Technical Report Documentation Page

1. Report No. FHWA/TX-05/0-1713-2	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

IMPACT OF CHANGING TRAFFIC CHARACTERISTICS AND ENVIRONMENTAL CONDITIONS ON PERFORMANCE OF PAVEMENTS

5. Report Date

October 2000
Revised: October 2001, September 2002, May 2003, October 2004, February 2005

6. Performing Organization Code

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8. Performing Organization Report No.
Technical Report 0-1713-2

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.
0-1713

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Implementation Office
P.O. Box 5080
Austin, TX 78763-5080

13. Type of Report and Period Covered
Technical Report (9/99 – 8/00)

14. Sponsoring Agency Code

15. Supplementary Notes
Project conducted in cooperation with the Texas Department of Transportation and the Federal Highway Administration. Project title: Evaluation of the AASHTO 18-kip Equivalency Concept.

16. Abstract
Critical to the AASHTO pavement design methods are the AASHTO load equivalency factors (LEFs), which are used to convert the mixed traffic axle loads into standard 18-kip equivalent single axle loads (ESALs). Over the years the composition and characteristics of traffic using Texas highways have changed. At the same time, NAFTA has accelerated such changes in the sense that more trucks, primarily moving through mid-western states, Texas, and Mexico, are traveling on Texas highways. In addition, the original AASHO Road Test was conducted at a site whose environmental conditions significantly differ from those environmental conditions found in Texas. It is therefore critical to fully understand the impact of such changing traffic characteristics and environmental conditions on pavements in Texas. This report (1) presents the methodology used to analyze the impact of these factors on the AASHTO LEFs and (2) discusses the results.

17. Key Words

Load equivalency, ESALs, pavement damage

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	90	

Impact of Changing Traffic Characteristics and Environmental Conditions on Performance of Pavements

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CTR Research Report:	0-1713-2
Report Date:	October 2000
	Revised: October 2001, September 2002, May 2003, October 2004
Research Project:	0-1713
Research Project Title:	*Evaluation of the AASHTO 18-Kip Load Equivalency Concept*

This research was conducted for the Texas Department of Transportation in cooperation with the Federal Highway Administration by the Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin.

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Disclaimers

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Acknowledgments

This project has been conducted under the guidance of and has been directly assisted by Joseph P. Leidy, Project Director, Design Division of the Texas Department of Transportation. Without his generous help and guidance, this final product would be severely diminished.

Research performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

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1. Introduction

1.1 Background

A load equivalency factor (LEF) is a multiplier that, when applied to a given axle-load magnitude and axle type, estimates the number of applications of a specified standard axle-load magnitude and axle type that will have an equivalent effect upon a defined pavement structure. Even though the trend in pavement design methods is shifting toward mechanistic design, the use of design methods based on the American Association of State Highway Officials (AASHO) Road Test results is still the current design practice for the American Association of State Highway and Transportation Officials (AASHTO), the State of Texas, and most other states. Critical to these design methods are the AASHTO load equivalency factors (LEFs) that are used to convert mixed traffic axle loads into standard (18-kip) equivalent single axle loads (ESALs). Since the AASHO Road Test in 1958-61, traffic characteristics have changed. A better understanding of the impact of changing traffic characteristics on LEFs and on pavement damage will provide useful information on mechanistic pavement design methods, as well as a more accurate characterization of traffic loading effects for current design.

The AASHTO LEFs were developed in the 1960s based on empirical data obtained at the AASHO Road Test, which was the most comprehensive field experiment ever carried out in the pavement field [HRB 62E, AASHTO 72, AASHTO 86, AASHTO 93]. Other load equivalency methods have been developed based on pavement response to load (deflection, stress, etc.) or distress manifestations (rutting, fatigue, cracking, etc.). The AASHO Road Test results are used worldwide to design pavements, and the AASHTO LEFs are the most widely used conversions in the world.

Recent research reflects the controversies associated with the validity of extrapolating the AASHTO guide equations beyond the range and associated test parameters of the original 1961 data. Some agencies and scholars advocate the mechanistic approach, in which LEFs are defined in terms of pavement response to load such as stress or strain [Southgate 93, Zaghloul 94a, Zaghloul 94b, Ioannides 91, Ioannides 93, Papagiannakis 90, Seeds 88, High 88, Hudson S 88, Horak 88]. Others prefer empirical models (such as AASHO), in which LEFs are subjectively defined in terms of user acceptance of the pavement ride quality and fatigue or distress manifestations [Huhtala 92a, Fernando 92, Kenis 92, Southgate 91]. A recent study conducted by Hajek proposed general axle load equivalency factors that are independent of pavement variables. Such LEFs are valid based on the argument that uncertainties resulting from traffic volume variables and projections are much larger than those inherent to LEF estimates [Hajek 95]. This point merits further investigation, since other studies that have compared LEF approaches (such as AASHO versus mechanistic) were unable to discriminate between discrepancies resulting from intrinsic differences among methods and those caused by experimental errors [Papagiannakis 90].

Smaller road tests have been conducted by several agencies, but the controversy still remains. Sebaaly and Tabatabaee conducted a full-scale testing program to investigate the effects of tire pressure, tire type, axle load, and axle configuration on the response and LEFs of flexible pavements [Sebaaly 92]. The Federal Highway Administration (FHWA) financed a test road to investigate pavement response to tire pressure, axle load, axle configuration, vehicle speed, layer thickness, suspension systems, and time-dependent material properties. Numerous studies ensued, sometimes with conflicting conclusions [Black 92, Bonaquist 88a, Bonaquist 88b, Kenis 92].

Road tests and analytical studies conducted in other countries reflect concern with modern tire configurations and higher pressures. In Finland, LEFs were developed for high axle loads using cracking as the performance indicator [Huhtala 92a]. They also studied new tires and tire pressures [Huhtala 92b]. In Canada, data from a flexible pavement test section were used to investigate the validity of American Society of Testing and Materials (ASTM) E1049-85 "Standard Practices for Cycle Counting in Fatigue Analysis." The study found that LEFs decreased as vehicle speed increased, and that the sum of LEFs of axle groups of a vehicle can be different from the LEFs calculated for the vehicle [Papagiannakis 90]. In France, a comprehensive analytical study investigated the combined effects of heavy truck configurations on pavement performance. The study assessed and modeled the separate and combined effects of factors that affect pavement distress, including dynamic loads, climatic factors, truck characteristics, and surface distress types.

The study also discussed the load equivalence law, models for predicting temperature distributions in pavements, and pavement distress models [OECD 88]. Another Canadian study used data from nine sites across Canada to develop LEFs for single-axle, tandem-axle, and tridem-axle groups. The LEFs developed for tandem and tridem axles were significantly higher than the AASHTO LEFs [Rilett 88].

Often the AASHTO LEFs are described by the power law concept. According to the AASHTO Guide [AASHTO 93], the LEFs increase as a function of the ratio of any given axle load to the standard 18-kip single axle load raised to the power coefficient of 4. However, the findings of some researchers differ regarding the power coefficient. Some studies show that statistical procedures used to calibrate the models from empirical data can also have a fundamental influence on the final results. For example, Small and Winston reanalyzed the original AASHO Road Test data using survival analysis techniques (also called Tobit analysis) with an underlying normal distribution [Small 89]. Weissmann and Hudson did similar analyses using an underlying Weibull distribution, which is considered valid for modeling life spans of any system that fails because one or more of its components wear out [Bury 75, Weissmann 90]. Both results were closer to a 3.3 than a 4th power coefficient. Hudson and Irick re-analyzed the original AASHO data using the traditional statistical technique, but they disaggregated the data by loop. Each loop gave a different model that resulted in power coefficients varying from 2.5 to 6, with an average of 4 [Hudson S 92].

The findings of these studies are inconclusive, and conflicting findings and opinions have generated as many new questions as they have provided answers to old ones. In terms of tire pressure and width, some studies have found that wide and twin tires cause considerably more damage, while other studies found that axle load is a much more important factor in damage. Findings regarding the effect of suspension systems have been relatively few and inconclusive. LEFs vary widely for new axle configurations and tire types. These issues clearly merit further investigation, as was recognized in a workshop carried out by the FHWA [Trapani 89].

1.2 The AASHTO LEFs and Their Limitations

AASHO and the Bureau of Public Roads introduced the 18-kip equivalency concept soon after the AASHO Road Test was completed in 1961 [Irick 91]. The 18-kip single-axle load was chosen mainly because it was the legal maximum load in most states at the time of the AASHO Road Test [Van Til 72]. LEFs were based on empirical data obtained during the Road Test. They were published in the AASHTO Interim Guide for Design of Pavement Structures and in all subsequent editions of the AASHTO Design Guide [AASHTO 72, AASHTO 86, AASHTO 93].

However, the developers of these AASHTO LEFs took into consideration only four variables:

1. Axle load on load axles (the damaging effects of the steering axles were incorporated into the LEFs)
2. Axle configuration (single, tandem, or tridem)
3. Structural number for flexible pavements or slab thickness for rigid pavements
4. Terminal serviceability level

Clearly, there are more variables that could affect LEFs. The fact that the current LEFs are based on the AASHO Road Test prompts concerns about the following:

1. *Extrapolation of AASHO models outside the test parameters.* Because empirical models are usually valid only within the range of the data used to develop them, the AASHO model is theoretically valid only when it is used with the environmental conditions, materials, and vehicle characteristics that prevailed during the test.
2. *New axle configurations, tire type and widths, and suspension systems.* There are concerns about the validity of using AASHO equivalencies for supersingle tires, suspension systems, and tridem axles not present in the AASHO Road Test.
3. *Effects of higher tire pressures.* As the axle load increases, higher tire pressures become more popular for long-haul trucks. Several studies have been conducted to determine the effects of tire pressures on LEFs. It was

reported that increased tire pressure increases the values of primary responses and can affect the fatigue life of pavements [Hudson S 88, Bonaquist 88a].

4. *Composite pavements.* Most highway agencies approximate the behavior of composite pavements to that of asphalt or concrete pavements. In fact, the 1993 AASHTO Design Guide suggests that concrete pavement LEFs be used to assess the effects of traffic on composite pavements. This approximation still needs further validation through field measurements and analytical procedures.
5. *Statistical techniques used to analyze the data.* Subsequent analyses of the original AASHO data have yielded different equivalency ratios through the use of more accurate statistical methods than those available in the early 1960s.

1.3 Changing Traffic Characteristics and Environmental Conditions in Texas

Over the years, the composition and characteristics of traffic using Texas highways have changed. The NAFTA agreement has accelerated such changes because more trucks from Canada and Mexico are traveling on Texas highways. It is, therefore, critical that researchers fully understand the impact of such changing traffic characteristics on pavements in Texas. In addition, the original AASHO Road Test was conducted at a site where environmental conditions are significantly different from those found in Texas. It is equally important to understand the underlying implications of the difference in environmental conditions with regard to LEFs. More specifically, the impact of the following factors on the AASHTO LEF is of great importance to pavement design and rehabilitation in Texas:

1. Higher tire pressures
2. New tire widths, such as wide base supersingles and adoption of the radial tire
3. New axle configurations, such as tridems
4. Environmental factors

Clearly, these concerns coincide with the limitations of the AASHTO LEFs previously outlined. However, since the AASHO Road Test provides raw data for conducting such analyses, the approach in this study is to evaluate such impacts on the 18-

kip LEFs by using mechanistic analysis of AASHO Road Test pavement sections. More specifically, the changes in the magnitude of the primary pavement responses such as stress, strain, and deflection can be used as indicators to capture the impact of these factors. Furthermore, the real impact of these factors on the AASHTO LEFs cannot be properly quantified without taking the following conditions into consideration:

1. Fatigue effects of repeated loading
2. The need to relate the response outputs from mechanistic analyses back to the AASHO Road Test data

One approach to solving this problem is the use of a performance-based fatigue model developed from the AASHO Road Test data.

1.4 Scope, Objectives, and Approach to Research

The scope of the research includes the evaluation of the AASHTO LEF model for flexible and rigid pavements. The research investigates the impact of higher tire pressure, supersingles, tridems, and Texas environmental factors on the AASHTO LEFs. The objective of this research is to extend LEFs' validation for the factors mentioned above. This objective can be accomplished through the development of a performance-based fatigue model that could then be used to evaluate changing traffic characteristics.

Figure 1.1 presents a research approach to validate the AASHO LEFs. A mechanistic-empirical approach is used to evaluate effects of selected factors such as higher tire pressure, supersingles, tridems, and Texas environmental factors.

Mechanistic-Empirical Approach

↓

Performance-Based Fatigue Model Development

- ♦ Selection of candidate primary responses for flexible and rigid pavements.
- ♦ Structural analysis of the AASHO Road Test pavement sections: calculation of selected candidate primary responses.
- ♦ Regression analysis using the Statistical Analysis System (SAS) software.
- ♦ Model selection based on criteria: agreement with the current LEFs for AASHO load conditions, R^2, C_p, engineering judgment.

↓

Evaluation of the Impact of Selected Factors on the LEFs Using the Developed Model

- ♦ Factors to be evaluated: higher tire pressure, supersingles, tridems, environmental factors.

↓

Conclusions

- ♦ Quantified impact of considered factors on the AASHTO LEFs.

↓

Final Conclusion About Validity of the LEFs

Figure 1.1 Validation of the AASHTO LEFs

A performance-based fatigue model was developed through the following stages:

1. Selection of primary pavement structural responses
2. Structural analysis of AASHO Road Test pavement sections
3. Regression analysis using the Statistical Analysis System (SAS) software
4. Model selection

The model is used to validate the AASHTO LEFs for changing traffic characteristics; then conclusions and recommendations are made.

2. Research Methodology

This chapter presents a methodology for developing models to estimate the number of load applications possible when a pavement reaches its terminal level of serviceability in relation with a primary pavement response (such as strain or stress) applied to the pavement. With the developed models, the impact of changing traffic characteristics on pavement performance can be analyzed; accordingly, the effects of changing traffic characteristics on the AASHTO LEFs can also be evaluated.

The AASHO Road Test produced the most comprehensive pavement performance test database available to date. As a part of the AASHO Road Test, the pavement performance of 840 test sections and the corresponding load repetitions applied to the pavement sections were recorded. This made possible the development of pavement performance models that are used in wide varieties of analyses and design comparisons.

2.1 Potential Methodologies for the Development of Models

There are three possible approaches to the development of LEF models using the AASHO Road Test data:

- A mechanistic approach
- An empirical approach
- A mechanistic-empirical approach

A mechanistic approach refers to a methodology that is based on the mechanistic analysis of a pavement. An example of the mechanistic approach is the equivalent single-wheel load (ESWL) concept. ESWL is defined as the load on a single tire that will cause an equal magnitude of a preselected parameter (stress, strain, deflection, or distress) at a given location within a specific pavement to that resulting from a multiple-wheel load at the same location within the pavement structure [Yoder 75].

An empirical approach is usually based on the statistical analysis of experimental data. An example of the empirical approach is the AASHTO pavement performance models established through the statistical analysis of the AASHO Road Test data [HRB 62E]. The AASHTO pavement performance models include four independent variables: 1) axle load, 2) axle type, 3) structural number for flexible pavements or portland cement concrete (PCC) thickness for rigid pavements, and 4) terminal serviceability. These models can be used to predict the number of load applications that will cause a section with known strength to reach the specified terminal serviceability.

The mechanistic approach and the empirical approach have their own benefits and drawbacks. The shortcoming of the mechanistic approach is that the primary pavement responses are not related to the performance of the pavement. The shortcoming of the empirical approach is that it cannot evaluate variables that did not exist as factors in the AASHO Road Test design. For example, an increased tire pressure cannot be evaluated using the AASHO Road Test model, because in the AASHO Road Test, the tire pressure was set at a constant 75-80 psi and was not considered as a factor. Additionally, with the empirical approach, it is not possible to evaluate supersingles or tridems, since they were not included in the AASHO Road Test. Originally, the AASHO Road Test models were used to calculate LEFs only for single and tandem axles [HRB 62E, AASHTO 72]. Later, the AASHO models were adapted to evaluate tridems by setting the value of the axle type code variable to 3 [AASHTO 86, AASHTO 93], thereby extrapolating the qualitative axle type code variable. This is an inaccurate approximation, because a qualitative variable like axle type code should not be extrapolated since its value is assigned, not measured.

An mechanistic-empirical approach has the potential to remedy these problems by employing a primary response variable to predict pavement serviceability life. The typical primary responses used in the mechanistic-empirical models are surface deflection, peak tensile strain at the bottom of the asphalt concrete (AC) surface layer, peak vertical compressive strain at the top of the subgrade for flexible pavements and peak tensile stress at the bottom of PCC slab for rigid pavements. When peak responses of a pavement reach their limits, damage occurs in the pavement structure. Since any change in load conditions would normally cause a change in primary responses, proper mechanistic-empirical models based on primary responses should be able to characterize the impact of changing load conditions on pavement performance. Therefore, the mechanistic-empirical approach was selected as the approach to develop analysis models for this study.

2.2 Methodology for the Development of the Performance-Based Fatigue Models (PBFM)

Owing to the unavailability of historical AASHO Road Test data (such as the impact of tire pressure, tire type, and tridem axles on pavement deterioration) for conducting such analyses, the best approach to evaluating the impact of the above referenced factors on the 18-kip LEFs is to use computerized mechanistic analyses. More specifically, the changes in the magnitude of the primary pavement responses such as stress, strain, and deflection can be used as good indicators to capture the impact of these factors. Furthermore, the true impact of these factors on the AASHTO LEFs cannot be properly quantified without taking the following conditions into consideration:

1. Fatigue effects of repeated loading
2. Relating the response outputs from computerized mechanistic analyses back to AASHO Road Test data

One approach to solving this problem is through the use of a performance-based fatigue model that can be developed from AASHO Road Test data, where different kinds of distress, including rutting, are considered in the performance measurement.

Traditional fatigue failure criteria (or fatigue curves) are usually developed through laboratory fatigue tests. It is very difficult to use these fatigue criteria to conduct meaningful evaluations of the impact of the previously referenced new factors on the 18-kip LEFs because the loading conditions and failure definitions for the laboratory tests differ from those used for the AASHO Road Test. Since pavement performance and its corresponding load repetitions were well recorded as part of the AASHO Road Test data, a performance-based fatigue model can be developed using the data. The performance-based fatigue model, once developed, can be used in a wide variety of analyses and comparisons to capture the impact of changing traffic characteristics and environmental conditions on LEFs. The performance-based fatigue model serves as the bridge for both fatigue effects and relating the response outputs from computer analyses back to AASHO Road Test data. The performance-based fatigue model can be developed by following the procedures outlined below:

1. Select candidate primary responses to be included in the PBFM.

2. Select all test sections with a terminal Present Serviceability Index (PSI) of 2.5 or less from the AASHO Road Test data set, where each section received a known number of load repetitions of a known axle load magnitude when the PSI reached 2.5. The selection of PSI level was based on the lowest tolerable service level before any rehabilitation, resurfacing, or reconstruction became necessary. According to the AASHTO Guide [AASHTO 93], a PSI of 2.5 or more is suggested for the design of major highways.
3. Select a computer program to calculate the candidate primary responses defined in Step 1.
4. Calculate the selected primary responses in the pavement structure for the AASHO Road Test pavement sections with the selected computer program, using the structural data (such as thickness, modulus, etc.) and the corresponding axle load of each selected section as inputs.
5. Develop the general form of candidate models for predicting the number of load applications.
6. Establish criteria for selecting the best PBFM. The criteria could include such considerations as how well the AASHTO LEFs are related to the AASHO Road Test conditions, maximum R^2, minimum C_p, and engineering judgment.

   The statistical measurements, R^2 and C_p, were used to determine the statistical quality of the model candidates. R^2 is a criterion that determines how well the model fits the data. C_p is a criterion concerned with the total mean squared error of the n fitted values for each subset regression model [Neter 96]. Engineering judgment was used to check the rationality of values and engineering interaction. For example, a coefficient for load should have a minus sign, because an increased load applied to the pavement structure will cause the pavement to deteriorate faster. Similarly, a coefficient for the structural number should have a plus sign, because stronger pavements should carry more applications of the same axle load.
7. Generate candidate models using the SAS program.

8. Select a final PBFM based on the criteria established from the generated models.

2.3 Methodology for Evaluating Effects of Changing Traffic Characteristics on the AASHTO LEFs

Once the PBFM model is established, the effects of changes in tire pressure, supersingle tires, tridem axles, and environmental factors on the AASHTO LEFs can be estimated through the following four steps:

1. Calculate the primary responses required for the PBFM for a specific load with dual tires inflated at the AASHO Road Test tire pressure.
2. Calculate the primary responses for the same magnitude of load under a new loading condition such as higher tire pressure in dual tires or the replacement of dual tires by supersingles.
3. Estimate the number of axle load applications according to the calculated primary response values obtained under Steps 1 and 2, using the established PBFM.
4. Calculate the relative damage with the estimated terminal load applications for the two analyzed loading conditions.

Figure 2.1 illustrates an example of a comparison of the performance of two tires, where one tire has a pressure of 75 psi and the other has a pressure of 115 psi.

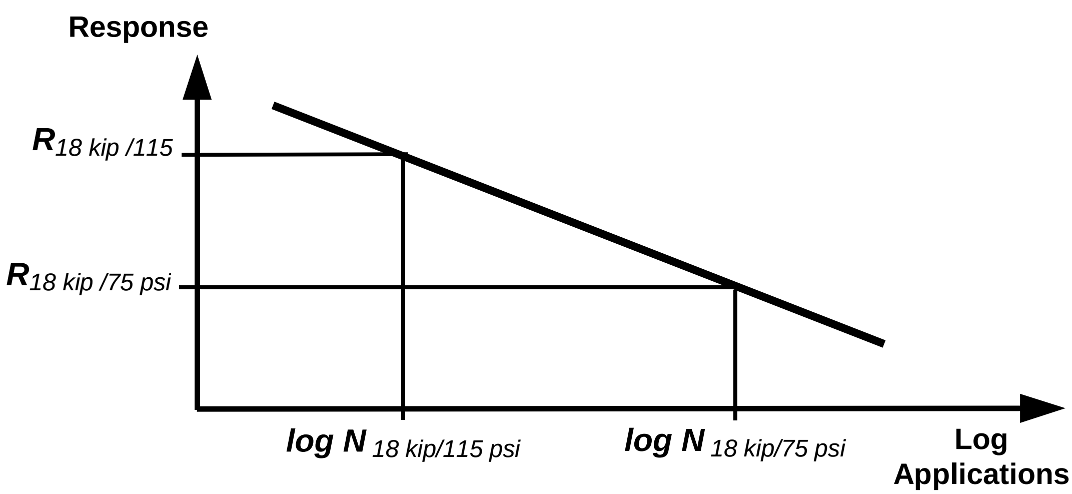

Figure 2.1 Illustration of an Evaluation of Higher Tire Pressure

3. Development of Performance-Based Fatigue Models

This chapter describes the development of performance-based fatigue models (PBFMs) for flexible and rigid pavements using the AASHO Road Test data. Because there are differences in behavior and characteristics between flexible and rigid pavements, the PBFM models should be developed separately to accommodate these differences.

3.1 PBFM for Flexible Pavements

The following sections outline the process and steps taken to develop the PBFMs for flexible pavements.

3.1.1 Selection of Candidate Primary Responses to be Included in the PBFM

Past studies by various researchers show that the primary responses most commonly used for predicting the life of flexible pavements are the following:

- deflection on the surface of a pavement
- horizontal tensile strain at the bottom of asphalt concrete (AC) surface layer
- vertical compressive strain at the top of the subgrade

These primary responses are illustrated in Figure 3.1.

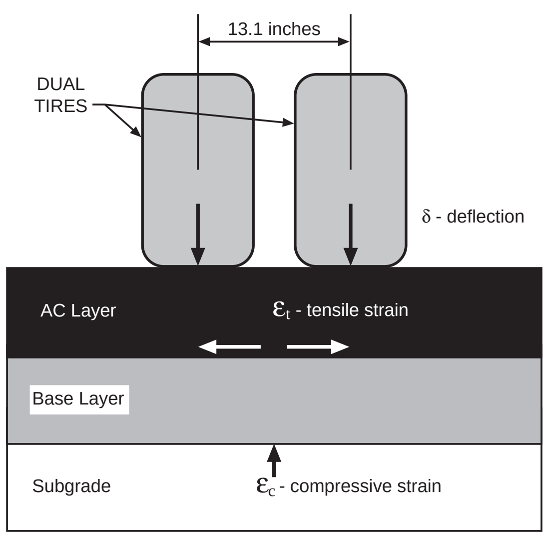

Figure 3.1 Critical Primary Responses in Flexible Pavement Structure

3.1.2 Selection of the Flexible Sections with PSI ≤ 2.5 from the AASHO Road Test Data

For the AASHO Road Test data, 132 out of 164 flexible pavement sections trafficked with single axle loads reached a PSI level of 2.5 or less, and 107 out of 120 flexible pavement sections trafficked with tandem axle loads reached a PSI level of 2.5 or less. Overall, 239 out of 284 flexible pavement sections trafficked with single and tandem axle loads reached a PSI level of 2.5 or less.

3.1.3 The Computer Program for Analyzing the Primary Responses in Flexible Pavements

Three computer programs were considered for the calculation of primary responses in flexible pavements: ELSYM-5, Kenlayer, and Abaqus. ELSYM-5 and Kenlayer programs analyze flexible pavements based on elastic layer theory. However, elastic layer theory has its limitations, such as the assumption of uniform, static, and circular load patterns. It was initially thought that a complex, finite element program such as Abaqus would be required. After a careful literature review, it was found that the assumption of nonuniform, noncircular loads for elastic layer theory results in an error of less that 2 percent in comparing uniform and circular loads under the whole range of realistic tire and loads [Lister 67]. Gross overloading of a tire results in an error of about 7 percent. These and other examples seemed to justify the use of elastic layer theory.

Table 3.1 presents a comparison of the calculated responses, using the three selected computer programs, for a pavement structure with a 6-inch thick AC layer and a 10-inch thick base layer. The modulus values assumed for AC, base, and subgrade layers were 1,000,000, 60,000, and 10,000 psi, respectively. Though a high value of AC modulus is assumed, it does not affect the results in any significant way because of the linear nature of the models involved. From Table 3.1 it is clear that ELSYM-5 and Kenlayer give almost identical results. The results from Abaqus are slightly lower in comparing those from ELSYM-5 and Kenlayer.

Among the three computer programs, ELSYM-5 is the fastest and easiest to use and it gives reliable results comparable with other computer programs. Therefore, ELSYM-5 was selected to calculate the primary responses in flexible pavements.

Table 3.1 Comparison of the Primary Responses from Three Computer Programs

Wheel Load [kip]	Tire Pressure [psi]	Surface Deflection [inch]		
		ELSYM-5	KENLAYER	ABAQUS
10	80	1.5550E-02	1.5610E-02	1.1285E-02
	120	1.5920E-02	1.5970E-02	1.1668E-02
20	80	2.9970E-02	2.9850E-02	2.0996E-02
	120	3.0660E-02	3.0680E-02	2.1995E-02
Wheel Load [kip]	**Tire Pressure [psi]**	**Peak Horizontal Strain at the Bottom of AC Surface Layer [inch/inch]**		
		ELSYM-5	**KENLAYER**	**ABAQUS**
10	80	1.1760E-04	1.1750E-04	8.3332E-05
	120	1.3730E-04	1.3740E-04	9.8702E-05
20	80	1.7010E-04	1.7000E-04	1.1758E-04
	120	2.0740E-04	2.0710E-04	1.4568E-04
Wheel Load [kip]	**Tire Pressure [psi]**	**Peak Vertical Strain at the Top of Subgrade [inch/inch]**		
		ELSYM-5	**KENLAYER**	**ABAQUS**
10	80	-3.35E-04	-3.35E-04	-3.10E-04
	120	-3.39E-04	-3.44E-04	-3.20E-04
20	80	-6.24E-04	-6.22E-04	-5.65E-04
	120	-6.55E-04	-6.53E-04	-6.01E-04

3.1.4 Calculation of the Primary Responses for Flexible Pavement Sections Selected from the AASHO Road Test Data

Using ELSYM-5, the primary responses were calculated for the selected flexible pavement sections. Figures 3.2, 3.3, and 3.4 show the calculated primary responses versus load applications for the AASHO Road Test sections that reached a PSI level of 2.5.

Clearly, the strongest correlation exists between the vertical compressive strain at the top of the subgrade and the number of load applications, where the vertical compressive strain is directly related to the rutting that is included in the determination of the present Serviceability Index (PSI). Additionally, the figures show that the magnitude of the load is an important factor in explaining the variability in the number of load repetitions.

For example, Figure 3.3 indicates a clear trend that the tensile strains at the bottom of the AC layer are affected by the magnitude of the load. This suggests that the inclusion of the load variable into the model will increase the predictability of the variability in the load applications.

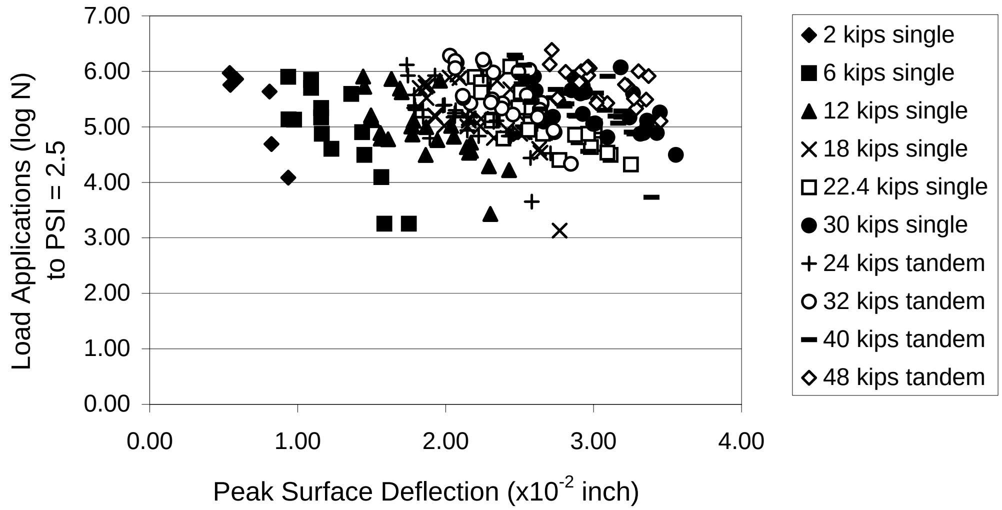

Figure 3.2 Surface Deflection

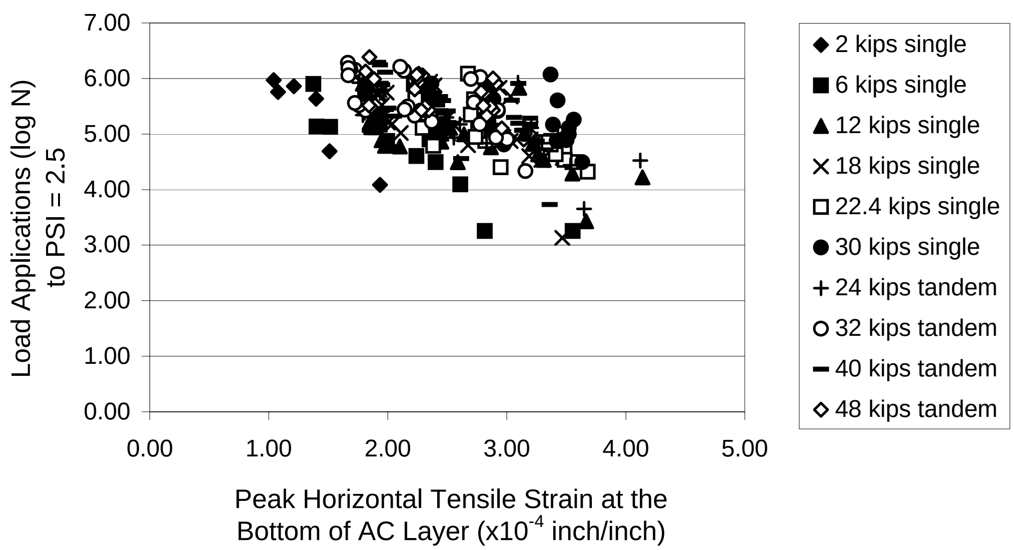

Figure 3.3 Horizontal Tensile Strain at the Bottom of the AC Surface Layer

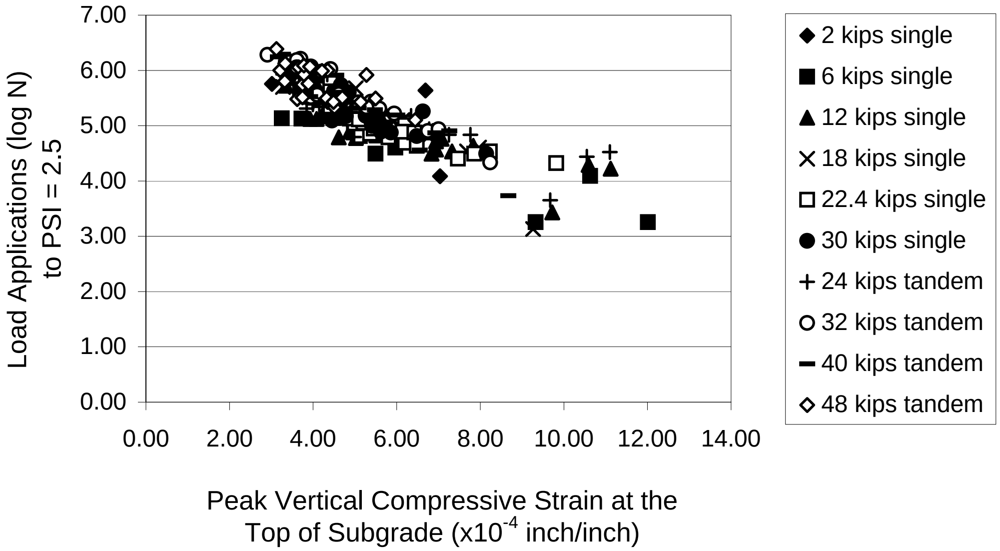

Figure 3.4 Vertical Compressive Strain at the Top of Subgrade

3.1.5 General Form of PBFM for Flexible Pavements

The general form for the PBFM for flexible pavements can be expressed as follows:

$$\text{Log } N_{PSI=2.5} = f(SN, L, \delta, \varepsilon_t, \varepsilon_c) \qquad \text{(Eq 3.1)}$$

where:

δ	=	deflection at the top of the AC layer.
ε_t	=	tensile strain at the bottom of the AC layer.
ε_c	=	compressive strain at the top of the subgrade.
SN	=	structural number.
L	=	wheel load.

More specifically the model can be expressed as:

$$\text{Log } N_{PSI=2.5} = a + b_1{*}SN + b_2{*}\log(SN) + c_1{*}L + c_2{*}\log(L) + d_1{*}\delta + d_2 \log(\delta) + e_1{*}\varepsilon_t + e_2{*}\log(\varepsilon_t) + f_1{*}\varepsilon_c + f_2{*}\log(\varepsilon_c) \qquad \text{(Eq 3.2)}$$

The exact form of the model will depend on the results of the regression analysis. In searching for the best model, various variable combinations and transformations can be used during the model selection and construction process. However, the final model will contain only one form for each independent variable. For example, if SN contributes significantly to the model, the final model could contain expressions such as b_1*SN or b_2*log(SN), whichever best fits the model.

3.1.6 Establishing Criteria for the Selection of PBFM

The SAS program [SAS 90] has the capability for the user to generate alternative models. Three criteria were established as the basis for making the final selection of the PBFM:

1. For AASHO Road Test conditions, the PBFM should produce Load Equivalency Factors (LEFs) similar to the current AASHTO LEFs.
2. R^2 should be maximized and C_p should be minimized,
3. All terms should have the proper sign (to be determined through engineering judgment).

First, the LEFs for each pavement structure and axle load used in the AASHO Road Test conditions were obtained from the AASHTO Guide [AASHTO 93]. Next, the LEFs were calculated using the PBFM. Models producing LEFs close to the AASHTO LEFs are primary candidates to be the final PBFM. It is desirable that the model explain much of the variation in log applications, therefore indicating a high R^2. Finally, engineering judgment was used to check the rationality of values and engineering interactions. For example, the coefficient for load should be negative, because increased load applied to the pavement structure will cause faster deterioration of the pavement structure.

3.1.7 Final Selection of the PBFM Based on Established Criteria

Alternative models were generated using the SAS software [SAS 90]. For each generated alternative model, the associated R^2 and C_p statistics were calculated. From the large group of generated models, only those models with an R^2 above 0.70 were considered as candidates. Then, the models with more than one form of the same independent variable were eliminated. For example, models that included both SN and log(SN+1) were eliminated. For the set of models that were not eliminated, regression analyses were conducted to obtain the regression coefficients. Analyses on the coefficients of regression were then performed to exclude models with incorrect signs for the coefficients. For example, coefficients for structural number (SN) should be positive, since a stronger pavement should carry more peak strain applications before reaching a PSI level of 2.5. Therefore, models containing negative coefficients for SN were eliminated. Table 3.2 shows the remaining models after the preliminary scanning with these considerations, where the R^2 values range from 0.733 to 0.790. All of the models have either SN or log(SN+1) as one of their independent variables. Additionally, all of the models have at least one of the primary responses as an independent variable: surface deflection, horizontal tensile strain at the bottom of the AC layer, or vertical compressive strain at the top of subgrade. Except in model 3, the wheel load seems to be a significant factor in the model as well.

Table 3.2 List of Candidate Models for Final Selection of the PBFM

Model No.	**Model**	**C_p**	**R^2**
1	$11.960 + 0.32728*SN - 0.06069*L - 2.63491*\log(\varepsilon_c)$	20.6	0.790
2	$5.5862 + 0.45615*SN - 0.09393*L - 0.00158*\varepsilon_c$	23.0	0.787
3	$14.585 + 0.72446*\log(SN+1) - 3.6046*\log(\varepsilon_c)$	27.2	0.782
4	$6.2742 + 0.77949*SN - 0.15500*L - 0.80447*\log(\varepsilon_t)$	62.0	0.755
5	$6.2697 + 5.5687*\log(SN+1) - 0.12109*L - 1.3158*\log(\varepsilon_t)$	85.0	0.736
6	$4.2774 + 6.4272*\log(SN+1) - 0.12228*L - 1.2151*\log(\delta)$	88.0	0.733

To test the validity of these models, a set of LEFs were calculated with the models. Tables 3.3 and 3.4 present the LEFs calculated by using the selected models for two flexible pavement structures, one with a 3-inch AC surface layer and the other with a 6-inch AC surface layer. Even though model 5 does not have the smallest C_p value, the differences between the AASHTO LEFs and the LEFs calculated using model 5 are the smallest; therefore, model 5 was selected as the final PBFM:

$$\log N_{PSI=2.5} = 6.2697 + 5.5687*\log(SN + 1) - 0.12109*L - 1.3158*\log(\varepsilon_t)$$

(R^2= 0.73) (Eq 3.3)

where:

$N_{PSI=2.5}$ = number of peak strain applications of axle load at which the pavement reaches PSI = 2.5;

L = dual wheel load [kip]; and

$\log(\varepsilon_t)$ = peak strain (microstrain) at the bottom of AC surface layer.

Table 3.3 Comparison of the AASHTO LEFs and the Calculated LEFs from Candidate Models (3-Inch AC Surface Layer)

Model	**Axle Load [kip]**	**LEF (AC thickness 3 inches)**		
		Model LEF (AASHO Cond.)	**AASHTO LEF**	**Difference**
1	18	1.00	1.00	0.00%
	24	3.14	2.91	7.87%
	30	8.40	7.00	19.94%
2	18	1.00	1.00	0.00%
	24	3.58	2.91	22.87%
	30	12.73	7.00	81.91%
3	18	1.00	1.00	0.00%
	24	2.70	2.91	-7.38%
	30	5.83	7.00	-16.65%
4	18	1.00	1.00	0.00%
	24	3.11	2.91	6.86%
	30	10.03	7.00	43.22%
5	18	1.00	1.00	0.00%
	24	2.56	2.91	**-11.95%**
	30	6.96	7.00	**-0.52%**
6	18	1.00	1.00	0.00%
	24	3.23	2.91	11.00%
	30	9.75	7.00	39.35%

Table 3.4 Comparison of the AASHTO LEFs and the Calculated LEFs from Candidate Models (6-Inch Thick AC Surface Layer)

Model	**Axle Load [kip]**	**LEF (AC thickness 6 inches)**		
		Model LEF (AASHO Cond.)	**AASHTO LEF**	**Difference**
1	18	1.00	1.00	0.00%
	24	3.16	3.04	3.96%
	30	8.49	7.00	21.31%
2	18	1.00	1.00	0.00%
	24	2.89	3.04	-5.03%
	30	8.32	7.00	18.82%
3	18	1.00	1.00	0.00%
	24	2.72	3.04	-10.52%
	30	5.93	7.00	-15.35%
4	18	1.00	1.00	0.00%
	24	3.45	3.04	13.42%
	30	11.65	7.00	66.48%
5	18	1.00	1.00	0.00%
	24	3.03	3.04	**-0.21%**
	30	8.91	7.00	**27.24%**
6	18	1.00	1.00	0.00%
	24	3.24	3.04	6.72%
	30	9.83	7.00	40.38%

Figures 3.5 and 3.6 show the comparison of average power law coefficients obtained from the AASHO data points, the AASHTO Model, and the PBFM model 5. Clearly, the power law coefficient calculated from model 5 follows the general trend of the power law coefficient from AASHO Road Test data.

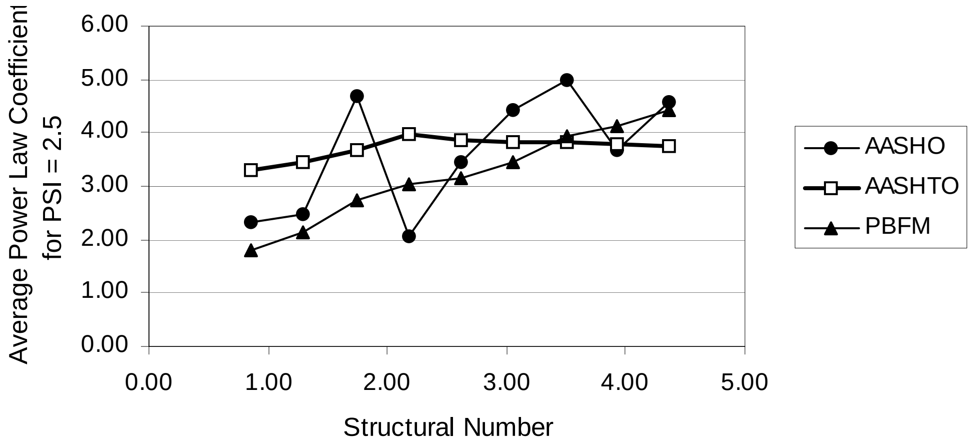

Figure 3.5 Average Power Law Coefficient for Flexible Pavements Trafficked with Single Axle Loads

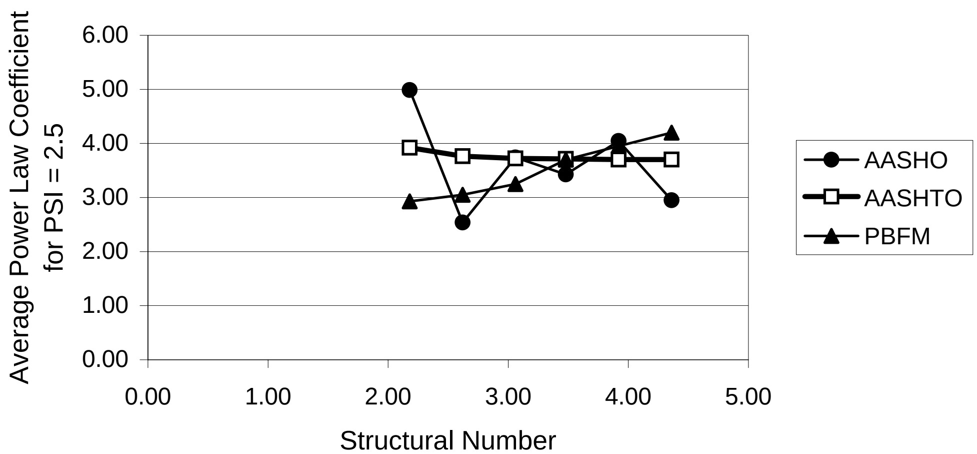

Figure 3.6 Power Law Coefficient for Flexible Pavements Trafficked with Tandem Axle Group Loads

3.2 PBFM for Rigid Pavements

The following sections outline the process and steps taken to develop the PBFM for rigid pavements.

3.2.1 Selection of Primary Responses to be Included in the PBFM

A carefully conducted literature review shows that the horizontal tensile stress at the bottom of the PCC slab is a good predictor of the performance of rigid pavements. Therefore, this response was selected to be included in the PBFM. Values of the horizontal tensile stress at the bottom of the PCC slab were calculated for each of the AASHO Road Test sections selected with the procedure as discussed in the following Section.

3.2.2 Selection of the Rigid AASHO Road Test Sections with PSI ≤ 2.5

Since a PSI value of 2.5 is normally used as the minimum acceptable PSI for interstate highways, the selection of test sections to be included in the analysis was based on this PSI threshold of 2.5. The AASHO Road Test data indicates that only 32 of the 152 rigid pavement sections trafficked with single axle loads reached a PSI level of 2.5 or less; 41 out of the 112 rigid pavement sections trafficked with tandem axle loads reached a PSI level of 2.5 or less. Overall, 73 of the 264 rigid pavement sections reached a PSI level of 2.5 or less.

3.2.3 The Computer Program for Analyzing the Stress in Rigid Pavements

Two programs were selected for the calculation of primary responses in rigid pavements: Abaqus and Kenslabs. These programs were used to analyze the rigid pavement structure under various conditions (Table 3.5), and their results are compared to the theoretical solution–stresses calculated from the Westergaard equation (Table 3.6).

Table 3.5 Data for Analyzed Rigid Pavement Structure

	Thickness [inch]	Modulus [psi]	Poisson Ratio
PCC	8, 12	5,000,000	0.15
Subbase	10	30,000	0.40
Subgrade		10,000	0.45

Table 3.6 shows the values of the calculated peak horizontal tensile stress at the bottom of the PCC slab using Abaqus and Kenslabs programs for the edge loading condition. These values are close to the values obtained by the Westergaard equation.

The edge loading condition is chosen for the reason that it produces more severe tensile stresses at the bottom of the slab than would an equivalent load at the center of the slab.

Table 3.6 Evaluation of Horizontal Stress at the Bottom of PCC Slab for Edge Loading Condition

Wheel Load [kip]	**Tire Pressure [psi]**	**Peak Horizontal Tensile Stress at the Bottom of PCC Slab [psi]**		
		ABAQUS	**Westergaard**	**KENSLABS**
8 Inch Thick PCC Slab				
10	**80**	330.00	327.10	321.94
	120	342.60	355.40	362.62
20	**80**	542.00	543.10	522.14
	120	603.00	610.30	591.57
12 Inch Thick PCC Slab				
10	**80**	172.90	158.30	181.82
	120	174.70	167.40	200.60
20	**80**	298.60	277.50	306.20
	120	321.60	301.70	339.13

Generally, stresses calculated using Abaqus and Kenslabs are slightly lower than those obtained using the Westergaard equation for the rigid pavements with 8-inch thick PCC slabs. However, stresses calculated using Abaqus and Kenslabs are slightly higher than those obtained using the Westergaard equation for the rigid pavement structure with 12-inch thick PCC slabs. However, these differences are generally in the range of ± 10% or less.

Ultimately, Kenslabs was selected for the calculation of the primary responses in rigid pavements for the following reasons:

- It provides results similar to Abaqus program and the Westergaard equation.
- It has an option for modeling joints.
- It requires less time for data input and modeling of the rigid pavement structure.

3.2.4 Calculation of Horizontal Tensile Stress at the Bottom of the PCC Slab for the AASHO Road Test Data Using Kenslabs

The preparation of input data for the actual operation of the Kenslabs program consisted of two steps:

1. Modeling of Rigid Pavement Structure Using Kenslabs.

Figure 3.7 shows the analysis configuration of a rigid pavement section from the AASHO Road Test. Each trafficked loop consisted of two 12-foot wide lanes connected by a longitudinal joint. Smaller finite elements were used for the area near the applied loads so the team could obtain more accurate results of calculated stresses.

The mean distance from the pavement edge to the outermost edge of the dual tires for the AASHO Road Test rigid pavement sections ranged from 1.32 to 2.27 feet [HRB 61C]. Therefore, in the computer model, the center of the outermost tire was placed 2 feet from the edge of the slab, which is about 1.7 feet from the pavement edge to the outer edge of the dual tires. Figure 3.7 illustrates an example of a single axle with dual tires.

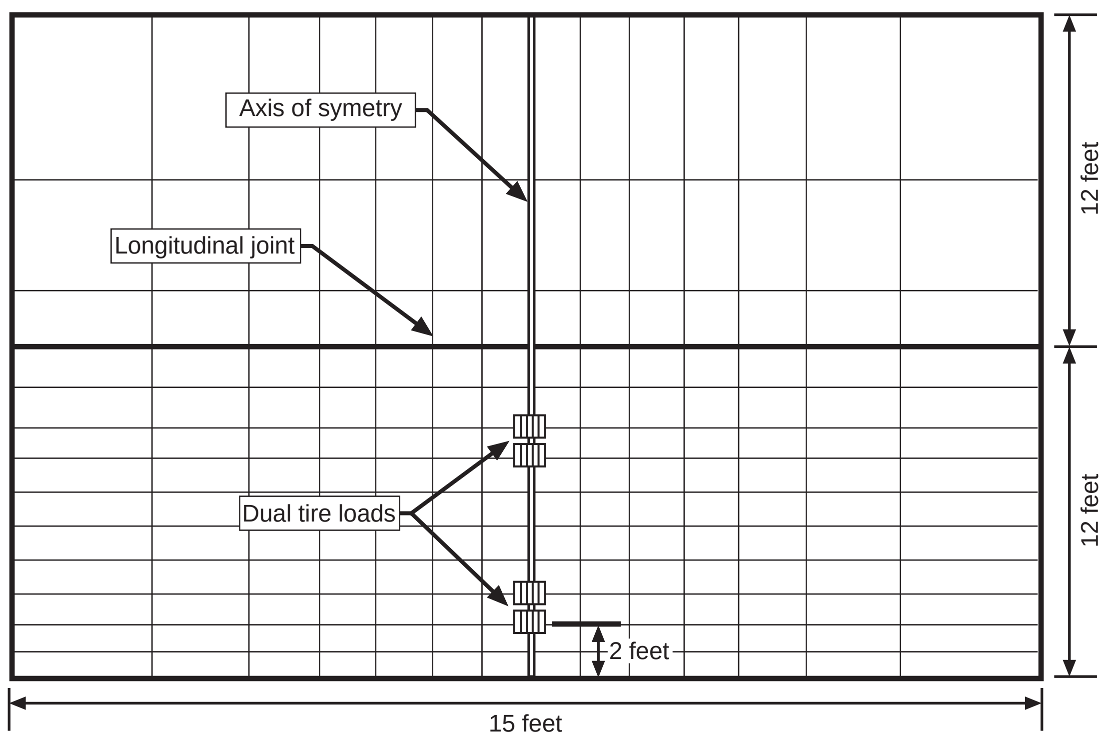

Figure 3.7 Computer Model of Rigid Pavement Structure for Kenslabs

2. Calculation of Contact Area.

In calculating the tire contact area, it is assumed that the contact pressure is equal to the tire pressure and uniformly distributed. Therefore, the contact area A_c is estimated by dividing the load on the tire by the tire pressure. Figure 3.8a shows the approximate shape of the contact area for a tire. The value of L is calculated according to the formula:

$$L = \sqrt{\frac{A_c}{0.5227}} \quad \text{(Eq 3.4)}$$

Where A_c is the total area of contact.

The actual area shown in Figure 3.8a is approximated by the equivalent area shown in Figure 3.8b.

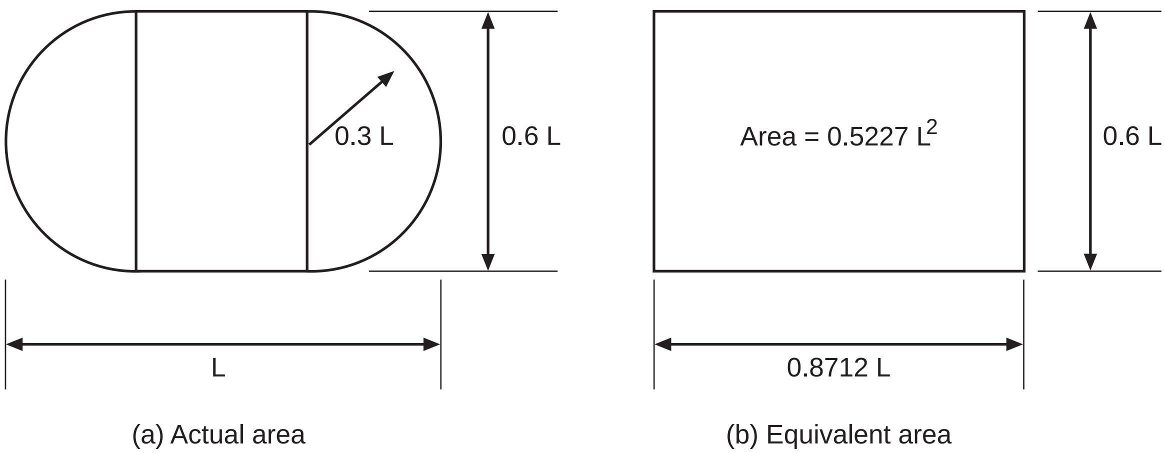

Figure 3.8 Dimension of Tire Contact Area [Huang 1993]

The structural analyses of selected AASHO Road Test pavement sections with PSI ≤ 2.5 were conducted using the configurations described in the previous sections. Figure 3.9 shows that there is a reasonable linear relationship between the number of load applications (in log scale) when PSI reached 2.5 and horizontal tensile peak stress generated at the bottom of the PCC slab by the applied loads.

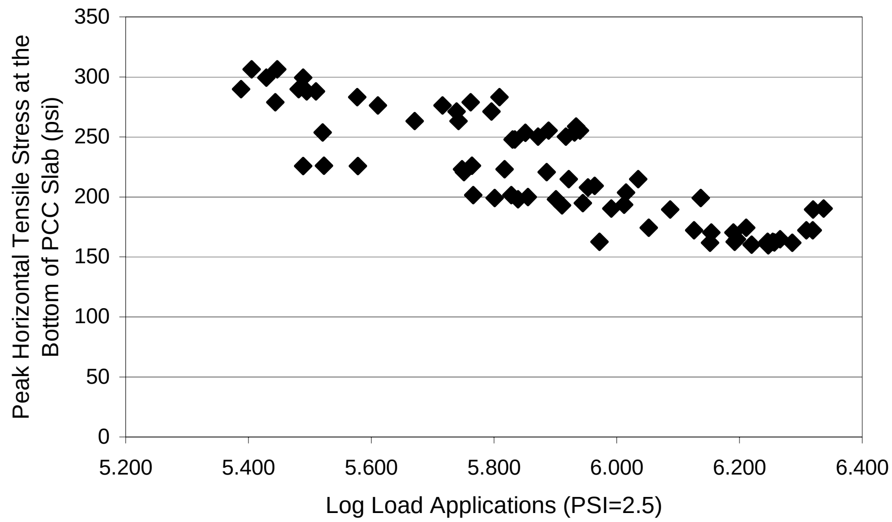

Figure 3.9 Horizontal Tensile Stress at the Bottom of PCC Slab for the AASHO Road Test Data

3.2.5 General Form of the Candidate Models for Rigid Pavements

The following general form of the Performance-Based Fatigue Model for rigid pavements was proposed:

$$\text{Log } N_{PSI=2.5} = f(PCC, \log PCC, L, \log L, \varepsilon_t, \log \varepsilon_t) \quad \text{(Eq 3.5)}$$

where:

$N_{PSI=2.5}$ = number of peak stress applications applied to the rigid pavement structure causing the pavement structure to reach PSI = 2.5;

ε_t = tensile stress at the bottom of PCC slab;

PCC = thickness of PCC slab; and

L = wheel load.

More specifically, the form of the model can be expressed as:

$$\text{Log } N_{PSI=2.5} = a + b_1{*}PCC + b_2{*}\log(PCC) + c_1{*}L + c_2{*}\log(L) + d_1{*}\,\varepsilon_t + d_2 \log(\varepsilon_t) \quad \text{(Eq 3.6)}$$

The exact form of the model will depend on the regression analysis, which gives the best regression coefficients. In searching for the best model, the general form in Equation

3.6 was intended to test both a linear and a logarithmic form for each independent variable. However, the final model contains only one form for each independent variable that gives the best equation. For example, if PCC contributes significantly to the model, the final model could contain either b_1*PCC or b_2*log(PCC), whichever best fits the model.

3.2.6 Criteria for the Selection of the PBFM for Rigid Pavements

The criteria for the selection of the PBFM for rigid pavements are the same as the criteria used for flexible pavements in Section 3.1.6.

3.2.7 Generation of Candidate Models Using the SAS Program

Several possible models were generated using the SAS software [SAS 90]. For each generated model, the R^2 and C_p statistics were analyzed.

3.2.8 Final Selection of the PBFM Based on Established Criteria

From the large group of generated models, only models with R^2 larger than 0.70 were considered. The models that had more than one form of the same independent variable were eliminated. For example, models that included both PCC and log(PCC) were eliminated. For the remaining set of models, the research team ran the regression analysis to obtain regression coefficients. Models with the incorrect coefficient sign were eliminated. For example, coefficients for PCC thickness should be positive, since a stronger pavement should carry more peak stress applications before reaching a PSI level of 2.5. Table 3.7 shows the models that remained at this stage.

Table 3.7 Candidate Models for the Final Selection of the PBFM

Model No.	Model	C_p	R^2
1	$11.062 + 0.02826*PCC - 2.2834*\log(\sigma_t)$	5.36	0.756
2	$10.978 + 0.34018*\log(PCC) - 2.2848*\log(\sigma_t)$	5.58	0.755
3	$6.7221 + 0.02721*PCC - 0.00446*\sigma_t$	7.91	0.748
4	$6.6349 + 0.33111*\log(PCC) - 0.00446*\sigma_t$	7.91	0.748
5	$6.5160 + 0.73969*\log(PCC) - 0.3307*\log(L) - 0.00393*\sigma_t$	9.71	0.748
6	$11.861 - 2.5551*\log(\sigma_t)$	11.94	0.727
7	$6.9961 - 0.00499*\sigma_t$	13.75	0.721
8	$5.6100 + 3.4905*\log(PCC) - 2.5134*\log(L)$	17.22	0.716

Tables 3.8 and 3.9 present the LEFs calculated by using the eight selected models for two rigid pavement structures with an 8-inch and 12-inch PCC slab, respectively. Overall, for all the models under analysis, the differences between LEFs obtained from the established models and those obtained from the AASHTO LEFs are significant.

For example, the AASHTO LEF for an axle load of 24 kips and a pavement with an 8-inch thick PCC slab is 3.22, compared to the LEF of 1.82 obtained from model 1. This observation is similar to that in a research report by Irick [Irick 91].

Based on all criteria, model 1 was considered to be the best choice because it has the highest R^2 and the lowest C_p value. To make the final selection, the F-test was conducted to see if adding variables to the simplest models has statistical significance. The F-test was conducted according to Equation 3.7.

$$F = \frac{\left(R_a^2 - R_b^2\right)/1}{\left(1 - R_a^2\right)/df_a} \quad \text{(Eq 3.7)}$$

where:

R_a^2 = R^2 for model a (with extra variable not included in model b);

R_b^2 = R^2 for a simpler model b; and

df_a = degree of freedom for model a.

Table 3.8 Comparison of the AASHTO LEFs and the Calculated LEFs from Generated Models for Rigid Pavement Structure with an 8-Inch Thick PCC Slab

Model	**Axle Load [kip]**	**LEF (PCC thickness 8 inches)**		
		Model LEF (AASHO Cond.)	**AASHTO LEF**	**Difference**
1	18	1.00	1.00	0.00%
	24	1.82	3.22	-43.49%
	30	2.92	7.79	-62.47%
2	18	1.00	1.00	0.00%
	24	1.82	3.22	-43.47%
	30	2.93	7.79	-62.44%
3	18	1.00	1.00	0.00%
	24	1.64	3.22	-49.20%
	30	2.68	7.79	-65.64%
4	18	1.00	1.00	0.00%
	24	1.64	3.22	-49.20%
	30	2.68	7.79	-65.64%
5	18	1.00	1.00	0.00%
	24	1.70	3.22	-47.31%
	30	2.82	7.79	-63.81%
6	18	1.00	1.00	0.00%
	24	1.95	3.22	-39.32%
	30	3.32	7.79	-57.35%
7	18	1.00	1.00	0.00%
	24	1.73	3.22	-46.15%
	30	3.01	7.79	-61.37%
8	18	1.00	1.00	0.00%
	24	2.06	3.22	-36.00%
	30	3.61	7.79	-53.65%

Table 3.9 Comparison of the AASHTO LEFs and the Calculated LEFs from Generated Models for Rigid Pavement Structure with a 12-Inch Thick PCC Slab

Model	Axle Load [kip]	LEF (PCC thickness 12 inches)		
		Model LEF (AASHO Cond.)	AASHTO LEF	Difference
1	18	1.00	1.00	0.00%
	24	1.85	3.53	-47.65%
	30	3.00	9.35	-67.94%
2	18	1.00	1.00	0.00%
	24	1.85	3.53	-47.63%
	30	3.00	9.35	-67.92%
3	18	1.00	1.00	0.00%
	24	1.37	3.53	-61.13%
	30	1.88	9.35	-79.86%
4	18	1.00	1.00	0.00%
	24	1.37	3.53	-61.13%
	30	1.88	9.35	-79.86%
5	18	1.00	1.00	0.00%
	24	1.45	3.53	-58.83%
	30	2.07	9.35	-77.88%
6	18	1.00	1.00	0.00%
	24	1.99	3.53	-43.68%
	30	3.42	9.35	-63.47%
7	18	1.00	1.00	0.00%
	24	1.42	3.53	-59.64%
	30	2.03	9.35	-78.28%
8	18	1.00	1.00	0.00%
	24	2.06	3.53	-41.62%
	30	3.61	9.35	-61.38%

Table 3.10 The F-Test Results for the Selected Models

Models	**R square**	**$F_{1, 71}$**	**$Fcr_{1, 71}$**
Model 1	0.7567	7.51	4.00
Model 6	0.7279		
Model 3	0.7482	6.74	4.00
Model 7	0.7218		

The F-test in Table 3.10 indicates that adding an additional variable to model 6 or model 7 is statistically significant, but not too significant. Finally, model 1 (Eq. 3.8) was selected as the PBFM for the evaluation of changing traffic characteristics for rigid pavements because it had the highest R^2 value and the lowest C_p value:

$$\log N_{PSI=2.5} = 11.062 - 0.02826 * PCC - 2.2834 * \log(\sigma_t)$$

$$(R^2 = 0.76) \qquad \text{(Eq 3.8)}$$

where:

$N_{PSI=2.5}$	=	number of peak stress applications that a rigid pavement structure sustained until the PSI reached 2.5;
$\log(\sigma_t)$	=	log tensile stress (in psi) at the bottom of the PCC slab; and
PCC	=	thickness of the PCC slab in inches.

4. Evaluation of the Changing Traffic Characteristics — Synthesis of the Results

The performance-based fatigue models (PBFMs) developed for flexible and rigid pavements can now be used to evaluate the impact of various traffic characteristics on the LEFs. For example, an increase in tire pressure may affect the peak horizontal tensile strain at the bottom of the AC surface layer in flexible pavements and may also affect the peak tensile stress at the bottom of the PCC slab in rigid pavements. Moreover, such changes in the strain or stress will affect the performance of the pavement structure because the strain is included in the PBFM for flexible pavements and the stress is included in the PBFM for rigid pavements. Therefore, the PBFM should reasonably reflect the impact that the changes in the loading condition have on the performance of the analyzed pavement section. Having the estimated performance (number of load applications) of a pavement section for two different loading conditions, it is possible to calculate the LEFs, as was done for the AASHO LEFs.

4.1 Evaluation of LEFs for Flexible Pavements

The impact imposed on LEFs by changing traffic characteristics for flexible pavements is evaluated using Equation 4.1 for the selected pavement structures with layer characteristics shown in Figure 4.1.

$$\log N_{PSI=2.5} = 6.2697 + 5.5687 \cdot \log(SN + 1) - 0.12109 \cdot L - 1.3158 \cdot \log(\varepsilon_t) \qquad \text{(Eq 4.1)}$$

where:

$N_{PSI=2.5}$	=	number of peak strains applications to flexible pavement structure causing the pavement structure to reach PSI=2.5;
SN	=	structural number;
L	=	dual wheel load [kip]; and
ε_t	=	peak horizontal tensile strain (microstrain) at the bottom of the AC surface layer.

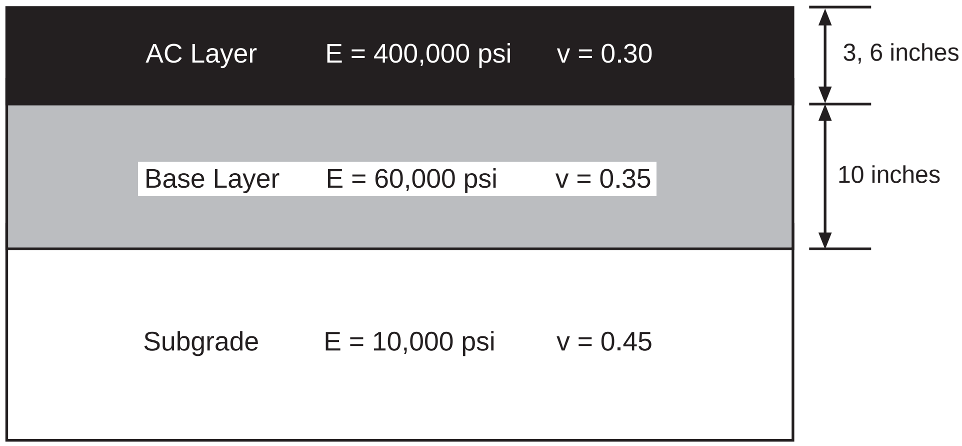

Figure 4.1 Typical Flexible Pavement Section

4.1.1 Evaluation of the Impact of Increased Tire Pressure and Supersingles on LEFs

To evaluate the impact of changing traffic load characteristics on the LEFs, the performance of a pavement section trafficked with an axle load in a new loading condition must be compared with the performance of an identical pavement section trafficked by an axle load representing a loading condition present at the AASHO Road Test. The AASHO loading conditions were single and tandem axle loads on dual tires; the tire pressures are presented in Table 4.1.

Table 4.1 Tire Pressure for Different Load Conditions

Axle Load [kip]	Tire Pressure [psi]		
	Dual Tires AASHO Condition	**Dual Tires Increased Tire Pressure**	**Supersingles**
18	75	120	115
24	75	120	120
30	80	125	125

The levels of increased tire pressure for dual tires were selected based on the recommendation of the Tire and Rim Association. The supersingle tire uses axle loads on single tires with the tire pressures recommended by the Tire and Rim Association [GoodYear 97]. Table 4.1 shows that the manufacturer's recommended tire pressure depends on wheel load. For example, the supersingle 385/65R22.5, loaded with a 9-kip wheel load (18-kip axle load), should have a recommended tire inflation pressure of 115 psi. The values of tire pressure for loads that were not provided in the tables were extrapolated.

The evaluation of increased tire pressure and supersingles for flexible pavements proceeded in four steps:

1. Calculate the peak horizontal tensile strain at the bottom of the AC surface layer in the flexible pavement section loaded with specific loads on dual tires with the AASHO Road Test pressure.

2. Calculate the peak horizontal tensile strain at the bottom of the AC surface layer in an identical flexible pavement section with load magnitudes identical to the AASHO Road Test, but with two loading conditions: (1) loads on dual tires with increased tire pressures, and (2) on supersingles.

Table 4.2 Peak Horizontal Tensile Strains at the Bottom of AC Surface Layer

Axle Load [kip]	**Horizontal Tensile Strain at the Bottom of AC Surface Layer [inch/inch]**			**Percent Change**	
	Dual Tires AASHO Condition	**Dual Tires Increased Tire Pressure**	**Supersingles**	**Dual Tires Increased Tire Pressure**	**Supersingles**
3-Inch Thick AC Surface Layer					
18	1.901E-04	2.620E-04	2.837E-04	37.8%	49.2%
24	2.058E-04	2.889E-04	3.010E-04	40.4%	46.3%
30	2.330E-04	3.168E-04	3.131E-04	36.0%	34.4%
6-Inch Thick AC Surface Layer					
18	1.421E-04	1.598E-04	2.000E-04	12.5%	40.8%
24	1.749E-04	1.989E-04	2.373E-04	13.7%	35.7%
30	2.100E-04	2.369E-04	2.695E-04	12.8%	28.3%

Table 4.2 presents calculations for all three conditions. The horizontal tensile peak strain at the bottom of the AC surface layer was calculated for the analyzed loading conditions with loads of 18, 24, and 30 kip. For the pavement structure with a 3-inch thick AC surface layer, increased tire pressure caused an increase of 35-40 percent in strain over the AASHO condition. Replacing dual tires with supersingles caused an increase of 34-49 percent in strain. For the 6-inch thick AC surface layer, increased tire pressure caused an increase of 12-13 percent in strain. This change was about 3 times less than the change for the 3-inch thick AC surface layer. Replacing dual tires with supersingles caused an increase of 28-40 percent in strain.

3. Estimate flexible pavement section performance based on the PBFM.

The log peak strain applications for the analyzed load conditions were estimated using the PBFM. Then the number of peak strain applications and the load equivalency factors for selected loads were calculated.

4. Calculate relative damage by using the estimated serviceability life for the two analyzed loading conditions.

Table 4.3 presents the results of calculations according to Steps 3 and 4 for the structures with 3-inch and 6-inch thick AC surface layers. This table shows that LEFs for dual tires with increased tire pressure and for supersingles differ from the LEFs with the AASHO Road Test condition.

According to the results in Table 4.4, the impact of increased tire pressure varies with AC thickness. For a 3-inch AC surface layer, the dual tires with increased tire pressure were 50-56 percent more damaging than dual tires used during the AASHO Road Test for the identical loads.

Table 4.3 Analysis Results for Flexible Pavements

AC Thickness [inch]	Axle Load [kip]	Dual Tires AASHO Condition	Dual Tires Increased Tire Pressure	Supersingles
Log Load Applications				
3	**18**	5.358	5.175	5.130
	24	4.950	4.756	4.732
	30	4.515	4.340	4.347
6	**18**	6.259	6.192	6.064
	24	5.777	5.704	5.603
	30	5.309	5.240	5.167
Axle Load Applications (in thousands)				
3	**18**	228	150	135
	24	89	57	54
	30	33	22	22
6	**18**	1,816	1,556	1,158
	24	599	505	401
	30	204	174	147
LEF				
3	**18**	1.00	1.53	1.69
	24	2.56	4.00	4.23
	30	6.96	10.43	10.27
6	**18**	1.00	1.17	1.57
	24	3.03	3.59	4.53
	30	8.91	10.44	12.37

Table 4.4 Impact of Increased Tire Pressure and Supersingles on LEFs

AC Thickness [inch]	Axle Load [kip]	Increase in LEF for Identical Loads Due to:	
		Dual Tires Increased Tire Pressure	**Supersingles**
3	**18**	1.53	1.69
	24	1.56	1.65
	30	1.50	1.48
6	**18**	1.17	1.57
	24	1.18	1.49
	30	1.17	1.39

For the 6-inch thick AC surface layer, the dual tires with increased tire pressure were 17-18 percent more damaging than the dual tires used during the AASHO Road Test. Table 4.4 also shows that supersingles were 48-69 percent more damaging than the low-pressure dual tires used during the AASHO Road Test with identical loads for the 3-inch thick AC surface, and were 39-57 percent more damaging to the 6-inch thick AC surface layer.

The results show that the impact of increased tire pressure decreases as the thickness of the AC surface increases. On the other hand, the thickness of the AC surface layer has insignificant impact on the damaging effects of supersingles.

4.1.2 LEFs for Tandem and Tridem Axle Group Loads

As another verification process, the performance based fatigue model can also be used to evaluate LEFs for tandems and tridems. Table 4.5 shows the calculated peak horizontal tensile strains at the bottom of the AC surface layer for various axle loads using the ELSYM-5 program. Because the peak horizontal tensile strain for tridem axles under the middle axle line is lower than that under the other two loads, average peak strain is calculated from the three peak strains under the three loads.

Tables 4.5 and 4.6 show strains for tandem and tridem axle loads on AC surface layers that are 3 and 6 inches thick, respectively. The tables also show the percentage difference of strains between each loading condition and the standard 18-kip single axle load.

The calculated strains were then used in the PBFM to estimate the number of log peak strain applications that would yield a PSI level of 2.5. For single axles, the number of the axle applications equals the number of the peak strain applications. For tandem axles, there are two peak strain applications per tandem axle; therefore, the number of peak strain applications is divided by 2 to obtain the number of tandem axle applications. For tridem axles, there are three peak strain applications per tridem axle, where the difference in strain levels generated by the outside axles of a tridem set and the middle axle is generally less than 10 percent. Therefore, the number of peak strain applications is divided by 3 to obtain the number of tridem axle applications.

Tables 4.7 and 4.8 show the LEFs resulting from the PBFM analysis of the 3- and 6-inch AC surface layers, respectively.

Table 4.5 Peak Horizontal Tensile Strains at the Bottom of the 3-Inch Thick AC Surface Layer for Various Axle Group Loads

	Single Axle	**Tandem Axle Group**		
Axle Load [kip]	**18**	**27**	**28**	**33**
ε_t	1.9010E-04	1.7500E-04	1.7720E-04	1.8630E-04
Percentage change in peak strain relative to single axle peak strain		-7.9%	-6.8%	-2.0%
		Tridem Axle Group		
Axle Load [kip]		**34**	**35**	**48**
ε_t		1.6523E-04	1.6670E-04	1.8553E-04
Percentage change in peak strain relative to single axle peak strain		-13.1%	-12.3%	-2.4%

Table 4.6 Peak Horizontal Tensile Strains at the Bottom of the 6-Inch Thick AC Surface Layer for Various Axle Group Loads

	Single Axle	**Tandem Axle Group**		
Axle Load [kip]	**18**	**29**	**30**	**33**
ε_t	1.4210E-04	1.1640E-04	1.1940E-04	1.2800E-04
Percentage change in peak strain relative to single axle peak strain		-18.1%	-16.0%	-9.9%
		Tridem Axle Group		
Axle Load [kip]		**38**	**39**	**48**
ε_t		1.0350E-04	1.0547E-04	1.2297E-04
Percentage change in peak strain relative to single axle peak strain		-27.2%	-25.8%	-13.5%

Table 4.7 LEFs for Various Axle Group Loads and the 3-Inch Thick AC Surface Layer

	Single Axle	**Tandem Axle Group**		
Axle Load [kip]	**18**	**27**	**28**	**33**
Log Peak Stress Appl.	5.358	5.678	5.641	5.461
Peak Stress Appl.	228,206	476,515	437,185	288,858
Axle Applications	228,206	238,258	218,592	144,429
LEF	**1.00**	**0.96**	**1.04**	**1.58**
		Tridem Axle Group		
Axle Load [kip]		**34**	**35**	**48**
Log Peak Stress Appl.		5.842	5.817	5.493
Peak Stress Appl.		695,145	655,909	311,396
Axle Applications		231,715	218,636	103,799
LEF		**0.98**	**1.04**	**2.20**

Table 4.8 LEFs for Various Axle Group Loads and the 6-Inch Thick AC Surface Layer

	Single Axle	**Tandem Axle Group**		
Axle Load [kip]	**18**	**29**	**30**	**33**
Log Peak Stress Appl.	6.259	6.585	6.540	6.410
Peak Stress Appl.	1,815,795	3,845,722	3,468,677	2,568,036
Axle Applications	1,815,795	1,922,861	1,734,338	1,284,018
LEF	**1.00**	**0.94**	**1.05**	**1.41**
		Tridem Axle Group		
Axle Load [kip]		**38**	**39**	**48**
Log Peak Stress Appl.		6.763	6.732	6.463
Peak Stress Appl.		5,795,623	5,397,117	2,902,675
Axle Applications		1,931,874	1,799,039	967,558
LEF		**0.94**	**1.01**	**1.88**

Tables 4.7 and 4.8 show that the damaging effects of tandem and tridem axles decrease with an increase in the AC surface thickness. Table 4.9 summarizes the 18-kip equivalent axle loads of tandem and tridem axles for flexible pavements, based on the PBFM.

Table 4.9 18-Kip Equivalent Axle Loads of Tandem and Tridem Axle Groups for Flexible Pavements

AC Thickness [inch]	**Tandem Axle Group [kip]**		**Tridem Axle Group [kip]**	
	PBFM	**AASHTO**	**PBFM**	**AASHTO**
3	27.5	33	34.5	48
6	29.5	33	39	48

4.1.3 Evaluation of the Impact of Environmental Factors on LEFs

Pavement performance can vary under different environmental conditions. Temperature and moisture may affect the values of pavement layer moduli. Changes in layer moduli affect the values of primary response and may change the performance of the pavement structure. To evaluate changes in the environmental conditions, the LEFs for the same loads were calculated in different environmental conditions. A set of pavement layer moduli for flexible pavements was obtained from a report by Irick [Irick 91]. Table 4.10 shows values of layer moduli for flexible pavement sections at the AASHO Road Test for various seasons. The impact of environmental factors on LEFs was evaluated by comparing the calculated LEFs for a particular load for the same pavement structure in different environmental conditions.

Table 4.10 *Estimates of Layer Moduli for the AASHO Road Test Pavement Sections* [Irick 91]

Layers	Estimates of Layer Moduli [ksi]					
	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
AC Layer	710.0	230.0	450.0	1700.0	1700.0	742.5
Base	11.5	15.9	17.1	14.2	50.0	20.4
Subbase	8.9	11.2	12.6	11.7	50.0	17.0
Subgrade	2.9	3.6	4.9	4.2	50.0	10.7

Based on the analysis results presented in Tables 3.3 and 3.4, the difference between the estimated LEFs for a pavement with a 3-inch AC surface layer and those for a pavement with a 6-inch AC surface layer is not significant. Therefore, a typical structure with a 6-inch AC surface layer and a 10-inch base layer was selected for the evaluation of environmental factors. The peak horizontal tensile strain (Table 4.11) at the bottom of the AC surface layer was calculated for various seasons, using the moduli from Table 4.10, and for various loads.

Table 4.11 Peak Horizontal Tensile Strain at the Bottom of the 6-Inch AC Surface Layer for Various Seasons

Single Axle Load	Peak Horizontal Strains at the Bottom of AC Surface Layer					
	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
12 kip	1.473E-04	2.704E-04	1.735E-04	7.152E-05	4.421E-05	1.105E-04
18 kip	2.114E-04	3.752E-04	2.441E-04	1.039E-04	6.159E-05	1.555E-04
20 kip	2.327E-04	4.078E-04	2.665E-04	1.145E-04	6.709E-05	1.698E-04
30 kip	3.368E-04	5.731E-04	3.793E-04	1.664E-04	9.469E-05	2.414E-04

The calculated tensile strain was then applied to the PBFM to estimate the performance of a pavement section under a particular axle load.

Table 4.12 shows that the number of load applications a pavement section can carry to the PSI level of 2.5 greatly depends on the seasonal modulus. For example, one pavement structure under spring conditions can carry 2.7 million single axle applications when it reaches a PSI of 2.5. However, the same pavement structure can carry 12.7 million single axle applications during winter in frozen conditions but only 1.2 million single axle applications during summer before the PSI reaches 2.5. The reduced number of applications this pavement structure can carry in summer is primarily due to a reduced layer modulus for the AC surface layer.

Table 4.12 Strain Applications to PSI = 2.5 for Various Seasons and Axle Loads for Flexible Pavement with the 6-Inch AC Surface Layer

	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
12 kip Axle Load						
Log($N\varepsilon_t$)	6.432	6.093	6.341	6.836	7.104	6.593
$N\varepsilon_t$	2,705,392	1,239,159	2,191,997	6,848,076	12,708,823	3,914,757
18 kip Axle Load						
Log($N\varepsilon_t$)	5.893	5.573	5.813	6.290	6.582	6.065
$N\varepsilon_t$	782,185	374,139	650,156	1,949,185	3,817,532	1,160,791
20 kip Axle Load						
Log($N\varepsilon_t$)	5.727	5.414	5.652	6.123	6.422	5.903
$N\varepsilon_t$	533,712	259,483	448,325	1,328,035	2,640,102	800,258
30 kip Axle Load						
Log($N\varepsilon_t$)	4.959	4.662	4.892	5.352	5.667	5.145
$N\varepsilon_t$	90,958	45,929	78,073	225,147	464,734	139,560

Table 4.13 shows the calculated LEFs based on results from Table 4.12. Although the number of applications the example pavement structure can carry before the PSI reaches 2.5 varies greatly, as seen in Table 4.12, the LEFs for all analyzed loads remain almost constant for all seasons, according to the results summarized in Table 4.13. Therefore, it can be concluded that although the environmental factors impact the pavement performance, they do not significantly affect LEFs. The relative effect is constant for a range of loads.

Table 4.13 LEFs for Pavement Section with the 6-Inch Thick AC Surface Layer

	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
$LEF_{12} = (N_{18}/N_{12})$	0.29	0.30	0.30	0.28	0.30	0.30
$LEF_{20} = (N_{18}/N_{20})$	1.47	1.44	1.45	1.47	1.45	1.45
$LEF_{30} = (N_{18}/N_{30})$	8.60	8.15	8.33	8.66	8.21	8.32

4.2 Evaluation of LEFs for Rigid Pavements

The methodology for evaluating the impact of changing traffic characteristics on the LEFs for rigid pavements is similar to the methodology for flexible pavements. Equation 4.2 was used to evaluate the performance of rigid pavements for selected pavement structures with the layer characteristics shown in Figure 4.2.

$$\log N_{PSI=2.5} = 11.062 - 0.02826*PCC - 2.2834*\log(\sigma_t)$$

$$(R^2 = 0.76) \qquad \text{(Eq 4.2)}$$

where:

$N_{PSI=2.5}$ = number of peak horizontal tensile peak stress applications to rigid pavement structure causing the pavement structure to reach PSI of 2.5;

$\log(\varepsilon_t)$ = log peak horizontal tensile stress [psi] at the bottom of PCC slab; and

PCC = thickness of PCC slab [inch].

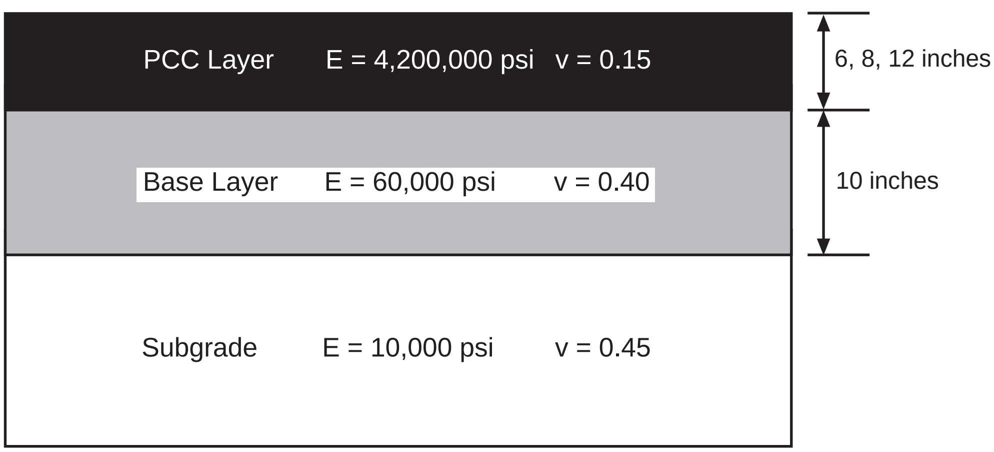

Figure 4.2 Typical Rigid Pavement Section

4.2.1 Impact of Increased Tire Pressure and Supersingles on LEFs

Table 4.14 presents the AASHO Road Test tire pressures, the increased tire pressures, and the supersingles tire pressures. At the AASHO Road Test, truck axle loads were applied on dual tires having tire pressures of 75 and 80 psi. The selection of the increased tire pressure and supersingles conditions is discussed in Section 4.1.1.

Table 4.14 Tire Pressure for Changing Traffic Characteristics

Axle Load [kip]	Tire Pressure [psi]		
	Dual Tires AASHO Condition	Dual Tires Increased Tire Pressure	Supersingles
18	75	120	115
24	75	120	120
30	80	125	125

The evaluation of increased tire pressure and supersingles for rigid pavements proceeded according to a four-step process:

1. Calculate the peak horizontal tensile stress at the bottom of PCC slab in rigid pavement section loaded with specific loads on dual tires with the AASHO Road Test pressure;
2. Calculate the peak horizontal tensile stress at the bottom of the PCC slab in an identical rigid pavement section with load magnitudes identical to those in Step 1 for two loading conditions — loads on dual tires with increased tire pressures, and loads on supersingles;
3. Estimate the log peak stress applications for the analyzed load conditions using the PBFM. Then calculate the number of peak stress applications and the load equivalency factors for selected loads.
4. Calculate the relative damage using the estimated serviceability life for two analyzed loading conditions.

Table 4.15 presents the calculation results for all three conditions. The peak horizontal tensile stress at the bottom of PCC slab was calculated for the analyzed loading conditions with loads of 18, 24, and 30 kips. For the 6-inch PCC slab, the increased tire pressure caused an increase in stress of 4-5 percent over the AASHO condition. The replacement of dual tires with supersingles caused an increase in stress of 25-28 percent. For the 8-inch PCC slab, the increased tire pressure caused an increase in stress of 4 percent. The replacement of dual tires with supersingles caused an increase in stress of 22-

24 percent. For the 12-inch PCC slab, the increased tire pressure caused an increase in stress of 3 percent. The use of supersingles caused an increase in stress of 17-19 percent.

The effect of increased tire pressure and supersingles on tensile stress at the bottom of the PCC slab decreases with an increase in the thickness of the PCC slab. Additionally, for heavier loads, the effect of increased tire pressure on tensile stress at the bottom of the PCC slab increases, while the effect of supersingles on tensile stress at the bottom of the PCC slab decreases.

Table 4.15 Effect of Changing Traffic Characteristics on Tensile Peak Stress at the Bottom of the PCC Slab

Axle Load [kip]	Horizontal Tensile Stress at the Bottom of the PCC Slab [psi]			Percent Change	
	Dual Tires AASHO Condition	Dual Tires Increased Tire Pressure	Supersingles	Dual Tires Increased Tire Pressure	Supersingles
6-Inch Thick PCC Slab					
18	222.87	232.18	286.22	4.2%	28.4%
24	288.11	302.26	366.49	4.9%	27.2%
30	353.39	371.46	442.93	5.1%	25.3%
8-Inch Thick PCC Slab					
18	159.85	165.37	198.64	3.5%	24.3%
24	207.76	216.15	256.00	4.0%	23.2%
30	255.73	266.42	311.13	4.2%	21.7%
12-Inch Thick PCC Slab					
18	99.85	102.42	119.14	2.6%	19.3%
24	130.66	134.55	154.79	3.0%	18.5%
30	161.49	166.45	189.44	3.1%	17.3%

Table 4.16 shows the predicted load applications in Steps 3 and 4 and the LEFs for pavements with 6-, 8-, and 12-inch thick PCC slab, respectively. Table 4.16 shows that when the PCC slab thickness increases in the range from 6 to 12 inches, the number of axle load applications that a pavement structure carries until it reaches a PSI level of 2.5 increases significantly. When an axle load increases, the number of applications that a pavement structure carries decreases. Table 4.16 shows that the LEFs for dual tires with

increased tire pressure and supersingles differ from the LEFs for dual tires in the AASHO Road Test condition.

Table 4.16 Analysis Results for Increased Tire Pressure and Supersingles for Rigid Pavement

PCC Thickness [inch]	Axle Load [kip]	Dual Tires AASHO Condition	Dual Tires Increased Tire Pressure	Supersingles
Log Load Applications				
6	**18**	5.870	5.830	5.652
	24	5.616	5.568	5.407
	30	5.413	5.364	5.220
8	**18**	6.256	6.223	6.072
	24	5.996	5.957	5.821
	30	5.790	5.750	5.628
12	**18**	6.836	6.811	6.701
	24	6.569	6.540	6.442
	30	6.359	6.329	6.242

PCC Thickness [inch]	Axle Load [kip]	Dual Tires AASHO Condition	Dual Tires Increased Tire Pressure	Supersingles
Axle Load Applications (in thousands)				
6	**18**	742	675	448
	24	413	370	255
	30	259	231	166

(Table 4.16 continued on next page)

Table 4.16 (cont.) Analysis Results for Increased Tire Pressure and Supersingles for Rigid Pavement

PCC Thickness [inch]	Axle Load [kip]	Dual Tires AASHO Condition	Dual Tires Increased Tire Pressure	Supersingles
Axle Load Applications (in thousands)				
8	**18**	1,804	1,670	1,180
	24	992	906	662
	30	617	562	425
12	**18**	6,855	6,469	5,018
	24	3,710	3,470	2,766
	30	2,287	2,134	1,747
LEF				
6	**18**	1.00	1.10	1.65
	24	1.80	2.01	2.91
	30	2.87	3.21	4.47
8	**18**	1.00	1.08	1.53
	24	1.82	1.99	2.72
	30	2.92	3.21	4.25
12	**18**	1.00	1.06	1.37
	24	1.85	1.98	2.48
	30	3.00	3.21	3.92

Table 4.17 Impact of Increased Tire Pressure and Supersingles on LEFs

PCC Thickness [inch]	Axle Load [kip]	LEF for Identical Loads Using AASHO Loading Condition as the Basis	
		Dual Tires Increased Tire Pressure	Supersingles
6	**18**	1.10	1.65
	24	1.12	1.62
	30	1.12	1.56
8	**18**	1.08	1.53
	24	1.09	1.50
	30	1.10	1.45
12	**18**	1.06	1.37
	24	1.07	1.34
	30	1.07	1.31

Table 4.17 shows how increased tire pressure and supersingles affect the LEFs for rigid pavements. For the 6-inch thick PCC slab, dual tires with the increased tire pressure are 10-12 percent more damaging than the AASHO dual tires, and that the supersingles are 56-65 percent more damaging than the AASHO dual tires. With the increase in PCC slab thickness, the damaging effects of increased tires pressure in duals and supersingles on the LEFs decreases. For the 12-inch PCC slab, dual tires with the increased tire pressure are 6-7 percent more damaging than the AASHO dual tires, and the supersingles are 31-37 percent more damaging than the AASHO dual tires. Table 4.17 also shows that for heavier loads the effect of increased tire pressure on LEFs increases and the effect of supersingles on LEFs decreases.

4.2.2 LEFs for Tandem and Tridem Axles

As another step to show the validity of the developed models, LEFs for tandem and tridem axles for rigid pavements were evaluated in a fashion similar to that for LEFs for tandem and tridem for flexible pavements. Equation 4.2, representing the PBFM for rigid pavements, was used to predict the number of peak horizontal tensile stress applications applied to the pavement structure. Tables 4.18, 4.19, and 4.20 present peak stresses under single, tandem, and tridem axles for a rigid pavement structure with 6, 8, and 12-inch PCC slab, respectively. Table 4.18 shows the horizontal peak tensile stresses from different loading conditions and a 6-inch PCC slab. The table also shows the percent difference in stress between the single- and multi-axle loads. Further testing showed that, for increasing layer thickness, this percent difference decreases, as indicated in Tables 4.19 and 4.20.

Table 4.18 Peak Horizontal Tensile Stresses at the Bottom of the 6-Inch Thick PCC Slab for Single, Tandem, and Tridem Axle Group Loads

	Single Axle	**Tandem Axle Group**	
Axle Load [kip]	**18**	**29**	**30**
σ_t	222.87	162.93	168.02
Percentage change in peak stress relative to single axle peak stress		-26.9%	-24.6%
		Tridem Axle Group	
Axle Load [kip]		**39**	**40**
σ_t		137.19	140.42
Percentage change in peak stress relative to single axle peak stress		-38.4%	-37.0%

Table 4.19 Peak Horizontal Tensile Stresses at the Bottom of the 8-Inch Thick PCC Slab for Single, Tandem, and Tridem Axle Group Loads

	Single Axle	**Tandem Axle Group**	
Axle Load [kip]	**18**	**29**	**30**
σ_t	159.85	117.23	121.09
Percentage change in peak stress relative to single axle peak stress		-26.7%	-24.2%
		Tridem Axle Group	
Axle Load		**39**	**40**
σ_t		98.68	101.18
Percentage change in peak stress relative to single axle peak stress		-38.3%	-36.7%

Table 4.20 Peak Horizontal Tensile Stresses at the Bottom of the 12-Inch Thick PCC Slab for Single, Tandem, and Tridem Axle Group Loads

	Single Axle	**Tandem Axle Group**		
Axle Load [kip]	**18**	**25**	**26**	**29**
σ_t	99.85	72.71	75.51	83.78
Percentage change in peak stress relative to single axle peak stress		-27.2%	-24.4%	-16.1%
		Tridem Axle Group		
Axle Load [kip]		**35**	**36**	**39**
σ_t		60.65	62.15	67.10
Percentage change in peak stress relative to single axle peak stress		-39.3%	-37.8%	-32.8%

Tables 4.21, 4.22, and 4.23 present the LEFs calculated for tandem and tridem axles. The number of axle applications is obtained by dividing the number of peak stress applications by 2 in the case of tandem axles, and by 3 in the case of tridem axles, since a tandem axle applies two and a tridem axle applies three peak stress applications to pavement. For the 29-kip tandem and the 39-kip tridem loads, both the AASHTO Guide and the PBFM calculated the LEF=1.0 for the 6-inch PCC slab. However, as shown in Tables 4.22 and 4.23, tandem and tridem loads can actually be more damaging as slab thickness increases. This is reflected by the axle loads with LEFs greater than 1.0. For example, the 39-kip tridem in Table 4.22 gives an LEF of 1.06, which is higher than the AASHTO LEF of 1.0.

Table 4.21 LEFs for Single, Tandem, and Tridem Axle Groups for the 6-Inch Thick PCC Slab

	Single Axle	Tandem Axle Group	
Axle Load [kip]	**18**	**29**	**30**
Log Peak Stress Appl.	5.870	6.181	6.150
Peak Stress Appl.	741,569	1,516,416	1,413,588
Axle Applications	741,569	758,208	706,794
LEF		0.98	1.05
		Tridem Axle Group	
Axle Load [kip]		**39**	**40**
Log Peak Stress Appl.		6.351	6.328
Peak Stress Appl.		2,245,439	2,129,288
Axle Applications		748,480	709,763
LEF		0.99	1.04

Table 4.22 LEFs for Single, Tandem, and Tridem Axle Groups for the 8-Inch Thick PCC Slab

	Single Axle	Tandem Axle Group	
Axle Load [kip]	**18**	**28**	**29**
Log Peak Stress Appl.	6.256	6.564	6.532
Peak Stress Appl.	1,804,280	3,662,580	3,401,187
Axle Applications	1,804,280	1,831,290	1,700,593
LEF		0.99	1.06
		Tridem Axle Group	
Axle Load [kip]		**38**	**39**
Log Peak Stress Appl.		6.735	6.710
Peak Stress Appl.		5,427,944	5,125,726
Axle Applications		1,809,315	1,708,575
LEF		1.00	1.06

Table 4.23 LEFs for Single, Tandem, and Tridem Axle Groups for the 12-Inch Thick PCC Slab

	Single Axle	Tandem Axle Group		
Axle Load [kip]	**18**	**25**	**26**	**29**
Log Peak Stress Appl.	6.836	7.151	7.113	7.010
Peak Stress Appl.	6,854,515	14,143,405	12,973,873	10,233,092
Axle Applications	6,854,515	7,071,703	6,486,937	5,116,546
LEF		0.97	1.06	1.34
.		**Tridem Axle Group**		
Axle Load [kip]		**35**	**36**	**39**
Log Peak Stress Appl.		7.330	7.306	7.230
Peak Stress Appl.		21,396,681	20,236,848	16,988,842
Axle Applications		7,132,227	6,745,616	5,662,947
LEF		0.96	1.02	1.21

Table 4.24 summarizes the 18-kip equivalent axle loads for tandem and tridem axle for rigid pavements based on the PBFM.

Table 4.24 Tandem and Tridem Axle Group Loads Having LEF = 1 for Rigid Pavements

PCC Thickness [inch]	Tandem Axle Group [kip]		Tridem Axle Group [kip]	
	PBFM	**AASHTO**	**PBFM**	**AASHTO**
6	29	30	39	40
8	28	30	38	40
12	25.5	29	36	39

4.2.3 Impact of Environmental Factors on LEFs

The impact of environmental factors on the LEFs for rigid pavements was evaluated in a fashion similar to that used for flexible pavements. A set of pavement layer moduli for rigid pavements were obtained from a report by Irick [Irick 91], as shown in Table 4.25. Although the PCC modulus is constant, the subbase and subgrade moduli vary significantly and could affect values of calculated primary responses and pavement performance.

Table 4.25 Layer Moduli for Rigid Pavements at the AASHO Road Test [Irick 91]

Slabs	Estimates of Layer Moduli [ksi]					
	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
PCC Slab	4,200.0	4,200.0	4,200.0	4,200.0	4,200.0	4,200.0
Subbase	8.9	11.2	12.6	11.7	50.0	17.0
Subgrade	2.9	3.6	4.9	4.2	50.0	10.7

Horizontal stresses for the analyzed pavement structure and estimated layer moduli were calculated using the Kenslabs program. Table 4.26 shows that the calculated maximum horizontal tensile stress for a particular axle load occurs during the spring season. The minimum value of the calculated horizontal tensile stress for a particular axle load occurs in the winter season (when the soil was frozen).

The developed PBFM was used to estimate pavement performance for the analyzed pavement structure using the calculated peak horizontal tensile stresses in Table 4.26. The results in Table 4.27 indicate that pavement performance is significantly affected by the changes in layer moduli. The pavement structure can carry the least number of applications of a particular axle load in the spring season and the maximum number of axle load applications in the winter season (again, when the soil is frozen).

From Tables 4.26, 4.27, and 4.28, it can be concluded that the environmental conditions do affect horizontal tensile stress at the bottom of the PCC slab and, consequently, do affect rigid pavement performance. However, the LEFs for the rigid pavement structure do not vary significantly. While the weighted annual LEFs increase with layer thickness, the change is relatively small.

Table 4.26 Stresses for the Rigid Pavement Structure for Various Seasons

Axle Load [kip]	Peak Horizontal Tensile Stress at the Bottom of PCC Slab					
	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
6-Inch Thick PCC Slab						
18	320.4	301.8	279.1	290.3	151.8	225.4
24	417.5	392.7	362.6	377.4	194.1	291.3
30	514.7	483.7	446.1	464.6	236.5	357.2
8-Inch Thick PCC Slab						
18	227.8	215.2	198.8	206.9	108.2	159.2
24	298.1	281.3	259.5	270.4	139.3	206.9
30	368.5	347.6	320.3	333.8	170.3	254.6
12-Inch Thick PCC Slab						
18	131.4	126.7	119.6	123.2	65.6	98.7
24	172.7	166.4	156.9	161.7	85.1	129.1
30	214.0	206.2	194.3	200.3	104.6	159.5

Table 4.27 Log Stress Applications for the Environmental Factors

Axle Load [kip]	Log Peak Tensile Stress Applications					
	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
6-Inch Thick PCC Slab						
18	5.510	5.569	5.647	5.608	6.251	5.859
24	5.248	5.308	5.388	5.348	6.007	5.605
30	5.040	5.102	5.182	5.142	5.811	5.402
8-Inch Thick PCC Slab						
18	5.905	5.961	6.040	6.000	6.643	6.260
24	5.638	5.696	5.776	5.735	6.393	6.001
30	5.428	5.486	5.567	5.526	6.193	5.795
12-Inch Thick PCC Slab						
18	6.564	6.600	6.657	6.628	7.253	6.848
24	6.293	6.329	6.388	6.358	6.995	6.581
30	6.080	6.117	6.176	6.146	6.790	6.372

Table 4.28 LEFs for the Environmental Factors

	Load Equivalency Factors					
	Seasons					Weighted Annual Values
	Spring	Summer	Fall	Winter		
				Unfrozen	Frozen	
6-Inch Thick PCC Slab						
$LEF_{24} = (N_{18}/N_{24})$	1.83	1.82	1.82	1.82	1.75	1.80
$LEF_{30} = (N_{18}/N_{30})$	2.95	2.94	2.92	2.93	2.75	2.86
8-Inch Thick PCC Slab						
$LEF_{24} = (N_{18}/N_{24})$	1.85	1.84	1.84	1.84	1.78	1.82
$LEF_{30} = (N_{18}/N_{30})$	3.00	2.99	2.97	2.98	2.82	2.92
12-Inch Thick PCC Slab						
$LEF_{24} = (N_{18}/N_{24})$	1.86	1.86	1.86	1.86	1.81	1.85
$LEF_{30} = (N_{18}/N_{30})$	3.04	3.04	3.03	3.03	2.90	2.99

5. Summary, Conclusions, and Recommendations for Further Research

5.1 Summary

The main objective of this study was to determine whether the LEFs based on axle load, axle configuration, and pavement structure used by the AASHO Road Test change significantly with higher tire pressure, new axle configurations, environmental conditions, and the use of supersingle tires.

The scope of the study covered flexible and rigid pavements. The extension and validation of the AASHTO LEFs include dual tires with increased tire pressure, supersingles, tridem axles, and the environment found in Texas.

A methodology was developed to produce a performance-based fatigue model (PBFM). The PBFM was developed based on the re-analysis of the AASHO Road Test data using mechanistic analysis techniques. The PBFM was then used with the developed methodology to evaluate changing traffic characteristics, including higher tire pressure, new axle configurations, environmental conditions, and the use of supersingle tires.

5.2 Conclusions

The following conclusions can be drawn from this study:

1. While the trend for the next generation of pavement design methods is shifting toward a mechanistic approach, load equivalency factors will continue to be the primary design tools used in Texas and in other states for many years. A better understanding of the impact of changing traffic characteristics and environmental conditions on the LEFs is therefore important for the proper design of pavements.
2. A robust, performance-based pavement fatigue model based on the outputs of mechanistic analysis of pavements and the original AASHO Road Test data can bridge the gap between AASHO Road Test traffic conditions and current (as well as future) conditions.
3. For the same axle load, the damage to flexible pavement increases as tire pressure increases and pavement thickness decreases. An increase of tire

pressure from 75 psi to 120 psi for dual tires at an axle load of 18-30 kips causes about 17–18 % more damage to flexible pavements with a 6-inch thick AC surface and 50–56 % more damage to a 3-inch thick AC surface.

4. Supersingles with high tire pressure cause more damage to flexible pavements than the normal dual tires used in the AASHO Road Test. For flexible pavements with a 6-inch thick AC surface, damage is 39–57 % higher and for a 3-inch thick AC surface layer, damage is 48–69 % higher.
5. For a flexible pavement with a 6-inch thick AC surface layer, a tandem axle of 29.5 kips, or a tridem axle of 39 kips and a tire pressure of 80 psi, is approximately equivalent to a single axle of 18 kips with the same tire pressure. This finding is consistent with the results from most of the studies conducted by other researchers. However, for a flexible pavement with a 3-inch thick AC surface layer, a tandem axle of 27.5 kips, or a tridem axle of 34.5 kips, is approximately equivalent to a single axle of 18 kips. These values are lower than values given in the AASHTO Guide, which specifies equivalence for a tandem axle of 33 kips, or a tridem axle of 48 kips. Table 5.1 summarizes results for tandem and tridem axle loads for flexible pavements.

Table 5.1 Tandem and Tridem Axle Group Loads Having LEF = 1 for Flexible Pavements

AC Thickness	**Tandem Axle Group**		**Tridem Axle Group**	
	PBFM	**AASHTO**	**PBFM**	**AASHTO**
3 inch	27.5 kip	33 kip	34.5 kip	48 kip
6 inch	29.5 kip	33 kip	39 kip	48 kip

6. LEFs for flexible pavements change insignificantly owing to environmental conditions. However, absolute performance can be significantly impacted. The range of values for all seasons and the weighted annual value are summarized in Table 5.2.

Table 5.2 LEFs for Pavement Section with 6-Inch Thick AC Surface Layer

	Range for All Seasons	Weighted Annual Value
$LEF_{12} = (N_{18}/N_{12})$	0.27-0.28	0.28
$LEF_{20} = (N_{18}/N_{20})$	1.47-1.50	1.48
$LEF_{30} = (N_{18}/N_{30})$	9.30-9.90	9.50

7. For the same axle load, the damage to rigid pavement increases as tire pressure increases. An increase of tire pressure from 75 psi to 120 psi for dual tires at an axle load of 18–30 kips causes about 6–12 percent more damage to rigid pavements with a 6–12 inch PCC slab.
8. Supersingles with high tire pressure cause more damage to rigid pavements than the normal dual tires used in the AASHO Road Test. For rigid pavements with a 6-inch PCC slab, damage is 56–65 percent higher; for rigid pavements with a 8-inch PCC slab, damage is 45–53 percent higher; and for rigid pavements with a 12-inch PCC slab, damage is 31–37 percent higher.
9. A tandem axle of 29 kips, or a tridem axle of 39 kips, is approximately equivalent to a single axle of 18 kips for rigid pavements with a 6-inch PCC slab. A tandem axle of 28 kips, or a tridem axle of 38 kips, is approximately equivalent to a single axle of 18 kips for rigid pavements with a 8-inch PCC slab; a tandem axle of 25.5 kips, or a tridem axle of 36 kips, is approximately equivalent to a single axle of 18 kips for rigid pavements with a 12-inch PCC slab. Equivalent axle loads for tandem and tridem axle loads of the AASHTO model are about 1–3.5 kips higher than those for the PBFM model. Table 5.3 summarizes results for tandem and tridem axle loads for rigid pavements.

Table 5.3 Tandem and Tridem Axle Group Loads Having LEF = 1 for Rigid Pavements

PCC Thickness	Tandem Axle Group		Tridem Axle Group	
	PBFM	AASHTO	PBFM	AASHTO
6 inch	29 kip	29 kip	39 kip	39 kip
8 inch	28 kip	29 kip	38 kip	39 kip
12 inch	25.5 kip	29 kip	36 kip	39 kip

10. LEFs for rigid pavements change insignificantly owing to environmental conditions. However, absolute performance can be significantly impacted. The range of values for all seasons and the weighted annual average are summarized in Table 5.4.

Table 5.4 LEFs for Rigid Pavement Section

	Load Equivalency Factors	
	Range for All Seasons	Weighted Annual Values
6-Inch Thick PCC Slab		
$LEF_{24} = (N_{18}/N_{24})$	1.75-1.83	1.80
$LEF_{30} = (N_{18}/N_{30})$	2.75-2.95	2.86
8-Inch Thick PCC Slab		
$LEF_{24} = (N_{18}/N_{24})$	1.78-1.85	1.82
$LEF_{30} = (N_{18}/N_{30})$	2.82-3.00	2.92
12-Inch Thick PCC Slab		
$LEF_{24} = (N_{18}/N_{24})$	1.81-1.86	1.85
$LEF_{30} = (N_{18}/N_{30})$	2.90-3.04	2.99

Overall, the research shows that an increased tire pressure and the use of supersingles increase damage to flexible and rigid pavements. Therefore, pavements designed using the current AASHTO LEFs and trafficked with loads having increased tire pressure or supersingles could possibly fail earlier than expected.

From Table 5.5, which summarizes the results of the impact of traffic characteristics on the LEFs, the following trends can be observed:

- According to the PBFM, the impact of increased tire pressure and supersingles decrease with an increase in the thickness of the surface layer for flexible and rigid pavements.

- The difference between the AASHTO LEFs and the PBFM LEFs decreases with an increase in thickness of the AC surface layer for flexible pavements.
- The difference between the AASHTO LEFs and the PBFM LEFs increase for tandem and tridems axle loads with an increase in PCC thickness, but decrease for increased tire pressure and supersingle axles.

Table 5.5 Summary of Impact of Traffic Characteristics on the LEFs

Traffic Condition	**Flexible Pavement**		**Rigid Pavement**		
	3-inch thick AC	**6-inch thick AC**	**6-inch thick PCC**	**8-inch thick PCC**	**12-inch thick PCC**
Increased tire pressure in dual tires	50-56 %	17-18 %	10-12 %	8-10 %	6-7 %
Supersingles	48-69 %	39-57 %	56-65 %	45-53 %	31-37 %
Tandem	58 %	41 %	5 %	6 %	34 %
Tridems	120 %	88 %	4 %	6 %	21 %

5.3 Recommendations for Further Research

There is a great deal of confidence in the developed PBFM for flexible pavements, since 239 out of 284 flexible pavement sections at the AASHO Road Test reached terminal serviceability. The confidence in the developed PBFM for rigid pavements is not as high as that in the PBFM for flexible pavements since only 73 out of 264 rigid pavement sections reached terminal serviceability. However, a sample of 73 should be reasonably good for the analysis.

An accelerated testing facility would be an excellent source of data for rigid pavement sections trafficked with axle loads under different loading conditions. A factorial experiment could be designed in which tire pressure, supersingles, and number of axles would be factors. The collected data could confirm the developed PBFM for rigid pavements or could be analyzed statistically together with the AASHO Road Test data to develop an improved PBFM for rigid pavements.

It is recommended that LEFs for steering axles with loads bigger than 12 kips be developed, since the damaging effects of the steering axles were not analyzed separately but were incorporated into the LEFs for single and tandem axles.

In addition, since the AASHO Road Test did not include pavements with a thin-surfaced structure (i.e., 6 to 8 inches of flexible base plus a bituminous surface treatment) and yet Texas has a large percentage of such thin-surfaced pavements, it is recommended that additional LEF analysis be conducted for such pavements using experimental sections or the Texas Accelerated Pavement Tester (TxAPT) to collect field data.

6. Recommendations for Implementation of Findings

Increasing tire pressure from 75 psi to 120 psi increases the LEFs by 17–56 percent for a fixed axle load applied to flexible pavements. The change resulting from the increased tire pressure for rigid pavements is only 6–12 percent. The effect of changing from dual tires to supersingles increases the LEF by 31–69 percent, depending on pavement structure.

6.1 Practical Considerations for TxDOT

To implement new LEFs, TxDOT must consider the predicted traffic stream. The "Traffic Analysis for Highway Design" worksheet generated by the Traffic Section of TP&P provides the one-way cumulative ESAL count for flexible and rigid pavements based on a structural number of 3 and slab thickness of 8, respectively. Most designers at the District level may be oblivious to this design consideration. However, there is a bit of the cart-before-the-horse situation in the design process since the cumulative ESALs are needed to determine the pavement thickness, but the proposed thickness may affect the estimated ESALs.

To implement new LEFs, TxDOT would have to determine whether to calculate computer-based LEFs interactively with design or whether to use fixed LEFs (as is the current practice). It is worth noting that current computer technology makes it easy to establish ESALs based on pavement design thickness interactively in the design process.

6.2 Recommendations for First Step Implementation

Work done by Wang et al. [Wang 01] shows that current tire pressures operating over Texas highways range from 66–126 psi. The LEFs resulting from tire pressures of 100 and 120 psi are shown in Table 6.1. It must be kept in mind that, whereas 18-kip single axles had a LEF of 1.0 in the past, a revised LEF of 1.53 is estimated for an 18-kip single axle on dual tires of 120 psi.

Table 6.1 LEFs for 18-Kip Axle Load on Dual Tires with Different Tire Pressures

Tire Pressure [psi]	Flexible Pavement		Rigid Pavement		
	3-inch thick AC	6-inch thick AC	6-inch thick PCC	8-inch thick PCC	12-inch thick PCC
75	1.00	1.00	1.00	1.00	1.00
100	1.26	1.08	1.05	1.04	1.03
120	1.53	1.17	1.1	1.08	1.06

It is possible to calculate ESALs for a spectrum of tire pressure, but this would be too cumbersome, since exact tire pressures are unknown. Because the LEFs for flexible pavements under the increased tire pressure are considerably higher than those for rigid pavements, it is recommended that TxDOT begin calculating two sets of load equivalency factors: one for rigid pavements and one for flexible pavements. This recommendation, if implemented, could create a political problem for the Department in some respects, given the competition between rigid and flexible. Nevertheless, the facts are clear and we recommend this change. If this is unacceptable to TxDOT, then the flexible equivalency factors should be used for design because they are more conservative and because the larger factors will have relatively less effect on rigid pavement design.

It is currently impossible to predict the percentage of supersingles in a traffic stream. However, it would be possible for the Traffic Division of TxDOT to estimate the percentage of supersingles in a traffic stream. This figure is likely to be less than 10 percent. The load equivalency factors for axle loads ranging from 18 kips to 30 kips on supersingle tires are shown in Table 6.2 for flexible and rigid pavements, where the tire pressures are 115 psi, 120 psi, and 125 psi for axle groups of 18 kips, 24, kips, and 30 kips, respectively.

Table 6.2 LEFs for Single Axle Load on Supersingle Tires

Axle Load [kip]	**Flexible Pavement**		**Rigid Pavement**		
	3-inch thick AC	**6-inch thick AC**	**6-inch thick PCC**	**8-inch thick PCC**	**12-inch thick PCC**
18	1.69	1.57	1.65	1.53	1.37
24	4.23	4.53	2.91	2.72	2.48
30	10.27	12.37	4.47	4.25	3.92

The damaging effects of supersingles are greater on thin pavements than they are on thicker asphalt pavements when the axle load is 18 kip, where as for an axle load of 24 kip and 30 kip, the damaging effects of supersingles on thin asphalt pavements are less than those on thick asphalt pavements. If TxDOT chooses to consider the impact of supersingles on pavement damage, then it would be necessary to calculate a separate set of ESALs for supersingle tires. Thus, instead of calculating axle loads on dual tires at the increased tire pressure, on tandem axles at the increased tire pressure, and on tridem axles at the increased tire pressure, researchers would need to add supersingles for each of the classes above; this would double the work required. Since supersingles currently make up less than 3 percent of the traffic in Texas, we recommend that supersingles be ignored in the first simplified implementation — except in special design cases.

Table 6.3 shows the axle load level for tandem and tridem axle loads for which the AASHTO LEFs are set to 1.0. For example, whereas AASHTO indicated that a 48 kip tridem axle load on dual tires had an LEF of 1.0 for flexible pavement, the actual LEFs for a 48 kip tridem range from 1.88–2.20, depending on surface thickness.

Table 6.3 Axle Load Levels for Tandem and Tridem Axle Groups for which the AASHTO LEFs Are Set to 1.0

	Flexible Pavement		**Rigid Pavement**		
	3-inch thick AC	**6-inch thick AC**	**6-inch thick PCC**	**8-inch thick PCC**	**12-inch thick PCC**
Tandem Axle	33 kips	33 kips	29 kips	29 kips	29 kips
PBFM LEF	1.58	1.41	1.05	1.06	1.34
Tridem Axle	48 kips	48 kips	39 kips	39 kips	39 kips
PBFM LEF	2.2	1.88	1.04	1.06	1.21

Because the LEFs for flexible pavements estimated by the PBFM for tandem and tridem axles are considerably higher than those for rigid pavements, we recommend that TxDOT begin calculating two sets of load equivalency factors: one for use in rigid pavements and one for use in flexible pavements. As was discussed in those cases of increased tire pressure, if this is unacceptable to the Department administration, then the flexible LEFs should be used for design, given that they are more damaging and given that the increase in cumulative ESALs will have relatively less effect on rigid pavements design.

6.3 Comprehensive Implementation Plan

With current computer technology, it is possible to conduct an interactive pavement design using the entire spectrum of LEFs for various axle loads (such as single axles, supersingles, tandems, and tridems) with increased tire pressure. It is possible to evaluate the effects of steering axles (which are embedded in the LEFs from the AASHO Road Test but which are separately calculated in weigh-in-motion systems). The comprehensive procedure would calculate ESALs for various tire pressures, various tire types, for all load configurations expected to be encountered on Texas highways. These values would be stored in the design computer’s axle ESAL calculation sub-routine. It would be possible to make these calculations for various pavement structural thicknesses. However, the use of too much detail makes implementation more difficult. It is, therefore, recommended that the implementation be carried out on a stage-by-stage basis.

1. As an intermediate alternative, four levels of pavement structural capacity should be used: low, medium, high, and very high. It will clearly be necessary to separate rigid and flexible pavements in this detailed procedure for greatest benefit. Separate LEFs would be calculated for tridem, tandem, and single axles — both on dual tires and on supersingle tires. This would create a matrix in the computer, as illustrated in Table 6.4.

Table 6.4 Recommended LEFs for Different Traffic Loading Characteristics for Rigid and Flexible Pavements

		Traffic Loading Characteristic					
		Increased Tire Pressure in Dual Tires	**Super-singles**	**Tandem Axles on Dual Tires**	**Tridem Axles on Dual Tires**	**Tandem Axles on Super-singles**	**Tridem Axles on Super-singles**
Flexible Pavement	**Low**	1.9-2.1	1.7-1.9	1.6-2.0	2.4-3.8	2.9-3.6	4.3-6.8
	Medium	1.5-1.6	1.5-1.7	1.6-1.9	2.2-3.0	2.5-3.0	3.5-4.8
	High	1.17-1.18	1.4-1.6	1.4-1.8	1.8-2.1	2.1-2.8	2.8-3.8
	Very High	1.07-1.08	1.2-1.4	1.3-1.6	1.6-1.8	1.8-2.5	2.2-2.5
Rigid Pavement	**Low**	1.10-1.12	1.5-1.7	1.02-1.05	1.02-1.04	1.6-1.7	1.6-1.7
	Medium	1.08-1.10	1.4-1.5	1.03-1.06	1.04-1.06	1.5-1.6	1.5-1.6
	High	1.06-1.07	1.3-1.4	1.3-1.6	1.2-1.3	1.8-2.2	1.6-1.8
	Very High	1.04-1.05	1.2-1.3	1.5-1.9	1.3-1.4	1.9-2.3	1.6-1.7

2. To calculate more accurate LEFs using the models and procedure developed under this project, additional information associated with traffic data should be reported, including tire type, tire pressure, and axle configurations.

3. To facilitate the calculation of LEFs using improved traffic data as recommended under 2., a spreadsheet-based program or a computer sub-routine should be developed with an implementation project.

6.4 Summary of Implementation Considerations

In summary, we recommend that TxDOT immediately implement these findings by first building a test section. This step would entail using in the test section design a matrix of load equivalency factors that are a compromise between rigid and flexible, as shown in Table 6.5. The detailed design of the test section should be carried out through close coordination between the PD and the researcher at the time when such an implementation is initiated.

This matrix of load equivalency factors is larger than that currently used by TxDOT, since it adds the additional categories for supersingles and for tridems. However, it is still a manageable matrix and produces a single set of equivalencies for use in design. The recommended simple set of LEFs is shown in Table 6.5.

For a second stage, we recommend that the research team work with the TxDOT staff in developing a more comprehensive implementation activity as outlined under Section 6.3. This stage would require additional application of the PBFM and would be an ideal implementation project for the TxDOT Implementation Program.

Table 6.5 Recommended LEFs for Different Traffic Loading Characteristics for Pavements

		Traffic Loading Characteristics					
		Increased Tire Pressure in Dual Tires	**Super-singles**	**Tandem Axles on Dual Tires**	**Tridem Axles on Dual Tires**	**Tandem Axles on Super-singles**	**Tridem Axles on Super-singles**
Pavement Structure	**Low**	2.0	1.8	1.8	3.1	3.2	5.5
	Medium	1.5	1.6	1.7	2.6	2.7	4.1
	High	1.17	1.5	1.6	1.9	2.4	3.3
	Very High	1.07	1.3	1.5	1.7	2.1	2.3

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