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Final Report 930-564

TRUCK EQUIVALENCY FACTORS, LOAD SPECTRA MODELING AND EFFECTS ON PAVEMENT DESIGN

Prepared by

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OCTOBER 2005

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Sponsored by

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ABSTRACT

The objectives of this study were to develop truck factors for pavement design in Alabama and axle load distribution models for mechanistic-empirical pavement design. In addition, the effects of variations in axle load spectra obtained from different sites on pavement design requirements using both the 1993 AASHTO pavement design guide and a mechanistic-empirical (M-E) design approach were evaluated. Information from thirteen weigh-in-motion (WIM) sites on rural principal arterials was provided by the Alabama Department of Transportation for this study. Statistical and practical tests were used to determine the daily, monthly, directional, and site variations in truck traffic relating to the development of truck factors. A sensitivity analysis was performed to determine the effect the variation in truck factors would have on the final pavement design thickness. It was determined that using a statewide average truck factor would be sufficient for pavement design of rural principal arterials in Alabama.

The data from the WIM sites were also used to create an innovative statistical model of axle load distributions. Separate models were developed for single and tandem axles at each site and for the statewide average. A mixture of either a lognormal, normal, and normal distribution or a lognormal and normal distribution was used for the single axles. For all tandem axle loads a mixture of a lognormal and normal distribution was found to be the best fit. All of the developed single axle models were found to explain at least 98.6 percent of the total variation in the data and all the developed tandem axle models were found to explain at least 96.2 percent of the total variation.

ACKNOWLEDGMENTS

The authors wish to thank many people who assisted with the research documented in this report and who provided guidance along the way. Julia Bower, a student in the Department of Civil Engineering at Auburn University, assisted with much of the data analysis to determine the sensitivity of mechanistic-empirical design to axle load distributions. Larry Lockett, Scott George, Gary Brunson, and Charles Turney of the Alabama Department of Transportation were all willing to provide their insights on the research, meet with the principal investigators, and provide comments on drafts of this report.

CHAPTER 1: INTRODUCTION

1.1 Background

Designing and maintaining the statewide network of roads is an essential responsibility of State highway agencies. A pavement design that accurately reflects the environmental and traffic conditions over the life of the pavement results in less maintenance, repair, and traffic disruptions and therefore, benefits the State through savings in cost and time. There are several input parameters that are required to design a pavement structure. One vital component is an accurate account of the expected magnitude and frequency of traffic loads over the design life of the pavement. Traffic can be characterized using equivalent single axle loads (ESALs). ESALs convert the effect of mixed axle load applications into the equivalent number of applications of an 18,000 lb single axle that would be required to produce the same amount of pavement distress. Typically, ESALs are calculated per vehicle and then multiplied by the average annual daily traffic (AADT), growth factor, lane distribution, and directional distribution to compute the total ESALs for design. The effect of motorcycles, passenger cars, and pick-up trucks on calculation of ESALs per vehicle, or the "truck factor", are very small. Some agencies, including the Alabama Department of Transportation, choose to include these light vehicles while others consider their contributions negligible and omit them from the process of determining truck factors.

The Alabama Department of Transportation (ALDOT) currently uses a statewide average truck factor that was determined in 1993. Since truck volumes and weights can change from year to year, new truck factors that accurately reflect the existing truck traffic are needed. Also, the appropriateness of using an average truck factor instead of site or facility type-specific truck factors needs to be verified. In addition to variations between sites, the variations in truck traffic by day of the week, month of the year, and direction needs to be examined. If the differences are not accounted for, the resulting truck factors may inaccurately portray the loads on the pavement and consequently ESAL computations. Underestimating the traffic loads on the pavement could lead to underdesigned facilities and premature failure and overestimating the traffic loads is not economically efficient.

It is also beneficial to know if variations exist for data collection purposes. For example, if data cannot be collected every day of the week and it is known that the truck factors for a typical Sunday are significantly higher than for the rest of the week, then Sunday should not be left out of the data collection. Conversely, money can be saved if it is known that the truck factors do not vary significantly by day and therefore data do not need to be collected every day. The existence and extent of variations must first be determined in order to decide whether or not it is appropriate to use average truck factors and when to collect data.

The forthcoming “2002” *Guide for Design of Pavement Structures* will use mechanistic-empirical (M-E) based pavement design procedures. Instead of using ESALs for the traffic input, the full axle load distribution for each axle type is required. The axle load distribution is required because the strain on the pavement and subgrade caused by the individual axle loads of each axle type is determined using response models. The strains are input into distress models which account for distresses such as fatigue cracking, rutting, pumping, and joint deterioration. The distress models determine the number of applications to failure for each axle load on each axle type, which is compared to the actual number of axle loads expected over the life of the pavement. Since observed axle load distributions are not always readily available, a model of axle load distributions is very useful for mechanistic-empirical design.

The current state of the practice is to use polynomial regression equations to model axle load distributions. These models may have up to five discontinuous equations and 20 regression constants per axle load distribution. Also, they do not take advantage of the central tendencies and dispersion in the natural axle load distributions. Therefore, there is a need to develop simpler and more robust axle load models that accurately reflect the properties of the truck traffic.

1.2 Objectives

The two goals of this research were to develop accurate truck factors for use in pavement design for Alabama and to develop new statistical models of axle load distributions. The specific research objectives are:

1. To review and assess research on variations of axle load distributions and truck factors;
2. To review and assess current methods of modeling axle load distributions;
3. To review and assess past ALDOT procedures for determining truck factors;

4. To determine truck factor variations by day, month, direction, and site;
5. To evaluate the sensitivity of pavement design to truck factors;
6. To develop recommended truck factors for ALDOT;
7. To compare the recommended truck factors to the truck factors used by ALDOT in the past;
8. To develop a new statistical model of axle load distributions;
9. To evaluate the sensitivity of pavement design relative to load spectra using an M-E approach.

1.3 Scope

This study consisted of using data from 13 Alabama Weigh-in-Motion (WIM) sites collected in 2001 to compare axle load distributions and truck factors for daily, monthly, directional, and site differences. Statistical and practical differences between the axle load distributions and truck factors were determined. A sensitivity analysis was also conducted to determine the effect of differences among the truck factors on pavement design. The axle load distributions for each site and the statewide average were used to create new statistical models for use in M-E design. A sensitivity analysis was used to determine the effect of differences among site-specific load spectra, for three values of soil resilient modulus, on flexible pavement design using an M-E approach.

1.4 Organization of This Report

The literature review that discusses research that has been done on variations of axle load distributions and truck factors is presented in Chapter 2. Also, Chapter 2 presents recent research on modeling axle load distributions. The research that ALDOT has done specifically to determine truck factors for use in pavement design in Alabama is discussed in Chapter 3. Chapter 4 describes the data that were supplied by ALDOT and used for this project. The methodology to determine differences in axle load distributions and truck factors as well as the sensitivity of the pavement design parameters, using the 1993 AASHTO method, to truck factors is described in Chapter 5. Chapter 5 also describes the procedure used to create a model of axle load distributions and then applies an M-E design approach to evaluate the sensitivity of required flexible pavement thickness to the deviations in site-specific load distributions from the combined statewide distribution. The methodology was then applied to the data supplied by ALDOT and the results are displayed in Chapter 6. The conclusions and recommendations pertaining to truck factors for pavement design in Alabama, and recommendations for data collection, are made in Chapter 7. Also in Chapter 7 are the conclusions about the statistical models of the axle load distributions and the impacts of site-specific differences in these distributions on M-E pavement design. Chapters 5, 6, and 7 are each divided into three sections: the first pertains to development of new truck factors and the sensitivity of pavement design to site-specific differences based on the 1993 AASHTO procedure, the second describes the development of statistical models of axle load distributions, and the third describes the sensitivity of M-E pavement design (using the M-E design software, PerRoad) to site-specific differences in axle load distributions.

CHAPTER 2. LITERATURE REVIEW

An extensive literature review was performed to gather information on variations in traffic characterization, determination of ESALs, and axle load modeling. The purpose of this literature review was to determine what characteristics of traffic data are important when calculating ESALs. Traffic characteristics include variations in vehicle classes, days of the week, months, years, seasons, sites, and between directions.

The forthcoming "2002" Pavement Design Guide uses mechanistic-empirical design which requires the input of axle load distributions, rather than ESALs. Since axle load distributions are not available for every design location, a procedure to develop axle load distribution models is beneficial to mechanistic-empirical design. Therefore, the current methods of modeling axle load distributions were examined.

2.1 Variations in Traffic Characteristics

Key factors in designing a pavement structure are the magnitude and number of repeated loads. Axle loads can be converted into ESALs using AASHTO design procedures (AASHTO Guide for Design of Pavement Structures, 1993). ESALs require the input of a terminal serviceability, axle load distribution, and structural number (SN) or depth of concrete (D). The terminal serviceability can be defined as the point at which the pavement reaches a minimum tolerable level of serviceability, at which rehabilitation activities typically occur. The SN is an index number that may be converted into the thicknesses of the flexible pavement layers by using layer coefficients that are dependent upon the material type of the layer. ESALs can be calculated separately for each vehicle class or for the aggregate traffic mix. Other considerations when calculating ESALs are daily, monthly, yearly, seasonal, and regional variations in truck traffic. The following sections discuss research that has been done in those areas.

2.1.1 Vehicle Classes

The Federal Highway Administration (FHWA) divides vehicles into thirteen different classes as shown in Figure 2.1. When ESALs are calculated, the effects of vehicle classes 1-3 (motorcycles, passenger cars, and pickup trucks) are minimal since their axle loads are so light compared to the other vehicle classes. For example, one tractor-semitrailer combination is equivalent to about 2.0 ESALs and one passenger car

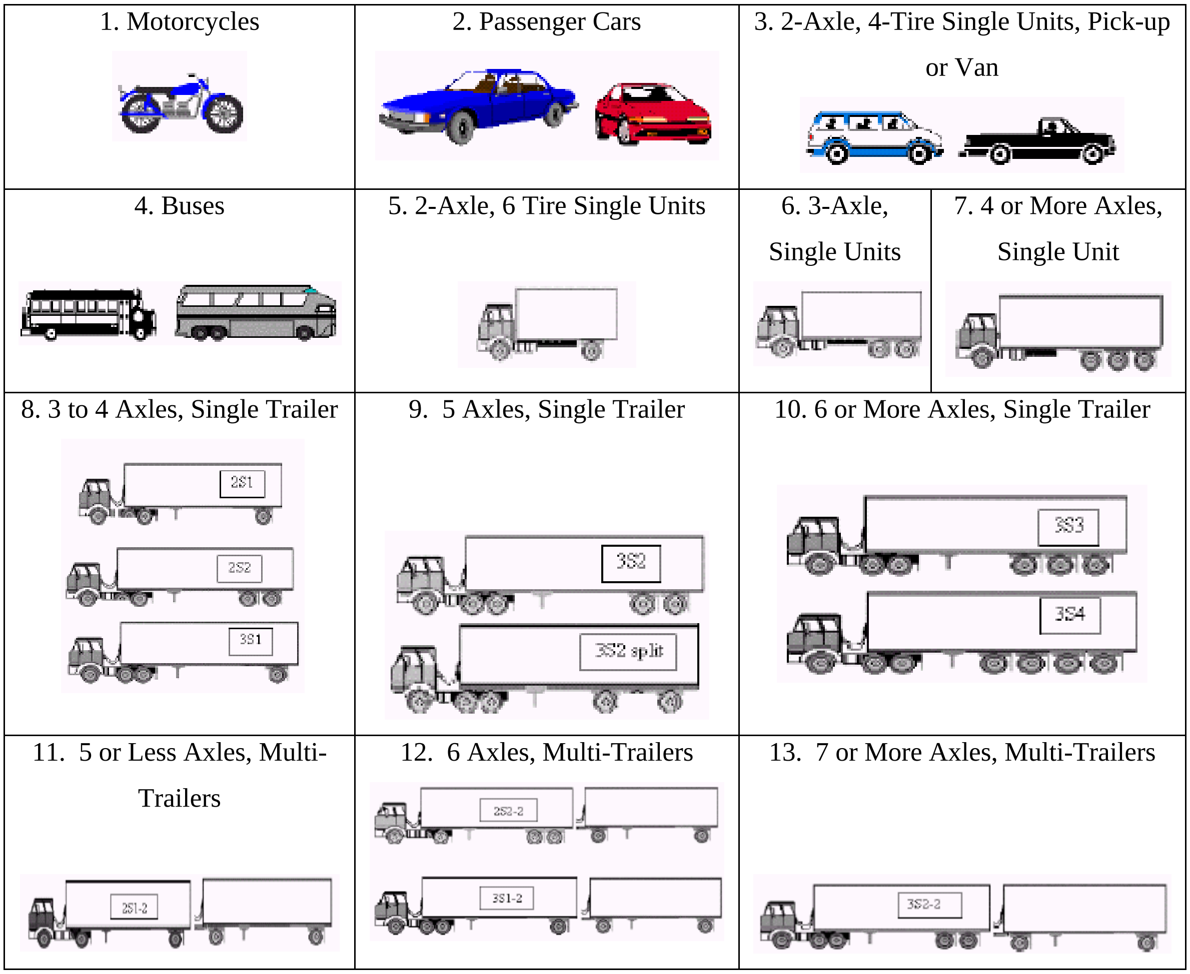


Figure 2.1 FHWA Vehicle Classes (Traffic Data and Analysis Manual, 2001)

to only 0.0004 ESAL (Fwa et al, 1993). A study conducted for the Arizona Department of Transportation (ADOT) to create a new ESAL table found that FHWA vehicles classes 1-3 have a minimal impact on the overall number of ESALs a segment will experience (Alavi and Senn, 1999). Therefore, it was determined that classes 1-3 could be ignored when calculating ESALs.

ESALs can be calculated individually per truck class or for an average of all trucks. ESALs are sometimes separated by truck class because each truck class has a separate growth rate. ADOT found that the composition of truck traffic had been changing between 1993 and

1997. Class 9 trucks had increased in increments of approximately 2.5 percent per year relative to the total truck traffic and in increments of approximately 0.8 percent relative to the entire traffic stream. It was recommended that this issue be revisited in 3 to 5 years to see if Class 9 vehicles are still increasing in percentage. If so, then consideration should be given to modifying growth factors by vehicle class.

A study conducted for the Texas Department of Transportation (TxDOT) used data from 1993-1995 and a time series analysis to conclude that Class 9 and Class 4 trucks had an annual rate of change of 6% and 5%, while the percentage of other truck classes did not increase over the given time period (Qu et al, 1997). TxDOT also compared the axle load distributions of the same axle type in the same or different truck class. It was observed that the same axle types would have different load distributions when they were in different truck classes or at a different position, such as the front or the rear, on the same truck class. Therefore, ESALs were calculated separately by truck class and by the position on the truck.

2.1.2 Daily Variation

It is important to know if truck traffic varies greatly between days so that the significantly heavy or light days are not neglected in the determination of ESALs. Load distributions have been used to determine if a daily variation in traffic loading was present. A study conducted using WIM data collected for 3 years from a site on a four lane freeway in North Carolina used the Kruskal-Wallis (Conover, 1980) test to determine whether the gross weight distribution varied daily (Wu, 1996). The Kruskal-Wallis test tests the null hypothesis that when *k* samples are taken from *k* possible different populations, the entire population is identical. In other words, the gross vehicle weight distributions for each day were tested to determine if they were identical. For single unit trucks with single axles (SUS), the null hypothesis that the daily gross weight distributions were the same was rejected. When Sunday was removed from the data set the null hypothesis was accepted. This means that differences among the daily gross weight distributions were not statistically significant except for Sunday.

Other sites with higher Sunday truck traffic were tested, and it was found that Sunday distribution functions were identical to those for weekdays. These results suggested that the Sunday gross weight distribution only differed significantly when recorded truck traffic was very low. The error this will cause in pavement design was estimated to be minimal because it would have an insignificant impact on the accuracy of the overall average ESALs. For single trailer vehicles the daily gross weight distribution variation was found to be insignificant. Seasonal variation was also tested using the Kruskal-Wallis test. Four samples were used from the same site and it was determined that there was no seasonal variation.

2.1.3 Variation between Years

The axle load patterns can change throughout the design life of a pavement. If a significant increase or decrease in ESALs is expected over the design life of the pavement, it is necessary to account for it in the pavement design procedure. Studies have been undertaken to determine if axle load distributions vary between years.

A study done for TxDOT used WIM data from two sites for 1993, 1994, and 1995 to analyze yearly axle load distributions (Qu et al, 1997). The purpose of the analysis was to determine if axle load distributions should be adjusted for the forecasted design year when computing ESALs. To compare the axle load distributions between the three years the data from both sites were combined for each year. Since both stations only monitored southbound traffic, direction of the traffic could not be compared. By plotting the axle load distributions for the three years it was determined that the axle load distributions among the three years were almost identical; this observation was not validated through statistical testing. Therefore, it was decided to use the axle load distribution from 1995 when calculating ESALs.

A study using LTPP data from 21 sites in the North Central Region for interstate highways used axle type distribution, ESAL distribution, and axle load distribution to characterize trends in the traffic data (Kim et al, 1998). The North Central Region included the following states; Iowa, Illinois, Indiana, Kansas, Kentucky, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. The Kruskal-Wallis test was used to determine if there were statistically significant differences in axle type, ESAL, and axle load distribution within the region. The sites had to be subdivided into three regions before the traffic patterns were not significantly different. Within the three regions the Kruskal-Wallis test indicated that the distribution by axle type, ESAL, and axle load for both single and tandem axle did not change significantly over time for the three years studied. It was therefore concluded that axle load distribution could be extrapolated over reasonable periods of time. No definition of what would be considered a reasonable amount of time was given.

2.1.4 Variation between Sites

Truck traffic can vary considerable between sites, even if they are in the same state or same region of a state. Therefore it is important to know what regional differences exist when calculating ESALs. A comparison between sites can be made using axle load distributions.

A study done for TxDOT used three years of WIM to compare the axle load distributions for two sites by plotting the distributions (Qu et al, 1997). The method of analysis was to visually inspect the plots for any differences. They were very similar, but they were not identical because one site experienced slightly more traffic than the other. It was decided that ESAL calculations should be performed separately for both sites.

A study conducted in Taiwan used data collected for the ten years from static weighbridges at four toll stations (Huang et al, 2002). The Kolmogorov-Smirnov (K-S) Test was used to determine whether or not there were significant variations or differences in the traffic patterns among the four toll stations. The K-S test determines if two independently drawn samples are from the same distribution function. Each toll station was compared to the other three toll stations separately, so there were six comparisons made. For each comparison, axle load distributions for single and tandem axle loads were compared. The null hypothesis was that the axle load distributions of the two stations being compared could be considered identical and the alternative hypothesis was that they were not identical. For the four toll stations compared, it was determined that there were significant differences in the axle load patterns between paired stations at a significance level of 5%. The toll stations were only compared to each other, not to an average of all four toll stations. Since the stations were found to be statistically significantly different they were analyzed separately.

2.1.5 Sensitivity Analysis

It is beneficial to know how sensitive the AASHTO design equations are to input parameters when trying to determine the required depth of pavement. For example, if it is determined that a specific increase in ESALs does not change the required depth of pavement, then that particular increase in ESALs would be insignificant in the final design.

A study was conducted for the New York State Department of Transportation (NYSDOT) to analyze the effect of input parameters on pavement thickness using the

AASHTO procedure (Chen et al, 1996). The sensitivity analysis was conducted by varying one input parameter at a time. The independent input parameters tested for flexible pavements were reliability, standard deviation, serviceability loss, soil resilient modulus, asphalt concrete (AC) base layer coefficient, subbase layer coefficient, subbase drainage coefficient, and design traffic in ESALs. For rigid pavements the test variables were reliability, standard deviation, serviceability loss, modulus of subgrade reaction, drainage coefficient, concrete modulus of rupture, load transfer coefficient, and design traffic in ESALs. The AASHTO recommended value was selected for the baseline value and upper and lower bounds were selected for the sensitivity analysis. Changes in design thickness were categorized by the percentage change in design thickness of AC or Portland cement concrete (PCC) per ten percent change in the input parameter. The percent change was considered low if it was less than 2.5 percent, moderate for 2.6 to 5.0 percent, and high for more than 5.0 percent.

For both rigid and flexible pavement it was determined that changes in thickness due to changes in ESALs are moderate when they are below the baseline value and low when they are above the baseline value. So, as the magnitude of design ESALs increase, their effect on pavement design decreases. To calculate design ESALs a growth rate, design life, ESALs per vehicle class, and AADT must be determined. These values could all have varying effects on the outcome of design ESALs and consequently pavement thickness. For this study, however, they were not included in the analysis.

2.2 Axle Load Modeling

ESALs, which are widely used today, provide a quick analysis of traffic for pavement design, but it does not take into account all the distresses traffic loading may have on a pavement. The forthcoming 2002 AASHTO Design Guide includes mechanistic-empirical design procedures, which will require the full axle load distribution of each axle type instead of ESALs. Therefore, researchers have attempted to model axle load distributions using regression techniques. The current method to model axle load distributions is to break the distributions into four or five sections and then model each section using a regression equation. Therefore, the models are not continuous or differentiable. There are four or five equations with this type of model and up to 20 regression constants. Also, statistical tests to validate the goodness of fit of the model to the actual axle load distribution cannot be performed because they are not based on a theoretical distribution.

As mentioned previously the study of LTPP data from the North Central Region divided axle load distributions into three separate regions (Kim et al, 1998). For each of the three regions axle load distribution models were created for single and tandem axles using regression models. The basic procedure included developing axle load distribution factors, using the axle load factors to model the axle load cumulative frequency, and developing a 90 percent prediction interval for the axle load cumulative frequency model developed to account for differences that might exist at a specific site. The cumulative axle load distribution was divided into four sections. For each section a polynomial regression equation was fit to the curve. The first three sections required a 3rd order polynomial and the last section required a 4th order polynomial. The model form was as follows:

For single axles (0 kips $\leq$ W < 8.3 kips) and tandem axles (0 kips $\leq$ W < 15.1 kips),

$$CF = \alpha_1 W^3 + \alpha_2 W^2 + \alpha_3 W$$

For single axles (8.3 kips $\leq$ W < 13.5 kips) and tandem axles (15.1 kips $\leq$ W < 31.0 kips),

$$CF = \alpha_4 W^3 + \alpha_5 W^2 + \alpha_6 W + \alpha_7$$

For single axles (13.5 kips$\leq$ W < 20.5 kips) and tandem axles (31.0 kips $\leq$ W < 45 kips),

$$CF = \alpha_8 W^3 + \alpha_9 W^2 + \alpha_{10} W + \alpha_{11}$$

For single axles (20.5 kips $\leq$ W < 34 kips) and tandem axles (45 kips $\leq$ W < 58.5 kips),

$$CF = \alpha_{12-} W^4 + \alpha_{13} W^3 + \alpha_{14} W^2 + \alpha_{15} W + \alpha_{16}$$

where,

CF	=	cumulative frequency
W	=	axle load
α_i	=	regression constants

These equations require a large number of regression constants; sixteen for each sub- region and 96 total for the project. Since there is always variability in estimating traffic parameters, a model that requires fewer input parameters to describe axle load distributions would be more ideal. A statistical test for goodness of fit could not be performed for these equations since the functions are not theoretical probability distributions. The coefficient of determination (R^2) was calculated and ranged from 0.93 to 0.99, which the study found to be adequate for predicting the cumulative frequency for single and tandem axles.

After determining that the axle load models were adequate, the study recommended the following procedure to estimate axle loads for Interstate highways within the study area. First, the number of axle passes was obtained for a given site. It was assumed from previously gathered information that 50 percent of the total axles were single axles, 49 percent were tandem axles, and 1 percent were tridem axles. The polynomial regression models for single and tandem axles are then used to determine the axle load distribution for both single and tandem axles. Using data from 1995 that were not part of the data used in the analysis, it was determined that these steps gave a good prediction of the axle load distributions for both axle types. The coefficient of determination was 0.98 for single axles and 0.95 for tandem axles.

In Taiwan, a similar study was performed using data collected from static weighbridges at 4 toll stations on the Sun Yat-sen Freeway for ten years (Huang et al, 2002). The axle load distribution models were developed using regression techniques. The same procedure described previously was used for this analysis. The only difference was the cumulative frequency was divided into five sections instead of four. The equations require 20 coefficients for each particular site and axle type. The model form was as follows:

For single axles (0 kips $\leq$W< 12.4 kips) and tandem axles (0 kips $\leq$W< 12.4 kips),

$$CF = \alpha_1 W^3 + \alpha_2 W^2 + \alpha_3 W$$

For single axles (12.4 kips $\leq$W<19.1 kips) and tandem axles (12.4 kips $\leq$W< 29.2 kips),

$$CF = \alpha_4 W^3 + \alpha_5 W^2 + \alpha_6 W + \alpha_7$$

For single axles (19.1 kips $\leq$W< 24.7 kips) and tandem axles (29.2 kips $\leq$W< 40.5 kips),

$$CF = \alpha_8 W^3 + \alpha_9 W^2 + \alpha_{10} W + \alpha_{11}$$

For single axles (24.7 kips $\leq$W< 31.5 kips) and tandem axles (40.5 kips $\leq$W< 47.2 kips),

$$CF = \alpha_{12} W^3 + \alpha_{13} W^2 + \alpha_{14} W + \alpha_{15}$$

For single axles (31.5 kips $\leq$W< 49.5 kips) and tandem axles (47.2 kips $\leq$W< 74.2 kips),

$$CF = \alpha_{16} W^4 + \alpha_{17} W^3 + \alpha_{18} W^2 + \alpha_{19} W + \alpha_{20}$$

where,

CF	=	cumulative frequency
W	=	axle load

α_i = regression constants

Data collected in 2000 were used to check the models. Predicted versus the measured axle load frequency was plotted for comparison. No justification of the goodness of fit of the model was given in the published literature. There was only a visual comparison of the difference between the predicted and the actual axle load frequency. Figures 2.2 and 2.3 display the results for the Yuan-Lin station on the Sun Yat-sen Freeway. Since only a visual comparison was made, there was no quantifiable measure of how well the data were modeled using the polynomial regression equations. Basing the goodness of fit on visual inspection alone is subjective and would vary from person to person.

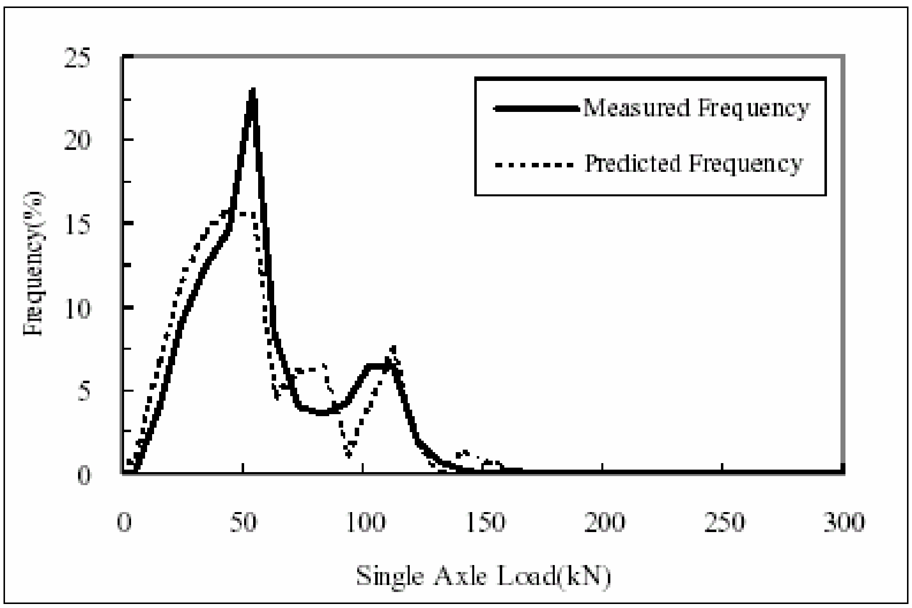


Figure 2.2 Yuan-Lin, Single Axle (Huang et al, 2002)

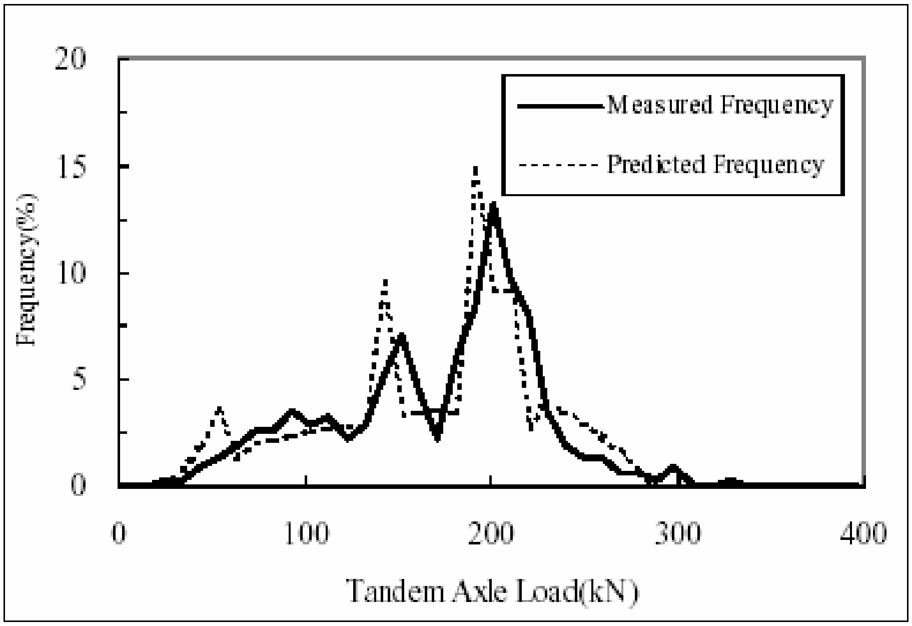


Figure 2.3 Yuan-Lin, Tandem Axle (Huang et al, 2002)

This chapter has summarized the research that has been done to identify traffic characteristics that are important when calculating ESALs. Comparing axle load distributions was the primary way to determine if ESALs should be calculated by vehicle class, day of the week, season, year, and by region or site. There was a lack of information on separating ESALs by month or direction of travel. Also, the current method of modeling axle load distributions is to use a polynomial regression model. The next chapter illustrates ALDOT's past research in determining truck factors for use in pavement design in Alabama.

CHAPTER 3. STATE OF PRACTICE IN ALABAMA AND NEIGHBORING STATES

Since the development of truck factors during a loadometer study in 1964, the Alabama Department of Transportation (ALDOT) has updated its truck factors twice. In 1983 a report was published documenting the procedures and data used to calculate truck factors and ESALs for Alabama pavement design. The truck factors were again updated in 1993, but an official report was not created. A survey of Alabama's neighboring states was conducted to determine what procedures are currently used for pavement design.

3.1 Truck Factors Updated in 1983

From 1964 to 1983, ALDOT used truck factors obtained from 1964 loadometer studies for pavement design. In 1982 a research study was initiated with the following objectives: (1) use truck weight data from currently operating ten Weigh-In-Motion (WIM) sites in Alabama to determine truck weight distribution factors and compare them with the factors currently being used, (2) at each WIM determine the total traffic count, percent trucks, and lane usage (on multi-lane facilities) (Alabama Highway Department, 1983). All WIM sites were located on four lane highways, with the exception of three sites located on two lane highways. The sites were classified as either urban or rural and interstate or other federal aid system.

WIM devices were used to collect axle weight data for trucks over an approximately twenty-four hour period at each site. The outside lane of each roadway was used to collect measurements for the four lane highways. The number of trucks using the inside or non-instrumented lanes of the four lane highways were recorded manually. The total number of axles passing a given site was determined through the use of pneumatic tube counters. An axle load frequency distribution was developed for each site by grouping the single or tandem axles into 1 kip increments.

The truck distribution factors were determined by using a program written for an Apple III microcomputer. For each axle load frequency distribution at each site, the total number of ESALs was computed using the method described in the *AASHTO Interim Guide for Design of Pavement Structures*. The method required the input of terminal serviceability (p_t) and structural number (SN) for flexible pavement or depth of concrete (D) for rigid pavement, to determine the load equivalency factor (LEF). The only p_t values used in the calculations were 2.0 and 2.5. The values used for SN were 1-10 (flexible pavements), and the D values ranged from 6 to 15 inches (rigid pavements). The LEFs were calculated by using equations from the *AASHTO Interim Guide for Design of Pavement Structures* (Appendix MM).

The following equation was used for flexible pavements (Appendix MM):

$$\log_{10}\left[\frac{w_{tx}}{w_{t18}}\right] = 4.79\log_{10}(18+1) - 4.79\log_{10}(L_x + L_2) + 4.33\log_{10} L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \qquad (1)$$

where:

$$G_t = \log_{10}\left[\frac{4.2 - P_t}{4.2 - 1.5}\right]$$

$$\beta = 0.40 + \left[\frac{0.081(L_1 + L_2)^{3.23}}{(SN+1)^{5.19} L_2^{3.23}}\right]$$

L_x = load on one single axle or one tandem axle set (kips)

L_2 = axle code (1 for single axle and 2 for tandem axle)

β_{18} = value of β_x when L_x is equal to 18 and L_2 is equal to one

SN = structural number

Pt = terminal serviceability

The following equation was used for rigid pavements (Appendix MM):

$$\log_{10}\left[\frac{w_{tx}}{w_{t18}}\right] = 4.62\log_{10}(18+1) - 4.62\log_{10}(L_x + L_2) + 3.28\log_{10} L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \qquad (2)$$

where:

$$G_t = \log_{10}\left[\frac{4.5 - P_t}{4.5 - 1.5}\right]$$

$$\beta = 1.0 + \left[\frac{3.63(L_1 + L_2)^{5.20}}{(D+1)^{8.46} L_2^{3.52}}\right]$$

L_x = load on one single axle or one tandem axle set (kips)

L_2 = axle code (1 for single axle and 2 for tandem axle)

β_{18} = value of β_x when L_x is equal to 18 and L_2 is equal to one

D = depth of concrete, in

Pt = terminal serviceability

For both the flexible and rigid pavements, the LEF was determined by taking the inverse of the ratio w_{tx}/w_{t18} (LEF = w_{t18}/ w_{tx}). Therefore, equations (1) and (2) solve for the log (base 10) of the inverse of the equivalency factor. The LEFs and axle load distributions for single and tandem axles were used to determine the ESALs. The ESAL value was then divided by the number of trucks weighed to calculate the ESAL per truck or truck factor. The procedure was done at each WIM site for both p_t values and all SN and D values.

There were four sets of truck factors from the 1964 study that were classified as Interstate rural, Interstate urban, other federal rural, and other federal urban. For the 1983 study there were six sites classified as other rural, two sites classified as other urban, and one each classified as Interstate Rural and Interstate Urban. For the 1964 study the four sites truck factors ranged from 0.36385 to 0.45664 ($p_{t\,=}$2.5 and SN = 5), while the 1983 truck factors ranged from 0.43846 to 1.04329 ($p_{t\,=}$2.5 and SN = 5).The truck factors for the 1982 study were double or more the factors that had been used since 1964. It was decided not to group the factors by highway classification because six of the ten sites were classified as Other Rural. Instead, one statewide average truck factor was determined using the data from all ten WIM sites. For a SN = 5 and p_t = 2.5 the resulting truck factor was 0.80447.

Data collected from all but two sites were also used in the 1982 loadometer study where an eight hour count (10 AM to 6 PM) was used in place of the twenty-four hour count. The average number of equivalent 18 kip single axle loads per 1,000 trucks was computed at each site for a p_t of 2.5 and SN of 5 for flexible pavements and D of 9 inches for rigid pavements. The truck factors from the eight hour period were a good approximation of those from all the continuous WIM sites except one. Therefore, it was recommended that eight hour counts be used in the future to reduce personnel requirements and avoid problems with local power outages.

The results for the percentage of trucks using the outside lane at each four lane site range from 79.1% to 92.0%. The average percent of trucks in the outside lane was calculated to be 84.1%. The study recommended that a value of no less than 85% be used for pavement design purposes.

3.2 Truck Factors Updated in 1993

In 1993 the truck factors were again updated, but there was no official documentation of the procedure or information used to obtain them. From the information supplied by ALDOT it was determined that the same equations from *The Design of Pavement Structures* (Appendix MM) were used to determine the truck factors. The new truck factors used tridem axles as well as single and tandem axles. This was accounted for in the design equation by using an axle code (L_2) of three. The terminal serviceability was also extended to include 3.0 and 3.5. An average truck factor was calculated by using a weighted average for vehicle classes 5-13 as shown in steps 1 to 3.

1. Multiply each vehicle class by its average daily count.
2. Sum the values from step 1.
3. Divide the sum by the total average daily count for classes 5-13.

Truck factors were computed this way for five WIM stations and for the statewide average. It was common practice for ALDOT to use the statewide average truck factor for pavement design. For a SN = 5 and p_t = 2.5 the resulting truck factor was 0.9896, which was an increase of 23% from the 1983 truck factor. The recommended truck factors for use in pavement design in Alabama are summarized in Table 3.1 (p_t = 2.5 and SN = 5).

Table 3.1 Truck Factors in Alabama

Year	Recommended Truck Factor	
	Flexible Pavement	Rigid Pavement
1964	0.46952*	0.60635*
1982	0.80447	1.35282
1993	0.9896	1.5797

*Classified as Other Urban

3.3 Surveys of Practice in Other States

As part of this study, a survey was conducted of Georgia, Florida, Mississippi, and Tennessee to gain insight into their methods for pavement design. The responses of each state to the survey are included in Appendix A. The results of the survey concluded that all four states use AASHTO design procedures and ESALs for pavement design. All states but Georgia have operating WIM stations that are used for data collection. Tennessee is the only state that uses a different ESAL for each design location based upon individual loading information. The other states use a statewide average for different vehicle classes. A summary of the response to the surveys is displayed in Table 3.2.

Table 3.2 Summary of Surveys

Question	Georgia	Florida	Mississippi	Tennessee
Breakdown of Vehicle Classification	Flexible-No Breakdown Rigid-Multi-Unit, Single-Unit, and other	FHWA Classes 4-13 (Averaged)	FHWA Classes 4-13 (Separately)	FHWA Classes 1-13 (Separately)
Use of Growth Factor	No	Yes	Yes	Yes
How often ESAL Updated	Last Update 1984	Reviewed Annually	Every 2-3 years	As-Need Basis
Use Average ESAL factors	Yes (Rigid Pavement)	No	No	Yes

It has been common practice for Alabama and 3 of the four states surrounding Alabama to use a statewide average truck factor for pavement design. Current data from WIM devices in Alabama was used to determine if Alabama should continue to use a statewide average. The next chapter will describe the WIM data that were used.

CHAPTER 4. DATA COLLECTION AND MANAGEMENT

ALDOT provided the 2001 weight and vehicle classification data that were used for this project. The weight data came from two types of WIM stations; HESTIA and PAT. The PAT stations were for enforcement only. The HESTIA stations are a rack mounted piezo electric sensor, while the PAT stations use the following sensors; bending plates, piezo, and loops. For the classification of vehicles the HESTIA stations have a user definable classification system and the PAT stations use a "Scheme F Default", which is the FHWA vehicle classification system. There were five HESTIA sites and eleven PAT sites. Each site has two stations that recorded data in both directions except for HESTIA site 920, which recorded traffic in one direction only. Figure 4.1 and Table 4.1 shows the locations of all the WIM sites.

Table 4.1 Location of WIM Sites

Equipment Manufacturer	Site	Direction of Travel	Location	Milepost
HESTIA	48	North and South	I-65	210.0
	906	East and West	US 84	201.0
	914	North and South	US 280	132.15
	917	North and South	US 431	38.0
	920	South only	I-59	196.2
PAT	931	North and South	I-65	355.7
	961	North and South	I-65	21.0
	963	East and West	I-10	5.0
	918	North and South	I-59	100.0
	911	North and South	US 280	55.8
	915	North and South	US 43	49.2
	933	East and West	AL 20	30.8
	934	East and West	US 78	79.0
	939	East and West	AL 41	124.7
	960	North and South	US 84	49.9
	964	North and South	US 231	36.0

Figure 4.1 Location of WIM Sites

The PAT sites had nearly complete data for the year 2001 with the exception of stations 963 and 918. Since there was very little information provided for those two stations, it was decided to not include them in the analysis. Site 960 was also not included in the analysis because the data from the site resulted in unrealistically high monthly truck factors. The remaining PAT stations had at least 83% of the year's data. The data from the HESTIA stations were not as complete as the PAT stations, but it was decided that there was enough information to proceed with the analysis. Table 4.2 shows the data completeness for each station. The last number of the station ID represents the direction of travel; 1 (North), 5 (South), 3 (East), and 7 (West). The percentage of data completeness was determined by comparing the total hours of operation for a month with the total hours for that month. The average hours of operation for the entire year were also calculated.

The software program Vehicle Travel Information System (VTRIS), available from the Federal Highway Administration (FHWA), was used to generate annual, monthly, and daily summaries of the raw traffic data for all stations. VTRIS was then used to derive information from the vehicle classification and weight data, and organized it into several tables. The W-4 Table segregated the average daily axle counts for each vehicle class by axle load bins. For single axles the axle load bin ranged from 0 kips to 44.1 kips in increments of 2.2 kips and for tandem axles the axle load bin ranged from 0 kips to 88.2 kips in increments of 4.4 kips.

The method used to average the axle counts was the "Hour of the Day Method". For each class, the average number of axles was calculated for each hour in the year. Then the hourly averages are summed and divided by 24 to obtain the daily average for the class (Equation 1 and 2).

$$\frac{WC(1)}{TH(1)} + \frac{WC(2)}{TH(2)} + \ldots + \frac{WC(24)}{TH(24)} = \sum \frac{WC_i}{TH_i} = \frac{\sum_{i=1}^{24} WCi}{\sum_{i=1}^{24} THi} \qquad (1)$$

$$AverageDailyValue = \frac{\sum_{i=1}^{i=24} \frac{WC_i}{TH_i}}{24} \qquad (2)$$

where,

WC(x) = Weight count for hour x

TH(x) = Total number of hours counted for hour x

At each axle load bin the axle counts for FHWA vehicle classes 5 to 13 were added to create an axle load distribution for heavy vehicles. This was done for both single and tandem axles for the given time period. A spreadsheet was used to calculate the relative and cumulative frequencies because VTRIS was not able to generate frequencies. After this was done a procedure was developed to analyze the difference between axle load distributions and ESALs, which is described in the next chapter. The data from these sites were also used to create a model for axle load distributions.

Table 4.2 Data Completeness

	STATION	% DATA COMPLETE												
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	AVG
HESTIA	481	0	0	0	0	8	100	56	0	0	53	100	39	30
	485	0	0	0	0	8	98	45	0	0	53	100	36	30
	9063	0	0	0	0	0	36	70	44	6	50	90	94	34
	9067	0	0	0	0	0	45	69	70	6	50	92	90	36
	9141	0	0	0	0	6	0	0	93	50	56	63	80	29
	9145	0	0	0	0	7	0	0	93	50	55	63	81	29
	9171	95	98	100	99	97	100	0	63	21	0	77	50	68
	9175	97	99	98	99	98	100	0	64	22	0	75	55	68
	9205	41	64	90	98	0	32	19	76	50	18	0	0	45
PAT	9113	99	100	100	100	100	100	42	72	100	100	100	100	93
	9117	100	100	100	100	100	100	42	72	100	100	100	100	93
	9151	100	98	100	100	100	100	100	100	99	100	100	99	100
	9155	99	100	100	99	100	100	100	100	99	100	100	97	100
	9181	100	79	0	0	0	0	0	0	0	0	0	0	15
	9185	50	63	0	0	0	0	0	0	0	0	0	0	9
	9311	88	100	100	100	90	100	87	74	97	100	100	100	95
	9315	88	100	100	100	90	100	87	74	97	100	100	100	95
	9333	100	100	100	100	100	100	87	97	87	100	100	100	98
	9337	100	100	100	100	100	100	87	97	87	100	100	100	98
	9343	95	98	100	100	100	100	45	77	100	100	100	100	93
	9347	95	98	100	100	100	100	45	77	100	100	100	100	93
	9393	97	100	100	100	100	100	100	100	100	100	97	100	100
	9397	97	100	100	100	100	100	100	98	41	100	97	100	94
	9603	100	100	100	100	100	100	100	98	100	100	95	100	99
	9607	100	100	100	100	100	100	100	100	100	100	95	100	100
	9611	100	100	35	87	44	89	84	71	100	90	100	100	83
	9615	100	100	35	87	44	89	84	71	100	90	100	100	83
	9633	0	0	0	0	0	0	0	0	0	23	100	90	18
	9637	0	0	0	0	0	0	0	0	0	23	100	90	18
	9641	100	100	15	100	97	100	94	77	100	98	100	100	90
	9645	93	100	12	50	61	100	94	77	100	98	100	100	82

CHAPTER 5. ANALYSIS PROCEDURE

Truck factors may be computed independently for each day of the week, month of the year, and direction of travel. The analysis would require that data from WIM stations be collected year round for seven days a week. However, the truck factors only need to be separated if the differences in truck factors cause a significant difference in the resulting thickness of pavement. The purpose of this analysis was to determine if the differences in truck traffic at each site warranted the separate determination of truck factors by day, month, and direction. Also, site specific truck factors are needed if there are variations in truck traffic throughout the region or state. If no variations exist one truck factor for the region or state could be used.

Statistical and practical tests were created to determine if the truck factors should be determined separately for each day, month, direction, and site or if a statewide average could be used. Practical tests were used as well as statistical tests because a comparison could result in a statistical difference without any difference in the resulting pavement thickness.

The use of truck factors to calculate ESALs for pavement design are important for the empirical design procedures of the 1993 AASHTO Guide. However, the forthcoming “2002” Guide and other M-E design approaches require the knowledge of axle load distributions. An innovative procedure was created to model axle load distributions using a mixture of normal and lognormal distributions. A procedure to compare M-E pavement designs required for various site-specific load spectra and their deviations from the combined statewide distribution was developed.

5.1 Variations in Axle Load Distributions and Truck Factors

The 2001 weight data organized by VTRIS were used to determine variations in axle load distributions and truck factors. Procedures were developed to determine the statistical and practical differences on a daily, monthly, directional, and site basis. A sensitivity analysis tested the impact of variations in truck factors on pavement design. The results of the tests were used to determine if the truck factors should be separated by day, month, direction, or site.

5.1.1 Daily Variation

At each station, and for the statewide average, the axle load distributions for heavy vehicles were determined for each day of the week. Each daily axle load distribution was then compared to the average yearly axle load distribution for that station. The Kolmogorov-Smirnov (K-S) test was used to test if the axle load distributions were statistically significantly different by day of the week (Siegel, 1956). The K-S two-sample test determines if two independent samples have been drawn from the same population by comparing the cumulative distribution functions (CDFs) of the samples. For this test the following hypothesis was tested:

Null Hypothesis (H_o): the CDFs are equal

Alternative Hypothesis (H_1): the CDFs are statistically significantly different

The K-S test required the total yearly axle counts for the analysis. Since the data were compiled into average daily axle counts, they were expanded by multiplying the number of hours that data was collected for the specific day and then dividing by 24. At stations with two lanes of traffic, the lane with the most hours of operation was used for the analysis.

To perform the test, the maximum of the differences (D) between the CDFs at each axle load bin for each day and the average across all days was determined. For example, the maximum difference can be seen in Figure 5.1 as the difference between 21.8% and 15.4% at 3 kips. The difference was then compared to critical values at various levels of significance, as shown in Table 5.1. For D values greater than the critical value the null hypothesis was rejected, which means there is a statistically significant difference between the axle load distributions being compared.

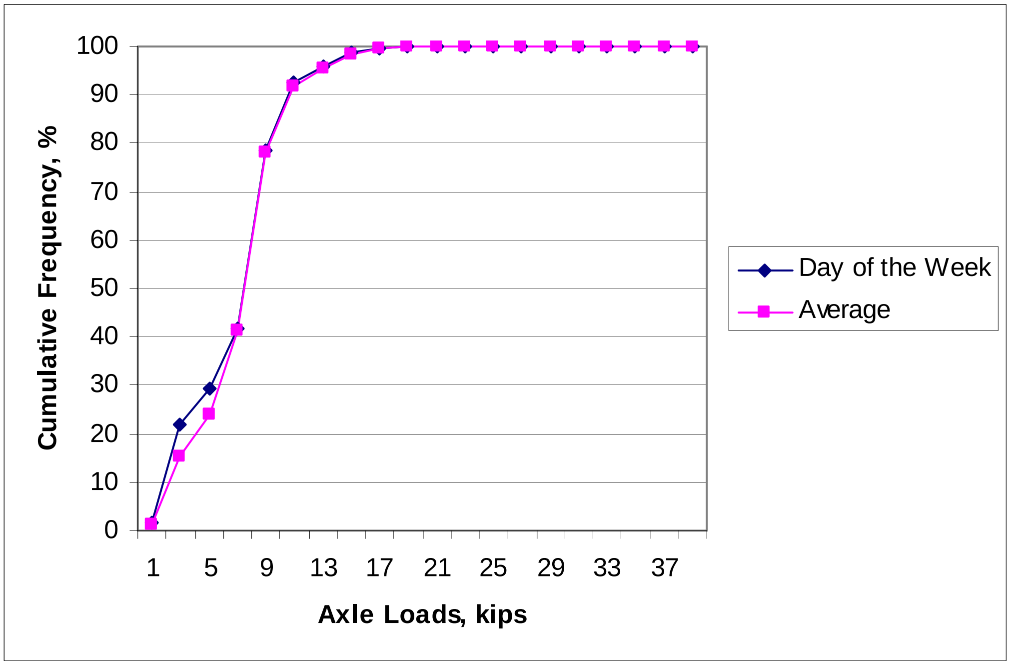


Figure 5.1 Example of Comparison of Cumulative Distribution Function

Table 5.1 Critical Values for K-S Test

Level of Significance	Value of D so large as to call for rejection of H_o at the indicated level of significance
0.05	$1.36\sqrt{\frac{n_1+n_2}{n_1 n_2}}$
0.001	$1.95\sqrt{\frac{n_1+n_2}{n_1 n_2}}$

Note: The values of n_1 and n_2 are the total axle counts

The axle load distributions are used to calculate the truck factors. Even if the axle load distributions are statistically significantly different, the resulting truck factors may not cause a practical difference for pavement design. Therefore, a comparison of truck factors was conducted to test for practical differences. The W-4 table generated in VTRIS calculated the load equivalency factors for the given terminal serviceability (P_t) and structural number (SN) for flexible pavement or depth of pavement (D) for rigid pavement. The terminal serviceability is defined as the point at which the pavement is no longer serviceable. The SN is an index number that may be converted into the thicknesses of the flexible pavement layers by using layer coefficients that are dependent upon the material type of the layer. The load equivalency factors are multiplied by the corresponding axle count for each of the 13 vehicle classes to calculate the ESAL's. The ESAL's are divided by the number of vehicles for each vehicle class to determine the ESAL's per vehicle. To test the practical difference, the ESAL's per truck for heavy vehicles with a P_t of 2.0 and 2.5 for SN ranging from 1 to 10 and D ranging from 5 to 14 were calculated. The ESAL's per truck were combined into an average ESAL's per truck for heavy vehicles, or truck factor, by using a weighted average (Equation 5.1). The weighted average takes into account the proportion of heavy vehicles by vehicle class.

$$WeightedESAL = TruckFactor = \frac{\sum_{i=5}^{13} Count_i * \left(\frac{ESAL_i}{vehicle_i} \right)}{\sum_{i=5}^{13} Count_i} \tag{5.1}$$

where,

$Count_i$ = Daily Average Count for vehicle class i

$ESAL_i$ = ESAL's per truck value for vehicle class i

$vehicle_i$ = Vehicle classes 5-13

The percent error was then calculated to compare the difference in the daily truck factors and the average yearly truck factor (Equation 5.2). The percent error shows the how much the daily truck factors deviate from the average yearly truck factor.

$$PercentError = \left[\frac{TruckFactor_x - TruckFactor_{avg}}{TruckFactor_{avg}} \right] * 100 \tag{5.2}$$

where,

$Truck\ Factor_x$ = Truck factor for a specific day of the week

$Truck\ Factor_{avg}$ = Average truck factor for all days combined

5.1.2 Monthly Variation

For the eight PAT stations and the statewide average, the axle load distributions of heavy vehicles for each month were determined. The HESTIA stations were not included in the monthly analysis because of the large amount of missing data at those WIM stations. The CDF's for each month were compared to the CDF of the average across all months for each station and the statewide average using the K-S Test. The truck factor for each month was also compared to the average yearly truck factor using percent error as defined above. The same methodology described in the preceding section was used to determine the practical and statistical significance of the monthly variations.

5.1.3 Variation by Direction

For the daily and monthly variations, each direction was independently tested for each station. To detect directional variations, each direction of a site was compared to the average of both directions for that site. Station 9205 was not included in the analysis because traffic was monitored in only one direction. The K-S Test was used to determine if there were statistically significant differences between the CDF's for each direction at a site and the site average. To expand the daily axle counts for the directions combined, the hours of operation for the station with the least amount of operating hours was used. Since there was always less than 437 hours difference in operating hours between directions, the choice of which hours of operation to use made an insignificant difference. The K-S test was performed in the same manner described previously to determine whether the differences were statistically significant.

The percent error between the directional truck factor and the average yearly truck factor was also compared. To determine the effect the percent error in truck factors would have on the final SN or D, a sensitivity analysis was performed. AASHTO's recommended design equations from *1993 AASHTO Guide for Design of Pavement Structures* were used to calculate SN and D. The following equation was used for flexible pavements (Huang, 1993):

$$\log_{10} W_{18} = z_r * s_o + 9.36 * \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07 \qquad (5.3)$$

where,

W_{18}	=	ESAL's
Z_r	=	-1.645, @ 95 % Reliability
S_o	=	Variability
SN	=	Structural Number
ΔPSI	=	Design Serviceability Loss
M_R	=	Resilient Modulus of Soil

Since the purpose of the sensitivity analysis was to determine the effect of the truck factors on pavement design, a general pavement structure was assumed and held constant. The flexible pavement had an initial serviceability of 4.2 and terminal serviceability of 2.5, which is recommended for major highway facilities (Yoder, 1975). The variability and reliability were assumed to be 0.45 and 95%, respectively. A variability of 0.45 is the standard number used for flexible pavement design and a reliability of 95% is a reasonable value for interstates, freeways, and principal arterials. The values for variability and reliability are the recommended values from the 1993 Guide. Three different values of resilient modulus were used to include a wide range of soil stiffness. The three values used were 5000 psi, 10,000 psi, and 25,000 psi.

For rigid pavements the following equation was used (Huang, 1993):

$$\log_{10} W_{18} = z_r * s_o + 7.35 * \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624*10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) * \log_{10}\left[\frac{s'_c * c_d\left[D^{0.75} - 1.132\right]}{215.63 * J\left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right]}\right] \quad (5.4)$$

where,

W_{18}	=	ESAL’s
Z_r	=	-1.645 @ 95 % Reliability
S_o	=	Variability
D	=	Depth of concrete slab, in
ΔPSI	=	Design Serviceability Loss
s'_c	=	Concrete Modulus of Rupture, psi
c_d	=	load transfer coefficient, unitless
E_c	=	Concrete Elastic Modulus, psi
K	=	Effective Roadbed Soil Modulus, pci

The rigid pavement was assumed to have Portland cement concrete (PCC) shoulders with dowel bars and good drainage capabilities. These assumptions meant the load transfer coefficient (J) was 2.8 and the drainage coefficient (c_d) was 1.15. Table 5.2 displays the standard values of initial serviceability, terminal serviceability, concrete elastic modulus (E_c), reliability, and variability for AASHTO design of PCC pavement (Huang, 1993). The concrete modulus of rupture (S'_c) of 662.5 psi was calculated using the E_c value and the following equation (Huang, 1993):

$$S'_c = \frac{43.5E_c}{10^6} + 488.5 \tag{5.5}$$

Three different values of 258, 515, and 773 pci were used for the effective roadbed soil, which corresponds to the three resilient modulus values used in the sensitivity analysis for flexible pavement. The effective roadbed soil modulus is equal to the resilient modulus divided by 19.4 (Huang, 1993).

Table 5.2 Constant Input Parameters for Calculation of D

Input Parameter	Constant Value
Concrete Elastic Modulus	4 x 10^6 psi
Modulus of Rupture	662.5 psi
Reliability	95%
Variability	0.35
Effective Roadbed Soil Modulus	258, 515, 773 pci

In order to determine W_{18}, or ESAL's over the entire design life of the pavements, a growth rate, number of years in the design life, average daily truck traffic, lane distribution, and directional distribution had to be assumed (Equation 5.6).

$$W_{18} = GrowthFactor * ADTT * 365 * TruckFactor * LaneDistribution * DirectionalDistribution \tag{5.6}$$

where,

Growth Factor	=	$\frac{((1+GrowthRate)^n - 1)}{GrowthRate}$
N	=	Design Life
ADTT	=	Average Daily Truck Traffic
Truck Factor	=	ESAL's per truck
Lane Distribution	=	% of vehicles on heaviest loaded lane
Directional Distribution	=	Distribution of vehicles by direction

Typical values were selected and held constant as shown in Table 5.3. Though ALDOT uses lane distribution factors of 0.85 for urban and 0.95 for rural four-lane facilities, it was decided to use 0.85 uniformly in the analysis regardless of location. This was done to evaluate, on an even basis, the effects of differing load distributions. In practice, the site-specific lane distribution factors should be used. The directional distribution was set to one since a comparison was made between each direction and the average for that direction. Four different values of 100, 800, 1500, and 2500 trucks were used for the ADTT in order to capture a range of truck traffic. On highways with particularly high truck traffic volumes, such as many Interstate highways, site-specific data are often available and generally should be used in lieu of axle load distribution models aggregated from other sites. The final variable needed to calculate the ESAL's was the truck factor for each station. For rigid pavements the truck factor corresponding to a D of 9 inches was used and for flexible pavements SN of 5 was used.

Table 5.3 Constant Input Parameters for Calculation of Design ESALs

Design Variable	Value
Growth Rate	4%
Design Life	25 Years
Lane Distribution Factor	0.85
Direction Distribution	1.0
ADTT	100, 800, 1500, 2500

For each ADTT there were three SN or D's calculated, one for each resilient modulus or effective roadbed soil modulus. The calculations were performed for each direction and the two directions of travel at each station combined. Each direction was then compared to the average of both directions. The truck factors were compared by observing how much the resulting SN or D fluctuated. For example, if the pavement depth increased or decreased by less than half an inch between truck factors, then that would indicate an insignificant difference, from a practical perspective, between the truck factors. A ½ inch differential was selected because it is unrealistic to design and build a pavement thickness to a finer level.

5.1.4 Variations between Sites and Statewide Average

A comparison was made between each of the 13 sites (directions combined) and the statewide average. The K-S Test was used to detect statistical differences and the percent error was used to determine if there were any practical differences using the same procedures described previously. A sensitivity analysis was also conducted to determine the effect of differences in truck factors on the final SN and D values. The methodology was the same as described in the preceding section.

5.1.5 Trends in Truck Factors Over Time

ALDOT calculated truck factors for 1964, 1983, and 1993. In 1964, truck factors were calculated for four different functional classes; urban interstate, urban other, rural interstate, and rural other. In 1983 and 1993 a statewide average was used. The rural other truck factor for 1964 and statewide average truck factors for 1983, 1993, and 2001 were plotted to determine if there are any trends in the truck factors over time.

5.2 Axle Load Modeling

ESALs are a useful tool to characterize heavy traffic loads, but recently several states have implemented mechanistic-empirical design procedures. The forthcoming "2002" *Guide for Design of Pavement Structures* is a mechanistic-based design guide and requires the use of the full axle load distribution by main axle types, i.e. single, tandem, and tridem. In the past axle load distributions have been modeled using regression models. The axle load distribution is divided into four or more parts and then a polynomial regression equation is fitted to each part. It would be useful to create a model based on a theoretical distribution instead so that it would be continuous, differentiable, and more meaningful.

For this study, a mixture of normal and lognormal distributions was used to decompose the axle load distributions for single and tandem axles at the 13 sites and for the statewide average based on the data. These distributions were chosen because axle load distributions generally have two distinct peaks that resemble normal or lognormal distributions. It was found that for single axles, the first peak represents Class 5 vehicles and the second peak represents the steering axles of Class 9 vehicles. For tandem axles, the two peaks probably represent unloaded and loaded trucks. The mean and standard deviation of the normal and lognormal distributions can be used to characterize the data. The mean gives the location of the peak axle load and the standard deviation describes the dispersion of observed axle loads about the peak.

The process to generate the axle load distribution models involved a number of steps:

1. Fitting the distributions to the data,
2. The computation of R^2 to determine how much of the observed error is explained by the model.

3. Performing a chi-squared test to determine the fit of the theoretical probability density function (PDF) to the actual PDF

The theory behind the axle load model was that the bimodality of the axle load distributions was due to a mixture of statistical functions. The general mixture model is presented in the Equation (5.7) (NIST/SEMATECH e-Handbook of Statistical Methods):

$$M = p\phi_1 + (1-p)\phi_2 \tag{5.7}$$

where

p = proportion of first distribution

ϕ = normal or lognormal probability functions of respective distributions

M = probability distribution function for the mixed model

For the mixture of two distributions, there were five unknown parameters that had to be determined. The five parameters were the mixing proportion and the mean and standard deviation of both distributions. For example, the first mean shows the location of the first peak and the second mean shows the location of the second peak as illustrated in Figure 5.2. The standard deviations describe the dispersion of the axle loads about the means. For example, the higher the standard deviation, the lower and wider the peak.

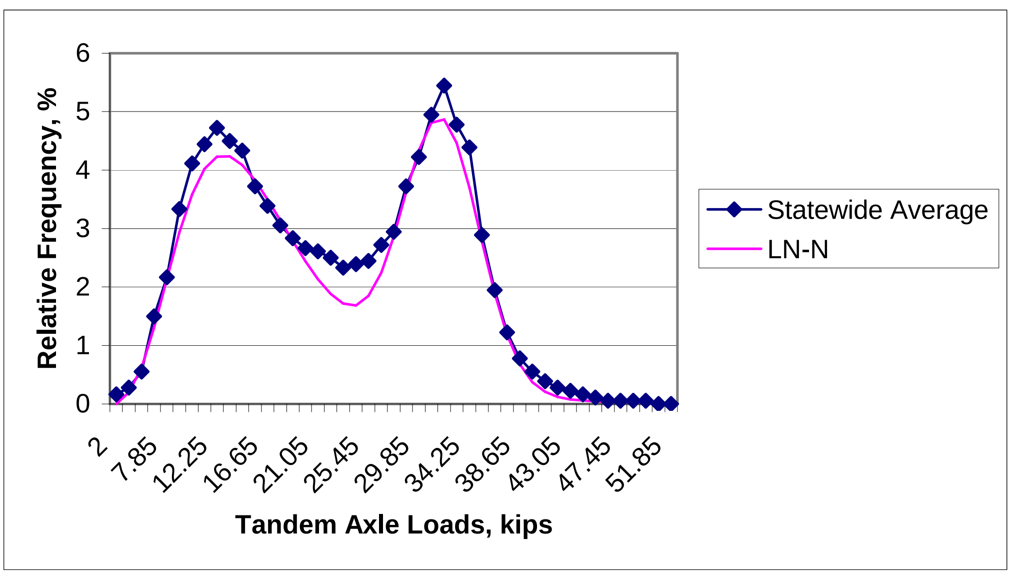


Figure 5.2 Axle Load Distribution for Statewide Average

A least squares regression technique was used to solve for the five parameters that best fit the model to the observed data. Initial seed values for the mixing proportion, the means, and the standard deviations were required to start the iterative process. The five initial seed values were used to calculate the theoretical distribution. The squared difference of the theoretical distribution and the actual distribution was calculated for each axle load bin. The squared difference was then summed for all bins. The process was repeated to solve for the five parameters that resulted in the minimum sum of the squared errors, which was determined to be the best fit. The squared error was defined by Equation (5.8):

$$SSE = \sum_{i=1}^{n} \left(PDF_i - M_i\right)^2 \qquad (5.8)$$

where

SSE	=	Sum of the squared errors
N	=	number of axle load bins
PDF_i	=	actual probability at axle load bin i
M_i	=	theoretical probability at axle load bin i

The axle load bins were divided into 1,000 lb increments. Initially 500 lb increments were used, but it was discovered that observed peaks were minimized as the increments were decreased. Without the peaks, the lognormal and normal distributions cannot be used to model the data. There were not enough data point if increments of more than 1,000 lb were used, therefore, 1,000 lb increments were determined to be the optimal size of axle load bins.

For some of the single axle load distributions a combination of three distributions was used to get a better fit because there was a small third peak among the heaviest axle loads (Figure 5.3). Theoretically, equation 5.8 can be expanded to solve for an infinite number of subdivisions, given the number of underlying probability distributions. The general mixture model for three distributions is:

$$M = p_1\phi_1 + p_2\phi_2 + \left(1 - p_1 - p_2\right)\phi_3 \qquad (5.9)$$

where

p	=	proportion of distribution i
ϕ	=	probability density function of distribution i

When the mixture model for three distributions was used there were eight parameters instead of five parameters to determine. The same method was used to determine the best fit model.

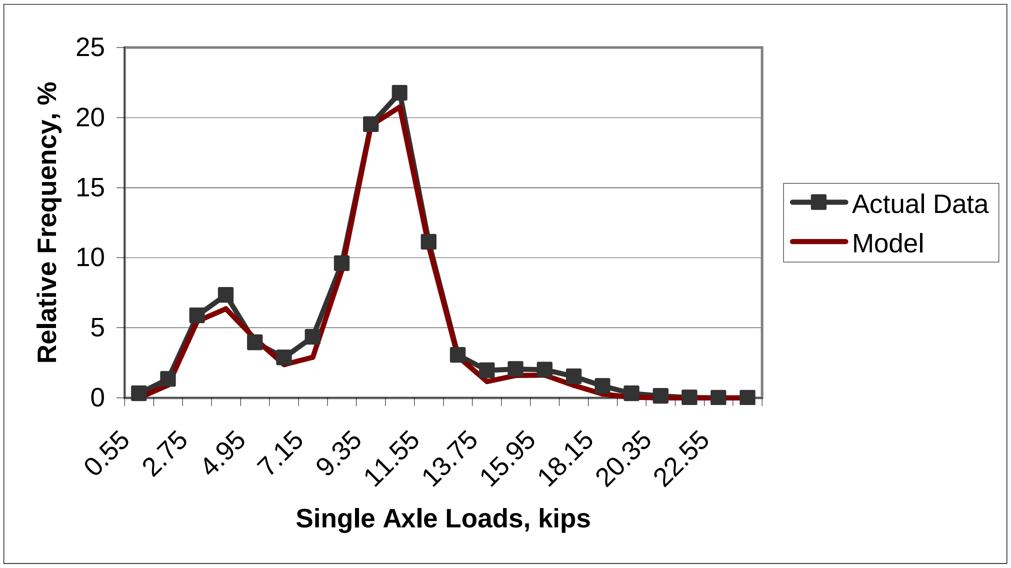


Figure 5.3 Example of Three Peaks in an Axle Load Distribution

The R^2 statistic was determined for all the models. The R^2 statistic relates the proportion of the observed error that is explained by the theoretical model. R^2 values range from 0 to 1, with $R^2 = 1$ representing a perfect fit. The following equation was used to determine the R^2 statistic for each model:

$$R^2 = 1 - \left(\frac{SSE}{SST} \right) \qquad (5.10)$$

$$SST = \sum_{i=1}^{n} \left(y_i - \bar{y} \right)$$

where

SSE	=	Sum of the Squared Errors
SST	=	Total Sum of Squares
y_i	=	actual probability distribution function at axle load bin i
y	=	average of probability distribution function

An advantage of using a mixture of distributions to model the axle load distributions was the ability to test the statistical properties of the theoretical distribution. The Chi-Squared Goodness of Fit Test was used to measure the conformity of the data to the theoretical distribution for a specified confidence level (D'Agostino, 1986). For each axle load bin there was an observed number of axle counts. The rule for the chi-squared test is if the axle counts in a particular bin are less than five, they must be combined with the adjoining bin(s) until the axle counts are five or greater. The expected number of axle counts at each bin was computed by multiplying the total number of counted axles by the theoretical frequency at that bin. The following equation is then applied to the data:

$$\chi_{obs}{}^{2} = \sum_{0}^{i} \frac{(O_i - E_i)}{E_i} \qquad (5.11)$$

where

χ^2_{obs} = observed chi-square value

O_i = observed number of axle counts

E_i = expected number of axle counts

The χ^2_{obs} is then compared to the critical chi-squared value. The χ^2_{obs} must be less than the critical chi-squared value for a given significance level for the theoretical model to be considered a good fit.

The described procedures were applied to the Alabama's 2001 data to determine the traffic variations that existed. The resulting axle load distributions and truck factors as well as the statistical and practical differences between them are discussed in the next chapter. The sensitivity of pavement thickness to the variations in truck factors in Alabama is also described. In addition to the truck factors, the mixture model for each site is shown along with the results from the R^2 and Chi-Squared Test.

5.3 Effect Of Load Spectra On Mechanistic-Empirical Pavement Design

Mechanistic-empirical (M-E) pavement design represents a dramatic change in pavement engineering that agencies at the federal, state and local level are currently facing. Due to the limitations of the existing design methodology (AASHTO, 1993), based upon the AASHO Road Test conducted in the late 1950's (HRB, 1962), it is commonly understood that a change is needed to accommodate current traffic, materials and environmental conditions. While the end result of M-E design is still pavement layer thickness, there are significant changes in how the traffic loadings, material properties and environmental conditions are modeled for design. For agencies, this translates into assessing the current practice and how it may be adapted to M-E design.

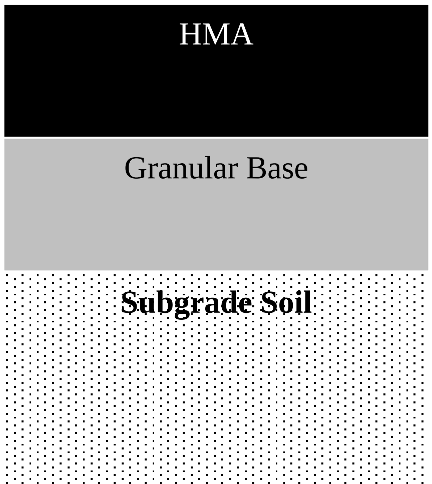
Concerning traffic characterization, most modern M-E design approaches (e.g., Eres, 2004; MnDOT, 2005; Timm and Young, 2004) utilize load spectra rather than converting mixed traffic into equivalent single axle loads (ESALs). Under the existing AASHTO empirical pavement design method (AASHTO, 1993) these axle weights and frequencies would be converted into ESALs using the fourth-power law in consideration of pavement type and expected serviceability loss. The fourth-power law, established at the AASHO Road Test (HRB, 1962), states that pavement damage increases with axle weight raised to the fourth power and is the basis for converting mixed traffic into ESALs. In M-E design, these distributions are used for mechanistic pavement response modeling and empirical damage functions to determine the expected life of the pavement structure.

Given the needs discussed above, the objective of this part of the research project was to determine the practical impact of site-specific load spectra on flexible pavement M-E thickness design. To accomplish this objective, the site-specific load spectra were evaluated using the M-E design software PerRoad (Timm and Young, 2004). The software incorporates linear layer elastic theory, Monte Carlo simulation and transfer functions to estimate pavement performance. Designs were developed for a typical three-layer pavement structure with three levels of soil support.

5.3.1 Pavement Cross-Section and Traffic Loading

For the purposes of this study, all the load spectra were evaluated with a fixed traffic volume of 10 million axle load repetitions. In reality, traffic volume is certainly site-dependent, but one purpose of this study was to examine the practicality of using a representative axle load spectra statewide. Therefore, it was necessary to evaluate each load spectra at a fixed traffic volume according to the axle load distribution of each particular WIM site.

A typical three-layer pavement structure comprised of hot-mix asphalt (HMA) over an unbound granular base on top of subgrade soil was selected for analysis. Figure 5.4 illustrates the pavement cross-section and test matrix variables. The material properties were chosen to be representative and consistent with a previous study of load spectra effects on pavement design. Three soil stiffnesses were included to evaluate the impact of soil strength. Three HMA thicknesses were included to facilitate M-E design whereby trial sections are attempted in order to meet the design requirements, as will be explained below.



H, in	Modulus, psi	Poisson's Ratio
4, 8, 16	500,000	0.35
10	30,000	0.40
Infinite	5,000 10,000 15,000	0.45 0.45 0.45

Figure 5.4 Three-Layer Pavement Structure.

5.3.2 Mechanistic-Empirical Pavement Design Procedure

The M-E design software PerRoad 2.4 (Timm and Young, 2004), depicted schematically in Figure 5.5, was used to facilitate this study. Although PerRoad can model material property and thickness variability, only load spectra were considered in this study as shown in Figure 5.5. Load spectra were modeled using Monte Carlo simulation and critical pavement responses were computed using WESLEA, a layered elastic pavement analysis program (Van Cauwelaert et al., 1989), at the bottom of the HMA layer and top of subgrade to predict fatigue cracking and rutting, respectively. Shown schematically in Figure 5.5, the actual strain distributions generated from sites 920 and 933 and the statewide distribution are shown in Figures 5.6 and 5.7, respectively. It is interesting to note that the modes of each distribution, for both tensile and compressive strain, appear very similar amongst the different sites. For example, the mode of compressive strain in Figure 5.7 is approximately 160 $\mu\varepsilon$. Also, the bi-modality evident in the raw load spectra (Figure 4.1) appears to be diminished when transforming the axle weights through the mechanistic load response model. This was also observed in a previous study of load spectra and pavement response (Timm et al., 2000).

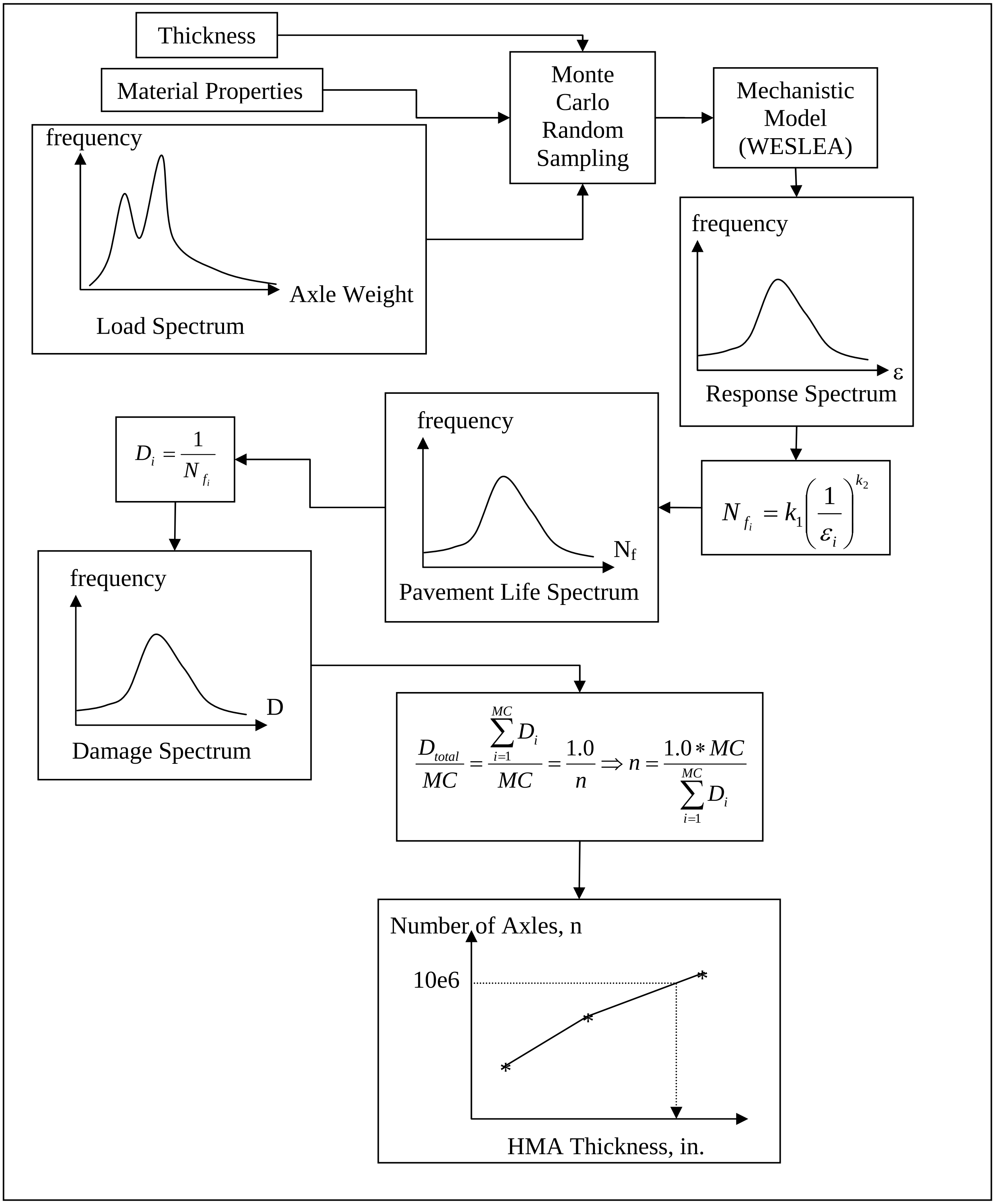


Figure 5.5 Stochastic-Based M-E Analysis.

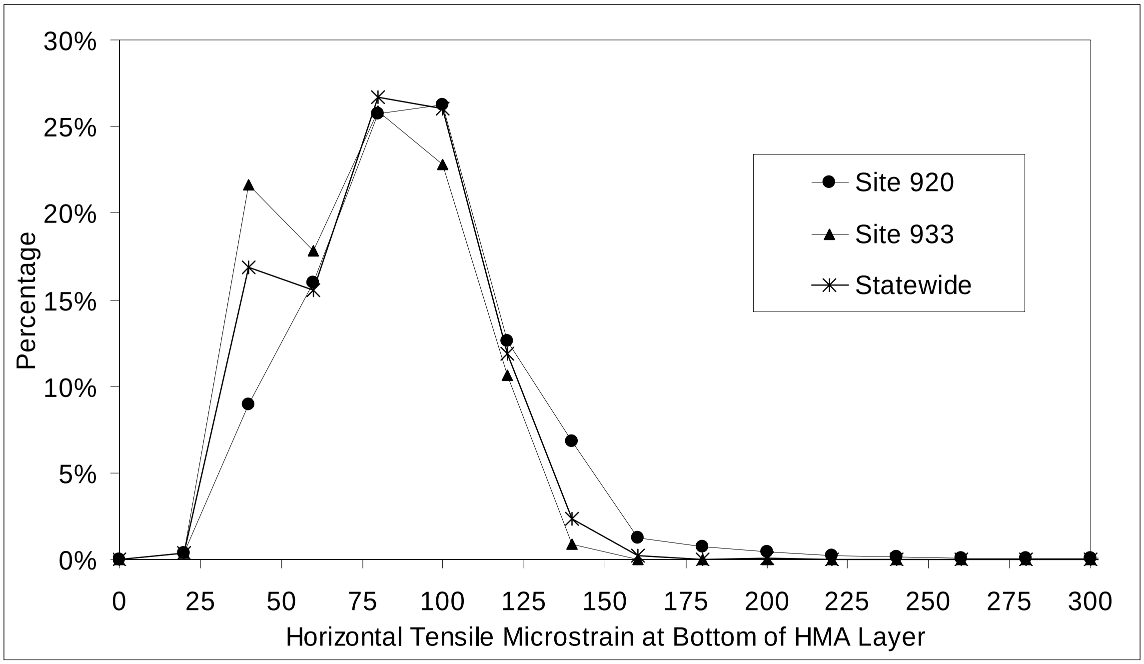


Figure 5.6 Asphalt Horizontal Tensile Microstrain Spectra.

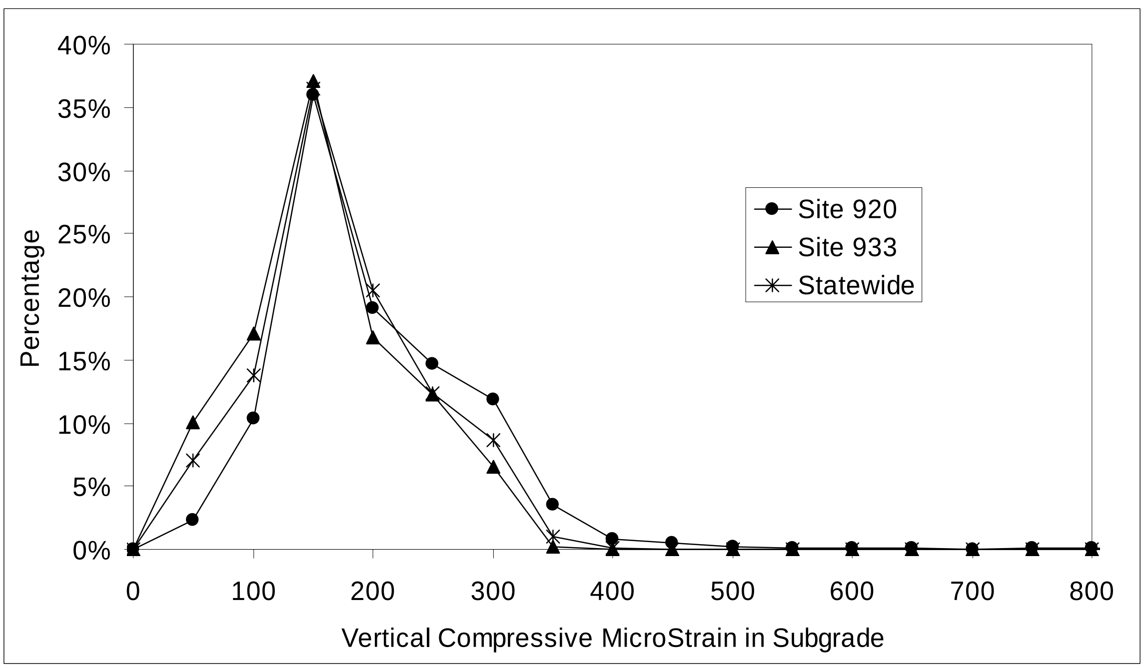


Figure 5.7 Subgrade Vertical Compressive Microstrain Spectra.

After the strain distributions were generated, pavement performance transfer functions were used to compute predicted number of cycles until failure for each strain level. While many such functions are available, the following were used to predict fatigue and rutting performance, respectively (Timm and Newcomb, 2003):

$$N_f = 2.83 \times 10^{-6} \left(\frac{10^6}{\varepsilon_t} \right)^{3.148} \quad (5.12)$$

$$N_r = 1 \times 10^{16} \left(\frac{1}{\varepsilon_v} \right)^{3.87} \quad (5.13)$$

Where:

N_f = number of cycles until fatigue failure

N_r = number of cycles until rutting failure

ε_t = horizontal tensile microstrain at bottom of HMA layer

ε_v = vertical compressive microstrain at top of subgrade layer

Equations 5.12 and 5.13 were utilized for each Monte Carlo cycle (i) so that distributions of performance were generated as depicted schematically in Figure 5.5. Further, Miner’s Hypothesis, a typical damage accumulation model used in M-E design, was used to compute damage (D_i) for each Monte Carlo cycle (i) by:

$$D_i = \frac{1}{N_{f_i}} \quad (5.14)$$

The total damage (D_{total}/MC) was calculated by summing over all the Monte Carlo cycles (MC):

$$\frac{D_{total}}{MC} = \frac{\sum_{i=1}^{MC} D_i}{MC} \quad (5.15)$$

The number of load repetitions to failure (n) for the given pavement cross section and load spectra were then determined by scaling the damage to the critical value of 1.0:

$$n = \frac{1.0 * MC}{\sum_{i=1}^{MC} D_i} \quad (5.16)$$

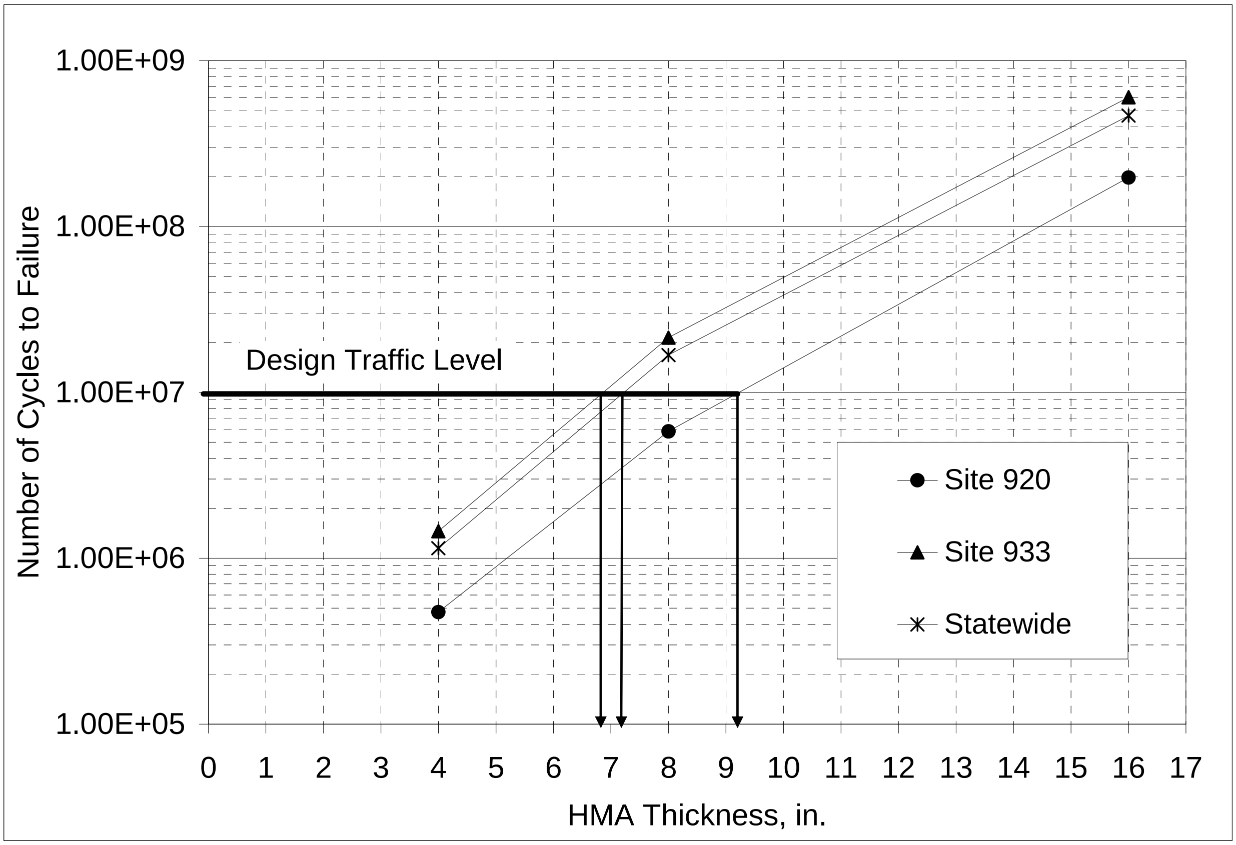


Figure 5.8 Thickness Determination – Example

Figure 5.8 shows that thickness was determined, for each soil stiffness and site, by plotting the number of load repetitions (n) versus HMA thickness and finding the thickness where n equaled 10 million, the design traffic level.

CHAPTER 6. RESULTS

The procedures described in the previous chapter were applied to the 2001 WIM data to determine the variations between axle load distributions and truck factors. The comparisons were made for daily, monthly, directional, and site differences. The results indicate that a statistically significant difference in CDFs does not mean that there is a practical difference in truck factors.

The 2001 WIM data were also used to successfully create axle load models for single and tandem axles. A mixture of a lognormal and normal distribution or a mixture a lognormal and two normal distributions was the best fit for single axles. Though the data did not conform well to the theoretical distribution, according to the chi-squared test, the models had very high R^2 values, indicating that the models fit the observed data well. The best fit for tandem axles was the mixture of a lognormal and normal distribution. At most sites, the tandem axle models conformed well to the theoretical models, and all of the models had very high R^2 values.

6.1 Variations in Axle Load Distributions and Truck Factors

The K-S Test revealed that for almost all of the cases the daily, monthly, directional, and regional differences in axle loads were statistically significantly different; due primarily to the large sample sizes. However, the percent error test did not show a considerable difference in truck factors. The sensitivity analysis illustrated that the differences in truck factors had an insignificant effect on the resulting pavement design.

6.1.1 Daily Variation

According to the K-S test there is a significant statistical difference in axle load distributions between the days of the week and the yearly average for each station. For the null hypothesis that the CDFs were identical to be accepted, the greatest allowable difference, D, between CDFs was always less than 2% and sometimes as low as 0.3%. Figure 6.1 shows the single axle CDF curves for the statewide average. The Tuesday CDF appears almost identical to the average CDF since the percent greatest difference between the two is 2.34%. However, for the CDFs to be considered identical by the K-S Test there can be a difference no greater than 0.83%, at a significance level of $\alpha = 0.05$, as shown in Table 6.1. Figure 6.2 and Table 6.2

show the same scenario for the statewide average tandem axles. The reason for the very small critical values was the large sample size, which was the number of axle counts.

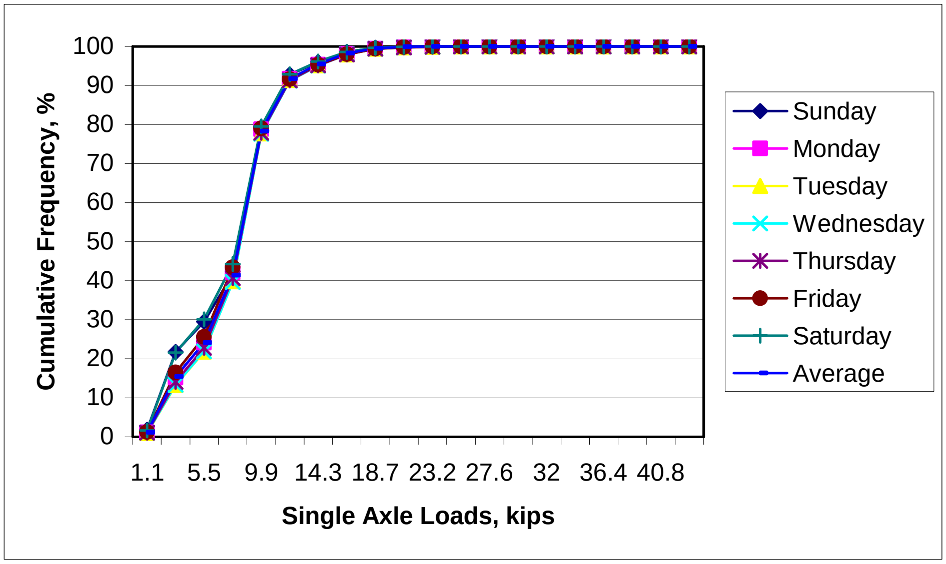


Figure 6.1 Single Axle CDFs for Statewide Average

Table 6.1 K-S Test for Statewide Average Single Axles

SINGLE AXLES			
DAYS	LARGEST DIFFERENCE IN CDFS	CRITICAL VALUES OF D	
		α=0.05	α=0.001
SUNDAY	0.0631	0.0115	0.0166
MONDAY	0.0060	0.0087	0.0124
TUESDAY	0.0234	0.0083	0.0119
WEDNESDAY	0.0227	0.0078	0.0112
THURSDAY	0.0137	0.0078	0.0112
FRIDAY	0.0205	0.0081	0.0117
SATURDAY	0.0610	0.0110	0.0158

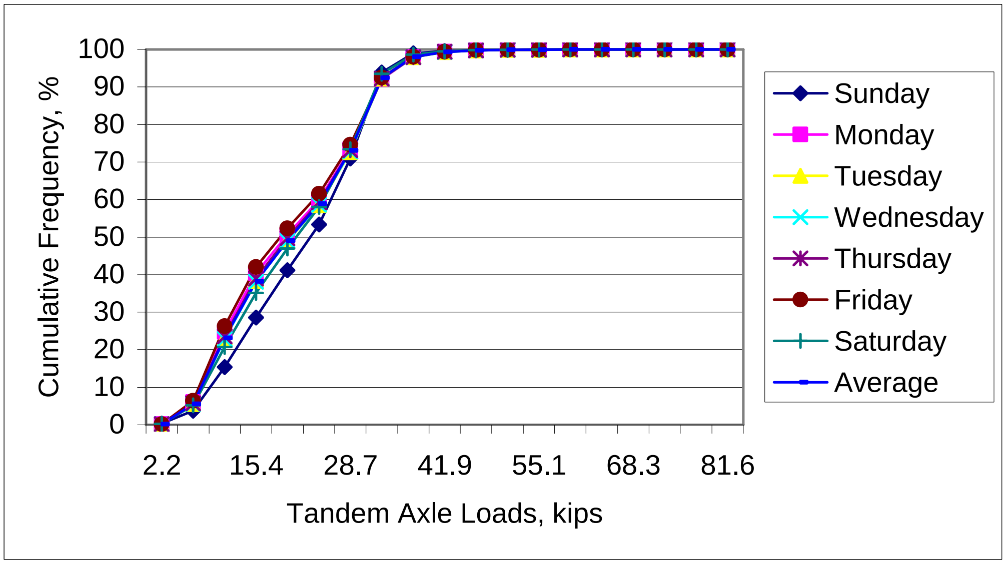


Figure 6.2 Tandem Axle CDFs for Statewide Average

Table 6.2 K-S Test for Statewide Average Tandem Axles

TANDEM AXLES			
DAYS	LARGEST DIFFERENCE IN CDFS	CRITICAL VALUES OF D	
		α=0.05	α=0.001
SUNDAY	0.0965	0.0117	0.0168
MONDAY	0.0207	0.0088	0.0126
TUESDAY	0.0037	0.0083	0.0119
WEDNESDAY	0.0023	0.0070	0.0113
THURSDAY	0.0072	0.0079	0.0114
FRIDAY	0.0379	0.0085	0.0121
SATURDAY	0.0308	0.0115	0.0165

However, the analysis did identify which daily axle load distributions vary the most from the average axle load distribution. The daily axle load distributions for single axles generally did not deviate much from the average. At nine of the stations, Saturday and Sunday axle loads were lighter than the rest of the days, but for the remainder of the stations there was not a noticeable difference. For tandem axles, Monday through Thursday remain fairly constant and were the closest to the average. These days of the week were typically so close together on the CDF curve, that they were indistinguishable by visual comparison. The axle load distributions that deviate noticeably from the average were Friday, Saturday, and Sunday. Saturday and Sunday were typically the days when trucks were carrying their heaviest loads, whereas Friday they were carrying their lightest loads. The difference between CDFs was greater than 3% for Sundays at 88% of the stations, for Saturday at 60% of the stations, and for Fridays at 52% of the stations. Station 9063 had the highest difference of 17% between Sunday and the average. Recall that a study in North Carolina found that the gross vehicle weight distribution for Sunday was statistically significantly different from the other days of the week (Wu, 1996). However, it was determined that the difference in Sunday traffic would have an insignificant impact on the accuracy of the overall average ESALs.

Even though Saturday and Sunday carried the heaviest loads, they did not always have the highest truck factor (Table 6.3). The reason for this was the lower truck volumes on the weekends (Table 6.4). The lower truck volumes affect the truck factor because the it is a weighted average of heavy vehicles. The lowest truck volume occurred on Sunday at 18 of the stations and on Saturday at the remaining 7 of the stations. The lowest truck factors occurred on Friday (8), Saturday (12), or Sunday (5).

Table 6.3 Daily Truck Factors; Pt =2.5 and SN = 5.0

Station	SUN	MON	TUES	WED	THURS	FRI	SAT	AVG
481	1.0500	0.9299	0.9377	0.9237	0.8988	0.8385	0.8765	0.9139
485	1.0319	1.0655	1.0772	1.0847	1.0899	1.0203	0.9809	1.0589
9311	0.7171	0.6423	0.6955	0.7072	0.6913	0.6303	0.6488	0.6752
9315	0.8674	0.7996	0.8584	0.8523	0.8113	0.7034	0.7273	0.8075
9205	1.5779	1.4224	1.4729	1.4695	1.4385	1.3987	1.5365	1.4663
9171	0.7198	0.7847	0.7428	0.7425	0.7389	0.6672	0.6585	0.7217
9175	0.8446	0.8905	0.8894	0.9037	0.8796	0.8776	0.8166	0.8840
9141	0.8418	0.8861	0.9042	0.8873	0.8807	0.8297	0.7688	0.8688
9145	1.1768	1.1208	1.1634	1.1499	1.1619	1.0582	0.9591	1.1271
9113	0.2245	0.6952	0.7409	0.7305	0.7034	0.6155	0.2703	0.6097
9117	0.5764	0.8977	0.9415	0.9301	0.9250	0.8312	0.5286	0.8478
9063	0.9157	0.8275	0.7928	0.9643	0.8900	0.8000	0.6670	0.8336
9067	0.7166	0.8659	0.8383	0.7107	0.7185	0.7879	0.6840	0.7789
9611	0.8785	0.8158	0.8987	0.8879	0.8541	0.7716	0.8905	0.8552
9615	0.6820	0.7488	0.8283	0.8362	0.8101	0.7460	0.7024	0.7781
9151	0.4261	0.8100	0.8440	0.8554	0.8315	0.6958	0.4797	0.7514
9155	0.3936	1.1829	1.1758	1.1765	1.1286	1.0484	0.5852	1.0373
9393	0.6249	0.6354	0.6503	0.6710	0.6690	0.6347	0.5880	0.6475
9397	0.6332	0.8118	0.8552	0.8638	0.8600	0.7799	0.6028	0.7984
9343	1.0915	1.2010	1.2072	1.2486	1.2355	1.1176	1.1581	1.1944
9347	0.9590	0.8691	0.9019	0.8997	0.9022	0.8555	0.8853	0.8939
9333	0.6248	0.7204	0.7270	0.7213	0.7106	0.6593	0.5179	0.6860
9337	0.6037	0.6078	0.6244	0.6196	0.6056	0.5744	0.5465	0.6026
9641	0.5940	0.5748	0.6109	0.6120	0.5876	0.5511	0.5802	0.5887
9645	0.6699	0.6758	0.6956	0.6932	0.6787	0.6179	0.5861	0.6680
AVG	**0.8474**	**0.8748**	**0.9090**	**0.9138**	**0.8981**	**0.8301**	**0.8100**	**0.8785**

The greatest percent error between truck factors was 25.3%, with the exception of sites 9113, 9117, 9151, 9155 (Table 6.5). These stations had high percent errors for Saturday and Sunday. The main difference between these stations and the others was the fact that the axle loads were significantly lower on Saturday and Sunday at these four stations. Therefore, the combination of very light loads and few trucks caused the truck factors for Saturday and Sunday to be much lower than the other days of the week at these stations.

Table 6.4 Average Daily Truck Volumes

Station	SUN	MON	TUES	WED	THURS	FRI	SAT	AVG
481	1199	2998	3350	3219	3135	2877	1326	2579
485	1374	2839	3156	3094	3094	2747	1346	2528
9311	1338	2134	2621	2663	2726	2535	1498	2211
9315	1876	2952	3420	3474	3350	2782	1599	2780
9205	1008	1429	1898	2046	1966	1765	1221	1619
9171	210	458	502	503	502	455	201	402
9175	179	403	456	483	494	462	218	385
9141	345	1025	1171	1183	1232	1133	417	924
9145	372	943	1061	1102	1180	997	416	862
9113	624	1030	1089	1130	1148	1153	673	975
9117	358	806	866	888	918	926	458	745
9063	75	370	343	380	382	313	98	275
9067	66	375	385	401	409	366	126	304
9611	1354	2253	2669	2791	2721	2442	1465	2254
9615	1379	2271	2669	2797	2809	2649	1634	2328
9151	324	747	807	793	824	852	410	676
9155	366	739	783	775	800	795	413	661
9393	383	968	1090	1107	1095	1024	480	878
9397	627	1210	1331	1357	1369	1285	705	1125
9343	891	2231	2682	2780	2751	2627	1348	2179
9347	1517	2566	2975	3066	3002	2597	1451	2448
9333	973	1850	1951	2012	1969	1796	882	1638
9337	584	1679	1855	1913	1897	1879	877	1532
9641	678	1282	1470	1469	1445	1247	647	1175
9645	926	1214	1375	1426	1334	1010	636	1129

The truck factors and percent error between the daily truck factors and the average were calculated for values of SN between 1and 10 and D 9-14. Figures 6.3 and 6.4 show the percent error did not vary greatly among values of SN or D. The 0% line represents the average of all days, while the other lines represent the percentage of deviation of the days of the week from the average. The error tends to decrease for D ranging from 8 to 11 and SN ranging from 4 to 7. The chart also shows that the greatest deviations from the average were Friday, Saturday, and Sunday. The truck factors also did not vary between the Pt values of 2.0 and 2.5.

The only noticeable variation was between the SN and D. It can be seen that Sunday varied more from the average with changing SN and D than the other days. Sunday was the only day where the actual shape of the cumulative axle load distribution was noticeably different from the average, based on visual inspection (Figure 6.2). That could be a possible cause of the varying percent errors seen in Figures 6.3 and 6.4. The percent error for Sunday only varies up to 3%, so the trend is not significant.

Table 6.5 Daily Percent Error of Truck Factors for Pt =2.5 and SN = 5.0

Station	SUN	MON	TUES	WED	THURS	FRI	SAT
481	14.9	1.8	2.6	1.1	-1.6	-8.2	-4.1
485	-2.6	0.6	1.7	2.4	2.9	-3.6	-7.4
9311	6.2	-4.9	3.0	4.7	2.4	-6.6	-3.9
9315	7.4	-1.0	6.3	5.5	0.5	-12.9	-9.9
9205	7.6	-3.0	0.5	0.2	-1.9	-4.6	4.8
9171	-0.3	8.7	2.9	2.9	2.4	-7.5	-8.8
9175	-4.5	0.7	0.6	2.2	-0.5	-0.7	-7.6
9141	-3.1	2.0	4.1	2.1	1.4	-4.5	-11.5
9145	4.4	-0.6	3.2	2.0	3.1	-6.1	-14.9
9113	-63.2	14.0	21.5	19.8	15.4	0.9	-55.7
9117	-32.0	5.9	11.1	9.7	9.1	-2.0	-37.7
9063	9.8	-0.7	-4.9	15.7	6.8	-4.0	-20.0
9067	-8.0	11.2	7.6	-8.8	-7.8	1.2	-12.2
9611	2.7	-4.6	5.1	3.8	-0.1	-9.8	4.1
9615	-12.3	-3.8	6.5	7.5	4.1	-4.1	-9.7
9151	-43.3	7.8	12.3	13.9	10.7	-7.4	-36.1
9155	-62.1	14.0	13.4	13.4	8.8	1.1	-43.6
9393	-3.5	-1.9	0.4	3.6	3.3	-2.0	-9.2
9397	-20.7	1.7	7.1	8.2	7.7	-2.3	-24.5
9343	-8.6	0.6	1.1	4.5	3.4	-6.4	-3.0
9347	7.3	-2.8	0.9	0.6	0.9	-4.3	-1.0
9333	-8.9	5.0	6.0	5.1	3.6	-3.9	-24.5
9337	0.2	0.9	3.6	2.8	0.5	-4.7	-9.3
9641	0.9	-2.4	3.8	4.0	-0.2	-6.4	-1.4
9645	0.3	1.2	4.1	3.8	1.6	-7.5	-12.3
AVG	**-3.5**	**-0.4**	**3.5**	**4.0**	**2.2**	**-5.5**	**-7.8**

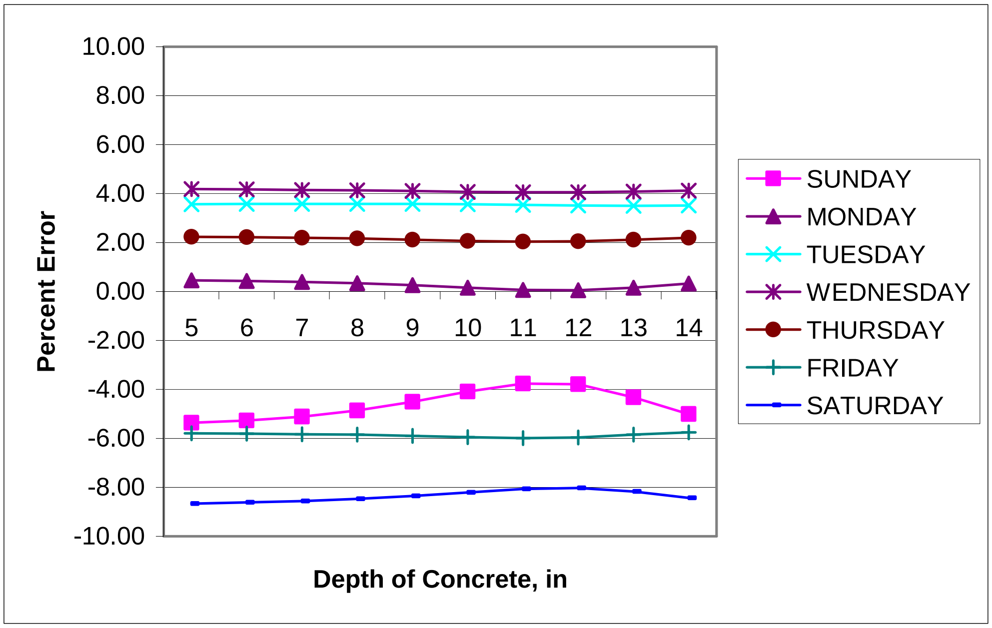


Figure 6.3 Variation of Percent Error by Depth of Concrete

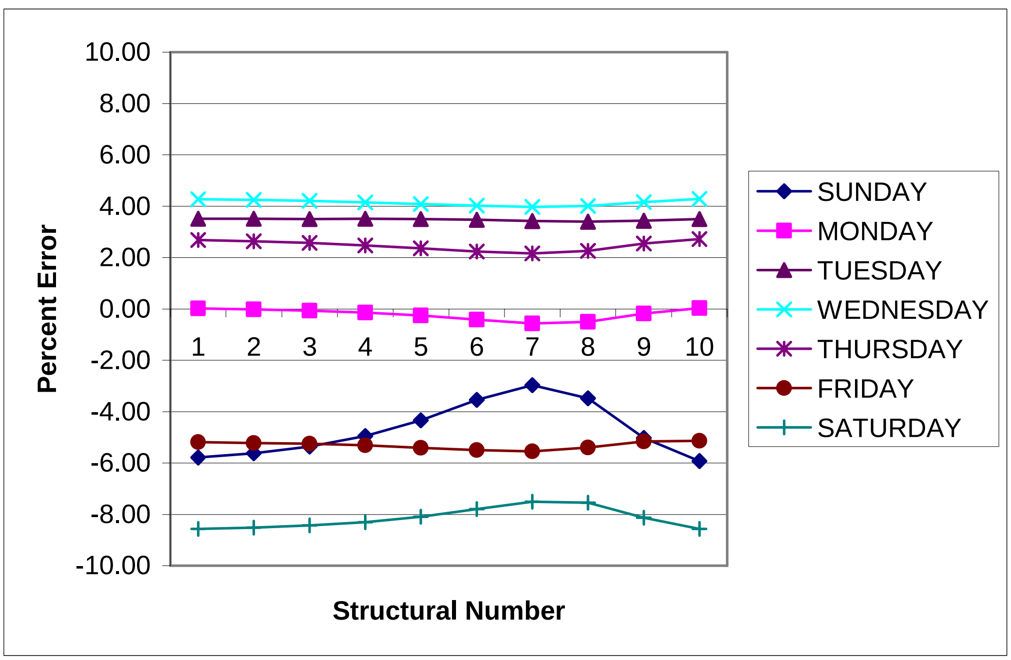


Figure 6.4 Variation of Percent Error by Structural Number

6.1.2 Monthly Variation

The K-S Test determined that there were statistically significant differences between the months and the statewide average for each station. The maximum difference between CDFs ranged from 0.37% to 14.61% for single axles, and 0.56% to 32.8% for tandem axles. The reason the monthly variation was considered statistically significant was the amount of variation between CDFs could not be greater than 2% (with the exception of stations 9063 and 9067 which allowed 4%). The amount of variation in CDFs varied at each site, but typically the months of April through July tended to have the heaviest axle loads, while January and December had the lightest axle loads

Table 6.6 displays the truck factors for each month. With the exception of station 9343, there was no percent error in truck factor greater than 22.8% (Table 6.7). Station 9343 had very high truck factors for May – July, which caused the large percent errors. July had a value of 2.5490 (p_t =2.5 and SN = 5) which was extremely high, relative to the other sites. The data for station 9343 were questionable because of the obvious difference in truck factors. It was decided to keep station 9343 in the data set because of the low amount of data. Figure 6.5 shows the distribution of truck factors over the year for the statewide average. It can be seen that values increased from January to May and then began to drop off again in August. The increase in the loads during the summer months could probably attributed to increased commerce and construction truck traffic.

Table 6.6 Monthly Truck Factors; Pt = 2.5 and SN = 5.0

Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
9311	0.6294	0.7228	0.6964	0.6817	0.7071	0.6935	0.6731	0.6939	0.6746	0.6596	0.6379	0.6312	0.6752
9315	0.7724	0.7539	0.7402	0.8435	0.9186	0.9062	0.8396	0.8343	0.7997	0.7849	0.7537	0.7324	0.8075
9611	0.8341	0.8662	0.8223	0.8961	0.9169	0.9369	0.9015	0.8283	0.8526	0.8434	0.8253	0.7856	0.8552
9615	0.6930	0.7569	0.7902	0.8410	0.8957	0.8678	0.8036	0.7805	0.7657	0.7715	0.7289	0.7128	0.7781
9113	0.7028	0.7253	0.7093	0.6939	0.6406	0.6108	0.5827	0.6543	0.5723	0.5526	0.5281	0.4708	0.6097
9117	0.7006	0.8105	0.8167	0.7990	0.8104	0.8105	0.7811	0.9355	0.9491	0.9895	0.9456	0.8183	0.8478
9151	0.7775	0.7741	0.6732	0.7800	0.7661	0.8298	0.7947	0.7422	0.6988	0.7083	0.6929	0.7885	0.7514
9155	1.0004	1.0717	1.0575	0.9264	1.0108	0.9908	1.0320	1.1402	1.0904	1.0908	1.0390	0.9821	1.0373
9333	0.6663	0.6795	0.6572	0.7116	0.6909	0.7045	0.7128	0.6886	0.7173	0.7110	0.6663	0.6342	0.6860
9337	0.5628	0.5756	0.5865	0.5879	0.6462	0.6274	0.6400	0.6506	0.6105	0.6081	0.5569	0.5377	0.6026
9343	0.6832	0.7532	0.9306	1.4017	1.8241	1.7426	2.4101	1.2868	1.2665	1.0217	0.9632	0.7822	1.1944
9347	0.7377	0.8556	0.8994	0.9379	0.9412	0.9382	0.9460	0.9340	0.9059	0.8769	0.8673	0.8931	0.8939
9393	0.6309	0.6890	0.6757	0.6363	0.6070	0.6519	0.6403	0.7123	0.6880	0.6475	0.5905	0.5641	0.6475
9397	0.9319	0.9614	0.9060	0.8110	0.8060	0.7823	0.6677	0.7616	0.7475	0.7547	0.7359	0.7235	0.7984
9641	0.5112	0.5479	0.5284	0.6082	0.7059	0.6729	0.5595	0.5640	0.5883	0.5803	0.5761	0.5617	0.5887
9645	0.6875	0.6207	0.5589	0.6296	0.6614	0.6522	0.6873	0.7517	0.6571	0.6918	0.6834	0.6236	0.6680
AVG	**0.7570**	**0.8067**	**0.8240**	**0.9216**	**0.9538**	**0.9405**	**0.9509**	**0.8647**	**0.8471**	**0.8595**	**0.8057**	**0.7802**	**0.8785**

Table 6.7 Monthly Percent Error of Truck Factors for Pt =2.5 and SN = 5.0

Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
9311	-6.8	7.1	3.1	1.0	4.7	2.7	-0.3	2.8	-0.1	-2.3	-5.5	-6.5
9315	-4.3	-6.6	-8.3	4.5	13.8	12.2	4.0	3.3	-1.0	-2.8	-6.7	-9.3
9611	-2.5	1.3	-3.8	4.8	7.2	9.5	5.4	-3.2	-0.3	-1.4	-3.5	-8.1
9615	-10.9	-2.7	1.6	8.1	15.1	11.5	3.3	0.3	-1.6	-0.9	-6.3	-8.4
9113	15.3	19.0	16.3	13.8	5.1	0.2	-4.4	7.3	-6.1	-9.4	-13.4	-22.8
9117	-17.4	-4.4	-3.7	-5.7	-4.4	-4.4	-7.9	10.3	11.9	16.7	11.5	-3.5
9151	3.5	3.0	-10.4	3.8	2.0	10.4	5.8	-1.2	-7.0	-5.7	-7.8	4.9
9155	-3.6	3.3	1.9	-10.7	-2.6	-4.5	-0.5	9.9	5.1	5.2	0.2	-5.3
9333	-2.9	-1.0	-4.4	3.7	0.7	2.7	3.9	0.4	4.6	3.6	-2.9	-7.5
9337	-6.6	-4.5	-2.7	-2.4	7.2	4.1	6.2	8.0	1.3	0.9	-7.6	-10.8
9343	-42.8	-36.9	-22.1	17.4	52.7	45.9	101.8	7.7	6.0	-14.5	-19.4	-34.5
9347	-17.5	-4.3	0.6	4.9	5.3	5	5.8	4.5	1.3	-1.9	-3.0	-0.1
9393	-2.6	6.4	4.3	-1.7	-6.3	0.7	-1.1	10.0	6.3	0.0	-8.8	-12.9
9397	16.7	20.4	13.5	1.6	1.0	-2.0	-16.4	-4.6	-6.4	-5.5	-7.8	-9.4
9641	-13.2	-6.9	-10.2	3.3	19.9	14.3	-5.0	-4.2	-0.1	-1.4	-2.1	-4.6
9645	2.9	-7.1	-16.3	-5.7	-1.0	-2.4	2.9	12.5	-1.6	3.6	2.3	-6.6
AVG	**-13.8**	**-8.2**	**-6.2**	**4.9**	**8.6**	**7.1**	**8.2**	**-1.6**	**-3.6**	**-2.2**	**-8.3**	**-11.2**

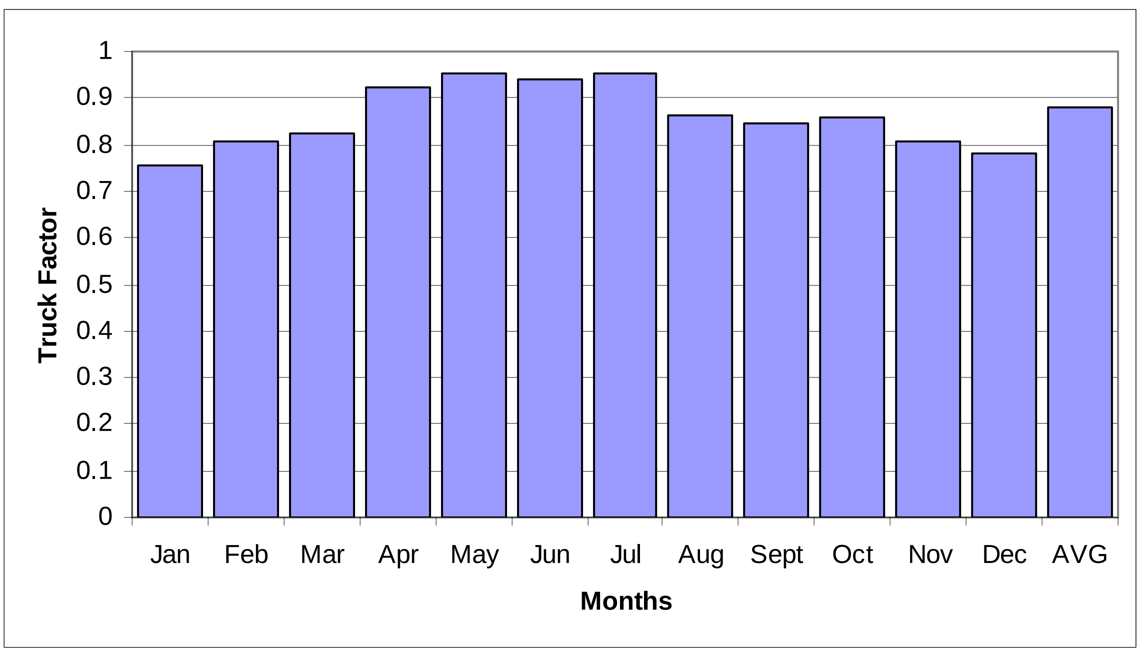


Figure 6.5 Monthly Variation for Statewide Average

6.1.3 Variation by Direction

The axle load distributions for each direction were statistically significantly different from the average of the two directions according to the K-S Test. The large sample size of axle counts caused the critical value to be very small, as observed with the daily and monthly comparisons. The CDFs showed more variation of axle load distributions at non-Interstate stations. For Interstate stations, the greatest difference between direction and the average was 10% and the greatest difference in truck factors for non-Interstate stations was 18.6% (Table 6.8).

The sensitivity analysis was designed to demonstrate the effect the variation in truck factors actually had on the design of a pavement structure. For example, Station 9117 has a percent error of 17.9% when compared to the average of both directions. If an initial SN of 5 is applied to the design equations and all other variables held constant as mentioned in the analysis procedure, then Station 9117 (direction-specific) ends up with a SN of 5.1 and Station 911 (average of both directions) ends up with a SN of 5.0. Table 6.8 shows the directional comparison made at each site with ADTT = 1500 and M_R = 10,000 psi. The greatest difference between SN for each direction to the average at a site was 0.2. As ADTT was increased the SN increased as well. The increases were consistent for each truck factor, so that the greatest difference between truck factors is no more than 0.2 at any ADTT. If an a_1 of 0.44 is used, the difference of 0.2 for the SN results in less than ½ inch difference in asphalt thickness.

For rigid pavement the greatest percent error was 18.6% for Station 9117, which resulted in a difference of 0.3 inches of pavement. Table 6.8 shows the comparison made at each site with ADTT = 1500 and k = 515 pci. The greatest difference in D was 0.3 inches for any ADTT and k combination. The amount of variation in truck factors was independent of the ADTT and subgrade modulus for rigid pavement.

When NYSDOT conducted a sensitivity analysis of the AASHTO design equations, it was discovered that the total design ESALs only have a moderate impact on the resulting SN or D (Chen et al, 1996). As the design ESALs increase in magnitude their effect on the final depth of concrete decreases. For this study the impact of truck factors on SN of D was determined, which is only one input parameter into the calculation of design ESALs. The other input parameters are design life, growth factor, ADTT, lane distribution, and directional distribution. From this analysis it was determined that a percent error in truck factors of 18% for flexible pavement and 19% for rigid pavement results in less than ½ inch difference of pavement thickness.

Pavements are not designed to the nearest 0.1 inch because it is not possible to construct a pavement layer to that fine of a specification. The smallest increment to which a pavement layer could be realistically designed is a ½ inch. Therefore, the difference between the SNs and the depth of concrete was not practically significant. Since none of the differences between a direction and the average of the directions is greater than ½ inch of pavement, it would not be practical to use truck factors separately for each direction.

For flexible pavement the largest percent error was 18% between directions and 19% for rigid pavement, which proved to be insignificant for the final design of a pavement structure. For the daily comparison 92% of the days had a percent error less

Table 6.8 Variation of Truck Factors by Direction

Station	Flexible Pavement			Rigid Pavement		
	Truck Factor	Percent Error	SN	Truck Factor	Percent Error	D
9311	0.6752	-10	4.9	1.0289	-11.3	9.3
931	0.7493		5	1.1595		9.5
9315	0.8075	7.9	5.1	1.2713	8.9	9.6
9611	0.8552	4.7	5.1	1.3966	5.5	9.8
961	0.8170		5.1	1.3086		9.7
9615	0.7781	-4.8	5	1.2487	-5.6	9.6
481	0.9139	-7.4	5.2	1.4611	-7.5	9.8
48	0.9864		5.2	1.5792		10
485	1.0589	7.3	5.3	1.6860	7.4	10.1
9205	1.4663	NA	5.5	2.3971	NA	10.7
9113	0.6097	-15.2	4.9	1.0053	-16.0	9.2
911	0.7188		5	1.1968		9.5
9117	0.8478	17.9	5.1	1.4197	18.6	9.8
9151	0.7514	-15.9	5	1.2556	-16.9	9.6
915	0.8931		5.1	1.5106		9.9
9155	1.0373	16.1	5.3	1.7722	17.3	10.2
9333	0.6860	6.3	5.0	1.1016	6.8	9.4
933	0.6453		4.9	1.0311		9.3

9337	0.6026	-6.6	4.9	0.9573	-7.2	9.1
9343	1.1944	14.9	5.4	1.8892	14.6	10.3
934	1.0399		5.3	1.6479		10.0
9347	0.8939	-14.0	5.1	1.4201	-13.8	9.8
9393	0.6475	-12.1	4.9	1.0346	-13.6	9.3
939	0.7370		5	1.1968		9.5
9397	0.7984	8.3	5.1	1.3092	9.4	9.7
9641	0.5887	-6.4	4.8	0.9086	-7.7	9.1
964	0.6290		4.9	0.9847		9.2
9645	0.6680	6.2	4.9	1.0583	7.5	9.3
9063	0.8336	1.2	5.1	1.3737	2.0	9.7
906	0.8235		5.1	1.3466		9.7
9067	0.7789	-5.4	5.0	1.2534	-6.9	9.6
9141	0.8688	-12.5	5.1	1.3819	-13.8	9.7
914	0.9926		5.2	1.6203		10
9145	1.1271	13.6	5.3	1.8455	15.2	10.2
9171	0.7217	-10.2	5	1.1003	-12.6	9.4
917	0.8039		5.1	1.2595		9.6
9175	0.8840	10	5.1	1.4183	12.6	9.8

than 18% for flexible pavement and 92% of the days had a percent error less than 19% for rigid pavement. Also, 94% of the months had a percent error less than 18% for flexible pavement. For rigid pavement, 93% of the months had a percent error less than 19 %. Based on the results from the sensitivity analysis, the days of the week and the months of the year do not deviate enough from the yearly average in most cases to warrant separate truck factors.

6.1.4 Variation between Sites and Statewide Average

The CDFs for each site varied from the statewide average and were statistically significantly different according to the K-S Test. Tables 6.9 and 6.10 show the truck factors and percent error for each site for both flexible and rigid pavements. For flexible and rigid pavement the truck factors that caused a variation greater then ½ inch were from stations 964, 933, and 9205. For flexible pavement and stations 964 and 933 the SN variation was 0.3 when the low value of M_R = 5000 psi was used. For rigid pavement and stations 964 and 933 the variation in D ranged from 0.4 to 0.6 with one exception. For station 964 when ADTT = 2500 and k = 515 the variation was 0.7. Overall, these variations are still closer to a ½ inch than 1 inch.

Station 9205 varied the most from the statewide average. The percent error for station 9205 was 67% for flexible pavements, which resulted in an SN that was higher than the statewide average by a degree of 0.3 to 0.5. The difference of 0.5 translates into less than 1.2 inches of asphalt. For rigid pavement, the percent error was 70%, which resulted in the depth of concrete between 0.7 to 1.2 inches greater than specified for the statewide average, which means that rigid or flexible pavement at station 9205, would be underdesigned by up to an inch if the statewide average were used in lieu of site specific data. In general, the statewide average was a good representation of truck factors throughout the state, with respect to pavement design, based on the sites from this study.

Table 6.9 Variation by Site from the Statewide Average for Pt = 2.5 and SN = 5.0

Station ID	Truck Factor	Percent Error	Structural Number											
			ADTT = 100			ADTT = 800			ADTT = 1500			ADTT = 2500		
			M_R, ksi			M_R, ksi			M_R, ksi			M_R, ksi		
			5	10	15	5	10	15	5	10	15	5	10	15
964	0.629	-28.4	4.2	3.2	2.7	5.6	4.5	3.9	6.1	4.9	4.3	6.5	5.3	4.6
933	0.6453	-26.5	4.2	3.2	2.8	5.6	4.5	3.9	6.1	4.9	4.3	6.5	5.3	4.6
911	0.7188	-18.2	4.2	3.3	2.8	5.7	4.6	3.9	6.2	5	4.3	6.6	5.4	4.7
939	0.737	-12.3	4.3	3.3	2.8	5.7	4.6	4	6.2	5	4.4	6.7	5.4	4.7
931	0.7493	-14.7	4.3	3.3	2.8	5.8	4.6	4	6.2	5	4.4	6.7	5.4	4.7
917	0.8039	-8.5	4.3	3.3	2.9	5.8	4.6	4	6.3	5.1	4.4	6.7	5.4	4.8
961	0.8107	-7.0	4.3	3.3	2.9	5.8	4.7	4	6.3	5.1	4.4	6.7	5.5	4.8
906	0.8235	-6.3	4.3	3.4	2.9	5.8	4.6	4	6.3	5.1	4.4	6.8	5.5	4.8
AVG	**0.8785**	---	**4.4**	**3.4**	**2.9**	**5.9**	**4.7**	**4.1**	**6.4**	**5.1**	**4.5**	**6.8**	**5.5**	**4.8**
915	0.8931	1.7	4.4	3.4	2.9	5.9	4.7	4.1	6.4	5.1	4.5	6.8	5.5	4.8
48	0.9826	12.3	4.4	3.4	3	6	4.8	4.1	6.5	5.2	4.6	6.9	5.6	4.9
914	0.9926	13.0	4.5	3.5	3	6	4.8	4.1	6.5	5.2	4.6	6.9	5.6	4.9
934	1.0399	18.4	4.5	3.5	3	6	4.8	4.2	6.5	5.3	4.6	7	5.6	5
9205	1.4663	66.9	4.7	3.7	3.2	6.3	5.1	4.4	6.8	5.5	4.8	7.3	5.9	5.2

Table 6.10 Variation by Site from the Statewide Average for Pt = 2.5 and D = 9.0

Station ID	Truck Factor	Percent Error	Depth of Concrete, in											
			ADTT = 100			ADTT = 800			ADTT = 1500			ADTT = 2500		
			Soil Modulus, pci			Soil Modulus, pci			Soil Modulus, pci			Soil Modulus, pci		
			258	515	773	258	515	773	258	515	773	258	515	773
964	0.9847	-30.2	5.9	5.0	--	8.7	8.2	7.8	9.6	9.2	8.8	10.5	10.0	9.7
933	1.0311	-26.9	5.9	5.1	--	8.8	8.3	7.8	9.7	9.3	8.9	10.6	10.1	9.8
931	1.1595	-17.8	6.1	5.3	--	8.9	8.4	8.0	9.9	9.5	9.1	10.8	10.3	10.0
911	1.1968	-15.4	6.1	5.3	--	9.0	8.5	8.1	10.0	9.5	9.1	10.8	10.4	10.0
939	1.1968	-12.4	6.1	5.3	--	9.0	8.5	8.1	10.0	9.5	9.1	10.8	10.4	10.0
917	1.2595	-10.7	6.2	5.4	--	9.1	8.6	8.2	10.1	9.6	9.2	10.9	10.5	10.1
961	1.3086	-7.2	6.3	5.5	--	9.2	8.7	8.3	10.2	9.7	9.4	11.1	10.6	10.3
906	1.3466	-4.5	6.3	5.5	--	9.2	8.7	8.3	10.2	9.7	9.3	11.0	10.6	10.2
AVG	**1.4103**	**---**	**6.3**	**5.6**	**4.5**	**9.2**	**8.8**	**8.4**	**10.2**	**9.8**	**9.4**	**11.1**	**10.7**	**10.3**
915	1.5106	7.1	6.4	5.7	4.7	9.3	8.9	8.5	10.4	9.9	9.5	11.2	10.8	10.4
48	1.5792	12	6.5	5.7	4.8	9.4	8.9	8.5	10.4	10.0	9.6	11.3	10.9	10.5
914	1.6023	13.6	6.5	5.8	4.9	9.4	9.0	8.6	10.4	10.0	9.6	11.3	10.9	10.5
934	1.6479	16.8	6.5	5.8	4.9	9.5	9.0	8.6	10.5	10.0	9.7	11.4	11.0	10.6
9205	2.3971	70	7.0	6.4	5.7	10.1	9.6	9.2	11.1	10.7	10.4	12.1	11.6	11.3

6.1.5 Trends in Truck Factors Over Time

The truck factors determined in this study are compared with the truck factors determined in 1993 in Table 6.11. The statewide average for 2001 was less than was determined in 1993. A possible reason for this is the fact that data from five functional classes were used in 1993 while only data from rural principal arterials (interstate and other) were used in 2001. It can be seen in Table 6.11 that the highest truck factors in 1993 can be attributed to the three functional classes that are not represented in 2001. The truck factors determined from data collected at rural principal arterial Interstate sites increased by about 1.9% from 1993 to 2001.

Table 6.11 Comparison of 1993 and 2001 Truck Factors

	Year	Rural Principal Arterial - Interstate	Rural Principal Arterial - Other	Rural Minor Arterial	Urban Principal Arterial - Interstate	Urban Principal Arterial – Other	Statewide Average
SN	1993	0.9187	1.0107	1.1665	1.5582	1.1703	0.9896
	2001	0.9362	0.9439	NA	NA	NA	0.8785
D	1993	1.4458	1.6492	1.9739	2.5090	1.9354	1.5797
	2001	1.5024	1.5199	NA	NA	NA	1.4103
# of Stations	1993	20	20	4	3	4	51
	2001	7	18	0	0	0	25

There were twice as many WIM stations used in the 1993 calculation of truck factors. Yet, only eleven of the 51 sites used in 1993 were used in this study. The remaining 14 sites in this study may experience lighter loads than the non-repeated stations in the 1993 study, which could be another reason the statewide average truck factor is lower. Also, it is unknown if the data in 1993 was checked for quality assurance, which might have led to high truck factors. For 2001, as stated in the data collection chapter, two stations were not used because of data completeness problems and one station was not used because of suspiciously high data. Figure 6.6 displays the trend in truck factors from 1964 to 2001.

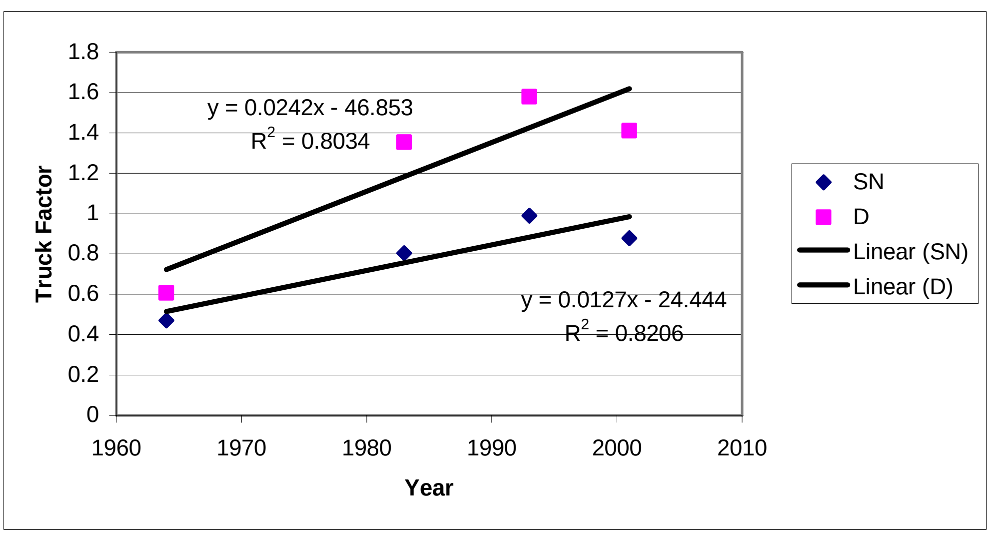


Figure 6.6 Trends Over Time of Truck Factors

There was an increase from 1964 to 1993 and then a decrease from 1993 to 2001. Though the truck factors seem to have a linear trend up to 1993, the truck factors should not be extrapolated over time. One reason for this is an increase in truck factors can not always be expected. For example, legal weight limits can increase or decrease, which consequentially affects the truck factor.

6.2 Axle Load Modeling

It was determined that a lognormal-normal-normal distribution mixture was the best fit for single axles at eight of the sites. For the other five the lognormal-normal mixture was the best fit. The distributions for single axles did not conform to the fitted theoretical distribution according to the chi-squared goodness of fit test at a significance level of $\alpha = 0.05$, but they did have R^2 values greater than 0.986. The best fit for tandem axles at all the sites was a lognormal-normal distribution. Most of the distributions conformed according to the chi-squared goodness of fit test and had high R^2 values ($R^2 > 0.962$).

6.2.1 Single Axles

The weight data came from equipment manufactured by two different companies; PAT and HESTIA WIM stations. Figures 6.7 and 6.8 illustrate the typical difference observed between the two sources. Generally, the PAT sites had three distinct peaks, while the HESTIA sites only have one distinct peak at the 12 kip range with two smaller peaks on each side. It was determined that one possible reason for this was the HESTIA sites were weighing less Class 5 vehicles than the PAT sites (Table 6.12). The HESTIA sites were counting the Class 5 vehicles but they were not weighing all of them. This resulted in the PAT sites having a different model than the HESTIA sites.

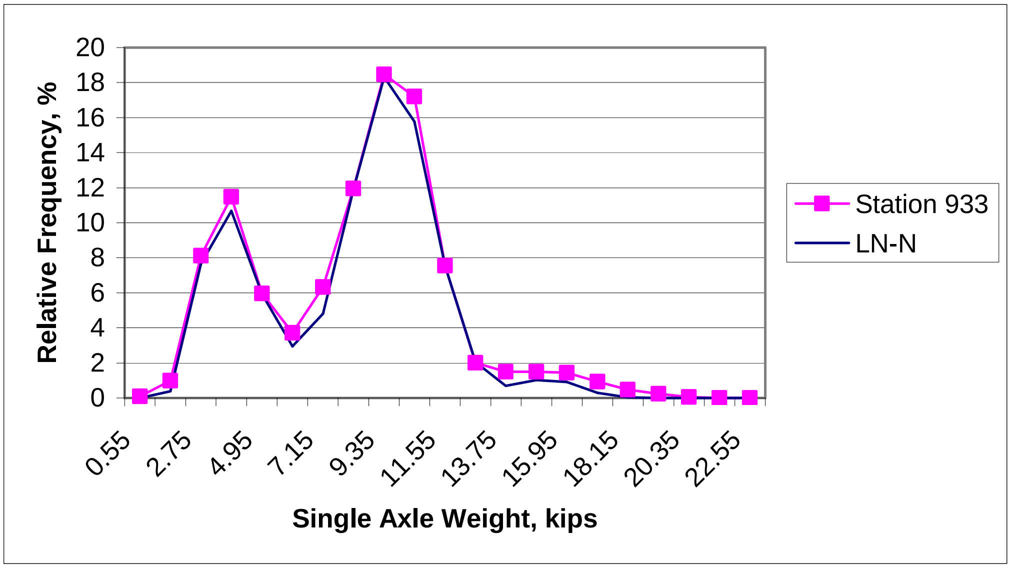


Figure 6.7 Three Distribution Mixture for PAT Station

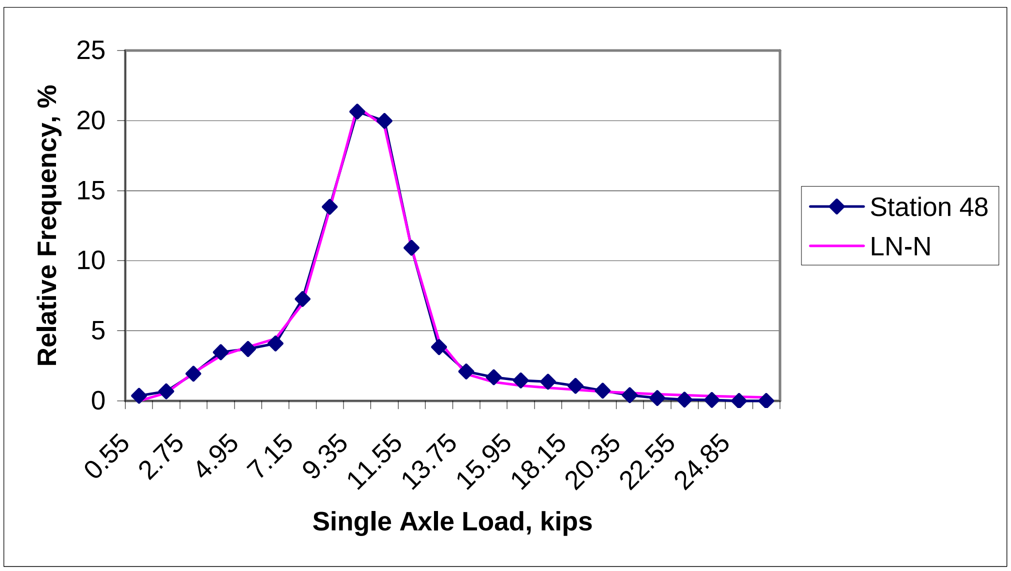


Figure 6.8 Two Distribution Mixture for Hestia Station

Table 6.12 Comparison of Weighed and Counted Class 5 Vehicles

Site (Directions Combined)		Class 5		% of Class 5 Vehicles in the Truck Traffic
		Average Daily Count	Average Daily Weighed	
HESTIA	48	343	273	11.03
	9205	120	95	6.08
	906	84	78	27.56

	914	143	129	14.81
	917	74	65	17.02
PAT	931	225	386	15.53
	961	323	538	23.58
	911	237	389	45.18
	915	165	327	48.81
	933	247	428	27.09
	934	352	508	22.15
	939	146	284	28.57
	964	168	244	21.35

For the HESTIA sites, a mixture of the lognormal and normal distribution fit the measured axle load distribution best. The best fit was determined by solving for the minimum sum of squared errors. A mixture of two distributions did not fit the PAT sites well because the model left out the third peak and resulted in a high value for the sum of squared errors. A mixture of three distributions was applied to the data next, and it was found that two different mixtures resulted in almost identical sum of squared errors; 1) lognormal, normal, and lognormal and 2) lognormal, normal, and normal. Figure 6.9 illustrates the difference between the two distributions. The lognormal distribution did not capture as much of the third peak as the normal distribution. Since the reason for using three distributions instead of two was to capture more of the third peak, the lognormal, normal, and normal distribution was determined to be the best fit. Table 6.13 shows the mixing proportions, means, and standard deviations for each model.

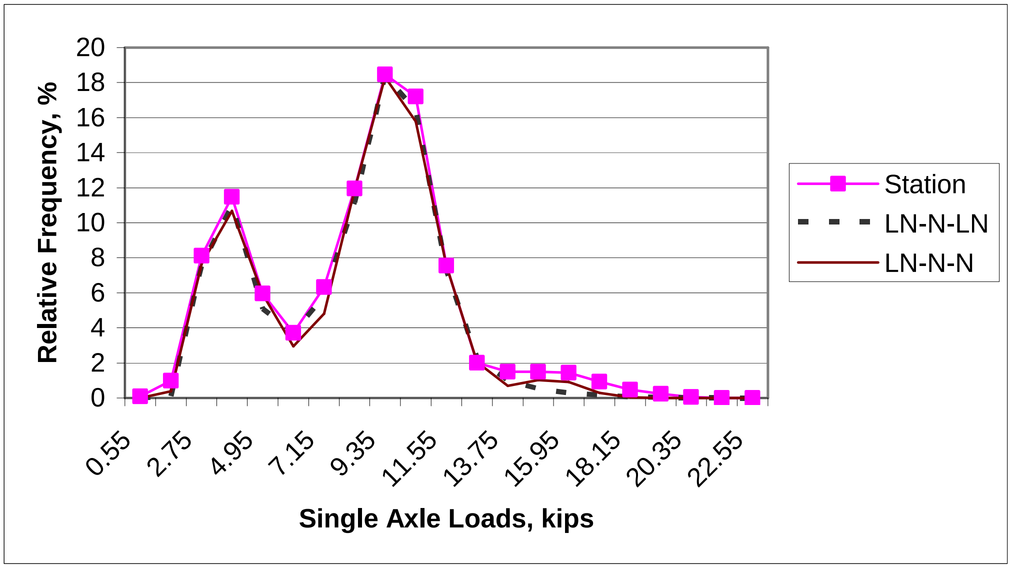


Figure 6.9 Differences between LN-N-N and LN-N-LN Distribution

Table 6.13 Distribution Parameters for Single Axles

Mixture	Site	p_1	p_2	p_3	M_1	SD_1	M_2	SD_2	M_3	SD_3	R^2
LN-N	48	0.33	0.67	--	10.06	7.49	9.80	1.41	--	--	0.9978
	9205	0.40	0.60	--	11.76	8.65	9.70	1.38	--	--	0.9968
	906	0.52	0.48	--	8.57	5.18	9.39	1.56	--	--	0.9969
	914	0.38	0.62	--	9.40	6.16	9.71	1.44	--	--	0.9979
	917	0.48	0.52	--	8.69	5.55	9.83	1.39	--	--	0.9979
LN-N-N	931	0.23	0.71	0.06	4.27	1.65	10.01	1.29	15.45	1.41	0.9927
	961	0.26	0.71	0.03	4.12	1.33	10.05	1.41	15.54	1.09	0.9879
	911	0.43	0.55	0.02	3.94	1.08	9.73	1.71	15.48	1.31	0.9932
	915	0.53	0.39	0.05	3.64	0.80	9.71	2.05	18.24	2.59	0.9859
	933	0.30	0.67	0.03	4.04	1.21	9.63	1.43	15.29	1.09	0.9908
	934	0.24	0.68	0.08	4.29	1.53	10.05	1.38	15.38	1.92	0.9922
	939	0.29	0.68	0.03	3.89	1.08	9.57	1.50	15.12	1.31	0.9925
	964	0.27	0.70	0.03	4.34	1.70	9.65	1.47	15.06	1.17	0.9918
	AVG	0.25	0.71	0.05	4.27	1.48	9.83	1.48	15.47	1.44	0.9923

Note: p_i = mixing proportion of distribution i, M_i = mean of distribution i, and SD_i = standard deviation of distribution i

The results of the R^2 were very good for each site and the statewide average. According to the R^2 statistic the observed error was explained by the models for each site. As shown in Table 6.14, the R^2 values all are greater than 0.9859, which is very high. For the polynomial regression models discussed in the literature review the R^2 values ranged from 0.93 to 0.99, so a mixture of theoretical distributions results in a model that explained a higher proportion of the variation. The mixture models are also continuous and differentiable, which the polynomial regression equations are not. The mixture models reflect the actual properties of the data with the means and standard deviations unlike the polynomial regression equations.

Only two of the sites' data conformed to the theoretical distributions according to the Chi-squared goodness of fit test at $\alpha = 0.05$ (Table 6.14). For single axles the number of bins with axle counts was 22 or less which resulted in low degrees of freedom and therefore low χ^2_{crit} values. Lower χ^2_{crit} values increased the likelihood of rejecting the null hypothesis that the observed data conform to the tested theoretical distribution according to the Chi-squared test. Also, the chi-squared test is very sensitive to values at the tails of the distribution. Therefore any difference between the theoretical distribution and the actual distribution at the tails was magnified. Even though all the models did not conform according to the Chi-squared test, it does not mean that the models were not a good fit of the data, as evidenced by the R^2 values.

Table 6.14 Results for Chi-Squared and R^2 Tests for Single Axles

Functional Class	Site	# of Axles Counted	$X^2_{obs,}$ (O-E)^2/E	Chi-Squared Test		R^2	
				$X^2_{critical}$	Conforms	SSE	R^2
INT	931	3462	357.87	16.919	NO	7.02	0.9927
	961	3030	1045.99	15.507	NO	11.25	0.9879
	48	3329	124.67	37.652	NO	2.16	0.9978
	9205	2089	108.99	37.652	NO	2.81	0.9968
NON-INT	911	1136	681.30	15.507	NO	5.28	0.9932
	915	863	137.40	18.307	NO	12.18	0.9859
	933	2132	833.03	15.507	NO	8.04	0.9908
	934	1210	249.12	16.919	NO	6.47	0.9922
	939	1283	319.23	15.507	NO	6.41	0.9925
	964	1640	712.01	15.507	NO	7.05	0.9918
	906	391	7.10	15.507	YES	2.51	0.9969
	914	1203	36.13	21.026	NO	1.98	0.9979
	917	567	10.57	19.675	YES	1.79	0.9979
Combined	Statewide Average	1872	59.72	9.488	NO	6.58	0.9923

6.2.2 Tandem Axles

There were two distinct peaks for all the tandem axle load distributions, which correspond to heavy and light trucks. Therefore, all the stations were modeled with a lognormal-normal distribution. Figure 6.10 shows the axle load distribution and model for the statewide average. The mixing proportion means and standard deviations for each station are displayed in Table 6.15.

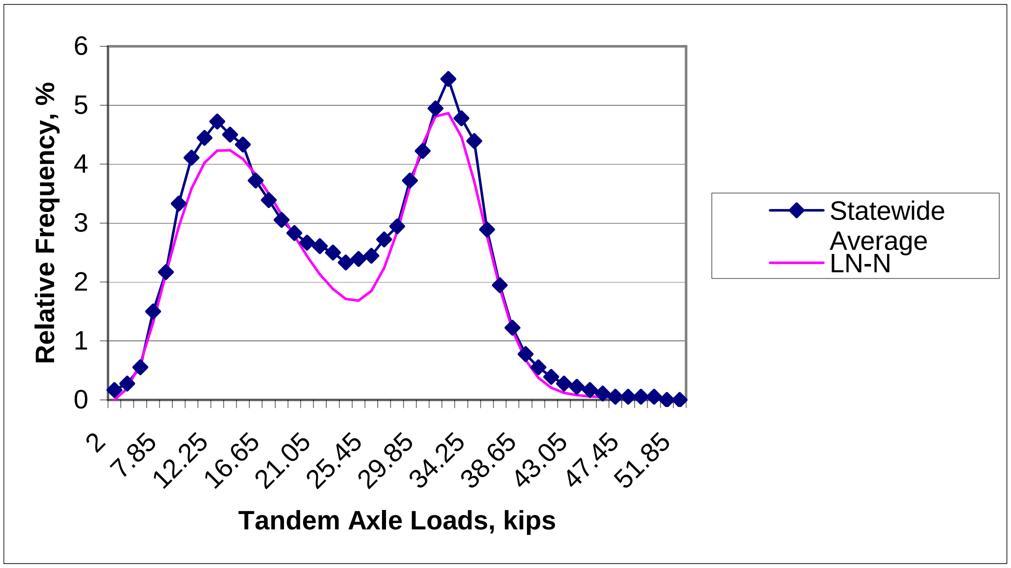


Figure 6.10 Axle Load Distribution for Statewide Average

As with single axles, the results for the R^2 test were very good. All of the R^2 values were greater than 0.9622. The Chi-squared goodness of fit test showed much better results for the tandem axles. All but four stations passed the goodness of fit test (Table 7.16). The results show that a mixture distribution modeled the tandem axles very well.

Table 6.15 Distribution Parameters for Tandem Axles

Site	Mixing Proportion, p_1	Mixing Proportion, p_2	Lognormal Distribution		Normal Distribution		R^2
			M_1	SD_1	M_2	SD_2	
915	0.55	0.45	14.40	4.42	36.76	4.24	0.9726
48	0.59	0.41	12.96	4.79	32.41	3.49	0.9773
931	0.60	0.40	17.51	8.16	30.67	3.03	0.9622
933	0.62	0.38	14.36	5.43	31.08	3.30	0.9800
911	0.62	0.38	14.69	5.66	33.86	4.28	0.9717
9205	0.62	0.38	18.91	9.57	32.63	4.42	0.9843
964	0.62	0.38	14.85	6.03	30.21	2.93	0.9782
961	0.63	0.37	18.93	7.79	32.55	2.41	0.9726
939	0.63	0.37	16.41	7.41	31.25	3.44	0.9835
914	0.64	0.36	14.85	6.00	32.94	3.57	0.9759
917	0.65	0.36	13.13	4.93	31.94	5.11	0.9773
934	0.70	0.30	20.03	8.41	32.15	2.82	0.9833
906	0.71	0.29	15.86	6.67	32.26	5.31	0.9842
Statewide Average	0.62	0.38	16.67	7.28	31.80	3.34	0.9806

Table 6.16 Results for Chi-Squared and R^2 Tests for Tandem Axles

Functional Class	Site	# of Axles Counted	$X^2_{obs,}$ (O-E)^2/E	$X^2_{critical}$	Conforms	SSE	R^2
INT	931	3477	147.19	37.652	NO	9.79	0.9622
	961	3016	77.46	38.885	NO	7.46	0.9726
	48	3910	88.28	42.557	NO	5.13	0.9773
	9205	2551	57.95	43.773	NO	2.66	0.9843
NON-INT	911	761	17.84	41.337	YES	6.09	0.9717
	915	524	34.62	48.602	YES	6.11	0.9726
	933	1930	66.13	42.557	NO	5.09	0.9800
	934	2835	38.81	38.885	YES	3.77	0.9833
	939	1195	14.94	46.194	YES	3.65	0.9835
	964	1455	28.41	55.758	YES	5.8	0.9782
	906	317	4.07	38.885	YES	4.15	0.9842
	914	1268	37.8	42.557	YES	5.54	0.9759
	917	509	13.45	41.337	YES	5.58	0.9773
COMBINED	Statewide Average	1800	33.08	44.985	YES	4.34	0.9806

6.3 Mechanistic-Empirical Pavement Design Results And Discussion

Figure 6.11 summarizes the thickness designs resulting from the 12 sites and the statewide distribution. It must be noted that the thicknesses for the highest soil stiffness were governed by fatigue while the two softer soils (5 and 10 ksi) were governed by rutting. The table in the upper right corner indicates the required thickness when using the statewide distribution. The graphical portion indicates the thickness difference when using site-specific load spectra. For example, at the lowest soil stiffness, site 48 would require approximately 1.25 in. more HMA when compared to the statewide distribution. Another interpretation is that site 48 would be underdesigned by 1.25 in. if the statewide load spectra were used rather than the site-specific load spectra.

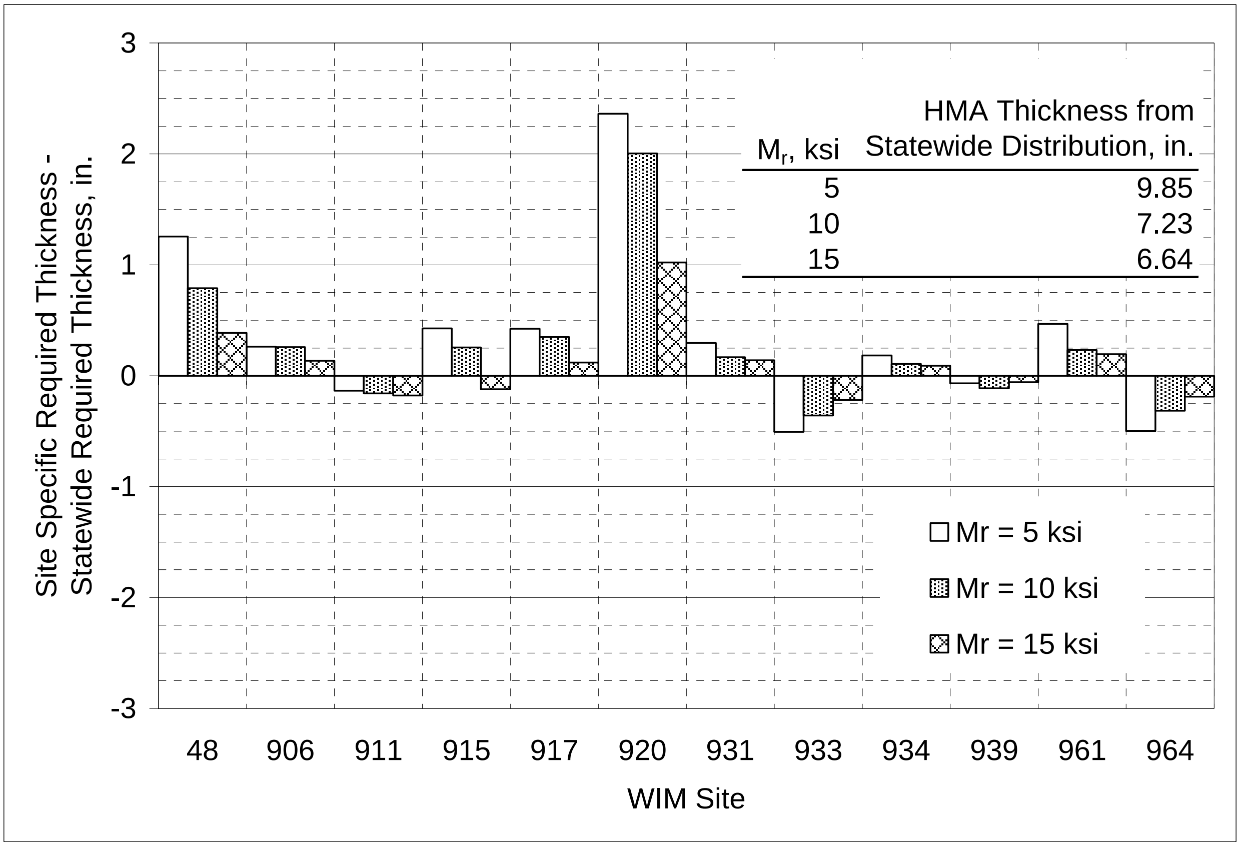


Figure 6.11 M-E Pavement Thickness Design Summary.

Some general trends are evident from Figure 6.11. First, as expected, required pavement thickness tends to decrease with increasing soil stiffness. Second, for most cases the differences between the statewide thickness and site-specific thickness tended to diminish with increasing soil stiffness. This may be due to vertical compressive strain controlling the designs at the lower stiffnesses. As the stiffness increases, the compressive strain is more a function simply of the soil stiffness rather than the thickness of the overlying pavement structure and is therefore less sensitive to differences in load spectra. This observation, however, requires further investigation and may be limited to the conditions considered in this study.

Regarding differences in required thickness resulting from site-specific load spectra, 31 out of 36 (86%) design scenarios were within 0.5 in. of the statewide design thickness. Using 0.5 in. as a practical limit, the data provide strong motivation for using a statewide load spectra when conducting M-E pavement design for the types of routes considered in this study. However, as demonstrated by sites 48 and 920, there are certainly instances where site-specific data are warranted and should be collected. For example, in the case of site 920, it can be seen from simple calculations on the traffic data that the percentage of heavy trucks is substantially higher than at the other sites and therefore could be treated separately. Site 920 is on Interstate 59 northeast of Birmingham, a major freight corridor known for heavy truck traffic. In fact, class 9 vehicles (typical tractor-single trailer combinations) constitute 22.9% of the traffic at this site. This value ranged between 1.8 and 18.7 percent at the other study sites.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Truck Factors

7.1.1 Conclusions

From the results it can be concluded that a 18% variation in truck factors for flexible pavement and a 19% variation for rigid pavement creates less than a half inch variation in the depth of pavement, which is not considered practically significant. For flexible pavement, 92% of the daily truck factors for the seven days of the week and 94% of the monthly truck factors for the 12 months of the year across all 13 sites and the statewide average varied less than 18% from the average yearly truck factor. For rigid pavement 92% of the daily truck factors for the seven days of the week and 93% of the monthly truck factors for the 12 months of the year across all 13 sites and the statewide average varied less than 19% from the average yearly truck factor. Since the majority of truck factors for each day and month of the year used in this study would cause a difference in pavement thickness of less than a half inch when compared to the yearly average for each station, it is not necessary to calculate truck factors by day of week or month of the year. To ensure that the average truck factor is representative of all days and months, the data should be collected on the lightest and heaviest days and months. All of the directional variations were less than 19% so there is no need to calculate truck factors separately for each direction of travel.

The sensitivity analysis of pavement thickness to truck factors showed that all of the sites but three had less than a half inch variation in the resulting depth of pavement from the statewide average. Stations 964 and 933 were lighter than the average and resulted in a reduction of 0.4 to 0.7 inches of pavement thickness from the statewide average for flexible and rigid pavement. Station 9205, which is a high volume station on I-59, varied up to 1.2 inches from the statewide average. The use of Station 9205 in the calculation of the statewide average truck factor causes it to be a little higher than stations 964 and 933, which adds a factor of safety into the statewide average truck factor. Overall, the statewide average is representative of rural principal arterials in Alabama.

The resulting statewide average for flexible and rigid pavement determined from this study is lower than the statewide average truck factor determined in 1993. While this study only used data from rural principal arterials, the 1993 truck factors used data from rural principal arterials, rural minor arterials, and urban principal arterials. The 1993 truck factors were determined from information from 50 stations, while the data for this study came from 25 stations. Only eleven of the 50 stations used in 1993 were used for this study. All these factors contributed to the statewide average truck factor decrease from 1993 to 2001.

7.1.2 Recommendations

It is recommended that statewide average truck factors can be used for pavement design of rural principal arterials in Alabama. In this study, statewide average factors (based on the 25 sites for which data were available) were determined to be 0.8785 for flexible pavements and 1.411 for rigid pavements. However, for several reasons, it may be prudent to continue use of the factors derived in the last update performed by ALDOT in 1993, which yielded factors of 0.9896 for flexible pavements (SN=5) and 1.579 for rigid pavements (depth of 9 inches). Among these reasons are that the 1993 study used data from 51 sites, covering four different highway functional classifications, and that the sensitivity of pavement thickness design is less sensitive to small changes in total ESALs than changes in many other inputs.

While truck factors can not directly be extrapolated over time, they should be revisited periodically (e.g., every 10 years). Also, engineering judgment should be used to determine if a road needs additional analysis. Though truck factors do not need to be separated by day or month, WIM data should be collected so that the data are representative of axle loads throughout the year. The following recommendations are made for collecting WIM data:

- Data should at least be collected on the following three days 1) Friday, 2) Saturday or Sunday, and 3) Monday, Tuesday, Wednesday, or Thursday.
- Data should at least be collected in either November, December or January to account for the decline in winter truck traffic and either April, May or June to account for the higher summer truck traffic.

7.2 Axle Load Modeling

7.2.1 Conclusions

The use of a mixture of lognormal and normal distributions is a good model of single and tandem axle load distributions. Depending on the proportion of Class 5 vehicles in the truck traffic, either a lognormal-normal or lognormal-normal-normal distribution should be used for single axles. The R^2 value for all the models was greater than 0.986. The data did not conform to the theoretical distribution used to model single axles according to the Chi-squared goodness of fit test. However, the goodness of fit of the model to the data can be seen from the PDF plots and is supported by the high R^2 values.

For tandem axles, a lognormal-normal distribution was determined to be the best fit for all the sites and the statewide average. The R^2 value for all the models was greater than 0.962 and the axle load distributions at 64% of the sites do not differ significantly from the theoretical probability distribution used to model them. Therefore, the lognormal-normal mixture models provide an accurate representation of tandem axle loads.

7.2.2 Recommendations

The use of a mixture model of axle loads would be useful for mechanistic-empirical pavement design. The lognormal and normal mixture distribution for tandem axle loads at most sites represents the data well and is recommended for use on principal rural arterials. Further research that is recommended for using a mixture model for axle load distributions includes:

- Investigation into why some single axle models required a mixture of two distributions while others required a mixture of three distributions.
- Use the methodology presented in this report to model axle load distributions from functional classes other than rural principal arterials.

7.3 Application of Mechanistic-Empirical Pavement Design to Axle Load Distributions

7.3.1 Conclusions

- Monte Carlo simulation can be an effective tool in evaluating load spectra effects on pavement design. The approach can be used to evaluate load spectra on a wider scale, such as regional or nationwide.
- Similar to empirically-based design (i.e. the 1993 AASHTO procedure), it is the heavier axle loads that govern M-E thickness design. Therefore, heavy axle weights must be carefully measured; especially overloads.

7.3.2 Recommendations

- Based on the rural principal arterials considered in this study, statewide load spectra for M-E design are recommended when site-specific data are not available. In most cases, this approach will not overly affect resulting HMA design thicknesses. This is consistent with the findings using the same load spectra with the current AASHTO empirical design approach. As always, site-specific information should be used when readily available. Also, local knowledge and experience should help determine when site-specific data must be collected and used for design. Alternatively, a quick examination of vehicle classification distribution at a site (such as site 920 in this study), when compared to several other sites on highways in the same functional classification, can help to determine whether site-specific data should be collected.
- When considering differences in load spectra between site-specific conditions and a more general (e.g., statewide) distribution, it is critical to assess the practical significance in addition to statistical significance since considerable resources and personnel are required to gather site-specific load spectra. In this study, 86% of the design scenarios (combinations of site-specific load spectra and soil strength) required HMA thickness within one half-inch of the statewide distribution.
- Further studies should be conducted using the design software developed through the National Cooperative Highway Research Program Project 1-37A (NCHRP, 2005) to evaluate similar load spectra and the practical effects on pavement thickness design.

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APPENDIX A. RESULTS OF SURVEYS OF STATE TRANSPORTATION AGENCIES ON ESAL CALCULATIONS

ESAL Calculation Survey for Florida

1. Does your State use as its basis for pavement design and rehabilitation (e.g. AASHTO Guide, customized system, etc.)? **AASHTO 1993 Guide**

2. What types of data do you use to come up with the ESAL table values and how are they collected? **Approximately 40 WIM sites, 18 continuous, 23 at 1 week quarterly or semi-annual samples.**

3. Do you use a single ESAL table for all design locations within your state or is a different ESAL value computed for different locations based upon load information for that location? **Average statewide values by four system types.**

4. How often do you update your ESAL tables? **Reviewed annually**

5. Do you break down ESALs by vehicle classification and, if so what vehicle classes do you use? **No. Classes 4-13 are averaged.**

6. Do you apply average ESAL factors to the vehicles in each classification? What are they? **No**

7. Do use growth factors to expand ESALs to design years? How do you determine growth factors? **Yes, each project is forecast by a trained planning analyst using historical trends and/or growth models.**

8. Do you use WIM data? If, not what do you use for load data? **Yes**

9. Do you collect classification data? How? How often? **Yes 1950 portable classifiers (2 to 8 day samples) and 249 continuous.**

10. How much confidence do you have in the values you use for pavement design and rehabilitation? **Pretty Good**

Additional Comments:

ESAL Calculation Survey for Georgia

1. Does your State use as its basis for pavement design and rehabilitation (e.g. AASHTO Guide, customized system, etc.)? **1972 AASHTO Interim Guide, 1981 revision**

2. What types of data do you use to come up with the ESAL table values and how are they collected? **ESAL factors have not been updated in last ten years due to lack of data**

3. Do you use a single ESAL table for all design locations within your state or is a different ESAL value computed for different locations based upon load information for that location? **Single table with breakdown for functional classification and percent trucks**

4. How often do you update your ESAL tables? **Last update 1984**

5. Do you break down ESALs by vehicle classification and, if so what vehicle classes do you use? **Flexible pavement- no breakdown; Rigid pavement- Multi-unit trucks, single-unit trucks, and Other**

6. Do you apply average ESAL factors to the vehicles in each classification? What are they?
Rigid pavement: Multi-unit - 2.68
Single unit - 0.5
Other - 0.004

7. Do use growth factors to expand ESALs to design years? How do you determine growth factors? **No growth factors used**

8. Do you use WIM data? If, not what do you use for load data? **No load data**

9. Do you collect classification data? How? How often? **No**

10. How much confidence do you have in the values you use for pavement design and rehabilitation?

Additional Comments: **An effort is underway to collect WIM and classification data to update the ESAL factors during 2003.**

ESAL Calculation Survey for Mississippi

1. Does your State use as its basis for pavement design and rehabilitation (e.g. AASHTO Guide, customized system, etc.)? **The AASHTO Guide.**

2. What types of data do you use to come up with the ESAL table values and how are they collected? **From data obtained from permanent WIM stations, and portable WIM equipment.**

3. Do you use a single ESAL table for all design locations within your state or is a different ESAL value computed for different locations based upon load information for that location? **We use a single ESAL table statewide with different factors based on rigid or flexible pavement, and rural or urban interstate or other road classifications.**

4. How often do you update your ESAL tables? **Every 2-3 years.**

5. Do you break down ESALs by vehicle classification and, if so what vehicle classes do you use? **Yes, Classes 4-13 as defined in FHWA's Traffic Monitoring Guide.**

6. Do you apply average ESAL factors to the vehicles in each classification? What are they? **No.**

7. Do use growth factors to expand ESALs to design years? How do you determine growth factors? **Yes, growth factors are calculated from historical traffic data, and applied to the section being evaluated at the time a design traffic request is made.**

8. Do you use WIM data? If, not what do you use for load data? **Yes**

9. Do you collect classification data? How? How often? **Yes, we collect classification data year round from our permanent locations; plus, classification data is collected from additional sites as necessary under contract (Southern Traffic Services). Approximately 1/3 of our traffic sections are counted each year. This amounts to approximately 900 sites counted every year.**

10. How much confidence do you have in the values you use for pavement design and rehabilitation? **Approximately 80%**

Additional Comments:

ESAL Calculation Survey for Tennessee

1. Does your State use as its basis for pavement design and rehabilitation (e.g. AASHTO Guide, customized system, etc.)?

Our state department of Transportation uses the AASHTO guidelines for pavement design including the ESAL values for different axle loadings provided by AASHTO.

2. What types of data do you use to come up with the ESAL table values and how are they collected?

We, at TDOT, use traffic and classification counts as well as weight-in-motion (WIM) technology to gather data annually on axle loads of different types of trucks. This data is collected at various locations on Tennessee highways.

3. Do you use a single ESAL table for all design locations within your state or is a different ESAL value computed for different locations based upon load information for that location?

No we don't use a single ESAL table for all design locations, each design location is computed with a different ESAL value based upon its individual loading information.

4. How often do you update your ESAL tables?

All ESAL tables are updated on as-need basis only

5. Do you break down ESALs by vehicle classification and, if so what vehicle classes do you use?

Yes, we at TDOT, categorize ESAL's into 13 types of vehicle classification. They are listed below with the sequence numbers corresponding to the Federal Highway Administration vehicle type code.

1. Motorcycles
2. Passenger Cars
3. Single Unit Vehicles: 2-Axle, 4-Tier (pickup, panel, van)
4. Buses
5. Single Unit Truck: 2-Axle, 6 Tire
6. Single Unit Truck: 3-Axle
7. Single Unit Truck: 4-Axle or More
8. Single Unit Truck: 4-Axle or Less
9. Single Unit Truck: 5-Axle
10. Single Unit Truck: 6-Axle or More
11. Multi-Trailer Trucks: 5-Axle or Less
12. Multi-Trailer Trucks: 6-Axle
13. Multi-Trailer Trucks: 7-Axle or Less
14. Other

6. Do you apply average ESAL factors to the vehicles in each classification? What are they?

Yes, please see attachment

7. Do use growth factors to expand ESALs to design years? How do you determine growth factors?

Yes, we at TDOT, use growth factors to expand ESALS to design years as it applies to traffic counts. Our growth factors are annually counted at various locations along Tennessee's highways from out database computer software, Advance Traffic Data Analysis Management.

8. Do you use WIM data? If, not what do you use for load data?

Yes, our state department uses WIM (weight-in-motion) technology to gather data annually on axle loads of different types of trucks.

9. Do you collect classification data? How? How often?

Yes we collect classification data (200 class counts per year) every three years on a rotating basis. This data is collected by our field crew both manually and with machines.

10. How much confidence do you have in the values you use for pavement design and rehabilitation?

Since we follow all necessary guidelines and procedures according to the American Association of State Highway & Transportation Officials (AASHTO) manual in pavement design and rehabilitation, we have the utmost confidence in those values and the results that they provide.

Additional Comments: