), also referred to as % duals, and multi-unit (MU) trucks (class 8 through 13) which are referred to as % TTST (Truck Tractor and Semi Trailer). Under this task, the effect of aggregating vehicle classes on predicted flexible and rigid pavement performance has been investigated.

8.4.2 Aggregation Approach

Initially, Site specific VCD for the ten vehicle classes (class 3 through 13) were divided into two groups, the first group represents the % duals and the second represents % TTST. Ten LTPP flexible pavement sites and four rigid pavement sites have been assigned for this study. Two average percentages of vehicle classes were then calculated; one to represent every vehicle class in % duals and the other to represent every vehicle class in % TTST. These averages are shown in Table 8-4. Table 8-4 also shows the differences between site specific VCD for every vehicle class and the corresponding average VCD. In other words, if the vehicle class is within the % duals group, the difference in Table 8-4 will be that between site specific and the SU average VCD. Similarly, if the vehicle class happen to belong to the % TTST group, then the difference represents the site specific VCD for that vehicle class and the MU average VCD. Table 8-4 suggests that there is a fairly wide range of differences which range from -20.6 to 37.2 percent for SU vehicles and from -13.0 to 61.7 for MU vehicles.

The MEPDG was then executed twice for every site; once to predict the pavement performance using site specific VCD, i.e., every vehicle class has its own contribution to the total truck traffic, and second, to predict performance with aggregated average VCD. The way the MEPDG is executed using the average VCD is by entering the same SU average VCD for classes 4 through 7 and the same MU average VCD for vehicle classes 8 through 13. The differences in predicted performance using site specific VCD and aggregated SU and MU VCDs are then analyzed.

Figure 8-7 presents the differences in flexible pavement performance predicted using site specific VCDs and SU and MU vehicle class averages for all 10 sites. Figure 8-7 suggests that aggregating vehicle classes has a significant effect (based on the sensitivity criteria developed and presented above on three of the flexible pavement performance measures; total rut depth, alligator cracking, and longitudinal cracking. Aggregating vehicle classes was found to have an insignificant effect on flexible pavement predicted IRI. It is worth mentioning that the negative numbers in Figure 8-7 mean that the performance was improved when vehicle classes were aggregated.

Similarly, Figure 8-8 shows the differences in rigid pavement performance predicted using site specific VCDs and SU and MU vehicle class averages for all 4 rigid pavement sites. Negative differences mean that performance was improved when clusters were aggregated. Figure 8-8 shows that aggregating vehicle classes has no significant effect on the predicted performance of rigid pavements. Therefore, VCD derived from 48-hr counts can be aggregated into two groups; % duals and % TTST, for rigid pavement design.

Table 8-4 Difference between Site Specific VCD and Average VCD for SU and MU Trucks

Pavt. Type	Site	Avgerage VCD		Difference Between Site Specific VCD and Average VCD for SU				Difference Between Site Specific VCD and Average VCD for MU					
		SU	MU	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
Flexible	501	11.38	9.08	-8.91	25.19	-5.36	-10.92	-5.67	40.94	-8.53	-8.67	-9.03	-9.04
	504	8.31	11.13	-4.60	11.72	0.88	-8.01	-7.50	48.73	-10.35	-9.65	-10.23	-11.01
	506	10.61	9.59	-3.21	15.23	-1.69	-10.32	0.61	35.43	-8.43	-8.81	-9.30	-9.49
	509	7.59	11.61	-4.10	10.14	1.24	-7.28	-6.71	49.73	-10.59	-9.69	-11.45	-11.31
	512	15.26	6.50	-5.32	16.57	3.36	-14.61	1.35	21.34	-6.01	-5.84	-4.40	-6.46
	516	21.37	2.42	7.14	25.76	-12.32	-20.59	4.62	4.50	-1.96	-2.39	-2.41	-2.35
	520	6.89	12.07	-2.70	9.89	-0.79	-6.39	-8.83	53.85	-11.61	-9.96	-11.44	-12.00
	521	17.95	4.70	-14.13	37.17	-5.97	-17.08	18.08	0.25	-4.23	-4.70	-4.70	-4.69
	525	7.16	11.90	-2.47	11.04	-1.66	-6.92	-7.54	52.24	-10.55	-10.55	-11.78	-11.84
	530	10.22	9.85	-5.99	14.87	0.83	-9.71	-5.10	41.57	-8.21	-9.57	-9.73	-8.94
Rigid	503	5.05	13.30	-0.61	6.16	-0.54	-5.01	-10.34	61.74	-12.75	-12.67	-12.76	-13.22
	510	4.96	13.36	-0.86	6.82	-1.12	-4.84	-4.02	50.79	-12.94	-7.95	-12.57	-13.31
	515	4.69	13.54	-0.82	5.38	0.04	-4.59	-11.21	59.49	-13.17	-9.71	-11.92	-13.49
	531	6.92	12.06	-1.55	10.95	-2.62	-6.79	-7.68	49.30	-11.69	-7.70	-10.23	-12.02

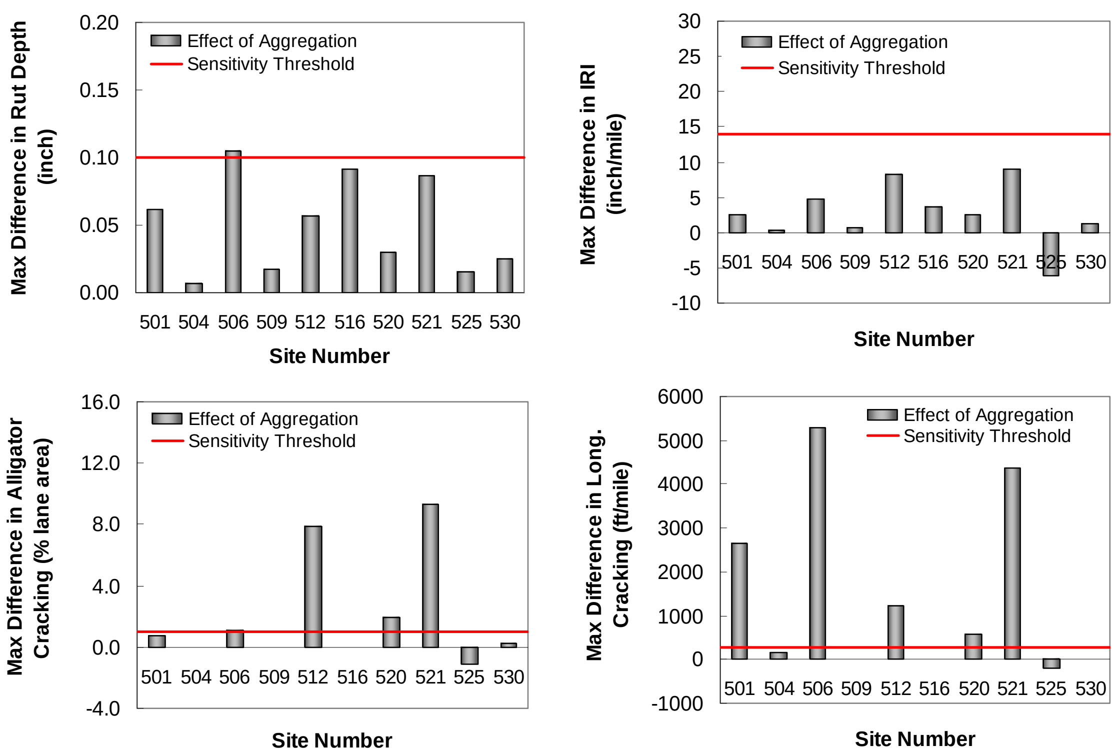


Figure 8-7 Effect of Aggregating Vehicle Classes on Flexible Pavement Performance

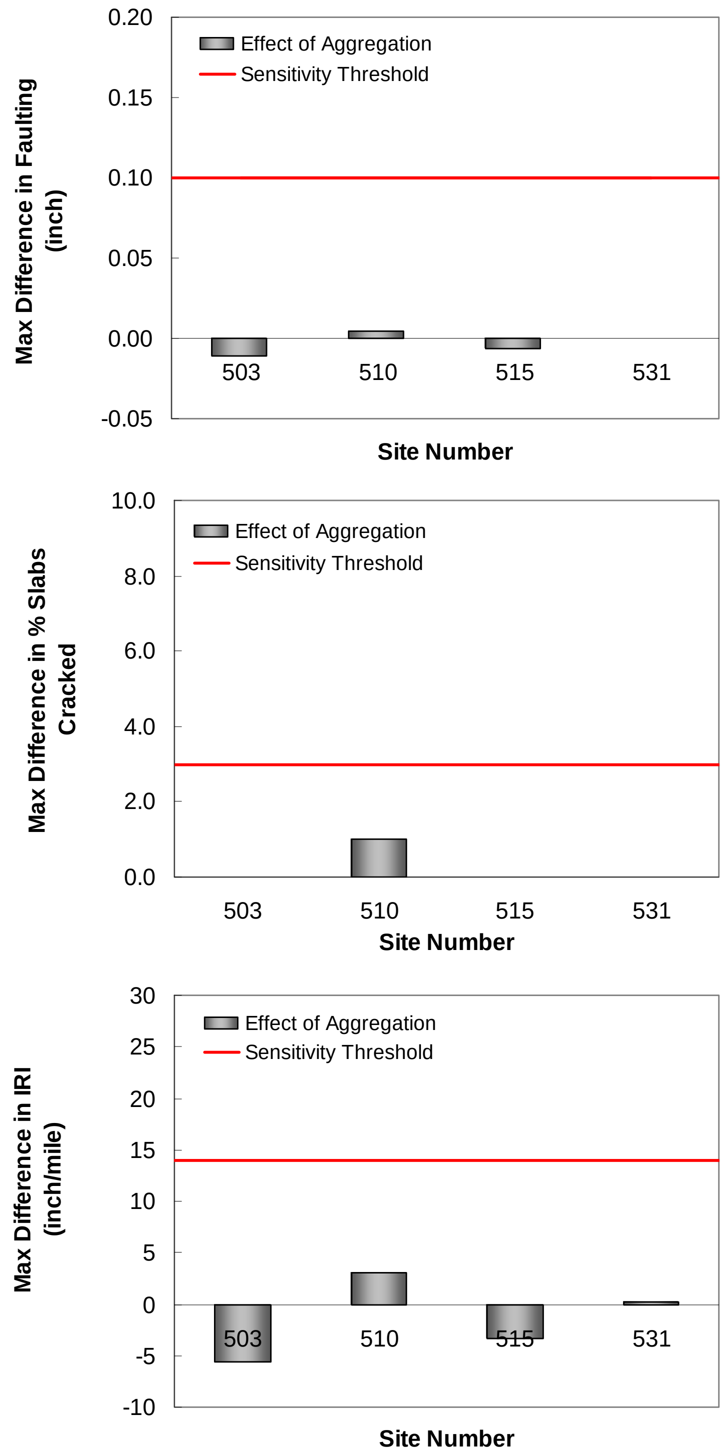


Figure 8-8 Effect of Aggregating Vehicle Classes on Rigid Pavement Performance

8.5 Results and Discussions

Sensitivity study was done to determine how different clusters for different traffic parameters affect the predicted performance of flexible and rigid pavements in the MEPDG. The ultimate purpose is to simplify the MEPDG design process by aggregating different clusters of traffic parameters. The results showed that all MAF and HDF clusters, when individually implemented in the MEPDG, would result in similar predicted performances measures based on the threshold values. Thus the average statewide MAF and HDF values may be used as input to MEPDG. This is a valuable finding that simplifies the design process. The sensitivity results shows that VCD clusters, on the other hand, resulted in predicted distresses that are significantly different for flexible pavements. For JPCP however, different VCD clusters resulted in predicted faulting that is insignificantly different and also a predicted percent slabs cracked that is insignificantly different. The results suggest that pavement performance is sensitive to VCD cluster. A seasonal factoring procedure is used to convert 48-hour class counts into annual average truck volumes to generate site-specific VCD inputs to MEPDG (Chapter 3). Finally, the sensitivity results showed that different ALDF clusters result in different predicted flexible pavement distresses; i.e., the pavement performance is sensitive to different ALDF distributions. Aggregating ALDF clusters is also investigated based on all 3 sensitive performance parameters for flexible pavements; total rut depth, IRI, and alligator cracking, respectively. The results suggest that ALDF clusters cannot be aggregated and should be considered separately. A decision tree is developed based on easy-to-obtain traffic parameters and road category that will help the designer to select the proper ALDF cluster as input to MEPDG (Chapter 6).

CHAPTER 9.   SEASONAL SAMPLING PLAN

This chapter explores the problem of sampling sparse WIM data to generate estimates of traffic inputs for MEPDG. Previous research has shown that sampling improvements can be achieved by increasing the sample repetitions, testing more sampling schemes, including the predictable seasonal variation (stability) of truck traffic, and establishing a baseline comparing the sampled estimates of ALDF to the ALDF from annual WIM data. The proposed NC sampling scheme has different frequencies (annual, semiannual, quarterly, and monthly) and different lengths of sampled data (two consecutive weekdays and five consecutive weekdays). The sampling analysis showed that the choice of the proper sampling scheme depends on the seasonal variation of the truck traffic.

9.1 Introduction

9.1.1 Background

The 2002 MEPDG developed under National Cooperative Highway Research Study 1-37A is based on mechanistic-empirical (M-E) pavement damage analysis that requires truck traffic data for new and rehabilitated pavement design [*NCHRP Project 1-37A,2004*]. Among the required traffic data are ALDF, MAF, HDF, and VCD. Weight-in-motion (WIM) stations continuously collect weight data for each passing vehicle in addition to volume data by vehicle class. The comprehensive range of traffic data collected by WIM sites makes them an appealing option for DOTs to collect traffic data for M-E design. However, WIM sites require sophisticated data collection sensors, controlled operating environment (strong, smooth, level pavement in good condition), and costly equipment for set up and calibration [*TMG, 2001*]. Given resource limitations and budget constraints at state DOTs, it has been challenging to provide optimum requirements for WIM sites to collect and to report complete data for long periods of time. There are also unexpected situations in which a WIM site may be destroyed or damaged or perform intermittently. In such circumstances, DOTs need guidelines for efficient and reliable data collection and sampling schemes. Thus, this chapter seeks to answer to the question: "How much WIM data collected at an individual site is enough to characterize the truck traffic for use in M-E pavement design?"

9.1.2 Literature Review

Over the last decade, researchers and practitioners have developed numerous approaches to generate traffic input for MEPDG [*Kim et al. 1998, Prozzi and Hong 2005, Papagiannakis (a) 2006, Lu and Harvey 2006, Tran and Hall 2007, Wang et al. 2007, Swan et al. 2008, Sherif et al. 2010*].North Carolina has also participated in this national effort geared toward characterizing the traffic input for MEPDG [*Sayyady et al. 2010, Ramachandran et al. 2010*]. Using NC WIM data, MEPDG damage-based sensitivity analysis showed that pavement performance is sensitive to NC site-specific ALDF and VCD. The approach to generate VCD factors is to employ a seasonal factoring procedure that converts the site-specific 48-hour classification counts into annual average truck volumes which are used to generate site-specific VCD inputs. Based on sensitivity analysis results, pavement performance is found to be insensitive to NC site-specific and national default values of HDF and MAF, thus the NC approach is to use the average statewide HDF and MAF values as input to MEPDG. In light of the different approaches used to generate VCD, HDF, and MAF, a potential sampling scheme should primarily focus on ALDF. Obviously, if we have a year of data, we have all the data we need to generate ALDF input. However, for less than a year, how much data is sufficient for a reliable ALDF estimate for MEPDG?

Several research projects have studied the problem of sampling sparse WIM data. For example, to improve the quality of the load data the Long Term Pavement Performance (LTPP) program established a traffic data collection plan. The LTPP data collection protocol states that reasonably accurate estimates of annual loading rates can be computed from fairly small samples of data if the WIM equipment is well calibrated and the traffic pattern is fairly stable at the location. In particular, for most General Pavement Studies (GPS) LTPP recommends sampling load data of two days per year to produce ±50% load estimates within a 95% confidence interval [*Hallenbeck, 2010*]. Another study investigated the effect of different sampling scenarios on pavement performance by comparing percentage errors in pavement life predictions with respect to the predictions obtained with continuous WIM data [*Papagiannakis (b), 2006*]. The two sampling scenarios for the WIM data sets were one month per season and one week per season. The results showed that sampling one month per season produced a life prediction percentage error of 13.42% at a 95% confidence level compared to estimates produced by continuous traffic input. For the one week per season samples, the error was 17.33% with a 95% confidence level.

NCHRP Project 1-39 documents the effect of the length of the data collection period on the accuracy of pavement damage factors for short-duration WIM data [*NCHRP Project 1-39, 2005*]. The two data collection scenarios were: seven consecutive days and two consecutive weekdays. Short-duration WIM data estimates of annual average equivalent single-axle loads per vehicle (AAEPV) were compared to the estimates of AAEPV derived from annual WIM data. The results showed that using a WIM data sample of two consecutive weekdays produces moderate mean absolute percent error (MAPE) in the estimates of AAEPV (7.3% to 13% for different vehicle classes), while the use of seven consecutive days of data produces better MAPEs (5.7% to 10.1% for different vehicle classes). Li *et al*. has also investigated the effect of sampled WIM data on pavement design by examining five sampling schemes: 1 month, 3 months, 6 months, 9 months, and 12 months. They concluded that three random months of WIM data result in statistically sound traffic input for MEPDG [*Li et al., 2007*]. In a recent study, Hong *et al*. evaluated the effect of different sampling schemes on estimates of axle load distribution using three evaluation criteria: sum of absolute error of axle load distribution factor, errors in average ESALs per axle, and errors in pavement life estimates [*Hong et al., 2008*]. The sampling schemes involved different frequencies (month, quarter, and year) and different lengths of data collection (one day, two consecutive days, and one week). The results showed that sampled data from one day, two days, and one week per month, and two days and one week per quarter are sufficient to provide accurate traffic data for pavement design.

In summary, previous research has shown the effectiveness of several sampling schemes to generate estimates of traffic inputs for MEPDG. Some used relatively small samples assuming inherent randomness in truck traffic data. Some used damage analysis as a baseline comparison. Other research considered a relatively few sampling schemes. Thus, improvements can be achieved by increasing the sample repetitions, testing more sampling schemes, including the predictable seasonal variation (stability) of truck traffic, and establishing a baseline comparing the sampled estimates of ALDF to the ALDF from annual WIM data.

9.1.3 Overview

As discussed above North Carolina pavement performance is sensitive to NC site-specific ALDF and VCD, and this study focuses on axle load distributions only. The ALDF represents the frequency of individual load intervals, known as load bins, for four axle types: single, tandem, tridem, and quad. Among the four axle types, single and tandem axles are more frequent (57.7% and 41.9%) than tridem and quad axles (0.3%, and 0.1%). And tandem axles also have a larger effect on pavement performance (35% and 64%) than tridem and quad axles (both less than 1%) as demonstrated below by damage factor analysis that quantifies the effect of different axle types on pavement performance. Thus, it is justifiable to examine the effectiveness of different sampling schemes on the accuracy of single and tandem ALDFs. The proposed NC sampling scheme has different frequencies (annual, semiannual, quarterly, and monthly) and different lengths of sampled data (two consecutive weekdays and five consecutive weekdays). The sampling analysis showed that the choice of the proper sampling scheme depends on the seasonal variation of the truck traffic. In locations with fairly stable truck traffic most of the sampling schemes generate encouraging results while in other locations with high seasonal variations in truck traffic, semiannual and quarterly sampling schemes are required to generate acceptably accurate estimates of single and tandem ALDFs. The Sampling scheme is supposed to capture the variations in truck traffic. Thus, it is not sufficient to identify the critical season and collect data only then. Rather, it is necessary to collect data in other seasons as well as the critical season to capture the variations in truck traffic.

The results also showed that a larger amount of sampled data does not necessarily generate more accurate estimates of ALDF. For example, there is relatively little improvement in estimating single and tandem ALDFs as the sampling scheme changes from five consecutive weekdays per quarter (20 days total), to two days per month (24 days total), and to five days per month (60 days total). It appears that sampling five days per quarter can sufficiently capture the seasonal variations in truck traffic.

9.2 Objectives

This study focuses on ALDF required for M-E pavement design. Sampling for VCD, MAF and HDF is not necessary based on the approaches adopted in NC to generate traffic factors for M-E pavement design. The objectives that we pursue are twofold. First, the chapter examines the effect of different sampling schemes on the accuracy of the axle load distribution. The effectiveness of different sampling schemes was evaluated using the sum of the relative error (SRE) in estimating single and tandem ALDFs derived from sampled WIM data compared to estimates of ALDFs derived from annual WIM data. Second, we investigate the relation between data sampling and seasonal variations in traffic where annual WIM data is not available. Three regions in NC with different climatic characteristics are studied for this purpose.

9.3 Traffic Data

Currently, NCDOT has operated44 WIM sites including 19 LTPP stations. These WIM sites are located in three regions: the eastern coastal plain, central Piedmont, and western mountains. NCDOT provided twelve consecutive months of calibrated volume and weight data for each WIM site. The data were checked for completeness and anomalies. The quality control procedure confirmed that the data were reliable [*Ramachandran et al., 2010*]. For this sampling analysis, three WIM sites were selected from three geographical regions in NC (Figure 9-1). The reason for selecting different regions is to study whether the differences in climatic characteristics and seasons of regions contribute to the difference among sampling schemes. The WIM sites were:

- WIM site 501 (LTPP Section 371028) located on US 17 in coastal plain, AADTT = 940,
- WIM site 530 (LTPP Section 370900) located on US1 in central Piedmont, AADTT = 1736,
- WIM site 520 (LTPP Section 371801) located on I-40 in western mountains, AADTT = 6093.

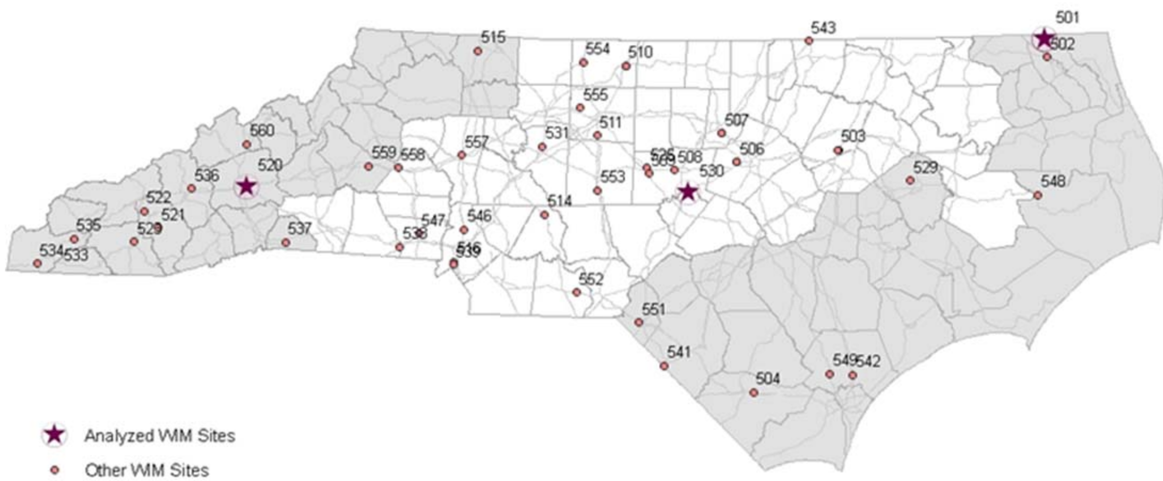


Figure 9-1 Distribution of WIM Sites in North Carolina

9.4 Sampling Methodology

9.4.1 <u>Proposed Sampling Schemes</u>

The proposed sampling schemes have different frequencies (annual, semiannual, quarterly, and monthly) and different durations of sampled data (two consecutive weekdays and five consecutive weekdays): 2-consecutive weekdays per year, 2-consecutive weekdays per six months, 2-consecutive weekdays per quarter, 2-consecutive weekdays per month, 5-consecutive weekdays per year, 5-consecutive weekdays per six months, 5-consecutive weekdays per quarter, 5-consecutive weekdays per month (Table 9-1). These sampling schemes were adjusted based on NCDOT input and borrowed from the literature [NCHRP Project 1-39, 2005, Hong et al., 2008]. The sampling schemes including two consecutive weekdays are considered because collecting and analyzing data for two consecutive days is a general practice of most state DOTs including NCDOT. Sampling schemes including five consecutive weekdays are adopted because they account for temporal variations of traffic over weekdays. Every effort is made to consider typical weekday travel conditions: no holidays or days immediately before and after holidays, and no days with construction delays or bad weather. The annual sampling schemes require the fewest days of data collection and analysis, but may not capture the temporal variation of truck traffic. However, in the case of the M-E pavement design, the sampling plans should be developed and implemented to identify seasonal and monthly differences that may be present in traffic patterns [ARA, 2004]. To satisfy this requirement, sampling schemes with higher frequencies (semiannual, quarterly, and monthly) are also examined. These sampling schemes demand more data analysis, but they can capture the temporal variation of truck traffic.

Table 9-1 shows the sampling schemes with different frequencies and durations of sampled data. As presented in Table 9-1, the sampling schemes become more demanding as the number of days increase, that is, the frequency and duration of the samples increase. For example, 60 (5×12) days of data are required for the sampling scheme of five consecutive weekdays per month. On the other hand, two days of data (2×1) are required for sampling two consecutive days per year.

Subsequent sections define different axle types and evaluate the proposed sampling schemes with respect to their effectiveness in estimating the axle load distribution for different axle types.

Table 9-1 Proposed Sampling Schemes

	Annual	Semiannual	Quarterly	Monthly
2-consecutive weekdays	2d/yr (2 days)	2d/6 mos (4 days)	2d/qtr (8 days)	2d/mo (24 days)
5-consecutive weekdays	5d/yr (5 days)	5d/6 mos (10 days)	5d/qtr (20 days)	5d/mo (60 days)

9.4.2 Identifying Axle Types

ALDF represents the frequency of individual load intervals, known as load bins, for four axle types: single, tandem, tridem, and quad. Axle type definitions come from Long Term Pavement Performance (LTPP) functional specifications adjusted to comply with the prevalent axle configurations in NC, and ASTM E 1572-93 procedure identifies the axle types [*ASTM, 1994*]. A validation procedure eliminates invalid axle types. Then, all axles are evaluated in sequence from front to back of the truck using spacing criteria to determine if the current axle should be grouped with previous axle(s) or should form a new axle group [*Sayyady et al., 2010*].

Single, tandem, tridem, and quad axles contribute differently to the pavement damage. To quantify the pavement damage caused by different axle types and load combinations at WIM locations, the axle frequency for a specific load bin is multiplied by its damage factor as shown by Equation 1.

Single, tandem, tridem, and quad axles contribute differently to the pavement damage. To quantify the pavement damage caused by different axle types and load combinations at WIM locations, the axle frequency for a specific load bin is multiplied by its damage factor as shown by Equation 1.

$$\text{Total Damage Caused by Axle Type } t = \sum_{i_t=1}^{\text{max load range for axle type t}} \text{Axle Frequency}_{i_t} \times \text{Damage Factor}_{i_t}$$

where, i_t is the load bin i for axle type t (i = 3 – 41 kip single load bins at 1-kip interval, i = 6 – 82 kip tandem load bin at 2- kip interval, i = 12 – 102 kip tridem and quad load bin at 3-kip interval). A damage factor for any axle type and load combination is defined as the ratio of the fatigue damage caused by that combination to fatigue damage caused by a standard 18-kip Equivalent Single Axle Load (ESAL). The damage factors were developed by a simplified simulation and regression modeling analysis based on bottom-up fatigue damage. Results of the damage analysis showed that for the same axle load, tridem and quad axles cause less fatigue damage to the pavement compared to single and tandem axles [*Jadoun, 2010*]. Equation 1 is used to calculate the total damage caused by each axle type and the results are normalized to show the relative contribution of each axle type on pavement performance (damage). It is learned that in NC, on average 35% and 64% of pavement damage is caused by single and tandem axles, respectively, while the contribution of tridem and quad axles is negligible (less than 1%) at most WIM locations (Figure 9-2*a*). Figure 2*b* also illustrates that the average frequencies of single, tandem, tridem, and quad axles are 57.7%, 41.9%, 0.3%, and 0.1%, respectively. The high frequency and the large effect of single and tandem axles require a higher level of accuracy than tridem and quad axles that are infrequent and have relatively small effects on pavement. Thus, it is justifiable to use single and tandem axles to discover the effectiveness of different sampling schemes on ALDF accuracy.

The WIM location that is shown with a dashed line in Figure 9-2 is an exception. This specific WIM site is located on a state road with relatively few trucks (600 AADTT). In most WIM locations the low frequency of tridem axles is dominated by the relative high frequency of single and tandem axles as shown by the solid lines in Figure 9-2.

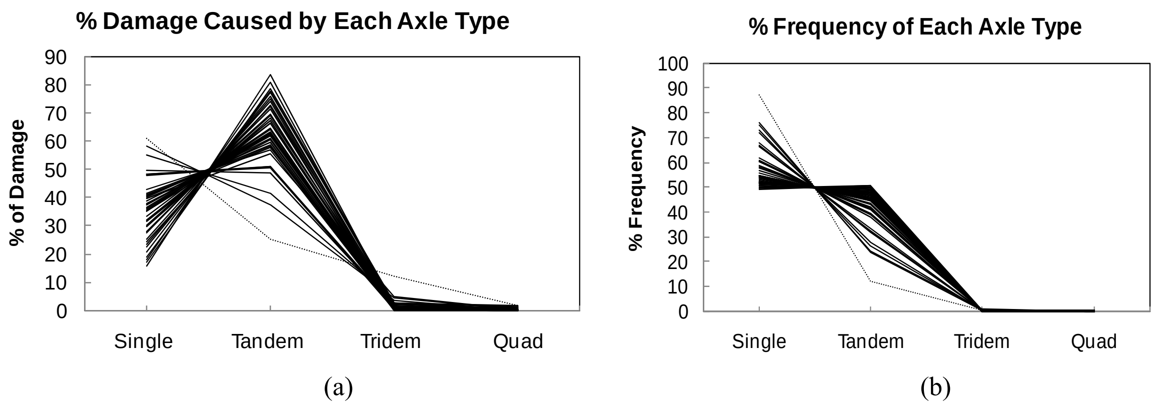


Figure 9-2 (a) Percentage Damage Caused By Each Axle Type at WIM Sites, (b) Percentage Frequency of Each Axle Type at WIM Sites

9.4.3 Sampling Analysis

The sampling analysis in this chapter uses WIM data collected at three locations in different regions by NCDOT (Figure 9-1). The effectiveness of using different sampling schemes is evaluated using the sum of relative error (SRE) in estimating single and tandem ALDFs derived from WIM data collected over a short period of time compared to estimates of ALDFs derived from annual WIM data. The formal definition of the SRE criteria follows:

$$SRE = \sum_i \frac{|f_i^a - f_i^s|}{f_i^a} \times 100 \quad (2)$$

f_i^s Normalized frequency of the ith load interval of ALDF from WIM data collected over a short period of time

f_i^a Normalized frequency of the ith load interval of ALDF from annual WIM data

The use of the absolute difference between frequencies restrains large positive errors from being offset by large negative errors.

To satisfy the minimum randomness requirement, 30 independent samples are drawn randomly from the WIM data for each sampling scheme. For the sampling scheme with two consecutive weekdays, the samples are randomly selected from all possible pairs of weekdays with a maximum of four pairs per week. For the sampling scheme with five consecutive weekdays, the samples are drawn from all periods of five consecutive days not including holidays. For each of the three WIM sites selected, the database contains data for at least 36 weeks (three weeks per month). Hence, for all three WIM sites the data are available for a random selection of 30 sampled data to generate the SRESRE for single and tandem ALDFs. Each of the resulting SRE values are averaged for 30 random samples, producing values of mean sum of relative error (MSRE).

9.5 Results

To perform the analysis, three WIM sites are selected from the three geographical regions in North Carolina: the eastern coastal plain, central Piedmont, and western mountains. The goal is to study whether alternative sampling schemes perform differently in three regions with different climatic characteristics. The seasonal analysis of 44 WIM sites in NC reveals that the monthly differences in truck traffic patterns vary over the three geographical regions. For example, in the coastal region, the distribution of trucks is slightly higher in the first half of the year compared to the second half of the year. In central Piedmont, the seasonal variation of truck traffic is fairly stable compared to other regions, though it slightly drops at the end of the year. Rural-recreational roads in mountains have high truck traffic from April until October but the traffic drops to a very low level from November through February because of snowfalls that limit the access to roads [*Sayyady et al., 2010*].

Figure 9-3 shows the monthly variation of truck traffic at the three locations mentioned above. For M-E pavement design, the MAF characterizes the monthly variation of truck traffic. The MAF is defined as the ratio of the monthly truck volume to the average monthly truck volume. As shown in Figure 9-3, the monthly variation of truck traffic at WIM location 501 (coastal region) is higher compared to other locations (high truck traffic in first half of the year followed by low truck traffic in the second half). The existence of farming industries (cotton, soybeans and corn) near the coast explains the higher number of trucks in June and July. Among these locations WIM 530 (Piedmont region) experiences rather stable truck traffic on relatively level highways through the year with a slight decrease in the winter months November and December. At WIM 520 (mountain region), the truck traffic decreases appreciably over winter months (November – February) when snowfalls discourage truckers from using steep slippery roads.

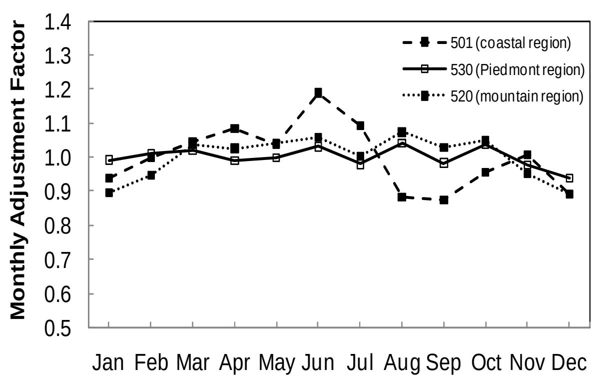
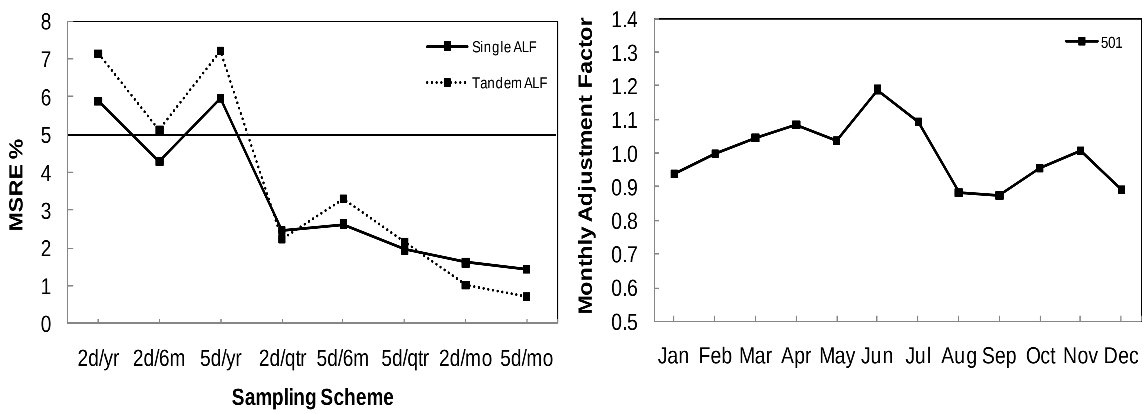


Figure 9-3 Monthly Adjustment Factor of Three WIM Sites in Different Geographical Regions

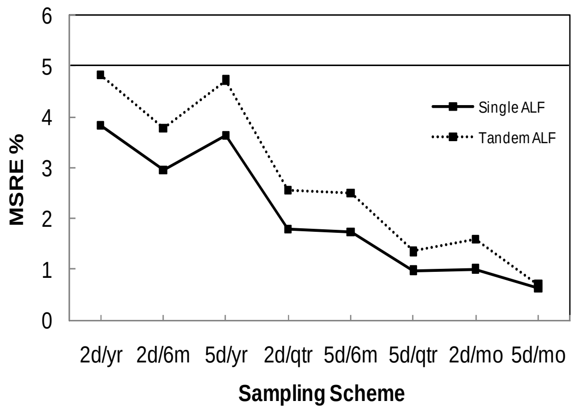
For each of these WIM sites, a complete set of MSRE% was developed for different sampling schemes. The results of the sampling analysis and the MAF of WIM sites 501, 530, and 520 are presented in Figure 9-4*a-f*. The *x*-axis of Figure 9-4*a*, Figure 9-4*c*, and Figure 9-4*e* is the direction of increasing effort in analyzing the data in terms of number of days considered. Some unique observations are noted:

1. For all sampling frequencies (annual, semiannual, quarterly, and monthly), five consecutive weekdays of sampled data either reduce or make no change in MSRE% compared to samples with two days of data. That is the accuracy of the single and tandem ALDFs improves if extended time coverage of WIM data is available (Figure 9-4*a*, Figure 9-4*c*, and Figure 9-4*e*).

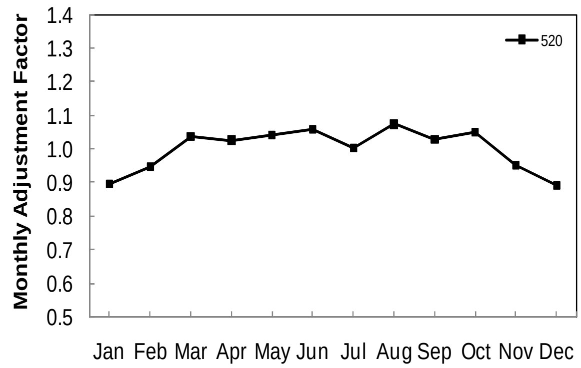
2. For WIM site 501 with high variability in truck traffic, the MSRE% of single ALDF drops from 6% to below 1.5% by extending the number of days analyzed. The same observation applies to single ALDF: the MSRE% drops from 7% associated with the two-day per year case to 2% associated with the five-day per month case (Figure 9-4*a* and Figure 9-4*b*).
3. Observation 2 is valid for WIM site 520; the MSRE% of single and tandem ALDFs improves with extending the number of days analyzed (Figure 9-4*c*).
4. For WIM site 530 that has the most stable truck traffic, the results of the sampling scheme with the smallest number of days (two days per year) are promising: the MSRE% is below 4% for both single and tandem ALDFs (Figure 9-4*e* and Figure 9-4*f*).
5. For all WIM site, sampling five weekdays per year does not improve the MSRE% of ALDFs compared to two days per six months though the number of days analyzed are higher (five days compared to four days). This outcome is expected because sampling two consecutive weekdays every six months captures the temporal variation of truck traffic within a year, while sampling five days per year does not (Figure 9-4*a*, Figure 9-4*c*, and Figure 9-4*e*).
6. Observation 4 is valid when the five-day semiannual scheme is compared to the two-day per quarter scheme. Although the former involves a longer data period, the latter results in lower MSRE % of ALDFs because of its higher frequency in capturing the temporal variation in truck traffic. In general, the sampling schemes that involve quarterly and monthly data analysis demonstrate lower MSRE % compared to annual sampling schemes.
7. The results also show that there is relatively little improvement in MSRE% for estimating single and tandem ALDFs when the sampling scheme changes from five days per quarter, to two days per month, and to five days per month. Hence, there should be time and financial savings incurred especially if there is no appreciable impact on the expected pavement performance.



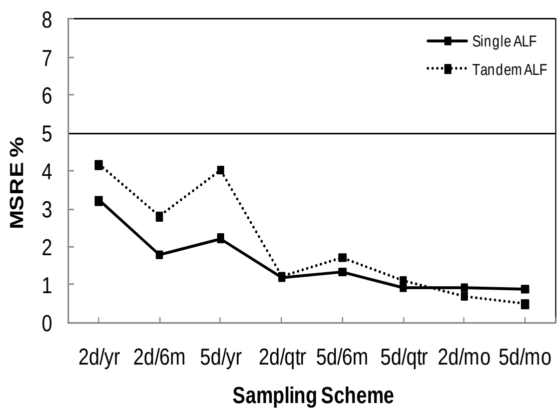
(a) (b)



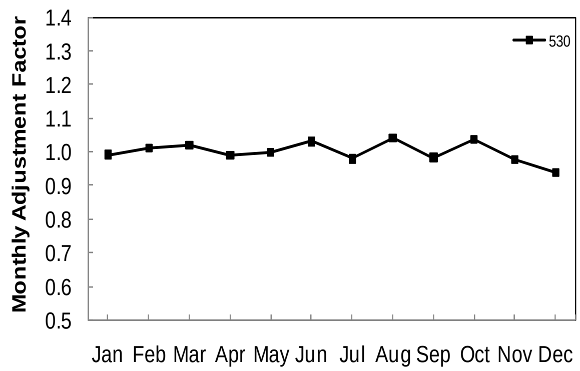
(c)



(d)



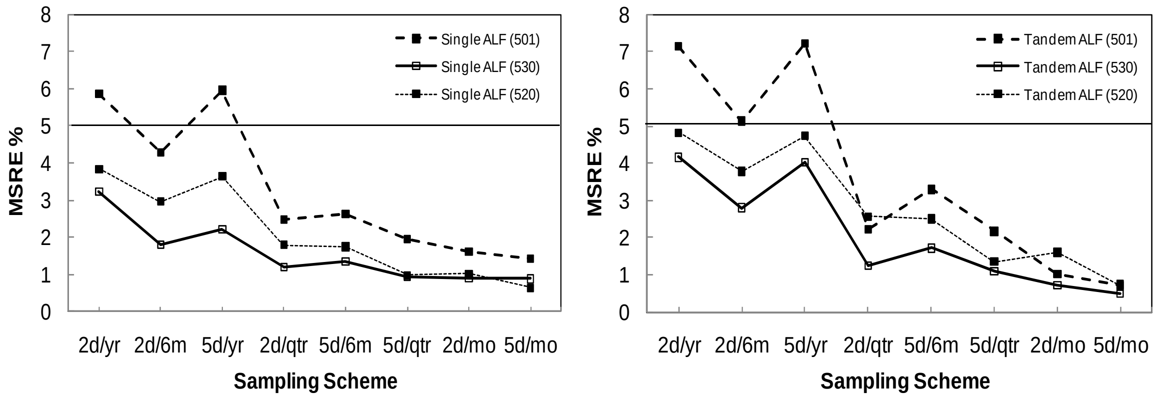
(e)



(f)

Figure 9-4 (a) WIM 501MSRE% for Different Sampling Schemes, (b) WIM 501 MAF, (c) WIM 520MSRE% for Different Sampling Schemes; (d) WIM 520 MAF, (e) WIM 530MSRE% for Different Sampling Schemes, (f) WIM 530 MAF

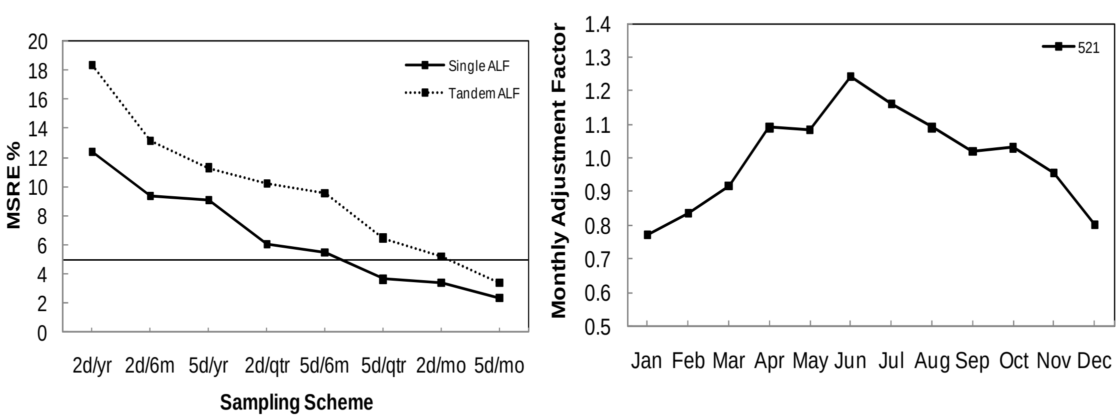
Figure 9-5*a* and Figure 9-5*b* facilitate the comparison of MSRE% for different WIM locations. For most of the sampling schemes, there is a direct relation between the MSRE% and the seasonal variation of truck traffic at WIM sites: the more stable the truck traffic is, the lower (better) MSRE% are achieved. For example, WIM 530 in the Piedmont region has the most stable truck traffic patterns compared to the other WIM sites and its MSRE% are the lowest compared to others (Figure 9-5*a* and Figure 9-5*b*). Likewise, most of the sampling schemes result in smaller MSRE% for WIM 520 (mountain region) than WIM 501 (coastal region) because WIM location 520 has more stable truck traffic than WIM 501. These findings can be used as guidance if only sampled data are available at WIM sites in different geographical regions. Assuming that a 5% error in estimating single and tandem ALDFs is acceptable to the pavement designer, then all sampling schemes are attractive choices in the Piedmont region where truck traffic is fairly stable. In the coastal region, however, noticeable variations in truck traffic rule out the two-day per year and five-day per year schemes. That is because few days of sampled data per year cannot sufficiently capture the seasonal variations of truck traffic.



(a) (b)

Figure 9-5 (a) MSRE% for Single ALDFs for WIM Sites 501, 530, 520 Caused By Different Sampling Schemes, (b) MSRE% for Tandem ALDFs for WIM Sites 501, 530, 520 Caused By Different Sampling Schemes

The observations made so far apply to locations where the temporal variations in truck traffic are not very high. However, there are some locations in the mountains with steep grades and winter snow that truckers avoid. One example is WIM site 521 located on NC 107. The effectiveness of the sampling schemes is less at such locations because a sampling scheme with a long data analysis period is required to obtain small MSRE % (Figure 9-6). In such a case, sampling schemes with five consecutive weekdays per quarter (20 days) and five consecutive weekdays per month (60 days) are required to produce relatively low MSRE % (less than 5%). This example emphasizes that knowledge of seasonal variations of truck traffic is necessary before using data collected over a short period of time instead of annual WIM data to estimate axle load factor.



(a) (b)

Figure 9-6 (a) The MSRE% for WIM 521; (b) Monthly Adjustment Factor for WIM 521

9.6 Conclusions and Recommendations

The effect of different sampling schemes on the accuracy of the axle load distribution derived from sampled WIM data compared to estimates of ALDFs derived from annual WIM data was evaluated. Also the relation between data sampling and seasonal variations in traffic was investigated. As expected, where truck traffic is stable (Piedmont region) all sampling schemes are attractive. Where truck traffic is not stable (coastal region) noticeable variations in truck traffic degrade annual-based sampling schemes because annually sampled data cannot sufficiently capture the seasonal variations of truck traffic. The sampling analysis also revealed that knowledge of seasonal variations of truck traffic is necessary to select a proper sampling scheme. It should be noted that besides WIM data, DOTs have several traffic monitoring programs that can help them quantify the seasonal variation of truck traffic. Another interesting finding is that increasing the amount of sampled data does not necessarily reduce the error in estimating single and tandem ALDFs. There is relatively little improvement in MSRE% as the sampling scheme changes from five consecutive weekdays per quarter (20 days), to two days per month (24 days), and to five days per month (60 days). This finding results because sampling five consecutive weekdays per quarter can efficiently capture the seasonal variation of truck traffic.

CHAPTER 10. WIM LOCATION PROBLEM

Besides providing vehicle weight and volume information for use in pavement design and management, WIM stations provide data for bridge management, overweight vehicle and permit enforcement, and transportation planning. Future applications of WIM stations combined with other technologies will enhance statewide traffic management and freight logistics. Thus, careful attention to WIM station location, replacement and expansion of sites is important. This chapter is written in response to Task 9 of the project: *Examine existing NCDOT traffic data resources to identify deficiencies*. Results based on seasonal factor analysis and ALDF analysis show more WIM sites are needed on some highways to reach the TMG desired levels of precision and confidence. On the other hand, related seasonal factor and ALDF analysis shows that TMG levels are exceeded at some factor groups/clusters. These WIM sites candidates for continued monitoring or abandonment depending on such factors as: pavement surrounding the WIM sensor, WIM equipment condition, urban/rural location, high/low truck volumes, and the expectation that the traffic pattern at a particular site is established or may change. After the number of new additional WIM sites is established, coverage count locations are evaluated as candidate sites. Priority selections of candidates are made as a result of clustering analysis, ALDF ranking factors, technical installation requirements, and NCDOT knowledge of site needs.

10.1 WIM Location Approach

The goal of this task is to make recommendations for locating new WIM sites to collect vehicle class counts and axle load data. A related result is recommended locations for WIM site abandonment. Figure 10-1 shows an overview of our proposed approach.

There are four major traffic inputs required for M-E pavement design: ALDF, MAF, HDF, and VCD. MEPDG damage-based sensitivity analysis showed that pavement performance is sensitive to NC site-specific ALDF, and VCD. Hierarchical clustering analysis based on NC ALDF develops representative ALDF patterns that have distinct characteristics for primary arterial, secondary arterial, collectors, and local roads. A simplified decision tree helps the pavement designer select the proper representative patterns of ALDF. To develop VCD factors, our approach uses 48-hour classification counts and a seasonal factoring procedure to account for day-of-week and seasonal variations. A seasonal factor decision tree was developed that helps the traffic engineer select the proper seasonal factors to annualize 48-hour classification counts that are eventually used to generate VCD factors. Based on sensitivity analysis results, pavement performance was found to be insensitive to NC site-specific and national default values of HDF and MAF, thus the average statewide HDF and MAF values are used as input to MEPDG. Among the four major traffic inputs, generating ALDF and VCD factors are more challenging because the process involves averaging ALDF factors and seasonal factors that belong to same ALDF cluster or seasonal factor group. To rely on the averaged factors as robust statistics that are not influenced by outliers, it is necessary to study the variability of *seasonal factor groups,* as well as *ALDF clusters*.

The variability (reliability) study can be used to identify the required number of WIM sites to achieve a desired level of precision. The first step in determining the variability is to determine which statistic guides the analysis. The objective of forming the seasonal factor groups is to eliminate the temporal bias in the 48-hour truck traffic volume by using the seasonal factors. Thus, the combined months and day of week factors computed for the SU trucks and MU trucks are appropriate statistics to guide the groups' sizes.

Initially, the team analyzed the variability of SU and MU seasonal factor groups. Variability of the factor groups serves two purposes: 1) to compute the precision of the factor group; and 2) to determine the number of WIM sites required within each factor group to attain a specific level of precision. To determine the precision of each group factor, the team used a slight variation of statistical procedure suggested in Section 4 of the TMG 2001. Figure 10 1 shows an overview of our proposed approach.

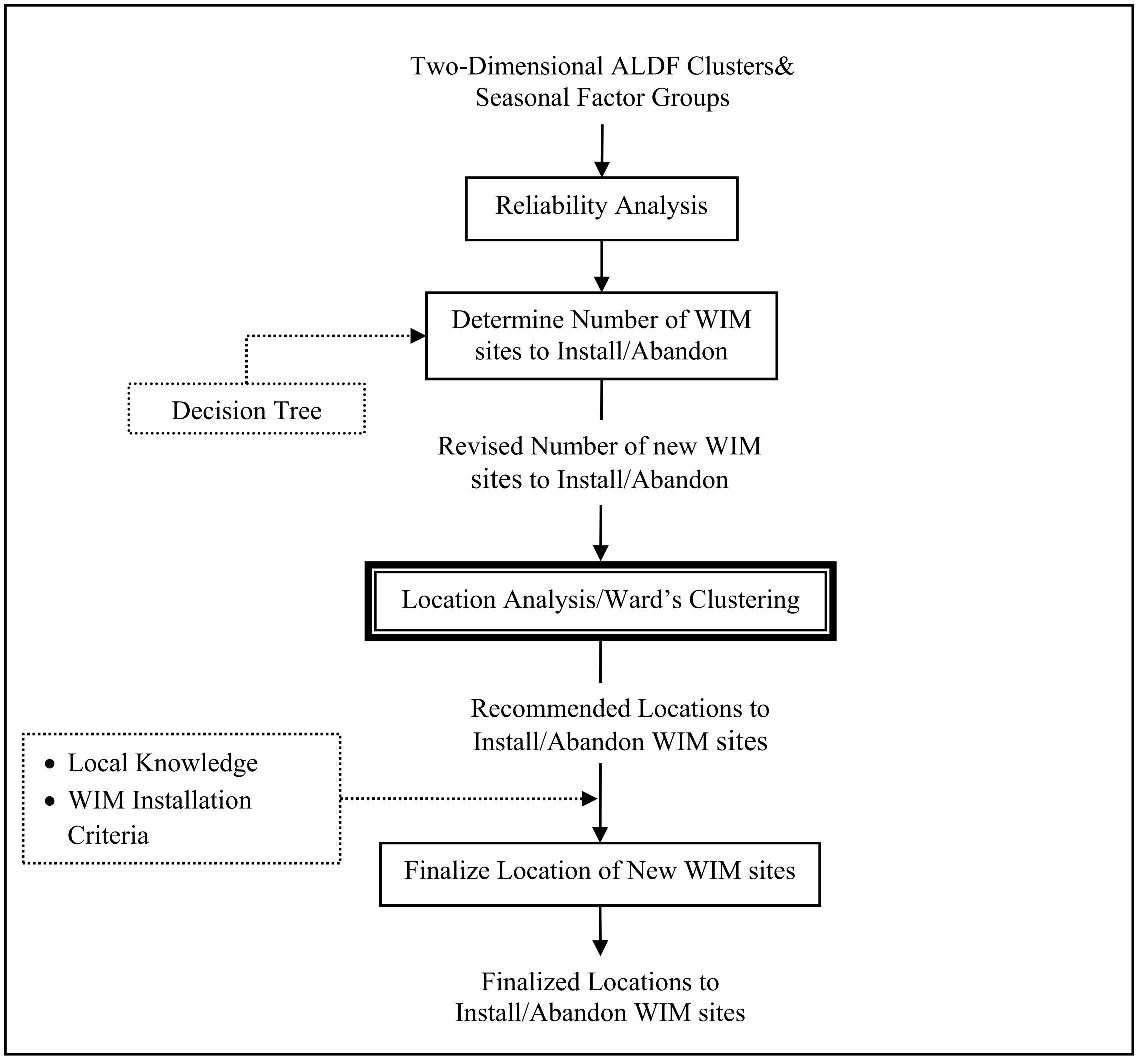


Figure 10-1 Research Methodology To Identify Locations of WIM Sites To Install/Abandon.

10.2 Data Source

WIM Data

The traffic data used in this study were collected by NCDOT from 1997 to mid 2007 for 44 WIM sites including 19 LTPP stations. NCDOT provided twelve consecutive months of calibrated volume and weight data for each WIM site. The data were checked for completeness and any anomalies. The quality control procedure (Chapter 2) confirmed that the data were reliable. For the worst cases only five percent of the data were excluded.

Truck Traffic Ground Count Data (Coverage Counts)

NCDOT conducted a statewide 48-hour truck traffic count survey in 2006 and 2007 and collected vehicle classification counts at 1000+ locations across the state. Truck traffic is classified based on the FHWA vehicle classification scheme, which includes bus; 2-, 3-, and 4-axle single-unit trucks; 4-, 5-, and 6-axle single-trailer trucks; and 5-, 6-, and 7-axle multi-trailer trucks. To begin the analysis we assume that coverage count locations are candidate locations for future continuous monitoring (installing new WIM sites). These locations enter a pool of locations for which a few are selected based on technical requirements to install WIM sites and NCDOT staff professional knowledge.

10.3 Reliability Analysis

10.3.1 SU and MU Seasonal Factor Groups

The number of WIM sites can be determined for a required level of precision using a statistical procedure suggested in Section 4 of the TMG 2001. The first step in determining the number of WIM sites needed is to determine which statistics guide the analysis. The objective of forming the factor groups is to eliminate the temporal bias in 48-hour truck traffic volume by using the seasonal factor. Thus, the combined month and DOW factors computed for the SU and MU trucks are appropriate statistics to guide the group size.

We use the confidence interval equation suggested in Section 4 of the TMG 2001:

$$D = t_{0.95,n-1} C/\sqrt{n} \quad (1)$$

$$\xrightarrow{yields} \quad n = (t_{0.95,n-1} C/D)^2 \quad (2)$$

D = precision interval as a proportion of the mean,
$t_{0.95,n-1}$ = value of the t-distribution with the 95% level of confidence and*n-1*degree of freedom,
n= number of WIM sites,
C = coefficient of variation (the ratio of the standard deviation to the mean).

Since the seasonal factors are calculated over the twelve-month period, the month with the most variable combined month and DOW seasonal factor should be used to determine the total number of WIM sites required. As a result, the seasonal factors computed for other months will have higher precision.

Table 10-2 show the precision level for the SU factor groups and MU factor groups, respectively.

Table 10-1 Precision Level for the SU Factor Groups (FG)

	n	$t_{0.95,n-1}$	month with the most variability	C	D
SU FG 1	12	2.20	Feb	0.062	0.04
SU FG 2	10	2.26	Mar	0.087	0.06
SU FG 3	6	2.57	Feb	0.120	0.13
SU FG 4	2	12.71	Apr	0.131	1.18

Table 10-2 Precision Level for the MU Factor Groups

	n	$t_{0.95,n-1}$	month with the most variability	C	D
MU FG 1	18	2.11	Feb	0.080	0.04
MU FG 2	10	2.26	Dec	0.091	0.07
MU FG 3	7	2.45	Dec	0.122	0.11
MU FG 4	2	12.71	Jul	0.051	0.46

The TMG 2001 recommends at least six traffic monitoring stations be included within each factor group. For each particular factor group (except factor group 4), the current number of WIM sites are higher than 6, however, the precision levels range from 4% to 118% (Table 10-1 and 10-2). Here we calculate the number of required WIM sites for each factor group, considering two levels of precision, namely 5% and 10%. Although the analysis are done using 5% and 10% precision level, 10% precision level is the acceptable level by NCDOT (discussed and confirmed by NCDOT in February and June 2010).

Table 10-3 shows the required number of WIM sites for 95% confidence interval and 5% and 10% precision levels. To facilitate the comparison, the currently available WIM sites of each group are also presented. The results for SU factor groups suggest installing 7 additional WIM sites on the I-95 corridor. Currently there are two WIM sites on I-95 (SU and MU factor group 4), adding 7 more WIM sites will increase the number of WIM sites to 9. The length of I-95 is about 180 miles from the Virginia border to the South Carolina border meaning one WIM every 20 miles. Given that the traffic pattern does not change drastically for every 20 miles, it is not necessary to add 7 more WIM sites along I-95. After our discussion with NCDOT, we agreed that installing 2 more WIM sites will provide essentially a pseudo Level 1 coverage for the entire corridor. The locations will be determined by future needs to distinguish which routes trucks will likely be taking to and from the NC ports and other freight distribution centers.

Table 10-3 Required Number of WIM Sites for Each SU and MU Factor Group

		SU Factor Groups			MU Factor Groups		
	D	C	Current Number of WIM Sites	Required Number of WIM Sites*	C	Current Number of WIM Sites	Required Number of WIM Sites*
FG 1	0.05	0.062	12	8	0.080	18	12
	0.10	0.062		4	0.080		5
FG 2	0.05	0.087	10	14	0.091	10	15
	0.10	0.087		5	0.091		5
FG 3	0.05	0.120	6	25	0.122	7	25
	0.10	0.120		8	0.122		8
FG 4	0.05	0.131	2	29	0.051	2	6
	0.10	0.131		4	0.051		3

* To achieve 10% (and 5%) precision level specified in Section 4 of TMG 2001.

10.3.2 Two-Dimensional ALDF Clusters

Similar reliability analysis is performed based on two-dimensional ALDF clusters. As mentioned earlier, the first step is to determine which statistics guide the analysis. The objective of forming two-dimensional ALDF clusters is to find the similarity among truck traffic pattern at different locations with respect to axle types that contribute the most to the pavement damage.

The clustering is performed based on aggregated load bins in order to eliminate the effect of minor variations in individuals load bins. The aggregated load bins do not necessarily include an equal number of original bins. The decision of selecting load bins to be aggregated into larger bins is mainly derived by the effect of axle types on pavement performance. Tandem axles account for 63% percent of damage on pavement while single axles account for 35%. Thus, aggregated bins are selected to resemble the relative importance of single and tandem axles. Table 10-4 shows the final set of aggregated load bins considered in clustering analysis along with the percent contribution of each aggregated load bins in pavement damage. Single and Tandem axles account for 98% of damage on pavement while the effect of tridem and quad axles is 2 % in total (tridem and quad axles are excluded from analysis because of their minimal effect on pavement damage).

Table 10-4 Results for Principal Component Analysis for Single-Tandem ALDF

Aggregated Load Bin	% Damage Caused Aggregated Load Bin
Heavy Tandem (22-50 Kips)	58.10
Light Tandem (6-20 Kips)	2.55
Single(11-20 Kips)	25.01
Single (6-10 Kips)	4.26
Single (3 Kips)	0.02
Single (4 Kips)	0.01
Single (5 Kips)	0.00

Table 10-4 shows that the effect of 4-kip single axles is about 0.01 % compared to 25.01 % associated to 11-20 kips single axles. These percentages imply that any small variation in the 11-20 kip single axle load bin caused by more/less trucks is more noticeable in pavement damage compared to that of former. Thus, aggregated load bins with a considerable contribution to pavement damage are included in reliability analysis. These load bins include heavy tandem bins (22-50 Kips), light tandem bins (6-20 Kips), single bins (11-20 Kips), and single bins (6-10 Kips).

For reliability analysis, the aggregated load bin with the highest coefficient of variation should be used to determine the precision of each ALDF cluster as well as the number of WIM sites required attaining the desired precision level for the desired confidence interval. The highest coefficient of variation used for reliability analysis, guarantees the desired precision level for other load bins with low coefficient of variation.

There are cases where modifying the ALDF cluster results in tighter confidence intervals. A close review of WIM sites in ALDF clusters revealed that if WIM 516 is removed from ALDF Cluster 1, the maximum computed standard deviation of the axle frequency of WIM sites in this cluster drops from 3.3% to 2.3%. This has an appreciable impact on the precision of the estimates computed for the cluster. WIM 516 is located on SR 1138 (urban minor arterial) with very low and variable truck traffic throughout the year (AADTT = 600).

Although 10% precision level for 95 % confidence interval is considered acceptable for SU and MU seasonal factor groups, for ALDF clusters the precision level needs to be adjusted using MEPDG damage analysis (as discussed with NCDOT in February 08, 2010 and June 1, 2010). Section 10.4.1.1 discusses how damage factors are developed using MEPDG damage analysis. These factors are used to modify the precision level of 10% recommended by the Traffic Monitoring Guide (TMG) in order to reflect the different effect each of the clusters has on predicted pavement performance.

ALDF Cluster 4 was selected as the reference for two reasons. First because it represents the principal arterials / interstates which are considered of top priority from a pavement performance point of view. Second, ALDF Cluster 4 was found to have the highest damage factor i.e., it has the highest negative impact on pavement structures (details are presented in Section10.4.1.1). Given that, the desired precision level of ALDF Cluster 4 is considered to be 10% and the precision level of other ALDF clusters is adjusted using developed damage factors. Fatigue-based damage factors (presented in Section 10.4.1.1) are used to modify the precision level of ALDF clusters because fatigue damage is the most important damage in NC. Table 10-5 shows the modified (desired) precision levels for all ALDF clusters.

Table 10-5 Desired Precision Level for Two-Dimensional (Two-Dim) ALDF Clusters

	Fatigue-based Damage Factor	**Desired Precision Level**
Two-Dim ALDF Cluster 1	0.97	0.10/0.97=0.10
Two-Dim ALDF Cluster 2	0.74	0.10/0.74=0.14
Two-Dim ALDF Cluster 3	0.75	0.10/0.75=0.13
Two-Dim ALDF Cluster 4	1.00	0.10/1=0.10

Table 10-6 shows the current precision level for the ALDF clusters. The current precision levels of ALDF Clusters 2, 3, and 4 are as good as the desired precision levels (the current precision levels are higher than desired levels).

Table 10-6 Current Precision Level for the Two-Dimensional ALDF Clusters

	n	$t_{0.95,n-1}$	C	D
Two-Dim ALDF Cluster 1	7	2.45	0.246	0.23
Two-Dim ALDF Cluster 2	8	2.37	0.171	0.14
Two-Dim ALDF Cluster 3	13	2.18	0.090	0.05
Two-Dim ALDF Cluster 4	13	2.18	0.172	0.10

Table 10-8 shows the required number of WIM sites for 95% confidence interval and desired precision levels for ALDF clustering. The required number of WIM sites for seasonal factor groups and two-dimensional ALDF clusters are summarized in Table 10-9.

Table 10-8 shows that many WIM sites (26 WIM sites) are required for ALDF Cluster 1 to achieve the desired precision level (10%). There 7 WIM sites that belong to ALDF Cluster 1 meaning that 19 additional WIM sites are required for ALDF cluster 1 to achieve 10% precision level for 95% confidence interval. The large number of WIM sites required to improve the precision level relates to the significant amount of variability between the individual single ALDF of the sites (see Figure 6-5). The damage analysis at WIM sites in ALDF Cluster 1 showed that the contribution of single axles in pavement performance is appreciable ranging from 30% to 58% (Table 10-7). Thus, it would be necessary to install additional WIM sites to improve the precision level of ALDF estimates derived from ALDF Cluster 1. However, the WIM sites that belong to ALDF cluster 1 are all local roads with low truck traffic (500 ≤AADTT ≤ 2000), and it may be not be economically justified for NCDOT to maintain 19 more WIM sites on local roads to improve the precision level for this specific cluster. The number of stations assigned to ALDF Cluster 1 depends on the importance assigned by the planning agency to monitoring local roads, and the importance of local roads from a pavement design perspective. In North Carolina, local roads have lower performing pavements; however, they comprise most of the highway mileage in North Carolina.

If agencies decide that monitoring certain local roads is important for pavement design and if more funding is available, then a higher number of locations may be considered for installing new WIM sites. Regardless of the number of WIMs recommended, WIM sites should be added in stages, evaluating where they fall in the groups/clusters, before moving on to the next stage and selecting new sites to install. The actual precision levels are evaluated as new WIM sites are installed and the process terminates when the desired level is achieved.

Table 10-7 Percent Damage Caused by Axle Types at WIM Sites in ALDF Cluster 1

	% Damage Caused by Axle Types			
WIM ID	**Single**	**Tandem**	**Tridem**	**Quad**
522	35	62	3	0
523	32	67	1	0
534	40	58	2	0
535	30	68	2	0
545/507	48	51	1	0
546	58	37	4	0
556	48	51	1	0
Average	**41**	**56**	**2**	**0**

Table 10-8 Required Number of WIM Sites for Each Two-Dimensional ALDF Cluster

	D	C	$t_{0.95,n-1}$	**Required Number of WIM Sites**
Two-Dim ALDF Cluster 1	0.10	0.246	2.060	26
Two-Dim ALDF Cluster 2	0.14	0.171	2.365	8
Two-Dim ALDF Cluster 3	0.13	0.090	2.776	5
Two-Dim ALDF Cluster 4	0.10	0.172	2.160	14

Table 10-9 Required Number of WIM Sites for Seasonal Factor Groups and Two-Dimensional ALDF Cluster

	Current Number of WIM Sites	Required Number of WIM Sites*	Future Number of WIM Sites to Install (Abandon)
SU FG 1	12	4	(8)
SU FG 2	10	5	(5)
SU FG 3	6	8	2
SU FG 4	2	4	2
MU FG 1	18	5	(13)
MU FG 2	10	5	(5)
MU FG 3	7	8	1
MU FG 4	2	3	1
Two-Dim ALDF Cluster 1	7	26	19
Two-Dim ALDF Cluster 2	8	8	-
Two-Dim ALDF Cluster 3	13	5	(8)
Two-Dim ALDF Cluster 4	13	14	1
Total # of WIM Sites to Install			= 2 + 2+ 1+ 1+ 19+ 1 = 26
Total # of WIM Sites to Abandon			= 8+ 5+ 13+ 5+ 8 = 39

* To achieve 10% precision level specified in Section 4 of TMG 2001 for seasonal factor groups and modified precision levels for ALDF clusters.

10.4 Discussion on Installing/Abandoning WIM Sites

The analysis performed earlier leads to the conclusion that the size of the factor groups and clusters is a function of the variability of groups/clusters and the precision desired for them. As discussed in previous section, some seasonal factor groups and ALDF clusters need additional WIM sites to reach the desire level of precision for a specific confidence interval. On the other hand, there are other seasonal factor groups and ALDF clusters for which their precision level is higher than the desired level. For WIM sites that belong to these groups and clusters, a decision should be made to either continue monitoring traffic or abandon the WIM sites. These groups include SU factor groups 1 and 2, MU factor groups 1 and 2 and ALDF cluster 3.

The failure of pavement surrounding the WIM sensor, failure of the equipment itself, or the fact that the traffic pattern at WIM location is already established and continuing monitoring is unnecessary, are other factors that need to be addressed when a traffic agency considers discontinuing a WIM site.

10.4.1 Installing New WIM Sites

Among the seasonal factor groups and ALDF clusters, SU factor groups 3 and 4, MU factor groups 3 and 4, and ALDF clusters 1 and 4 have precision levels which are worse than the desired level. Thus, additional WIM sites are required to improve the precision level to the desired level. When exploring alternative WIM sites, we examined whether coordination among different seasonal factor groups and ALDF clusters results in reduction of the number of required WIM sites, without scarifying the desired precision level for any group/cluster. The decision tree associated to seasonal factor groups and ALDF clusters is a major tool for use in optimizing the number of additional WIM sites.

In order to find potential locations that can be used for different group/clusters, a reference to decision tree is necessary. A decision tree is meant to present the attributes that are associated with WIM sites belonging to each seasonal factor group and ALDF cluster.

Here are some observations made from decision trees:

- For WIM sites in SU seasonal factor group 3, the percentage of SU trucks obtained from 48_hour classification counts is between 50 and 71.
- For WIM sites in MU seasonal factor group 3, the percentage of SU trucks obtained from 48_hour classification counts is between 50 and 71.
- For WIM sites in two-dimensional ALDF cluster 1, the percentage of class 5 vehicles obtained from 48_hour classification counts is between 30 and 54 and the percentage of class 9 vehicles is between 4 and 44.

A comparison of WIM sites classified in SU/MU seasonal factor groups 3 and ALDF Cluster 1, shows that identical WIM sites belong to these groups except for WIM site 516. WIM 516 was identified an outlier in seasonal factor analysis; the WIM is located on SR 1138 (urban minor arterial) with very low unstable truck traffic throughout the year (AADTT = 600), thus it originally was not classified in any seasonal factor group. The observation made leads to the conclusion that a new WIM site that can improve the precision level of SU seasonal factor group 3 can also be used for the same purpose for MU seasonal factor group 3 and ALDF cluster 1.

Another observation made from decision tree relates to SU and MU factor groups 4. The observations are as follows:

- WIM sites in SU seasonal factor group 4 are located on I-95 and their percentage of SU trucks obtained from 48_hour classification counts is between 10 and 23.
- WIM sites in MU seasonal factor group 4 are located on I-95 and their percentage of SU trucks obtained from 48_hour classification counts is between 10 and 23.

Among all 45 WIM sites, there are two WIM sites (503/527 and 541) that belong to SU and MU seasonal factor groups. I-95 is a north-south highway in eastern NC that stretches from South Carolina to Virginia. It serves east coast recreational travel (SUs) and long haul trucks (MUs). It was NCDOT staff judgment to classify WIM sites stations on I-95 as a separate group because the truck traffic pattern on this road is very specific. Since similar WIM sites belong to these two factor groups, any new WIM that improves the precision level of SU factor group 4 can also serve for improving the precision level of MU factor group 4. The results for SU factor groups suggest installing 9 additional WIM on I-95 corridor. Currently there are two WIM sites on I-95, adding 9 more WIM sites will increase the number of WIM sites to 11. The length of I-95 is about 180 miles from the Virginia border to the South Carolina border, which means one WIM every 20 miles. Given that the traffic pattern does not change drastically for every 20 miles, it is not necessary to add 7 more WIM sites along I-95. After our discussion with NCDOT, we agreed that 2 additional WIM sites is necessary to improve the precision level of SU and MU factor group 4 (instead of 9; 7 for SU factor group 4 and 2 for MU factor group 4).

To summarize, the number of required new WIM sites for SU/MU seasonal factor groups and ALDF clusters are as follows (Table 10-10):

Table 10-10 Candidate New WIM Sites for Seasonal Factor Groups and Two-Dimensional ALDF Clusters (subject to adjustment based on local knowledge)

	Minimum Number of WIM Sites to Install
SU FG 3	19*
MU FG 3	
Two-dim ALDF Cluster 1	
SU FG 4	2*
MU FG 4	
Two-dim ALDF Cluster 4	1
Total # of WIM Sites to Install	19+ 2 + 1 = 22

* The same 19 WIM sites may be used for SU and MU factor group 3 and ALDF cluster 1.
** The same 2 WIM sites may be used for SU and MU factor group 4.

After the number of additional WIM sites is established, the next step involves identifying the location of the new WIM sites. We assume that coverage count locations are candidate locations for future continuous monitoring (installing new WIM sites). These locations enter a pool of locations from which a few are selected. The selected locations are further investigated with respect to the technical requirements of installing WIM sites and NCDOT staff expert knowledge.

Table 10-10 shows that ALDF 2 and ALDF 3 clusters do not need additional WIM (because their current precision levels are satisfactory). Thus, additional WIM sites are necessary for ALDF 1 and ALDF 4 clusters only. In the process of installing WIM sites, it is important to prioritize the candidate locations and identify those that have priority to receive a new WIM station. The *ALDF Ranking Factors* are used in the process of prioritizing the WIM locations (the procedure to develop the ALDF Ranking Factors is explained in next subsection). Table 10-15 suggests that sites that have traffic data in line with ALDF 4 WIM sites will have the highest priority to receive new WIM stations followed by locations that have traffic data in line with ALDF Cluster 1. On the other hand, sites that have traffic data in line with WIM sites in ALDF 2 and ALDF 3 clusters will be the last on the priority list to get assigned new WIM stations. The following sections provide some recommendations regarding the candidate locations to install additional WIM sites.

10.4.1.1 Development of ALDF Ranking Factors

ALDF Ranking Factors refer to normalized damage values obtained through executing the MEPDG for the 10 LTPP flexible pavement sections that were included in the sensitivity analysis study throughout this project. For this task, the MEPDG was executed a total of 40 times; 4 ALDF factors for every LTPP section. ALDF factors that were used in these runs were the two-dimensional factors developed based on single and tandem axles.

There are two purposes for *ALDF Ranking Factors*; first is to modify the precision level of 10% recommended by the TMG in order to reflect the different effect each of the clusters has on predicted pavement performance. The second purpose is to aid in the assignment of new WIM locations based on ALDF characteristics at these different locations.

Table 10-11 summarizes predicted fatigue distress (% of lane area) at the end of the design life (20 years) for each of the 10 LTPP sections. Table 10-11 shows that sites 509 and 516 both have zero predicted fatigue damage and hence, they were both excluded from the average calculations so that bias can be avoided. Table 10-12 presents the normalized fatigue distresses with respect to ALDF Cluster 4. ALDF Cluster 4 was selected as the reference for two reasons, first because it represents the principal arterials / interstates which are considered of top priority from a pavement performance point of view. Second because ALDF Cluster 4 was found to be the highest damage factor i.e., it has the highest negative impact on pavement structures as seen in Table 10-11 and Table 10-12.

Similarly, Table 10-13 summarizes predicted rut depth for the 10 LTPP sections and Table 10-14 shows the normalized rut depth values that correspond to each of the ALDF clusters with respect to ALDF Cluster 4.

Tables 10-13 and 10-14 suggest that ALDF ranking is similar regardless of the distress type. However, since fatigue distress is the major distress in NC, the decision was made to use the normalized fatigue predictions as the *ALDF Ranking Factors*. Table 10-15 summarizes *ALDF Ranking Factors* based on fatigue as well as rut depth.

Table 10-15 suggests that sites that have ALDF data similar to ALDF Cluster 4 will have the highest priority to receive new WIM stations followed by sites that have ALDF data in line with ALDF Cluster 1. On the other hand, sites that have ALDF data in line with any of ALDF Cluster 2 or ALDF Cluster 3 will be the last on the priority list to get assigned new WIM stations. Assignment of new WIM stations for sites with ALDF Cluster 2 or ALDF Cluster 3 will in large be based on the local knowledge of NCDOT Traffic Survey Group personnel.

Table 10-11 Fatigue Predictions at the end of Design Life for 10 LTPP Sites

ALDF Cluster	WIM Site ID									
	501	504	506	509	512	516	520	521	525	530
F-ALDF-1	0.76	0.01	2.76	0.00	52.80	0.00	28.60	12.00	92.00	2.45
F-ALDF-2	0.57	0.01	2.02	0.00	42.10	0.00	23.00	7.07	88.60	1.80
F-ALDF-3	0.56	0.01	2.05	0.00	42.40	0.00	22.50	8.11	87.80	1.78
F-ALDF-4	0.84	0.01	2.99	0.00	52.40	0.00	31.50	9.38	93.50	2.69

Table 10-12 Normalized Fatigue Predictions Based on ALDF Cluster 4

ALDF Cluster	WIM Site ID									
	501	504	506	509	512	516	520	521	525	530
F-ALDF-1	0.90	0.87	0.92	Excluded	1.01	Excluded	0.91	1.28	0.98	0.91
F-ALDF-2	0.68	0.70	0.68	Excluded	0.80	Excluded	0.73	0.75	0.95	0.67
F-ALDF-3	0.66	0.65	0.69	Excluded	0.81	Excluded	0.71	0.86	0.94	0.66
F-ALDF-4	1.00	1.00	1.00	Excluded	1.00	Excluded	1.00	1.00	1.00	1.00

Table 10-13 Rut Depth Predictions at the end of Design Life for 10 LTPP Sites

ALDF Cluster	WIM Site ID									
	501	504	506	509	512	516	520	521	525	530
F-ALDF-1	0.35	0.59	0.71	0.56	0.60	0.28	0.73	0.41	1.07	0.48
F-ALDF-2	0.33	0.56	0.67	0.53	0.55	0.25	0.69	0.36	1.01	0.44
F-ALDF-3	0.33	0.56	0.66	0.53	0.54	0.26	0.68	0.37	1.00	0.44
F-ALDF-4	0.36	0.62	0.73	0.59	0.59	0.27	0.76	0.38	1.12	0.49

Table10-14 Normalized Rut Depth Predictions Based on ALDF Cluster 4

ALDF Cluster	WIM Site ID									
	501	504	506	509	512	516	520	521	525	530
F-ALDF-1	0.96	0.96	0.98	0.96	1.01	1.01	0.96	1.08	0.95	0.98
F-ALDF-2	0.91	0.91	0.91	0.91	0.92	0.93	0.90	0.94	0.90	0.91
F-ALDF-3	0.90	0.90	0.91	0.90	0.92	0.94	0.89	0.96	0.89	0.90
F-ALDF-4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 10-15 Fatigue and Rutting-Based ALDF Ranking Factors Normalized based on ALDF Cluster 4

ALDF Cluster	Fatigue-Based	Rutting-Based
F-ALDF-1	0.97	0.98
F-ALDF-2	0.74	0.91
F-ALDF-3	0.75	0.91
F-ALDF-4	1.00	1.00

10.4.1.2 Location of New WIM Sites for ALDF Cluster 4

Table 10-10 suggests that at least one new WIM is required to improve the precision level of ALDF cluster 4 to the desired level (10%). As mentioned earlier, coverage count locations are potential locations to install a new WIM site. Among 1000+ coverage count locations, there are 80 locations that have traffic characteristics similar to those of WIM sites in ALDF Cluster 4. These candidate locations are presented in Appendix 5.

The traffic characteristics include:

- 4,500 ≤ AADTT values ≤ 12,000
- 24% ≤ vehicle class 5% ≤ 37%,
- 44% ≤ vehicle class 9% ≤ 68%.

In order to specify the location of the minimum required WIM sites, clustering analysis is performed using the annualized values based on the count data collected at 80 locations. Clustering analysis helps to categorize these locations based on their annual average daily traffic (AADT) by class. The clustering analysis resulted in 3 clusters of variations in annualized number of trucks. The average of annual average daily traffic for all stations that fall in coverage count clusters are presented in Table 10-16. Figure 10-2 also presents the AADT by class for all stations that fall in coverage count cluster. The average AADTT increases as the cluster number increases. This means that the average AADTT of Cluster 2 is higher than the average AADTT of Cluster 1. The AADTT is a sound factor that can be used to prioritize the candidate locations to install new WIM stations. Here, coverage count locations in Cluster 3 are recommended as having priority to receive a new WIM site. There are 10 coverage count locations in this cluster among which one should be selected considering TMG guidelines discussed below.

Table 10-16 Average of AADT by Class for all Stations that fall in the Coverage Count Clusters (associated with ALDF Cluster 4)

	VC 4	VC 5	VC 6	VC 7	VC 8	VC 9	VC 10	VC 11	VC 12	VC 13	AADTT
Cluster 1	284	989	401	27	399	3400	106	90	35	20	5751
Cluster 2	375	1257	442	38	611	5117	144	178	60	23	8245
Cluster 3	542	1807	529	27	993	7249	141	248	95	17	11649

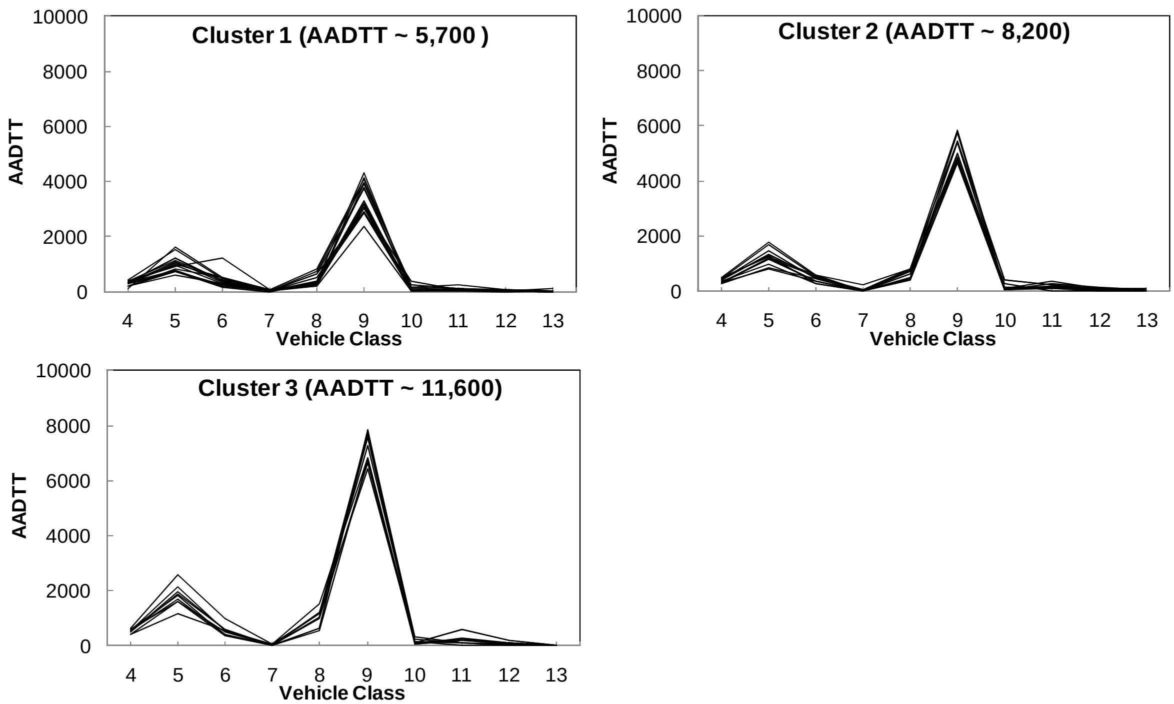


Figure 10-2 AADT by Class for all Stations that fall in the Coverage Count Clusters (associated with ALDF Cluster 4)

Besides quantitative considerations to select location of new WIM sites, TMG also provides some guidelines in this process [*TMG, 2001*]. These guidelines are presented below. The selection of new WIM locations should be based on the needs of the data collection program and the site characteristics of the roadway sections that meet those needs. The needs of the data collection program include, but are not limited to, the following:

- the need to obtain more vehicle weight data on roads within a given truck weight roadway group,
- the need to collect data in geographic regions that are poorly represented in the existing WIM data collection effort,
- the need to collect data on specific facilities of high importance (e.g., Interstate highways or other National Highway System routes),
- the need to collect data for specific research projects or other special needs of the State, and

- the need to collect weight information on specific commodity movements of importance to the State.

However, just because a roadway section meets some or all of the above characteristics does not make it a good WIM site. With current technologies, WIM systems only accurately weigh trucks when the equipment is located in a physical environment that meets specific criteria. Thus, States should place WIM equipment only in pavements that allow for accurate vehicle weighing. While individual equipment vendors may require slightly different pavement characteristics to achieve specified results, in general all WIM sites should have the following characteristics:

- Smooth, flat (in all planes) pavement,
- Pavement that is in good condition and that has enough strength to adequately support axle weight sensors,
- Vehicles traveling at constant speeds over the sensors,
- Access to power and communications (although these can be supplied from solar panels, and through various forms of wireless communications),
- Sufficient truck traffic at the site to justify the installation of a WIM data collection site.

10.4.1.3Location of New WIM Sites for ALDF Cluster 1 and SU/MU Factor Group 3

Among 1000+ coverage count locations, there are 100 locations that have traffic characteristics similar to those of WIM sites in ALDF Cluster 1 and SU/MU factor Group 3. These characteristics include

- low AADTT values (less than 2000),
- 50% ≤ SU trucks% ≤ 71%,
- 29% ≤ MU trucks% ≤ 50%,
- 30% ≤ vehicle class 5% ≤ 54%,
- 4% ≤ vehicle class 9% ≤ 4%.

As discussed in Section10.4.1, at least 19 new WIM sites are required to boost up the precision level of the ALDF Cluster 1 and SU/MU Factor Groups 3 into the desired level. These 19locations are chosen from 100 candidate locations. The specifications of these candidate locations are presented in Appendix 5.

In order to specify the location of these 19WIM sites, clustering analysis is performed using the annualized classification counts collected at 100 locations. Clustering analysis helps to categorize these locations based on AADT by class for each station (the seasonal factoring procedure presented in Chapter 3 is used to annualize the 48-hour classification counts.) The clustering analysis resulted in 6 clusters of variations in AADT by class. The average AADT by class for all clusters are presented in Table 10-17.

Figure 10-3 also presents the AADT by class for all individual coverage count location in each cluster. The average AADTT increases as the cluster number increases, that is, the average AADTT of Cluster 2 is higher than the average AADTT of Cluster 1. The AADTT is a sound factor that can be used to prioritize the candidate locations to install new WIM stations. There are only three coverage count locations in Clusters 5 and 6; these locations have priority over other locations that fall in other clusters. If the funding is available, then these locations may be selected as new WIM sites. The remaining 16 locations (19-3=16) are now selected from Clusters 1 to 4. As a general rule, it is recommended that four locations be selected from each cluster; these locations are sorted in an increasing order of their AADTT values. If enough funding is available to install all new WIM stations, then each location receives one, otherwise, the locations with higher AADTT should have priority over other locations to receive new WIM stations. As more funding becomes available, WIM stations are installed at the other locations with lower priority (lower AADTT).

Table 10-17 Average of AADT by Class for all Stations that fall in the Coverage Count Clusters (associated with ALDF Cluster 1 and SU/MU Factor Group 3)

	VC 4	VC 5	VC 6	VC 7	VC 8	VC 9	VC 10	VC 11	VC 12	VC 13	AADTT
Cluster 1	38	248	63	6	66	149	8	1	0	1	581
Cluster 2	60	348	110	12	111	202	18	2	1	3	867
Cluster 3	81	458	140	17	141	309	21	3	1	3	1174
Cluster 4	97	618	174	21	188	413	36	5	1	5	1558
Cluster 5	131	935	124	6	271	341	27	1	0	3	1838
Cluster 6	165	617	193	9	73	870	9	3	1	0	1939

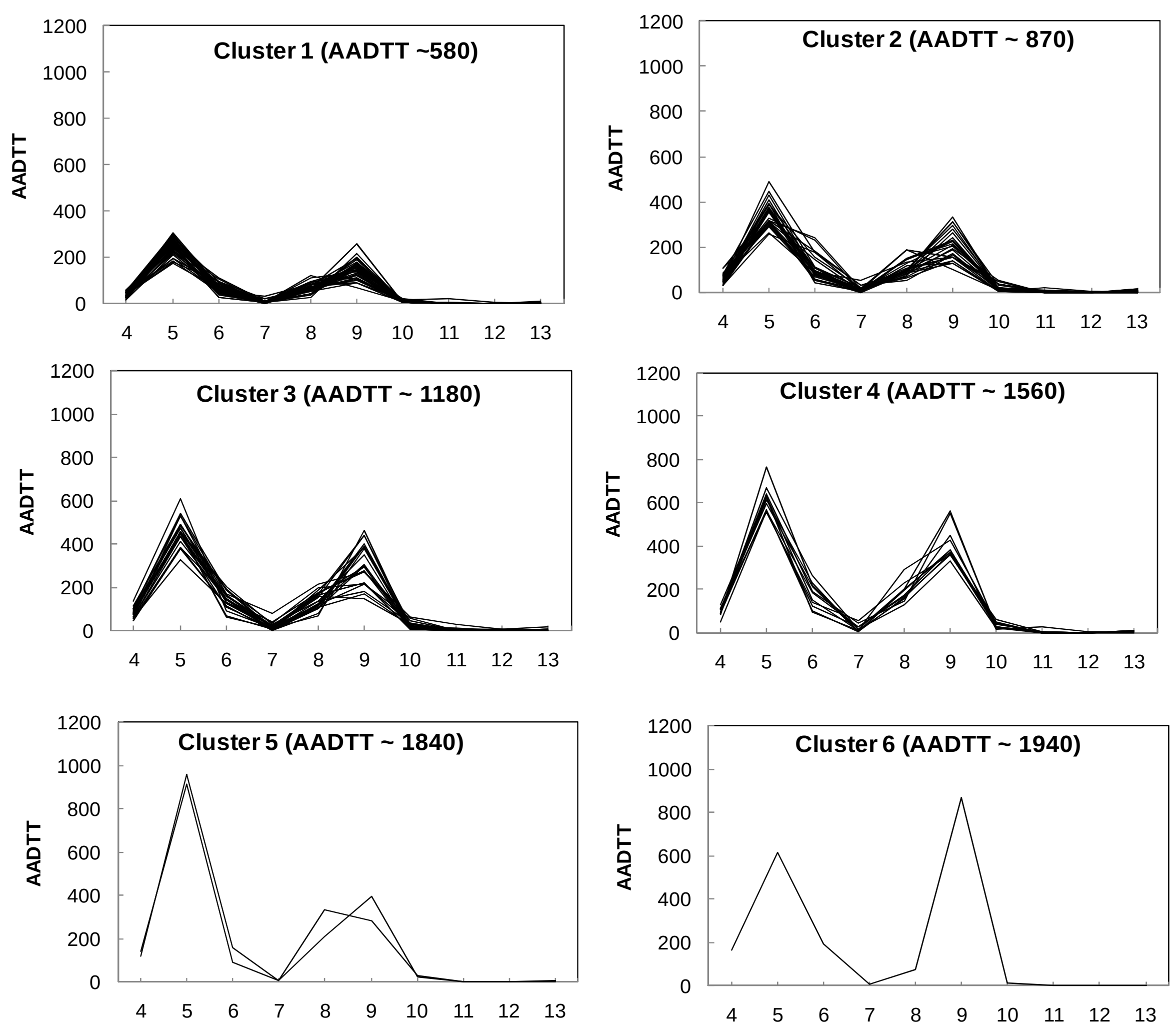


Figure 10-3 AADT by Class for all Stations that fall in the Coverage Count Clusters (associated with ALDF Cluster 1 and SU/MU Factor Group 3)

10.4.1.4 Location of New WIM Sites for SU/MU Factor Group 4

The SU and MU Factor Groups includes WIM sites located on Interstate 95 (I-95). I-95 is a 180 miles long north-south highway in eastern NC that stretches from South Carolina to Virginia. The traffic patterns show that this highway services east coast recreational travel (SUs) and long haul trucks (MUs). NCDOT has operated two WIM sites on this road (marked by stars in F):

- WIM 503/527 (located on I-95, AADTT = 7300)
- WIM 541 (located on I-95, AADTT = 8027)

The results of the reliability analysis were communicated with NCDOT and it was agreed to add two new WIM sites to improve the precision level of SU/MY factor Group 4. The coverage count locations are candidate locations to install new WIM sites. There are 15 coverage count location along I-95 (F). The specification of these locations are presented is Table 10-18.

In order to recommend the location of new WIM sites, the truck traffic pattern of coverage count locations are studied to find out whether the truck traffic pattern on a long highway changes because of changing economic activity, traffic generators, or intervening intersections. There are three major intervening intersections along I-95: US 64, US 70, and I-40. These highways divide I-95 into four major segments: Segments 1 (40 miles), 2 (20 miles), 3 (40 miles), and 4 (80 miles). Weinblatt, (1996) states that rural arterial segments which are 50 miles apart are considered nearby segments; that is they have similar truck traffic patterns. Given the length of these segments and the fact that there are no changes in economic activities and traffic generators along the segments, it is desired to maintain a WIM site on each of these segments to monitor the truck traffic. NCDOT has operated two WIM sites on Segments 2 and 4: (WIM 503/527 is located on Segment 2, and WIM 541 is located on Segment 4). It is recommended to install two WIM sites on Segments 1 and 3. Coverage count locations with higher AADTT values have priority over other locations. Another consideration relates to the truck traffic pattern at coverage count locations. The AADTT by vehicle class on these two segments are plotted in Figure 10-6. As Figure 10-6*a* shows the traffic pattern at VC 6304 is slightly different from that at other coverage count locations in Segment 1. Such observation may make VC 6304 a better candidate location to install a new WIM site, though its AADTT is lower than VC 6504. In summary, the following locations are recommended to install new WIM sites on Segments 1 and 3.

The recommended locations are:

- VC6504 (1.2 Miles North of NC 48), AADTT = 10156)
- VC5005 (From North of US 701 to South of SR 1007, AADTT = 9247)

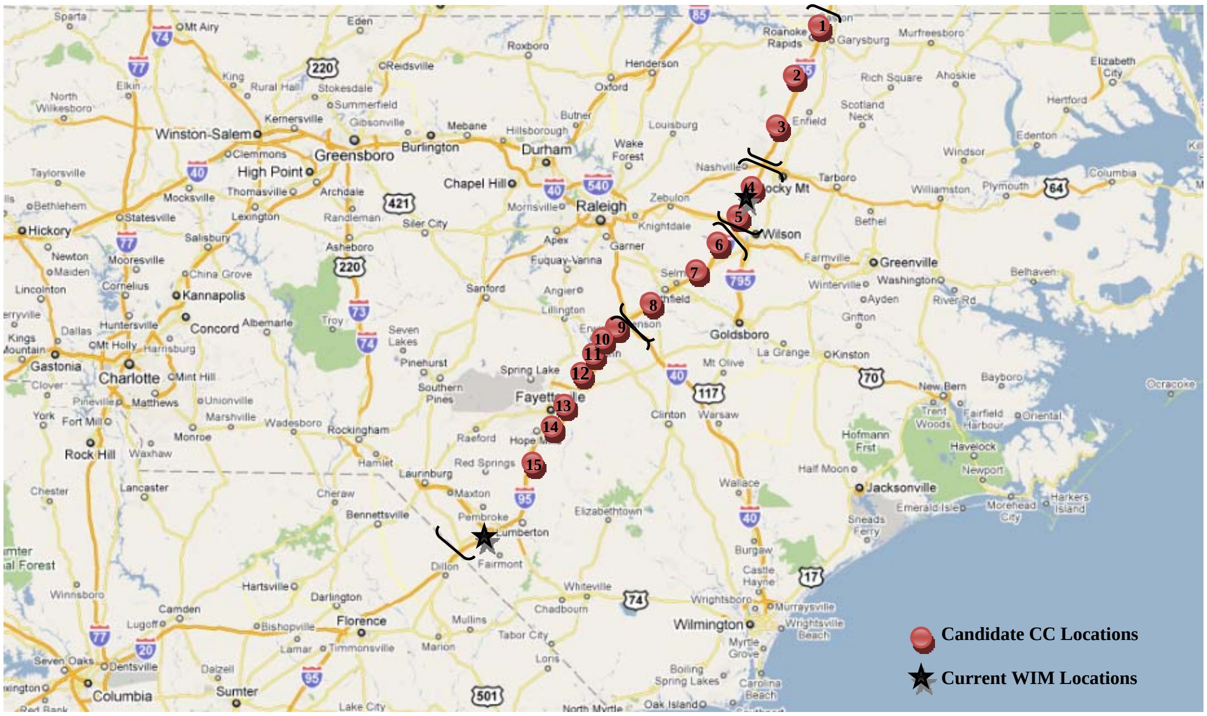


Figure 10-4 Location of Coverage Counts and WIM Sites on I-95

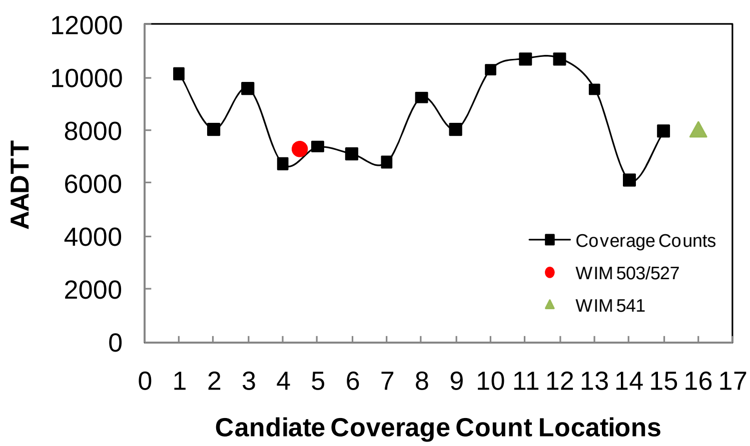
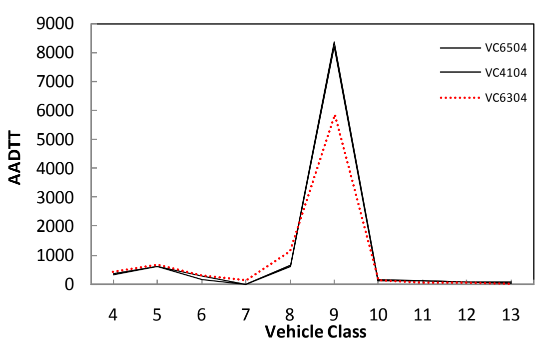


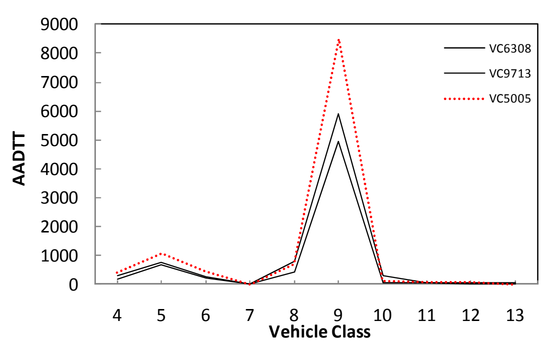
Figure 10-5 AADTT Values of 15 Coverage Count Locations on I-95

Table 10-18 Specifications of Coverage Count Locations on I-95

Segment	ID	VC_STA_ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT
1	1	VC6504	I-95	1.2 MILES N OF NC 48	NORTHAMPTON	6504 – 052404	10156
	2	VC4104	I-95	2.5 MILES S OF NC 481	HALIFAX	4104 – 052504	8048
	3	VC6304	I-95	FROM 1.5 MILES S OF NC 33	NASH	6304 – 080700	9592
2	4	VC6325	I-95	1.1 MILES S OF NC 97	NASH	6325 – 081007	6737
	5	VC9706	I-95	FROM NC 42 FOR 0.5 MILE NORTH	WILSON	9706 – 022106	7379
3	6	VC6308	I-95	SOUTH OF US 64 TO NORTH OF SR 1770	NASH	6308 – 022106	7123
	7	VC9713	I-95	8.2 MILES S OF NC 42	WILSON	9713 – 031907	6811
	8	VC5005	I-95	FROM NORTH OF US 701 TO SOUTH OF SR 1007	JOHNSTON	5005 – 062006	9247
4	9	VC5019	I-95	1.3 MILES S OF NC 50-242	JOHNSTON	5019 – 030707	8040
	10	VC5009	I-95	SOUTH OF NC 50 TO NORTH OF SR 1178	JOHNSTON	5009 – 062006	10299
	11	VC4217	I-95	1.4 MILES S OF SR 1002	HARNETT	2507 – 101104	10703
	12	VC2507	I-95	FROM NC 82 TO HARNETT CO	CUMBERLAND	2507 – 101104	10703
	13	VC2501	I-95	0.5 MILE NORTH OF US 13	CUMBERLAND	2501 – 022205	9555
	14	VC2526	I-95	2.3 MILES S OF NC 59	CUMBERLAND	2526 – 081607	6133
	15	VC7722	I-95	0.2 MILES N OF US 301	ROBESON	7722 – 031207	7980



APPENDIX 1



(b)

Figure 10-6 AADTT Values of Coverage Count Locations in (a) Segment 1, (b) Segment 3

10.4.2 Abandoning Old WIM Sites

The superior precision level of SU and MU factor groups 1 and 2 and also ALDF cluster 3 suggest a reduction in number of current WIM sites. The discontinuation of WIM sites shall be entertained to the point that the precision level of any group/cluster does not drop below the desired precision level. Numbers of WIM sites that can be abandoned for each group/cluster are presented in Table 10-9. For each group/cluster, not all WIM sites are candidate locations for discontinuation. The reduction should ensure that discontinuing a WIM site at one seasonal factor group does not jeopardize the precision level at other ALDF clusters. Again, the WIM sites that are candidate for discontinuation shall be coordinated among groups and clusters.

Among the above mentioned groups and clusters, ALDF cluster 3 and SU/MU factor groups 1 and 2 share some WIM sites. These WIM sites are presented in Table 10-19.

Table 10-19 Specification of WIM Sites Classified as ALDF Cluster 3

WIM ID	Installation Date	Road	AADTT	ALDF Cluster	SU FG	MU FG
558	12-Aug-03	US 321	2,393	3	2	2
554	17-Oct-03	US 220	6,959	3	Outlier	1
552	28-Mar-04	US 74	1,710	3	1	1
547	11-Sep-03	US 321	839	3	2	2
531	11-Feb-04	US 52	2,032	3	1	1
553	14-Feb-04	US 220	4,705	3	1	1
509	3-Nov-03	US 421	2,969	3	1	1
525	30-Oct-03	US 421	1,736	3	1	1
504	14-Apr-04	US 74	2,219	3	1	1
551	18-Apr-04	US 74	1,922	3	1	1
529	19-May-04	US 264	1,643	3	Outlier	2
539	1-Nov-00	I-77	604	3	1	1
557	24-Aug-03	I-40	1,039	3	1	1

The installation date of WIM sites in ALDF cluster 2 that goes back to 9 to 10 years implies that most of these WIM sites are candidate sites for discontinuation. However, the WIM sites may be prioritized based on their level of depreciation and also the level of truck traffic monitored by them. In general, WIM sites which are depreciated more and monitor fewer number of trucks have higher priority for discontinuation. Table 10-9 shows that eight WIM sites can be discarded from ALDF cluster 3. We examined different combination of WIM sites and selected a combination which its exclusion does not bring the precision level of any group/cluster below the desired level. These WIM sites are shadowed in Table 10-19. The precision level of ALDF cluster 3 and SU/MU seasonal factors 1 and 2 after removing the identified WIM sites are presented in Table 10-20 (although the current precision level is worse than the initial level, it is still acceptable because it is better than the desired level.

Table 10-20 Precision Level for ALDF Cluster 3 and SU/MU Factor Groups after Discontinuing WIM Sites

	Number of WIM Sites after Removing Candidate WIM Sites	$t_{0.95,n-1}$	C	D
SU FG 1	7	2.45	0.065	0.06 ≤ 0.10
SU FG 2	8	2.37	0.093	0.08 ≤ 0.10
MU FG 1	13	2.18	0.081	0.05 ≤ 0.10
MU FG 2	8	2.37	0.101	0.08 ≤ 0.10
Two-dimensional ALDF Cluster 3	6	2.57	0.086	0.09 ≤ 0.13

The reduction could be carried out in stages after ensuring that the discontinuation does not affect the reliability of groups/clusters. For example, these 7 WIM sites can be discontinued, two locations annually, over a period of three years. The reliability analysis should be repeated each of three years to ensure that the desired precision has been maintained. Another important consideration before discontinuation of WIM sites is other use of existing truck information or other reasons that the station is important. NCDOT should ensure that these criteria are met before discontinuing the WIM sites. Table 10-21 shows the number of WIM sites that are candidate for discontinuation (these 7 WIM sites are highlighted in Table 10-19). The reliability analysis initially suggested that 13 WIM sites could be removed from MU Factor Group 1 without decreasing the precision level of the group below 10 %. However, removing more than five WIM sites from the MU Factor Group 1 will decrease the precision level of some ALDF clusters below the desired level.

Table 10-21 Candidate WIM Sites for Discontinuation
(subject to adjustment based on local knowledge)

	Number of WIM Sites
SU FG 1	5
SU FG 2	2
MU FG 1	5
MU FG 2	2
Two-dim ALDF Cluster 3	7
Total # of WIM Sites to Discontinue	7

10.5 Conclusions and Recommendations

Reliability analysis was performed to determine the precision level of SU/MU seasonal factor groups and ALDF clusters. It also identifies the required number of WIM sites to achieve a desired level of precision. The analysis however does not consider tradeoffs in terms of lifecycle cost, budget, and possible need to use *less expensive* sensors now instead of fewer, *more expensive* sensors that should last longer. These considerations are left for future research.

Results based on seasonal factor analysis and ALDF analysis show more WIM sites are needed on some highways to reach the TMG desired levels of precision and confidence. On the other hand, related seasonal factor and ALDF analysis shows that TMG levels are exceeded in some factor groups/clusters. Selection of WIM site candidates for continued monitoring or abandonment depends upon such factors as: pavement surrounding the WIM sensor, WIM equipment condition, urban/rural location, high/low truck volumes, and the expectation that the traffic pattern at a particular site is established or may change. In summary, 22additional WIM sites are required to achieve the preset precision levels of factor groups/clusters. The number of new sites could be adjusted depending on specific NCDOT needs, budget and timetable based on age of sensors in the field. The type of WIM technology to install is also dependent on a tradeoff between many low cost sensors to cover what is needed now versus higher cost sensors that might last longer but reduce the number of locations monitored. Prioritized selections of new WIM locations are made as a result of clustering analysis, ALDF ranking factors, technical installation requirements [*TMG, 2001*], and NCDOT knowledge of site needs. New WIM data is needed to improve the precision level of seasonal factor groups and ALDF clusters.

Finally, 7 WIM sites are candidates for abandonment. These WIM sites may be prioritized based on their level of depreciation and also the level of truck traffic monitored by them. In general, WIM sites which are depreciated more and monitor fewer number of trucks have higher priority for abandonment.

Before concluding this section, a brief discussion on system-wide monitoring of truck weights seems relevant. The technique employed in traffic monitoring programs is to have a *continuous count* component and a *coverage count* component. The *continuous count* program is comprised of a limited number of sites (about 40 currently) where traffic is monitored continuously to provide detailed information on the types of traffic patterns by vehicle class, weight, and number of axles. The *coverage count* program has relatively many locations (100 or more across the state) to define system-wide travel patterns, where short term counts are collected and annualized to provide estimates of traffic on the system. Short term coverage counts define volume and vehicle class data only, not weights or number of axles. According to the 2009 AASHTO Guide for Traffic Data Programs Research, the available technologies (portable WIMs) is not reliable for short term weight and axles measurements and that agencies should not use these technologies [*AASHTO 2009*]. The only methods available to expand the knowledge of the system-wide patterns as related to truck weights are technologies used for the *continuous* program, i.e., permanently installed and calibrated WIMs.

It is thus recommended that NCDOT manage WIMs so that they meet the *continuous* component while supporting a process of expanding the knowledge base for technologies and methods for *coverage* counts. This may require use of less expensive sensors and reuse of equipment. The techniques and guidelines developed in the research support this approach. It is recommended that NCDOT set up a dynamic program, where new WIM sites are added regularly (site selection), adequate data are collected (sampling), sites are discontinued after an appropriate period (site abandonment), while the data needed for MEPDG input are maintained (reliability analysis). The collected data may not be "research quality" data, but the data are valuable for expanding knowledge of system characteristics at a slow and steady pace.

10.6 WIM Technologies

There are several WIM technologies that can be used for permanent, continuous weight data collection [*Hallenbeck and Weinblatt, 2004*]:

- Piezoelectric sensors; ceramic, polymer, and quartz
- Bending plates,
- Load cells,
- Capacitance mats
- Other WIM technologies (fiber-optic, subsurface strain gauge, multi-sensor).

For the purposes of this research effort, only piezoelectric sensors (ceramic, polymer, and quartz), bending plates, and load cells,are considered. These five technologies are currently in common use throughout the United States. Other sensor designs are under active development.

10.6.1 Piezoelectric Sensors

The most common WIM sensor is the piezoelectric sensor (Figure 10-7). The piezoelectric sensor consists of a copper strand, surrounded by a piezoelectric material, which is covered by a copper sheath. When pressure is applied to the piezoelectric material an electrical charge is produced. By measuring and analyzing the charge produced, the sensor measures the weight of a passing tire or axle group. The various types of permanent piezoelectric sensors have similar layouts and slightly different operating characteristics but different installation requirements to obtain better results, and longer life. A complete lane installation consisting of two sensors and two loops can be accomplished in less than a full day, including curing time. When properly installed and calibrated, a piezoelectric WIM system should be expected to provide gross vehicle weights that are within 15% of the actual vehicle weight for 95% of the trucks measured [*Bushman and Pratt 1998, IRD 2009, WSDOT*].After a successful installation, it is assumed that the entire system will have a life of four years, after which time the in-road equipment will be replaced. During the four year life of the system, sensor failures are assumed as follows [*Bushman and Pratt, 1998*]:

5% in year one
15% in year two
25% in year three, and
total replacement in year four.

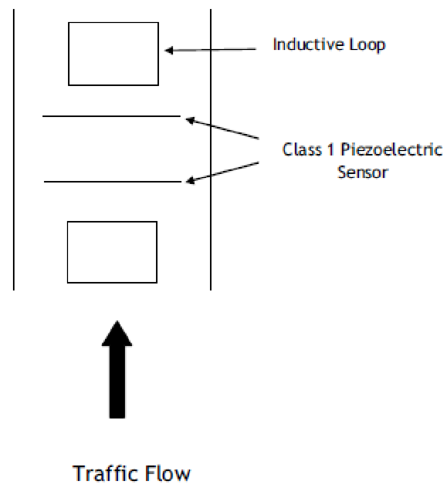


Figure 10-7 Common Configurations of Piezoelectric Sensors

Different types of piezoelectric sensors include: piezo ceramic, piezo polymer, and piezo quartz sensors.

Piezo Ceramic Sensors

Piezo ceramic sensors use ceramic material which is compressed between outer sheaths of copper. This type of sensor has lost favor in recent years due to durability problems. They have largely been replaced in the market by piezo polymer sensors [*Szary and Maher, 2009*].

Piezo Polymer Sensors

The most popular commercially available sensor of this type is the Brass Linguini (BL) sensor. The flexible nature of the polymer provides more flexibility in handling when conducting the installation. This sensor has similar characteristics as other piezoelectric sensors and has the same benefits and drawbacks but it has a relatively low cost. However, the BL sensor is temperature sensitive, and its accuracy is affected by structural response of the roadway. The low cost and ease of installation often result in placement in slightly rutted pavements, resulting in loss of accuracy [*Szary and Maher, 2009*].

Piezo Quartz Sensors

The piezo quartz sensor differs from the other piezoelectric sensors both in the material used and in the design of the sensor. In general, the piezo quartz sensor is more expensive per sensor than the other piezoelectric style sensors. The piezo quartz sensor also has the distinct advantage of being insensitive to changes in temperature. Therefore, it is generally more accurate than other piezoelectric sensors. However, the sensor will show some changes in response to a given axle load as a result of the change in pavement flexural stiffness due to temperature changes [*Hallenbeck and Weinblatt, 2004*].

10.6.2 Bending Plate

The bending scale consists of two steel platforms that are 2′× 6′, adjacently placed to fully cover a normal 12′ traffic lane. The plates are instrumented with strain gages. The measured strains are analyzed to determine the tire load. The maintenance is difficult, and the installation is hard and expensive. Installing a complete lane of scales, loops and axle sensor can be accomplished in a day using the shallow excavation method and in three days using a concrete vault. A properly installed and calibrated bending plate WIM system can provide gross vehicle weights that are within 8-10% of the actual vehicle weight for 95% of the measured trucks for Configuration 1 and within 6-8% for Configuration 2 (Figure 10-8) [*Bushman and Pratt 1998, IRD 2009*].

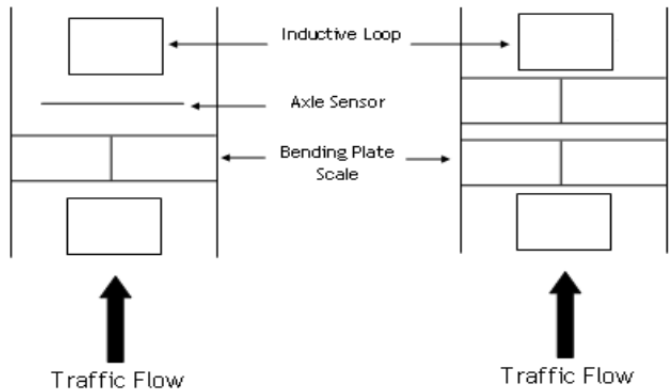


Figure 10-8 Different Configurations of Bending Plates: (a) Configuration 1: Single Threshold, (b) Configuration 2: Double Threshold [*IRD, 2009*]

Regular six month maintenance visits are assumed for the Bending Plate system. In addition to these maintenance visits the cost for sensor replacement or repair, based on the original installation cost, is included. The costs due to sensor failure or repair were estimated as follows [*Bushman and Pratt, 1998*]:

4% in year one
6% in year two
8% in year three
10% in year four
15% in year five, and
replacement in year six.

10.6.3 <u>Load Cell</u>

A load cell WIM sensor is mounted centrally in each scale mechanism (Figure 10-9). All loading on the weighing surface sensor will be transferred to the load cell through load transfer tubes. The load measurements are recorded and analyzed by the system electronics to determine the axle loads. This kind of sensor is sensitive and is the most accurate one among the commercially available WIM sensors. When properly installed and calibrated, the Single Load Cell WIM system should be expected to provide gross vehicle weights that are within 4-6% of the actual vehicle weight for 95% of the trucks measured. However, it's also expensive and hard to install [*IRD, 2009*].

Regular six month maintenance visits are assumed for the Single Load Cell system. In addition to these maintenance visits a cost for sensor and scale replacement or repair, based on the original installation cost, is included. The cost due to sensor failure or repair is estimated as follows [*Bushman and Pratt, 1998*]:

4% of equipment cost per year over the life of the scale, and
a major overhaul in year six.

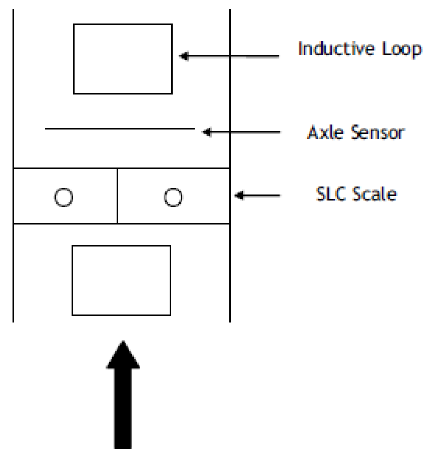


Figure 10-9 Configuration of Load Cell Sensors [*IRD, 2009*]

10.6.4 <u>Comparison of WIM Technology Accuracies and Costs</u>

In order to evaluate which technology is most appropriate, the accuracy of each technology must be considered as well as its cost. Accuracy is the quality of conformity of a measured value to an accepted standard value. The overall accuracy of a WIM system is a function of the actual difference in the dynamic tire force of the moving vehicle and the corresponding constant tire force of the static vehicle [*Hallenbeck and Weinblatt, 2004*]. There are many factors to include in the cost of a WIM technology beyond equipment cost or the installation cost. Other factors to consider include the expected life, maintenance cost, and replacement costs. Other factors including road deterioration and repair, traffic delay costs, and data reliability are not considered.

In 2004, the National Cooperative Highway Research Program (NCHRP) conducted a study on equipment for collecting traffic data. A summary of this research is presented in Table 10-22, which shows the various WIM equipment options and their associated life cycle costs. The costs that were considered ignored the pavement rehabilitation aspect [*Hallenbeck and Weinblatt, 2004*]. Table 10-22 also includes the results of a study comparing WIM technologies done by International Road Dynamics Inc. The results of this study are based on the assumption that the cost of the electronics, cabinet, power supply, telephone connection, and road preparation are relatively constant, regardless of technology used. In addition, the initial installation cost includes the equipment supply, installation by a local contractor, installation supervision and calibration by a vendor representative and traffic control during installation and curing [*IRD, 2009*]. A simplified comparison of WIM technologies is presented in Table 10-23 [*Liu et al., 2005*].

Table 10-22 NCHRP Table Estimating WIM Equipment Costs

Site Cost Considerations[2]	Load Cell	Piezo	Piezo Quartz	Bending Plate	
				Single Threshold	Double Threshold
Accuracy (GVW)[3]	3%	10%	5%	8-10%	6-8%
Service Life	12	3	3	7	7
Initial Cost					
Sensor Cost, Per Lane[4]	$55,239[5]	$2,500 $2,324[5]	$17,000	$10,000 $21,548[5]	$37,548[5]
Roadside Electronics		7,500	8,500	8,000	
Roadside Cabinet		3,500	3,500	3,500	
Installation Cost/Lane					
Labor and Materials	$24,310[6]	6,500 $5,962[6]	12,000	13,500 $17,238[6]	$34,476[6]
Traffic Control	3 days	0.5 day ≤ 1 day	1 day	2 days 3 days	3 days
Calibration		2,600	2,600	2,600	
Annual Recurring Cost/Lane					
Site Maintenance	$1,867	4,750 $4,750	7,500	5,300 $1,867	$3,734
Recalibration		2,600	2,600	2,600	

1. The underlined figures are cited from IRD (2009), the rest of the figures are from Hallenbeck and Weinblatt (2004).
2. Costs vary over time and from vendor bid to vendor bid. Thus actual cot can vary considerably from what is presented here.
3. All accuracies stated at a 95% confidence level.
4. These cost can vary considerably based on the exact sensor configuration chosen for a given site, as well as the specific bid prices provided by vendors.
5. The cost of the electronics, cabinet, power supply, telephone connection, and road preparation are assumed to be relatively constant, regardless of technology used and are not included in these estimates.
6. Initial Budgetary installation costs include materials to install and physical installation.
7. The cost items for some of the WIM technologies are left blank. No estimate of these items were included in two reference used here (*IRD, 2009 and Hallenbeck and Weinblatt, 2004*). These cost items are not necessarily blank.

Table 10-23 Comparison Table of Different WIM Sensors

Comparison Factors	Load Cell	Piezoelectric	Bending Plate
Accuracy	High	Low	Medium
Expected Life	Long	Short	Medium
Installation	Hard & high cost	Easy & low cost	Hard & high cost

Another study performed in Canada (presented at NATMEC '98) compared the three common WIM technologies discussed above on the basis of accuracy and cost [*Bushman and Pratt, 1998*]. The accuracy assumed according to ASTM standards for each technology are outlined below. The costs are the direct costs of the inroad equipment only and do not include related conduit work, system electronics, time delays, etc. The results of the comparison are presented in Table 10-24.

Table 10-24 Comparison Table of Different WIM Sensors

Comparison Factors	Piezoelectric	Bending Plate	Single Load Cell
Accuracy (95% confidence)	± 15 %	± 10 %	± 6 %
Expected Life	4 Years	6 Years	12 Years
Initial Installation Cost	$9,000	$21,500	$48,700
Annual Life Cycle Cost	$4,750	$6,400	$8,300

[*Bushman & Pratt, 1998*]

CHAPTER 11. SUMMARY OF RESEARCH METHODOLOGY, FINDINGS AND RECOMMENDATIONS

11.1 Summary of Research Methodology and Findings

This study developed traffic inputs for use with the Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures (MEPDG) in North Carolina. The research examined existing NCDOT traffic data resources to identify deficiencies and to recommend candidate locations for future monitoring of traffic data. This study also explored the problem of sampling sparse WIM data to generate estimates of traffic inputs for MEPDG.

11.1.1 Development of Traffic Inputs

To generate MEPDG traffic inputs the WIM volume and weight data are reviewed with respect to completeness and anomalies using a quality control (QC) procedure. The QC procedure involved using an MS Access-based tool that examines each WIM station's data (44 stations representing about 60 gigabytes of data), identifies the problem data and alerts the user. The user can then replace the data or edit it. The cleaned data are then processed using computer programming to generate traffic factors including VCD, MAF, HDF, ALDF, and number of axles per truck.

MEPDG damage-based sensitivity analysis was performed to identify sensitive traffic factors that affect pavement performance measures and those that do not. Performance measures for flexible pavements are rutting, alligator cracking, longitudinal cracking, and the International Roughness Index (IRI). For rigid pavements, only Jointed Plain Concrete Pavement (JPCP) is considered because Continuously Reinforced Concrete Pavement (CRCP) is being phased out from use in the North Carolina road network. The performance measures for JPCP are faulting, percentage of slabs cracked, and the IRI. Structural and materials data were available for LTPP sections only. Representative LTPP sections were used in this sensitivity analysis. To evaluate whether or not the effect of different traffic factors on pavement performance is significant, damage-based sensitivity criteria were developed in cooperation with the North Carolina Department of Transportation (NCDOT). These criteria suggest that an IRI of 14 inches/mile is the limit between being significant and insignificant for both flexible and rigid pavements. Similarly, the limits are 0.1 inch for rutting, 1% of the lane area for alligator cracking, 264 feet/mile for longitudinal cracking, and 0.1 inch for JPCP faulting.

Based on the results, flexible pavement performance and rigid pavement performance were found to be insensitive to HDF. Thus, HDF statewide averages may be used for Level 2 and Level 3 design. Similar results are found when comparing the impact on pavement performance of national default values of HDF. This is a valuable finding that simplifies the design process. Similarly, sensitivity analysis showed that rigid pavement performance is insensitive to MAF in NC. For flexible pavements, the predicted fatigue cracking (the most important damage in NC) was found insensitive to MAF for all sites. However, the longitudinal cracking fell beyond the acceptable sensitivity criteria defined by NCDOT. Since the longitudinal cracking model in MEPDG has been found not to be dependable, using engineering judgment, the performance of flexible pavement is assumed to be insensitive to different distributions of MAF experienced in North Carolina. Therefore, the statewide MAF averages are used as input to Levels 2 and 3 pavement designs. The approach simplifies the M-E pavement design process without losing accuracy.

Unlike HDF, pavement performance was found to be sensitive to ALDF and VCD. To develop ALDF inputs, multidimensional clustering analysis was proposed. Multidimensional clustering analysis considers similarity of multiple attributes simultaneously and generates ALDF clusters for which their distinctions can be easily explained. In order to decide what axle types and load combinations to include in clustering analysis, the following rules were developed. These rules consider the effect of axle type frequency and damage together:

- Rule 1: If the combined effect of damage factors and frequency for a certain axle type-load combination is less than 1% (normalized damage factor × frequency), this combination can be excluded from ALDF clustering.
- Rule 2: If the frequency, i.e., the contribution, of a certain axle type-load combination is less than 1% normalized frequency, this combination can be excluded from ALDF clustering.

When both rules are applied, the 3 – 21 kip load bins (at 1-kip intervals) of the normalized axle load distribution of *single axles* and 6 – 50 kip load bins (at 2-kip intervals) of the normalized axle load distribution of *tandem axles* remain. Using the remaining single and tandem axle type-load combinations, multidimensional clustering was carried out. Two-dimensional hierarchical clustering analysis resulted in ALDF clusters of variations in the frequencies of light-weight and heavy-weight single and tandem axles. Post-clustering analysis that incorporates local knowledge of the design road and easy-to-obtain traffic parameters (percent of class 5 and class 9 vehicles derived from 48-hour class counts) found that a strong relation exits between two-dimensional ALDF clusters and the road category: primary arterials, secondary arterials, collectors, and local roadways. These qualitative and quantitative explanatory parameters are summarized in an easy-to-use decision tree that helps the pavement engineer select the proper ALDF input.

Damage-based sensitivity analysis also investigated aggregating ALDF clusters based on all 3 sensitive performance parameters for flexible pavements: total rut depth, IRI, and alligator cracking. The results suggest that ALDF clusters cannot be aggregated and should be considered separately. Therefore, it is recommended to include all four ALDF clusters into the final decision tree being developed.

The results of the sensitivity analysis also showed that pavement performance was sensitive to VCD. The proposed approach to generate VCD inputs is based on using the site-specific 48-hour vehicle classification counts plus a seasonal factoring procedure that accounts for day-of-week and seasonal variations in truck traffic volume. The proposed approach results in accurate VCD inputs because it incorporates site-specific knowledge of truck traffic. Following TMG recommendations, the seasonal factors are developed for two aggregated vehicle classes: single-unit trucks (SU); and multi-unit trucks (MU). The clustering analysis resulted in four SU and MU factor groups. The traffic parameters (percent of SU trucks and percent of MU trucks) distinguish factor groups and form two decision trees that may be used for selecting the right seasonal factor for converting 48-hour classification counts of SU trucks and MU trucks into annual average volumes. Note that, the 48-hour class counts should be collected on typical weekdays excluding holidays, adverse weather events, and other conditions that cause significant variations in travel.

Besides traffic volume adjustment factors (VCD, HDF, and MAF) and ALDF, MEPDG requires some general traffic data to fully characterize the traffic pattern for the design of new or rehabilitated pavement structures. The required traffic data are the same for designing either new or rehabilitated or for either flexible or rigid pavements. These data items describe lateral traffic wander, axle configurations, axle spacing, wheelbase distribution, directional distribution factor, traffic lane distribution, and operational speed. Table 11-1 provides a comprehensive list of MEPDG traffic input requirements and sources of data.

Table 11-1 MEPDG Traffic Input Requirements and Sources of Data

Traffic Input	Manual Input (Yes/No)	Provider	Level 1	Level 2	Level 3
Axle Load Distribution Factor (ALDF) – **Flexible Pavement**	No	TSG based on NC WIM weight data	ALDF files[1]	ALDF files[2] NC User's Guide	ALDF file[3]
Axle Load Distribution Factor (ALDF) – **Rigid Pavement (JPCP)**				ALDF file[3]	
Two Way AADTT	Yes	TPB	Appendix 2 (Table A2-1)	TPB uses the base year AADTT developed by TSG to estimate the future year AADTT	
Vehicle Class Distribution (VCD)	Yes	TPB	Appendix 2 (Table A2-2)	TPB uses the VCD developed by TSG to estimate the VCD for future year	
Hourly Distribution Factors (HDF)	Yes	TSG based on NC WIM class data	Appendix 2 (Table A2-3)	Table 4-1 (Statewide Averages)	
Monthly Adjustment Factors (MAF)	Yes	TSG based on NC WIM class data	Appendix 2 (Table A2-4)	Table 4-2 (Statewide Averages)	
Number of Axles per Vehicle Class	Yes	TSG based on NC WIM weight data	Appendix 2 (Table A2-5, 6)	Table 4-3 (Statewide Averages)	
Traffic Growth Factor	Yes	Supplied by TPB/TF	Hierarchical levels does not apply		
Lateral Traffic Wander	Yes	MEPDG Default Values: Mean wheel location = 18 inches from the lane marking Traffic wander standard deviation = 10 inches Design lane width = 12 feet			
Axle Configuration	Yes	MEPDG Default Values: Average axle width = 8.5 feet Dual tire spacing = 12 inches Tire Pressure = 120 psi			
Axle Spacing	Yes	Supplied by TSG based on NC WIM weight data tandem axle = 48.9 inches tridem axle = 52.7 inches quad axle = 50.0 inches			
Wheelbase Distribution	Yes	MEPDG Default Values: Average axle spacing – Short (12 feet), Medium (15 feet), Long (18 feet) Percent of trucks – Short (33%), Medium (33%), Long (34%)			
Directional Distribution Factor (DDF)	Yes	MEPDG default values: Class 4, except for local or municipal routes = use 50% Class 4, for local or municipal routes = use 80%-100% Class 5, 6, 7 = use 62% Class 8, 9, 10 = use 55% Class 11, 12, 13 = use 50%			

(also shown as Table 4-4)

Table 11-2 MEPDG Traffic Input Requirements and Sources of Data (cntd.)

Traffic Input	Manual Input (Yes/No)	Supplier
Lane Distribution Factor (LDF)[4]	Yes	MEPDG default values: Single-lane roadways in one direction = 100% Two-lane roadways in one direction, = 90% Three-lane roadways in one direction = 60% Four-lane roadways in one direction = 45% MEPDG default values is 95%
Operational Speed	Yes	Supplied by PMU (can be found in Highway Capacity Manual). If local data is not available use MEPDG default values (60 mph)

1. Axle Load Distribution of all 44 WIM sites are delivered electronically in a format of ALDF files.
2. Level 2 ALDF files represent four ALDF clusters, and they are delivered to NCDOT electronically
3. Level 3 ALDF file is the statewide ALDF averages, and it is delivered to NCDOT electronically.
4. PMU Level 3 indicated that national defaults would be used for %Trucks in the design lane

Since traffic data inputs for MEPDG pavement design differ from those currently used in conventional pavement, there is a need to provide clear information on truck traffic forecasting. The study reviewed available truck traffic forecasting methods, NCDOT truck traffic forecasting procedures, truck traffic forecasting options in the M-E pavement design software. Finally, it proposed MEPDG truck traffic forecasting guidelines for NCDOT.

11.1.2 Seasonal Sampling Plan

This part of the research explored the problem of sampling sparse WIM data to generate estimates of traffic inputs for MEPDG. The proposed NC sampling scheme has different frequencies (annual, semiannual, quarterly, and monthly) and different lengths of sampled data (two consecutive weekdays and five consecutive weekdays). The sampling analysis showed that the choice of the proper sampling scheme depends on the seasonal variation of the truck traffic. As expected, where truck traffic is stable (Piedmont region) all sampling schemes are attractive. Where truck traffic is less stable (coastal region) noticeable variations in truck traffic degrade annual-based sampling schemes because annually sampled data cannot sufficiently capture the seasonal variations of truck traffic. The sampling analysis also revealed that knowledge of seasonal variations of truck traffic is necessary to select a proper sampling scheme. It should be noted that besides WIM data, DOTs have other traffic monitoring programs (Continuous Count Programs) that can help them quantify the seasonal variation of truck traffic. Another interesting finding is that increasing the amount of sampled data does not necessarily reduce the error in estimating single and tandem ALDFs. There is relatively little improvement in MSRE% as the sampling scheme changes from five consecutive weekdays per quarter (20 days), to two days per month (24 days), and to five days per month (60 days). This finding results because sampling five consecutive weekdays per quarter can efficiently capture the seasonal variation of truck traffic.

11.1.3 Installation/Abandonment of WIM Sites

Besides providing vehicle weight and volume information for use in pavement design and management, WIM stations provide data for bridge management, overweight vehicle and permit enforcement, and transportation planning. Future applications of WIM stations combined with other technologies will enhance statewide traffic management and freight logistics. Thus, careful attention to WIM station location, replacement and expansion of sites is important. The reliability analysis of seasonal factor groups and ALDF clusters shows at least 22additional WIM sites are needed on some highways to reach the TMG desired levels of precision and confidence. The number of new sites could be adjusted depending on specific NCDOT needs, budget and timetable based on age of sensors in the field. The type of WIM technology to install is also dependent on a tradeoff between many low cost sensors to cover what is needed now versus higher cost sensors that might last longer but reduce the number of locations monitored. Prioritized selections of new WIM locations are made as a result of clustering analysis, ALDF ranking factors, technical installation requirements [*TMG, 2001*], and NCDOT knowledge of site needs.

On the other hand, related seasonal factor group and ALDF reliability analysis shows that TMG levels are exceeded at some factor groups/clusters. Selection of WIM site for abandonment depends upon such factors as: WIM equipment condition, urban/rural location, high/low truck volumes, and the expectation that the traffic pattern at a particular site is established or may change. Seven WIM sites are candidates for abandonment (these WIM sites are presented in Table 10-19). These WIM sites may be prioritized based on their level of depreciation and also the level of truck traffic monitored by them. In general, WIM sites which are depreciated more and monitor fewer number of trucks have higher priority for abandonment.

11.2 Recommendations for Implementation

The outcome of this research project provides the necessary traffic data for the implementation of MEPDG software. Using site-specific traffic data, average values for clustered sites, statewide averages, and default values as recommended in this study (Table 11-1) will allow for pavement designs that more accurately reflect the current traffic loading on roadways in North Carolina. The results of the MEPDG analysis (predicted pavement performance) are only as reliable as the quality of the input data. Thus, the various input factors are critical components to consider in the analysis. The implementation of the recommendations in this study and the use of the MEPDG in general will provide NCDOT with a more advanced means of designing and analyzing pavements. The following paragraphs briefly explain how a user may enter or import the required traffic data for a specific design. A comprehensive traffic data implementation plan is included in MEPDG NC User's Guide [*Kim and Jadoun, 2010*]. A summary of the guide is presented in Appendix 6.

11.2.1 Implementation of VCD

To facilitate the process of generating VCD factors for a selected location, an Excel-based *VCD Generator & ALDF Cluster Selector* tool was developed that can generate VCD factors [*Kim and Jadoun, 2010*]. The month and day of week seasonal factors, single-unit and multi-unit decision trees are fundamental for the development of the tool. To generate VCD using the tool, the TSG user enters the 48-hour classification counts collected at the design road during typical weekdays (Tuesday-Thursday). The TSG user also specifies whether the counts were collected on Interstate I-95 or not. The tool will automatically generate the base year VCD factors. The base year VCD and AADTT values are sent to TPB/TF to forecast future year AADTT and VCD for the subject highway with and without the improvement. The resulting forecasts are sent to the pavement designer who will manually enter the values in the VCD table in MEPDG.

11.2.2 Implementation of HDF

The statewide HDF averages may be used for North Carolina Levels 2 and 3 designs. Table 4-1 is a summary of state-wide average HDF values that are recommended for use in the MEPDG. Users manually input HDF data in MEPDG software.

11.2.3 Implementation of MAF

The statewide MAF averages may be used for North Carolina Levels 2 and 3 designs. Table 4-2 is a summary of state-wide average MAF values that are recommended for use in the MEPDG. Users may either input MAF data manually or import them directly from MAF file that is delivered to NCDOT.

11.2.4 Traffic Growth Factor

Traffic growth functions and rates will be typically supplied by the TPB/TF. Chapter 5 provides guidelines to choose proper growth rates and functions for single-unit and multi-unit trucks. With MEPDG software the user has the option to manually select the same growth rate and function for all vehicle classes, groups of vehicle classes, or individual classes.

11.2.5 Implementation of General Traffic Input

Here are the other traffic inputs that the user will either manually update or use the national default values:

- The manual input data for the number of axles per truck are provided in Table 4-3.
- Axle spacing; manually input the data provided in Table 4-4.
- Percent trucks in design lane; manually input the data provided in Table 4-4.
- Lateral traffic wander; use MEPDG national default values.
- Average axle width, tire pressure, and dual tire spacing; use MEPDG national default values.
- Wheelbase distribution; use MEPDG national default values.
- Percent trucks in design direction; use MEPDG national default values.
- Operational speed; use MEPDG national default values.

11.2.6 Implementation of ALDF

The 2-dimensional clustering analysis resulted in four representative ALDF clusters. Four ALDF files are generated that include the average ALDF of WIM sites forming four ALDF clusters. The ALDF files were delivered to NCDOT. A decision tree (Figure 6-18) was also developed that helps the designer select the proper ALDF input given percentage of class 5 and class 9 vehicles at design road as well as the road category: primary highways, secondary highways, collectors or local roads. The ALDF decision tree (Figure 6-18) and class 5% versus class 9% plot (Figure 6-11) are aggregated into the "VCD Generator and ALDF Cluster Selector" tool [*Kim and Jadoun, 2010*]. The user initially inputs the 48-hour classification counts collected at design road along with roadway category and the tool automatically suggests a representative ALDF cluster. Knowing the ALDF cluster, the user can import the associated ALDF file into MEPDG. There are cases for which the tool fails to suggest any representative ALDF clusters. These are cases that are not represented in the existing WIM data. It is suggested that users refer to Figure 6-11 and use their engineering judgment to select an ALDF cluster that has the closest class 5% and class 9% to those anticipated on the design road.

11.3 Recommendations

11.3.1 Quality Control Procedure

The following recommendations can be implemented to improve upon the quality control procedures.

1. Explore data sampling procedures to reduce the size of databases.

2. Consider quality control as part of a comprehensive process called quality assurance – The quality assurance consists of various quality considerations which are made during data

collection and after data summarization and reporting. Some of the quality assurance actions are listed in the following.

- Develop effective equipment procurement procedures.
- Establish inspection procedures for newly installed equipments.
- Schedule periodic maintenance and calibration activities.
- Develop automated quality control procedure to review and detect corrupt data.
- Be in contact with the data customer and ask for feedback [*Turner, 2007*].

3. Assign severity level to quality control rules. Currently, the NCDOT QC database simply excludes all the data which are rejected based on identified QC rules. In other words, a simple accept/reject decision is made for each rule. It will be more beneficial to assign a severity level to data which are not valid based on QC rules. Suggested severity levels are:
   - <u>High</u> – A high level of severity may happen because of equipment failure. The suggested action for data with high level of severity would be to exclude the data from further analysis.
   - <u>Medium</u> – Data with a medium level of severity are outside the acceptance range, however, medium severity is not very significant. The suggested action for data with medium level of severity is to perform more analysis based on local knowledge of traffic and site conditions at the WIM site.
   - <u>Low</u> – Data with a low level of severity correspond to rules with boundary limits (maximum and minimum limits). It is recommended to investigate such data further based on local knowledge of the WIM site to build more confidence on data quality [*Turner, 2007*].

4. Plan for long term WIM data storage and analysis. A Microsoft Access database or spreadsheet program can be used to analyze small datasets, but they are not feasible for analyzing a statewide WIM program. Therefore, the best way to effectively handle the tremendous amount of data generated by a WIM monitoring program is to upload it to a more robust relational database, such as Oracle or Microsoft SQL Server [*Nichols et.al, 2004*].

11.3.2 <u>Seasonal Factoring Procedure</u>

48-hour classification counts collected at a design location are critical components in selecting the right traffic input for MEPDG. These counts are used for various purposes: to select the proper seasonal factor group using SU and MU factor group decision tree, and to select the proper ALDF cluster using ALDF decision tree. The classification counts are also annualized using seasonal factoring procedure (Chapter 3) and adjusted based on engineering knowledge of TPB/TF staff. The annualized counts are used to generate VCD and AADTT. Considering the important role of the 48-hour counts, NCDOT should supply sufficiently accurate class counts. To produce that accuracy, some data collection recommendations follow:

1. Collect 48-hour class counts on typical days. Exclude holidays, adverse weather events, and other conditions that cause significant variations in travel.
2. Compare one day's hourly traffic counts against the second day's counts to check for any abnormal patterns in truck traffic. If a significant difference exists between two days' traffic, then collect additional counts.
3. In most WIM locations, ALDF of single and tandem axles do not vary significantly from month to month. However, there are a few WIM locations for which the ALDF patterns vary

in some specific months including July and August. Thus, it is recommended that NCDOT avoid these specific months (July and August) for collecting short duration counts.

As the TMG emphasizes, the seasonal factoring process should be reviewed periodically to ensure that it is performing as intended [*TMG, 2001*]. For the first few years after initial development, these evaluations should be conducted every year. After that, the seasonal factoring procedure should be reviewed periodically every 3 years. When new WIM data is also available, they should be included in seasonal factoring analysis. New WIM data will help to improve the precision level of seasonal factor groups.

Before conducting any analysis using WIM data, it is important to identify observations (WIM sites) that are inconsistent with the remainder of the data (i.e., outliers). These outliers can have a disproportionate effect on the analysis and should be discarded. A graphical presentation of the data set is an easy way to identify outliers. The large number of variables involved (e.g., seasonal factors) rules out the graphical identification of possible outliers. Numerous methods have been suggested for detecting outliers. Principal component analysis is recommended for this purpose because it can be accomplished easily using statistical software including MATLAB.

11.3.3 Seasonal Sampling Plan (*Future Research*)

This research evaluated the effect of different sampling schemes on the accuracy of the axle load distribution derived from sampled WIM data compared to estimates of ALDFs derived from annual WIM data. Extensive MEPDG simulations need to be conducted to quantify the impact of different sampling on pavement performance (pavement life). In this regards, the MEPDG can be applied to estimate pavement performance until failure under different axle load distributions derived from the proposed sampling schemes. Major pavement distresses (such as fatigue cracking which is the most important damage in NC) could be considered in determining pavement life.

11.3.4 Traffic Forecasts for NCDOT M-E Pavement Design (*Future Research*)

The most common NCDOT approach for project-level traffic forecasts is utilization of the Traffic Forecasting Utility or TFU (previously called the Trend Program) to develop initial trend line information using linear and / or exponential functions. This tool utilizes ADT and AADT data provided by the Traffic Survey Unit (TSU) and estimates a total traffic growth factor based on available historic years of data. Also, the spreadsheet provides statistical results by analyzing the traffic data from ADT. Some adjustment can be implemented on the existing utility to perform additional analysis using ADT by vehicle class (SUs and MUs). The current utility would need to be adjusted to accommodate historical class counts (VCDs) as well as total traffic counts. The research of HWY 2004-11 describes how truck traffic forecasts may be calculated directly from historic NCDOT truck counts, VTRIS, and WIM data. The findings of the 2004 and this research justify changes to the TFU utility.

Other productive future research topics include: the effects of bypass and widening projects on traffic diversion by truck class; truck traffic growth as functions of urban and rural highway classifications including transitions from rural to urban fringe areas; changes in SU and MU truck traffic percentages (of overall traffic) over time; sensitivity of pavement performance to errors in estimated growth rates, and prediction of the growth rate based on roadway characteristics and socio-economic activates. The truck traffic data collected by WIMs and 48-hour counts over years will support the analysis. The expected outcomes may include: different growth patterns for different vehicle classes, the effect of socio-economic activities on growth patterns of different vehicle classes, the sensitivity of the pavement performance to parameters used in the truck traffic growth models (linear or compound), and factors that are associated with traffic growth such as population density and land use.

11.3.5 Installation/Abandonment of WIM Sites

The selection of new WIM locations should be based on the needs of the data collection program and the site characteristics of the roadway sections that meet those needs [*TMG 2001*]. However, just because a roadway section meets some or all of the above characteristics does not make it a good WIM site. With current technologies, WIM systems only accurately weigh trucks when the equipment is located in a site that meets specific criteria. These criteria include the smoothness of the pavement, access to power and communications, sufficient truck traffic at the site, and etc[*TMG 2001*].

The recommended number of new sites (22) could be adjusted depending on specific NCDOT needs, and budget. Prioritizing selections of new WIM locations are made as a result of clustering analysis, ALDF ranking factors, technical installation requirements [*TMG, 2001*], and NCDOT knowledge of site needs. New WIM data will help to improve the precision level of traffic factors derived from seasonal factor groups and ALDF clusters as well as the statewide HDF, statewide MAF, and statewide number of axles per truck. Regardless of the number of WIMs recommended, it is recommended that WIM sites are added in stages, evaluating where they fall in the groups/clusters, before moving on to the next stage and selecting new sites to install. The actual precision levels are evaluated as new WIM sites are installed and the process terminates when the desired level is achieved.

The abandonment of WIM sites is recommended to be carried out in stages after ensuring that the discontinuation does not affect the reliability of groups/clusters. For example, the seven candidate WIM sites for abandonments can be discontinued, two locations annually, over a period of three years. The reliability analysis should be repeated every three years to ensure that the desired precision has been maintained. Another important consideration before discontinuation of WIM sites is other use of existing truck information or other reasons that the station is important. NCDOT should ensure that these criteria are met before discontinuing the WIM sites.

Finally, a brief discussion on system wide monitoring of truck weights seems relevant. The technique employed in traffic monitoring programs is to have a *continuous count* component and a *coverage count* component. The *continuous count* component is comprised of a limited number of sites where traffic is monitored continuously to provide detailed information on the types of traffic patterns and generate factors for short term counts. The *coverage count* component is comprised of many locations, enough to define system-wide travel patterns, where short term counts are collected and annualized to provide monitoring of demand on the system. This is done for both volume and vehicle class data types as there are technologies available to collect both continuous and short term counts. This is not the case for truck weights. There is no viable technology to collect truck weights in short term sessions to support a *coverage* component for this data type. The 2009 AASHTO Guide for Traffic Data Programs Research has shown that these technologies (portable WIMs) are not reliable and that agencies should not use these technologies [*AASHTO 2009*]. The only methods available to expand the knowledge of the system-wide patterns as related to truck weights are technologies used for the *continuous* component.

The NCSU team recommends that NCDOT manage WIMs so that they meet the *continuous* component while supporting a process of expanding their knowledge base as there is no *coverage* component. This requires use of less expensive sensors, reuse of equipment, and makes treatment of pavements impractical. The techniques and guidelines developed in the research supports this approach. The recommendation is to set up a dynamic program, where new WIM sites are added regularly (site selection), adequate data are collected (sampling), sites are discontinued after a short period (site abandonment), while the data needed for MEPDG input are maintained (reliability analysis). The collected data may not be "research quality" data, but they are valuable in expanding the knowledge of system characteristics at a slow and steady pace.

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APPENDIX 1

ACRONYMS

Acronym	Meaning
AADTT	Annual Average Daily Truck Traffic
AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
ALDF	Axle Load Distribution Factors
APT	Axles per Truck
AASHTO	American Association of State Highway and Transportation Officials
BY	Base Year
CRCP	Continuously Reinforced Concrete Pavement
DOW	Day of Week
DDF	Directional Distribution Factor
FHWA	Federal Highway Administration
FC	Functional Class
FY	Future Year
HDF	Hourly Distribution Factors
HPMS	Highway Performance Monitoring System
IRD	International Road Dynamics
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement (JPCP)
LDF	Lane Distribution Factor
LTPP	Long Term Pavement Performance
MAF	Monthly Adjustment Factors
MADTT	Monthly Average Day-of-week Truck Traffic
MEPDG	Mechanistic Empirical Pavement Design Guide
MU	Multi-Unit Trucks (Vehicle Classes 8-13)
NCSU	North Carolina State University
PC	Principal Component
PCA	Principal Component Analysis
PDU	Pavement Design Unit
SU	Single-Unit Trucks (Vehicle Classes 4-7)
TFU	Traffic Forecasting Utility
TPB	Transportation Planning Branch
TPB/TF	Transportation Planning Branch/Traffic Forecast
TMG	Traffic Monitoring Guide
TSG	Traffic Survey Group
VCD	Vehicle Class Distribution
VTRIS	Vehicle Travel Information System
WIM	Weigh-in-Motion

APPENDIX 2

LEVEL 1 TRAFFIC DATA FOR THE 44 WIM SITES

Table A2-1 Annual Average Daily Truck Traffic for the 44 WM Sites

SHRP ID	Site ID	Route Name	Location	Lanes	County	Nearest City/Town	AADTT
1 Sites (Cabinets) at 1 Station							
371030	502	US 17	0.4 Miles South of US 158	2S, 2N.	Pasquotank	Elizabeth City	1175
371645	504	US 74	1.9 Miles West of SR 1001	2W, 2E.	Columbus	Whiteville	1649
371805	508	US 64	0.7 Miles West of US 15-501	2W, 2E.	Chatham	Pittsboro	839
372824	509	US 421	1.9 Miles South of US 64	2S, 2N.	Chatham	Siler City	1968
372819	511	US 220	1.6 Miles North of NC 62	2S, 2N.	Guilford	Greensboro	2969
371817	512	US 311	0.6 Miles East of SR 2698	2S.	Forsyth	Salem	-
375826	515	I-77	0.5 Miles North of SR 1345 (Mp 98)	2S, 2N.	Surry	Mount Airy	7092
372825	516	SR 1138	0.7 Miles East of NC 49	2W, 2E.	Mecklenburg	Charlotte	604
375037	519	I-40	1.6 Miles West of SR 2838 (Mp 55)	2W.	Buncombe	Oteen	-
371801	520	I-40	1.3 Miles West of SR 2740	2W, 2E.	Buncombe	Swannanoa	6093
371024	521	NC 107	0.3 Miles North of SR 1001	1N, 1S	Jackson	Cullowhee	367
371803	522	US 74-441	0.2 Miles East of SR 1391	2W, 2E.	Jackson	Whittier	1155
371814	523	US 23-441	0.2 Miles South of SR 1504	2S, 2N.	Macon	Franklin	1039
371992	525	US 421	0.8 Miles North of US 64	2S, 2N.	Chatham	Siler City	1945
377302	529	US 264	0.3 Miles West of NC 33	2W, 2E.	Pitt	Greenville	1467
370900	530	US 1	0.1 Miles South of SR 1423	2S, 2N.	Lee	Sanford	1736
370200	531	US 52	0.4 Miles North of US 64 (Mp 92)	2S, 2N.	Davidson	Lexington	3039
370800	532	SR 1245	0.1 Miles North of SR 1209	1N, 1S	Onslow	Jacksonville	-
372101	533	US 64	0.5 Miles East of SR 1304	1E, 1W	Clay	Hayesville	354
371901	534	US 64	0.4 Miles East of US 19/129	2W, 2E.	Cherokee	Murphy	760
371902	535	US 74	0.3 Miles West of SR 1390	2W, 2E.	Cherokee	Andrews	507
374301	536	I-40	1.0 Miles West of US 19-23-74 Conn	2W, 2E.	Haywood	Clyde	8142
377401	537	I-26	0.5 Miles East of US 74 (MP 67)	2W, 2E.	Polk	Columbus	4428
372202	538	I-85	0.3 Miles East of NC 161 (MP 8)	2S, 2N.	Cleveland	Kings	11583
375902	539	I-77	0.1 Miles South of I-485 (Mp 2)	3N, 3S	Mecklenburg	Charlotte	9611
377701	541	I-95	1.0 Miles South of NC 130 (Mp 1)	2S, 2N.	Robeson	McDonald	8027
377001	542	I-40	0.3 Miles West of NC 210 (Mp 408)	2W, 2E.	Pender	Rocky Point	1710
379201	543	I-85	0.2 Miles East of US 1 (Mp 233)	2S, 2N.	Warren	Wise	5370
375903	546	NC 24	0.2 Miles East of US 21	2W, 2E.	Mecklenburg	Charlotte	1922
373501	547	US 321	0.1 Miles South of NC 279	3S, 3N.	Gaston	Dallas	4716
374701	548	US 264	0.1 Miles East of SR 1168	1W, 1E.	Hyde	Scranton	4705.014
377002	549	US 421	0.2 Miles South of NC 210	2S, 2N.	Pender	Currie	535
378201	551	US 74	0.1 Miles East of NC 79	2W, 2E.	Scotland	Laurinburg	2401
370301	552	US 74	0.1 Miles West of SR 1740	2W, 2E.	Anson	Lilesville	2146
377501	553	US 220	0.1 Miles North of SR 1247	2S, 2N.	Randolph	Asheboro	2652
377803	554	US 220	0.5 Miles South of SR 2150	2S, 2N.	Rockingham	Madison	2630
374002	555	NC 68	0.5 Miles North of Bryan Blvd	2S, 2N.	Guilford	Greensboro	2393
371003	556	I-240	0.5 Miles East of US 70 (Mp 8)	2E, 3W.	Buncombe	Asheville	1643
374801	557	I-40	0.3 Miles West of US 21 (Mp 151)	2W, 2E.	Iredell	Statesville	8907
371701	558	US 321	1.0 Miles North of I-40 (At US 70)	2S, 2N.	Catawba	Hickory	2835
371101	559	I-40	0.3 Miles West of SR 1744 (Mp 109)	2W, 2E.	Burke	Valdese	6158
375601	560	I-26	0.1 Miles West of US 19 (Mp 3)	2W, 2E.	Madison	Mars Hill	1141

Table A2-1 Annual Average Daily Truck Traffic for the 44 WM Sites (continued)

SHRP ID	Site ID	Route Name	Location	Lanes	Nearest City/Town	Nearest City/Town	AADTT
2 Sites (Cabinets) at 1 Station							
371028	501	US 17	0.7 Miles North of SR 1231	2N.	South Mills	South Mills	942
371402	540			2S.	South Mills	South Mills	
373011	503	I-95	0.5 Miles South of SR 1745	2N.	Rocky Mount	Rocky Mount	7300
376302	527			2S.	Rocky Mount	Rocky Mount	
373102	545	NC 147	0.4 Miles North of SR 1940	2S.	Durham	Durham	2219
373816	507			2N.	Durham	Durham	
371006	506	I-40	0.8 Miles East of NC 54	2E.	Raleigh	Raleigh	6959
379102	544			2W.	Raleigh	Raleigh	
375827	510	US 29	1.8 Miles North of US 158	2S.	Reidsville	Reidsville	2032
377802	526			2N.	Reidsville	Reidsville	

Table A2-2 Vehicle Class Distribution for the 44 WM Sites

WIM ID	VC 4	VC 5	VC 6	VC 7	VC 8	VC 9	VC 10	VC 11	VC 12	VC 13
501/540	2.59	36.27	6.51	0.43	3.70	49.06	0.76	0.60	0.04	0.04
502	2.22	38.85	8.88	0.45	3.65	42.72	0.84	0.47	0.04	0.06
503/527	3.53	12.46	4.54	0.04	3.18	74.51	0.50	0.65	0.54	0.07
504	3.71	20.03	9.19	0.30	3.63	59.86	0.78	1.48	0.90	0.13
506/544	7.40	25.77	8.90	0.29	10.22	45.07	1.16	0.80	0.29	0.10
507/545	7.76	41.90	10.13	0.37	7.05	30.95	0.73	0.75	0.25	0.10
508	6.01	32.77	5.76	0.32	5.64	47.39	0.82	0.45	0.63	0.20
509	3.49	17.73	8.83	0.31	4.90	61.34	1.02	1.92	0.16	0.31
510/526	4.13	11.93	3.86	0.11	9.98	63.33	0.40	5.42	0.80	0.04
511	6.15	25.89	6.13	0.41	4.46	54.05	1.25	1.27	0.36	0.04
515	3.87	10.07	4.73	0.10	2.33	73.03	0.37	3.83	1.62	0.04
516	28.51	47.13	9.05	0.78	7.04	6.92	0.46	0.03	0.01	0.06
520	4.19	16.78	6.10	0.50	3.24	65.92	0.46	2.11	0.63	0.07
521	3.82	55.12	11.98	0.87	22.78	4.95	0.47	0.00	0.00	0.01
522	5.56	38.73	13.69	1.13	17.40	22.32	0.88	0.11	0.06	0.11
523	5.43	47.47	5.71	0.44	3.91	36.58	0.29	0.08	0.02	0.08
525	4.69	18.20	5.50	0.24	4.36	64.13	1.35	1.35	0.12	0.06
529	4.02	23.53	12.76	1.03	5.59	50.61	0.87	0.93	0.52	0.13
530	4.23	25.09	11.05	0.51	4.75	51.42	1.64	0.28	0.12	0.91
531	5.37	17.87	4.30	0.13	4.38	61.35	0.37	4.36	1.83	0.04
533	4.80	51.16	15.13	2.31	10.64	14.86	1.08	0.00	0.01	0.01
534	4.50	51.24	9.62	0.83	10.63	22.34	0.63	0.01	0.00	0.21
535	4.13	42.71	9.65	0.73	8.34	32.19	2.14	0.01	0.01	0.09
536	2.59	5.99	2.60	0.09	6.44	76.46	0.56	4.19	1.03	0.06
537	3.16	11.12	3.27	0.09	6.94	71.62	0.74	2.49	0.50	0.07
538	4.23	9.56	3.85	0.09	6.38	69.44	0.32	4.57	1.51	0.04
539	5.94	16.24	7.10	0.41	10.56	55.41	0.50	2.57	1.23	0.05
541	4.04	7.63	3.43	0.14	8.82	73.78	0.63	0.74	0.54	0.26
542	7.71	32.42	6.71	0.22	5.48	44.82	1.00	1.04	0.39	0.21
543	4.96	6.67	2.01	0.12	6.12	74.61	0.41	4.10	0.97	0.03
546	9.49	48.01	10.00	1.51	5.95	19.07	0.82	3.61	1.47	0.07
547	5.97	23.83	6.40	0.47	4.94	55.77	0.33	1.43	0.83	0.03
548	5.92	41.43	11.62	0.16	4.24	34.87	1.41	0.01	0.00	0.35
549	0.92	26.87	14.77	0.49	4.31	50.15	1.42	0.70	0.20	0.16
551	3.58	16.29	14.10	0.85	3.63	58.20	0.76	1.80	0.67	0.12
552	5.39	19.17	7.70	0.59	3.85	58.84	1.32	2.03	1.06	0.04
553	4.47	19.14	5.84	0.32	5.85	61.53	1.49	0.99	0.34	0.03
554	5.05	16.26	6.87	1.45	4.59	59.15	0.52	4.75	1.34	0.02
555	6.24	30.13	10.54	0.86	4.23	47.13	0.58	0.15	0.12	0.02
556	6.63	53.00	9.23	0.77	3.76	25.89	0.43	0.10	0.16	0.04
557	4.83	18.66	4.83	0.18	5.86	62.45	0.41	2.21	0.52	0.06
558	6.63	24.16	6.77	0.36	8.59	52.58	0.47	0.14	0.28	0.03
559	4.83	16.49	4.47	0.10	4.44	66.38	0.40	2.14	0.65	0.11
560	7.33	19.46	5.33	0.20	5.54	60.76	0.47	0.55	0.29	0.06

Table A2-3 Hourly Distribution Factors for the 44 WM Sites

WIM ID	Midnight	1:00 am	2:00 am	3:00 am	4:00 am	5:00 am	6:00 am	7:00 am	8:00 am	9:00 am	10:00 am	11:00 am	Noon	1:00 pm	2:00 pm	3:00 pm	4:00 pm	5:00 pm	6:00 pm	7:00 pm	8:00 pm	9:00 pm	10:00 pm	11:00 pm
501/540	1.22	1.16	0.87	1.29	1.69	3.49	4.90	5.04	6.15	6.86	7.24	7.06	6.91	6.92	6.83	6.62	5.85	5.27	4.08	3.06	2.30	2.02	1.76	1.44
502	1.03	0.98	1.22	1.52	2.58	4.13	5.32	6.28	7.00	7.18	7.23	7.05	7.72	7.04	6.62	6.02	5.70	4.10	3.12	2.24	2.00	1.51	1.30	1.11
503/527	2.56	2.25	2.11	2.06	2.25	2.59	3.27	3.83	4.46	5.14	5.51	5.60	5.65	5.64	5.66	5.72	5.67	5.57	5.05	4.55	4.25	3.88	3.63	3.09
504	1.29	1.28	1.65	2.05	2.53	3.67	4.69	5.13	5.67	6.29	6.81	6.81	6.94	6.42	6.22	5.97	5.41	4.99	4.05	3.27	2.90	2.49	1.90	1.55
506/544	1.46	1.41	1.43	1.54	2.19	3.09	4.95	5.58	6.02	6.73	7.04	6.88	6.58	6.48	6.33	6.02	5.33	4.62	4.23	3.34	2.65	2.24	2.08	1.80
507/545	1.34	1.00	1.05	1.42	1.68	2.66	5.03	6.46	6.99	7.04	7.13	6.88	6.54	6.37	6.55	6.63	5.79	5.23	4.01	2.77	2.22	2.02	1.72	1.48
508	1.33	1.18	1.63	2.28	3.46	4.35	5.15	6.39	6.74	6.90	6.78	6.49	6.60	6.50	6.38	6.10	5.09	4.17	3.32	2.75	2.00	1.88	1.39	1.15
509	1.97	1.58	1.95	2.52	3.50	4.37	4.92	5.81	6.70	6.80	6.74	6.51	6.47	6.14	5.77	5.08	4.39	3.85	3.18	2.78	2.61	2.35	2.13	1.88
510/526	2.54	2.25	2.13	2.29	2.96	3.69	4.49	4.59	4.92	5.55	5.74	5.76	5.49	5.40	5.53	5.31	5.32	4.94	4.24	4.07	3.75	3.31	3.02	2.73
511	1.44	1.40	1.59	2.21	3.25	5.21	5.66	6.20	6.49	6.45	6.48	6.35	6.30	6.20	6.00	5.52	5.06	4.15	3.28	2.76	2.39	2.10	1.84	1.67
515	2.39	2.19	2.35	2.47	2.77	3.07	3.59	4.16	4.72	5.18	5.31	5.49	5.56	5.64	5.67	5.58	5.41	5.04	4.89	4.54	4.14	3.82	3.26	2.76
516	1.27	1.09	0.86	0.81	0.95	2.09	2.90	4.00	5.71	6.84	7.54	7.13	6.80	7.28	6.96	6.72	6.93	6.13	4.99	4.09	3.28	2.22	1.89	1.53
520	2.19	2.16	2.17	2.45	2.76	3.47	4.35	5.10	5.55	5.88	5.98	5.97	5.92	5.90	5.75	5.49	5.08	4.49	4.02	3.75	3.45	3.07	2.69	2.35
521	0.56	0.37	0.26	0.27	0.36	1.38	3.39	6.46	7.34	7.32	7.17	7.27	7.37	7.65	7.50	8.46	7.59	6.41	4.49	3.09	2.04	1.64	0.98	0.63
522	0.99	0.91	0.96	1.12	1.52	2.18	4.08	5.02	6.86	7.64	8.10	8.05	7.52	7.45	7.21	6.74	5.97	5.16	3.73	2.70	1.98	1.64	1.37	1.10
523	1.07	0.98	1.14	1.52	2.07	3.57	5.44	6.39	7.12	7.24	7.35	7.23	7.25	7.05	6.85	6.37	5.71	4.16	3.13	2.47	2.00	1.72	1.28	0.91
525	1.85	1.55	1.89	2.53	3.69	4.49	5.08	6.05	6.80	6.65	6.67	6.48	6.41	6.07	5.74	5.05	4.35	3.85	3.21	2.84	2.60	2.29	2.04	1.82
529	0.88	0.83	1.07	1.53	2.68	4.21	6.08	7.28	7.49	7.55	7.23	6.90	7.08	6.90	6.61	5.92	5.04	3.65	2.75	2.41	2.03	1.65	1.29	0.93
530	1.23	1.45	1.97	2.73	3.79	5.26	5.86	6.91	7.33	7.50	7.32	7.07	6.75	6.41	5.74	5.06	4.26	3.24	2.53	2.02	1.62	1.46	1.33	1.15
531	2.20	1.93	2.09	2.69	3.41	4.38	5.06	5.91	6.49	6.45	6.27	5.99	5.87	5.78	5.41	4.94	4.39	3.79	3.30	2.93	2.82	2.95	2.54	2.41
533	0.53	0.55	0.55	0.61	0.56	1.13	3.61	6.44	7.02	7.52	8.60	7.86	7.54	7.72	8.02	8.03	6.60	5.57	3.54	2.43	1.99	1.58	1.23	0.78
534	0.79	0.75	0.70	1.19	1.48	2.22	3.14	5.02	6.56	7.36	7.72	7.74	7.66	7.79	7.62	7.36	6.61	5.29	3.91	2.85	2.32	1.76	1.25	0.91
535	1.01	0.87	1.29	1.70	1.87	2.54	4.66	5.66	6.00	6.95	7.07	7.22	6.90	7.10	6.99	6.67	6.12	5.39	4.22	2.98	2.29	1.87	1.47	1.16
536	3.20	2.83	2.61	2.57	2.66	2.80	2.90	3.30	3.74	4.27	4.85	5.11	5.26	5.27	5.40	5.50	5.46	5.37	5.24	4.91	4.68	4.37	4.08	3.62
537	2.35	2.10	2.00	2.12	2.53	2.89	3.53	4.16	4.73	5.40	5.85	6.17	6.07	5.96	5.82	5.69	5.40	5.18	4.63	4.10	3.74	3.57	3.22	2.79

Table A2-3 Hourly Distribution Factors for the 44 WM Sites (continued)

WIM ID	Midnight	1:00 am	2:00 am	3:00 am	4:00 am	5:00 am	6:00 am	7:00 am	8:00 am	9:00 am	10:00 am	11:00 am	Noon	1:00 pm	2:00 pm	3:00 pm	4:00 pm	5:00 pm	6:00 pm	7:00 pm	8:00 pm	9:00 pm	10:00 pm	11:00 pm
538	3.08	2.75	2.70	2.69	3.01	3.31	3.65	3.84	4.36	5.01	5.37	5.42	5.39	5.37	5.37	5.31	5.12	4.76	4.56	4.32	3.94	3.74	3.63	3.29
539	2.01	1.94	2.17	2.54	3.39	4.27	4.19	5.09	6.06	6.40	6.40	6.13	6.01	5.93	5.53	5.03	4.53	4.40	3.78	3.34	3.09	2.89	2.58	2.28
541	2.68	2.35	2.29	2.28	2.55	2.78	3.18	3.63	4.28	5.03	5.63	5.88	5.86	5.71	5.60	5.52	5.38	5.24	4.93	4.59	4.23	3.92	3.40	3.05
542	1.32	1.28	1.66	2.19	2.98	4.51	5.37	6.34	6.99	6.90	7.20	6.25	6.23	6.34	6.32	5.80	5.13	4.14	3.10	2.63	2.23	1.65	2.20	1.25
543	3.27	2.90	2.75	2.95	3.21	3.49	3.60	3.80	4.03	4.39	4.89	5.16	5.22	5.06	4.99	4.98	5.01	4.83	4.57	4.36	4.25	4.29	4.22	3.80
546	1.17	1.08	1.28	1.86	2.89	5.52	6.63	7.26	7.43	7.33	7.07	6.84	6.80	6.64	6.15	5.63	4.55	3.40	2.54	2.15	1.64	1.50	1.41	1.22
547	1.73	1.70	1.85	2.10	3.04	4.45	5.30	5.92	6.26	6.45	6.36	6.20	6.12	6.12	5.88	5.57	4.85	4.22	3.48	3.09	2.77	2.58	2.13	1.84
548	0.42	0.43	0.55	1.22	2.63	4.78	6.19	7.79	8.02	7.58	7.53	7.18	7.39	7.15	7.74	6.76	5.43	3.77	2.44	1.75	1.16	0.89	0.62	0.60
549	0.82	0.93	1.37	2.11	3.03	5.28	6.41	6.79	7.36	7.53	6.95	6.96	6.47	6.92	6.77	5.88	5.29	3.70	2.68	2.18	1.54	1.06	1.08	0.89
551	1.73	2.00	2.29	2.84	3.54	4.35	4.90	5.45	5.95	6.35	6.84	6.62	6.38	5.95	5.52	5.11	4.49	4.05	3.34	3.11	2.97	2.45	1.99	1.78
552	1.89	1.95	2.39	3.21	3.84	4.71	4.90	5.49	6.05	6.51	6.68	6.53	6.30	6.06	5.67	5.06	4.35	3.61	3.12	2.71	2.55	2.60	2.08	1.75
553	1.41	1.32	1.84	2.61	3.78	4.81	5.49	6.20	6.71	6.91	6.79	6.64	6.50	6.15	5.54	4.94	4.44	3.79	3.25	2.73	2.37	2.18	1.96	1.64
554	1.90	1.79	1.95	2.40	3.22	4.36	4.98	5.48	6.13	6.31	6.28	6.21	6.30	6.41	6.08	5.33	4.75	4.04	3.43	3.04	2.75	2.58	2.22	2.05
555	1.38	1.35	1.36	1.64	2.57	4.57	5.69	6.45	6.66	6.64	6.56	6.42	6.59	6.62	6.47	6.01	5.28	3.98	3.34	2.69	2.31	2.08	1.77	1.56
556	0.91	0.69	0.63	0.83	1.16	1.68	3.72	6.01	6.89	7.54	7.54	7.54	7.39	7.45	7.43	7.04	6.31	5.47	4.12	2.92	2.20	1.82	1.56	1.16
557	1.81	1.68	1.79	2.27	2.88	3.74	4.54	5.26	5.85	6.13	6.24	6.26	6.30	6.23	6.05	5.64	5.13	4.53	3.81	3.46	3.13	2.80	2.42	2.04
558	1.80	1.88	2.24	2.61	3.34	4.31	5.49	6.54	6.72	6.99	6.70	6.43	6.80	6.76	6.08	5.22	4.23	3.39	2.67	2.26	2.14	1.96	1.85	1.60
559	2.07	1.89	2.05	2.23	2.70	3.47	4.34	4.98	5.57	6.02	6.10	6.08	6.09	6.07	5.86	5.59	5.14	4.54	4.02	3.67	3.42	3.13	2.66	2.31
560	1.79	1.58	1.66	2.14	2.88	3.55	4.18	5.10	5.88	6.43	6.36	6.22	6.04	5.97	5.72	5.41	5.17	4.69	4.33	3.71	3.45	3.08	2.63	2.03

Table A2-4 Monthly Adjustment Factors for the 44 WM Sites

WIM ID	January	February	March	April	May	June	July	August	September	October	November	December
501/540	0.9	1.0	1.0	1.1	1.0	1.2	1.1	0.9	0.9	1.0	1.0	0.9
502	0.9	0.8	1.0	1.1	1.1	1.2	1.2	0.9	0.9	1.0	1.0	1.0
503/527	1.0	1.0	1.0	1.1	1.1	1.1	1.0	1.0	0.9	1.0	1.0	1.0
504	0.9	1.0	1.0	1.0	1.0	1.1	1.0	1.0	1.0	1.0	0.9	0.9
506/544	0.9	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	1.0	1.0	0.9
507/545	0.9	0.9	1.0	1.0	1.0	1.0	0.9	1.1	1.1	1.2	1.1	0.9
508	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.9
509	0.9	0.9	1.0	1.0	1.1	1.1	1.0	1.0	1.0	1.0	1.0	0.9
510/526	0.9	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.1	1.0	0.9
511	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.9
515	0.9	0.9	1.0	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.0	0.9
516	0.8	0.9	1.0	1.2	1.0	1.0	1.0	1.1	1.1	1.0	0.9	1.0
520	0.9	0.9	1.0	1.0	1.0	1.1	1.0	1.1	1.0	1.1	1.0	0.9
521	0.8	0.8	0.9	1.1	1.1	1.2	1.2	1.1	1.0	1.0	1.0	0.8
522	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.2	1.1	1.2	1.0	0.8
523	0.9	0.9	1.0	1.1	1.1	1.1	1.1	1.0	1.0	1.1	1.0	0.9
525	0.8	0.9	1.0	1.0	1.1	1.1	1.0	1.1	1.0	1.1	1.0	0.9
529	1.0	1.0	1.0	1.1	1.0	1.1	0.9	1.0	1.0	1.1	1.0	1.0
530	0.9	0.9	1.1	1.1	1.0	1.0	1.0	0.9	1.1	0.9	0.9	1.1
531	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
533	0.7	0.8	1.0	1.2	1.1	1.2	1.3	1.2	1.2	1.2	0.7	0.5
534	0.9	0.9	0.9	1.0	1.1	1.1	1.1	1.1	1.0	1.1	1.0	0.8
535	0.8	1.0	1.1	1.1	1.1	1.1	0.9	0.8	1.1	1.0	1.0	1.1
536	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.0	0.9
537	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.9
538	0.9	1.0	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
539	0.9	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
541	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.1	1.0	1.0
542	0.9	0.9	1.0	1.0	1.1	1.1	1.0	1.1	0.9	1.0	0.9	1.0
543	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.9
546	0.9	1.0	1.1	1.0	1.1	1.0	1.0	1.1	1.0	0.9	0.9	1.0
547	0.9	1.0	1.1	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	0.9
548	0.8	1.0	0.9	1.0	0.9	1.1	0.9	1.0	1.1	1.1	1.2	0.9
549	0.9	1.0	1.0	1.1	1.0	1.1	1.0	1.0	1.0	0.9	0.8	1.1
551	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.9
552	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
553	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9
554	0.9	0.9	1.1	1.1	1.0	1.1	1.0	1.0	1.0	1.1	1.0	0.9
555	1.0	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.0	1.1	0.9	0.9
556	0.9	0.9	1.1	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.0	0.9
557	0.9	0.9	1.1	1.0	1.0	1.1	1.0	1.1	1.0	1.0	1.0	0.9
558	0.9	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	1.0	0.9	0.9
559	0.9	0.9	1.1	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	0.9
560	1.0	1.0	1.1	1.1	1.1	1.2	1.1	1.3	0.9	0.8	0.6	0.8

Table A2-5 Number of Axles for Single and Tandem Axle Types for the 44 WM Sites

	Single										Tandem									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
501/540	1.23	2.00	1.25	1.02	2.39	1.22	1.03	5.00	4.00	1.09	0.77	0.00	0.86	0.33	0.61	1.89	1.35	0.00	1.00	0.58
502	1.19	2.00	1.26	1.05	2.44	1.24	1.02	5.00	4.00	1.53	0.81	0.00	0.87	0.17	0.56	1.88	1.18	0.00	1.00	0.50
503/527	1.70	2.00	1.57	1.27	2.52	1.27	1.00	5.00	4.00	2.23	0.30	0.00	0.68	0.33	0.48	1.87	1.29	0.00	1.00	1.94
504	1.92	2.00	1.17	1.10	2.42	1.23	1.00	5.00	4.00	1.98	0.08	0.00	0.91	0.11	0.58	1.88	1.45	0.00	1.00	2.33
506/544	1.84	2.00	1.13	1.13	2.62	1.15	1.01	5.00	4.00	1.13	0.16	0.00	0.93	0.16	0.39	1.92	1.11	0.00	1.00	0.48
507/545	1.66	2.00	1.26	1.09	2.51	1.15	1.01	5.00	4.00	1.26	0.34	0.00	0.85	0.19	0.49	1.92	1.23	0.00	1.00	0.69
508	1.86	2.00	1.01	1.13	2.37	1.22	1.00	5.00	4.00	1.11	0.14	0.00	0.99	0.10	0.63	1.89	1.40	0.00	1.00	2.79
509	1.89	2.00	1.12	1.05	2.33	1.17	1.00	5.00	4.00	2.31	0.11	0.00	0.94	0.07	0.67	1.91	1.09	0.00	1.00	1.94
510/526	1.74	2.00	1.01	1.25	2.60	1.12	1.03	5.00	4.00	1.21	0.26	0.00	0.99	0.09	0.40	1.94	1.41	0.00	1.00	0.56
511	1.73	2.00	1.00	1.05	2.23	1.22	1.00	5.00	4.00	1.88	0.27	0.00	1.00	0.09	0.77	1.89	0.99	0.00	1.00	1.90
515	1.76	2.00	1.01	1.23	2.34	1.25	1.01	5.00	4.00	2.13	0.24	0.00	0.99	0.22	0.66	1.88	1.28	0.00	1.00	2.40
516	1.95	2.00	1.01	1.02	2.72	1.16	2.20	5.00	4.00	2.50	0.05	0.00	0.99	0.07	0.28	1.80	0.94	0.00	1.00	1.40
520	1.86	2.00	1.01	1.04	2.25	1.18	1.00	5.00	4.00	1.38	0.14	0.00	0.99	0.14	0.75	1.91	1.34	0.00	1.00	1.70
521	1.98	2.00	1.00	1.00	2.89	1.14	1.00	0.00	0.00	1.25	0.02	0.00	1.00	0.28	0.11	1.90	1.45	0.00	0.00	0.50
522	1.80	2.00	1.08	1.01	2.88	1.17	1.01	5.00	4.00	1.05	0.20	0.00	0.95	0.37	0.12	1.91	1.35	0.00	1.00	0.68
523	1.91	2.00	1.02	1.05	2.47	1.19	1.00	4.99	4.00	1.00	0.09	0.00	0.98	0.09	0.52	1.90	1.33	0.01	1.00	1.00
525	1.81	2.00	1.00	1.05	2.25	1.18	1.00	5.00	4.00	1.68	0.19	0.00	1.00	0.05	0.75	1.91	1.03	0.00	1.00	2.60
529	1.91	2.00	1.18	1.02	2.44	1.11	1.01	5.00	4.00	2.06	0.09	0.00	0.91	0.05	0.56	1.94	1.27	0.00	1.00	2.21
530	1.92	2.00	1.12	1.08	2.38	1.22	1.00	5.00	4.00	1.10	0.08	0.00	0.94	0.15	0.62	1.89	0.82	0.00	1.00	0.98
531	1.81	2.00	1.01	1.17	2.20	1.13	1.02	5.00	3.99	2.03	0.19	0.00	0.99	0.39	0.80	1.94	1.23	0.00	1.00	2.47
533	1.92	2.00	1.06	1.00	2.82	1.13	1.01	4.50	4.00	1.09	0.08	0.00	0.96	0.32	0.18	1.93	1.49	0.25	1.00	1.27
534	1.84	2.00	1.16	1.03	2.83	1.22	1.06	5.00	4.00	1.08	0.16	0.00	0.89	0.30	0.17	1.86	1.38	0.00	1.00	0.84
535	1.86	2.00	1.12	1.08	2.91	1.15	1.06	4.87	4.00	1.31	0.14	0.00	0.93	0.43	0.12	1.91	1.41	0.07	1.00	0.50
536	1.74	2.00	1.23	1.20	2.77	1.19	1.11	5.00	4.00	1.30	0.26	0.00	0.86	0.29	0.31	1.90	1.20	0.00	1.00	0.44

Table A2-5 Number of Axles for Single and Tandem Axle Types for the 44 WM Sites (continued)

	Single										Tandem									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
537	1.81	2.00	1.05	1.38	2.62	1.16	1.01	5.00	4.00	1.19	0.19	0.00	0.97	0.12	0.38	1.92	1.31	0.00	1.00	0.67
538	1.81	2.00	1.05	1.38	2.62	1.16	1.01	5.00	4.00	1.19	0.19	0.00	0.97	0.12	0.38	1.92	1.31	0.00	1.00	0.67
539	1.80	2.00	1.21	1.04	2.45	1.19	1.01	5.00	4.00	1.32	0.20	0.00	0.89	0.07	0.55	1.91	1.28	0.00	1.00	0.79
541	1.60	2.00	1.32	1.74	2.85	1.23	1.14	5.00	4.00	1.52	0.40	0.00	0.81	0.48	0.25	1.88	1.24	0.00	1.00	0.55
542	1.85	2.00	1.45	1.06	2.42	1.20	1.00	5.00	4.00	1.12	0.15	0.00	0.75	0.16	0.58	1.90	1.34	0.00	1.00	1.15
543	1.64	2.00	1.24	1.69	2.68	1.21	1.08	5.00	3.99	1.33	0.36	0.00	0.87	0.26	0.36	1.89	1.28	0.00	1.00	0.65
546	1.92	2.00	1.00	1.01	2.25	1.14	1.00	5.00	4.00	1.60	0.08	0.00	1.00	0.06	0.75	1.92	1.23	0.00	1.00	1.27
547	1.86	2.00	1.01	1.04	2.19	1.12	1.01	5.00	4.00	2.22	0.14	0.00	0.99	0.06	0.81	1.94	1.28	0.00	1.00	2.39
548	1.87	2.00	1.25	1.11	2.63	1.07	1.00	5.00	0.00	0.00	0.13	0.00	0.87	0.21	0.37	1.96	1.52	0.00	0.00	0.00
549	1.70	2.00	1.15	1.01	2.37	1.22	1.00	5.00	3.98	1.20	0.30	0.00	0.91	0.08	0.63	1.89	1.40	0.00	0.99	2.90
551	1.90	2.00	1.10	1.25	2.39	1.18	1.00	5.00	4.00	2.00	0.10	0.00	0.95	0.32	0.61	1.91	1.18	0.00	1.00	2.08
552	1.80	2.00	1.00	1.06	2.27	1.17	1.00	5.00	4.00	1.52	0.20	0.00	1.00	0.15	0.73	1.92	1.07	0.00	1.00	2.67
553	1.80	2.00	1.01	1.07	2.16	1.23	1.00	5.00	4.00	2.19	0.20	0.00	0.99	0.08	0.84	1.89	0.97	0.00	1.00	2.41
554	1.88	2.00	1.00	1.01	2.16	1.15	1.00	5.00	4.00	1.71	0.12	0.00	1.00	0.24	0.84	1.92	1.14	0.00	1.00	2.65
555	1.88	2.00	1.00	1.01	2.16	1.15	1.00	5.00	4.00	1.71	0.12	0.00	1.00	0.24	0.84	1.92	1.14	0.00	1.00	2.65
556	1.87	2.00	1.01	1.03	2.41	1.13	1.00	5.00	4.00	1.00	0.13	0.00	0.99	0.20	0.59	1.93	1.65	0.00	1.00	1.67
557	1.83	2.00	1.01	1.14	2.18	1.18	1.01	5.00	4.00	2.14	0.17	0.00	0.99	0.09	0.82	1.91	1.21	0.00	1.00	2.41
558	1.84	2.00	1.01	1.05	2.10	1.11	1.00	5.00	4.00	2.04	0.16	0.00	0.99	0.06	0.90	1.95	1.19	0.00	1.00	2.48
559	1.90	2.00	1.01	1.16	2.21	1.20	1.00	5.00	4.00	2.39	0.10	0.00	0.99	0.14	0.79	1.90	1.32	0.00	1.00	2.27
560	1.87	2.00	1.03	1.08	2.39	1.24	1.00	5.00	4.00	1.57	0.13	0.00	0.97	0.09	0.61	1.88	1.34	0.00	1.00	1.71

Table A2-6 Number of Axles for Tridem and Quad Axle Types for the 44 WM Sites

	Tridem										Quad									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
501/540	0.00	0.00	0.00	0.67	0.00	0.00	0.61	0.00	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.02
502	0.00	0.00	0.00	0.83	0.00	0.00	0.37	0.00	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.25
503/527	0.00	0.00	0.00	0.59	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
504	0.00	0.00	0.00	0.88	0.00	0.00	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
506/544	0.00	0.00	0.00	0.81	0.00	0.00	0.43	0.00	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.03
507/545	0.00	0.00	0.00	0.80	0.00	0.00	0.46	0.00	0.00	1.14	0.00	0.00	0.02	0.00	0.00	0.00	0.17	0.00	0.00	0.11
508	0.00	0.00	0.00	0.86	0.00	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.05
509	0.00	0.00	0.00	0.92	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.06
510/526	0.00	0.00	0.00	0.84	0.00	0.00	0.48	0.00	0.00	1.11	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.25
511	0.00	0.00	0.00	0.90	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.32
515	0.00	0.00	0.00	0.75	0.00	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
516	0.00	0.00	0.00	0.93	0.00	0.02	0.58	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.25
520	0.00	0.00	0.00	0.86	0.00	0.00	0.65	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.51
521	0.00	0.00	0.00	0.72	0.00	0.00	0.54	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75
522	0.00	0.00	0.00	0.62	0.00	0.00	0.51	0.00	0.00	0.83	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.46
523	0.00	0.00	0.00	0.90	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	1.00
525	0.00	0.00	0.00	0.94	0.00	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00
529	0.00	0.00	0.00	0.95	0.00	0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00
530	0.00	0.00	0.00	0.85	0.00	0.00	0.34	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.00	0.00	0.86
531	0.00	0.00	0.00	0.57	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00
533	0.00	0.00	0.00	0.68	0.00	0.00	0.30	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.18
534	0.00	0.00	0.00	0.69	0.00	0.00	0.48	0.00	0.00	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.01
535	0.00	0.00	0.00	0.56	0.00	0.00	0.31	0.00	0.00	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.13
536	0.00	0.00	0.00	0.68	0.00	0.00	0.59	0.00	0.00	1.37	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.09

Table A2-6 Number of Axles for Tridem and Quad Axle Types for the 44 WM Sites (continued)

	Tridem										Quad									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
537	0.00	0.00	0.00	0.78	0.00	0.00	0.66	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.37
538	0.00	0.00	0.00	0.78	0.00	0.00	0.66	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.37
539	0.00	0.00	0.00	0.92	0.00	0.00	0.56	0.00	0.00	1.22	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.05
541	0.00	0.00	0.00	0.33	0.00	0.00	0.60	0.00	0.00	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.22
542	0.00	0.00	0.00	0.84	0.00	0.00	0.59	0.00	0.00	0.34	0.00	0.00	0.01	0.00	0.00	0.00	0.04	0.00	0.00	0.56
543	0.00	0.00	0.00	0.59	0.00	0.00	0.64	0.00	0.00	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.18
546	0.00	0.00	0.00	0.94	0.00	0.00	0.65	0.00	0.00	0.82	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.05
547	0.00	0.00	0.00	0.93	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00
548	0.00	0.00	0.00	0.79	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
549	0.00	0.00	0.00	0.92	0.00	0.00	0.58	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
551	0.00	0.00	0.00	0.67	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.08
552	0.00	0.00	0.00	0.84	0.00	0.00	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.03
553	0.00	0.00	0.00	0.90	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00
554	0.00	0.00	0.00	0.76	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.00
555	0.00	0.00	0.00	0.76	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.00
556	0.00	0.00	0.00	0.79	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.67
557	0.00	0.00	0.00	0.87	0.00	0.00	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.01
558	0.00	0.00	0.00	0.92	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.00
559	0.00	0.00	0.00	0.82	0.00	0.00	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.01
560	0.00	0.00	0.00	0.89	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.43

APPENDIX 3

EXAMPLE TRAFFIC FORECASTING PROBLEM

Traditionally TPB Traffic Forecasters have produced future year AADT estimates for the project highway with and without improvement. They usually do not annualize vehicle classification counts collected in the base year. They express the base year truck class counts as percentages of base year AADT, specifically, percent single unit trucks (Duals) and percent truck tractor single trailer trucks (TTSTs). And they usually carry forward the base year truck percentages of AADT from the base year to the future year without a forecast adjustment unless there is significant reason to do so, like a new truck distribution hub or manufacturing center. Furthermore, the truck counts are not annualized, while the total traffic AADT is (by definition). This inconsistency is overcome when the TPB forecasters assume constant percent Duals and TTSTs from base to future year. The AADT forecasts and the constant base year to future year truck percentages have traditionally been used in North Carolina pavement design.

However, the MEPDG pavement design procedures require forecast values for truck distributions which are truck class percentages based on total truck traffic, not total vehicle AADT traffic (as discussed under “Terminology” in the Executive Summary). MEPDG requires either individual truck class forecasts or aggregate truck class forecasts. This appendix uses aggregate classes for single unit trucks (SUs), which are equivalent to truck classes 4-7 and multiunit trucks (MUs) equivalent to remaining classes 8-13. This appendix discusses forecasts for the truck classes and the growth function to be used in MEPDG pavement design for North Carolina. Furthermore, the appendix develops consistency between annualized traffic forecasts and annualized truck volumes that are used to generate forecasts of truck vehicle class distributions (VCD).

Elizabethtown Bypass, R-522, Bladen County

As an example of the traffic forecasting procedures required for MEPDG consider the Elizabethtown Bypass in Bladen County (Figures A3-1 and A3-2). The following steps use the Elizabethtown R-522 case to illustrate the guidelines of Chapter 5 to develop the MEPDG inputs for pavement design.

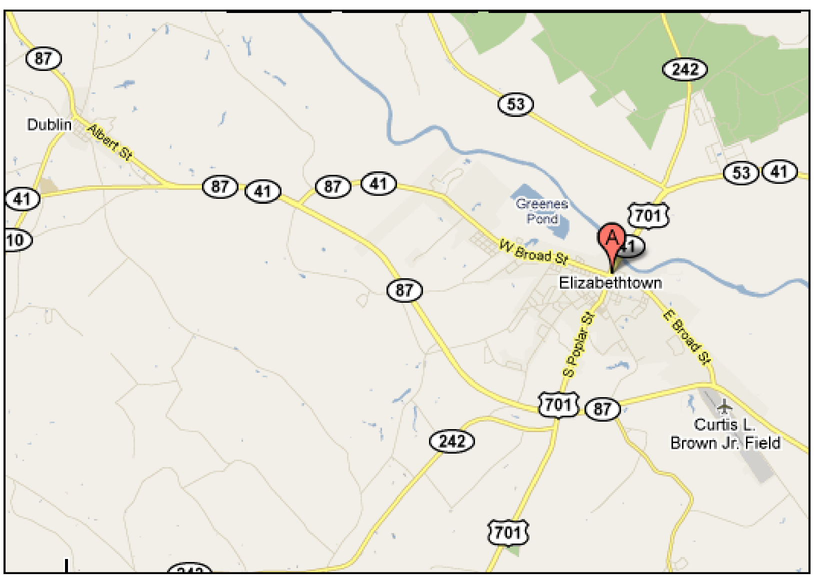

Figure A3-1 Elizabethtown Bypass and Business Routes NC 87 (*Source Google Maps*)

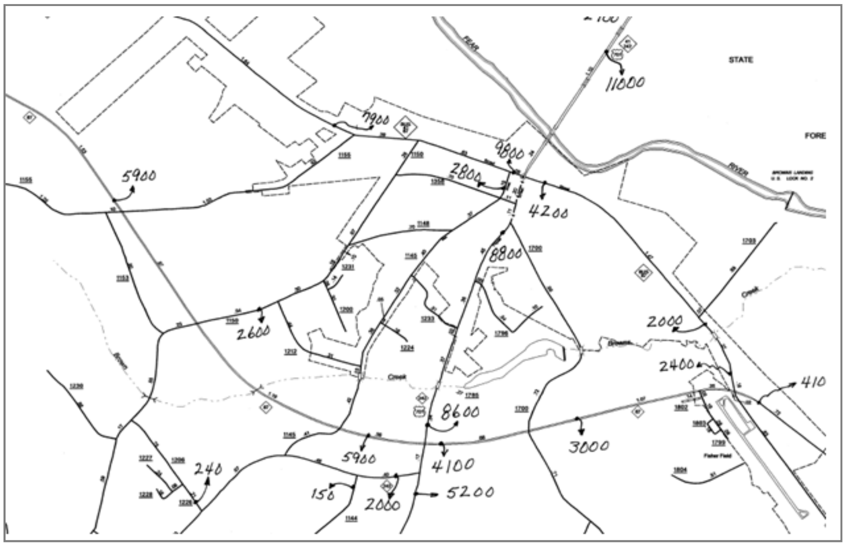

Figure A3-2 Elizabethtown Bypass and Business Routes NC 87 (*Source NCDOT, 2008 AADT*)

1. Discard vehicle classes 1 to 3. For pavement design light weight vehicle classes 1-3 will be ignored. However, light weight vehicles make up the majority of vehicle volumes and will continue to be part of the usual NCDOT forecasts for highway planning and design.

2. Consider two aggregated truck classes. Data analysis for traffic forecasts can be simplified by considering two aggregate truck classes: SU trucks (classes 4-7) and MU trucks (classes 8-13). SU and MU terminology is equivalent to Duals and TTSTs, respectively. Although the SU and MU percentages are still required for the traffic forecast, the more detailed VCD is required for pavement design. VCD are percentages of annualized truck traffic (AADTT), not percentages based on counts (not seasonally factored) as used for DUALs and TTSTs currently. It is recommended that the data used to generate SU (Duals) and MU (TTST) for the traffic forecast be based on the annualized truck volumes that are used to generate VCD. This will provide consistent data for both processes and will support transference of analyses performed for the traffic forecast to the pavement design data and vice versa.

3. Determine the base year traffic without improvement (no-build). Since we do not have the data for NC 87 west of the bypass, we are going to assume it is the sum of the business and bypass volumes. For a forecast like this, the TSG will collect a class count on the existing route where the bypass will meet the business route. We are using the class data as provided. The TSG needs to deliver annualized data to the TPB/TF staff member when this process is implemented. We are using 2008 as the base year and forecasting to 2035 as this is the typical method used in the forecasting process.

Table A3-1 2008 Data - Treated as Annualized Data for Demonstration Purposes

Route	Station	1*	2	3	4	5	6	7	8	9	10	11	12	13	AADTT (sum 4-13)	AADT (sum 1-13)
Bypass	VC0818	1	2012	639	51	143	25	2	59	340	11	1	0	0	632	3284
Business	VC0822	4	2601	855	49	133	60	3	15	13	3	0	0	1	277	3737

* Numbers 1 to 13 corresponds to 13 vehicle classes of FHWA vehicle classification scheme (see Table 3 of Executive Summary).

This combined data set would be representative of the counts collected on the existing facility and is used for the base year below. The combined data would represent the base year traffic without improvement.

Table A3-2 Base Year Traffic without Improvement (No-Build)

Route	1	2	3	4	5	6	7	8	9	10	11	12	13	AADTT	AADT
NC 87	5	4613	1494	100	276	85	5	74	353	14	1	0	1	909	7021
				SU				**MU**							
Truck Percentages				$\frac{100+276+85+5}{7021}=6.6\%$				$\frac{74+353+14+1+0+1}{7021}=6.3\%$							
				4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**		
Vehicle Class Distribution				$\frac{100}{909}=0.11$	0.30	0.09	0.01	0.08	0.39	0.02	0.00	0.00	0.00		

Note: This data must be provided in the report for a vehicle classification count collected by TSG.

4. Determine the base year traffic with improvement (build). Regarding traffic diverted to the bypass from the original business NC 87, Table A3-3 shows that in 2008 90% of the MU trucks, which are primarily on long haul through trips, took the NC 87 Bypass while 10% of the MU trucks stayed on NC 87 Business. On the other hand, 44% of the SU trucks took the bypass and 56% use the original business route through town. This is reasonable since SU trips are shorter and often serve local destinations.

   Such information regarding percentage trips by SU and MU class diverted to a proposed bypass can support refined estimates of traffic forecasts for pavement design purposes. Traffic monitoring of class data should be conducted for small, medium and large sized communities to support a database of bypass diversions for use in the traffic forecasts for similar facilities. The diversion rates included in Table A3-3 are taken from a similar facility bypassing a similar town.

Table A3-3 Diversion Rates

Route	Passenger Vehicles	SU	MU
Bypass	0.39	0.44	0.9
Business	0.61	0.56	0.1

Table A3-4 Calculated NC 87 Bypass Estimate

Route	1	2	3	4	5	6	7	8	9	10	11	12	13	AADTT	AADT
NC 87 Bypass	$0.39 \times 5 = 2$	1799	583	44	121	37	2	67	318	13	1	0	1	604	2988
				SU				**MU**							
Truck Percentages				$\frac{44+12+37+2}{2988}=6.8\%$				$\frac{67+318+13+1+0+1}{2988}=13.4\%$							
				4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**		
Vehicle Class Distribution				$\frac{44}{604}=0.07$	0.20	0.06	0.00	0.11	0.53	0.02	0.00	0.00	0.00		

5. Generate the traffic forecasts required by the MEPDG. After the network traffic estimates have been developed for the base year 2008 build scenario for the bypass, traffic forecasts may be made. The TPB/TF needs to generate the following items required for the mechanistic-empirical pavement design.
   - Base Year AADTT – for total trucks as needed for input into the software
   - Base Year VCD – as needed for input into the software; forecasters can perform their analysis using aggregated classes (SU and MU) but must disaggregate to the ten VCD classes as a last step to provide to the pavement designers
   - Truck Growth Rate(s) – This statistic can be developed using AADT growth (the current practice) aggregated classes (SU and MU), or individual truck classes (the 10 VCD classes)
   - Truck Growth Function – Should be identical to AADT function if AADT growth is used

6. Generate future year traffic with improvement. We consider four growth scenarios to demonstrate the different options and the calculations required to use those options to generate the above mentioned items (base year AADTT, base year VCD, truck growth rate and functions):

Scenario 1 - Match AADT Growth

The TPB/TF forecaster calculates AADT linear growth rates in the area on NC 87 and estimates the average rate to be 2.6% per year. Assume that the investigation of future conditions indicates that the future growth in this area will be similar to historic patterns. The forecaster uses the historic rate to estimate traffic projections. Future truck percentages are the same as base year.

Traffic Forecast Estimates:

Year	**AADT**
2008	$\text{round}(2988) = 3000$
2035	$\text{round}(2988 \times [1 + (2035 - 2008) \times 0.026]) = 5100$

Type	**Truck %**
SU	$\text{round}(6.8\%) = 7\%$
MU	$\text{round}(13.4\%) = 13\%$

Pavement Design Estimates:

2008 AADTT	600									
Class	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
2008 VCD	0.07	0.20	0.06	0.00	0.11	0.53	0.02	0.00	0.00	0.00
Growth Rate	2.6%									
Growth Function	Linear									

Scenario 2 - Adjust Future Year Truck Percentages

The TPB/TF forecaster calculates AADT linear growth rates in the area on NC 87 and estimates the average rate to be 2.6% per year. Assume that the investigation of future conditions indicates that the future growth will deviate significantly from historic patterns. Significant residential development has begun in the area. A number of developers have stated residential developments on the bypass alignment and one includes a shopping center. Future growth is estimated to be 5% compounded annually.

Traffic Forecast Estimates:

Year	**AADT**
2008	$\text{round}(2988) = 3000$
2035	$\text{round}\left(2988 \times [1 + 0.05]^{(2035-2008)}\right) = 11200$

The high truck percentages in the base year imply the high mobility (diversion to the bypass) the improvement has for trucks whereas many passenger vehicles are still attracted to Elizabethtown.

The type of development expected to occur has few trucks and the high volumes in the forecast year will be more passenger vehicle oriented. The forecaster decides to adjust the truck percentages to reflect this trend. The SU trucks will be less impacted by the bypass than MU trucks which make few trips to residential development.

	Base Year	**Adjustment Amount**	**Forecasted Truck%**
SU	7%	-3%	4%
MU	13%	-6%	7%

Pavement Design Estimates:

The adjustment of truck percentages means that the truck growth rates do not match AADT. Additionally, the difference in the adjustment means that the SU growth rate is different from the MU growth rate to obtain this future distribution of trucks.

Base year and future year truck volumes for SU and MU must be calculated to use as the basis for calculating individual growth rates.

	2008	**2035**	**Linear Growth Rates**
SU	$7\% \times 3000 = 210$	$4\% \times 11200 = 448$	$\frac{(448-210)/210}{2035-2008} \times 100 = 4.20\%$
MU	390	784	3.74%

2008 AADTT	600									
Class	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
2008 VCD	0.07	0.20	0.06	0.00	0.11	0.53	0.02	0.00	0.00	0.00
Class Group	SU				MU					
Growth Rate	4.2%				3.8%					
Growth Function	Linear				Linear					

Scenario 3 - Calculation Based Truck Growth Rates

The forecaster calculates AADT linear growth rates in the area on NC 87 and estimates the average rate to be 2.6% per year. Investigation of plans for the area indicates that the future growth in this area will be similar to historic patterns. The forecaster uses the historic rate to estimate AADT projections.

The forecaster finds current and historic vehicle classification data on the NC 87 corridor. They perform a trend analysis on historic truck growth patterns for SU and MU truck groups. The data shows that linear growth rates are 2.5% for SU and 2.0% for MU. Plans for the area indicate that truck growth will be similar to historic patterns.

In this scenario, the forecaster has an estimate of individual growth rates for AADT, SU, and MU. Although they have base year truck percentages, they don't know what impact the different growth rates will have on future truck percentages. The forecaster must calculate future AADT, SU, and MU volumes to calculate the future truck percentages needed in the traffic forecast.

Traffic Forecast Estimates:

Year	AADT
2008	$\text{round}(2988) = 3000$
2035	$\text{round}(2988 \times [1 + (2035 - 2008) \times 0.026]) = 5100$

Type	Linear Growth Rate	2008	2035	Truck %
SU	2.50%	$44 + 121 + 37 + 2 = 204$	$204 \times [1 + (2035 - 2008) \times 2.5\%] = 342$	$\frac{342}{5100} \times 100 = 7\%$
MU	2.00%	$67 + 318 + 13 + 1 + 0 + 1 = 400$	$400 \times [1 + (2035 - 2008) \times 2.0\%] = 616$	$\frac{616}{5100} \times 100 = 12\%$

Pavement Design Estimates:

2008 AADTT	600									
Class	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
2008 VCD	0.07	0.20	0.06	0.00	0.11	0.53	0.02	0.00	0.00	0.00
Class Group	SU				MU					
Growth Rate	2.5%				2.1%					
Growth Function	Linear				Linear					

Scenario 4 - Adjustment of Individual Classes

The forecaster calculates AADT linear growth rates in the area on NC 87 and estimates the average rate to be 2.6% per year. Investigation of plans for the area uncovers a development in progress for a FedEx distribution center to be built at the east end of the bypass. A traffic impact analysis was performed as part of the permitting process providing detailed analysis of traffic with the facility including an estimate of the number of trips on the bypass for the specific vehicle types used by FedEx. These are:

Type	**Trips**
Class 5	800
Class 8	150
Class 11	50
Total	1000

Based on the study and the anticipation that related development for the area will increase the forecaster estimates AADT will grow at 3.3% per year linearly.

The forecaster estimates growth in background truck volumes will be the same. The forecaster must add the FedEx truck trips to the future background trucks to generate both future truck percentages for the forecast and the individual growth rates for each vehicle class.

Truck Analysis by Class:

Class	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
2008 Trucks	44	121	37	2	67	318	13	1	0	1
Linear GR	3.3%	3.3%	3.3%	3.3%	3.3%	3.3%	3.3%	3.3%	3.3%	3.3%
2035 Trucks	83	229	70	4	127	601	25	2	0	2
FedEx Trucks		800			150			50		
Adj. 2035 Trucks	83	800+229= 1029	70	4	127+150= 277	601	25	50+2= 52	0	2
Adj. Linear GR	3.3%	27.8%	3.3%	3.3%	11.6%	3.3%	3.3%	188.9%	3.3%	3.3%

Traffic Forecast Estimates:

Year	**Base**	**FedEx**	**Adjusted**
2008	3000		3000
2035	5700	1000	5700+1000 = 6700

	2035	**FedEx**	**2035 Adj.**	**Truck%**
SU	386	800	1186	$\frac{1186}{6700} \times 100 = 18\%$
MU	757	200	957	14%

Pavement Design Estimate

2008 AADTT	600									
Class	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
2008 VCD	0.073	0.200	0.061	0.003	0.111	0.526	0.022	0.002	0.000	0.002
Growth Rate	3.3%	27.8%	3.3%	3.3%	11.6%	3.3%	3.3%	188.9%	3.3%	3.3%
Growth Function	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear

The issue here is the VCD for Class 11 rounds to zero when given to two places. The VCD was rounded to three places to ensure Class 11 volumes are estimated properly. Rounding of the MEPDG inputs needs to be addressed.

APPENDIX 4

DAMAGE FACTORS DEVELOPED FOR FOUR AXLE TYPES FOR THE 44 WIM SITES

Table 4A-1 Single Axle Damage Factors

Site ID	Axle Load (kip)																			
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
502	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
504	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
508	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
509	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
511	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
515	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
516	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
520	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
523	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
525	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.77	1.00	1.22	1.50	1.83	2.21
529	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
530	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
531	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
539	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
542	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
546	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
547	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
548	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
549	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
551	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
552	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
553	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
554	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
555	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
556	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
557	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
558	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
559	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
560	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
537	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
538	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
521	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.13	0.19	0.26	0.36	0.48	0.62	0.79	1.00	1.25	1.53	1.87	2.26
522	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
533	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
534	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
535	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.51	1.84	2.22
536	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
541	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
543	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
501/540	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
503/527	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.21
545/507	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
506/544	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22
510/526	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.61	0.78	1.00	1.22	1.50	1.83	2.22

Table 4A-2 Single Axle Damage Factors (continued)

Site ID	Axle Load (kip)																		
	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
502	2.65	3.16	3.73	4.37	5.16	5.91	6.81	7.82	8.93	10.17	11.52	13.01	14.63	16.32	18.34	20.45	22.72	25.19	27.48
504	2.65	3.16	3.73	4.37	5.15	5.91	6.81	7.82	8.93	10.16	11.52	13.01	14.63	16.31	18.34	20.44	22.72	25.19	27.51
508	2.65	3.15	3.72	4.36	5.14	5.90	6.80	7.80	8.92	10.15	11.50	12.98	14.60	16.29	18.31	20.40	22.67	25.13	27.43
509	2.66	3.16	3.73	4.38	5.16	5.92	6.82	7.83	8.95	10.18	11.54	13.03	14.66	16.36	18.37	20.48	22.76	25.23	27.55
511	2.65	3.15	3.72	4.36	5.13	5.90	6.80	7.81	8.92	10.16	11.51	12.99	14.62	16.33	18.33	20.43	22.71	25.17	27.48
515	2.65	3.15	3.72	4.36	5.14	5.90	6.80	7.81	8.92	10.15	11.50	12.98	14.61	16.31	18.31	20.40	22.68	25.13	27.43
516	2.66	3.16	3.73	4.38	5.16	5.92	6.82	7.83	8.95	10.18	11.54	13.03	14.66	16.38	18.38	20.48	22.77	25.23	27.52
520	2.66	3.16	3.73	4.38	5.16	5.92	6.82	7.83	8.95	10.18	11.54	13.03	14.66	16.35	18.37	20.48	22.76	25.23	27.58
523	2.65	3.16	3.73	4.37	5.16	5.91	6.81	7.82	8.94	10.17	11.52	13.01	14.64	16.33	18.35	20.45	22.73	25.19	27.48
525	2.65	3.15	3.71	4.36	5.13	5.89	6.79	7.79	8.91	10.13	11.48	12.96	14.59	16.25	18.28	20.38	22.65	25.10	27.40
529	2.65	3.15	3.72	4.37	5.15	5.90	6.81	7.82	8.93	10.16	11.52	13.01	14.63	16.34	18.34	20.44	22.72	25.19	27.48
530	2.66	3.16	3.73	4.38	5.17	5.92	6.83	7.84	8.96	10.19	11.55	13.04	14.67	16.40	18.39	20.50	22.78	25.26	27.53
531	2.65	3.16	3.72	4.37	5.14	5.90	6.81	7.81	8.93	10.16	11.51	13.00	14.62	16.33	18.33	20.43	22.70	25.16	27.46
539	2.65	3.15	3.72	4.37	5.15	5.90	6.80	7.81	8.92	10.15	11.50	12.99	14.61	16.34	18.32	20.41	22.68	25.14	27.37
542	2.65	3.16	3.73	4.37	5.16	5.91	6.81	7.82	8.93	10.17	11.52	13.01	14.63	16.33	18.34	20.44	22.72	25.18	27.46
546	2.66	3.16	3.73	4.37	5.16	5.91	6.82	7.82	8.94	10.17	11.53	13.02	14.64	16.32	18.36	20.46	22.74	25.21	27.54
547	2.65	3.16	3.72	4.37	5.15	5.90	6.81	7.82	8.93	10.16	11.51	13.00	14.62	16.33	18.33	20.43	22.70	25.17	27.43
548	2.65	3.15	3.72	4.37	5.14	5.90	6.81	7.81	8.93	10.16	11.51	12.99	14.62	16.32	18.32	20.42	22.69	25.15	27.46
549	2.65	3.15	3.72	4.37	5.14	5.90	6.81	7.82	8.93	10.16	11.52	13.00	14.63	16.32	18.34	20.44	22.72	25.18	27.51
551	2.65	3.15	3.72	4.37	5.14	5.90	6.81	7.82	8.93	10.16	11.52	13.00	14.63	16.33	18.34	20.44	22.72	25.18	27.48
552	2.66	3.16	3.73	4.37	5.17	5.91	6.82	7.83	8.95	10.18	11.54	13.03	14.65	16.34	18.37	20.48	22.76	25.23	27.52
553	2.65	3.15	3.72	4.37	5.14	5.90	6.81	7.81	8.93	10.16	11.51	13.00	14.62	16.33	18.33	20.43	22.71	25.17	27.45
554	2.65	3.15	3.72	4.36	5.14	5.90	6.80	7.81	8.92	10.15	11.51	12.99	14.62	16.30	18.32	20.42	22.70	25.16	27.46
555	2.66	3.16	3.73	4.37	5.15	5.91	6.82	7.82	8.94	10.17	11.53	13.02	14.64	16.36	18.36	20.46	22.74	25.20	27.48
556	2.65	3.15	3.72	4.37	5.15	5.90	6.81	7.81	8.93	10.16	11.51	12.99	14.62	16.33	18.32	20.42	22.70	25.16	27.44
557	2.65	3.15	3.72	4.37	5.14	5.90	6.80	7.81	8.92	10.15	11.51	12.99	14.61	16.30	18.32	20.42	22.69	25.15	27.48
558	2.66	3.16	3.73	4.37	5.16	5.91	6.82	7.82	8.94	10.17	11.53	13.01	14.64	16.31	18.35	20.46	22.74	25.20	27.54
559	2.65	3.16	3.73	4.37	5.15	5.91	6.81	7.82	8.94	10.17	11.52	13.01	14.64	16.37	18.35	20.45	22.73	25.20	27.43
560	2.65	3.15	3.72	4.36	5.14	5.90	6.80	7.81	8.92	10.15	11.51	12.99	14.62	16.33	18.32	20.42	22.69	25.15	27.41
537	2.66	3.16	3.73	4.38	5.15	5.91	6.82	7.83	8.95	10.18	11.54	13.03	14.66	16.36	18.37	20.48	22.76	25.23	27.55
538	2.65	3.16	3.73	4.37	5.15	5.91	6.81	7.82	8.94	10.17	11.53	13.01	14.64	16.35	18.35	20.46	22.74	25.20	27.50
521	2.71	3.21	3.77	4.43	5.15	5.96	6.87	7.85	8.96	10.17	11.51	12.98	14.58	16.32	18.22	20.31	22.44	24.95	27.47
522	2.66	3.16	3.73	4.38	5.15	5.92	6.82	7.83	8.95	10.18	11.54	13.03	14.66	16.34	18.38	20.49	22.78	25.25	27.64
533	2.65	3.15	3.72	4.37	5.15	5.90	6.81	7.81	8.93	10.16	11.51	13.00	14.62	16.32	18.33	20.43	22.71	25.17	27.44
534	2.65	3.15	3.72	4.37	5.17	5.91	6.81	7.82	8.93	10.16	11.52	13.01	14.63	16.31	18.34	20.45	22.72	25.19	27.45
535	2.66	3.16	3.74	4.38	5.17	5.92	6.83	7.84	8.96	10.20	11.55	13.05	14.68	16.37	18.40	20.51	22.79	25.27	27.61
536	2.65	3.15	3.72	4.36	5.15	5.90	6.80	7.81	8.92	10.15	11.50	12.99	14.61	16.31	18.32	20.42	22.69	25.15	27.43
541	2.65	3.16	3.73	4.37	5.14	5.91	6.82	7.82	8.94	10.17	11.53	13.02	14.65	16.34	18.36	20.46	22.74	25.21	27.55
543	2.65	3.15	3.72	4.36	5.14	5.90	6.80	7.81	8.92	10.15	11.51	12.99	14.62	16.30	18.32	20.42	22.70	25.16	27.46
501/540	2.65	3.15	3.72	4.37	5.15	5.90	6.81	7.81	8.93	10.16	11.51	13.00	14.62	16.31	18.33	20.43	22.70	25.16	27.47
503/527	2.65	3.15	3.72	4.37	5.14	5.90	6.81	7.82	8.93	10.16	11.52	13.00	14.63	16.33	18.34	20.44	22.72	25.18	27.50
545/507	2.65	3.16	3.73	4.37	5.15	5.91	6.81	7.82	8.93	10.16	11.52	13.00	14.63	16.34	18.34	20.44	22.72	25.18	27.47
506/544	2.65	3.16	3.72	4.37	5.15	5.91	6.81	7.82	8.93	10.16	11.52	13.00	14.63	16.34	18.34	20.44	22.72	25.18	27.48
510/526	2.66	3.16	3.73	4.37	5.16	5.91	6.82	7.83	8.95	10.18	11.54	13.03	14.66	16.34	18.37	20.48	22.76	25.23	27.56

Table 4A-3 Tandem Axle Damage Factors

Site ID	Axle Load (kip)																				
	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46
502	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.37	0.50	0.64	0.82	1.04	1.29	1.59	1.97	2.34	2.81
504	0.00	0.00	0.00	0.01	0.03	0.07	0.14	0.21	0.31	0.45	0.62	0.84	1.13	1.44	1.84	2.33	2.90	3.57	4.41	5.26	6.30
508	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.37	0.50	0.64	0.82	1.04	1.30	1.60	1.98	2.35	2.82
509	0.00	0.00	0.00	0.01	0.03	0.08	0.16	0.25	0.37	0.52	0.72	0.98	1.31	1.68	2.15	2.71	3.37	4.15	5.14	6.12	7.33
511	0.00	0.00	0.00	0.01	0.03	0.07	0.15	0.23	0.34	0.49	0.68	0.92	1.23	1.58	2.02	2.54	3.17	3.91	4.82	5.75	6.89
515	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.46	0.59	0.75	0.95	1.19	1.46	1.81	2.15	2.58
516	0.00	0.00	0.00	0.01	0.03	0.07	0.15	0.24	0.35	0.50	0.69	0.94	1.26	1.61	2.06	2.60	3.24	3.99	4.93	5.88	7.05
520	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.11	0.16	0.22	0.31	0.42	0.57	0.72	0.93	1.17	1.46	1.79	2.22	2.64	3.17
523	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.21	0.30	0.41	0.56	0.75	0.96	1.23	1.55	1.93	2.38	2.95	3.50	4.20
525	0.00	0.00	0.00	0.01	0.02	0.05	0.11	0.17	0.26	0.36	0.51	0.68	0.92	1.17	1.50	1.90	2.36	2.91	3.60	4.28	5.13
529	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.08	0.12	0.17	0.24	0.32	0.43	0.56	0.71	0.90	1.12	1.38	1.70	2.03	2.43
530	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.60	0.77	0.97	1.21	1.49	1.84	2.19	2.62
531	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.60	0.76	0.96	1.20	1.48	1.83	2.17	2.61
539	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.23	0.31	0.42	0.54	0.68	0.86	1.08	1.33	1.64	1.95	2.34
542	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.15	0.21	0.30	0.42	0.57	0.76	0.98	1.25	1.58	1.97	2.43	3.00	3.58	4.29
546	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.12	0.18	0.25	0.35	0.48	0.64	0.82	1.05	1.32	1.64	2.02	2.50	2.98	3.57
547	0.00	0.00	0.00	0.01	0.02	0.05	0.10	0.15	0.22	0.31	0.44	0.59	0.79	1.01	1.30	1.64	2.04	2.51	3.10	3.70	4.43
548	0.00	0.00	0.00	0.01	0.02	0.05	0.11	0.17	0.25	0.36	0.50	0.67	0.90	1.15	1.47	1.86	2.31	2.85	3.52	4.20	5.03
549	0.00	0.00	0.00	0.01	0.02	0.05	0.11	0.17	0.26	0.37	0.51	0.69	0.92	1.18	1.51	1.90	2.37	2.92	3.61	4.30	5.15
551	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.21	0.30	0.42	0.57	0.76	0.97	1.25	1.57	1.96	2.41	2.99	3.55	4.26
552	0.00	0.00	0.00	0.01	0.02	0.05	0.10	0.16	0.23	0.33	0.46	0.62	0.83	1.07	1.37	1.72	2.14	2.64	3.26	3.89	4.66
553	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.23	0.32	0.42	0.55	0.70	0.88	1.10	1.35	1.67	1.99	2.38
554	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.23	0.32	0.42	0.54	0.70	0.88	1.10	1.35	1.67	1.99	2.38
555	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.13	0.20	0.28	0.39	0.53	0.71	0.91	1.16	1.47	1.83	2.25	2.78	3.31	3.97
556	0.00	0.00	0.00	0.01	0.02	0.04	0.07	0.11	0.17	0.24	0.33	0.45	0.60	0.77	0.99	1.25	1.55	1.91	2.37	2.82	3.38
557	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.51	0.66	0.84	1.06	1.32	1.63	2.02	2.40	2.88
558	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.12	0.18	0.26	0.36	0.49	0.65	0.84	1.07	1.35	1.69	2.08	2.57	3.06	3.67
559	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.45	0.58	0.74	0.94	1.17	1.44	1.78	2.12	2.54
560	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.10	0.15	0.22	0.30	0.41	0.55	0.70	0.90	1.13	1.41	1.74	2.15	2.56	3.07
537	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.20	0.28	0.39	0.53	0.71	0.91	1.17	1.47	1.84	2.26	2.80	3.33	3.99
538	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.14	0.19	0.27	0.36	0.49	0.62	0.80	1.00	1.25	1.54	1.91	2.27	2.72
521	0.00	0.00	0.01	0.02	0.03	0.05	0.09	0.14	0.21	0.30	0.41	0.56	0.74	0.96	1.23	1.55	1.93	2.38	2.90	3.48	4.18
522	0.00	0.00	0.00	0.01	0.02	0.05	0.10	0.15	0.22	0.32	0.44	0.59	0.79	1.02	1.30	1.64	2.04	2.52	3.12	3.71	4.44
533	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.20	0.29	0.40	0.55	0.73	0.94	1.20	1.52	1.89	2.33	2.87	3.43	4.11
534	0.00	0.00	0.00	0.01	0.02	0.05	0.10	0.16	0.23	0.33	0.46	0.63	0.84	1.08	1.38	1.74	2.17	2.67	3.30	3.93	4.71
535	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.20	0.29	0.40	0.54	0.73	0.93	1.20	1.51	1.88	2.31	2.86	3.41	4.08
536	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.20	0.29	0.40	0.54	0.72	0.93	1.19	1.50	1.86	2.30	2.83	3.38	4.05
541	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.23	0.31	0.42	0.54	0.69	0.87	1.08	1.33	1.65	1.96	2.35
543	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.51	0.66	0.84	1.06	1.32	1.63	2.02	2.40	2.88
501/540	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.51	0.65	0.83	1.05	1.31	1.61	2.00	2.38	2.85
503/527	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.09	0.13	0.18	0.25	0.34	0.45	0.58	0.74	0.93	1.16	1.43	1.77	2.11	2.52
545/507	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.08	0.12	0.18	0.24	0.33	0.44	0.56	0.72	0.91	1.14	1.40	1.73	2.06	2.47
506/544	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.09	0.13	0.18	0.25	0.34	0.45	0.58	0.74	0.94	1.17	1.44	1.78	2.12	2.54
510/526	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.13	0.19	0.26	0.37	0.49	0.66	0.85	1.09	1.37	1.71	2.11	2.61	3.10	3.72

Table 4A-4 Tandem Axle Damage Factors (continued)

Site ID	Axle Load (kip)																	
	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82
502	3.34	3.94	4.62	5.42	6.25	7.20	8.27	9.45	10.75	12.14	13.75	15.47	17.35	19.39	21.61	24.02	26.62	28.99
504	7.49	8.85	10.38	12.17	14.02	16.18	18.57	21.21	24.14	27.34	30.88	34.74	38.96	43.55	48.54	53.94	59.79	65.08
508	3.35	3.95	4.64	5.43	6.27	7.23	8.30	9.48	10.79	12.19	13.80	15.53	17.41	19.46	21.69	24.11	26.72	29.10
509	8.72	10.29	12.07	14.17	16.30	18.80	21.58	24.66	28.05	31.72	35.89	40.38	45.27	50.60	56.40	62.67	69.47	75.50
511	8.20	9.67	11.35	13.32	15.34	17.69	20.30	23.19	26.39	29.82	33.76	37.99	42.60	47.62	53.07	58.98	65.37	71.24
515	3.07	3.62	4.25	5.00	5.74	6.62	7.60	8.68	9.88	11.17	12.64	14.22	15.94	17.82	19.86	22.08	24.47	26.58
516	8.38	9.89	11.60	13.62	15.67	18.08	20.75	23.70	26.97	30.48	34.50	38.81	43.52	48.64	54.21	60.24	66.77	72.76
520	3.77	4.44	5.21	6.12	7.05	8.13	9.33	10.66	12.13	13.70	15.52	17.46	19.58	21.89	24.39	27.11	30.05	32.74
523	4.99	5.89	6.91	8.11	9.34	10.77	12.36	14.12	16.06	18.15	20.55	23.12	25.93	28.98	32.30	35.89	39.78	43.24
525	6.10	7.20	8.45	9.90	11.42	13.17	15.11	17.26	19.64	22.21	25.13	28.27	31.70	35.43	39.48	43.88	48.63	52.98
529	2.89	3.41	4.00	4.69	5.40	6.23	7.15	8.17	9.29	10.52	11.89	13.38	15.00	16.77	18.68	20.76	23.02	25.05
530	3.12	3.68	4.32	5.07	5.83	6.73	7.72	8.82	10.04	11.33	12.84	14.45	16.20	18.11	20.18	22.43	24.86	27.07
531	3.10	3.66	4.29	5.04	5.79	6.68	7.67	8.76	9.97	11.27	12.75	14.35	16.09	17.98	20.04	22.27	24.69	26.84
539	2.78	3.28	3.85	4.53	5.21	6.01	6.89	7.88	8.96	10.14	11.47	12.90	14.47	16.17	18.02	20.03	22.20	24.15
542	5.09	6.01	7.05	8.28	9.53	10.99	12.62	14.42	16.41	18.51	20.99	23.61	26.48	29.60	32.99	36.66	40.64	44.31
546	4.25	5.01	5.88	6.90	7.95	9.17	10.52	12.02	13.68	15.44	17.50	19.68	22.07	24.67	27.50	30.56	33.87	36.93
547	5.27	6.22	7.30	8.56	9.86	11.37	13.05	14.91	16.97	19.18	21.71	24.42	27.38	30.61	34.11	37.91	42.02	45.80
548	5.98	7.05	8.27	9.71	11.18	12.89	14.79	16.90	19.23	21.75	24.60	27.67	31.02	34.68	38.64	42.94	47.60	51.75
549	6.13	7.23	8.48	9.95	11.46	13.22	15.17	17.33	19.72	22.30	25.23	28.38	31.82	35.57	39.64	44.06	48.83	53.11
551	5.06	5.97	7.01	8.24	9.47	10.92	12.53	14.32	16.29	18.42	20.85	23.45	26.30	29.39	32.76	36.41	40.35	43.88
552	5.54	6.54	7.67	9.00	10.37	11.96	13.72	15.68	17.83	20.18	22.82	25.67	28.78	32.17	35.85	39.84	44.16	48.04
553	2.83	3.34	3.92	4.60	5.30	6.11	7.01	8.01	9.11	10.29	11.65	13.11	14.70	16.43	18.31	20.35	22.55	24.57
554	2.83	3.34	3.92	4.60	5.29	6.10	7.01	8.01	9.11	10.29	11.65	13.11	14.70	16.43	18.31	20.35	22.55	24.57
555	4.72	5.57	6.54	7.69	8.84	10.19	11.70	13.37	15.21	17.20	19.46	21.90	24.56	27.45	30.60	34.01	37.70	40.98
556	4.02	4.74	5.56	6.52	7.51	8.66	9.94	11.36	12.92	14.62	16.53	18.60	20.85	23.31	25.98	28.87	32.00	34.83
557	3.42	4.04	4.74	5.56	6.41	7.39	8.48	9.69	11.03	12.45	14.11	15.88	17.81	19.91	22.19	24.66	27.33	29.81
558	4.36	5.15	6.04	7.08	8.16	9.41	10.80	12.34	14.04	15.90	17.97	20.21	22.67	25.34	28.24	31.38	34.79	37.87
559	3.02	3.57	4.18	4.91	5.65	6.52	7.48	8.55	9.72	10.98	12.44	14.00	15.70	17.54	19.55	21.73	24.09	26.22
560	3.65	4.31	5.05	5.94	6.83	7.88	9.04	10.33	11.75	13.27	15.03	16.91	18.97	21.20	23.63	26.26	29.10	31.70
537	4.75	5.60	6.57	7.71	8.88	10.24	11.75	13.43	15.28	17.27	19.55	21.99	24.66	27.56	30.72	34.14	37.84	41.18
538	3.23	3.81	4.47	5.25	6.05	6.97	8.00	9.14	10.40	11.76	13.31	14.97	16.79	18.76	20.91	23.24	25.76	28.04
521	4.95	5.84	6.85	7.97	9.23	10.64	12.19	13.89	15.78	17.85	20.12	22.63	25.34	28.24	31.53	34.82	38.68	42.55
522	5.28	6.24	7.31	8.59	9.88	11.40	13.08	14.95	17.00	19.21	21.75	24.47	27.44	30.67	34.18	37.99	42.10	45.80
533	4.88	5.76	6.76	7.93	9.13	10.54	12.09	13.82	15.72	17.74	20.11	22.63	25.37	28.36	31.61	35.13	38.94	42.48
534	5.60	6.61	7.75	9.08	10.47	12.08	13.87	15.84	18.02	20.37	23.06	25.94	29.09	32.52	36.24	40.28	44.64	48.71
535	4.86	5.73	6.72	7.89	9.09	10.48	12.03	13.74	15.64	17.70	20.01	22.51	25.24	28.21	31.44	34.95	38.74	42.12
536	4.82	5.69	6.67	7.83	9.02	10.40	11.93	13.64	15.51	17.57	19.85	22.33	25.04	27.99	31.20	34.67	38.43	41.85
541	2.80	3.30	3.87	4.55	5.23	6.03	6.93	7.91	9.00	10.17	11.52	12.96	14.53	16.24	18.10	20.12	22.30	24.28
543	3.42	4.04	4.73	5.55	6.40	7.38	8.46	9.67	11.00	12.43	14.08	15.84	17.76	19.85	22.12	24.58	27.24	29.65
501/540	3.39	4.00	4.69	5.50	6.34	7.31	8.39	9.59	10.91	12.34	13.95	15.70	17.60	19.68	21.93	24.37	27.02	29.40
503/527	3.00	3.54	4.15	4.88	5.61	6.47	7.43	8.49	9.65	10.92	12.35	13.89	15.58	17.41	19.41	21.57	23.90	25.99
545/507	2.93	3.46	4.06	4.76	5.49	6.33	7.27	8.30	9.45	10.68	12.08	13.60	15.24	17.04	18.99	21.11	23.39	25.48
506/544	3.02	3.56	4.18	4.90	5.65	6.51	7.48	8.54	9.72	10.99	12.44	14.00	15.69	17.54	19.55	21.73	24.09	26.24
510/526	4.42	5.22	6.12	7.18	8.27	9.53	10.94	12.50	14.22	16.08	18.19	20.47	22.95	25.65	28.59	31.77	35.22	38.32

Table 4A-5 Tridem Axle Damage Factors

Site ID	Axle Load (kip)																
	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60
502	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.21	0.29	0.40	0.55	0.73	0.94	1.21	1.52	1.92	2.34
504	0.00	0.01	0.02	0.06	0.14	0.33	0.51	0.76	1.08	1.50	2.05	2.68	3.49	4.46	5.63	7.11	8.65
508	0.00	0.00	0.00	0.01	0.04	0.08	0.13	0.18	0.26	0.37	0.50	0.65	0.85	1.09	1.37	1.73	2.11
509	0.00	0.01	0.04	0.11	0.28	0.63	0.99	1.45	2.07	2.87	3.93	5.14	6.68	8.55	10.79	13.64	16.58
511	0.00	0.01	0.03	0.08	0.20	0.47	0.73	1.08	1.53	2.13	2.91	3.81	4.95	6.34	8.00	10.09	12.29
515	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.23	0.31	0.43	0.56	0.73	0.93	1.17	1.48	1.80
516	0.00	0.01	0.04	0.11	0.29	0.67	1.05	1.54	2.20	3.05	4.18	5.47	7.11	9.10	11.48	14.48	17.64
520	0.00	0.00	0.01	0.02	0.04	0.09	0.15	0.22	0.31	0.43	0.59	0.77	1.00	1.28	1.62	2.04	2.49
523	0.00	0.00	0.01	0.02	0.06	0.14	0.22	0.32	0.46	0.63	0.86	1.13	1.47	1.88	2.37	3.00	3.65
525	0.00	0.00	0.01	0.03	0.07	0.17	0.27	0.39	0.56	0.77	1.06	1.38	1.80	2.31	2.91	3.67	4.47
529	0.00	0.00	0.00	0.01	0.03	0.07	0.10	0.15	0.21	0.30	0.40	0.53	0.69	0.88	1.12	1.41	1.71
530	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.23	0.32	0.44	0.58	0.75	0.97	1.22	1.54	1.87
531	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.23	0.32	0.43	0.57	0.74	0.95	1.19	1.51	1.83
539	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.50	0.64	0.83	1.04	1.31	1.60
542	0.00	0.00	0.01	0.02	0.06	0.14	0.23	0.33	0.47	0.66	0.90	1.18	1.53	1.96	2.47	3.12	3.80
546	0.00	0.00	0.01	0.02	0.05	0.12	0.18	0.27	0.38	0.53	0.72	0.94	1.22	1.57	1.98	2.49	3.04
547	0.00	0.00	0.01	0.03	0.07	0.15	0.23	0.35	0.49	0.68	0.93	1.22	1.59	2.04	2.57	3.25	3.95
548	0.00	0.00	0.01	0.03	0.07	0.17	0.26	0.39	0.55	0.76	1.04	1.37	1.78	2.28	2.87	3.62	4.41
549	0.00	0.00	0.01	0.03	0.07	0.17	0.27	0.39	0.56	0.78	1.06	1.39	1.81	2.31	2.92	3.68	4.49
551	0.00	0.00	0.01	0.02	0.06	0.14	0.22	0.33	0.47	0.65	0.89	1.16	1.51	1.94	2.45	3.08	3.76
552	0.00	0.00	0.01	0.03	0.07	0.16	0.25	0.36	0.52	0.72	0.98	1.28	1.67	2.14	2.70	3.41	4.14
553	0.00	0.00	0.00	0.01	0.03	0.07	0.10	0.15	0.22	0.31	0.42	0.55	0.71	0.91	1.15	1.45	1.77
554	0.00	0.00	0.00	0.01	0.03	0.07	0.10	0.15	0.22	0.30	0.41	0.54	0.70	0.90	1.13	1.43	1.74
555	0.00	0.00	0.01	0.02	0.06	0.13	0.20	0.30	0.43	0.59	0.81	1.06	1.38	1.76	2.22	2.81	3.42
556	0.00	0.00	0.01	0.02	0.05	0.11	0.16	0.24	0.35	0.48	0.66	0.86	1.12	1.43	1.81	2.28	2.77
557	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.21	0.30	0.42	0.57	0.75	0.97	1.24	1.57	1.98	2.41
558	0.00	0.00	0.01	0.02	0.05	0.12	0.19	0.27	0.39	0.54	0.74	0.97	1.26	1.62	2.04	2.57	3.13
559	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.23	0.32	0.44	0.58	0.76	0.97	1.22	1.54	1.87
560	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.21	0.30	0.41	0.56	0.74	0.96	1.23	1.55	1.96	2.39
537	0.00	0.00	0.01	0.02	0.06	0.13	0.21	0.30	0.43	0.60	0.82	1.08	1.40	1.79	2.26	2.85	3.48
538	0.00	0.00	0.00	0.01	0.04	0.08	0.13	0.19	0.27	0.37	0.50	0.66	0.86	1.10	1.39	1.75	2.13
521	0.00	0.01	0.03	0.05	0.09	0.14	0.22	0.33	0.47	0.65	0.88	1.17	1.53	1.95	2.46	3.08	3.77
522	0.00	0.00	0.01	0.03	0.07	0.16	0.25	0.36	0.52	0.72	0.99	1.29	1.68	2.15	2.71	3.41	4.17
533	0.00	0.00	0.01	0.02	0.06	0.14	0.22	0.33	0.46	0.64	0.88	1.15	1.50	1.92	2.42	3.05	3.71
534	0.00	0.00	0.01	0.03	0.07	0.16	0.25	0.36	0.52	0.72	0.98	1.28	1.67	2.14	2.70	3.40	4.14
535	0.00	0.00	0.01	0.02	0.06	0.14	0.21	0.31	0.44	0.61	0.84	1.10	1.43	1.83	2.31	2.91	3.54
536	0.00	0.00	0.01	0.02	0.06	0.13	0.21	0.31	0.44	0.60	0.83	1.08	1.40	1.80	2.27	2.87	3.49
541	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.39	0.50	0.66	0.84	1.06	1.34	1.63
543	0.00	0.00	0.00	0.01	0.04	0.08	0.13	0.19	0.27	0.37	0.51	0.67	0.87	1.11	1.40	1.77	2.16
501/540	0.00	0.00	0.01	0.02	0.04	0.09	0.14	0.21	0.30	0.41	0.57	0.74	0.96	1.23	1.56	1.96	2.39
503/527	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.22	0.31	0.42	0.55	0.72	0.92	1.16	1.47	1.78
545/507	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.15	0.21	0.29	0.39	0.51	0.67	0.86	1.08	1.36	1.66
506/544	0.00	0.00	0.00	0.01	0.03	0.07	0.10	0.15	0.22	0.30	0.42	0.54	0.71	0.91	1.14	1.45	1.76
510/526	0.00	0.00	0.01	0.02	0.05	0.12	0.19	0.28	0.40	0.56	0.76	1.00	1.30	1.67	2.10	2.66	3.23

Table 4A-6 Tridem Axle Damage Factors (continued)

Site ID	Axle Load (kip)													
	63	66	69	72	75	78	81	84	87	90	93	96	99	102
502	2.86	3.45	4.14	4.96	5.81	6.82	7.95	9.22	10.61	12.22	13.97	15.89	18.02	20.09
504	10.56	12.76	15.30	18.34	21.48	25.20	29.39	34.09	39.15	45.15	51.61	58.73	66.58	74.25
508	2.58	3.11	3.73	4.46	5.24	6.15	7.17	8.31	9.57	11.01	12.58	14.32	16.23	18.10
509	20.22	24.44	29.29	35.03	41.14	48.26	56.28	65.27	74.83	86.44	98.79	112.43	127.44	142.38
511	14.99	18.12	21.72	25.97	30.50	35.78	41.73	48.39	55.75	64.09	73.25	83.36	94.49	105.31
515	2.20	2.66	3.19	3.81	4.47	5.25	6.12	7.09	8.15	9.39	10.74	12.22	13.85	15.45
516	21.52	26.01	31.17	37.24	43.78	51.36	59.90	69.46	79.90	92.00	105.15	119.66	135.64	151.43
520	3.03	3.67	4.39	5.25	6.17	7.24	8.44	9.79	11.26	12.96	14.81	16.86	19.11	21.32
523	4.45	5.38	6.44	7.70	9.05	10.62	12.38	14.36	16.51	19.02	21.74	24.74	28.04	31.31
525	5.45	6.59	7.90	9.44	11.10	13.02	15.19	17.62	20.29	23.33	26.67	30.35	34.41	38.37
529	2.09	2.53	3.03	3.62	4.25	4.99	5.82	6.75	7.77	8.94	10.22	11.63	13.18	14.69
530	2.28	2.76	3.31	3.95	4.65	5.45	6.36	7.37	8.47	9.76	11.16	12.70	14.39	16.07
531	2.24	2.70	3.24	3.87	4.55	5.34	6.22	7.22	8.30	9.56	10.92	12.43	14.09	15.72
539	1.95	2.36	2.83	3.39	3.97	4.66	5.43	6.30	7.24	8.34	9.53	10.85	12.30	13.71
542	4.63	5.60	6.71	8.02	9.42	11.06	12.90	14.96	17.17	19.81	22.64	25.77	29.21	32.65
546	3.71	4.48	5.37	6.42	7.54	8.85	10.32	11.96	13.77	15.84	18.11	20.61	23.36	26.05
547	4.82	5.82	6.98	8.34	9.80	11.50	13.41	15.55	17.88	20.59	23.54	26.79	30.36	33.85
548	5.38	6.50	7.79	9.33	10.94	12.84	14.97	17.36	19.97	22.99	26.27	29.90	33.89	37.78
549	5.47	6.61	7.93	9.47	11.13	13.06	15.23	17.67	20.31	23.40	26.75	30.44	34.50	38.52
551	4.58	5.54	6.64	7.95	9.32	10.94	12.75	14.79	17.01	19.59	22.39	25.48	28.88	32.19
552	5.05	6.11	7.32	8.73	10.29	12.07	14.08	16.33	18.76	21.63	24.72	28.14	31.90	35.65
553	2.15	2.60	3.12	3.74	4.38	5.14	6.00	6.95	7.99	9.21	10.53	11.98	13.58	15.14
554	2.12	2.56	3.07	3.67	4.31	5.06	5.90	6.84	7.88	9.06	10.35	11.78	13.35	14.89
555	4.17	5.04	6.04	7.20	8.48	9.94	11.60	13.45	15.45	17.81	20.35	23.16	26.26	29.30
556	3.38	4.09	4.90	5.86	6.88	8.07	9.41	10.92	12.56	14.46	16.52	18.80	21.31	23.77
557	2.94	3.56	4.26	5.10	5.99	7.02	8.19	9.50	10.93	12.58	14.38	16.37	18.55	20.70
558	3.82	4.62	5.54	6.62	7.78	9.12	10.64	12.34	14.18	16.34	18.67	21.25	24.08	26.89
559	2.29	2.76	3.31	3.96	4.65	5.45	6.36	7.37	8.50	9.77	11.16	12.70	14.40	16.04
560	2.91	3.52	4.21	5.03	5.92	6.94	8.09	9.38	10.82	12.43	14.20	16.16	18.32	20.41
537	4.24	5.12	6.14	7.35	8.62	10.12	11.80	13.68	15.73	18.12	20.71	23.57	26.71	29.82
538	2.60	3.14	3.76	4.49	5.28	6.20	7.23	8.38	9.66	11.10	12.69	14.44	16.37	18.24
521	4.60	5.55	6.65	7.89	9.30	10.91	12.69	14.70	16.92	19.34	22.05	25.15	28.43	32.11
522	5.08	6.14	7.36	8.81	10.34	12.13	14.15	16.40	18.86	21.73	24.83	28.26	32.04	35.77
533	4.53	5.48	6.56	7.86	9.22	10.81	12.61	14.62	16.80	19.36	22.13	25.18	28.54	31.84
534	5.05	6.11	7.32	8.75	10.28	12.06	14.07	16.31	18.78	21.61	24.70	28.10	31.86	35.54
535	4.32	5.22	6.26	7.49	8.79	10.31	12.02	13.94	16.02	18.46	21.09	24.00	27.20	30.35
536	4.25	5.14	6.16	7.36	8.65	10.15	11.83	13.72	15.80	18.17	20.77	23.64	26.80	29.84
541	1.98	2.40	2.87	3.43	4.03	4.73	5.52	6.40	7.36	8.48	9.69	11.02	12.50	13.95
543	2.63	3.18	3.81	4.56	5.36	6.28	7.33	8.50	9.77	11.26	12.86	14.64	16.60	18.50
501/540	2.92	3.53	4.23	5.05	5.93	6.96	8.12	9.41	10.84	12.47	14.25	16.22	18.38	20.49
503/527	2.18	2.63	3.15	3.77	4.42	5.19	6.05	7.02	8.08	9.30	10.63	12.10	13.71	15.29
545/507	2.03	2.45	2.93	3.51	4.12	4.83	5.64	6.54	7.53	8.66	9.90	11.26	12.77	14.23
506/544	2.14	2.59	3.11	3.71	4.36	5.12	5.97	6.92	7.97	9.17	10.48	11.93	13.52	15.07
510/526	3.94	4.76	5.71	6.82	8.02	9.41	10.97	12.72	14.62	16.85	19.26	21.92	24.85	27.73

Table 4A-7 Quad Axle Damage Factors

Site ID	Axle Load (kip)																
	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60
502	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.12	0.17	0.23	0.30	0.40	0.51	0.64	0.81	0.98
504	0.00	0.00	0.01	0.02	0.06	0.14	0.22	0.33	0.46	0.64	0.88	1.15	1.49	1.91	2.41	3.05	3.71
508	0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.08	0.11	0.15	0.21	0.28	0.36	0.46	0.58	0.73	0.89
509	0.00	0.00	0.02	0.05	0.12	0.28	0.43	0.64	0.91	1.26	1.73	2.26	2.94	3.77	4.76	6.01	7.31
511	0.00	0.00	0.01	0.03	0.09	0.20	0.31	0.46	0.66	0.91	1.25	1.63	2.12	2.72	3.43	4.33	5.27
515	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.07	0.09	0.13	0.18	0.23	0.30	0.39	0.49	0.62	0.76
516	0.00	0.00	0.02	0.05	0.13	0.30	0.46	0.68	0.97	1.35	1.85	2.42	3.14	4.02	5.08	6.41	7.80
520	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.13	0.18	0.25	0.32	0.42	0.54	0.68	0.86	1.05
523	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.14	0.19	0.27	0.37	0.48	0.63	0.80	1.02	1.28	1.56
525	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.17	0.24	0.33	0.45	0.59	0.77	0.99	1.25	1.58	1.91
529	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.09	0.12	0.17	0.22	0.29	0.37	0.46	0.59	0.71
530	0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.07	0.10	0.14	0.19	0.24	0.32	0.41	0.51	0.65	0.79
531	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.07	0.10	0.13	0.18	0.24	0.31	0.40	0.50	0.63	0.77
539	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.08	0.11	0.16	0.21	0.27	0.34	0.43	0.54	0.66
542	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.50	0.65	0.84	1.06	1.33	1.62
546	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.11	0.16	0.22	0.31	0.40	0.52	0.67	0.84	1.06	1.29
547	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.15	0.21	0.29	0.40	0.52	0.68	0.87	1.10	1.39	1.69
548	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.17	0.24	0.33	0.45	0.59	0.76	0.97	1.23	1.55	1.89
549	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.17	0.24	0.33	0.45	0.59	0.77	0.99	1.25	1.58	1.92
551	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.50	0.65	0.83	1.04	1.32	1.60
552	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.22	0.31	0.42	0.55	0.71	0.91	1.15	1.46	1.77
553	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.09	0.13	0.17	0.23	0.29	0.38	0.48	0.60	0.73
554	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.09	0.12	0.17	0.22	0.29	0.37	0.47	0.59	0.72
555	0.00	0.00	0.00	0.01	0.02	0.06	0.09	0.13	0.18	0.25	0.34	0.45	0.59	0.75	0.95	1.20	1.46
556	0.00	0.00	0.00	0.01	0.02	0.04	0.07	0.10	0.15	0.20	0.28	0.36	0.47	0.61	0.77	0.97	1.18
557	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.12	0.17	0.23	0.31	0.40	0.51	0.65	0.82	0.99
558	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.23	0.32	0.41	0.54	0.69	0.87	1.10	1.34
559	0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.07	0.10	0.13	0.18	0.24	0.31	0.40	0.51	0.64	0.78
560	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.13	0.17	0.24	0.31	0.41	0.52	0.65	0.82	1.01
537	0.00	0.00	0.00	0.01	0.02	0.06	0.09	0.13	0.19	0.26	0.35	0.46	0.60	0.77	0.97	1.22	1.48
538	0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.08	0.11	0.15	0.21	0.27	0.35	0.45	0.57	0.72	0.88
521	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.14	0.20	0.28	0.38	0.50	0.65	0.83	1.05	1.30	1.61
522	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.22	0.31	0.42	0.55	0.72	0.92	1.16	1.46	1.78
533	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.14	0.20	0.27	0.38	0.49	0.64	0.82	1.03	1.30	1.59
534	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.16	0.22	0.31	0.42	0.55	0.71	0.91	1.15	1.46	1.77
535	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13	0.19	0.26	0.36	0.47	0.61	0.78	0.98	1.24	1.51
536	0.00	0.00	0.00	0.01	0.02	0.06	0.09	0.13	0.19	0.26	0.35	0.46	0.60	0.77	0.97	1.22	1.49
541	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.08	0.12	0.16	0.21	0.27	0.35	0.44	0.56	0.68
543	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.11	0.16	0.22	0.28	0.37	0.47	0.59	0.75	0.91
501/540	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.09	0.13	0.17	0.24	0.31	0.41	0.52	0.65	0.83	1.01
503/527	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.07	0.09	0.13	0.18	0.23	0.30	0.39	0.49	0.61	0.75
545/507	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.09	0.12	0.16	0.21	0.28	0.36	0.45	0.57	0.69
506/544	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.06	0.09	0.13	0.17	0.23	0.30	0.38	0.48	0.60	0.73
510/526	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.24	0.33	0.43	0.56	0.71	0.90	1.13	1.38

Table 4A-8 Quad Axle Damage Factors (continued)

Site ID	Axle Load (kip)													
	63	66	69	72	75	78	81	84	87	90	93	96	99	102
502	1.20	1.45	1.74	2.08	2.44	2.87	3.34	3.88	4.46	5.13	5.87	6.68	7.57	8.43
504	4.52	5.47	6.55	7.83	9.20	10.79	12.58	14.59	16.79	19.33	22.09	25.13	28.49	31.75
508	1.08	1.31	1.57	1.88	2.20	2.59	3.02	3.50	4.02	4.63	5.29	6.02	6.83	7.62
509	8.91	10.77	12.91	15.43	18.13	21.27	24.81	28.77	33.11	38.10	43.55	49.56	56.17	62.65
511	6.43	7.77	9.31	11.15	13.08	15.35	17.90	20.76	23.89	27.49	31.42	35.75	40.53	45.13
515	0.92	1.11	1.34	1.60	1.88	2.20	2.57	2.98	3.42	3.94	4.51	5.13	5.82	6.49
516	9.51	11.50	13.78	16.48	19.36	22.71	26.48	30.71	35.33	40.67	46.49	52.90	59.97	66.86
520	1.28	1.55	1.85	2.22	2.60	3.05	3.56	4.13	4.75	5.47	6.25	7.12	8.07	8.99
523	1.90	2.30	2.76	3.29	3.87	4.54	5.30	6.14	7.07	8.13	9.30	10.58	11.99	13.38
525	2.34	2.82	3.38	4.04	4.75	5.58	6.50	7.54	8.66	9.99	11.41	12.99	14.72	16.44
529	0.87	1.05	1.26	1.51	1.77	2.08	2.42	2.81	3.24	3.72	4.25	4.84	5.49	6.12
530	0.96	1.16	1.39	1.66	1.95	2.29	2.67	3.09	3.56	4.10	4.68	5.33	6.04	6.73
531	0.94	1.13	1.36	1.62	1.91	2.24	2.61	3.02	3.48	4.01	4.58	5.21	5.90	6.58
539	0.81	0.98	1.17	1.40	1.65	1.93	2.25	2.61	3.01	3.46	3.96	4.50	5.10	5.69
542	1.98	2.39	2.86	3.41	4.02	4.72	5.50	6.38	7.35	8.45	9.66	10.99	12.46	13.91
546	1.58	1.90	2.28	2.73	3.20	3.76	4.38	5.08	5.85	6.73	7.69	8.75	9.92	11.05
547	2.06	2.49	2.98	3.56	4.19	4.92	5.73	6.65	7.65	8.80	10.06	11.45	12.98	14.47
548	2.30	2.79	3.34	4.00	4.69	5.50	6.41	7.44	8.54	9.85	11.26	12.81	14.52	16.19
549	2.34	2.83	3.39	4.04	4.76	5.58	6.51	7.55	8.68	10.00	11.43	13.00	14.74	16.46
551	1.95	2.36	2.83	3.39	3.98	4.67	5.44	6.31	7.27	8.36	9.55	10.87	12.32	13.74
552	2.16	2.61	3.13	3.75	4.40	5.16	6.02	6.98	8.04	9.25	10.57	12.03	13.64	15.20
553	0.89	1.08	1.29	1.54	1.81	2.13	2.48	2.88	3.31	3.81	4.35	4.95	5.61	6.26
554	0.88	1.06	1.27	1.52	1.78	2.09	2.44	2.83	3.25	3.75	4.29	4.88	5.53	6.17
555	1.78	2.15	2.57	3.08	3.62	4.24	4.95	5.74	6.59	7.60	8.69	9.88	11.21	12.52
556	1.43	1.73	2.08	2.49	2.92	3.42	3.99	4.63	5.33	6.13	7.01	7.97	9.04	10.08
557	1.21	1.46	1.75	2.10	2.46	2.89	3.37	3.91	4.50	5.18	5.91	6.73	7.63	8.50
558	1.63	1.97	2.36	2.82	3.32	3.89	4.54	5.26	6.04	6.97	7.96	9.06	10.27	11.48
559	0.95	1.14	1.37	1.64	1.93	2.26	2.64	3.06	3.52	4.05	4.63	5.26	5.97	6.66
560	1.23	1.48	1.78	2.13	2.50	2.93	3.42	3.96	4.56	5.25	6.00	6.83	7.74	8.64
537	1.81	2.19	2.62	3.14	3.68	4.32	5.04	5.84	6.72	7.74	8.84	10.06	11.41	12.73
538	1.07	1.29	1.55	1.86	2.18	2.56	2.98	3.46	3.98	4.58	5.23	5.95	6.75	7.50
521	1.95	2.36	2.82	3.35	3.95	4.64	5.40	6.25	7.20	8.24	9.40	10.68	12.07	13.62
522	2.18	2.63	3.15	3.77	4.42	5.19	6.05	7.02	8.08	9.30	10.62	12.09	13.70	15.28
533	1.94	2.34	2.80	3.35	3.94	4.62	5.39	6.25	7.18	8.27	9.46	10.76	12.20	13.61
534	2.16	2.61	3.13	3.73	4.40	5.16	6.02	6.98	8.04	9.24	10.56	12.02	13.63	15.20
535	1.84	2.23	2.67	3.19	3.75	4.39	5.12	5.94	6.84	7.87	8.99	10.23	11.60	12.92
536	1.81	2.19	2.63	3.14	3.69	4.33	5.04	5.85	6.73	7.75	8.86	10.08	11.43	12.77
541	0.83	1.00	1.20	1.43	1.68	1.98	2.31	2.67	3.08	3.54	4.05	4.61	5.22	5.82
543	1.11	1.34	1.61	1.92	2.26	2.65	3.09	3.58	4.12	4.74	5.42	6.17	6.99	7.80
501/540	1.23	1.48	1.78	2.12	2.50	2.93	3.42	3.96	4.56	5.25	6.00	6.83	7.74	8.63
503/527	0.91	1.10	1.32	1.58	1.85	2.17	2.54	2.94	3.39	3.90	4.45	5.07	5.75	6.40
545/507	0.84	1.02	1.22	1.46	1.71	2.01	2.34	2.72	3.13	3.60	4.11	4.68	5.31	5.92
506/544	0.90	1.08	1.30	1.55	1.82	2.14	2.49	2.89	3.32	3.83	4.37	4.98	5.64	6.29
510/526	1.68	2.03	2.43	2.91	3.42	4.01	4.67	5.42	6.24	7.18	8.20	9.34	10.58	11.82

APPENDIX 5

CANDIDATE COVERAGE COUNT LOCATIONS (ALDF Cluster 4)

Table A5-1 Candidate Coverage Count (CC) Locations – CC Clusters 1, 2, and 3

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC5804	50	I-40	FROM W OF SR 1103 TO MILL CR.	McDowell	5804 - 013106	5089	1
VC2903	64	I-40	5.6 MILES W OF US 64	Davie	2903 - 121305	5392	1
VC1105	80	I-40	FROM SR 1708 TO SR 1001	Burke	1105 - 012406	6373	1
VC1704	82	I-40	0.9 MILES W OF SR 1124	Catawba	1704 - 011806	6983	1
B8	96	I-40	1.3 MI. WEST OF SR 2740 (MP 57)	Buncombe	W1002 - 042004	6192	1
VC1712	97	US 321	2.5 MILES S OF SR 1005	Catawba	1712 - 010907	4638	1
VC1110	109	I-40	0.9 MILES W OF SR 1129	Burke	1110 - 071207	4706	1
B9	112	US 74	1.9 MI. WEST OF SR 1001	Columbus	W2301 - 041804	6239	1
VC3128	116	I-85	0.4 MILES W OF NC 147	Durham	3128 - 072407	6629	1
VC5410	127	US 321	0.1 MILES S OF US 321 BUS	Lincoln	5410 - 050807	4646	1
VC1017	136	I-40	0.3 MILES E OF US 70	Buncombe	1017 - 070907	4572	1
VC3104	669	I-85	NORTH OF SR 1675 TO SOUTH OF SR 1632	Durham	3104 - 052306	8055	1
VC3328	665	I-40	2.0 MILES W OF SR 1103	Forsyth	3328 - 071907	5540	1
B25	961	US 321	0.1 MI. SOUTH OF NC 279	Gaston	W3501 - 041904	5472	1
VC3125	221	I-40	0.2 MILES E OF US 15-501	Durham	3125 - 072507	6165	1
VC5025	246	I-40	1.3 MILES N OF NC 42	Johnston	5025 - 072307	4565	1
B15	278	US 17	0.4 MI. SOUTH OF US 158	Pasquotank	W6901 - 041804	6518	1
VC4030	664	I-40	1.3 MILES W OF I-40 BUS	Guilford	4030 - 071107	7911	2
VC1812	69	US 421	0.1 MILES N OF SR 1300	Chatham	W1804 - 041804	7476	2
B6	70	I-40	0.3 MI. WEST OF SR 1744 (MP 109)	Burke	W1101 - 051605	7392	2
B7	78	US 421	1.9 MI. SOUTH OF US 64	Chatham	W1803 - 041804	7272	2
VC1026	86	I-26	0.7 MILES E OF NC 280	Buncombe	4404 - 021306	9288	2
VC4404	87	I-26	FROM BUNCOMBE CO LINE TO US 25	Henderson	4404 - 021306	9288	2
VC1025	124	I-40	0.5 MILES W OF SR 1200	Buncombe	1025 - 062807	9112	2
VC4024	126	I-85	0.5 MILES S OF NC 62	Guilford	4024 - 071607	7586	2
VC2810	141	I-85 BYP	0.8 MILES N OF SR 2085	Davidson	2810 - 080307	7404	2
VC4804	145	I-40	FROM E OF I-77 TO US 64	Iredell	4804 - 071006	7832	2
VC4814	670	I-77	2.6 MILES S OF SR 1109	Iredell	4814 - 012907	8994	2
B23	953	US 220	0.5 MI. SOUTH OF SR 2150	Rockingham	W7803 - 041804	9753	2
B24	956	US 1	0.1 MI. SOUTH OF SR 1423	Lee	W5201 - 041804	7880	2
B5	61	US 220	0.1 MI NORTH OF SR 1247	Randolph	W7501 - 041804	11567	3
VC2804	83	I-85	5.6 MILES S OF NC 47	Davidson	2804 - 030507	11548	3
VC2808	120	US 52	0.3 MILES N OF SR 1821	Davidson	W2802 - 041804	12095	3
B10	121	US 52	0.4 MI. NORTH OF US 64 (MP 92)	Davidson	W2802 - 041804	12095	3
B11	129	I-40	0.3 MI. WEST OF US 21 (MP 151)	Iredell	W4801 - 051605	10669	3
VC7913	135	I-85	0.6 MILES S OF SR 1500	Rowan	7913 - 030607	10877	3
VC7912	142	I-85	4.9 MILES S OF NC 152	Rowan	7912 - 071307	11835	3
VC4036	969	US 220	0.4 MILES S OF NC 62	Guilford	W4001 - 041804	12184	3
VC7013	213	I-40	5.3 MILES S OF NC 210	Pender	W7001 - 041804	10752	3
B14	253	NC 68	0.5 MI NORTH OF BRYAN BLVD	Guilford	W4002 - 041804	12870	3

CANDIDATE COVERAGE COUNT LOCATIONS (ALDF Cluster 1 & SU/MU Factor Group 3)

Table A5-2 Candidate Coverage Count (CC) Locations – CC Cluster 1

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC0203	1048	US 21	FROM N OF NC 18 TO S OF SR 1487	Alleghany	0203 - 092706	508	1
VC4503	483	US 13	SOUTH OF SR 1411 TO NORTH OF NC 561	Hertford	4503 - 061306	511	1
VC6006	413	NC 226	0.1 MILES S OF SR 1279	Mitchell	6006 - 050107	511	1
VC4016	541	NC 62	FROM E OF I-85 FOR 0.2 MILE EAST	Guilford	4016 - 070703	523	1
VC6204	528	US 15	SOUTH OF SR 1224 TO NORTH OF NC 73	Moore	6204 - 081605	526	1
VC8518	731	NC 268 BYP	0.1 MILES W OF SR 1150	Surry	8518 - 010307	526	1
VC9145	628	NC 98	0.2 MILES E OF SR 4912	Wake	9145 - 042407	531	1
VC3331	518	NC 109	0.1 MILES N OF SR 3858	Forsyth	3331 - 031907	533	1
VC5412	534	NC 150	0.1 MILES E OF SR 1169	Lincoln	3511 - 080706	534	1
VC3511	535	NC 150	0.1 MILES W OF SR 1426	Gaston	3511 - 080706	534	1
VC8303	704	NC 73	0.2 MILES W OF SR 1231	Stanly	8303 - 112800	535	1
VC3409	697	NC 96	0.1 MILES S OF SR 1128	Franklin	3409 - 071007	537	1
VC8904	360	NC 75	WEST OF SR 1111 TO EAST OF SR 1325	Union	8904 - 051605	541	1
VC8513	545	US 52	0.1 MILES S OF SR 1842	Surry	8513 - 121906	542	1
VC8913	453	NC 75	0.1 MILES W OF SR 1175	Union	8913 - 021207	544	1
VC3803	426	NC 56	WEST OF SR 1636 TO EAST OF NC 50	Granville	3803 - 082206	549	1
B17	439	US 64	0.4 MI. EAST OF US 19-129	Cherokee	W1901 - 031803	561	1
VC3122	520	NC 751	0.4 MILES S OF SR 1118	Durham	3122 - 070907	570	1
VC1107	470	US 64	0.4 MILES W OF SR 1971	Burke	1107 - 081506	571	1
VC0408	550	US 221	0.5 MILES S OF SR 1171	Ashe	0408 - 030607	574	1
VC6801	608	NC 55	WEST OF SR 1200 TO EAST OF NC 306	Pamlico	6801 - 100200	576	1
VC7916	521	NC 152	0.1 MILES W OF SR 1638	Rowan	7916 - 021307	577	1
VC7303	507	US 13	EAST OF SR 1128 TO WEST OF SR 1127	Pitt	7303 - 022706	592	1
VC6705	407	US 70 B	WEST OF SR 1562 TO EAST OF SR 1709	Orange	6705 - 030502	599	1
VC6001	490	US 19	0.2 MILES E OF SR 1002	Mitchell	6001 - 091206	611	1
VC0505	544	US 221	FROM S OF SR 1143 TO NC 194	Avery	0505 - 080403	615	1
VC2606	606	US 158	0.4 MILES W OF SR 1148	Currituck	2606 - 030607	615	1
VC9407	511	US 321	0.1 MILES N OF CHURCH ST	Watauga	9407 - 032607	617	1
VC2206	476	NC 18	SOUTH OF SR 1830 TO NORTH OF SR 1923	Cleveland	2206 - 081406	627	1
VC4028	630	NC 68	0.4 MILES W OF SR 1961	Guilford	4028 - 073007	629	1
VC5306	489	US 70 BUS	FROM US 70 TO WEST OF SR 1361	Lenoir	5306 - 102406	632	1
VC0501	539	NC 194	SOUTH OF SR 1361 TO NORTH OF SR1159	Avery	0501 - 091806	645	1
VC6214	765	NC 211	0.1 MILES S OF SR 2075	Moore	4602 - 061305	646	1
VC4602	766	NC 211	WEST OF SR 1315 TO EAST OF SR 1202	Hoke	4602 - 061305	646	1
VC1901	500	US 19-74	WEST OF NC 141 TO EAST OF SR 1554	Cherokee	1901 - 092506	665	1
VC5002	471	NC 42	SOUTH OF SR 1945 TO NORTH OF SR 1720	Johnston	5002 - 053106	680	1
VC9906	460	US 19	0.1 MILES N OF SR 1421	Yancey	9906 - 050107	758	1

Table A5-3 Candidate Coverage Count (CC) Locations – CC Cluster 2

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC1801	387	US 15	SOUTH OF SR 1724 TO NORTH OF SR 1717	Chatham	1801 - 080601	726	2
VC5023	651	NC 42	0.2 MILES E OF SR 1689	Johnston	5023 - 071707	731	2
VC7914	641	US 29	0.4 MILES S OF SR 1267	Rowan	7914 - 080707	735	2
VC8411	532	NC 8	0.1 MILES W OF SR 1955	Stokes	8411 - 032007	741	2
VC7504	607	SR 1595	FROM S OF SR 1592 TO SR 1596	Randolph	7504 - 081505	758	2
VC7917	478	NC 152	0.5 MILES W OF SR 1358	Rowan	7917 - 050807	814	2
VC1301	552	US 321	SOUTH OF NC 268 TO NORTH OF US 321A	Caldwell	1301 - 050206	814	2
VC2811	391	NC 109	0.1 MILES S OF SR 2055	Davidson	2811 - 062607	818	2
VC6708	609	US 15	0.2 MILES N OF SR 1919	Orange	6708 - 032707	822	2
VC3101	389	NC 98	EAST OF SR 1809 TO WEST OF SR 1805	Durham	3101 - 082100	837	2
VC8521	424	NC 89	0.2 MILES N OF SR 1665	Surry	8521 - 121806	842	2
VC3514	475	US 321	0.1 MILES S OF SR 2655	Gaston	3514 - 011607	843	2
VC7012	597	US 117	1.4 MILES S OF SR 1435	Pender	6402 - 052306	849	2
VC6402	598	US 117	S OF NE CAPE FEAR RIVER	New Hanover	6402 - 052306	849	2
VC9602	1006	US 421	0.1 MILES W OF SR 1377	Wilkes	9602 - 120406	861	2
VC7207	459	US 501	0.4 MILES S OF NC 57	Person	7207 - 032707	862	2
VC6606	992	US 17	1.5 MILES S OF NC 50	Onslow	6606 - 082806	867	2
VC9402	487	US 421	0.4 MILES N OF SR 1374	Watauga	9402 - 091906	870	2
VC4403	615	NC 280	0.3 MILES W OF SR 1323	Henderson	4403 - 090606	882	2
VC6805	361	NC 55	0.2 MILES W OF SR 1126	Pamlico	6805 - 031307	927	2
VC2404	365	US 17	FROM S OF SR 1602 TO NC 43	Craven	2404 - 091806	945	2
VC5001	523	NC 42	WEST OF SR 1704 TO EAST OF SR 1902	Johnston	5001 - 053106	954	2
VC7519	408	US 311	0.1 MILES N OF SR 1928	Randolph	7519 - 060407	959	2
VC4405	623	US 176	FROM US 25 TO SR 1764	Henderson	4405 - 082503	963	2
VC3316	591	SR 1801	FROM REYNOLDA RD TO US 52	Forsyth	3316 - 030904	992	2
VC5903	504	NC 73	1.0 MILES W OF SR 2182	Mecklenburg	5903 - 072604	1103	2

Table A5-4 Candidate Coverage Count (CC) Locations – CC Cluster 3

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC3405	419	US 401	FROM SR 1229 TO NC 39	Franklin	3405 - 102504	1008	3
VC0902	620	NC 211	WEST OF NC 133 TO EAST OF SR 1500	Brunswick	0902 - 102306	1038	3
VC6305	352	US 301	NORTH OF SR 1006 TO SOUTH OF NC 97	Nash	6305 - 071806	1038	2
VC1402	639	US 158	2.3 MILES W OF SR 1139	Camden	1402 - 111406	1040	3
VC3404	409	US 401	FROM NC 56-581 TO N OF SR 1232	Franklin	3404 - 102504	1043	3
VC8505	484	US 52	FROM SR 1773 TO SR 2116	Surry	8505 - 051506	1046	3
VC3506	696	NC 27	FROM SR 2180 TO MECKLENBURG CO LINE	Gaston	3506 - 073106	1067	3
B16	371	US 74-441	0.2 MI. EAST OF SR 1391	Jackson	W4902 - 031103	1077	3
VC4910	443	US 74	0.1 MILES E OS SR 1531	Jackson	4910 - 061907	1088	3
VC1506	479	NC 24	0.3 MILES W OF SR 1202	Carteret	6602 - 082806	1119	3
VC6602	480	NC 24	SOUTH OF SR 1434 TO NORTH OF SR 1744	Onslow	6602 - 082806	1119	3
VC1210	393	NC 73	0.1 MILES E OF SR 1833	Cabarrus	1210 - 080707	1121	3
VC0914	602	NC 211	0.2 MILES S OF SR 1115	Brunswick	0914 - 010307	1122	3
VC1203	428	US 601	SOUTH OF SR 1132 TO NORTH OF SR 1150	Cabarrus	1203 - 082806	1192	3
VC7308	385	US 264	FROM SR 1564 TO BEAUFORTCOUNTY	Pitt	7308 - 022706	1198	3
VC1202	455	US 29	WEST OF SR 1305 TO EAST OF SR 1300	Cabarrus	1202 - 102301	1204	3
VC7204	396	US 501	NORTH OF SR 1123	Person	7204 - 052206	1209	3
VC6706	636	US 15	FROM S OF SR 1742 TO DURHAM CO LINE	Orange	6706 - 070604	1234	3
VC7310	384	NC 11	0.9 MILES S OF SR 1103	Pitt	7310 - 121106	1238	3
VC1501	610	NC24	WEST OF SR 1124 TO EAST OF SR 1119	Carteret	1501 - 091106	1317	3
VC1020	394	US 25	0.1 MILES S OF SR 3530	Buncombe	1020 - 020507	1339	3
VC0608	355	US 264	0.1 MILES W OF SR 1410	Beaufort	0608 - 022707	1376	3
VC4904	379	US 23-441	1.3 MILES S OF SR 1305	Jackson	4904 - 101006	1381	3
VC4035	599	US 311	0.3 MILES S OF NC 610	Guilford	4035 - 073007	1418	3

Table A5-5 Candidate Coverage Count (CC) Locations – CC Cluster 4

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC5501	467	US 23	0.1 MILES N OF SR 1102	Macon	5501 - 100906	1380	4
VC4810	451	NC 150	FROM E OF NC 115 TO W OF NC 115	Iredell	4810 - 071106	1405	4
VC1206	466	NC 24-27	0.2 MILES E OF SR 1133	Cabarrus	1206 - 070907	1878	4
VC6605	436	US 17	FROM N OF SR 1107 TO S OF SR 1117	Onslow	6605 - 082806	1460	4
VC2410	441	US 70	1.0 MILES S OF SR 1824	Craven	2410 - 031307	1507	4
VC1021	461	NC 280	0.5 MILES S OF SR 3539	Buncombe	1021 - 020507	1524	4
VC1709	495	NC 16	0.3 MILES S OF NC 150	Catawba	1709 - 010807	1528	4
VC5935	404	US 29-74	0.1 MILES E OF SR 1600	Mecklenburg	5935 - 081307	1535	4
VC1502	437	US 70	WEST OF SR 1129 TO EAST OF CRAVEN COUNTYLINE	Carteret	1502 - 091106	1540	4
VC8311	414	NC 24-27	0.2 MILES W OF SR 1142	Stanly	8311 - 050707	1655	4
VC0912	397	US 17 BYP	0.2 MILES W OF US 17 BUS	Brunswick	0912 - 010307	1720	4

Table A5-6 Candidate Coverage Count (CC) Locations – CC Cluster 5

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC7009	557	US 17	0.1 MILES N OF SR 1572	Pender	7009 - 010807	1786	5
VC4801	645	NC 150	0.1 MILES W OF SR 3060	Iredell	4801 - 071706	1890	5

Table A5-7 Candidate Coverage Count (CC) Locations – CC Cluster 6

VC_STA_ID	ID	ROUTE	LOCATION	COUNTY	EVENT	AADTT	Coverage Count Cluster
VC7518	359	I-85 BUS	0.1 MILES W OF SR 1627	Randolph	7518 - 012607	1939	6

APPENDIX 6

SUMMARY OF MEPDG NC USER'S GUIDE

This document gives step-by-step procedures to implement the MEPDG in North Carolina. It describes how pavement designers can utilize the research-based local materials and performance databases for designing new and rehabilitated flexible pavements. Asphalt materials and performance databases were developed by North Carolina State University (NCSU) under three different projects sponsored by the NCDOT. These projects are:

- Typical Dynamic Moduli for North Carolina Asphalt Concrete Mixes (HWY 2003-09)
- Local Calibration of the MEPDG for Flexible Pavement Design (HWY-2007-07)
- Development of Traffic Data Input Resources for the Mechanistic Empirical-Pavement Design Process (HWY-2008-11)

The guide initially presents the inputs required to run the MEPDG in detail for each of the input levels (Level 1, Level 2 and Level 3) when applicable. Then, the guide offers users a step-by-step procedure to guide them to effectively select and enter and/or import the required parameters for a specific design. Screen shots from the MEPDG show users what they will see while using the software.

Here, we only summarize the implementation procedures that pertain to research project HWY-2008-11. An interested reader may refer to the entire guide for more detailed discussion on the implementation procedures related to Projects HWY 2003-09 and 2007-07.

The MEPDG version 1.1 allows for some traffic and materials input parameters to be directly imported from within the MEPDG. Other parameters, however, must be manually entered. For those parameters that can be imported and that are part of the database that do not change often, the authors developed files that will be available to NCDOT designers on a media storage device. Detailed instructions on how to import such files are presented in this document.

<u>The Hierarchical Traffic Data Input Levels</u>

Users of the MEPDG are offered three hierarchical data input levels to choose from; Level 1, Level 2, and Level 3. This flexibility is available for materials as well as for traffic input data. Level 1 is the most accurate and most demanding of all levels, whereas Level 3 is the least accurate and least demanding data input level:

- Level 1: most accurate design level requiring site-specific weight and volume data collected at or near the project site.
- Level 2: intermediate accuracy design level with modest knowledge of traffic characteristics requiring regional weight data and site-specific volume data.
- Level 3: least accurate design level with knowledge only of statewide default weight and volume data.

<u>Design steps that involve traffic information</u>

Step 1

Step 1 involves updating five different traffic parameters: initial two-way AADTT, number of lanes in design direction, percent of trucks in design direction, percent of trucks in design lane, and the vehicle operational speed. Table A5-1 shows the source and suppliers for the above mentioned parameters.

Table A6-1 Sources of the Traffic Inputs Found under the Traffic Main Window

Traffic Input	Source
Two Way AADTT	Supplied by TSG
Number of Lanes in Design Direction	Supplied by TPB/PMU
Percent Trucks in Design Direction	MEPDG Default Values
Percent Trucks in Design Lane	• Single-lane roadways in one direction = 100% • Two-lane roadways in one direction, = 90% • Three-lane roadways in one direction = 60% • Four-lane roadways in one direction = 45%
Operational Speed	MEPDG Default Values

Step 2

Step 2 involves updating traffic volume adjustment factors. The traffic volume adjustment factors window allows users to account for two things;

1. hourly changes in traffic, seasonal traffic changes, and traffic changes due to traffic growth;
2. contribution of different vehicle classes to the total traffic.

Table A5-2 shows the sources of the adjustment factors.

Table A6-2 Sources of the Traffic Adjustment Factors

Traffic Input	Source
Vehicle Class Distribution (VCD)	VCD Generator and ALDF Cluster Selector Tool
Hourly Distribution Factors (HDF)	Supplied by TSG / Use Statewide Averages
Monthly Adjustment Factors (MAF)	Supplied by TSG / Use Statewide Averages
Traffic Growth Factor	Supplied by TPB

Step 3

Step 3 involves updating axle load distribution factors. Four axle types are considered in the ALDF table: single, tandem, tridem, and quad. To facilitate the process of updating the ALDF, four computer files representing the four ALDF clusters were developed under project HWY-2008-11. The procedure of importing ALDF factors is a two-step as follows;

1. Selection of the most representative ALDF cluster based on the percentage of class 5 and class 9 vehicles obtained from 48-hour counts using the *VCD Generator* and *ALDF Cluster Selector* tool (see Figure 3).
2. Importing the ALDF file that the NCSU researchers delivered to NCDOT.

Step 4

Step 4 involves updating general traffic inputs. The General Traffic Inputs interface has three tabs: number axles/truck, axle configuration, and the wheelbase. Table A5-3 shows the source for updating traffic parameters that are listed on these tabs.

Table A6-3 Source and Suppliers of the General Traffic Input

Traffic Input	Source
Lateral Traffic Wander	MEPDG Default Values
Number of Axles per Vehicle Class	Supplied by TSG / Use Statewide Averages
Average Axle Width, Tire Pressure, and Dual Tire Spacing	MEPDG Default Values
Axle Spacing	• tandem axle = 48.9 in • tridem axle = 52.7 in • quad axle = 50.0 in
Wheelbase Distribution	MEPDG Default Values