EVALUATION OF OKLAHOMA WEIGH-IN-MOTION (WIM) DATA

By

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EVALUATION OF OKLAHOMA WEIGH-IN-MOTION (WIM) DATA

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Abstract: As an important component of data collection in traffic monitoring program, Weigh-In-Motion (WIM) systems record multiple types of traffic data which can be utilized for various applications. Due to the high rate of erroneous data and expensive device setup and calibration, it is critical to check WIM data quality and examine the variability levels of various traffic characteristics. Rigorous data quality algorithms have been implemented in the Prep-ME software. Five years of WIM data in Oklahoma are investigated and 2008 WIM data is selected as the data source for study of traffic variations. A comprehensive array of traffic parameters, including those for traffic volume, truck volume, gross vehicle weight, and axle load spectra are studied and their variations at different time periods (time-of-day, day-of-week, monthly, and seasonally) are evaluated and analyzed. The statistical required minimum number of traffic monitoring sites for each roadway group is estimated. In addition, the traffic variations at different locations are calculated to investigate traffic data consistency within each roadway group.

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CHAPTER I

INTRODUCTION

Background

Many transportation agencies have recognized that traffic data programs support a growing variety of functions and critical decision processes within their agencies *(1)*. Uses of traffic data include project and resource allocation programming; performance reporting; operations and emergency evacuation; capacity and congestion analysis; traffic forecasts; project evaluation; pavement design; safety analyses; emissions analysis; cost allocation studies; estimating the economic benefits of highways; preparing vehicle size and weight enforcement plans; freight movement activities; pavement and bridge management systems; and signal warrants, air quality conformity analysis, etc.

Traditionally, three types of traffic data are collected through various traffic monitoring equipment: volume data, classification data and weight data. Speed data has also been included in the 2013 version of Traffic Monitoring Guide (TMG) *(1)* to estimate travel time and the impact of speed on traveler safety. The commonly used equipment for traffic data collection includes:

- Traffic Counter – Collect vehicular characteristics data (such as volume, classification, speed and weight);

- Automated Traffic Recorder (ATR) or Counter – Record the distribution and variation of traffic flow by hour of the day, day of the week, and/or month of the year;
- Portable Traffic Recorder (PTR) or Counter – A mobile equipment to collect data of traffic volumes and classifications;
- Automatic Vehicle Classification (AVC) Counter – Record traffic volumes by classification;
- Weigh-In-Motion (WIM) – Measure the dynamic tire forces of a moving vehicle and estimate the corresponding tire loads of the static vehicle.

Of all the traffic monitoring activities, WIM requires the most sophisticated data collection sensors, the most controlled operating environment (strong, smooth, level pavement in good condition), and the most costly equipment set up and calibration *(1),* while provides the most comprehensive data sets for volume, vehicle classification, and weight. WIM data are used for a wide variety of tasks, which include but are not limited to the following:

- pavement design and maintenance
- bridge design
- pavement and bridge loading restrictions
- development and application of equitable tax structures
- determination of the need for and success of weight law enforcement actions
- determination of the need for geometric improvements related to vehicle size,

weight, and speed

- determination of the economic value of freight being moved on roadways
- determination of the need for and effect of appropriate safety improvements

Unfortunately, because WIM equipment is expensive to install and maintain, WIM data is available only at limited locations within a state agency. For most road sites, no WIM system is installed and no WIM data are collected. Instead, the traffic data is normally computed from a site-specific classification count with estimated total loading *(9)*. However, trucking characteristics vary significantly by road type, geographical location, economic development etc.

Various research efforts have been devoted to evaluate statewide traffic monitoring program mainly based on traffic volumes data. By contrast, the deployment of WIM systems is lacking of robust statistical data support mainly due to inadequate data sets and undiscovered truck patterns and characteristics. As a matter of fact, the number of WIM systems within state agencies is primarily constraint by available funds and determined based on engineers' judgments.

Literature Review

This thesis focuses on one important component on the development of WIM traffic monitoring program: how to determine the variability of various traffic characteristics and required number of WIM sites from a statistical prospective. Several papers have addressed this problem in previous research and are summarized as follows:

In the *Truck Flows and Loads for Pavement Management (3)* study by Washington DOT, the number of required WIM sites was determined in three steps: (1) Creating groups of roads that may contain reasonably homogeneous traffic populations and patterns, (2) Checking homogeneity of road groups through variation analysis of average annual damage factor (ESALs/vehicle), and (3) Applying statistical method based on variation analysis of damage factor to determine the number of WIM sites required.

Ardeshir Faghri, et al *(4)* presented a conceptual framework to estimate the number of WIM sites. Firstly, the monthly variations of traffic volume for each road group were estimated. Secondly, statistical analysis was conducted to determinate necessary number and road type group distribution of statewide ATR sites. Subsequently, combining the distribution of ATR, the number of WIM sites was estimated based on engineers' judgments.

Based on monthly variations of annual average daily traffic (AADT), Shy Bassan *(5)* used statistical methodologies to determine the number of required ATR sites. As far as the number of WIM sites, similar statistical method was utilized based on either the mean equivalent standard axle load (ESAL) or the average gross weight (GVW) of class 9 trucks.

In the latest 2013 version of *Traffic Monitoring Guide* (TMG) *(1)*, the number of WIM sites is determined statistically based on variations of the mean GVW of class 9 trucks and EASL for each roadway weight group.

Due to different traffic patterns and methods utilized by different DOTs to design statewide traffic monitoring program, the number of WIM sites varies among States. Idaho Transportation Department (ITD) currently maintains 26 WIM data collection sites; New York State DOT (NYSDOT) collects WIM data at 24 WIM sites *(1)*. In North Carolina, there are in total 44 WIM stations, while California has almost 100 WIM sites *(6)*: 71 in urban area and 26 in rural area. By 2009, Wisconsin has 17 WIM sites *(7)*; by 2013, Montana has 33 WIM sites *(8)*.

Problem Statement and Research Objectives

Limited research has been conducted to study traffic variability and determine the number of required WIM sites which are able to represent typical traffic characteristics within a state highway agency. Previous methods either depend on engineering judgments, or based on traffic volume data (e.g. AADT), or few weight-related parameters such as GVW of class 9 vehicle and ESAL. Therefore, a robust statistical-based methodology considering a comprehensive array of traffic parameters including traffic volume, classification and weight is desired for a well-designed WIM monitoring program.

To achieve this goal, the objectives of this thesis are given as follows:

- To examine the WIM data sets in Oklahoma, conduct rigorous data quality check, and identify data with good quality for subsequent analysis;
- To identify a comprehensive array of traffic parameters for volume, classification and weight data and calculate their variability;
- To develop a statistical framework on how to determine required number of WIM sites based on the variability of the traffic characteristics;
- To apply this framework and evaluate the WIM data in Oklahoma and propose recommendations for ODOT practices.
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Thesis Outline

Chapter I provides the literature review on the determination for the number of WIM sites and develop the objectives of this thesis;

Chapter II presents the development of the Prep-ME software, which is able to pre-process and import raw Weigh-In-Motion (WIM) traffic data, conduct rigorous data check so that only "good" data are used for variability analysis;

Chapter III proposes a framework on how to determine the number of WIM sites based on different time variation of various traffic factors;

Chapter IV applies this framework for Oklahoma and perform a preliminary evaluation of the WIM program in Oklahoma;

Chapter V presents the key conclusion of this study and provides recommendations.

CHAPTER II

PREP-ME FOR WIM DATA PROCESS

Prep-ME Software

Introduction

Even Pavement ME Design (MEPDG/DARWin-ME) is an advanced pavement design tool, much more inputs from various data sources are required. The data sources required by Pavement ME Design contains: design criteria, traffic level, environmental condition and material properties. Large amounts of investment have already been spent by states highway agencies on data preparation for Pavement ME Design implement. Through the transportation pooled fund study TPF-5(242): *Traffic and Data Preparation for AASHTO Pavement-ME Analysis and Design*, the software called Prep-ME is developed to assist state DOTs in data preparation and management for Pavement ME Design.

Prep-ME (version 3.0) (Figure 2.1) is developed mainly based on Microsoft Foundation Class (MFC) and Structured Query Language (SQL) local database. MFC, an application framework which encapsulates most of windows API functions in C/C++ development environment, can improve efficiency of software development and reduce workload of developers. SQL local database is an advancement in data storage, query, update and management with rapid data computation efficiency. Also, SQL local database has large data storage capability (10GB for express version and 16 TB for standard version of Microsoft SQL Server).

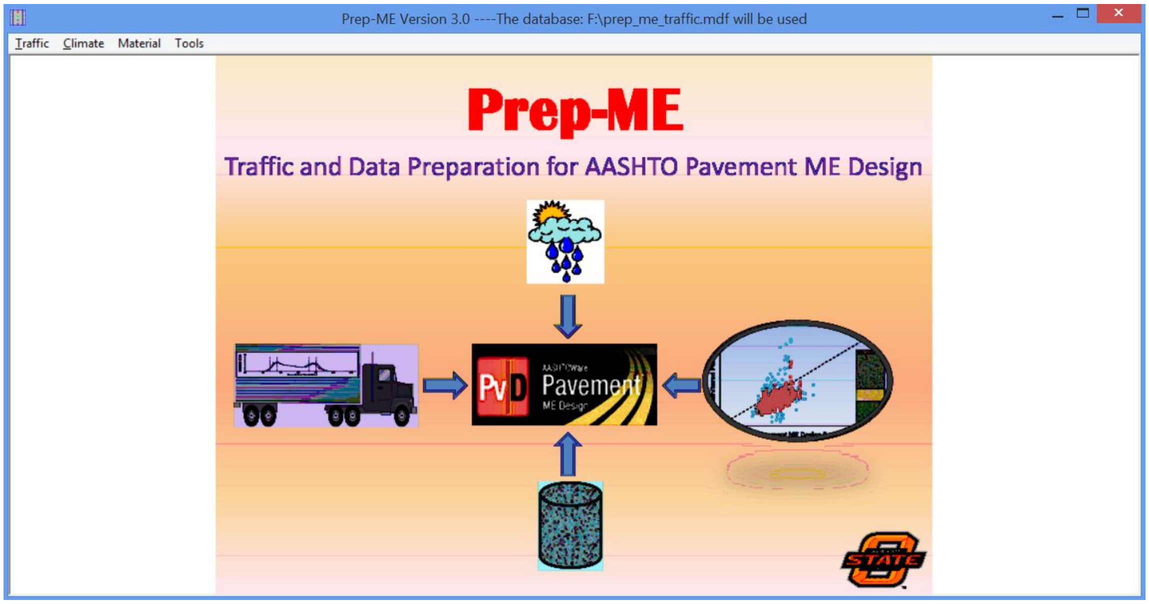


Figure 2.1 Prep-ME Software Main Interface

Based on requirements of inputs in Pavement ME Design, four main modules have been developed in Prep-ME: traffic module, climate module, materials module, and tools module. Traffic, climate and material module can import traffic, climate and material data respectively and then export data for the Pavement ME Design software. Prep-ME also provides tools to aid state DOTs in using the software.

Particularly, the traffic module in Prep-ME is capable of pre-processing, importing, checking the quality of raw WIM traffic data, and generating the required traffic data inputs by recognizing the differences in loading patterns or traffic groups. Prep-ME is TMG and TMAS compliant.

Traffic Data Import

The traffic data import module is applied to import an agency's WIM data complying with FHWA Traffic Monitoring Guide (TMG) *(9)* file formats, and store the data in SQL local database. During importing WIM data, the raw data is checked following Travel Monitoring Analysis System (TMAS 2.0) and a detailed TMAS check error log is generated.

Traffic Data Check

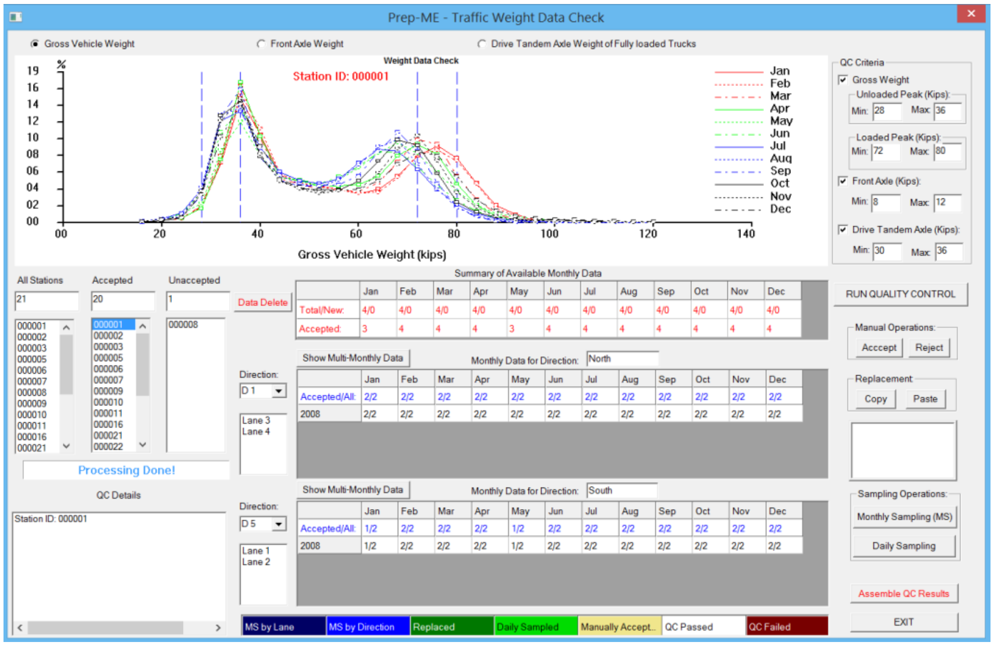
After importing WIM data, traffic data check module provides engineers with a function to automatically check WIM data quality (for both classification and weight data) by direction and lane of a WIM station following algorithms defined in TMG. For example, the automatically data check function can provide engineers with only the data with good quality in twelve consecutive months. In addition, through the interface of data check module, engineers can review monthly, weekly and daily traffic data. Besides, the WIM data that fails the automatic data quality check can be investigated or utilized as engineers' demand through various manual operations.

Automatic Data Check

The algorithm used in the 2001 3rd Edition of TMG *(9)* for weight is adopted for weight data quality control (QC). There are two basic steps to evaluate recorded vehicle weight data. Firstly, to check the front axle and drive tandem axle weights of Class 9 trucks. The front axle weight should be between 8,000 and 12,000 lb (10,000 ± 2,000 lb). The drive tandems of a fully loaded Class 9 truck should be between 30,000 and 36,000 lb (33,000 ± 3,000 lb). Secondly, to check the gross vehicle weights of Class 9 trucks. The histogram plot should have two peaks for most sites. One represents unloaded Class 9 trucks and should be between 28,000 and 36,000 lb (32,000 ± 4,000 lb). The second peak represents the most common loaded vehicle condition with a weigh between 72,000 and 80,000 lb (76,000 ± 4,000 lb).

Classification data check follows the four-step algorithms defined in the TMG guide *(9)*: (1) to compare the manual classification counts and the hourly vehicle classification data. The absolute difference should be less than five percent for each of the primary vehicle categories. (2) To check the number of Class 1 (motorcycles). The evaluation procedure recommended that the number of Class 1 should be less than five percent unless their presence is noted. (3) To check the reported number of unclassified vehicles. The number of unclassified vehicles should be less than five percent of the vehicles recorded. (4) To compare the current truck percentages by class with the corresponding historical percentages. No significant changes in the vehicle mix are anticipated. The first step is not used since no manually collected data are available. The second and third step can be checked with the imported vehicle classification data. In the fourth step, the TMAS2.0 consistency check is applied. By default, MADT from same month previous year should be within 30%.

Figure 2.2 demonstrates the interface for weight data check. Default TMG QC Criteria are built into Prep-ME. After running automatically weight data check, the WIM stations are automatically classified as "Accepted" and "Unaccepted". For each station, the corresponding histograms for each data check criterion can be checked by switching the radio buttons ("Gross Vehicle Weight", "Front Axle Weight", and “Drive Tandem Axle Weight of Fully Loaded Trucks").



● Gross Vehicle Weight ○ Front Axle Weight ○ Drive Tandem Axle Weight of Fully loaded Trucks

QC Criteria

☑ Gross Weight

Unloaded Peak (Kips): Min: 28 Max: 36

Loaded Peak (Kips): Min: 72 Max: 80

☑ Front Axle (Kips): Min: 8 Max: 12

☑ Drive Tandem Axle (Kips): Min: 30 Max: 36

All Stations: 21

Accepted: 20

Unaccepted: 1

All Stations list: 000001, 000002, 000003, 000005, 000006, 000007, 000008, 000009, 000010, 000011, 000016, 000021

Accepted list: 000001, 000002, 000003, 000005, 000006, 000007, 000009, 000010, 000011, 000016, 000021, 000022

Unaccepted list: 000008

Processing Done!

QC Details

Station ID: 000001

Summary of Available Monthly Data

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total/New:	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0	4/0
Accepted:	3	4	4	4	3	4	4	4	4	4	4	4

Monthly Data for Direction: North

Direction: D 1

Lane 3
Lane 4

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Accepted/All:	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2
2008	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2

Monthly Data for Direction: South

Direction: D 5

Lane 1
Lane 2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Accepted/All:	1/2	2/2	2/2	2/2	1/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2
2008	1/2	2/2	2/2	2/2	1/2	2/2	2/2	2/2	2/2	2/2	2/2	2/2

Figure 2.2 Weight Data Check by Direction

Prep-ME performs QC by direction and by lane for each month and each station. For example, as Figure 2.2 shows, WIM site 000001 has one-year data with two directions and two lanes in each direction, the total number of available data sets in January will be 4, which is 2 (directions) ×2 (lanes) ×1 (years). If there are more than one sample in January passes the automatic QC, this station is considered to pass the QC for this month. Only the WIM station with at least one QC-passed sample for each month can be automatically classified as “Accepted Station”.

The monthly QC check results can be viewed by direction and by lane for a WIM station. After selecting WIM site from “Accepted” or “Unaccepted” column, the interface shows two direction’s information simultaneously for facilitating comparisons. The data QC is summarized into three tables for the two directions. The first table provides the "Summary of Available Monthly Data", while the other two provides the QC details for both directions. Then after selecting the direction and lane of the WIM station, the interface will show how many days of data in each month, and the QC status. If a month has a failed QC checking status, it is marked with a dark red color background automatically.

Prep-ME also has capability to investigate the data trend for specific Day-of-Week. Multiple days of data can be showed in the QC Plots and Daily Data Summary interface. For example, Figure 2.3 demonstrates the comparisons of the Gross Vehicle Weight data for all four Mondays in the selected month. Seen in this figure, the data is consistent among the four Mondays. However, it is seen that the data for the second Monday shows different trend from others. Users may investigate the data and decide whether the data is reasonable.

QC Plots of Sampled Days

● Gross Vehicle Weight ○ Front Axle Weight ○ Drive Tandem Axle Weight of Fully loaded Trucks

Daily Data Summary

● Daily Class 9 Truck Counts ○ Percent of Front Axle Within TMG Tolerance (%) ○ Percent of Drive Tandem Within TMG Tolerance for Fully Loaded Trucks (%)

Mon	Tue	Wed	Thu	Fri	Sat	Sun
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

Figure 2.3 Daily Check Interface for Weight Data

Data Sampling and Repair

For the data that has not pass QC data check, Prep-ME provide manually operations to investigate the data, sample data and repair data. Three manually sampling and repair options are provided in the Prep-ME: Manual Operation (Accept and Reject), Replacement (Copy and Paste), and Sampling Operation (Daily Sampling and Monthly Sampling). Explanations for the sampling and repair options are given below:

- Manual Operation (Accept/Reject) – allow users to review and double check the automated QC results. If users confirm that the software has misclassified the data check status, users could manually accept or reject this month's data;

- Replacement (Copy/Paste) – when one month data is missing or fail to pass the data check algorithms, users can apply "Copy" and "Paste" operation by checking the similarity of the data in adjacent months, opposite direction, or different lane, same month but different year, and then identify a suitable month which can be used as the "source month" to substitute the failed or missing month (the "target month");

- Daily Sampling – when multiple days of data are missing with a month for some WIM stations, daily sampling is applied to sample the available data to represent this month.

- Monthly Sampling – since WIM sites can collect many years of data, users may only be interested in using twelve consecutive months' data right after a WIM system calibration or 12 selected months' data based on engineering judgment for pavement design.

Details are not provided since data sampling and repair is not the focus of this thesis.

Traffic Data Export

The traffic data export module is mainly utilized to generate three levels of traffic inputs for Pavement ME software: Level 1 site specific, Level 2 clustering average, Level 3 state average and LTPP TPF-5(004) defaults. The generated input files can be directly imported into Pavement ME Design. Furthermore, the export module fully implement the clustering methods developed by North Carolina, Michigan DOTs, Kentucky Transportation Cabinet (KYTC), the Truck Traffic Classification (TTC) method, and the simplified TTC approach, so that state agencies can flexibly generate Level 2 loading spectra inputs for Pavement ME Design. The traffic data export capability allows highway agencies to utilize existing limited WIM data for pavement design at any location. Details are not provided since this is not the focus in this thesis.

Oklahoma WIM Data

Oklahoma WIM Monitoring Program

In March 2013, Oklahoma Department of Transportation (ODOT) provided the OSU research team with raw WIM data collected from 2008 to 2012. The raw WIM data is following 2001 FHWA Traffic Monitoring Guide (TMG) *(9)* data format, which is used by most state DOTs for WIM data collection. Table 2.1 shows the summary and Figure 2.4 shows the distribution of 23 WIM stations in Oklahoma.

The WIM data following FHWA TMG *(9)* is consists of four types: traffic volume data, station description data (STA data), vehicle classification data (VCD data), and truck weight data (WGT data). The traffic volume file contains one record for each day of traffic monitoring. The station description file contains one record for each traffic monitoring station per year. The vehicle classification file contains one record for each hour with the traffic volume by vehicle class. And the truck weight file contains one record for each truck with its axle weights and spacing. Specific coding instructions and record layouts can also be found in Chapter 6 in the 2001 Traffic Monitoring Guide.

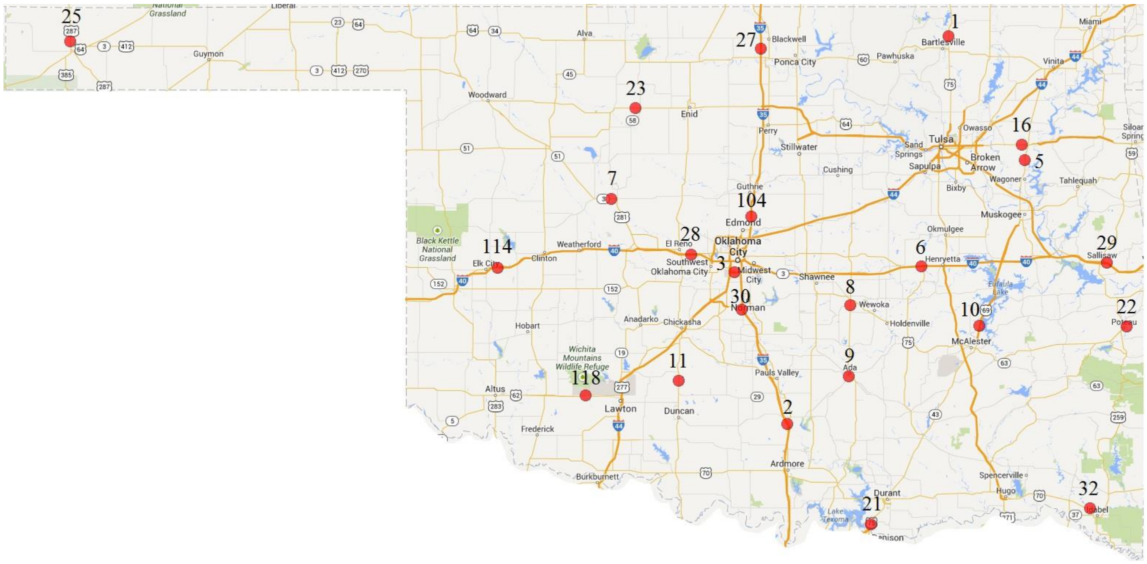


Figure 2.4 Distribution of WIM Stations in Oklahoma

Table 2.1 WIM Stations in Oklahoma

WIM ID	**Func. Class**	**Sensor**	**County FIPS**	**Route #**	**Location**
000001	2	P	74	75	6.3 miles south of Jt. US-60
000002	1	P	50	35	2.6 miles south of Jt. SH-7
000003	11	P	55	240	2.57 miles West of Jt. I-35
000005	2	P	73	69	6.4 miles south Jt. US-412
000006	1	P	54	40	1.0 miles west of Jt. US-75 south
000007	2	P	6	270	2.7 miles west of Jt. SH-8
000008	2	P	67	99	0.3 Miles North Jt. SH-59 West
000009	2	P	62	3	1.1 miles East of Jt. SH-1
000010	2	P	61	69	3.75 Miles North Jt. SH-113
000011	6	P	26	81	2.46 Miles South Jt. US-81bus South
000016	2	P	49	412	2.6 Miles West Jt. US-69
000021	7	P	40	69	1.10 miles north of the Red River Bridge
000022	7	P	40	112	1.2 miles East Jt. US-59
000023	2	P	47	412	2.2 miles West Jt. US-58
000025	2	P		287	5.6 miles north of intersect of SH-3 & US 287
000027	1	P	36	35	2.5 Miles North Jt. US-60
000028	1	P	9	40	Location Not set as of 10/21/02
000029	1	P	68	40	0.5 Miles East Mile Marker 311
000030	1	P	44	35	100 Ft. North of Mile Marker 105
000032	2	P		70	3.5 miles West of Junction US-259/US-70
000104	1	P	42	35	0.5 miles North of Jt. Waterloo Rd
000114	1	P	75	40	0.1 Miles West of Mile Marker 43
000118	2	P	16	62	1.3 Miles West Jt. SH-115

WIM Data Evaluation

After importing all five-year WIM data into Prep-ME database, automatically data quality check (in traffic data check module of Prep-ME) is implemented for both weight and classification data check. Only the weight or classification data with good quality in twelve consecutive months can pass the automatically data quality check since Pavement ME Design requires at least twelve months of data for load spectra inputs.

Table 2.2 summarize the QC check status of 2008-year WIM data. 18 WIM sites pass weight QC check, while 3 WIM sites fail; 20 WIM sites pass classification QC check, while 1 WIM site fail. 18 WIM sites have both "good" weight and classification data, and 2 WIM sites have only good data in classification. Only one WIM site (No. 000008) fails QC check for both weight and classification data.

Table 2.3 summarize the QC check status of 2009-year WIM data. 11 WIM sites pass weight QC check, and 16 WIM sites pass classification QC check. As a result, only 11 WIM sites have both "good" weight and classification data.

Table 2.2 QC Check of 2008-Year WIM Data

WIM Sites after Weight QC Check		**WIM Sites After Classification QC Check**		**WIM Sites with "Good" Data (Weights & Classification)**	**WIM Sites with "Good" Data (Classificatio)**	**WIM Sites with "No Good" Data (Weights & Classification)**
Pass	**Fail**	**Pass**	**Fail**			
000001	000008	000001	000008	000001	000030	000008
000002	000030	000002		000002	000114	
000003	000114	000003		000003		
000005		000005		000005		
000006		000006		000006		
000007		000007		000007		
000009		000009		000009		
000010		000010		000010		
000011		000011		000011		
000016		000016		000016		
000021		000021		000021		
000022		000022		000022		
000023		000023		000023		
000027		000027		000027		
000028		000028		000028		
000029		000029		000029		
000104		**000030**		000104		
000118		000104		000118		
		000114				
		000118				

Table 2.3 Summary of QC Check Status in 2009-Year WIM Data

WIM Sites after Weight QC Check		**WIM Sites After Classification QC Check**		**WIM Sites with "Good" Data (Weights & Classification)**	**WIM Sites with "Good" Data (Classification)**	**WIM Sites with "No Good" Data (Weights & Classification)**
Pass	**Fail**	**Pass**	**Fail**			
000001	000002	000001	000002	000001	000006	000002
000003	000006	000003	000007	000003	000009	000007
000005	000007	000005	000028	000005	000022	000028
000010	000009	**000006**		000010	000030	
000016	000022	**000009**		000016	000114	
000021	000028	000010		000021		
000023	000030	000016		000023		
000027	000114	000021		000027		
000029		**000022**		000029		
000104		000023		000104		
000118		000027		000118		
		000029				
		000030				
		000104				
		000114				
		000118				

Table 2.4 summarizes the number of five-year WIM sites with good data quality. For example, depending on 2008 WIM data, there are 18 WIM sites have effective data of both traffic weight and classification in twelve consecutive months, and 2 WIM sites have only effective data of classification in twelve consecutive months.

Table 2.4 Summary of WIM Stations that Pass QC Check

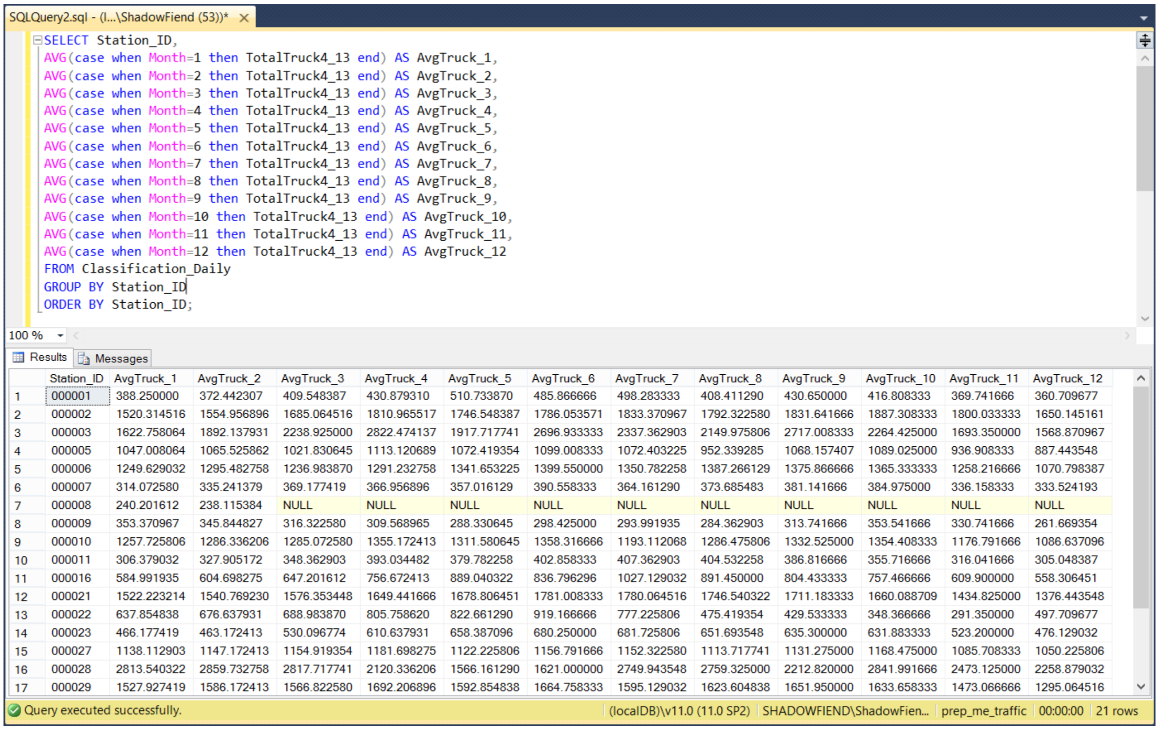
WIM Data Year	**# WIM Sites with "Good" Data (Weights & Classification)**	**# WIM Sites with "Good" Data (Classification)**
2008	18	2
2009	11	5
2010	5	11
2011	8	7
2012	10	8

Data Preparation

2008 WIM data are selected as the data source for subsequent data analysis. The next step for data preparation is extracting useful traffic data from Prep-ME database.

The database is consist of various tables storing different types of WIM data. The names and structures of tables are designed by programmers. To query data from specific tables in database, a series of SQL commands in SQL server management studio can be applied to extract desired WIM data. For example, the SQL command of "SELECT * FROM A" means query all the data in the table named A.

Figure 2.5 shows an operation interface while executing SQL commands to query the daily average truck volume data, which is stored in the table named "Classification_Daily", collected by different WIM sites in consecutive twelve months. The corresponding results are shown below the command window.



```sql
SELECT Station_ID,
AVG(case when Month=1 then TotalTruck4_13 end) AS AvgTruck_1,
AVG(case when Month=2 then TotalTruck4_13 end) AS AvgTruck_2,
AVG(case when Month=3 then TotalTruck4_13 end) AS AvgTruck_3,
AVG(case when Month=4 then TotalTruck4_13 end) AS AvgTruck_4,
AVG(case when Month=5 then TotalTruck4_13 end) AS AvgTruck_5,
AVG(case when Month=6 then TotalTruck4_13 end) AS AvgTruck_6,
AVG(case when Month=7 then TotalTruck4_13 end) AS AvgTruck_7,
AVG(case when Month=8 then TotalTruck4_13 end) AS AvgTruck_8,
AVG(case when Month=9 then TotalTruck4_13 end) AS AvgTruck_9,
AVG(case when Month=10 then TotalTruck4_13 end) AS AvgTruck_10,
AVG(case when Month=11 then TotalTruck4_13 end) AS AvgTruck_11,
AVG(case when Month=12 then TotalTruck4_13 end) AS AvgTruck_12
FROM Classification_Daily
GROUP BY Station_ID
ORDER BY Station_ID;
```

	Station_ID	AvgTruck_1	AvgTruck_2	AvgTruck_3	AvgTruck_4	AvgTruck_5	AvgTruck_6	AvgTruck_7	AvgTruck_8	AvgTruck_9	AvgTruck_10	AvgTruck_11	AvgTruck_12
1	000001	388.250000	372.442307	409.548387	430.879310	510.733870	485.866666	498.283333	408.411290	430.650000	416.808333	369.741666	360.709677
2	000002	1520.314516	1554.956896	1685.064516	1810.965517	1746.548387	1786.053571	1833.370967	1792.322580	1831.641666	1887.308333	1800.033333	1650.145161
3	000003	1622.758064	1892.137931	2238.925000	2822.474137	1917.717741	2696.933333	2337.362903	2149.975806	2717.008333	2264.425000	1693.350000	1568.870967
4	000005	1047.008064	1065.525862	1021.830645	1113.120689	1072.419354	1099.008333	1072.403225	952.339285	1068.157407	1089.025000	936.908333	887.443548
5	000006	1249.629032	1295.482758	1236.983870	1291.232758	1341.653225	1399.550000	1350.782258	1387.266129	1375.866666	1365.333333	1258.216666	1070.798387
6	000007	314.072580	335.241379	369.177419	366.956896	357.016129	390.558333	364.161290	373.685483	381.141666	384.975000	336.158333	333.524193
7	000008	240.201612	238.115384	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
8	000009	353.370967	345.844827	316.322580	309.568965	288.330645	298.425000	293.991935	284.362903	313.741666	353.541666	330.741666	261.669354
9	000010	1257.725806	1286.336206	1285.072580	1355.172413	1311.580645	1358.316666	1193.112068	1286.475806	1332.525000	1354.408333	1176.791666	1086.637096
10	000011	306.379032	327.905172	348.362903	393.034482	379.782258	402.858333	407.362903	404.532258	386.816666	355.716666	316.041666	305.048387
11	000016	584.991935	604.698275	647.201612	756.672413	889.040322	836.796296	1027.129032	891.450000	804.433333	757.466666	609.900000	558.306451
12	000021	1522.223214	1540.769230	1576.353448	1649.441666	1678.806451	1781.008333	1780.064516	1746.540322	1711.183333	1660.088709	1434.825000	1376.443548
13	000022	637.854838	676.637931	688.983870	805.758620	822.661290	919.166666	777.225806	475.419354	429.533333	348.366666	291.350000	497.709677
14	000023	466.177419	463.172413	530.096774	610.637931	658.387096	680.250000	681.725806	651.693548	635.300000	631.883333	523.200000	476.129032
15	000027	1138.112903	1147.172413	1154.919354	1181.698275	1122.225806	1156.791666	1152.322580	1113.717741	1131.275000	1168.475000	1085.708333	1050.225806
16	000028	2813.540322	2859.732758	2817.717741	2120.336206	1566.161290	1621.000000	2749.943548	2759.325000	2212.820000	2841.991666	2473.125000	2258.879032
17	000029	1527.927419	1586.172413	1566.822580	1692.206896	1592.854838	1664.758333	1595.129032	1623.604838	1651.950000	1633.658333	1473.066666	1295.064516

Query executed successfully. | (localDB)\v11.0 (11.0 SP2) | SHADOWFIEND\ShadowFien... | prep_me_traffic | 00:00:00 | 21 rows

Figure 2.5 Execution of SQL Commands in SQL Server Management Studio 2012

Four database tables are primarily used for WIM data preparation including:

- "Classification_Hourly" table, which stores hourly traffic distribution by classification as shown in Table 2.5. The hourly traffic and truck volume data is recorded in this table.
- "Classification_Daily" table, which saves daily traffic distribution by classification as shown in Table 2.6. The daily traffic and truck volume data is recorded in this table.
- "Weight_QC_Class9_daily" table, which keeps daily weight distribution of class 9 vehicles as shown in Table 2.7.The gross vehicle weight data is recorded in this

table;

- Weight_daily, which houses axle number distribution as shown in Table 2.8. The data of load bins by each axle is recorded in this table.

WIM data (including traffic volume, truck class, traffic weights) in the Prep-ME database are extracted using SQL commands and used for statistical computation and analysis of traffic variation.

Table 2.5 “Classification_Hourly” Table in Prep-ME Database

Column Name	**Data Type**	**Description**
State_Code	Char	Record the state code, such as “40” means Oklahoma
Station_ID	Char	Record the WIM station No.
Direction	Integer	Record the direction, such as “7” means “West” following TMG 2001
Lane	Integer	Record the lane, such as “1” means “Outside Lane” in TMG 2001
Year	Integer	Record the year when data is collected
Month	Integer	Record the month when data is collected
Day	Integer	Record the day when data is collected
Hour_of_Data	Integer	Record the hour when data is collected
Total_Volume	Decimal	Record traffic volume in specific direction, lane, year, month and day
Total_Truck4_13	Decimal	Record truck volume in specific direction, lane, year, month and day
C5	Decimal	Record C5 vehicle volume in specific direction, lane, year, month and day
C9	Decimal	Record C9 vehicle volume in specific direction, lane, year, month and day
C13	Decimal	Record C13 vehicle volume in specific direction, lane, year, month and day

Table 2.6 “Classification_Daily” Table in Prep-ME Database

Column Name	**Data Type**	**Description**
State_Code	Char	Record the state code, such as “40” means Oklahoma
Station_ID	Char	Record the WIM station No.
Direction	Integer	Record the direction, such as “7” means “West” following TMG 2001
Lane	Integer	Record the lane, such as “1” means “Outside Lane” in TMG 2001
Year	Integer	Record the year when data is collected
Month	Integer	Record the month when data is collected
Day	Integer	Record the day when data is collected
Total_Volume	Decimal	Record traffic volume in specific direction, lane, year, month and day
Total_Truck4_13	Decimal	Record truck volume in specific direction, lane, year, month and day
C5	Decimal	Record C5 vehicle volume in specific direction, lane, year, month and day
C9	Decimal	Record C9 vehicle volume in specific direction, lane, year, month and day
C13	Decimal	Record C13 vehicle volume in specific direction, lane, year, month and day

Table 2.7 “Weight_QC_Class9_daily” Table in Prep-ME Database

Column Name	**Data Type**	**Description**
State_Code	Char	Record the state code, such as “40” means Oklahoma
Station_ID	Char	Record the WIM station No.
Direction	Integer	Record the direction, such as “7” means “West” following TMG 2001
Lane	Integer	Record the lane, such as “1” means “Outside Lane” in TMG 2001
Year	Integer	Record the year when data is collected
Month	Integer	Record the month when data is collected
Day	Integer	Record the day when data is collected
W4k to W204k	Decimal	Record gross vehicle weight of C9 truck (kips) in specific direction, lane, year, month and day

Table 2.8 “Weight_daily” Table in Prep-ME Database

Column Name	**Data Type**	**Description**
State_Code	Char	Record the state code, such as “40” means Oklahoma
Station_ID	Char	Record the WIM station No.
Direction	Integer	Record the direction, such as “7” means “West” following TMG 2001
Lane	Integer	Record the lane, such as “1” means “Outside Lane” in TMG 2001
Year	Integer	Record the year when data is collected
Month	Integer	Record the month when data is collected
Day	Integer	Record the day when data is collected
S3k to S41k	Integer	Record the number of single axle load bins in specific direction, lane, year, month and day
T6k to T82k	Integer	Record the number of tandem axle load bins in specific direction, lane, year, month and day
Tr12k to Tr102k	Integer	Record the number of tridem axle load bins in specific direction, lane, year, month and day
Q12k to Q102k	Integer	Record the number of quad axle load bins in specific direction, lane, year, month and day

CHAPTER III

VARIATION OF TRUCK TRAFFIC CHARACTERISTICS

Characteristics of Traffic Stream

Based on the traffic analyses performed by Washington, different states are subject to different truck travel patterns *(4)*. In some states, Average Annual Daily Traffic (AADT), Average Annual Daily Truck Traffic (AADTT), and truck weight patterns vary significantly from morning to evening, from weekday to weekend, from month to month or from season to season. While other states have fairly stable AADT, AADTT and truck weight patterns.

Traffic Monitoring Guide *(9)* also shows that truck volumes vary in different time periods and locations. In addition, truck variations are different from one type of truck to another. Furthermore, variations in truck weights also change dramatically from time period to time period and location to location, even within a specific truck classification. Therefore, it is important for State DOTs to measure these variations to make correct decisions for design, operation and maintenance of roadways.

As mentioned above, traffic variations exist in different time periods. Based on the 2001 Traffic Monitoring Guide (TMG) *(9)*, traffic variations can be analyzed based on the following 4 categories:

- Time-of-Day: to calculate hour-of-day Coefficient of Variation;
- Day-of-Week: to calculate day-of-week Coefficient of Variation;
- Month-of-Year: to calculate month-of-year Coefficient of Variation;
- Season-of-Year: to calculate season-of-year Coefficient of Variation;

WIM data contains information of traffic volumes, vehicle classes and truck weights. To investigate different time variation in WIM data, the following eight typical traffic parameters are studied:

- Traffic Volume Data
    - AADT
- Truck Classification Data
    - AADTT
    - AADTT of class 5 vehicles (two-axle, six-tire, single-unit trucks) *(13)*
    - AADTT of class 9 vehicles (five-axle, single-trailer trucks) *(13)*
    - AADTT of class 13 vehicles (seven or more axle multi-trailer trucks) *(13)*
- Traffic Weight Data
    - Gross Vehicle Weight (GVW) of class 9 vehicles
    - Weight Damage by single axle load (obtained from damage factors and distribution of single axle load, which will discussed in the next section)
    - Weight Damage by tandem axle load (obtained from damage factors and distribution of tandem axle load, which will discussed in the next section)

Considering four time variations (Hour-of-Day, Day-of-Week, Month-of-Year, Season-of-Year) for each traffic parameter are computed, there are 4*8 = 32 different combinations. Because weight data (GVW, single and tandem axle load damage) has no hourly information, the total number of traffic characteristics combination is 32 – 3 = 29. The computation of variation of these traffic characteristics are presented later in this chapter.

Weight Damage by Axle Type

Axle load spectra, utilized to represent the percentage of total axle applications within each load interval for vehicle axles *(11)*, is an important component of traffic weight data. However, because of the load bins of each axle type are extremely detailed, it is necessary to deploy an aggregated indicator to represent truck weight load bins for statistical analysis. In this thesis, the methodology developed at the North Carolina State University is adopted to estimate the damage caused by each axle type based on the two following two parameters *(12)*:

- Axle numbers in each axle load bins of all trucks (or axle frequency);
- Damage factors (DF) in axle load bins.

The daily axle numbers in each load bin for each vehicle type (from class 4 to class 13) for each WIM site are obtained from the Prep-ME database. For example, Table 3.1 shows the average daily numbers of axle load bins for all trucks of WIM station No. 000001 in Oklahoma.

The damage factor (DF) for any load bin and axle type combination is defined as the ratio of the fatigue damage caused by that combination to that caused by a standard 18-kip Equivalent Single Axle Load (ESAL) *(12)*. Table 3.2 is the average DF developed in North Carolina for all the load bins and axle types *(12)*.

Subsequently the daily damage caused by each axle type is the summation of the daily axle number in each load bin multiplied by the damage factors for that bin. This concept has been included in the 2013 version of Traffic Monitoring Guide in Appendix G *(1)*. For example, daily damage caused by single axle load is calculated by the following formula *(12)*:

$$Daily\ Damage\ of\ Single\ Axle = \sum_{i=1}^{39} \text{DFi of SALB} * \text{\# in SALB (i)}$$

Where DFi of SALB = Damage Factor of Each Single Axle Load Bin; # in SALB (i) = Axle Number in Each Single Axle Load Bin. In total there are 39 axle bins for single axle, from 3000 lbs to 41,000lbs with an increment of 1,000lbs.

Table 3.3 shows the average results of daily damage of all the axle load types (single, tandem, tridem, and quad) for all trucks for WIM station 000001. Therefore the percentage of damage caused by single axle (164.58) among all four axles (164.58+365.84+7.31+0.45) equals to approximately 30.58%; while tandem axle account for 67.98% of damage, tridem axles 1.36%, and quad axles 0.08%.

The percentage of damages caused by each axle type of all 21 WIM stations in Oklahoma are shown in Figure 3.1. This figure illustrates that most damage are caused by single and tandem axle. Therefore, variation analysis on axle load damage is only focus on the damage caused by single and tandem axle.

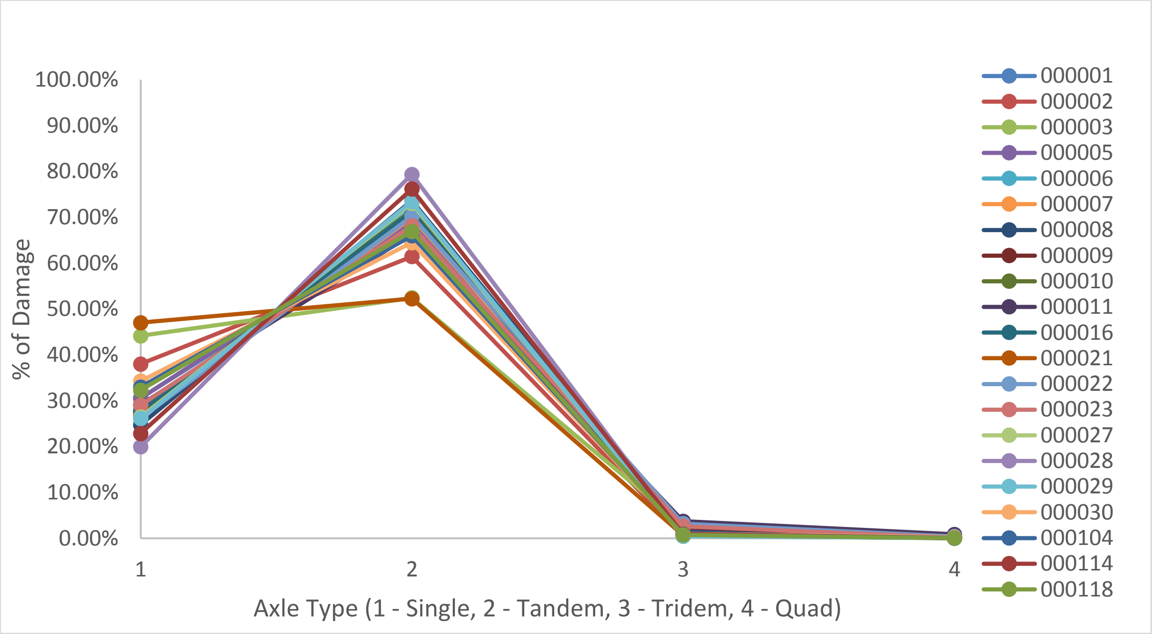


Figure 3.1 Percent of Damage Caused by Each Axle Type

Table 3.1 Average Daily Number of Axle Load Bins for Trucks in Station 000001

Axle Type							
Single		**Tandem**		**Tridem**		**Quad**	
Load (Kip)	**Daily #**	**Load (Kip)**	**Daily #**	**Load (Kip)**	**Daily #**	**Load (Kip)**	**Daily #**
3	754.03	**6**	67.79	**12**	2.54	**12**	0.00
4	541.92	**8**	90.95	**15**	1.57	**15**	0.04
5	320.65	**10**	147.90	**18**	1.16	**18**	0.06
6	142.82	**12**	149.91	**21**	0.88	**21**	0.03
7	161.39	**14**	108.44	**24**	0.86	**24**	0.02
8	194.30	**16**	69.60	**27**	0.77	**27**	0.02
9	325.29	**18**	56.36	**30**	0.75	**30**	0.03
10	177.79	**20**	54.33	**33**	0.92	**33**	0.01
11	87.63	**22**	57.55	**36**	0.80	**36**	0.01
12	34.45	**24**	69.61	**39**	0.83	**39**	0.02
13	31.50	**26**	94.54	**42**	0.78	**42**	0.01
14	26.78	**28**	94.91	**45**	0.63	**45**	0.04
15	19.43	**30**	80.40	**48**	0.54	**48**	0.03
16	21.29	**32**	54.66	**51**	0.43	**51**	0.05
17	13.22	**34**	31.91	**54**	0.25	**54**	0.06
18	11.24	**36**	17.29	**57**	0.16	**57**	0.02
19	5.87	**38**	9.11	**60**	0.08	**60**	0.02
20	4.34	**40**	5.20	**63**	0.06	**63**	0.01
21	2.14	**42**	2.98	**66**	0.01	**66**	0.01
22	1.76	**44**	1.94	**69**	0.02	**69**	0.01
23	1.01	**46**	1.32	**72**	0.01	**72**	0.01
24	0.88	**48**	0.87	**75**	0.00	**75**	0.01
25	0.53	**50**	0.58	**78**	0.01	**78**	0.00
26	0.49	**52**	0.50	**81**	0.01	**81**	0.01
27	0.37	**54**	0.32	**84**	0.00	**84**	0.00
28	0.24	**56**	0.22	**87**	0.00	**87**	0.00
29	0.21	**58**	0.19	**90**	0.01	**90**	0.00
30	0.09	**60**	0.13	**93**	0.00	**93**	0.00
31	0.12	**62**	0.10	**96**	0.00	**96**	0.00
32	0.08	**64**	0.07	**99**	0.00	**99**	0.00
33	0.05	**66**	0.06	**102**	0.00	**102**	0.00
34	0.03	**68**	0.06				
35	0.03	**70**	0.04				
36	0.02	**72**	0.04				
37	0.04	**74**	0.06				
38	0.02	**76**	0.05				
39	0.02	**78**	0.06				
40	0.02	**80**	0.04				
41	0.01	**82**	0.03				

Table 3.2 Average Damage Factors (DF) Developed in North Carolina

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**	0.06	**24**	0.03
8	0.03	**16**	0.04	**27**	0.15	**27**	0.06
9	0.06	**18**	0.08	**30**	0.23	**30**	0.10
10	0.09	**20**	0.13	**33**	0.34	**33**	0.15
11	0.13	**22**	0.19	**36**	0.48	**36**	0.21
12	0.19	**24**	0.27	**39**	0.67	**39**	0.28
13	0.26	**26**	0.37	**42**	0.91	**42**	0.39
14	0.35	**28**	0.50	**45**	1.19	**45**	0.51
15	0.47	**30**	0.67	**48**	1.55	**48**	0.66
16	0.61	**32**	0.86	**51**	1.98	**51**	0.85
17	0.78	**34**	1.10	**54**	2.50	**54**	1.07
18	1.00	**36**	1.39	**57**	3.16	**57**	1.35
19	1.22	**38**	1.73	**60**	3.84	**60**	1.65
20	1.50	**40**	2.13	**63**	4.69	**63**	2.01
21	1.83	**42**	2.64	**66**	5.67	**66**	2.43
22	2.22	**44**	3.14	**69**	6.79	**69**	2.91
23	2.65	**46**	3.76	**72**	8.12	**72**	3.47
24	3.16	**48**	4.47	**75**	9.54	**75**	4.08
25	3.73	**50**	5.28	**78**	11.19	**78**	4.79
26	4.37	**52**	6.19	**81**	13.05	**81**	5.58
27	5.15	**54**	7.27	**84**	15.13	**84**	6.48
28	5.91	**56**	8.37	**87**	17.40	**87**	7.45
29	6.81	**58**	9.65	**90**	20.04	**90**	8.58
30	7.82	**60**	11.08	**93**	22.90	**93**	9.80
31	8.93	**62**	12.65	**96**	26.07	**96**	11.15
32	10.16	**64**	14.40	**99**	29.55	**99**	12.64
33	11.52	**66**	16.27	**102**	32.97	**102**	14.10
34	13.01	**68**	18.42				
35	14.63	**70**	20.72				
36	16.33	**72**	23.23				
37	18.34	**74**	25.96				
38	20.44	**76**	28.94				
39	22.72	**78**	32.16				
40	25.18	**80**	35.64				
41	27.49	**82**	38.81				

Table 3.3 Average Daily Damage of Axle Load Types for All Trucks in Station 000001

Axle Type							
Single		**Tandem**		**Tridem**		**Quad**	
Load (Kip)	**Dmg**	**Load (Kip)**	**Dmg**	**Load (Kip)**	**Dmg**	**Load (Kip)**	**Dmg**
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**	0.03	**18**	0.01	**18**	0.00
6	0.03	**12**	0.92	**21**	0.02	**21**	0.00
7	1.65	**14**	1.80	**24**	0.06	**24**	0.00
8	5.87	**16**	2.74	**27**	0.11	**27**	0.00
9	19.52	**18**	4.60	**30**	0.17	**30**	0.00
10	16.00	**20**	6.94	**33**	0.31	**33**	0.00
11	11.39	**22**	10.79	**36**	0.38	**36**	0.00
12	6.55	**24**	18.57	**39**	0.55	**39**	0.00
13	8.19	**26**	34.98	**42**	0.71	**42**	0.01
14	9.38	**28**	47.56	**45**	0.75	**45**	0.02
15	9.14	**30**	53.94	**48**	0.84	**48**	0.02
16	12.99	**32**	47.04	**51**	0.86	**51**	0.04
17	10.31	**34**	35.15	**54**	0.62	**54**	0.06
18	11.24	**36**	24.02	**57**	0.51	**57**	0.03
19	7.16	**38**	15.78	**60**	0.30	**60**	0.04
20	6.53	**40**	11.09	**63**	0.30	**63**	0.02
21	3.92	**42**	7.85	**66**	0.08	**66**	0.02
22	3.90	**44**	6.08	**69**	0.11	**69**	0.02
23	2.67	**46**	4.97	**72**	0.11	**72**	0.04
24	2.79	**48**	3.89	**75**	0.00	**75**	0.03
25	1.98	**50**	3.06	**78**	0.09	**78**	0.00
26	2.16	**52**	3.07	**81**	0.07	**81**	0.03
27	1.93	**54**	2.34	**84**	0.04	**84**	0.02
28	1.42	**56**	1.83	**87**	0.05	**87**	0.00
29	1.42	**58**	1.82	**90**	0.17	**90**	0.00
30	0.71	**60**	1.47	**93**	0.00	**93**	0.00
31	1.09	**62**	1.23	**96**	0.00	**96**	0.03
32	0.82	**64**	1.04	**99**	0.00	**99**	0.00
33	0.57	**66**	0.95	**102**	0.09	**102**	0.00
34	0.36	**68**	1.02				
35	0.49	**70**	0.80				
36	0.27	**72**	0.90				
37	0.71	**74**	1.58				
38	0.34	**76**	1.52				
39	0.38	**78**	1.78				
40	0.56	**80**	1.58				
41	0.15	**82**	1.08				
Avg. Daily Damage of Single Axle	164.58	**Avg. Daily Damage of Tandem Axle**	365.84	**Avg. Daily Damage of Tridem Axle**	7.31	**Avg. Daily Damage of Quad Axle**	0.45

Variability of Traffic Characteristics

Greater variation (or dispersion) means that observations are quite different from center of the distribution *(10)*. For example, assume there are two data sets: data set A = {1, 2, 3, 4, 5, 6, 7, 8, 9} and data set B = {5, 5, 5, 5, 5, 5, 5, 5, 5}. Even though the average values of both data set A and B are 5. However, data fluctuates in set A, while data in set B is identical. In other words, set A and Set B have various level of variation, or the degree of data fluctuation.

The most commonly used methods to measure variation include data dispersion, mean deviation, standard deviation and coefficient of variation. The Coefficient of Variation (CV) is defined as the ratio of the standard deviation to the mean expressed as a percentage as follows:

$$CV = \frac{\left(\frac{1}{n} * \sum_{i=1}^{n} \left(Xi - \overline{X}\right)^{2}\right)^{\frac{1}{2}}}{\overline{X}}$$

Where

CV = coefficient of variation;

n = number of sample size;

Xi = values of each sample;

$\overline{X}$ = average values of all samples;

In this thesis, coefficient of variation is applied to estimate variability of WIM traffic characteristics. For example, the hour-of-day Coefficient of Variation in hourly truck volumes can be determined as:

$$\text{Hour of Day } CV = \frac{\left(\frac{1}{24} * \sum_{i=0}^{23} (Hi - \overline{H})^2\right)^{\frac{1}{2}}}{\overline{H}}$$

Where

Hour-of-Day CV = hour-of-day coefficient of variation in truck volumes;

Hi = hourly truck volume in specific hour period;

$\overline{H}$= Average hourly truck

Figure 3.2 shows hourly distribution of truck traffic volumes of WIM station 000003. The average hourly traffic volume is 358.76. The traffic volume from 00:00 am to 01:00 am is 73.04, the ADT from 01:00 am to 02:00 am is 47.2, etc. The hour-of-day CV for this WIM station is around 66.97%.

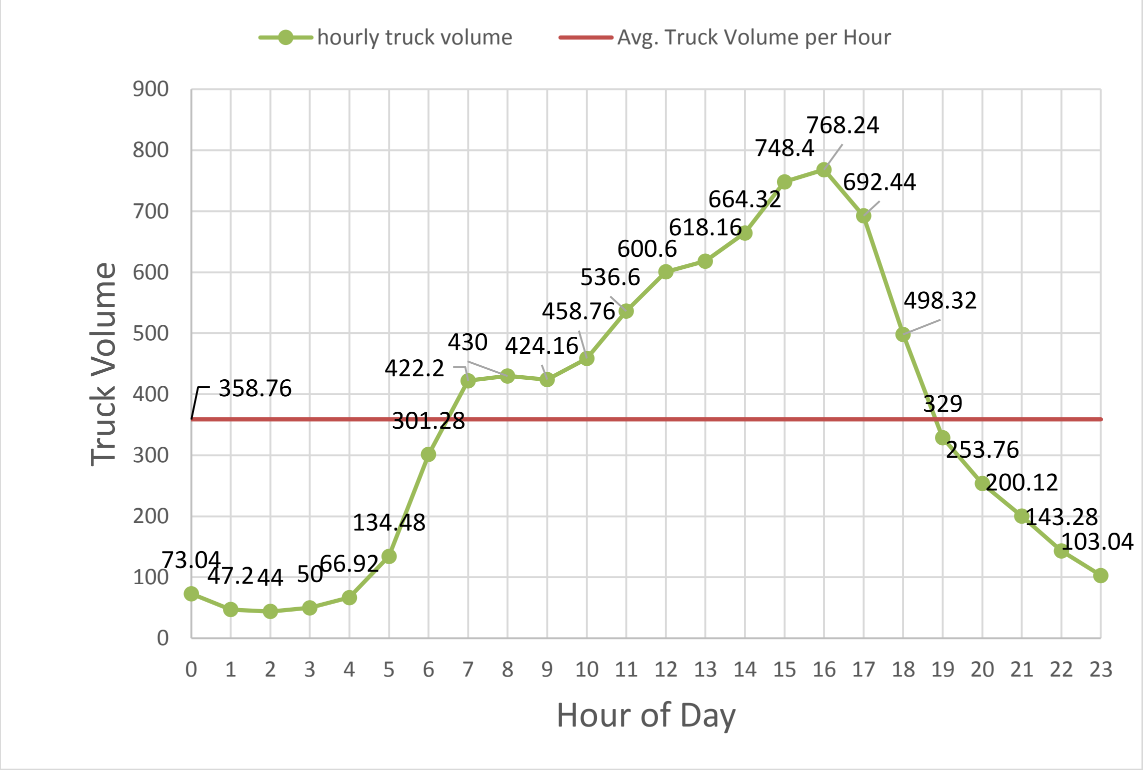


Figure 3.2 Distribution of Hourly Traffic Volume in a Day (Station No. 000003)

Aggregation Roadway Group

Twelve major types of public roads are defined through functional classification standard *(14)*. Considering there are only 21 WIM sites in 2008, analysis on WIM data for detailed highway functional classification would be statistically questionable due to small sample size. In this thesis, aggregate highway functional classification proposed by Kentucky Transportation Center (KYTC) is used. There are six aggregate classes *(15)*. Following this definition, the 21 WIM sites are grouped into four aggregate classes. Table 3.4 provides the aggregate classification and the WIM stations in each class. The variability of each traffic characteristic can be calculated and analyzed for each aggregated class.

Table 3.4 Aggregate Class based on KYTC Method

KYTC Agg. Class	**Functional Class**	**WIM Sites No.**
Class I	Rural Interstate (FC1)	000002 000006 000027 000028 000029 000030 000104 000114
Class II	Rural Principal Arterial (FC2)	000001 000005 000007 000008 000009 000010 000016 000021 000023 000118 000011
	Rural Minor Arterial (FC6)	
Class III	Rural Major Collector (FC7)	000022
	Rural Minor Collector (FC8)	
	Rural Local (FC9)	
Class IV	Urban Interstate (FC11)	000003
Class V	Urban Other Freeway and Expressway (FC12)	-
	Urban Other Principal Arterial (FC14)	
Class VI	Urban Minor Arterial (FC16)	-
	Urban Collector (FC17)	
	Urban Local (FC19)	

Time-of-Day Variation

Traffic Volume

Figure 3.3 shows the distributions of hour-of-day traffic volume data for each aggregate functional class.

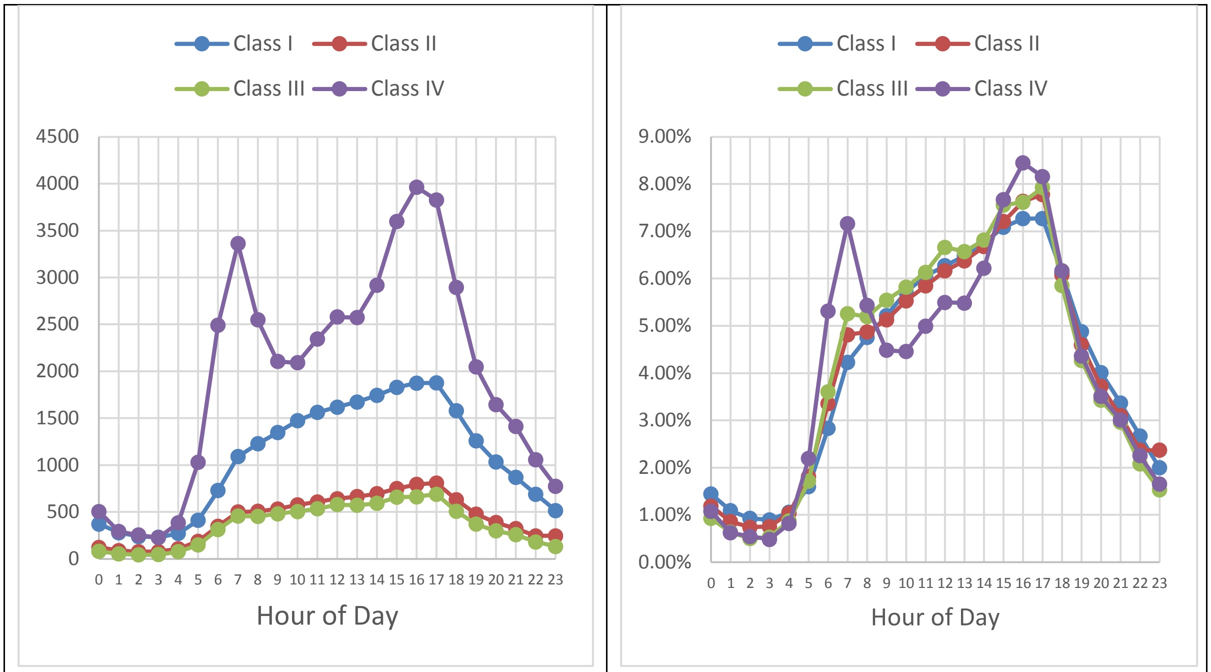
Based on Figure 3.3 (a), total traffic volumes on urban interstate (Class IV) are larger than those on rural roads. For rural roads, rural interstates (Class I) have larger traffic volumes than other rural functional roads (Class II and III), while traffic volumes on Class II roads are close to those on Class III.

Figure 3.3 (b) shows that percentage of traffic volumes follow either two-peak pattern or single-peak pattern. On urban roads (Class IV), two peaks are observed. Traffic volume begins to increase around 4:00 am and reach the first peak around 7:00 am in the morning. After a mildly drop at the noon, the traffic volumes reach the second peak around 4:00 pm in the afternoon. For rural roads, traffic tends to increase steadily from morning (around 4:00 am) to afternoon (around 4:00 pm), and descend slowly afterwards.

According to Figure 3.3 (c), truck volumes on urban interstates (Class IV) and rural interstates (Class I) are obviously larger than those on other rural roads (Class II and III). Class IV roads show obvious peak and off-peak traffic within a day, while Class I rural interstates remain relatively stable truck traffic.

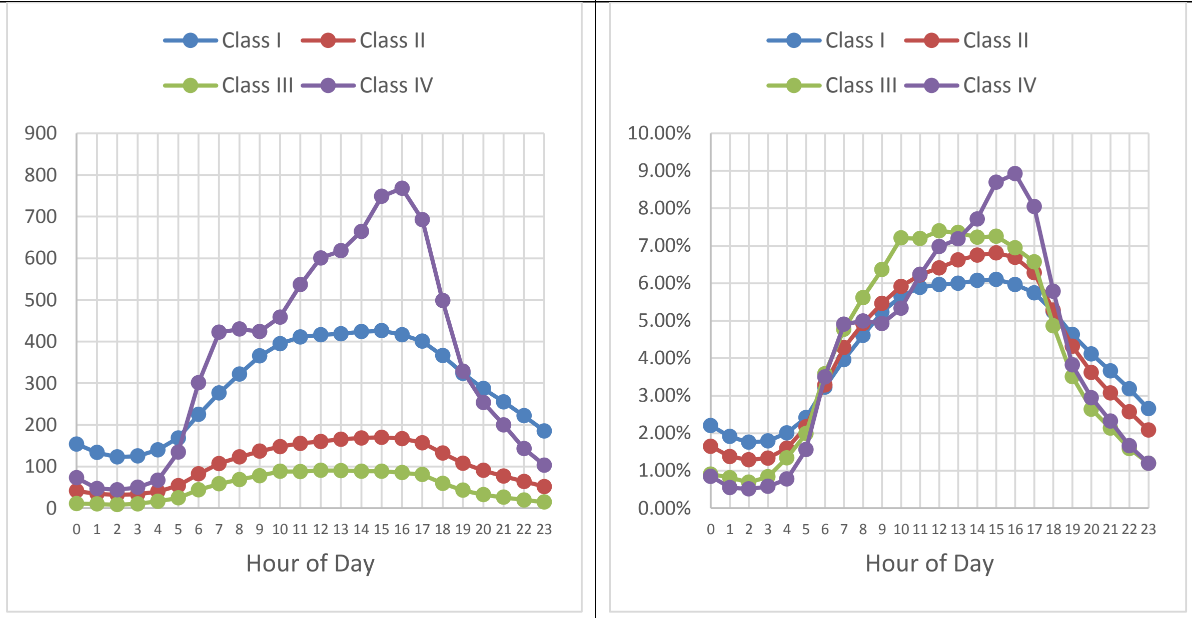
Figure 3.3 (d) shows that the hourly percentage changes of truck volumes. Comparing to Figure 3.3 (b), the morning peak is not as obvious as that for the total traffic. The afternoon peak is also observed on Class IV urban roads for truck traffic. However, for the other three rural road groups, the data show no distinctive peak truck traffic. There are significantly more trucks in the daytime than in the night.

Table 3.5 summarizes the hour-of-day CVs of both total traffic volume and truck volume, particularly, truck volumes for vehicle classes 5, 9, and 13 are provided as well. The results show that the hourly variations of both total traffic volume and truck volumes are significant.



(a) Hour-of-Day Average Traffic Volume

(b) Hour-of-Day Average Traffic Volume (%)



(c) Hour-of-Day Average Truck Volume

(d) Hour-of-Day Average Truck Volume (%)

Figure 3.3 Hourly Traffic Volume & Truck Classification in a Day

Table 3.5 Hour-of-Day CVs of Traffic Volume & Truck Classification

Agg. Class	WIM Sites No.	AADT	AADTT	C5 Trucks	C9 Trucks	C13 Trucks
Class I	**000002**	56.38%	35.84%	58.95%	31.83%	39.39%
	000006	54.67%	36.92%	59.85%	33.19%	49.80%
	000027	55.47%	39.71%	58.15%	39.54%	30.06%
	000028	54.30%	38.67%	59.58%	31.70%	36.71%
	000029	52.70%	35.63%	60.48%	32.97%	43.77%
	000030	56.44%	40.06%	60.03%	32.46%	38.56%
	000104	58.48%	44.51%	61.47%	39.63%	39.14%
	000114	48.97%	35.58%	57.47%	32.51%	75.86%
Class II	**000001**	60.73%	59.46%	73.09%	44.13%	93.82%
	000005	55.27%	43.87%	64.11%	42.07%	87.53%
	000007	60.86%	52.17%	62.37%	45.05%	82.07%
	000008	67.47%	65.43%	72.10%	54.10%	65.54%
	000009	61.86%	60.94%	63.57%	59.27%	80.36%
	000010	56.17%	41.53%	60.79%	39.60%	90.34%
	000011	63.64%	64.06%	66.76%	60.40%	94.34%
	000016	60.53%	64.96%	81.56%	57.92%	69.52%
	000021	51.62%	36.76%	65.60%	31.87%	74.45%
	000023	63.23%	59.48%	67.32%	54.12%	88.73%
	000118	61.23%	57.57%	63.92%	55.61%	57.79%
Class III	**000022**	61.34%	61.90%	68.32%	55.04%	81.16%
Class IV	**000003**	60.61%	66.97%	72.96%	55.25%	48.56%

Traffic Weight

Due to the huge size of WIM weight data, hourly data are not saved in the Prep-ME database. The calculation of time-of-day variation of traffic weight data is not available.

Day-of-Week Variation

Traffic Volume

Figure 3.4 shows the distributions of day-of-week traffic volume data for each aggregate functional class.

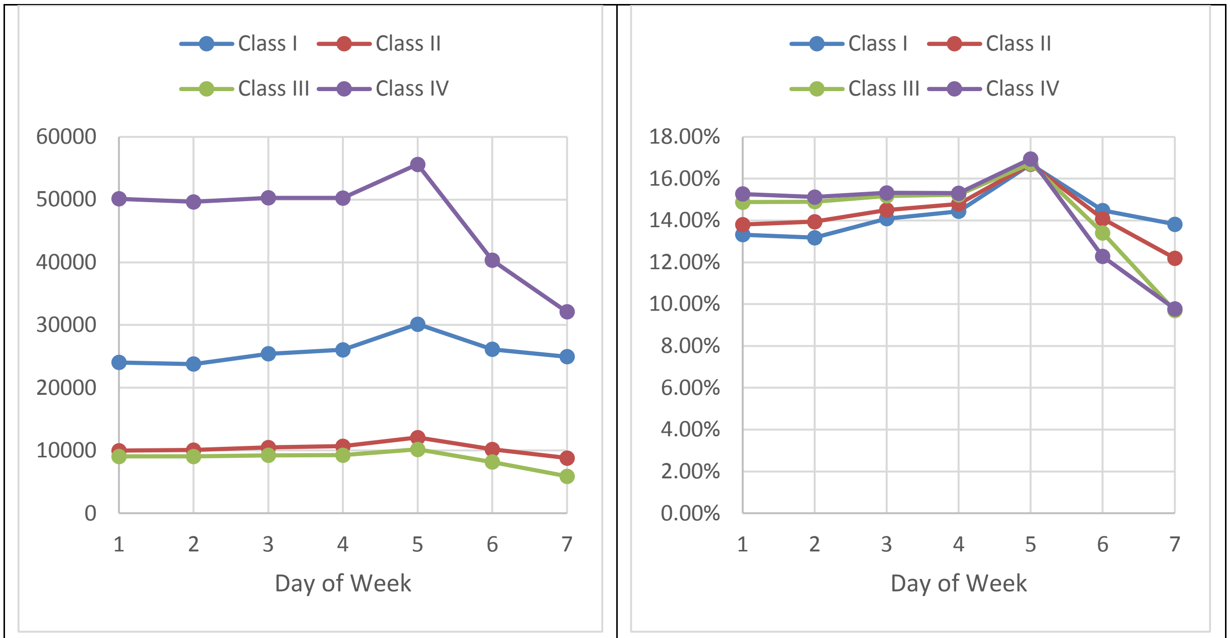
Based on Figure 3.4 (a), total traffic volumes on urban interstate (Class IV) are larger than those on rural roads. For rural roads, rural interstates (Class I) have larger traffic volumes than other rural functional roads (Class II and III), while traffic volumes on Class II roads are close to those on Class III.

Based on Figure 3.4 (b) traffic volumes on rural interstates (Class I) are relatively constant in a week, only with a slight increase on Friday. For other groups of roads, the total traffic volumes are fairly stable during weekdays and then decline in the weekends. For all four road groups, the traffic volumes on Friday are largest among those in a week. Usually in the weekend, traffic volumes on Sunday are lower than those on Saturday.

Based on Figure 3.4 (c), truck volumes on urban interstates (Class IV) and rural interstates (Class I) are obviously larger than those on other rural roads (Class II and III). Class IV roads show obvious peak and off-peak traffic within a week, while Class I rural interstates remain relatively stable truck traffic.

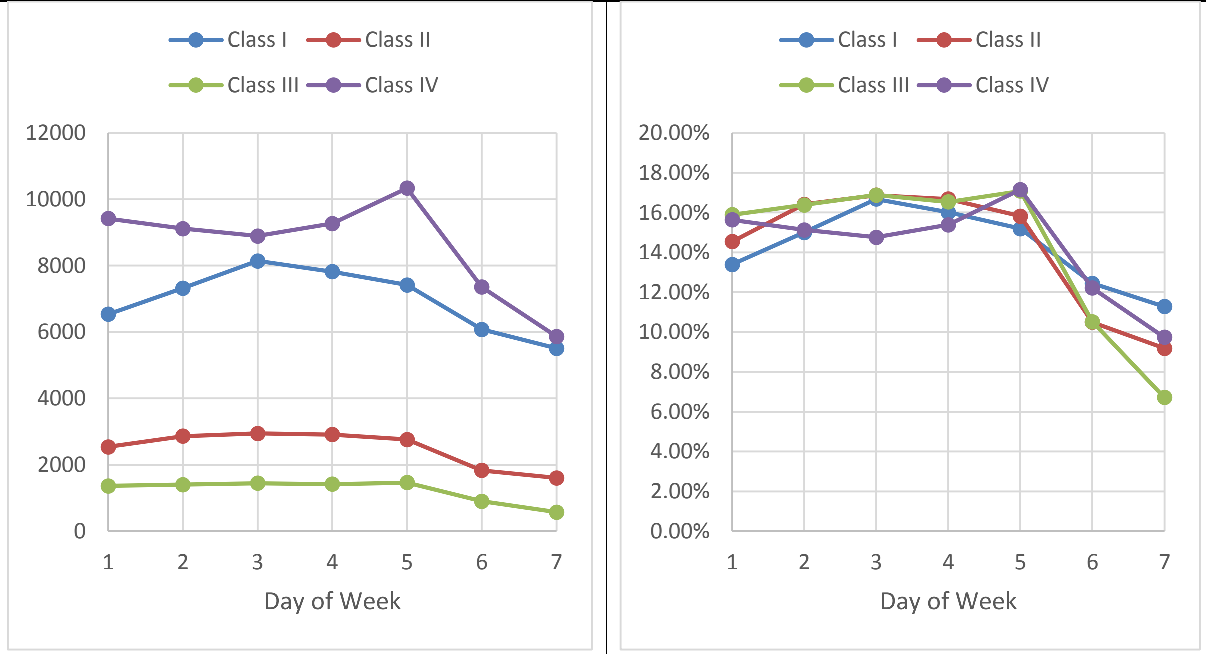
Figure 3.4 (d) shows that the daily percentage changes of truck volumes. Truck volumes on urban interstates (Class IV) follow a slight two-hump commute pattern. The truck volumes begin to increase and reach the first peak on Monday, and then taper off slightly until Friday when they rise again and reach to the second peak, and finally decline dramatically in the weekends. For rural functional roads (Class I, II, III), the truck volumes are relatively constant on the weekdays, with a slight decrease on the weekend.

Table 3.6 summarizes the day-of-week CVs of both total traffic volume and truck volume, particularly, volumes for vehicle classes 5, 9, and 13 are provided as well. Comparing with the hour-of-day CVs in traffic volumes, day-of-week CVs obviously decrease. It means that the daily variations are not as significant as hourly variations.



(a) Day-of-Week Average Traffic Volume

(b) Day-of-Week Average Traffic Volume (%)



(c) Day-of-Week Average Truck Volume

(d) Day-of-Week Average Truck Volume (%)

Figure 3.4 Day-of-Week Traffic Volume & Truck Classification

Table 3.6 Day-of-Week CVs of Traffic Volume & Truck Classification

Agg. Class	WIM Sites No.	AADT	AADTT	C5 Trucks	C9 Trucks	C13 Trucks
Class I	**000002**	13.44%	21.05%	12.44%	26.72%	31.58%
	000006	11.28%	10.47%	14.64%	10.00%	46.75%
	000027	11.49%	19.52%	9.74%	21.84%	45.07%
	000028	8.82%	10.20%	17.82%	14.53%	21.92%
	000029	8.29%	12.89%	16.06%	11.89%	22.54%
	000030	8.18%	24.61%	16.27%	29.04%	38.90%
	000104	8.22%	22.67%	18.49%	24.70%	46.08%
	000114	6.86%	11.33%	18.91%	17.22%	16.66%
Class II	**000001**	12.52%	23.08%	21.48%	24.42%	40.51%
	000005	7.77%	20.14%	14.79%	22.23%	26.79%
	000007	8.62%	20.54%	16.97%	24.21%	24.79%
	000008	15.40%	32.44%	24.97%	43.61%	40.68%
	000009	15.72%	32.17%	26.01%	34.69%	21.78%
	000010	8.60%	22.76%	16.75%	24.35%	26.30%
	000011	12.27%	22.05%	16.33%	35.05%	25.56%
	000016	11.53%	19.64%	12.37%	38.58%	44.39%
	000021	9.46%	22.05%	12.39%	28.33%	22.83%
	000023	12.61%	24.14%	16.59%	34.48%	25.73%
	000118	11.15%	31.07%	20.53%	40.22%	54.29%
Class III	**000022**	15.72%	28.20%	21.83%	39.49%	22.71%
Class IV	**000003**	16.94%	17.40%	13.08%	39.41%	40.57%

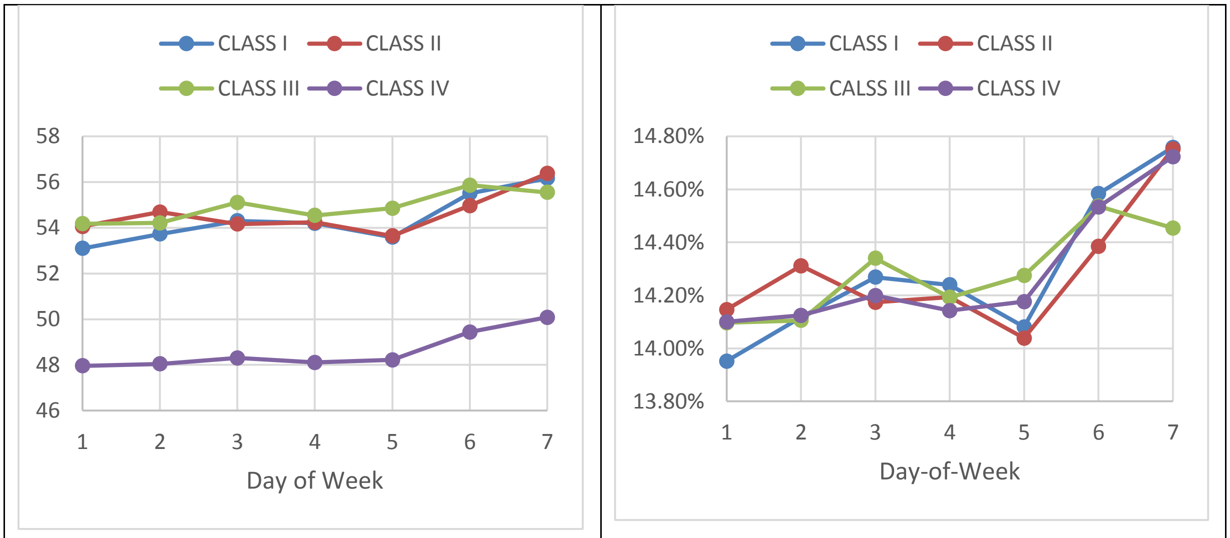
Traffic Weight

Figure 3.5 shows the distributions of day-of-week Gross Vehicle Weight (GVW) of class 9 vehicle for each aggregate roadway class.

In Figure 3.5 (a), the Class 9 GVWs on urban interstates (Class IV) are lower than those on rural functional roads. For rural roadway roads, no significant difference is observed for GVWs data.

Figure 3.5 (b) shows that the day-of-week percentage changes of truck volumes. Generally, Class 9 GVWs on all functional roads have no significant variation, only with a very slight increase on weekends.

Table 3.7shows the day-of-week CVs of Class 9 GVW, particularly, damage caused by single and tandem axle as well. The day-of-week CVs of axle load damage are much larger than those of GVW.



(a) Day-of-Week Average GVW (kips)

(b) Day-of-Week Average GVW (kips) (%)

Figure 3.5 Day-of-Week Gross Vehicle Weight

Table 3.7 Day-of-Week CVs of Traffic Weight

Agg. Class	WIM Sites No.	GVW	Single Axle Load Damage	Tandem Axle Load Damage
Class I	**000002**	2.24%	27.94%	22.99%
	000006	2.25%	18.68%	12.86%
	000027	2.60%	29.63%	21.00%
	000028	1.96%	13.80%	16.60%
	000029	2.07%	19.67%	11.17%
	000030	1.87%	33.13%	30.61%
	000104	3.20%	30.07%	24.73%
	000114	1.05%	12.42%	16.23%
Class II	**000001**	1.79%	39.97%	25.36%
	000005	1.81%	26.01%	21.41%
	000007	2.69%	31.60%	24.26%
	000008	4.21%	53.84%	49.96%
	000009	1.49%	38.28%	35.78%
	000010	2.16%	29.21%	23.71%
	000011	3.15%	37.47%	29.98%
	000016	2.15%	41.33%	37.15%
	000021	1.53%	31.80%	28.48%
	000023	0.74%	45.46%	35.54%
	000118	2.12%	43.26%	39.72%
Class III	**000022**	1.18%	43.83%	38.71%
Class IV	**000003**	1.70%	44.54%	39.11%

Monthly Variation

Traffic Volume

Figure 3.6 shows the distributions of month-of-year traffic volume data for each aggregate functional class.

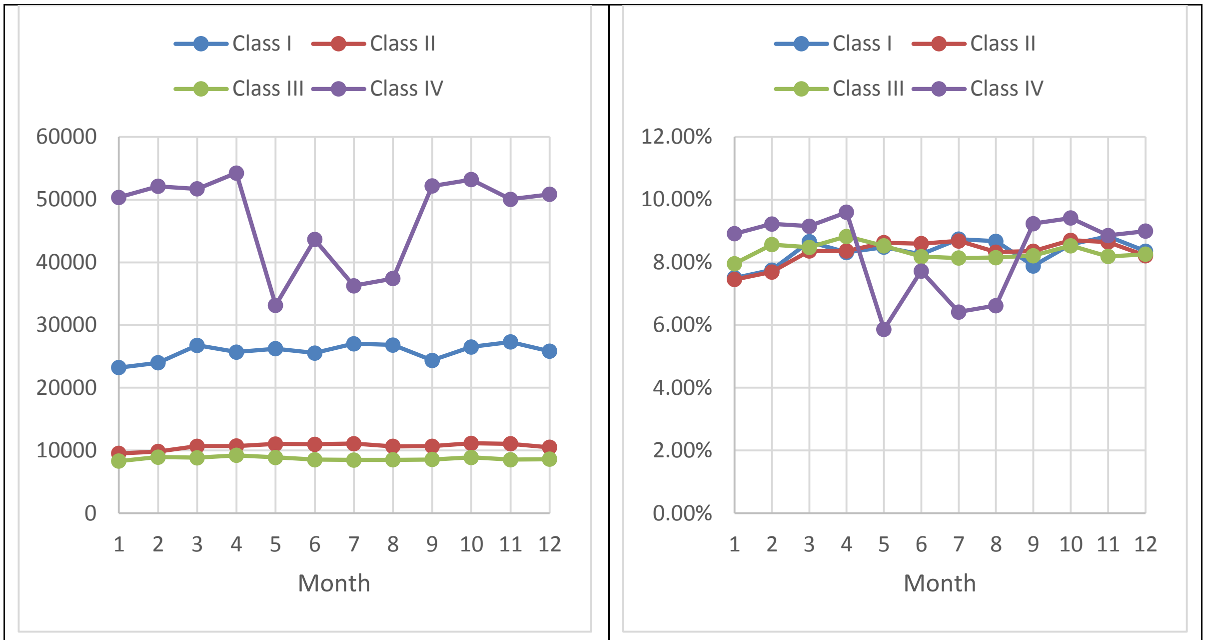
Based on Figure 3.6 (a), total traffic volumes on urban interstate (Class IV) are larger than those on rural roads. In addition, traffic volumes decrease in consecutive summer months. For rural roads, rural interstates (Class I) have larger traffic volumes than other rural functional roads (Class II and III), while traffic volumes on Class II roads are close to those on Class III.

Seen in Figure 3.6 (b), the traffic volumes on urban interstates (Class IV) have a significant decrease in the summer months (May, June, July, and August), while they are fairly constant in other months. For rural functional roads, the variations in traffic volumes from month to month are not very significant.

In Figure 3.6 (c), truck volumes on the urban interstates (Class IV) and rural interstates (Class I) are obviously larger than those on other rural roads (Class II and III). Class IV roads show obvious peak and off-peak traffic within a year, while Class I rural interstates remain relatively stable truck traffic. Interestingly, the truck volume increase obviously in summer while traffic volume decrease.

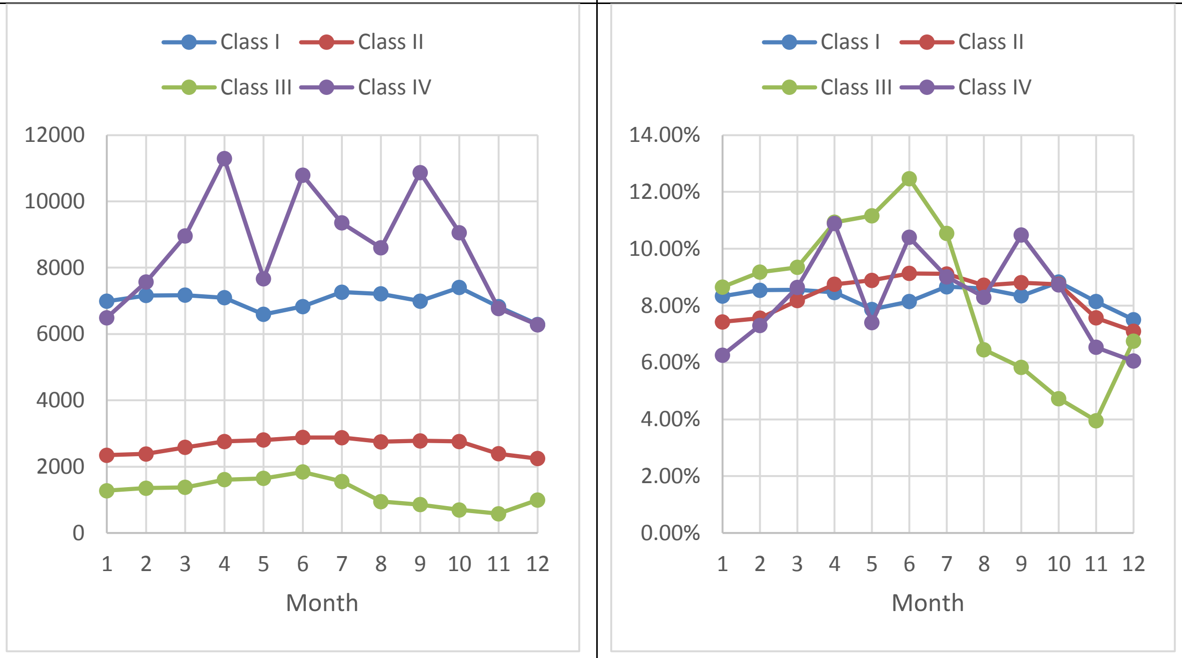
Based on Figure 3.6 (d), variations in truck volumes are anomalous on urban interstates (Class IV). For rural interstates and arterials (Class I and II), truck volumes keep fairly stable in most months, with slight decrease in winter months (Nov., Dec., and Jan.). For rural collectors and locals (Class III), truck volumes drop significantly in specific months (Jul., Aug., Sep., Oct. and Nov.), then keep to increase steadily from December to June.

Table 3.8 summarizes the results of month-of-year CVs of based on data of both traffic volume and truck classification. Comparing with the day-of-week CVs, month-of-year CVs decrease slightly. This illustrates that variations of traffic volumes and truck volumes from month to month are less obvious than those from day to day.



(a) Month-of-Year Average Traffic Volume

(b) Month-of-Year Average Traffic Volume (%)



(c) Month-of-Year Average Truck Volume

(d) Month-of-Year Average Truck Volume (%)

Figure 3.6 Monthly Traffic Volume & Truck Classification in a Year

Table 3.8 Month-of-Year CVs of Traffic Volume & Truck Classification

Agg. Class	WIM Sites No.	AADT	AADTT	C5 Trucks	C9 Trucks	C13 Trucks
Class I	**000002**	8.33%	6.62%	21.13%	4.18%	18.29%
	000006	7.67%	7.05%	2.90%	7.84%	10.74%
	000027	9.02%	3.24%	7.43%	4.28%	7.90%
	000028	10.58%	19.39%	24.29%	18.11%	23.54%
	000029	6.34%	6.78%	2.71%	7.29%	13.69%
	000030	4.50%	4.10%	2.75%	5.11%	17.65%
	000104	3.73%	3.64%	3.86%	5.06%	8.50%
	000114	4.16%	4.52%	4.24%	5.76%	14.99%
Class II	**000001**	5.36%	11.97%	18.99%	5.41%	25.81%
	000005	6.03%	6.92%	10.24%	8.37%	18.88%
	000007	5.50%	6.68%	5.60%	6.60%	36.90%
	000008	-	-	-	-	-
	000009	7.90%	9.33%	14.46%	13.35%	35.45%
	000010	5.03%	6.56%	5.59%	7.30%	16.10%
	000011	2.45%	10.97%	14.80%	5.70%	20.40%
	000016	4.98%	19.86%	36.49%	6.64%	29.53%
	000021	3.88%	8.16%	23.13%	6.21%	14.33%
	000023	6.82%	14.71%	22.38%	7.57%	42.57%
	000118	2.35%	3.97%	3.58%	4.60%	15.39%
Class III	**000022**	2.84%	32.99%	36.13%	32.01%	33.63%
Class IV	**000003**	15.19%	20.13%	24.83%	18.33%	18.54%

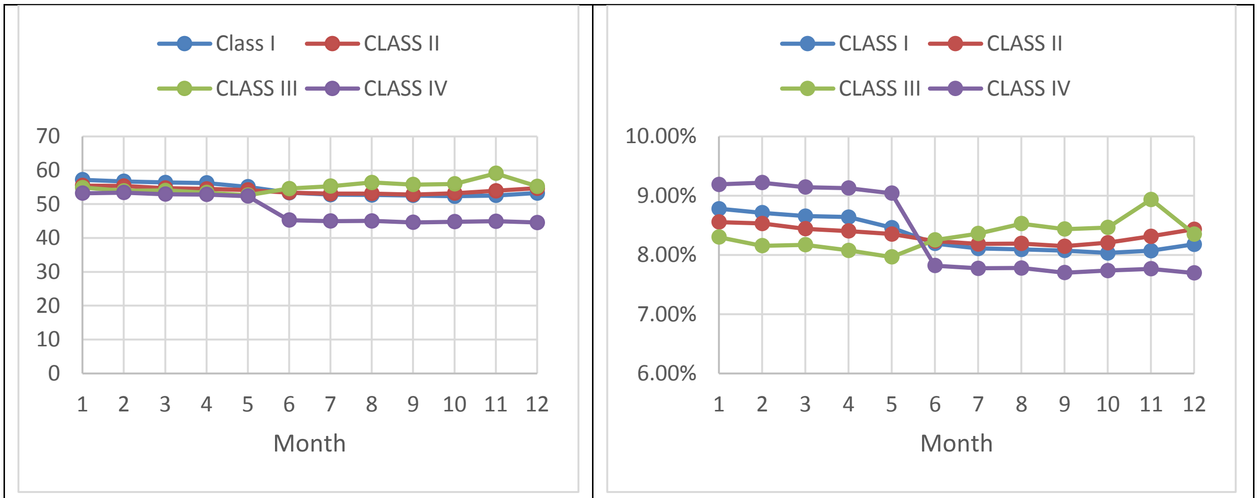
Traffic Weight

Figure 3.7 shows the distributions of month-of-year GVW of class 9 vehicle for each aggregate functional class.

In Figure 3.7 (a), the Class 9 GVWs on urban interstates (Class IV) are lower than those on rural functional roads. For rural functional roads, GVWs are relatively stable.

Figure 3.7 (b) shows that the month-of-year percentage changes of truck volumes. Generally, GVWs on all functional roads have no significant variation. For urban interstates (Class IV), GVW decrease slightly in the second half of year.

Table 3.9 shows the month-of-year CVs of Class 9 GVW, particularly, damage caused by single and tandem axle as well. The day-of-week CVs of GVW still much less than those of axle load damage.



(a) Month-of-Year Average GVW (kips)

(b) Month-of-Year Average GVW (kips) (%)

Figure 3.7 Monthly Gross Vehicle Weight

Table 3.9 Month-of-Year CVs of Traffic Weights

Agg. Class	**WIM Sites No.**	**GVW**	**Single Axle Load Damage**	**Tandem Axle Load Damage**
Class I	**000002**	1.16%	18.09%	5.48%
	000006	2.61%	11.14%	15.04%
	000027	4.09%	24.31%	29.65%
	000028	3.09%	12.67%	16.15%
	000029	1.60%	11.73%	9.24%
	000030	14.00%	35.39%	74.34%
	000104	1.54%	11.89%	13.06%
	000114	13.01%	48.12%	75.31%
Class II	**000001**	3.49%	24.07%	22.72%
	000005	1.33%	9.21%	8.49%
	000007	1.99%	31.11%	11.37%
	000008	-	-	-
	000009	2.04%	14.12%	8.81%
	000010	1.74%	10.94%	10.57%
	000011	2.16%	11.77%	16.48%
	000016	2.53%	13.49%	14.39%
	000021	2.59%	83.80%	10.99%
	000023	1.56%	5.94%	7.04%
	000118	7.73%	39.58%	40.54%
Class III	**000022**	3.02%	13.55%	11.36%
Class IV	**000003**	8.63%	39.00%	51.63%

Seasonal Variation

Traffic Volume

Figure 3.8 shows the distributions of season-of-year traffic volume data for each aggregate functional class.

In Figure 3.8 (a), the condition of season-of-year traffic volumes is similar to it of month-of-year traffic volumes. The total traffic volumes on urban interstate (Class IV) and rural interstate (Class I) are obviously larger than those on other rural roads (Class II and III), while traffic volumes on Class II roads are close to those on Class III.

Based on Figure 3.8 (b), traffic volumes on urban interstates (Class IV) decrease obviously in the summer. For rural functional roads (Class I, II, and III), traffic volumes are fairly constant in all seasons.

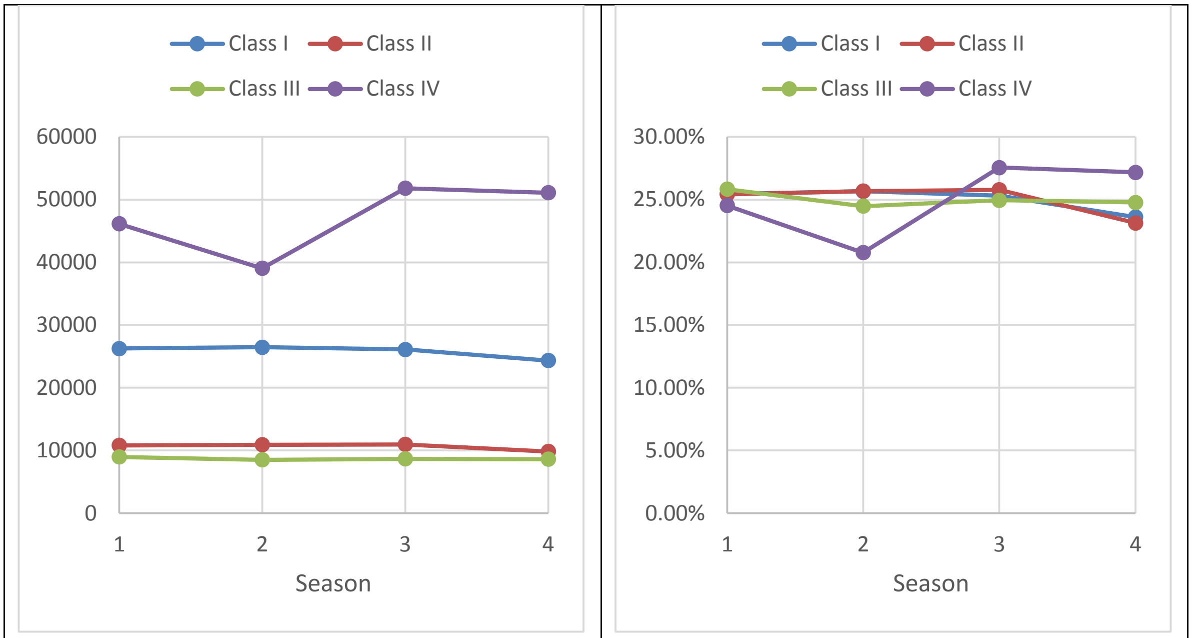
According to Figure 3.8 (c), truck volumes on the urban interstates (Class IV) and rural interstates (Class I) are obviously larger than those on other rural roads (Class II and III), while truck volumes on Class IV roads are higher than those on Class I.

In Figure 3.8 (d), truck volumes on rural collectors and locals (Class III) decrease obviously in the fall, while truck volumes on other functional roads are relatively stable.

Table 3.10 summarizes the season-of-year CVs of based on data of both traffic volume and truck classification. The season-of-year CVs are closed to month-of-year CVs.

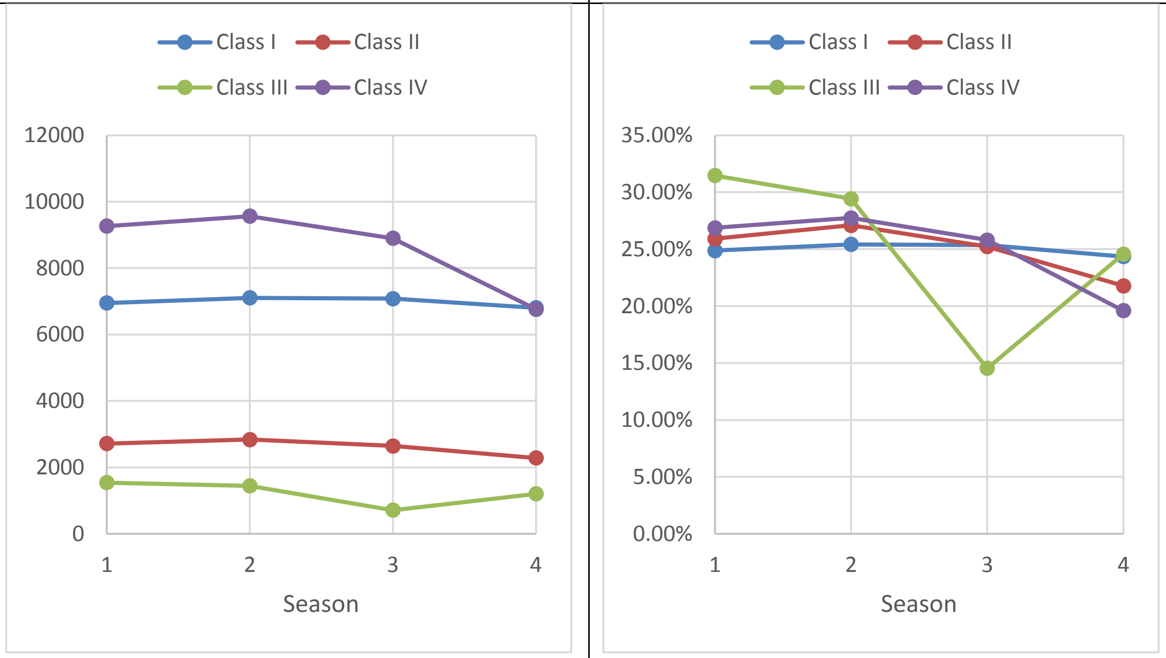
Table 3.10 Season-of-Year CVs of Traffic Volumes & Truck Classification

Agg. Class	WIM Sites No.	AADT	AADTT	C5 Trucks	C9 Trucks	C13 Trucks
Class I	**000002**	6.41%	6.73%	19.24%	2.71%	17.04%
	000006	7.99%	5.75%	2.41%	5.88%	10.03%
	000027	6.21%	1.56%	3.84%	1.29%	6.10%
	000028	2.92%	8.36%	13.58%	7.63%	12.33%
	000029	6.52%	4.66%	2.18%	4.42%	5.62%
	000030	3.07%	2.69%	2.06%	3.07%	14.98%
	000104	3.34%	2.10%	2.94%	2.56%	5.47%
	000114	4.52%	2.45%	3.27%	2.94%	12.94%
Class II	**000001**	4.61%	9.75%	16.22%	3.94%	19.47%
	000005	5.09%	2.80%	10.10%	3.92%	9.53%
	000007	5.14%	5.98%	4.16%	5.48%	26.37%
	000008	-	-	-	-	-
	000009	6.28%	5.65%	13.80%	1.07%	25.46%
	000010	4.73%	3.60%	4.81%	2.84%	12.99%
	000011	2.34%	10.69%	14.71%	2.82%	11.10%
	000016	4.81%	18.74%	34.55%	4.71%	23.70%
	000021	2.89%	7.45%	23.40%	2.85%	12.99%
	000023	6.93%	14.43%	21.55%	6.24%	36.62%
	000118	1.12%	1.83%	2.04%	1.50%	12.03%
Class III	**000022**	2.32%	30.17%	33.57%	28.25%	30.30%
Class IV	**000003**	12.49%	14.74%	20.66%	14.27%	9.96%



(a) Season-of-Year Average Traffic Volume

(b) Season-of-Year Average Traffic Volume (%)



(c) Season-of-Year Average Truck Volume

(d) Season-of-Year Average Truck Volume (%)

Figure 3.8 Seasonally Traffic Volume & Truck Classification

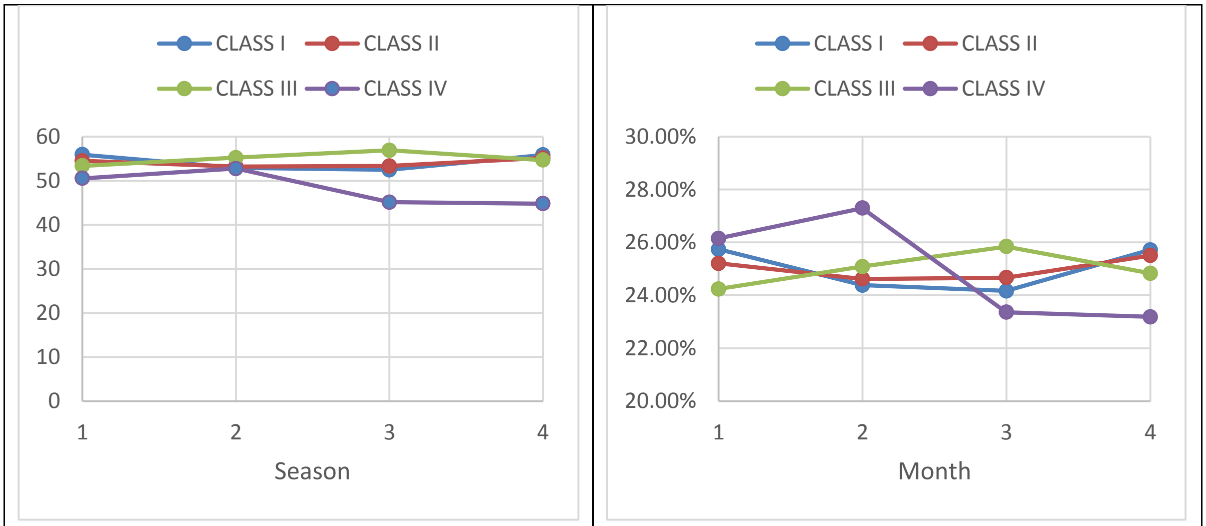
Traffic Weight

Figure 3.9 shows the distributions of season-of-year GVW of class 9 vehicle for each aggregate functional class.

Based on Figure 3.9 (a), the Class 9 GVWs on urban interstates (Class IV) are lower than those on rural functional roads. For rural functional roads, GVWs are relatively stable.

Figure 3.9 (b) shows that the season-of-year percentage changes of truck volumes. GVWs on urban interstates (Class IV) have slight decrease in fall and winter. For other rural functional roads, GVWs are relatively stable.

Table 3.11 shows the season-of-year CVs of Class 9 GVW, damage caused by single and tandem axle in one year. The season-of-year CVs are closed to month-of-year CVs.



(a) Season-of-Year Average GVW (kips)

(b) Season-of-Year Average GVW

Figure 3.9 Seasonally Gross Vehicle Weight

Table 3.11 Season-of-Year CVs of Traffic Weight

Agg. Class	**WIM Sites No.**	**GVW**	**Single Axle Load Damage**	**Tandem Axle Load Damage**
Class I	**000002**	1.00%	9.74%	4.44%
	000006	2.76%	10.80%	15.95%
	000027	4.00%	20.05%	27.60%
	000028	2.58%	12.97%	17.02%
	000029	0.98%	4.34%	2.92%
	000030	13.37%	25.04%	67.72%
	000104	1.45%	8.11%	13.15%
	000114	12.42%	40.82%	65.95%
Class II	**000001**	3.62%	16.40%	19.61%
	000005	0.95%	4.45%	6.04%
	000007	1.65%	17.74%	8.84%
	000008	-	-	-
	000009	1.06%	13.40%	8.84%
	000010	0.99%	4.09%	6.99%
	000011	2.01%	8.70%	13.73%
	000016	2.62%	10.86%	13.80%
	000021	2.54%	60.14%	10.46%
	000023	1.67%	4.22%	6.71%
	000118	7.28%	32.29%	38.37%
Class III	**000022**	2.65%	9.74%	10.69%
Class IV	**000003**	8.20%	34.68%	46.83%

Discussion

Table 3.12 summarizes the variations of each traffic parameter for each roadway group.

The variability levels are not consistent among all traffic parameters. For example, hour-of-day CV of AADT is 54.68% on Class I roads and 60.24% on Class II roads, which are approximately identical. On the other hand, hour-of-day CV of AADTT is 38.37 on Class I roads and 55.11% on Class II roads. The difference is noticeable. Another example, month-of-year CV of class 9 vehicles is 7.18% on Class II roads and 31.97% on Class III roads. These two month-of-year CVs are significantly different. However, month-of-year CV of Class 9 GVW is 2.72% on Class II roads and 3.02% on Class III roads. In other words, high variation of class 9 truck volumes do not necessarily mean the variation of GVWs is high.

In general, values of hour-of-day CVs are much larger than those of day-of-week CVs. Traffic in the daytime is usually much higher than that in the night, which causes significant traffic variation in a day. However, in a week, traffic tends to be relatively stable during weekdays, with a slight drop in the weekend. Similarly, day-of-week CVs are generally larger than month-of-year CVs and season-of-year CVs. Traffic characteristics are fairly constant by month and by season. The exception is that the traffic volumes on Class IV roads descend significantly in several consecutive summer months (May, June, July, and August).

Table 3.12 Variations of Each Traffic Parameter for Each Road Group

Agg. Class	**Variation**	**Traffic Volume**	**Truck Class**				**Traffic Weight**		
		AADT	**AADTT**	**VC5**	**VC9**	**VC13**	**GVW**	**SALD**	**TALD**
I	Time-of-Day	**54.68**	**38.37**	59.50	34.23	44.16	-	-	-
	Day-of-Week	9.57	16.59	15.55	19.49	33.69	2.16	23.17	19.52
	Month-of-Year	6.79	6.92	8.66	7.20	14.41	5.14	21.67	29.78
	Season-of-Year	5.12	4.29	6.19	3.81	10.56	4.82	16.48	26.84
II	Time-of-Day	**60.24**	**55.11**	67.38	49.47	80.41	-	-	-
	Day-of-Week	11.42	24.55	18.11	31.83	32.15	2.17	38.02	31.94
	Month-of-Year	5.03	9.91	15.53	**7.18**	25.54	**2.72**	24.40	15.14
	Season-of-Year	4.39	8.09	14.53	3.54	19.03	2.44	17.23	13.34
III	Time-of-Day	61.34	63.23	68.35	55.08	81.16	-	-	-
	Day-of-Week	15.72	28.31	21.89	39.7	22.8	1.18	43.33	39.78
	Month-of-Year	2.96	32.99	36.15	**31.97**	33.65	**3.02**	37.21	38.96
	Season-of-Year	2.32	30.22	33.64	28.28	30.33	2.65	32.27	38.34
IV	Time-of-Day	60.61	68.42	72.98	55.27	48.56	-	-	-
	Day-of-Week	16.94	17.43	13.1	39.58	40.74	1.7	44.58	39.14
	Month-of-Year	15.82	20.09	24.79	18.28	18.49	8.63	29.23	38.67
	Season-of-Year	12.49	14.74	20.66	14.26	9.95	9.2	34.66	46.79

*SALD = Single Axle Load Damage
*TALD = Tandem Axle Load Damage

CHAPTER IV

MINIMUM NUMBER OF TRAFFIC MONITORING SITES

Determination of Minimum Sample Size

Determining sample size is a very important issue because samples that are too large may waste time, resources and money, while samples that are too small may lead to inaccurate results. Various relationship have been developed between sample size and the precision of samples in both hypothesis testing and interval estimation. The following formula is widely applied for estimating the precision of samples *(16)*:

$$E = \frac{Z\alpha/2\ * \sigma}{n^{\frac{1}{2}}}$$

Where

E = a specified maximum value of precision

α = 1- (percent of confidence level chosen /100);

$Z_{\alpha/2}$ = (1- α)th percentile of the normal distribution

σ = standard deviation of sample

n = number of sample size

Rearranging this formula, the sample size necessary to produce results accurate to a specified confidence and margin of error can be determined as:

$$n = \frac{(Z\alpha/2 * \sigma)^2}{(E)^2}$$

In Traffic Monitoring and Forecasting Manual *(17)*, Tennessee Department of Transportation (TDOT) assumes that the traffic data population has a normal distribution. Because of indeterminacy of the mean and variance in the traffic data population, the *t*-distribution is applied to calculate the minimum sample size of Automated Traffic Recorders (ATR) stations needed to obtain selected level of accuracy *(17)*:

$$t\alpha = \frac{\overline{X} - \mu}{s/(n)^{\frac{1}{2}}}$$

Where

$t_\alpha = (1 - \alpha)^{th}$ percentile of the *t* distribution with (n – 1) degrees of freedom;

$\alpha = 1 -$ (percent of confidence level chosen / 100);

$\overline{X}$ = sample mean;

μ = mean of the population;

s = standard deviation of the sample; and

n = sample size (i.e. number of ATR stations).

The number of ATR stations is then determined as follows:

$$n = \frac{(\mathrm{t\alpha} \, * \mathrm{CV})^2}{(\mathrm{PL})^2}$$

Where

n = sample size (i.e. number of ATR stations);

$t_\alpha = (1 - \alpha)^{th}$ percentile of the *t* distribution with (n – 1) degrees of freedom;

α= 1 – (percent of confidence level chosen / 100);

CV = coefficient of variation; and

PL = precision level (i.e. ±error of the mean at the chosen confidence interval).

The table of t values (degree of freedom = ∞) can be found in Appendix D of the Highway Performance Monitoring System Field Manual *(18)*:

Table 4.1 t-Values of Different Confidence Level

Confidence Level	**Value of t**	**t Squared**
90 percent	1.645	2.706
80 Percent	1.282	1.644
70 Percent	1.040	1.082

Confidence Level and Precision

HPMS Field Manual suggests at least 80 percent confidence level and 10 percent precision level for road types based on functional system *(19)*. The CVs have already be computed in the previous chapter for various traffic characteristics. Therefore, the required number of WIM sites can also be determined following the final sample size formula above.

Number of Traffic Monitoring Sites

Table 4.2 summarizes the desired minimum number of traffic monitoring sites based on each traffic parameter for each aggregate roadway class.

For traffic volume parameter (ADT), the number of traffic monitoring sites based on hour-of-day variation is larger than those based on other time variations, which illustrates traffic volume varies most significantly in a day. The other three time variations (day-of-week, month-of-year, season-of-year) are relatively small and they only requires up to 5 WIM sites for aggregate roadway classes.

For truck class parameters, the number of traffic monitoring sites based on vehicle class 9 data tends to be similar to that of ADTT, which demonstrates that the variation of vehicle class 9 volumes is close to that for truck volumes. On the other hand, variations of vehicle Class 5 and Class 13 are different from that of truck volumes.

For traffic weight parameters, variation based on Class 9 GVW is very small and it only requires 1 or 2 traffic monitoring sites, which indicates that the average GVW of class 9 trucks is very consistent. However, the number of sites based on damage caused by axle type (or axle load spectra) shows significant variations. These two opposite observations demonstrate that the determination of WIM sites based on Class 9 GVW or axle load spectra may not be accurate and reliable.

Table 4.2 Desired Minimum Number of Monitoring Sites

Agg. Class	**Variation**	**Traffic Volume**	**Truck Class**				**Traffic Weight**		
		ADT	**ADTT**	**VC5**	**VC9**	**VC13**	**GVW**	**SALD**	**TALD**
I	Time-of-Day	50	25	59	20	33	**-**	**-**	**-**
	Day-of-Week	2	5	4	7	19	**1**	**9**	**7**
	Month-of-Year	1	1	2	1	4	**1**	**8**	**15**
	Season-of-Year	1	1	1	1	2	**1**	**5**	**12**
II	Time-of-Day	60	50	75	41	107	**-**	**-**	**-**
	Day-of-Week	3	10	6	17	17	**1**	**24**	**17**
	Month-of-Year	1	2	4	1	11	**1**	**10**	**4**
	Season-of-Year	1	2	4	1	6	**1**	**5**	**3**
III	Time-of-Day	62	66	77	50	109	**-**	**-**	**-**
	Day-of-Week	5	14	8	26	9	**1**	**31**	**27**
	Month-of-Year	1	18	22	17	19	**1**	**23**	**25**
	Season-of-Year	1	16	19	14	16	**1**	**18**	**25**
IV	Time-of-Day	61	77	88	51	39	**-**	**-**	**-**
	Day-of-Week	5	5	3	26	28	**1**	**33**	**26**
	Month-of-Year	5	7	11	6	6	**2**	**15**	**25**
	Season-of-Year	3	4	8	4	2	**2**	**20**	**36**

*SALD = Single Axle Load Damage
*TALD = Tandem Axle Load Damage

Discussions

The analysis of time variation for each traffic parameter has been conducted based on KYTC aggregate groups. However, since traffic characteristics vary from o time periods and locations, it is necessary to study location-related variations for each roadway group. The annual average daily traffic data is applied to study location-related variation for each road group. For example, Table 4.3 summarizes the CVs and corresponding minimum number of WIM sites based on ADT of different locations in each road group. The large CV values reflect significant variation in traffic volume among the locations in each road group. Location variation on Class III and IV road cannot be evaluated because there is only 1 WIM site on each road group.

Table 4.3 Number of WIM Sites based on Variation among Samples for Each Group

Agg. Class	**WIM Sites No.**	**ADT**	**Location CVs**	**Desired WIM Sites**
Class I	**000002**	24682.87	44.42%	33
	000006	15974.04		
	000027	14733.28		
	000028	35154.09		
	000029	19635.00		
	000030	43074.47		
	000104	33655.59		
	000114	19436.02		
Class II	**000001**	13467.54	67.52%	75
	000005	10301.19		
	000007	4697.843		
	000008	6427.568		
	000009	5660.173		
	000010	14665.40		
	000011	7087.602		
	000016	14732.45		
	000021	27444.30		
	000023	3552.898		
	000118	5706.989		
Class III	**000022**	8713.019	-	-
Class IV	**000003**	46983.54	-	-

Table 4.4 summarizes the desired number of traffic monitoring sites based on location-related CVs of each traffic parameter for each road group. For most traffic parameters, the required number of sites is large, which illustrates that traffic characteristics are not consistent within each KYTC road group. In other words, KYTC aggregate roadway class may not be an ideal method to group various traffic patterns and analyze variation of traffic characteristics.

The only exception of these traffic characteristics is GVW of Class 9 vehicles. The variation of GVW is very small and it only requires 1 and 2 WIM sites for Class I and Class II roadways. However, the damage factors from single and tandem axle load bins (or axle load spectra) of all vehicles demonstrate significant variations. Since both GVW and axle load damage factors are weight related parameters, these two opposite observation seems to be contradictory. On the other hand, it may reveal that using average Class 9 GVW to determine the minimum number of WIM sites is not accurate and reliable, because average Class 9 GVW information only cannot represent the variations of axle loading spectra of all vehicles carried on a roadway. The 2013 TMG recommends using GVW and ESAL to determine the minimum number of WIM sites, which should be applied with caution.

Table 4.4 Desired Number of WIM Sites based on Location CV for each road group

Agg. Class	**ADT**	**ADTT**	**VC5**	**VC9**	**VC13**	**GVW**	**Single Dmg.**	**Tandem Dmg.**
CLASS I	33	15	65	7	148	2	129	217
CLASS II	75	98	37	186	61	1	136	192
CLASS III	-	-	-	-	-	-	-	-
CLASS IV	-	-	-	-	-	-	-	-

CHAPTER V

CONCLUSIONS

Various statistical methodologies have been conducted to calculate the variability of traffic volume parameters and determine required traffic monitoring sites for each roadway group. However, limited research is focused on using WIM data. Using 2008 WIM data in Oklahoma, this thesis computes the variation coefficients of a comprehensive array of traffic factors. Subsequently, the number of traffic monitoring sites including required WIM sites for each road group is estimated. In this thesis, the following tasks are performed:

- The traffic module of Prep-ME is able to conduct automatically data quality check by direction and lane for any WIM site following criteria defined in TMG. In addition, manual operations are provided to further investigate data, sample data and repair data that has not pass QC data check.
- Rigorous data check is conducted for 5 years of WIM data in Oklahoma. Based on comparison of the QC results, 2008 WIM data is used for statistical analysis on WIM data variation.
- Variation analysis is conducted for a comprehensive array of traffic parameters covering traffic volume, truck volume and gross vehicle weight, axle load damage

as well as volumes for vehicle classes 5, 9, and 13.

- The statistical required minimum number of traffic monitoring sites is determined based on variation levels of each traffic parameter.

It is found that traffic data variation level within one KYTC roadway group is high. There is a need to develop more rigorous grouping methodology to characterize traffic patterns, especially for traffic weight data.

In addition, the 2013 TMG recommend using Class 9 GVW to determine the number of WIM sites, which turns out to be problematic based on the results from this study.

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