Technical Report Documentation Page

1. Report No. 0-1713-3	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle IMPACT OF TRUNNION AXLE GROUPS ON THE PERFORMANCE OF HIGHWAY INFRASTRUCTURE	5. Report Date October 2000 Revised: March 2001
7. Author(s) Zhanmin Zhang, Izydor Kawa, and W. R. Hudson	6. Performing Organization Code
	8. Performing Organization Report No. Research Report 0-1713-3
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. Research Project 0-1713
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section/Construction Division P.O. Box 5080 Austin, TX 78763-5080	13. Type of Report and Period Covered Research Report (9/1999 to 8/2000)
	14. Sponsoring Agency Code

15. Supplementary Notes

Project conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration, and the Texas Department of Transportation.

16. Abstract

The trunnion axle configuration has gained favor with many carriers of oversized and overweight loads. In addition, the frequency of interstate hauling of these specialized loads is increasing. The trunnion axle configuration allows for placement of more wheels in the transverse direction than conventional axle configurations, which may be more or less favorable to preventing premature load-induced damage on highway pavements and structures. Currently the load allowances on multiple axle groups are non-uniform; the non-uniform allowances are disruptive to interstate commerce. In order to determine whether comparable overload limits can be endorsed for routine permitting of these two axle configurations in Texas, and to work towards uniformity of permitting practices in neighboring states, it is essential that state agencies understand the relative impact of trunnion axle loading on the premature damage of pavements. A project sponsored by the Texas Department of Transportation (TxDOT) was therefore carried out at The University of Texas at Austin to determine the impact of trunnion axle loadings on the premature damage of both flexible and rigid pavements, relative to a standard tridem axle configuration. The research found that for flexible pavements, tridem axles are more damaging than trunnion axles; and for rigid pavements, trunnion axles are more damaging than tridem axles. For highway bridge structures, the damage caused by a truck with a trunnion axle does not significantly differ from that of a truck with a tandem axle.

17. Key Words Trunnion, tridem, load equivalency, pavement damage, bridge damage	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 46	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

IMPACT OF TRUNNION AXLE GROUPS ON THE PERFORMANCE OF HIGHWAY INFRASTRUCTURE

by
Zhanmin Zhang
Izydor Kawa
W. Ronald Hudson

Research Report Number 0-1713-3

Research Project 0-1713
Evaluation of the AASHTO 18-Kip Load Equivalency Concept

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

October 2000
Revised: March 2001

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PURPOSES

Zhanmin Zhang, Ph.D.
Research Supervisor

ACKNOWLEDGMENTS

This project has been conducted under the guidance of and has been directly assisted by many members of the TxDOT staff. Without their generous help and guidance, the value of this final product would have been severely diminished. The following people have helped by providing their knowledge and opinions:

Joseph P. Leidy, Project Director	Design Division
Monty G. Chamberlain	Motor Carrier Division
Keith L. Ramsey	Design Division

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The trunnion axle configuration has gained favor with many carriers of oversized and overweight loads. In addition, the frequency of interstate hauling of these specialized loads is increasing. The trunnion axle configuration allows for placement of more wheels in the transverse direction than conventional axle configurations, which may be more or less favorable to preventing premature, load-induced damage on highway pavements and structures. Currently the load allowances on multiple axle groups are non-uniform; the non-uniform allowances are disruptive to interstate commerce. In particular, load allowances for permitting overweight vehicles with triple axle tridem groups and trunnion axle groups differ considerably between California and Texas. Although in California routine overload permits are given to vehicles with trunnion axle groups but not to vehicles with tridem axles, Texas is issuing routine overload permits to vehicles with tridem axles but not to those with trunnion axles. Differences in state permitting policy can cause delays in obtaining specialized long-haul permits with added expenses in administrative time lost and the possibility of trans-loading en route.

In order to determine whether comparable overload limits can be endorsed for routine permitting of these two-axle configurations in Texas, and to work towards uniformity of permitting practices in neighboring states, it is essential to understand the relative impact of trunnion axle loading on the premature damage of pavements. A project sponsored by the Texas Department of Transportation (TxDOT) was therefore carried out at The University of Texas at Austin to determine the impact of trunnion axle loadings on the premature damage of both flexible and rigid pavements, relative to a standard tridem axle configuration.

1.2 CONFIGURATION OF TRIDEM AND TRUNNION AXLES

Figure 1.1 illustrates the typical configuration of tridem and trunnion axles in which the dimensions are labeled in inches. The major differences that have potential impact on the damage of pavements between tridem and trunnion axles include the following:

- The trunnion configuration has two axles, while a tridem configuration has three axles.
- There are a total of sixteen tires for a trunnion configuration, while there are twelve tires for a tridem configuration.
- The trunnion axle configuration allows for placement of more wheels in the transverse direction than the tridem axle configuration.
- The trunnion axle is generally 10 feet in width, while a tridem axle's typical width is 8 feet.

The loading characteristics of trunnion and tridem axles used for the analysis are summarized in Table 1.1. As for the load per tire with such configurations with the same magnitude of axle group load, the load per tire for a trunnion axle would be smaller than that for a tridem axle. For example, if the axle group load is 60 kips, the load per tire for a trunnion axle would be 3.75 kips compared to 5 kips for a tridem axle.

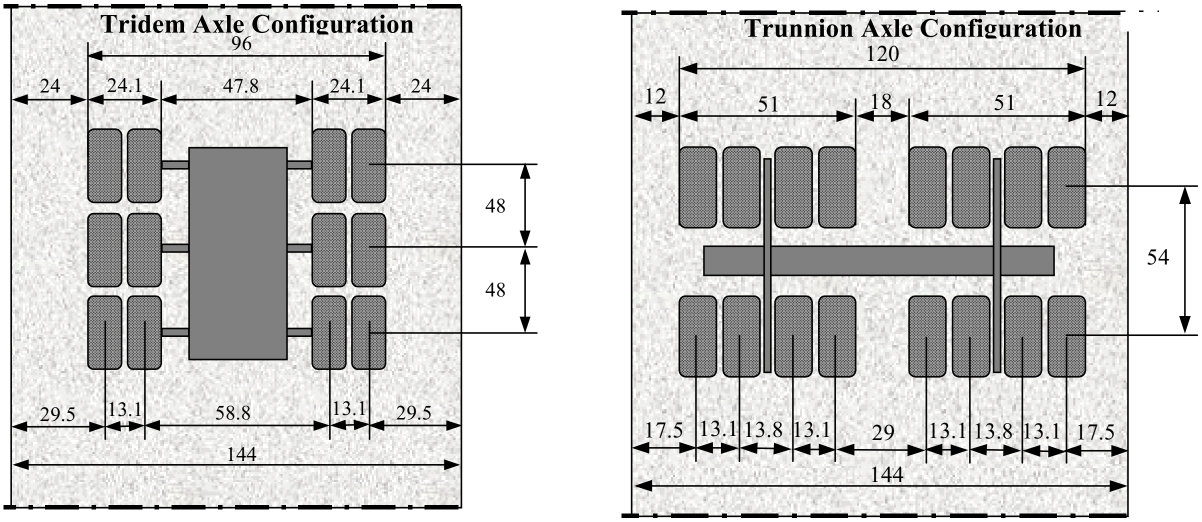

Figure 1.1. Illustration of the Configuration of Tridem and Trunnion Axles on a Typical 12-foot Traffic Lane

Table 1.1. Loading Characterization

	Tridem Axle	**Trunnion Axle**
Axle group load	60 kip	60 kip
Number of tires	12	16
Load per tire	5 kip	3.75 kip
Tire pressure	115 psi	115 psi

CHAPTER 2. ANALYSIS OF THE PRIMARY RESPONSES IN PAVEMENTS

2.1 PRIMARY RESPONSES IN FLEXIBLE PAVEMENTS

For the analysis of the primary responses of flexible pavements, two flexible pavement structures were used to represent structures typical of those used on the Texas Trunk System, where one pavement has a surface thickness of 3 inches and the other 6 inches. The characteristic values of pertinent design parameters of the two pavement structures are summarized in Table 2.1.

Table 2.1. Characteristic Values of the Flexible Pavements

	Thickness (inch)	**Elastic Modulus (psi)**	**Poisson Ratio**
AC Surface	3, 6	400,000	0.30
Base Layer	10	60,000	0.35
Subgrade		10,000	0.45

Using ELSYM5 [Huang 93] and the method of superposition, the tensile strain induced by trunnion and tridem axles at the bottom of the asphalt concrete (AC) layer were calculated as the primary responses in a flexible pavement structure. The input parameters for ELSYM5 are summarized in Appendix A. Each axle line within a configuration was evaluated independently because the influence of adjacent axles is negligible on the load responses attributable to any given axle in the group. Figures 2.1 and 2.2 present the strains at the bottom of the AC layer for flexible pavements with an AC surface of 3 inches and 6 inches respectively. The strains are graphed along the cross section, which is the direction transverse to travel of a pavement for a traffic lane with point 0.0 on the x-axis representing the middle of the lane. The corresponding positions of tires for tridem and trunnion axles are also indicated in the figures along with the strain profile. For pavements with either a 3-inch or 6-inch AC surface layer, the tensile strains induced at the bottom of the AC layer by a tridem axle are higher than those generated by a trunnion axle. The peaks of the strains are generally under the center of the tires for both tridem and trunnion axles. For a tridem axle, the peak strains are the same for all tires, but for a trunnion axle, the maximum peaks are under the center of the inner tires.

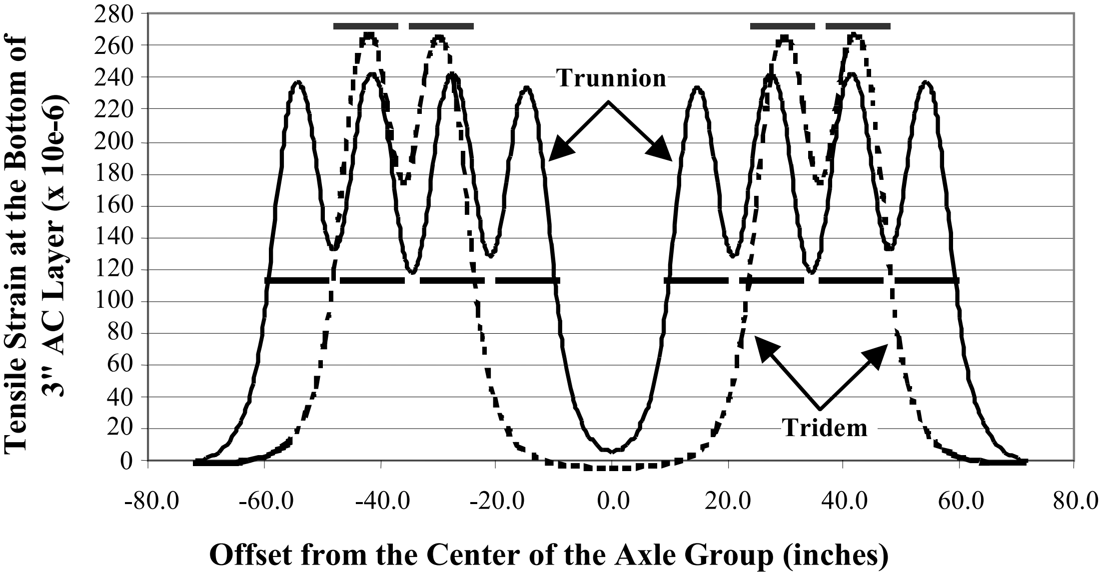

Figure 2.1. Strains in a Flexible Pavement with a 3-Inch AC Surface Layer

The maximum values of peak strains and the differences between the maximum strain induced by a tridem and that by a trunnion axle are summarized in Table 2.2. For a pavement with an AC surface of 3 inches, the maximum strain induced by a tridem axle is about 10 percent higher than that by a trunnion axle. However, when the AC surface is increased to 6 inches, the maximum values of peak strains show a decrease; even though the tridem axle still generates a higher maximum strain at the bottom of the AC layer, the percentage of difference drops to only about 3 percent.

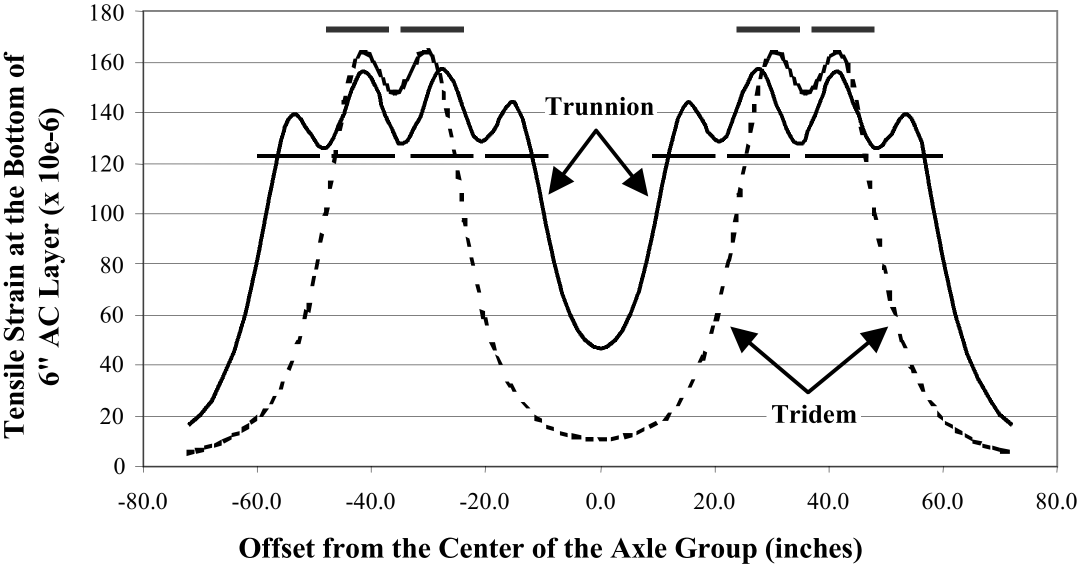

Figure 2.2. Strains in a Flexible Pavement with a 6-Inch AC Surface Layer

Table 2.2. Maximum Values of Peak Strains in Flexible Pavement Structure

AC Surface	**Maximum Strain at the Bottom of AC Surface Layer (In Microstrain)**		
Thickness	**Tridem**	**Trunnion**	**Difference (%)**
3 inch thick AC surface	267	243	9.67%
6 inch thick AC surface	162	157	3.16%

2.2 PRIMARY RESPONSES IN RIGID PAVEMENTS

The design characteristics of the rigid pavement structures that were used for the analysis of the primary responses are summarized in Table 2.3. Two portland cement concrete (PCC) thickness alternatives, 8 inches and 12 inches, are considered for the analysis. For each case, there is a 10-inch subbase layer between the subgrade and the PCC slab. Each slab is assumed to be 12 feet in width and 15 feet in length.

Table 2.3. Characteristic Values of the Rigid Pavement Structures

	Thickness (inch)	Elastic Modulus (psi)	Poisson Ratio
PCC Surface	8, 12	4,200,000	0.15
Subbase	10	60,000	0.40
Subgrade		10,000	0.45

Using KENSLABS [Huang 93], the maximum tensile stress at the bottom of the PCC slab was calculated as the primary response to loading for a rigid pavement. Figure 2.3 illustrates the analysis element configuration for the KENSLABS. The complete set of input parameters for KENSLABS is summarized in Appendix B.

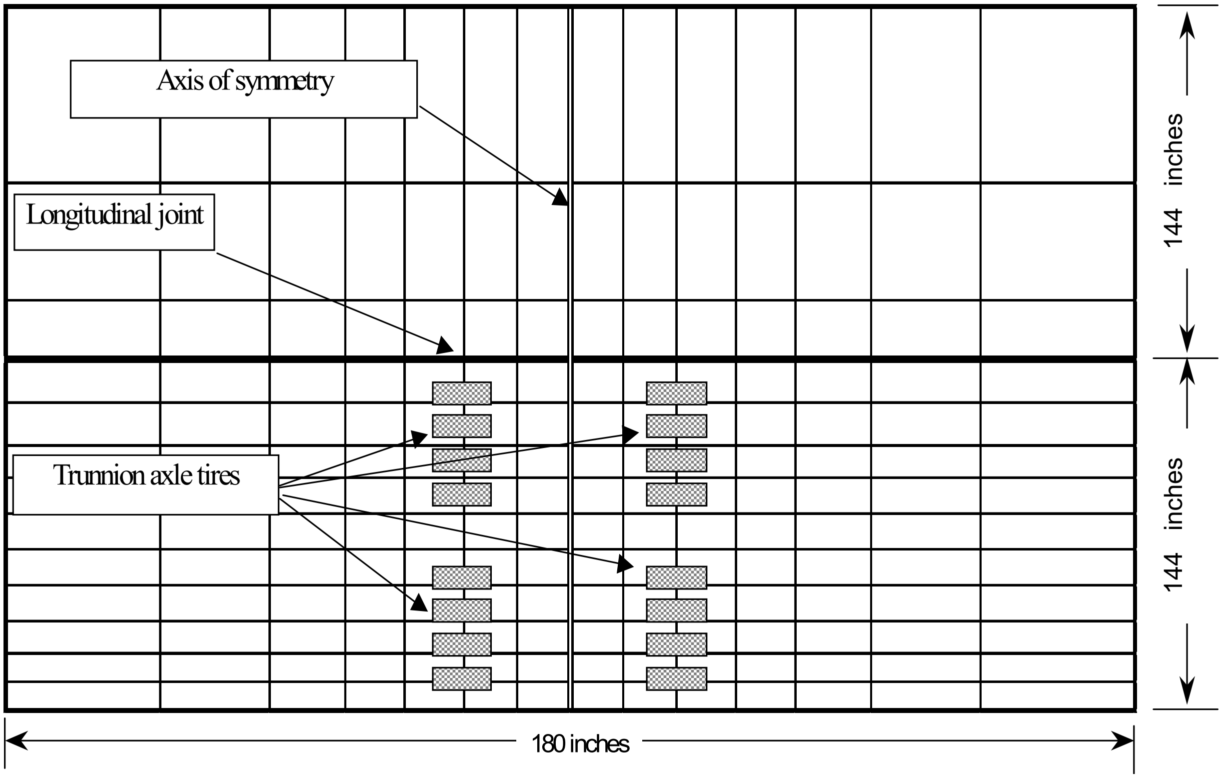

Figure 2.3. Analysis Configuration of Rigid Pavement Structure for KENSLABS Program

Figures 2.4 and 2.5 show the tensile stresses at the bottom of an 8-inch PCC slab in the direction of travel for two loading conditions respectively: (1) the axle loads centered in the middle of the lane, and (2) the axle with the outermost tire centered at the edge of the pavement. The figures clearly indicate that, for a tridem configuration, there are three peak stresses corresponding with the number of axles in a tridem configuration, but for trunnion axles, there are two peak stresses that are in accordance with the number of axles in a trunnion configuration. The overall stress trends are the same for a PCC slab of 12 inches, although the peak stress values are lower compared to those for an 8-inch PCC slab.

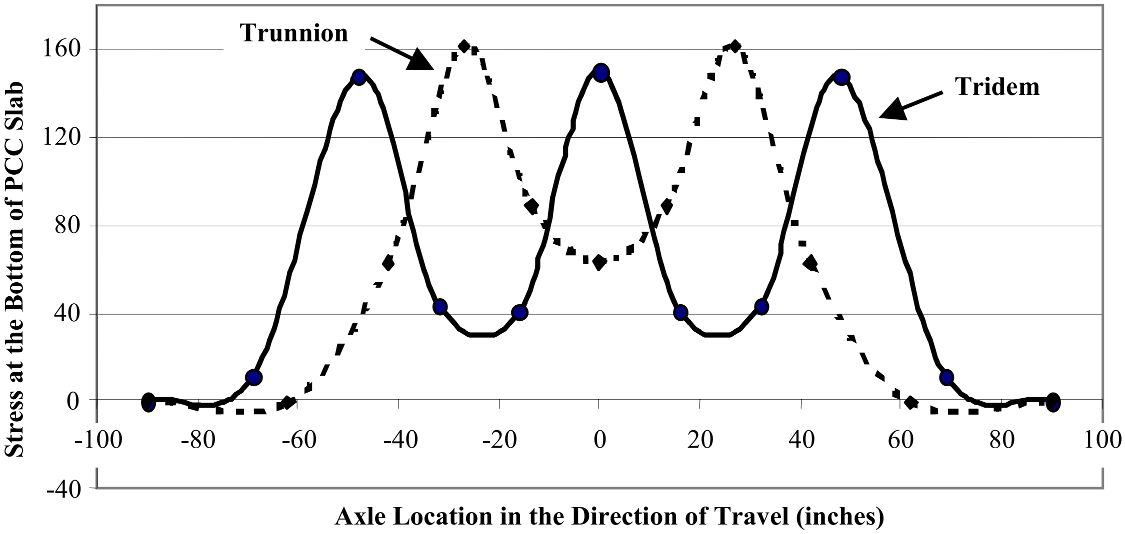

Figure 2.4. Stresses at the Bottom of an 8-Inch PCC Slab with the Axle Loads Centered in the Middle of the Slab

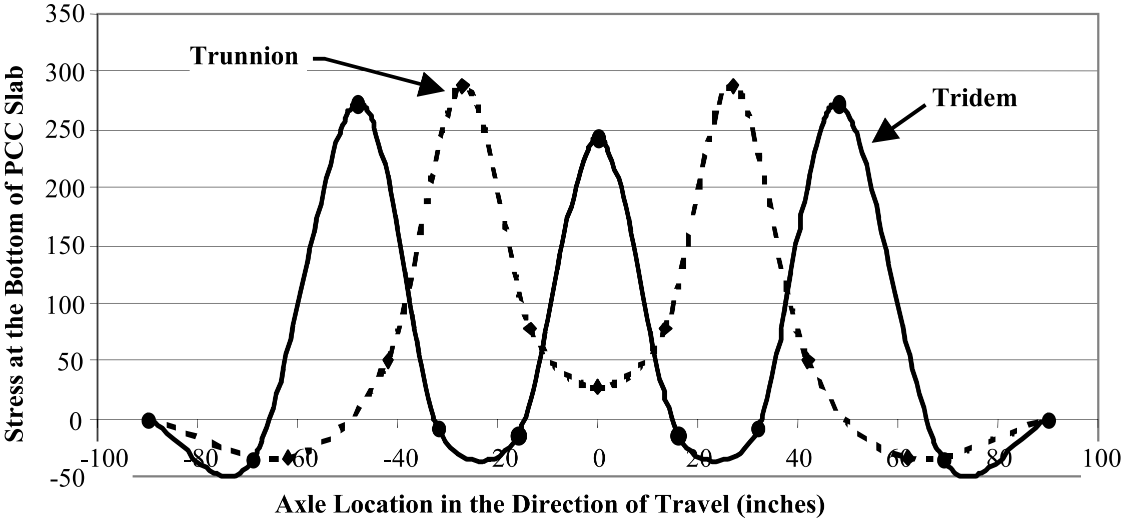

Figure 2.5. Stresses at the Bottom of an 8-Inch PCC Slab with the Outermost Tire Centered at the Edge of the Slab

Figure 2.6 illustrates the relationship between the lateral position of tires with respect to the slab edge and the maximum tensile stress at the bottom of the PCC slab. The horizontal axis in Figure 2.6 represents the distance from the center of the outermost tire to the edge of the slab, while the vertical axis represents the corresponding maximum stress in the PCC slab. Clearly, the critical stress occurs when the outermost tires are at the edge of the slab.

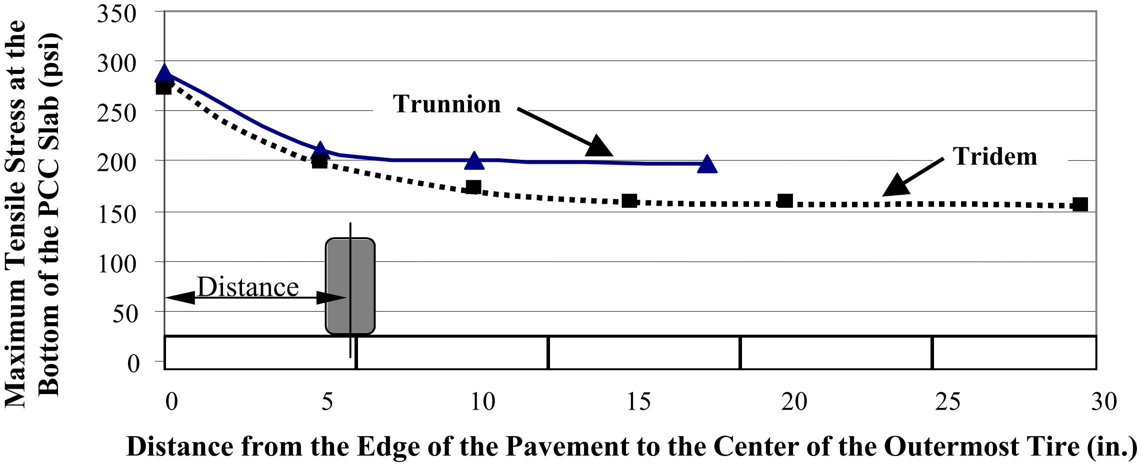

Figure 2.6. Relationship between the Lateral Position of Tires and the Maximum Tensile Stress at the Bottom of the PCC Slab

Table 2.4 summarizes the maximum tensile stresses and the differences of maximum stresses induced by a 60-kip tridem and trunnion axle. For a pavement with an 8-inch PCC surface, the maximum stress induced by a tridem axle is about 33 percent less than that induced by a trunnion axle. When the PCC slab is increased to 12 inches, the maximum stress decreases, but the percentage of difference is 33.29, which is almost the same as in the case of an 8-inch slab.

Table 2.4. Maximum Tensile Stress in Rigid Pavement Structure

PCC Slab	**Maximum Stress at the Bottom of PCC Slab (psi)**		
Thickness	**Trunnion**	**Tridem**	**Difference (%)**
8 inches	211.25	159.06	32.81
12 inches	159.97	120.01	33.29

CHAPTER 3. CONSIDERATION OF THE FATIGUE IMPACT ON THE LIFE-CYCLE PERFORMANCE OF PAVEMENTS

3.1 FATIGUE IMPACT ON THE LIFE-CYCLE PERFORMANCE OF PAVEMENTS

The analysis results represented in the earlier sections are for a single pass of the tridem or trunnion axle group. However, the accumulated impact of the axles on the damage of pavements should be considered for the life-cycle performance of the pavements. A performance-based fatigue model developed at The University of Texas at Austin was therefore used to accumulate the damage induced by the tridem and trunnion axles groups.

The performance-based fatigue model for flexible pavements was established by correlating the primary responses of pavement loading to the number of load repetitions at a terminating PSI (present serviceability index) level of 2.5 [Zhang 00]. The magnitude of wheel load (L), the structural number of the pavement (SN), and the tensile strain at the bottom of the AC surface layer (ε_t) are the independent variables of the model:

$$Log\ N_{PSI=2.5} = 6.269653 + 5.568672 * log(SN + 1) - 0.121091 * L - 1.315795 * log(\varepsilon_t)$$

where:

$N_{PSI=2.5}$ = the number of line axle load repetitions when a terminal PSI level of 2.5 is reached;

L = wheel (dual tire) load in kip;

SN = structural number of the pavement structure; and

ε_t = peak strain at the bottom of AC surface layer in microstrains (strain x 10^6).

After the strain values are applied to the performance-based fatigue model, the load equivalency factors (LEFs) are calculated for both tridem and trunnion axles, using the standard 18-kip single axle as the basis. Tables 3.1 and 3.2 summarize the analysis results for pavements with an AC surface layer thickness of 3 inches and 6 inches, respectively.

Table 3.1. The Impact of Tridem and Trunnion Axles on Pavements with a 3-Inch AC Surface

	Single Axle	**Trunnion Axle**	**Tridem Axle**
Axle Group Load (kip)	18	60	60
No. of Wheels	4	16	12
Load per Wheel (kip)	4.500	3.750	5.000
Load on Dual Tires	9.000	7.500	10.000
Peak Horizontal Tensile Strain at the Bottom of AC Surface (in microstrains)	188.5	243.0	266.5
Log N (no. of axle line reps.)	6.098	6.134	5.779
N	1,251,976	1,361,507	600,560
Axle Group Applications	1,251,976	680,754	200,187
LEF	**1**	**1.84**	**6.25**

Table 3.2. The Impact of Tridem and Trunnion Axles on Pavements with a 6-Inch AC Surface

	Single Axle	**Trunnion Axle**	**Tridem Axle**
Axle Group Load (kip)	18	60	60
No. of Wheels	4	16	12
Load per Wheel (kip)	4.500	3.750	5.000
Load on Dual Tires	9.000	7.500	10.000
Peak Horizontal Tensile Strain at the Bottom of AC Surface (in microstrains)	139.2	157.3	162.3
Log N (no. of axle line reps.)	6.271	6.383	6.062
N	1,865,733	2,413,047	1,153,587
Axle Group Applications	1,865,733	1,206,523	384,529
LEF	**1**	**1.55**	**4.85**

For both cases, tridem axles are more damaging to flexible pavements than trunnion axles. For a 3-inch AC surface, tridem axles are about 3.4 times more damaging than trunnion axles; and for a 6-inch AC surface, tridem axles are about 3.1 times more damaging than trunnion axles.

3.2 FATIGUE IMPACT ON THE LIFE-CYCLE PERFORMANCE OF RIGID PAVEMENTS

Using the same approach that was employed for flexible pavements, the researchers also developed a performance-based fatigue model for rigid pavements. For rigid pavements, the independent variables are the PCC slab thickness and the maximum tensile stress in the PCC slab:

$$Log\ N_{PSI=2.5} = 11.062 + 0.028 * PCC - 2.283 * log(\sigma_t)$$

where:

$N_{PSI=2.5}$ = number of line axle load repetitions for a terminal PSI level of 2.5;
σ_t = tensile stress at the bottom of PCC slab; and
PCC = thickness of PCC slab.

Because the maximum stress in the PCC slab is also a function of the distance from the center of the outermost tire to the edge of the PCC slab, the lateral distribution of the axle loadings on the slab must be taken into consideration when analyzing the damage caused by tridem and trunnion axles on the life-cycle performance of rigid pavements.

Based on the research finding by Lee and Pangburn [Lee 96], the lateral distribution of the outermost tire has been established for tridem and trunnion axles. Table 3.3 gives the percentage distribution values of the outermost tire along the lateral position of the PCC pavement slab for tridem and trunnion axles. When establishing the distribution for trunnion axles, the researchers recognized that trunnion axles generally have a tendency to drive closer to the edge — a result of the wider configuration of these axles. The lateral distribution of the outermost tire for trunnion axles is therefore skewed toward the slab edge. Figure 3.1 charts the lateral distribution. Apparently, the peak of the lateral distribution of the axles for the outermost tire is located 5 inches and 15 inches from the edge of the pavement for the trunnion axle and the tridem axle respectively. The stress at the location where the lateral distribution of the axles reaches its peak is used as the maximum stress in the pavement to estimate the fatigue life of the pavement.

Table 3.3. Lateral Distribution of the Outermost Tire for Tridem and Trunnion Axles

Lateral position of the outermost tire from the edge of slab (inches)	**Tridem Axle**		**Trunnion Axle**	
	Percent of vehicles	Cumulative percentage	Percent of vehicles	Cumulative percentage
45	1	1	0	0
40	3	4	0	0
35	7	11	1	1
30	11	22	3	4
25	15	37	6	10
20	18	55	8	18
15	**20**	**75**	13	31
10	12	87	20	51
5	7	94	**24**	**75**
0	4	98	18	93
-5	2	100	5	98
-10	0	100	2	100

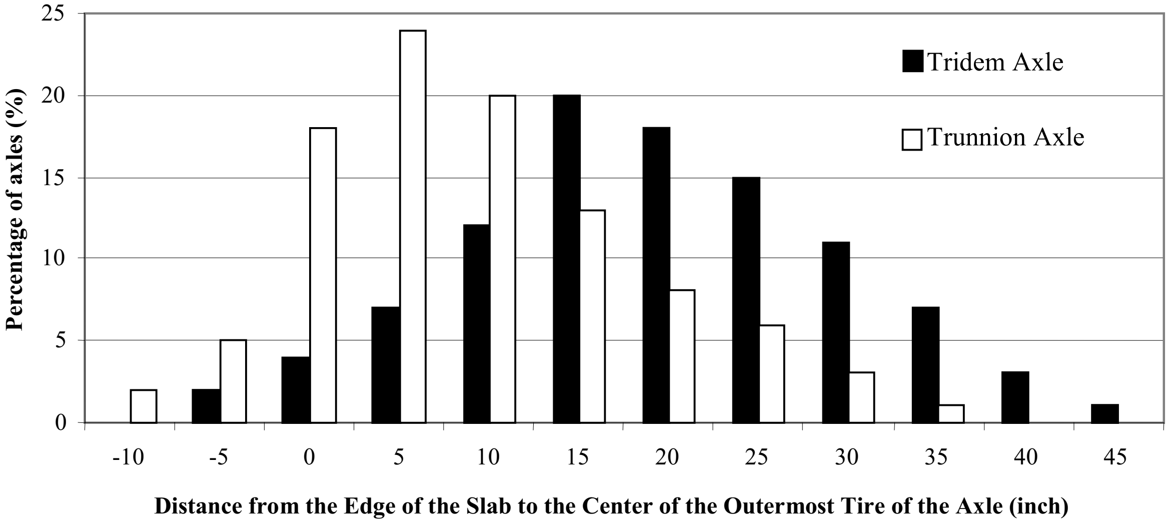

Figure 3.1. Lateral Distribution of the Outermost Tire for Tridem and Trunnion Axles

Similar to the procedure used for flexible pavements, the maximum stresses in the PCC slab are applied to the performance-based fatigue model for rigid pavements. The load equivalency factors (LEFs) are then calculated for both tridem and trunnion axles using the standard 18-kip single axle as the basis. Tables 3.4 and 3.5 summarize the analysis results for pavements with a PCC surface layer of 8 inches and 12 inches, respectively.

Table 3.4. The Impact of Tridem and Trunnion Axles on Pavements with an 8-Inch PCC Slab

	Single Axle	**Trunnion Axle**	**Tridem Axle**
Axle Group Load (kip)	18	60	60
No. of Wheels	4	16	12
Load per Wheel (kip)	4.500	3.750	5.000
Load on Dual Tires	9.000	7.500	10.000
Peak Horizontal Tensile Stress at the Bottom of PCC Slab (psi)	159.85	211.25	159.06
Log N (no. of axle line reps.)	6.256	5.980	6.261
N	1,804,280	954,549	1,824,643
Axle Group Applications	1,804,280	477,275	608,214
LEF	**1**	**3.78**	**2.97**

Table 3.5. The Impact of Tridem and Trunnion Axles on Pavements with a 12-inch PCC Slab

	Single Axle	**Trunnion Axle**	**Tridem Axle**
Axle Group Load (kip)	18	60	60
No. of Wheels	4	16	12
Load per Wheel (kip)	4.500	3.750	5.000
Load on Dual Tires	9.000	7.500	10.000
Peak Horizontal Tensile Stress at the Bottom of PCC Layer (psi)	99.85	159.97	120.01
Log N (no. of axle line reps.)	6.836	6.369	6.654
N	6,854,515	2,336,695	4,504,948
Axle Group Applications	6,854,515	1,168,347	1,501,649
LEF	**1**	**5.87**	**4.56**

It can be seen that, for pavements with either an 8-inch or 12-inch PCC surface, trunnion axles are more damaging to rigid pavement than tridem axles. For a pavement with an 8-inch PCC surface, trunnion axles are about 1.3 times more damaging than tridem axles; and for a pavement with a 12-inch PCC surface, trunnion axles are about 1.3 times more damaging than tridem axles. Clearly, the PCC slab thickness does not play a significant role in the relative damage caused by tridem and trunnion axles.

Another point worth mentioning is that even when the outer wheel load is centered on the edge of the 8-inch slab, the stress ratio (stress induced by the load/modulus of rupture - σ_t/S_c) is ≥ 0.50. The Portland Cement Association (PCA) pavement design procedure uses this ratio in estimating allowable load repetitions. TxDOT specifications call for a 28-day flexural strength (modulus of rupture) of 650 psi. According to PCA, for a stress ratio ≥ 0.50, unlimited equivalent stress load repetitions can be expected [Yoder, 75].

CHAPTER 4. ANALYSIS OF THE IMPACT ON BRIDGES

Bridges are a critical link in the transportation infrastructure. Structural failure in a bridge is much more dramatic and potentially catastrophic than a pavement failure, and can result in rendering miles of highway unusable. The impact of trunnion and tridem axles should be carefully examined as part of the basis for formulating the final recommendations regarding the permitting of trunnion trucks.

4.1 SELECTION OF COMPUTER PROGRAM FOR THE ANALYSIS

After a careful literature review of available computer programs for the structural analysis of bridges, the researchers selected SAP2000 [CSI 2000] to perform the analysis of bridge structures for the following reasons:

- SAP2000 represents the state of the art in three-dimensional, finite-element technology for structural engineering.
- It is completely integrated within the Windows 95/NT environment and has an easy-to-use graphical interface. Through templates, the creation and modification of models, execution of the analysis, viewing of the results, and design optimization can all be performed interactively within the same interface.
- Employing the latest developments in analytical techniques, SAP2000 provides powerful capabilities for modeling a wide range of structures, including bridges, dams, tanks, and buildings.

4.2 TYPICAL BRIDGES SELECTED FOR THE ANALYSIS

Based on the results of a literature review and suggestions received from the bridge engineers at TxDOT, the following three bridge structures were identified as the typical bridges to be analyzed with the SAP2000 program:

- 55-foot bridge structures with diaphragms;
- 55-foot bridge structures without diaphragms; and
- 25-foot bridge structures.

Figure 4.1 illustrates the model of a 55-foot bridge structure with diaphragms for analysis with SAP2000. The nominal span of the bridge is 55 feet. The bridge deck is assumed to have a thickness of 6.75 inches and a width of 28 feet and 3 inches. The concrete diaphragms are evenly spaced at 10 feet with the exception of the first diaphragm, which is placed 6 feet and 10-1/2 inches from the beginning of the bridge. The span length is 53 feet and 9 inches from the center of one bearing pad to the center of the other bearing pad. The girders are spaced 7.33 feet apart [Cornwell 83].

The basic configuration of the 55-foot bridge structure without diaphragms is the same as that for the structure with diaphragms, except that the diaphragms are excluded from the analysis. The 25-foot bridge is treated as a simple beam structure with support at the two ends of the beam.

4.3 CONSIDERATION OF DEAD LOAD AND LIVE LOAD

The dead load of a highway bridge consists of the weight of the structure plus any attached equipment. For the estimate of the bridge dead load, it was assumed that the average weight of the concrete material from which the bridge was built is 150 lb/ft^3 [Heins 84]. For the purpose of analysis, the live load is configured with the following four scenarios:

- Tridem axle centered in the middle of the bridge structure;
- Trunnion axle centered in the middle of the bridge structure;
- Tridem axle centered in the middle of the bridge structure plus tandem axle; and
- Trunnion axle centered in the middle of the bridge structure plus tandem axle.

Figures 4.2 and 4.3 illustrate the loading configurations. Figure 4.2 shows that the bridge structure is loaded with a tridem truck where both the tridem and tandem axles are on the bridge. The tridem axle is centered in the middle of the bridge structure. Figure 4.3 demonstrates that the bridge structure is loaded with a trunnion truck and both the trunnion and tandem axles are on the bridge. The trunnion axle is centered in the middle of the bridge structure. Appendix C shows the SAP 2000 input parameters used in these analyses.

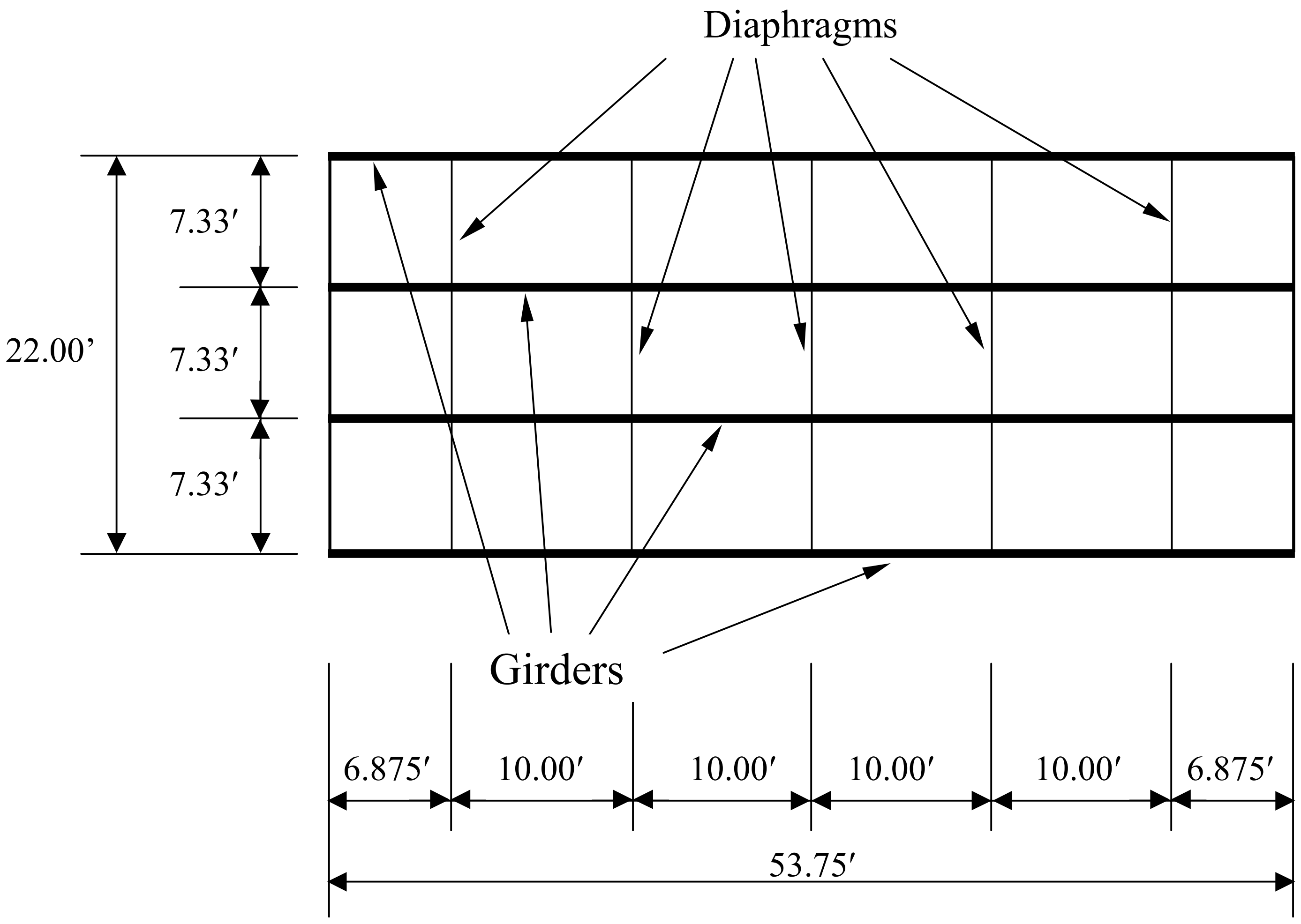

Figure 4.1. Bridge Model for SAP2000

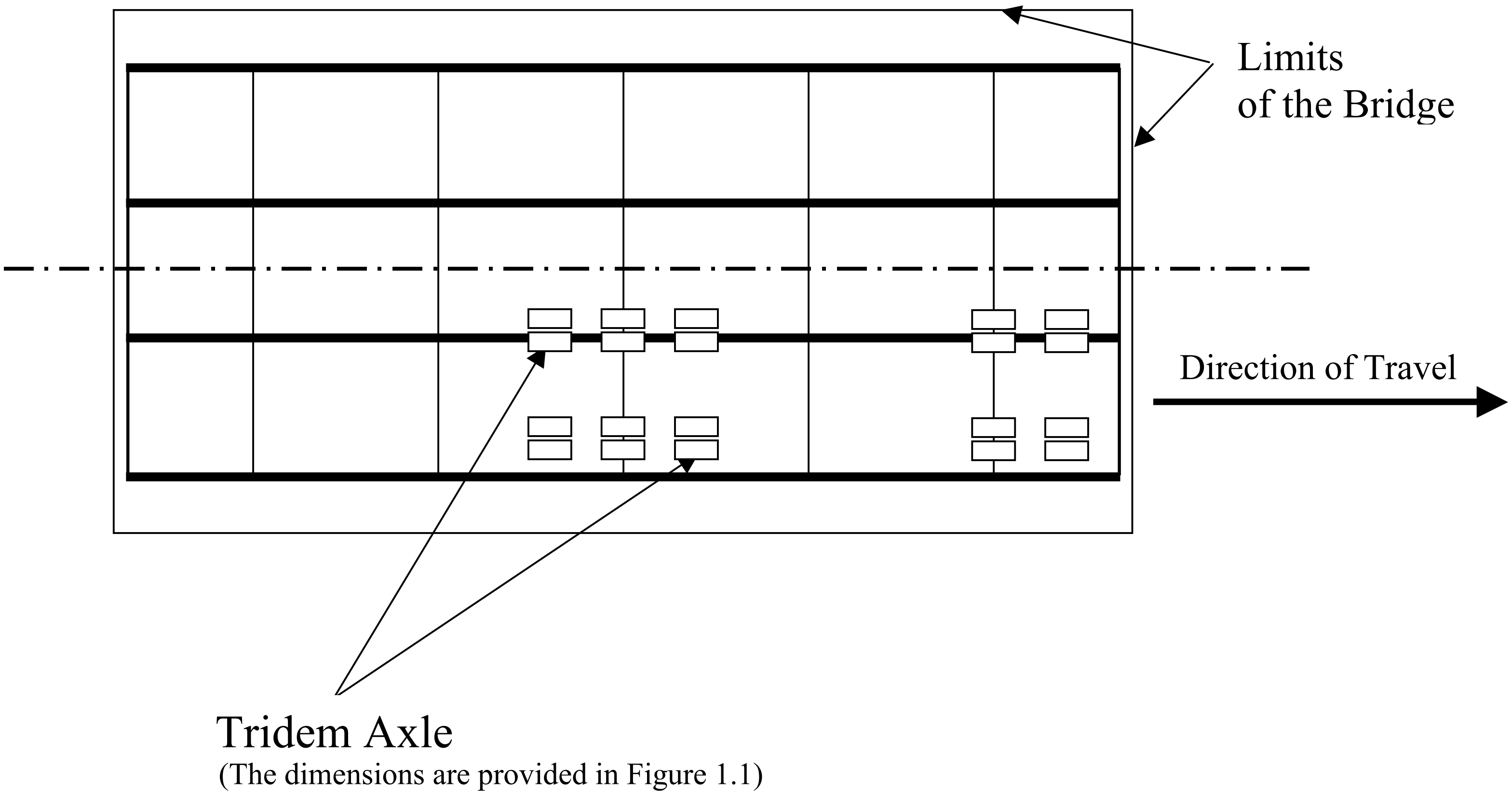

Figure 4.2. Input Loads for Truck with Tridem and Tandem Axles

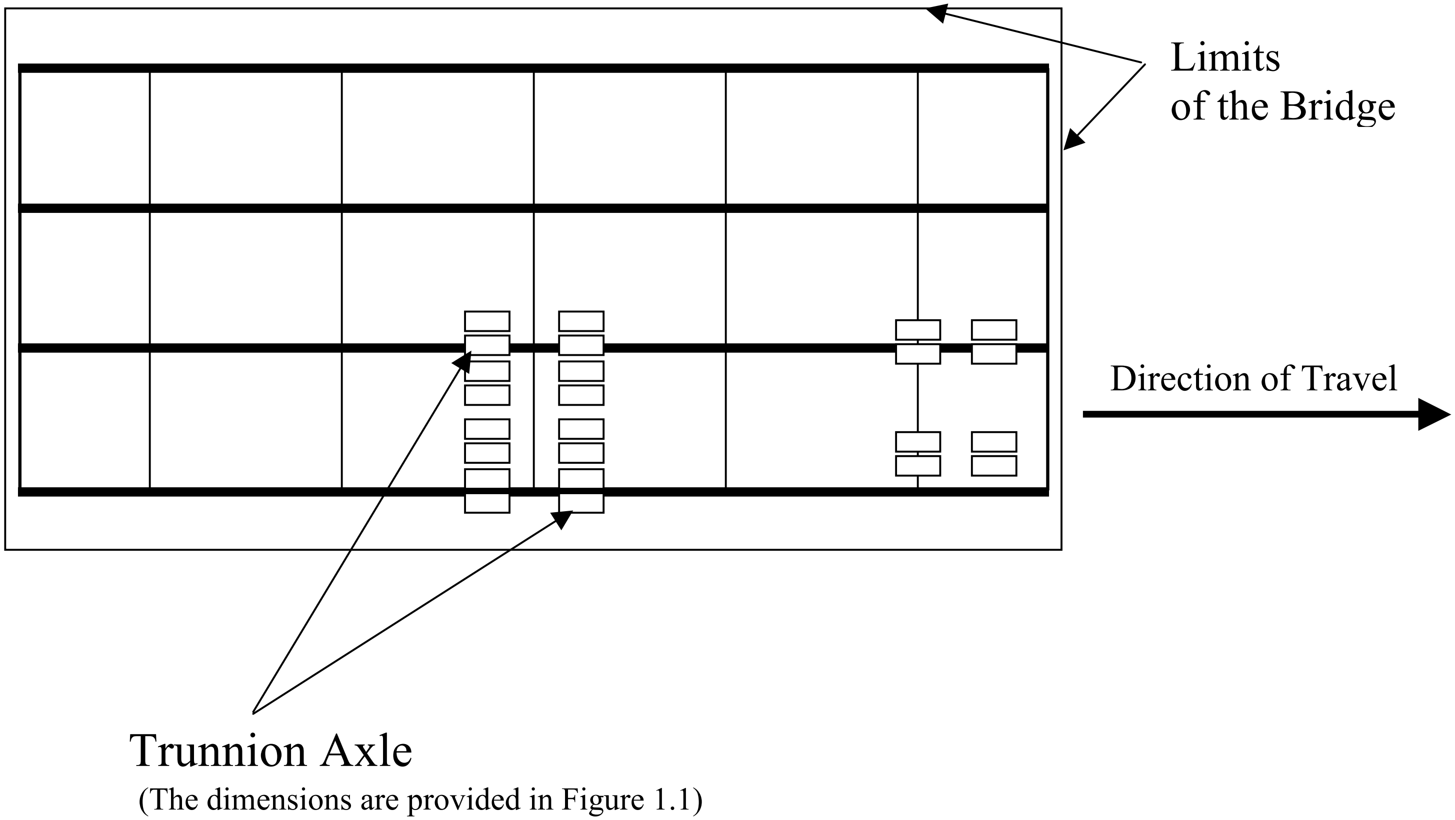

Figure 4.3. Input Loads for Truck with Trunnion and Tandem Axles

4.4 RESULTS OF SAP2000 ANALYSIS

Based on the loading configurations described in the earlier section, analyses were conducted with the SAP2000 computer program. The results of the analyses are presented in the following sections.

4.4.1 55-Foot Bridge Structure with Diaphragms

Table 4.1 presents the calculated maximum bending moments in bridge girders in eight scenarios of bridge loading for the 55-foot bridge structure with diaphragms.

Table 4.1. Maximum Bending Moments in Bridge Structure with Diaphragms

	Max. Bending Moment (kip – ft)	Difference (%)
Tridem Axle	372.79	1.38
Trunnion Axle	377.93	
Tridem and Tandem Axle	401.08	1.28
Trunnion and Tandem Axle	406.21	
Tridem Axle (including dead load of bridge)	600.11	0.85
Trunnion Axle (including dead load of bridge)	605.24	
Tridem + Tandem Axles (including dead load of bridge)	628.39	0.82
Trunnion + Tandem Axles (including dead load of bridge)	633.53	

The results show that a trunnion axle imposes slightly higher moments on the bridge structure than does a tridem axle. However, the difference is in the range of 0.82 to 1.38 percent and can thus be considered insignificant.

The results also show that adding the tandem drive axle of the towing tractor to the tridem or trunnion axle load slightly increases the maximum bending moments in the bridge girders. However, the relative difference between the moment generated by the tridem axle and that by the trunnion axle decreases when the tandem axle of the truck is included in the analysis.

Finally, the results indicate that including the dead load of the bridge structure increases the calculated maximum bending moments in the bridge girders. However, the relative increase in the maximum moment from a trunnion axle decreases when the dead load is considered.

4.4.2 55-Foot Bridge Structure without Diaphragms

Table 4.2 presents the calculated maximum bending moments in bridge girders in eight scenarios of bridge loading for the 55-foot bridge structure without diaphragms.

Table 4.2. Maximum Bending Moments in the Bridge Structure without Diaphragms

	Max. Bending Moment (kip – ft)	Difference (%)
Tridem Axle	451.13	-1.21
Trunnion Axle	445.69	
Tridem and Tandem Axle	492.40	-1.14
Trunnion and Tandem Axle	486.78	
Tridem Axle (including dead load of bridge)	556.45	1.87
Trunnion Axle (including dead load of bridge)	566.85	
Tridem + Tandem Axles (including dead load of bridge)	590.86	1.87
Trunnion + Tandem Axles (including dead load of bridge)	601.92	

The results show that the relative difference in maximum bending moment between trunnion and tridem axles ranges from –1.21 percent to 1.87 percent and can thus be considered insignificant.

The results indicate that adding the tandem axle of the loading truck to the tridem or trunnion axle load increases the maximum bending moments in the bridge girders. However, the relative differences in the maximum moment are basically not affected by the inclusion of the tandem axle.

Although the dead load of the bridge structure increases the calculated maximum bending moments in the bridge girders, the relative difference in the maximum moment is not significantly affected by the inclusion of the dead load in the calculation.

4.4.3 25-Foot Bridge Structure without Diaphragms

Table 4.3 summarizes the calculated maximum bending moments in the bridge girders for the 25-foot bridge structure without diaphragms under four loading scenarios. The results show that a trunnion axle imposes slightly higher moments on the bridge structure than does a tridem axle. However, the difference is in the range of 0.76 to 0.99 percent, which can be considered insignificant.

Table 4.3. Maximum Bending Moments in the 25-Foot Bridge Structure

	Max. Bending Moment (kip – ft)	Difference (%)
Tridem Axle	162.43	0.99
Trunnion Axle	164.04	
Tridem Axle (including dead load of bridge)	212.75	0.76
Trunnion Axle (including dead load of bridge)	214.36	

4.5 SUMMARY OF THE ANALYSIS

The maximum moments in the bridge girders and the relative change under various loading scenarios for the three typical bridges are summarized in Table 4.4. The results show that the differences in maximum bending moments between a tridem and a trunnion axle range from –1.21 to 1.38 percent. Therefore, it can be concluded that the trunnion axles are not significantly more damaging to highway bridges than tridem axles.

Table 4.4. Summary of the Analysis Results

	55-Foot Bridge with Diaphragms		55-Foot Bridge without Diaphragms		25-Foot Bridge without Diaphragms	
Tridem Axle	372.79	1.38%	451.13	-1.21%	162.43	0.99%
Trunnion Axle	377.93		445.69		164.04	
Tridem and Tandem Axle	401.08	1.28%	445.69	-1.14%	N/A	
Trunnion and Tandem Axle	406.21		486.78			
Tridem Axle (+ dead load of bridge)	600.11	0.85%	556.45	1.87%	212.75	0.76%
Trunnion Axle (+ dead load of bridge)	605.24		566.85		214.36	
Tridem + Tandem Axles (+ dead load of bridge)	628.39	0.82%	590.86	1.87%	N/A	
Trunnion + Tandem Axles (+ dead load of bridge)	633.53		601.92			

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Based on the research findings, the following conclusions can be drawn:

1. For flexible pavements, tridem axles are more damaging than trunnion axles. For a typical flexible pavement with a 3-inch AC surface, tridem axles are about 3.4 times more damaging than trunnion axles; for a typical flexible pavement with a 6-inch AC surface, tridem axles are about 3.1 times more damaging than trunnion axles. However, the issue of shear failures caused by pavement edge loading has not been addressed. In Texas there are hundreds of miles of “poor boy” four-lane highways with no paved shoulders that are part of the Texas Trunk System. The lateral tracking distribution analysis reported by another researcher [Lee 96] for rigid pavements may also be valid for these flexible pavements.

2. For rigid pavements, trunnion axles are more damaging than tridem axles. For a typical rigid pavement with an 8-inch PCC surface, trunnion axles are 1.27 times more damaging than tridem axles; for a typical rigid pavement with a 12-inch PCC surface, trunnion axles are about 1.29 times more damaging than tridem axles.

3. Clearly, the thickness of either the AC layer for flexible pavements or the PCC slab for rigid pavements does not play a significant role in the relative damage of tridem and trunnion axles on pavements.

4. The relatively higher damaging impact of trunnion axles compared to tridem axles on rigid pavements is partially a result of trunnion axles being wider than tridem axles; therefore, there is a higher probability that the outermost tires of a trunnion vehicle will be closer to the edge of the slab. However, even for an 8-inch slab, the stress ratio is less than 0.50 for edge loading. The Portland Cement Association (PCA) design procedure considers this relationship to yield unlimited load repetitions.

5. The potential damage caused by a 60-kip load on a trunnion axle group to highway bridges does not significantly differ from that of a tridem truck axle group loaded to 60 kips.

Recommendations are as follows:

In light of the findings from this project, it appears admissible to issue routine 60-kip trunnion axle group permits for routes where routine 60-kip tridem permits are currently allowed. One caveat is to restrict trunnion axle configurations to the Texas Trunk System, where highway structural standards for pavements and bridging are generally higher. Because there are considerable lane-miles of highways on the Trunk System without paved shoulders, monitoring of any acceleration in pavement edge damage is recommended.

REFERENCES

[Cornwell 83] Cornwell, R. E., Stollies, R. W., and Johnson, C. P., “Structural Evaluation of Bridges for Overload Conditions,” Research Report 201-1F, Center for Transportation Research, The University of Texas at Austin, August 1983.

[CSI 2000]] “Integrated Structural Analysis and Design Software,” Computers and Structures, Inc., Berkeley, CA, 2000.

[Heins 84] Heins, C. P., and Lawrie, R. A., *Design of Modern Concrete Highway Bridges,* New York: John Wiley & Sons, 1984.

[Huang 93] Huang, Yang H., *Pavement Analysis and Design*, Prentice Hall, 1993.

[Lee 96] Lee, C. E., and Pangburn, J. W., “Preliminary Research Findings of Traffic-Load Forecasting Using Weigh-in-Motion Data,” Research Report 987-5, Center for Transportation Research, The University of Texas at Austin, April 1996.

[Libby 76] Libby, J. R., and Perkins, N. D., *Modern Prestressed Concrete Highway Bridge Superstructures – Design Principles and Construction Methods*, San Diego: Grantville Publishing Company, 1976.

[Yoder 75] Yoder. E. J., and M. W. Witczak*, Principles of Pavement Design*, 2nd ed., John Wiley & Sons, 1975.

[Zhang 00] Zhang, Z., Leidy, J., Kawa, I., and Hudson, W. R., “Impact of Changing Traffic Characteristics and Environmental Conditions on Flexible Pavements,” CD-ROM Proceedings of the 79th Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C., January 2000.

APPENDIX A

ELSYM5 INPUTS FOR FLEXIBLE PAVEMENT ANALYSIS

The inputs for ELSYM5 are summarized in three categories and provided as follows:

1. **Configuration of Tridem and Trunnion Axles.**
   The configuration of the tridem and trunnion axles is illustrated in Figure A.1.

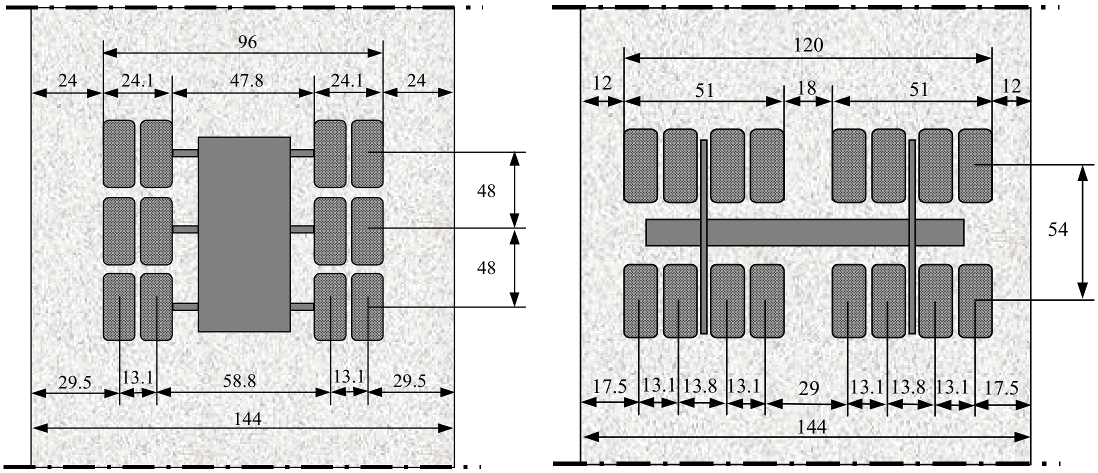

Figure A.1. Illustration of the Configuration of Tridem and Trunnion Axles

2. **Loading Characteristics.**
   The loading characteristic information for tridem and trunnion axles is provided in Table A.1.

Table A.1. Loading Characterization

	Tridem Axle	**Trunnion Axle**
Axle group load	60 kip	60 kip
Number of tires	12	16
Load per tire	5 kip	3.75 kip
Tire pressure	115 psi	115 psi

3. **Pavement material Characteristics.**
The characteristic values of the flexible pavements used as input for ELSYM5 are summarized in Table A.2.

Table A.2. Characteristic Values of the Flexible Pavements

	Thickness (inch)	**Elastic Modulus (psi)**	**Poisson Ratio**
AC Surface	3, 6	400,000	0.30
Base Layer	10	60,000	0.35
Subgrade		10,000	0.45

APPENDIX B

KENSLABS INPUTS FOR RIGID PAVEMENT ANALYSIS

The inputs for KENSLABS are summarized in four categories and provided as follows:

1. **Configuration of Tridem and Trunnion Axles.**
   The configuration of the tridem and trunnion axles is illustrated in Figure B.1.

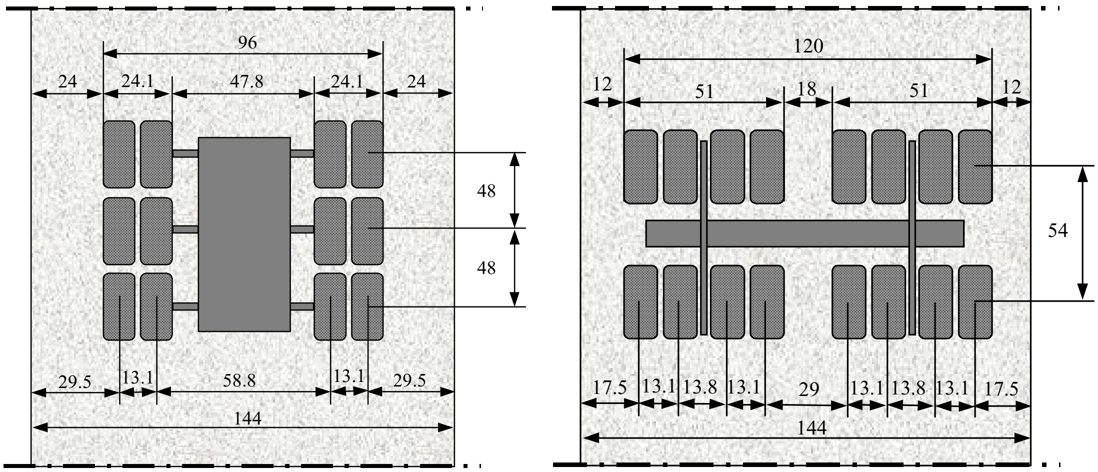

Figure B.1. Illustration of the Configuration of Tridem and Trunnion Axles

2. **Loading Characteristics.**
   The loading characteristic information for tridem and trunnion axles is provided in Table B.1.

Table B.1. Loading Characterization

	Tridem Axle	**Trunnion Axle**
Axle group load	60 kip	60 kip
Number of tires	12	16
Load per tire	5 kip	3.75 kip
Tire pressure	115 psi	115 psi

3. **Pavement Material Characteristics.**
   The characteristic values of the rigid pavements used as input for KENSLABS are summarized in Table B.2.

Table B.2. Characteristic Values of the Rigid Pavement Structures

	Thickness (inch)	**Elastic Modulus (psi)**	**Poisson Ratio**
PCC Surface	8, 12	4,200,000	0.15
Subbase	10	60,000	0.40
Subgrade		10,000	0.45

4. **Analysis Configuration.**
   The analysis configuration of the rigid pavement structure and loading location of the wheels are illustrated in Figure B.2.

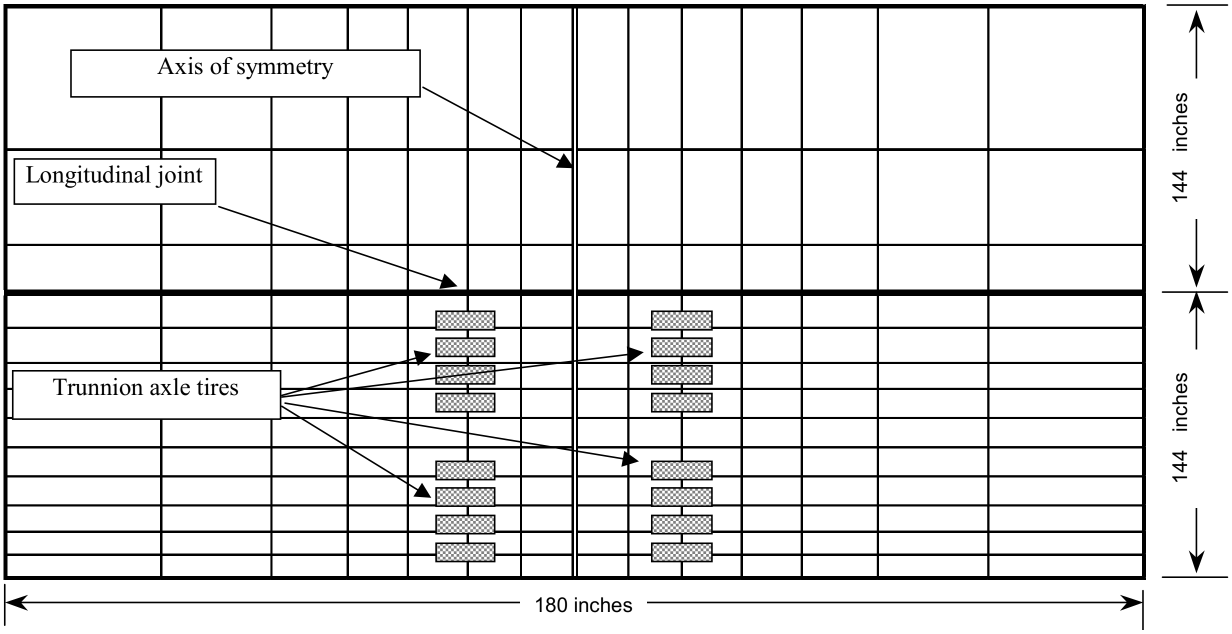

Figure B.2. Analysis Configuration of Rigid Pavement Structure for KENSLABS Program

APPENDIX C

SAP2000 INPUTS FOR BRIDGE ANALYSIS

The inputs for SAP2000 are summarized in three categories and provided as follows:

1. **Configuration of Tridem and Trunnion Axles.**
   The configuration of the tridem and trunnion axles is illustrated in Figure C.1.

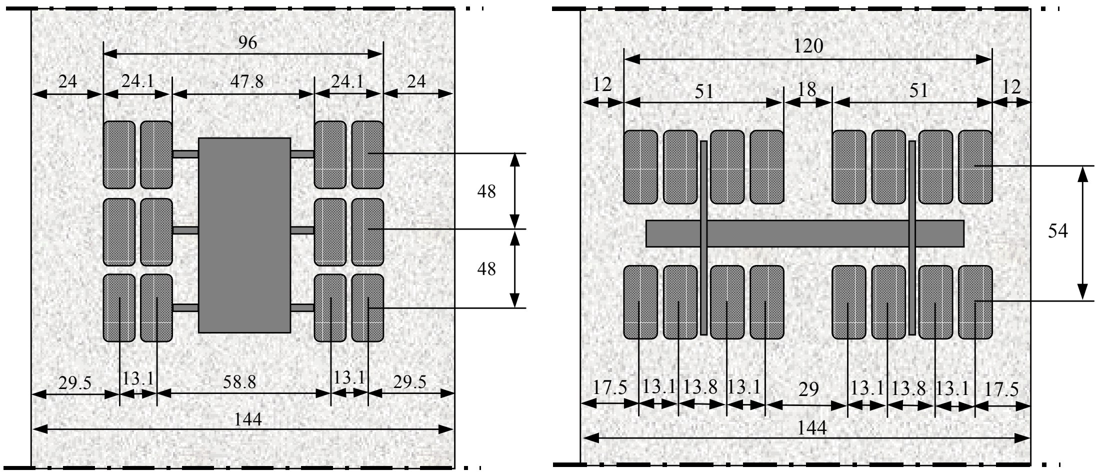

Figure C.1. Illustration of the Configuration of Tridem and Trunnion Axles

2. **Bridge Types.**
   The three types of bridges used for SAP2000 analysis are:

   1) 55-ft bridge structure with diaphragms.
   2) 55-ft bridge structure without diaphragms.
   3) 25-ft bridge structure.

3. **Live Load Configuration.**
   The four live load configurations used for the SAP2000 analysis are:

   1) Tridem axle centered in the middle of the bridge structure.
   2) Trunnion axle centered in the middle of the bridge structure.
   3) Tridem axle centered in the middle of the bridge structure plus tandem axle.
   4) Trunnion axle centered in the middle of the bridge structure plus tandem axle.

These configurations are illustrated in Figures C.2. and C.3.

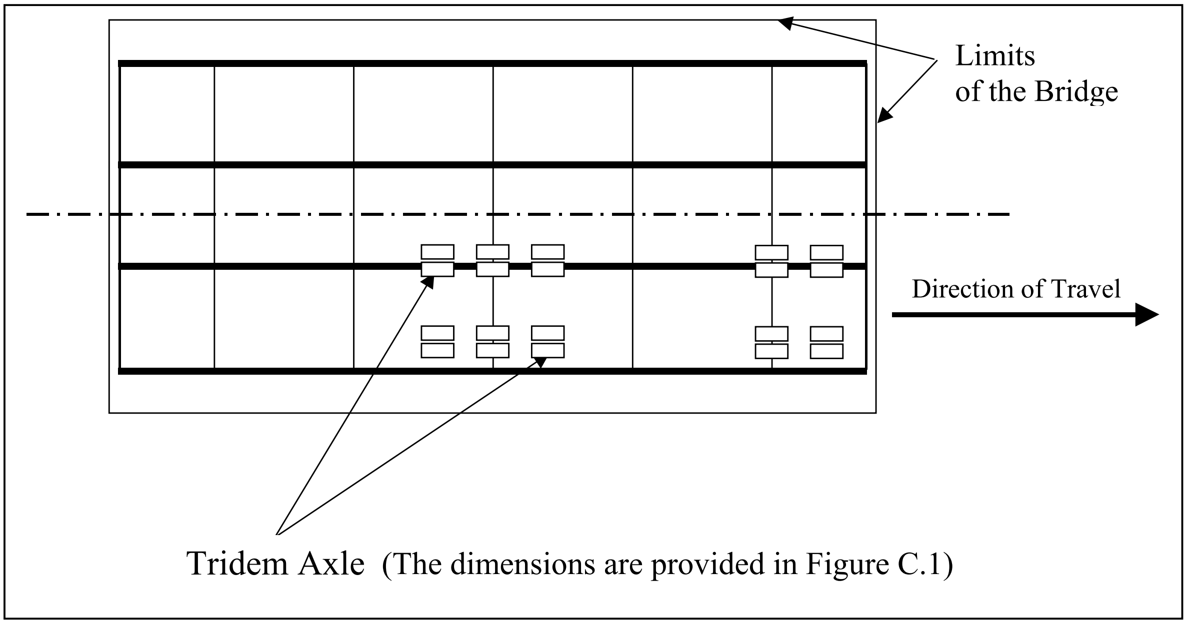

Figure C.2. Input Loads for Truck with Tridem and Tandem Axles

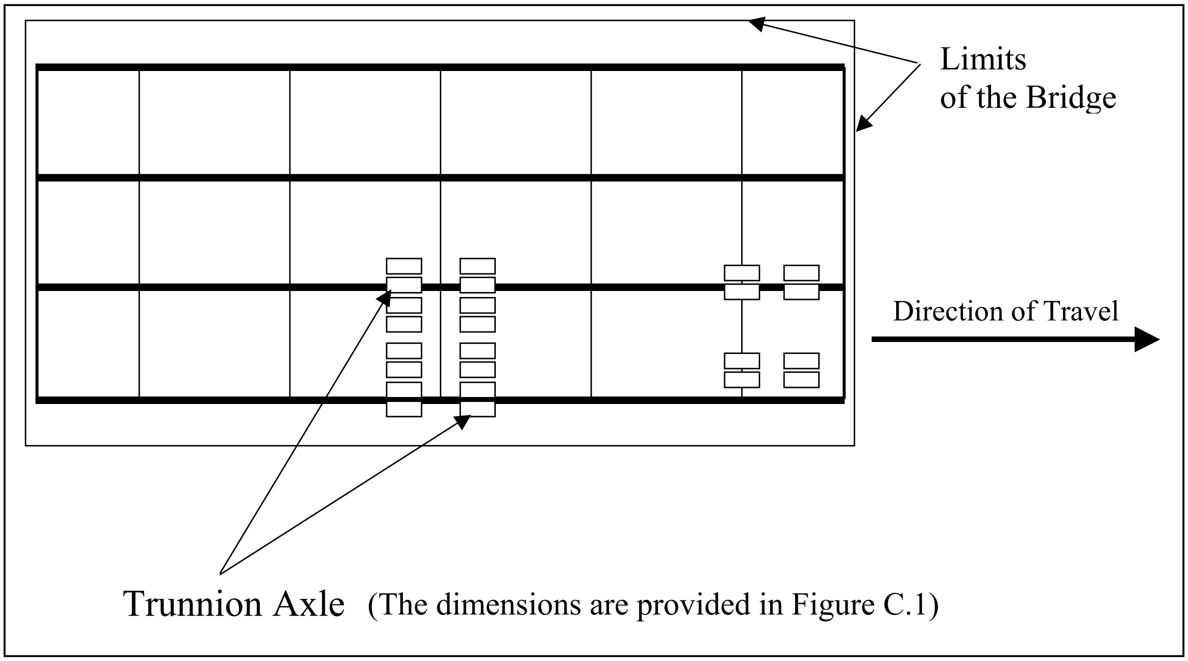

Figure C.3. Input Loads for Truck with Trunnion and Tandem Axles