SD92-06-F

SD Department of Transportation
Office of Research

The Effects of Increased Truck Tire Loads on Pavement

Study SD92-06
Final Report

Prepared by
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16. Abstract

Effect of increased use of super single and singled-out dual wheel assemblies on South Dakota's flexible pavement network was studied. A literature review was performed to document the history of tire loading laws in South Dakota and other neighboring states. A limited traffic survey was conducted to assess the present levels of the use of these wheel assemblies. Field tests and computer simulations were performed to assess the impact of the increased tire loads on South Dakota's flexible pavement network. An economic evaluation to assess the implications of the increased tire loads to South Dakota DOT was also made.

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TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

PROBLEM STATEMENT

Recent increases in tire load and pressure have raised questions regarding their effects on pavement performance, service life, and maintenance costs. There is continuing federal and state legislative interest in increasing the gross allowable truck load, axle loadings, and vehicle dimensions on the basis of energy conservation, availability of truck equipment, and efficiency within the trucking industry. In addition, there is evidence of an increasing use of Super Single (SS) and Singled-out Dual (SD) tires in place of the widely used Dual (DU) tires, and/or tag axles which has resulted in increased tire loads. Controversy exists regarding the benefits and lack of benefits associated with the potential impact of the increases on highway systems. A quantification of the overall effects of the increases would allow legislative decisions to be made using engineering and economic facts.

In view of the above, the South Dakota Department of Transportation (SD DOT) requested Austin Research Engineers (ARE), Inc. to conduct research and quantify the overall effect of the increased tire loads on pavement service life. The research was aimed at quantifying the effects of these changes on the applicability of current flexible pavement design procedures and their effect on pavement performance as related to South Dakota's highways.

PROJECT OBJECTIVES

The overall objective of this study was to evaluate the effect of increased truck tire loads on pavement service life. Increased tire loads in this study are defined as "carrying the same load on less tire width in configurations such as super singles, singled-out duals, and lift and/or tag axles." Also, for the purpose of this report, "Load" is defined as the force exerted on the pavement structure by the tire assembly. The detailed objectives of the study can be listed as:

1. Develop a history of truck size and weight legislation in South Dakota
2. Quantify the impact of increased tire loads relative to South Dakota's highways
3. Develop solution(s) which will reduce pavement damage due to increased tire loads

PROJECT SCOPE

The work in this project was divided into the following tasks:

Task 1. Literature Review

Task 2.	Traffic Studies
Task 3.	Estimate of Highway Damage
Task 4.	Project Growth and Highway Damage Cost under the Do-Nothing Alternative
Task 5.	Field Tests
Task 6.	Analysis of Field Data
Task 7.	Recommendations and Implementation Costs
Task 8.	Final Report and Executive Summary
Task 9.	Presentation of Findings and Results to South Dakota Department of Transportation Research Review Board

A brief description of each of the above tasks is given in the following paragraphs:

Task 1. Literature Review

This task was aimed at reviewing the existing legislative literature in order to determine the evolution of tire load laws in South Dakota. The end product from this task was a summary of the legislative history of the laws related to tire loads as well as vehicle dimensions.

Task 2. Traffic Studies

This purpose of this task was to perform a wheel configuration, pressure, and load survey at selected port-of-entry (POE) loadometer sites in South Dakota. Trucks which are stopped and weighed at a POE loadometer site were sampled for tire size and pressure, and their axle weights and configurations were recorded. In addition, any additional tire and weight data collected by the SD DOT or Highway Patrol personnel was also collected and evaluated.

Task 3. Estimate of Highway Damage

The work during this task consisted of comparing and evaluating the available deflection based damage models, develop evaluation criteria, and evaluate the selected model through computer simulations. The differences if any, in the damage caused by the three different wheel configurations (DU, SD, and SS) in use in South Dakota were also to be delineated.

Task 4. Project Growth and Highway Damage Cost

During this task, the results from Tasks 2 and 3 were used to project the growth of increased tire loads and their economic impact on the South Dakota flexible pavement network. Several alternative scenarios were analyzed.

Task 5. Perform Field Tests

In order to estimate load equivalency and pavement damage caused by SS and SD type tires on South Dakota pavements, an instrumented pavement section was established in South

Dakota. Pavement testing was accomplished four times throughout the year covering each major season. Deflection data was collected for two experimental matrices. The data obtained from these field tests was subsequently used to estimate pavement damage for South Dakota highways and conditions. The results of the field tests were compared to the computer generated solutions developed in Task 3.

Task 6. Analysis of Field Data

This task was used to perform statistical analyses of the data obtained in the field. Effects of all factors included in the experimental designs and their interactions were evaluated.

Task 7. Recommendations and Implementation Costs

Based on the results of the field testing and validation with computer simulations, recommendations for controlling tire loads, pressures, and configurations, if any, were made during this task.

Task 8. Final Report and Executive Summary

This task was aimed at summarizing the entire project and its findings in the form of a concise yet comprehensive final report. A brief executive summary has also been prepared as given in the section titled, "Executive Summary".

Task 9. Presentation of Findings and Results to SD DOT Research Review Board

This task consists of making a color slide presentation upon completion of the project to the SD DOT Research Review Board on the methodology used, the conclusions reached, and the benefits achieved with this project.

WHAT IS IN THIS REPORT

This report describes the approach and work undertaken to achieve the stated project objectives. The report outline does not follow the layout of tasks exactly as some of the later tasks in actuality were completed before the earlier ones.

An exposition of the background of load equivalency relationships including descriptions of directly applicable work which has been performed by others is presented in Chapter 2. Chapter 3 discusses the results of the literature survey performed during Task 1 of the study. A legislative history of tire load laws in South Dakota is reported in summary form. The results of tire survey performed during Task 2 of the study are reported in Chapter 4.

Chapter 5 describes the field testing and analysis of the field data. The selection of the damage model to determine load equivalency factors and the results of the computer simulations are reported in Chapter 6. The economic impact of the increases in tire loads have been evaluated in Chapter 7. Finally, the conclusions drawn from the research study are summarized in Chapter 8 along with recommendations for controlling the damage due to increases in tire loads.

This report is intended to provide a complete overview of the project by concisely describing the work performed and the results obtained. It provides interpretation of those results towards achieving the objectives of the project.

CHAPTER 2
BACKGROUND

INTRODUCTION

The concept of equivalent loads was introduced by AASHO and the Bureau of Public Roads soon after the AASHO Road Test was completed in 1961. Initial implementation of the concept was through the use of pavement performance equations that had been developed and reported by the road test staff. The resulting equivalent single axle load (ESAL) factors were published in the AASHTO Interim Guide for Design of Pavement Structures.

Major outputs from the AASHO Road Test were large quantities of observed data, and empirical equations for relationships between (1) pavement structure and traffic factors and (2) pavement response (e.g. deflection), pavement distress (e.g. cracking), and pavement performance (e.g. present serviceability index history). A unique feature of the road test was that traffic for each test section was constrained to a single vehicle type whose loading parameters (axle loads, axle configuration, tire pressure, transverse placement, speed, etc.) were fixed throughout the two year period of load application. Each loading condition was repeatedly applied to several pavement types (AC on granular base, AC on stabilized base, plain PCC, and reinforced PCC) and to several layer thickness combinations within each pavement type. Moreover, all combinations of pavement type and layer thickness were treated by at least two loading conditions, and some combinations were treated by as many as six different loading conditions. Thus, for fixed loading conditions, it was possible to observe the effects of certain structural factors on pavement response, distress, and performance. For fixed structural conditions, it was possible to observe the relative effects of different loading conditions.

The derived empirical equations thus expressed pavement response, distress, and performance for a given pavement type as functions of structural and loading factors. Although most of the equations contained terms for loading factors, only one loading condition could be entered for any particular application of the equation. Thus, the equations were for "fixed-loads", considering the repetitive effect of one type of load on the pavement structure. No effort was made by the road test staff to relate the findings to "mixed-load" conditions, such as those observed in practice where a pavement section receives combined application of several different types of loads during its lifetime, particularly since mixed-loading effects were not observed at the road test.

EQUIVALENCY FACTORS

In the practical world of pavement design and highway operations, loading conditions are in the mixed state rather than the fixed state. Loading conditions for an in-service pavement are generally different from vehicle-to-vehicle, hour-to-hour, day-to-day, and year-to-year throughout any phase of the pavement's life cycle. On the other hand, a large fraction of research-based knowledge of loading effects on pavement response/distress/performance is for fixed-load applications. A fundamental and important questions is therefore how best to translate research knowledge about fixed-load applications into a rational basis for pavement design and performance evaluation under mixed-load conditions.

The most widely-used answer to this question has been the use of load equivalency factors or LEF's. The following is a general definition of LEF.

Suppose that two different fixed-load conditions (Lx and Ly) are applied repeatedly to separate pavements that have the same structural design and the same environment. Suppose also that when a given distress variable (D) reaches a specified value, D*, some type of pavement maintenance or rehabilitation is required. Thus D* may be called a "failure" level for the distress mode represented by D. Finally, suppose the respective pavements reach the D* condition after Nx applications of loading condition Lx and Ny applications of loading condition Ly. Then, by definition, Ny and Nx are equivalent load applications relative to D*. The ratio Ny/Nx is the load equivalence factor for Lx relative to Ly, and the ratio Nx/Ny is the load equivalence factor for Ly relative to Lx. If Ly is a "standard" loading condition (e.g., 18,000-lb (8,172-kg) single axle load), then Ny/Nx is the factor for converting Nx to an equivalent number of standard Ny load applications. From this definition, it is clear that the load equivalence concept is relative to a particular mode of distress (D), a particular level of the selected distress mode (D*), and to fixed structural and environmental conditions.

Another approach to the mixed-load question is through the use of Miner's criterion for damage ratios associated with individual fixed-load conditions [*1*]. It must be understood however, that the damage-ratio approach is a special case of the load equivalence and response equivalence approach.

Virtually all reported load equivalence relationships and factors have been <u>derived</u> from pavement response/distress/performance relationships that represent fixed response/load conditions. From the general definition for LEF, it can be seen that the required relationships are those which predict the number of applications, under a given loading condition, at which a particular distress/performance variable will reach a specified failure or terminal level. The ratio of the prediction for the standard loading condition to the prediction for loading condition X is then the load equivalency factor for loading condition X. It is quite clear that derived LEF's are not only dependent upon the distress variable and its failure level, but also upon the relationships (equations) that have been used for the derivations.

CHAPTER 3
LITERATURE REVIEW

This chapter summarizes the results of a literature review conducted to study the legislative changes in vehicle dimensions and weights with time as per Task 1 of the study. The use of super singles and singled-out duals was also studied as a part of the literature search. This literature review covers material obtained not only for the State of South Dakota but other neighboring states as well.

The literature review basically consisted of gathering information regarding the state regulations governing vehicle loads and dimensions. Wherever possible, information on the history of these regulations was also collected. Literature from the following states, other than South Dakota, was also obtained:

1. Minnesota
2. North Dakota
3. Nebraska
4. Utah
5. Wyoming

Information collected during the survey consisted of the following categories:

1. Load per Unit Width of Tire
2. Vehicle Axle Loads
3. Gross Vehicle Weight
4. Vehicle Dimensions

A discussion of the information gathered is presented in the following paragraphs.

TIME HISTORY OF TRUCK LAWS IN SOUTH DAKOTA

The period used for collecting information related to truck loading and dimension regulations time history was selected as 1960 onwards. Information was obtained from the SD DOT in the form of session laws governing the use of motor vehicles in the State of South Dakota. Although information was available from 1930 onwards, it was not always consistent. As a result, it was decided to restrict the review period to 1960 onwards. The specific years on which the following discussion is based are: 1960, 1967, 1976, 1984, 1989, and 1992.

A review of the gathered literature revealed that regulations could be divided into two distinct periods, 1960 to 1976 and 1984 to 1992. A summary of the laws during each of these periods is reported in Tables 3.1 and 3.2, respectively. Each category of information is individually discussed in the following paragraphs:

Weight per Unit Width of Tire

The current motor vehicle laws in South Dakota limit the maximum weight per unit width of tire to 600 lb/in. This limit remained at 600 lb/in not only throughout the period of survey, i.e., from 1960 to date, but during earlier years as well, dating back to as early as 1943. Although, there have been some slight changes in the verbiage over the years, the weight per unit tire width has not changed.

Vehicle Axle Loads

For the purpose of specifying maximum axle loads, a distinction was made between low pressure (less than 100 psi) and high pressure (more than 100 psi) tires from 1960 through 1976. The maximum load on a single axle was restricted to 18,000 lb for low pressure pneumatic tires with an axle spacing equal to or more than 8 ft in 1960 and 1967. It remained the same for interstate and defense highways in 1976, however, for other highways, it was increased to 20,000 lb. For high pressure pneumatic tires with an axle spacing equal to or more than 8 ft, the corresponding limit was 16,000 lb, regardless of the type of highway. For pneumatic tires with an axle spacing of less than 8 ft, the maximum axle load on a single axle was designated as 16,000 lb in 1960 and 1967. In 1976, this limit was increased to 17,000 lb for highways other than the interstate and defense highways. In 1984, the distinction between low and high pressure tires was abolished and the single axle load limit was increased to 20,000 lb.

A tandem axle load limit of 34,000 lb was established in 1984, while the axle loads for a group of more than two axles had to be determined using the bridge formula:

$$W = 500 \left[\frac{L.N}{N-1} + 12.N + 36 \right] \tag{3-1}$$

In applying the above formula, W equals the overall gross weight on any group of two or more consecutive axles to the nearest 500 lb, L equals the distance measured longitudinally to the nearest foot from the foremost axles to the rearmost axle in a group of two or more consecutive axles, and N equals the number of axles in the group under consideration.

Gross Vehicle Weight

The gross vehicle weight was controlled through a table of loads from 1960 through 1976. The values in this table depended on axle spacing in 1960 and 1967 while in 1976, another factor, the number of axles was introduced. The maximum gross vehicle weight allowed in 1960 and 1967 was 73,280 lb, while in 1976 it was increased to 95,000 lb with a limitation that on interstate and defense routes, the limit would still be 73,280 lb. In 1984, the limit for interstate and defense highways was increased to 80,000 lb, while the limit for other highways would be determined using the bridge formula given above.

Vehicle Dimensions

These consist of the width, height and length of the vehicle. As can be seen in Tables 3.1 and 3.2, from 1960 to 1976, the vehicle width, measured at its widest point, either of the vehicle or the load and excluding any required safety equipment, was limited to a maximum of 96 in or 8 ft. From 1984 onwards, the width limit was increased to 102 in or 8 ft 6 in. The maximum height of a vehicle, including the load thereon, was limited to 13 ft in 1960, and was changed to 13 ft 6 in between 1967 to 1984. In 1989, the maximum height limit was increased to 14 ft and remains the same as of now.

The maximum length of a vehicle depends on the type of vehicle, whether a single truck or a combination vehicle. For single trucks, the maximum length, inclusive of front and rear bumpers, was limited to 35 ft from 1960 to 1976. In 1984, it was increased to 45 ft and remains the same as of 1993.

The maximum length limitation on combination vehicles is divided into several rules addressing various types of combinations. A summary of these rules is given below (see Tables 3.1 and 3.2):

- The overall length of a truck tractor-semitrailer combination was limited to 55 ft in 1960. In 1967, this limit was increased to 60 ft. From 1989 onward, the limit on overall length of the truck tractor-semitrailer combination was dropped.

- The overall length of any other two-unit combination vehicles was restricted to 60 ft from 1960 to 1984. From 1989 onward, this limit was dropped.

- The overall length of any three-unit combination vehicle (truck trailer-semitrailer-semitrailer or truck trailer-semitrailer-trailer) was also limited to 60 ft from 1960 to 1976. No such limitation is found in regulations from 1984 onwards.

- From 1984 onwards, the length of a semitrailer unit operating in a truck tractor-semitrailer combination was restricted to be 53 ft.

- Each trailer unit operating in a truck tractor-trailer-trailer combination was limited in length to 28 ft 6 in from 1984 onwards.

- Although, no restrictions were found on the overall length of a truck tractor-trailer-trailer or truck tractor-trailer combination until 1984, in 1989 it was limited to 80 ft and remains at that value as of 1993.

- From 1989 onwards, the length of each semitrailer-semitrailer or semitrailer-trailer unit operating in a truck tractor-semitrailer-semitrailer or truck tractor-semitrailer-trailer combination, exclusive of the length of the truck tractor, has been limited to 81 ft 6 in.

- In 1984, the first semitrailer unit in a truck tractor-semitrailer-semitrailer combination was restricted to 45 ft, while the second semitrailer unit was restricted to 28 ft 6 in. However, as of 1989, both units are restricted to be a maximum of 45 ft long with weight of second unit not being more than the weight of first unit by 3,000 lb.

- In 1984, the length of a semitrailer unit in a truck tractor-semitrailer-trailer combination was restricted to 45 ft, while that of the trailer unit was restricted to 28 ft 6 in. However, as of 1989, both units are restricted to be a maximum of 45 ft in length with weight of the second unit not being more than that of first unit by 3,000 lb.

TRUCK LAWS IN STATES OTHER THAN SOUTH DAKOTA

As mentioned earlier, information on the current truck tire loading regulations in several neighboring states was also collected during this study for comparison purposes. These states included: Minnesota, North Dakota, Nebraska, Utah, and Wyoming. Information collected included axle loads, gross vehicle weight, and tire loads. This data is presented in summary form in Table 3.3 and discussed in the following paragraphs.

Minnesota

In Minnesota, the maximum load allowed on any single axle in a group is 18,000 lb, however, on designated local routes and state trunk highways, this limit is increased to 20,000 lb. Certain other restrictions are also in effect. The maximum load on any axle of a tridem is limited to 15,000 lb. Also, for vehicles to which an additional axle was added before June 1, 1981, the maximum axle load is set at 16,000 lb provided the total load on the tridem does not exceed 39,900 lb.

The maximum load per unit width of a tire is limited to 500 lb/in, however, on the foremost and rearmost steering wheels the limit is 600 lb/in. Also for vehicles manufactured before August 2, 1991, the maximum load per unit width of tire is currently set at 600 lb/in, however, this figure will be reduced to 500 lb/in after July 31, 1996.

North Dakota

In North Dakota, the maximum permissible load on any single axle is 20,000 lb. All axles in a group spaced 40 in or less apart are considered one axle while axles spaced 8 ft or more are considered as individual axles. Each axle in a group of axles spaced more than 40 in but less than 8 ft apart is allowed to carry a maximum of only 17,000 lb. The gross weight of two or more axles is determined based on the bridge formula reported earlier [see Equation (3-1)]. Also, on highways other than the interstate, two axles spaced 8 ft or more apart may have a combined gross weight not to exceed 40,000 lb, while the load on three axles is not to exceed 48,000 lb.

The maximum gross vehicle weight on state highways is 105,500 lb, controlled through a table of loads that is dependent on the spacing and total number of axles. On interstate highways, however, this limit is reduced to 80,000 lb. This reduced limit also applies to county and other local highways unless otherwise posted, but not to exceed 105,500 lb in any case.

The load per unit width of tire is set at 550 lb/in.

Nebraska

The State of Nebraska also restricts the maximum load on any single axle in a group to 20,000 lb, however, the limiting values for groups of axles are dictated through tables depending on axle spacing and the number of axles in a group.

The maximum gross vehicle weight is set at 95,000 lb, however, for interstate and defense highways, this limit is reduced to 80,000 lb.

There are no regulations regarding tire size or the maximum load per unit width of tire in Nebraska.

Utah

In Utah, the maximum load on a single axle is limited to 20,000 lb while that on a tandem axle is restricted to 34,000 lb. There are no regulations on more than two axles and the gross vehicle weight.

The maximum load per unit width of tire is set at 600 lb/in for vehicles not requiring a permit. For vehicles requiring a permit to operate, this limit is 500 lb/in for tire widths of 11 in or more and 450 lb/in for tire widths of less than 11 in. Although tire load regulations had been present in Utah since late 1980's, the present reduced limits were introduced in 1990.

Wyoming

The loading regulations in Wyoming specify the maximum load on a single axle to be 20,000 lb. For tandem and tridem axles the maximum values are specified as 36,000 and 42,500 lb, respectively.

No regulations were found on the gross vehicle weight while the maximum load per unit width of tire is set at 750 lb/in on steering axle tires and 600 lb/in on all other tires.

REVIEW OF LITERATURE FROM OTHER SOURCES

WASHTO Regulations [*2*]

The Western Association of State and Transportation Highway Officials (WASHTO) approved a guide for uniform laws and regulations governing truck size and weight among the WASHTO states on June 26, 1993. This published guide recognizes the growing concern about industry's gradual conversion to super single and singled-out dual tires and has made several recommendations for consideration by the member states. A summary of these regulations for vehicles in regular operation is provided in the following paragraphs.

Load per Unit Width of Tire

The maximum load per unit width of tire has been recommended to be set at:

Steering axles	-	600 lb/in
All other axles	-	500 lb/in

Axle Loads

The maximum axle loads for single and tandem axles have been recommended to be 20,000 lb and 34,000 lb, respectively. The load on any group of two or more consecutive axles on a vehicle or combination of vehicles is restricted through the bridge formula as reported earlier [see Equation (3-1)].

Gross Vehicle Weight

The maximum gross vehicle weight of a single or combination vehicle has been set at 80,000 lb.

K-TRAN Study [*3*]

K-TRAN performed a detailed research study in 1992 on the effects of super single tires on pavement performance and vehicle regulatory legislation. A summary of some of the important points discussed in this report are summarized below:

1. The most correct approach to the regulation of truck wheel loads would be based on tire contact stresses acting on the pavement surface. These contact stresses are dependent upon wheel load, stiffness of the tire structure, vehicle speed, tire pressure, and the tire footprint. However, at present, there are no reliable and economic means of determining the tire contact pressures and their variation.

2. Until techniques for determining actual contact pressures are available, the regulation of tire pressure in conjunction with wheel load per unit width of tire has merit from a pavement engineering point of view.

3. Super single tires have been found to be more damaging as compared to dual tires.

4. WASHTO is currently considering a 500 lb/in tire load regulation. The proposal also specifically prohibits the singling out of conventional duals.

Table 3.1. Motor Vehicle Regulations History from 1960 to 1976

Description	Year 1960 [1]	1967	1976	Section Reference
Maximum Width, ft	8.0	8.0	8.0	32-22-3
Maximum Height, ft	13.0	13.5	13.5	32-22-14
Maximum Length, ft				
Single Truck	35.0	35.0	35.0	32-22-5
Multiple Unit Combinations				
TT-ST (Overall)	55.0	60.0	60.0	32-22-8
Any Other 2-Unit Combo	60.0	60.0	60.0	32-22-8
Any 3-Unit Combo (TT-ST-ST or TT-ST-T)	60.0	60.0	60.0	32-22-10
Maximum Axle Load, kip				
Low Pressure Pneumatic Tire & Spacing >= 8 ft	18.0 [2]	18.0 [2]	20.0 [5]	32-22-16
High Pressure Pneumatic Tire & Spacing >= 8 ft	16.0 [3]	16.0 [3]	16.0	32-22-16
Pneumatic Tire & Spacing < 8 ft	16.0	16.0	17.0 [6]	32-22-16
Maximum Gross Vehicle Weight, kip	73.28 [4]	73.28	95.0 [7,8]	32-22-17
Maximum Weight per Tire Width, lb/in	600	600	600	32-22-21

Notes:

1. For 1960, the reference is Section 44.0336.
2. Pressure <100 psi (Section 32-22-23).
3. Pressure > 100 psi (Section 32-22-23).
4. Table - depends on axle spacing.
5. Interstate and defense highways = 18 kip.
6. Interstate and defense highways = 16 kip.
7. Table - depends on axle spacing and no. of axles.
8. Interstate and defense highways = 73.28 kips

Legend:

TT = Truck Tractor
T = Trailer
ST = Semi-Trailer

Table 3.2. Motor Vehicle Regulations History from 1984 to 1992

Description	Year 1984	Year 1989	Year 1992	Section Reference
Maximum Width, ft	8.5	8.5	8.5	32-22-3
Maximum Height, ft	13.5	14.0	14.0	32-22-14
Maximum Length, ft				
Single Truck	45.0	45.0	45.0	32-22-5
Multiple Unit Combinations				
Tip to Tail Length of a TT-ST	60.0	60.0	60.0	32-22-8
Any Other 2-Unit Combo	60.0	60.0	60.0	32-22-8
ST Unit in TT-ST	53.0	53.0	53	32-22-8.1
Each T Unit in TT-T-T	28.5	28.5	28.5	32-22-8.1
Tip to Tail Length of a TT-T-T	NR	80.0	80	32-22-8.1
Tip to Tail Length of a TT-T	NR	80.0	80	32-22-8.1
Tip to Tail Lenght in a TT-ST-ST or TT-ST-T	NR	81.5	81.5	32-22-8.1
Each ST or T Unit in TT-ST-ST or TT-ST-T	NR	45.0	45	32-22-8.1
First ST Unit in TT-ST-ST	45.0	45.0	45.0	32-22-8.1
Second ST Unit in TT-ST-ST	28.5	28.5	28.5	32-22-8.1
ST Unit in TT-ST-T	45.0	45.0	45.0	32-22-8.1
T Unit in TT-ST-T	28.5	28.5	28.5	32-22-8.1
Maximum Axle Load, kip				
Single Axle	20.0	20.0	20.0	32-22-16
Tandem Axle	34.0	34.0	34.0	32-22-16
More than 2 Axles	Formula [1]	Formula [1]	Formula [1]	32-22-16
Maximum Gross Vehicle Weight, kip	80.0 [2]	80.0 [2]	80.0 [2]	32-22-16
Maximum Weight per Tire Width, lb/in	600	600	600	32-22-21

Notes:
1. Formula used is the Bridge Formual per Section 32-22-16.1.
2. On Interstate highways.

Legend:
TT = Truck Tractor
T = Trailer
ST = Semi-Trailer

Table 3.3. **Current Motor Vehicle Regulations for Neighboring States**

Description	State				
	MN	ND	NE	UT	WY
Maximum Axle Load, kip					
Single Axle	18.0 [1,2]	20.0 [4]	20.0 [8]	20.0	20.0
Tandem Axle	NR	Formula [5]	Table [9]	34.0	36.0
More than 2 Axles	NR [2]	Formula [6]	Table [9]	NR	42.5
Maximum Gross Vehicle Weight, kip		105.5 [7]	95.0 [9,10]	NR	NR
Maximum Weight per Tire Width, lb/in	500 [3]	550	NR	600 [11]	600 [12]

Notes:

1. a) Any axle in a group. b) Designated local routes and state trunk highways = 20.0 kip.
2. a) Any axle of a tridem = 15.0 kip. b) Vehicles to which an additional axle added before June 1, 1981 = 16.0 kip with total load on tridem <= 39.9 kip.
3. Steering axles and vehicles manufactured before August 2 ,1991 = 600 lb/in. All axles at 500 lb/in after July 31, 1996.
4. a) Axles spaced <= 40 in. considered one axle. b) Axles spaced 8 ft. or more considered individual axles. c) Axles spaced <8 ft. and > 40 in. = 17.0 kip
5. On highways other than interstate, two axles spaced >=8 ft., maximum = 40.0 kip.
6. On highways other than interstate and three or more axles, maximum = 48.0 kip.
7. Interstate = 80.0 kip. County and other local highways = 80.0 kip unless otherwise posted, but not to exceed 105.5 kip.
8. Any axle in a group spaced within a 40 inch spacing.
9. Tabel dependent on axle spacing and no. of axles in a group.
10. Interstate and defense highways = 80.0 kip.
11. For vehicles requiring permit, maximum = 500 lb/in. for tire size >= 11 in. and 450 lb/in. for tire size < 11 in.
12. Tires on steering axles = 750 lb/in.

Legend:

NR = No regulation found.
NA = Not applicable.
Formula = Bridge formula. See text.

MN = Minnesota
ND = North Dakota
NE = Nebraska
UT = Utah
WY = Wyoming

CHAPTER 4
TRAFFIC STUDY

The work reported in this chapter was performed under Task 2 of the project. The results of traffic surveys performed at several port-of-entry (POE) loadometer sites are summarized.

SURVEY RESULTS AND ANALYSIS OF DATA

Traffic surveys were conducted to collect information on the various tire and vehicle characteristics. During these surveys, trucks which are stopped and weighed at POE loadometer sites were counted and sampled for the following:

1. Wheel configuration, tire size and tire pressure
2. Tire footprint dimensions, and,
3. Wheel loads and axle configurations.

Traffic data was collected at the following five sites:

1. Yankton, US 81
2. Tilford POE
3. I-90, Mile Post 302, Aurora County
4. Milbank POE
5. Sisseton POE

Table 4.1 summarizes the number of trucks of different axle count observed at each of the above sites and the total number of trucks observed. This table also gives details on the date on which the survey was performed and the percentage of trucks in each axle count.

It can be seen that majority of the trucks counted were 5-axle trucks, amounting to 71.9 percent of the total. The remaining order was: 2-axle (11.7 percent), 3-axle (8.3 percent), 4-axle (3.5 percent), 6- or more-axle (3.0 percent), and 6-axle (1.6 percent). The ranking of trucks other than 5-axle trucks varied among the various sites, though.

Toward the end of the study, a separate survey was performed at the Tilford POE location since it was realized that not enough trucks were sampled at this location earlier. The new survey was performed for two days and basically yielded a count of the number of axles fitted with the various types of wheel configurations studied. The results of this survey are reported in Table 4.2.

The summary statistics of the data collected are reported in Table 4.3. The data reported includes tire widths, tire pressures, tire footprint dimensions, wheel loads, and weight per unit width of tire. The weight per unit width of tire was computed using the wheel load and the rated width of tire. Table 4.3 reports the following attributes for each of the parameters for each type of tire (regular singles, duals, super singles, and singled-out duals):

1. Minimum and maximum values, and total count
2. Averages and standard deviations, and,
3. 95-percent confidence interval limits.

The summary statistics computed are discussed in the following paragraphs.

Tire Composition

The proportion of various types of tires observed in the sampled traffic as reported in Tables 4.2 and 4.3 is as follows (numbers in parentheses indicate the results of the subsequent Tilford POE survey):

Regular Singles (RS)	-	23.4 percent	(19.9 percent)
Duals (DU)	-	56.0 percent	(70.3 percent)
Super Singles (SS)	-	17.9 percent	(6.2 percent)
Singled-out Duals (SD)	-	2.8 percent	(3.6 percent)

It can be seen that these two percentages differ from each other significantly for DU and SS wheel configurations. However, in view of the limited nature of the surveys performed during this study, these figures should be considered as ranges only. A detailed survey would need to be performed to establish the exact proportions of the various wheel configurations in the traffic mix.

Tire Width

Tire widths reported are the rated tire widths. The average tire widths for each type tire were as follows:

Regular single (RS) tires	-	11.1 in
Dual (DU) tires	-	11.1 in
Super single (SS) tires	-	15.2 in
Singled-out dual (SD) tires	-	10.8 in

Standard deviations for tire width ranged from 0.4 in for SD tires to 1.5 in for RS tires.

Frequency distributions of tire width for different wheel configurations are shown in Figures 4.1 through 4.4. It can be seen that the modal tire width for RS, DU, and SS type tires is 11 in, while the modal tire width for SS tires is 15 in. Most of the data seems to be normally distributed.

Tire Pressure

Tire pressure statistics reported in Table 4.2 indicate average tire pressure of 102 to 106 psi for RS, DU, and SD type tires. The average tire pressure for the SS tires is considerably higher, reported at 124 psi. As in the case of tire width, the variation in tire pressure for RS tires is the highest, with standard deviations ranging from 9 psi for SD to 15 for RS tires.

Figures 4.5 through 4.8 show the frequency distribution of tire pressures for the various types of tires surveyed. The modal tire pressure for RS, DU, and SD type tires is approximately 110 psi, while for SS tires, it is approximately 130 psi. This indicates the damaging effect that a super single tire will have on the pavement. Most of the data seems to be normally distributed.

Tire footprint Dimensions

Tire footprint dimensions, especially tire footprint widths, were measured for comparison with the rated dimensions and to evaluate their effect on the pavement.

Statistics reported in Table 4.2 indicate average tire footprint lengths of 10.2 to 11.5 in with the standard deviations ranging from 1.3 to 1.5 in for different type tires. The tire footprint length seems to be relatively independent of the wheel configuration.

The frequency distributions of tire footprint length are shown in Figures 4.9 through 4.12 for the different wheel configurations. The modal tire footprint lengths have been found to be 12, 10, 10, and 11 in, respectively for RS, DU, SS, and SD type tires. Most of the data seems to be normally distributed.

The tire footprint width averages between 8.1 to 9.1 in for RS, DU, and SD type tires, however, for SS tires, the average tire footprint width is 10.9 in. The standard deviations range from 0.7 in for singled-out dual tires to 1.0 in for super singles.

Figures 4.13 through 4.16 show the frequency distribution of tire footprint lengths for the different wheel configurations. The modal imprint lengths for RS, DU, and SD type tires are 9, 8, and 9 in, respectively. For SS tires, the modal imprint length has been found to be 11 in. Most of the data seems to be normally distributed.

In almost all instances, the tire footprint widths are smaller than the rated width of a tire, supporting the fact that the contact pressure on the surface of the pavement is not equal to the tire pressure. The contact pressure has been found to be dependent on the physical make up of a tire as well as the tire pressure.

Wheel Load

The wheel loads seem to vary considerably, with the maximum average wheel load determined to be 8403 lb for the super single tires. The other averages were 5175, 4478, and 4040 lb, respectively, for the RS, DU, and SD type tires. The standard deviations have been found to range between 413 lb for the singled-out dual tires to 3098 lb for the super singles. Once again, the damaging effect of the super singles is evident.

Frequency distributions of wheel loads for the various wheel configurations are shown in Figures 4.17 through 4.20. The modal wheel loads range from approximately 4000 to 6000 lb for the RS, DU, and SD type tires, however, for SS tires, the modal wheel load is approximately 7000 lb further reinforcing the conclusion that super single tires have the most damaging effect on pavement life. Most of the data seems to be normally distributed.

Weight per Unit Width of Tire

The wheel load and tire width data was further analyzed to determine the weight per unit width of tire. Statistics reported in Table 4.2 indicate that, for all wheel configurations other than super singles, the load per unit width of tire ranges from 375 to 464 lb/in. For super single tires, this value has been found to be 554 lb/in. However, the range of variations observed indicated a very wide variation for super singles (342 to 873 lb/in), as compared to any other tire type. The standard deviations have been found to range between 42 to 248 lb/in. Once again, the super single tires are seen to be most damaging.

Axle Configurations and Loads

The various types of axle configurations observed during the survey along with the computed axle loads have been reported in Table 4.3. The average values of axle loads seem to be within the limits set by the State of South Dakota. However, for tandem axles with dual and super single tires, the maximum axle loads have been found to exceed the allowable limit of 34000 lb.

The frequency distribution of axle loads for selected single and tandem axles are shown in Figures 4.21 through 4.24. All the modal values are within the allowable limits.

CONCLUSIONS

As a result of the traffic survey and subsequent analysis of the data, the following conclusions can be drawn:

1. The proportion of super single and singled-out dual tires in the sampled traffic is 17.9 and 2.8 percent, respectively. A detailed traffic survey should, however, be performed to get a better picture of the actual percentages

representative of the entire South Dakota network.

2. The super single tires are considered to be most damaging to the pavement, based on their increased tire pressures as well as wheel loads.

3. Averages and standard deviations for various parameters including tire width, tire pressure, tire footprint dimensions, wheel loads, load per unit width of tire, and axle loads have been reported.

4. Frequency distribution of the data indicates most of the data is normally distributed.

Table 4.1. Traffic Counts Summary

Site	Date Collected	No. of Axles	No. of Trucks	Percent Trucks
Yankton US 81	17-Sep-92	2	19	14.6
		3	30	23.1
		4	3	2.3
		5	72	55.4
		6	4	3.1
		>6	2	1.5
		Total	130	100.0
Yankton US 81	21-Sep-92	2	5	4.2
		3	12	10.1
		4	4	3.4
		5	95	79.8
		6	2	1.7
		>6	1	0.8
		Total	119	100.0
Tilford P.O.E.	15-Sep-92	2	0	0.0
		3	0	0.0
		4	0	0.0
		5	3	42.9
		6	0	0.0
		>6	4	57.1
		Total	7	100.0
Tilford P.O.E.	17-Sep-92	2	1	11.1
		3	1	11.1
		4	2	22.2
		5	2	22.2
		6	1	11.1
		>6	2	22.2
		Total	9	100.0
I-90 MP302 Aurora County	29-Sep-92	2	44	17.4
		3	8	3.2
		4	5	2.0
		5	189	74.7
		6	2	0.8
		>6	5	2.0
		Total	253	100.0
I-90 MP302 Aurora County	30-Sep-92	2	19	10.2
		3	8	4.3
		4	5	2.7
		5	144	77.0
		6	1	0.5
		>6	10	5.3
		Total	187	100.0

Table 4.1. Traffic Counts Summary (Continued)

Site	Date Collected	No. of Axles	No. of Trucks	Percent Trucks
Milbank P.O.E.	30-Sep-92	2	7	8.0
		3	9	10.3
		4	5	5.7
		5	61	70.1
		6	3	3.4
		>6	2	2.3
		Total	87	100.0
Sisseton P.O.E.	17-Sep-92	2	6	8.3
		3	4	5.6
		4	6	8.3
		5	55	76.4
		6	1	1.4
		>6	0	0.0
		Total	72	100.0
All Sites Combined	NA	2	101	11.7
		3	72	8.3
		4	30	3.5
		5	621	71.9
		6	14	1.6
		>6	26	3.0
		Total	864	100.0

Table 4.2. Traffic Summary Data from the Tilford Port of Entry

Wheel Configuration	Total No. of Axles Counted		Total	Percent (%)
	Day 1	Day 2		
Regular Singles	190	214	404	19.9
Super Singles	50	76	126	6.2
Sinlged-out Dual	31	43	74	3.6
Dual	680	746	1,426	70.3

Table 4.3. Traffic Data Summary Statistics

Tire Type	Attribute	Tire Width (in)	Tire Pressure: First Tire (psi)	Tire Pressure: Second Tire (psi)	Tire Footprint Length: First Tire (in)	Tire Footprint Length: Second Tire (in)	Tire Footprint Width: First Tire (in)	Tire Footprint Width: Second Tire (in)	Wheel Load (lb)	Wt./Unit Width (lb/in)
RS - Regular Singles	Minimum	8.0	44	NA	7.5	NA	7.0	NA	2170	197
(% of Total = 23.4%)	Maximum	18.0	130	NA	15.0	NA	13.0	NA	7860	671
	Count	51	51	NA	51	NA	51	NA	51	51
	Average	11.1	106	NA	11.5	NA	9.1	NA	5175	464
	Std. Dev.	1.5	15	NA	1.3	NA	1.2	NA	1190	90
	LL Conf. Int.	6.6	61	NA	7.8	NA	5.4	NA	1653	199
	UL Conf. Int.	15.7	151	NA	15.3	NA	12.7	NA	8697	729
DU - Duals	Minimum	9.0	46	0	7.0	8.3	6.8	6.8	1140	104
(% of Total = 56.0%)	Maximum	15.0	130	122	14.5	14.8	10.0	10.0	9650	877
	Count	122	122	107	122	67	122	67	122	122
	Average	11.1	102	96	10.2	11.1	8.4	8.6	4198	379
	Std. Dev.	0.8	11	29	1.5	1.2	0.7	0.6	1886	165
	LL Conf. Int.	8.6	70	10	5.8	7.6	6.5	6.7	-1385	-110
	UL Conf. Int.	13.5	133	182	14.6	14.5	10.4	10.4	9781	867
SS - Super Singles	Minimum	13.0	100	NA	9.0	NA	9.0	NA	5125	342
(% of Total = 17.9%)	Maximum	18.0	140	NA	14.0	NA	14.0	NA	9130	537
	Count	39	39	NA	39	NA	39	NA	39	39
	Average	15.2	124	NA	10.7	NA	10.9	NA	6438	423
	Std. Dev.	0.9	10	NA	1.3	NA	1.0	NA	941	49
	LL Conf. Int.	12.6	94	NA	7.0	NA	7.8	NA	3654	278
	UL Conf. Int.	17.8	154	NA	14.5	NA	14.0	NA	9222	568
SD - Singled-out Duals	Minimum	10.0	86	NA	9.0	NA	7.0	NA	3390	308
(% of Total = 2.8%)	Maximum	11.0	110	NA	13.0	NA	9.0	NA	4560	415
	Count	6	6	NA	6	NA	6	NA	6	6
	Average	10.8	102	NA	10.8	NA	8.1	NA	4040	375
	Std. Dev.	0.4	9	NA	1.4	NA	0.7	NA	413	42
	LL Conf. Int.	9.6	76	NA	6.6	NA	5.9	NA	2817	251
	UL Conf. Int.	12.0	128	NA	15.1	NA	10.3	NA	5263	499

Notes:

1. LL Conf. Int. = Lower limit for 95 percent confidence interval about mean.
2. UL Conf. Int. = Upper limit for 95 percent confidence interval about mean.
3. Second tire values are applicable for dual tires only.
4. Weight per unit width of tire computed using the rated tire width.

Table 4.4. Axle Loads Summary Statistics

Axle Type	Min.	Max.	Count	Avg.	Std. Dev.	LL Conf. Int.	UL Conf. Int.
DU	4,100	19,300	10	10,264	5,663	(6,498)	27,026
DU-DU	4,560	36,000	41	16,768	7,891	(6,588)	40,124
RS	4340	15,720	40	10,611	2,343	3,677	17,545
RS-DU	11,080	11,080	1	11,080	NA	NA	NA
RS*-DU-DU	23,870	27,090	3	25,957	1,809	20,601	31,312
SD	6,780	6,780	1	6,780	NA	NA	NA
SD-DU-DU	22,020	25,960	2	23,990	2,786	15,743	32,237
SD-SD	15,660	15,660	1	15,660	NA	NA	NA
SS	12,940	12,940	1	12,940	NA	NA	NA
SS-SS	20,500	34,860	17	26,355	3,566	15,799	36,910

* Lift Axle

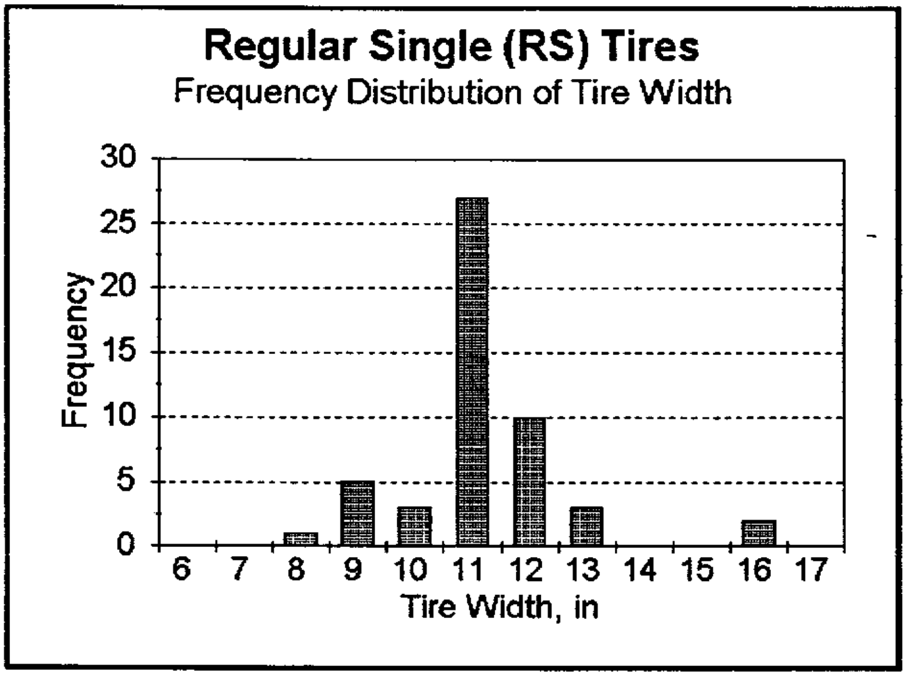

Figure 4.1. Frequency Distribution of Tire Width for Regular Single (RS) Tires

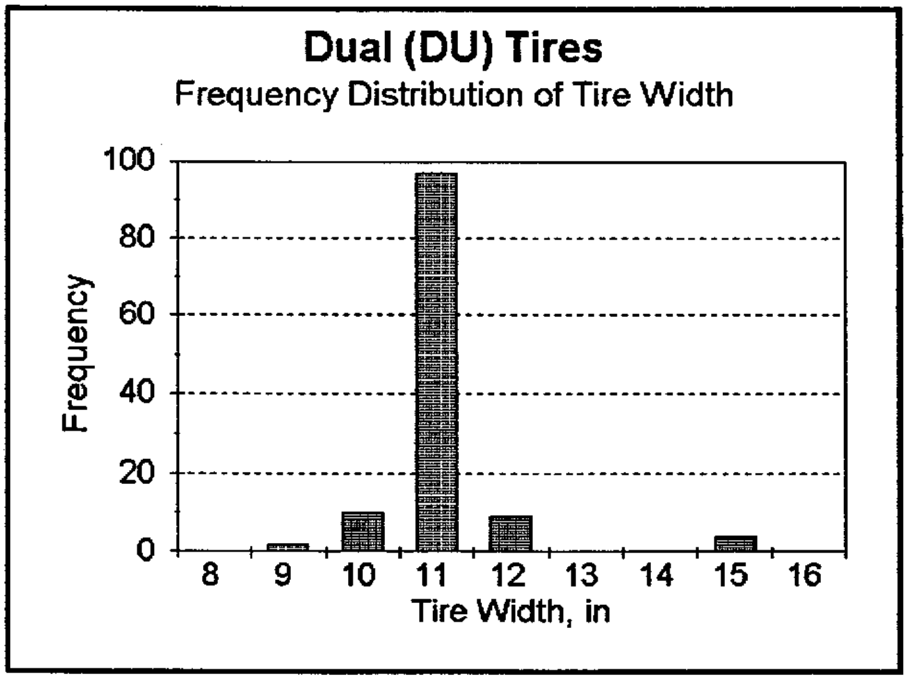

Figure 4.2. Frequency Distribution of Tire Width for Dual (DU) Tires

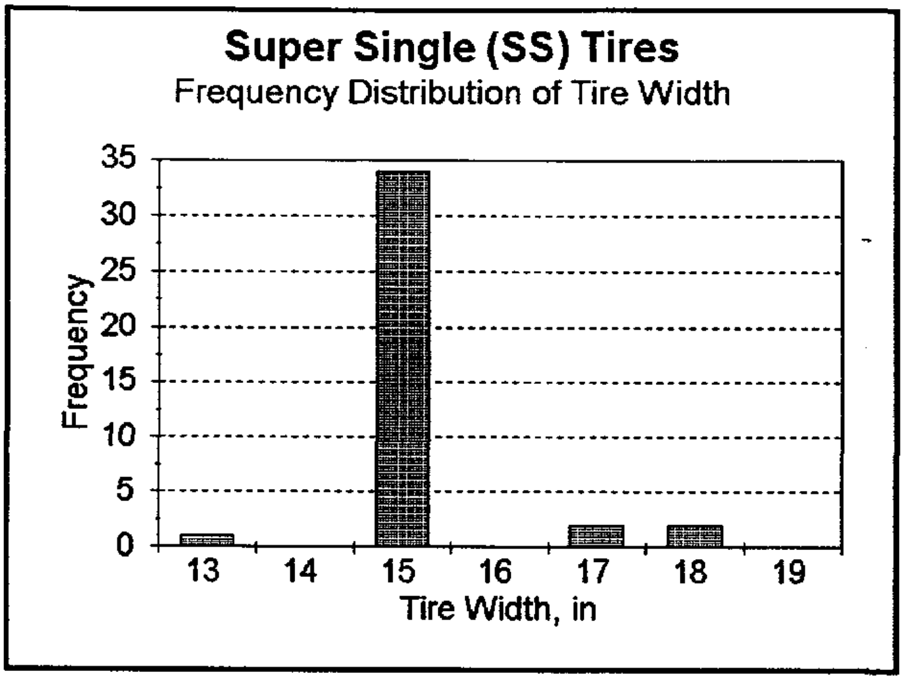

Figure 4.3. Frequency Distribution of Tire Width for Super Single (SS) Tires

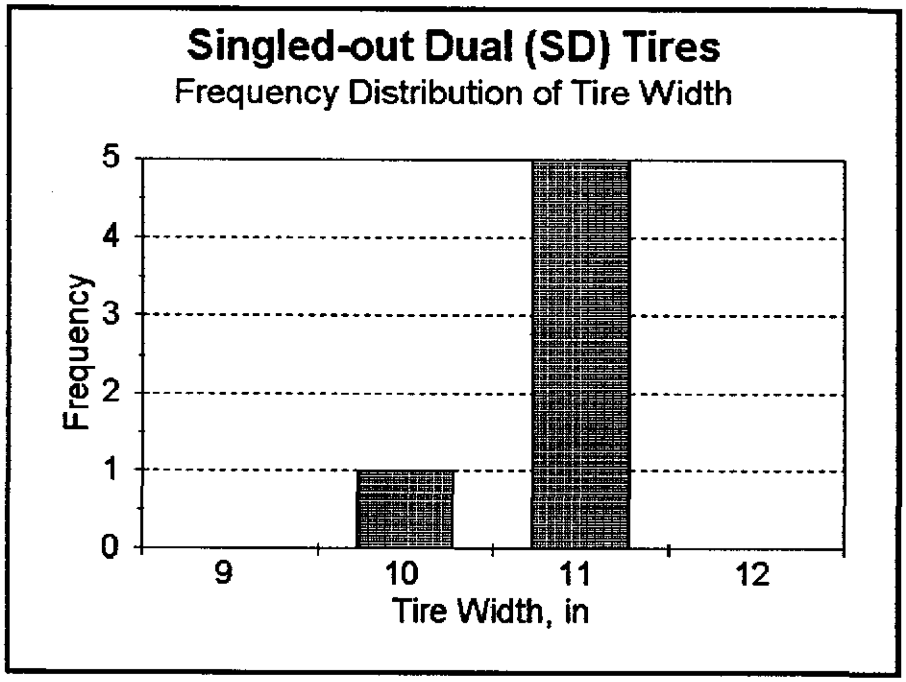

Figure 4.4. Frequency Distribution of Tire Width for Singled-out Dual (SD) Tires

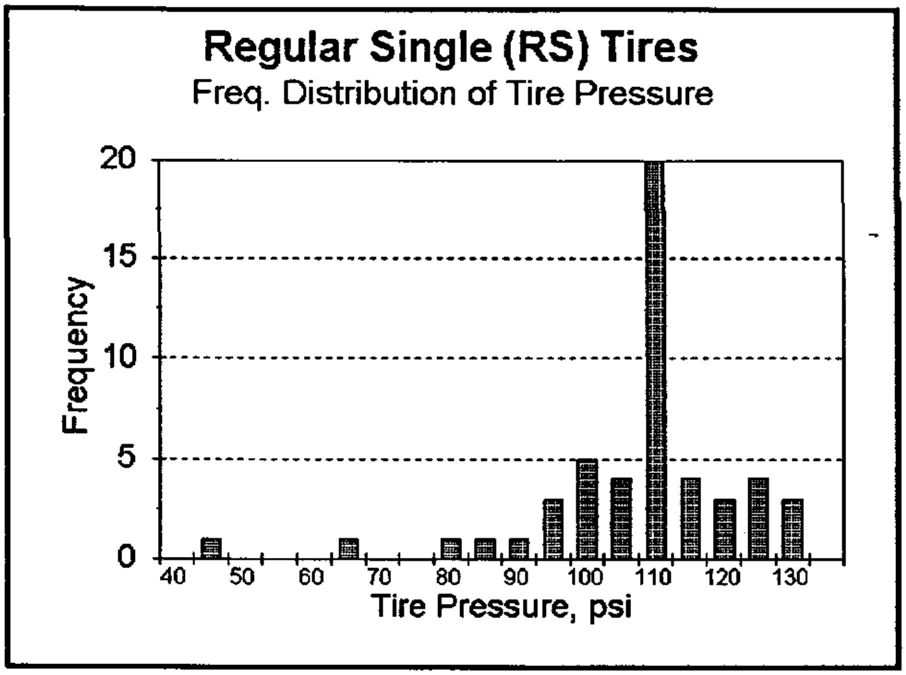

Figure 4.5. Frequency Distribution of Tire Pressure for Regular Single (RS) Tires

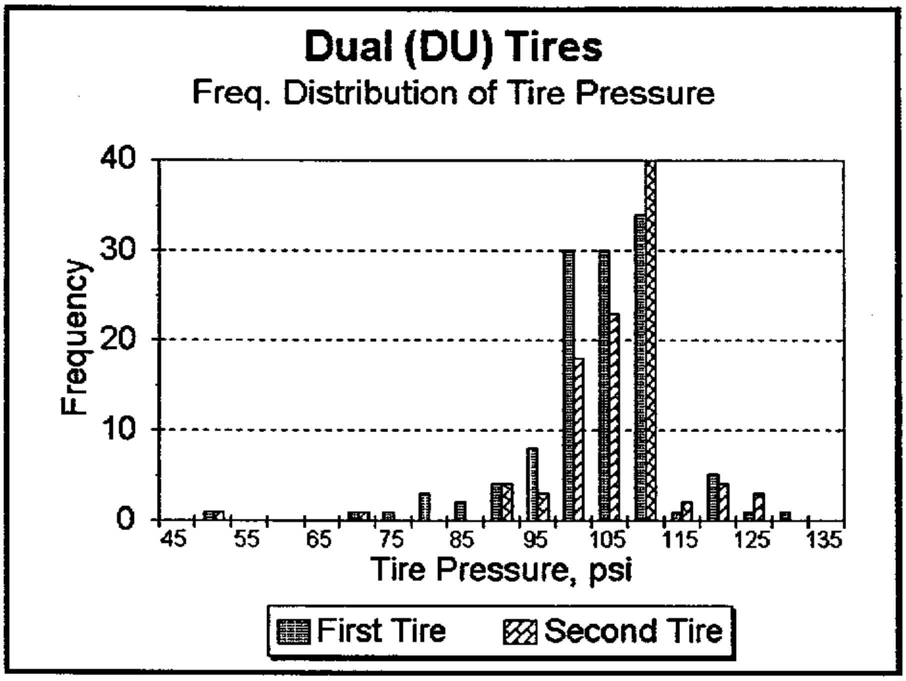

Figure 4.6. Frequency Distribution of Tire Pressure for Dual (DU) Tires

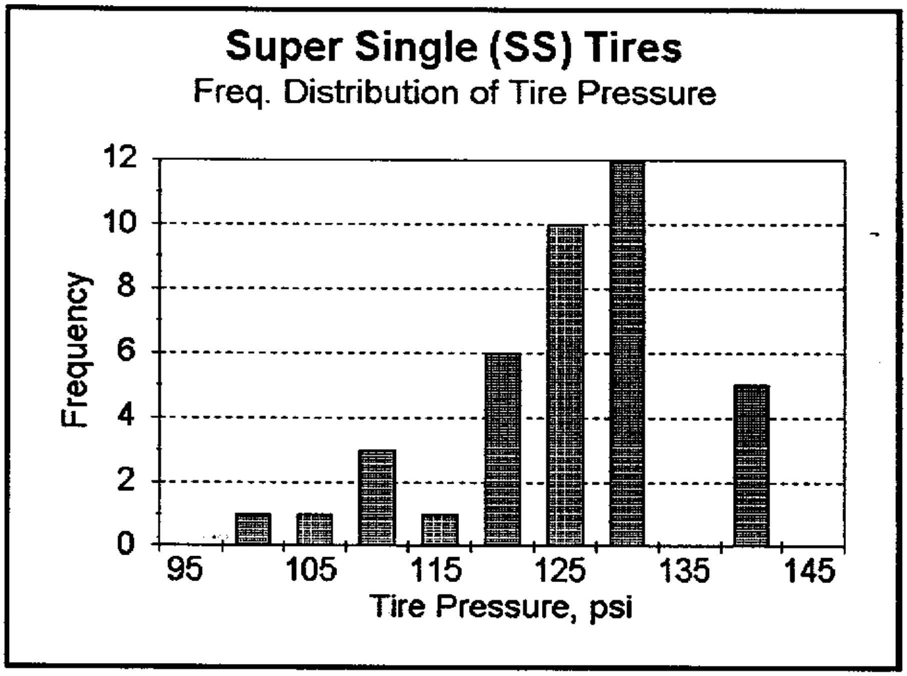

Figure 4.7. Frequency Distribution of Tire Pressure for Super Single (SS) Tires

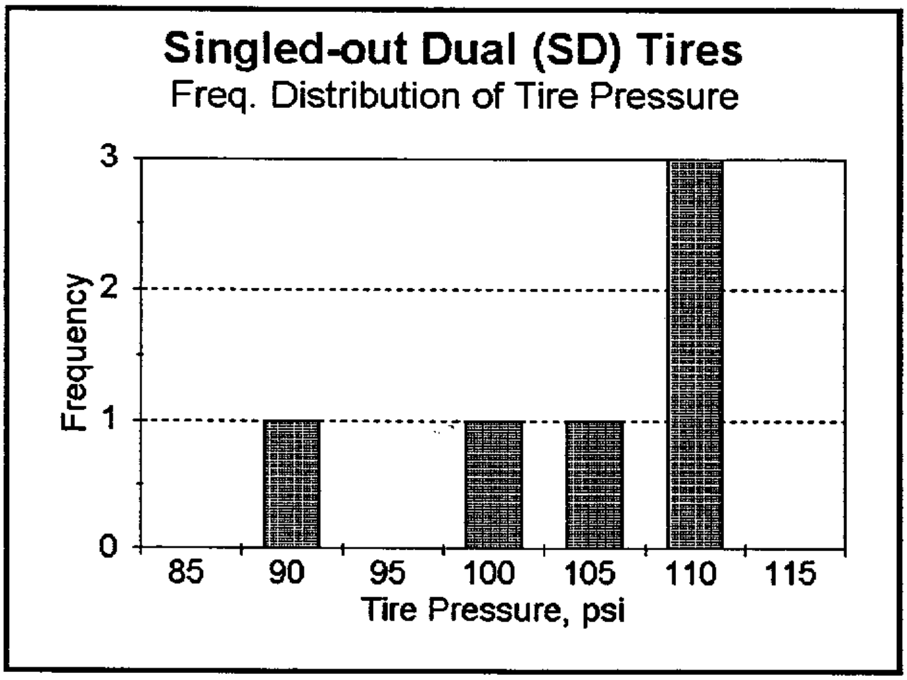

Figure 4.8. Frequency Distribution of Tire Pressure for Singled-out Dual (SD) Tires

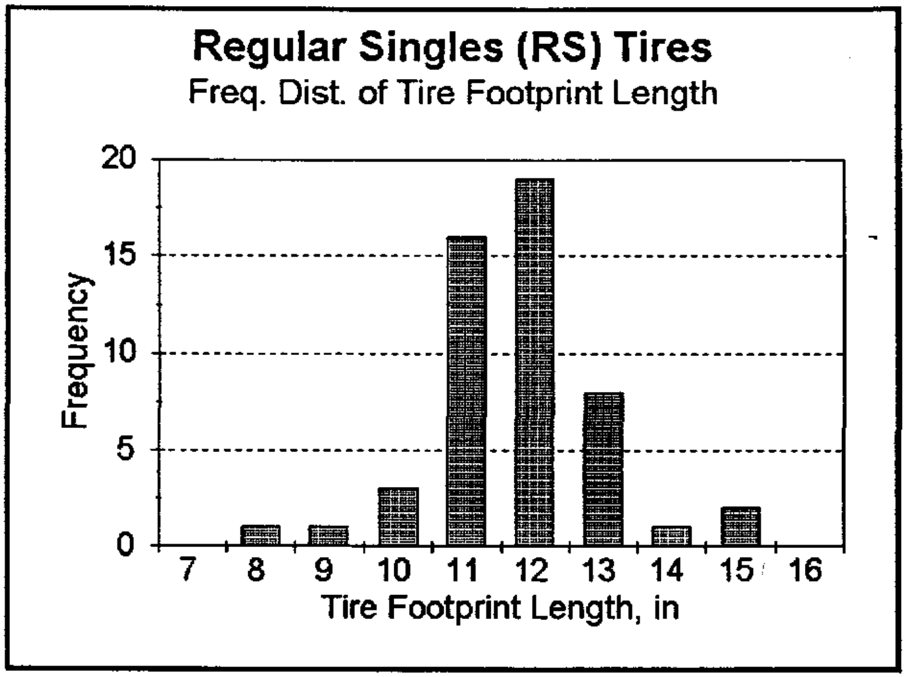

Figure 4.9. Frequency Distribution of Tire footprint Length for Regular Single (RS) Tires

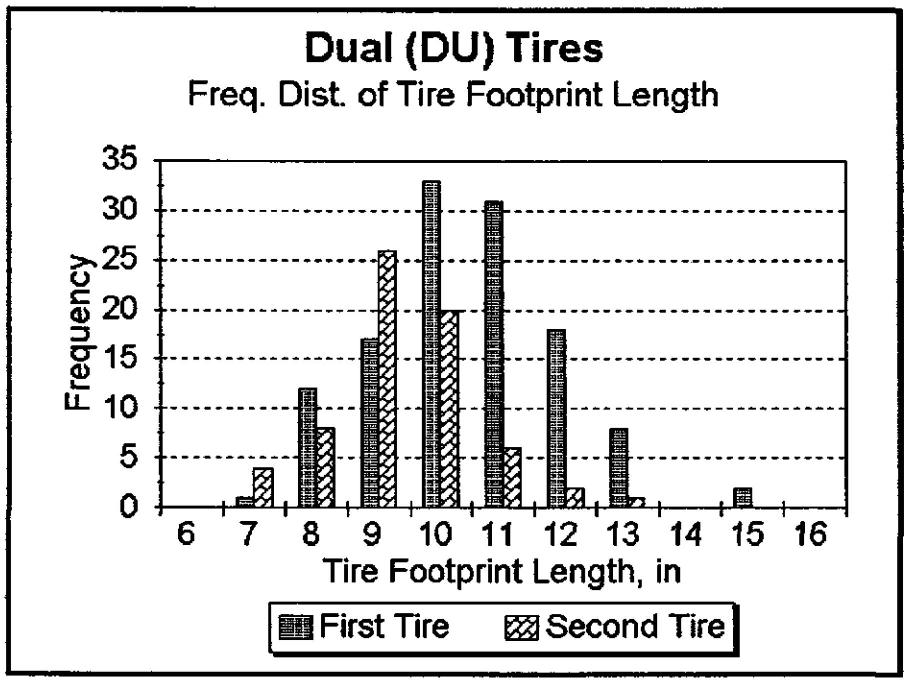

Figure 4.10. Frequency Distribution of Tire footprint Length for Dual (DU) Tires

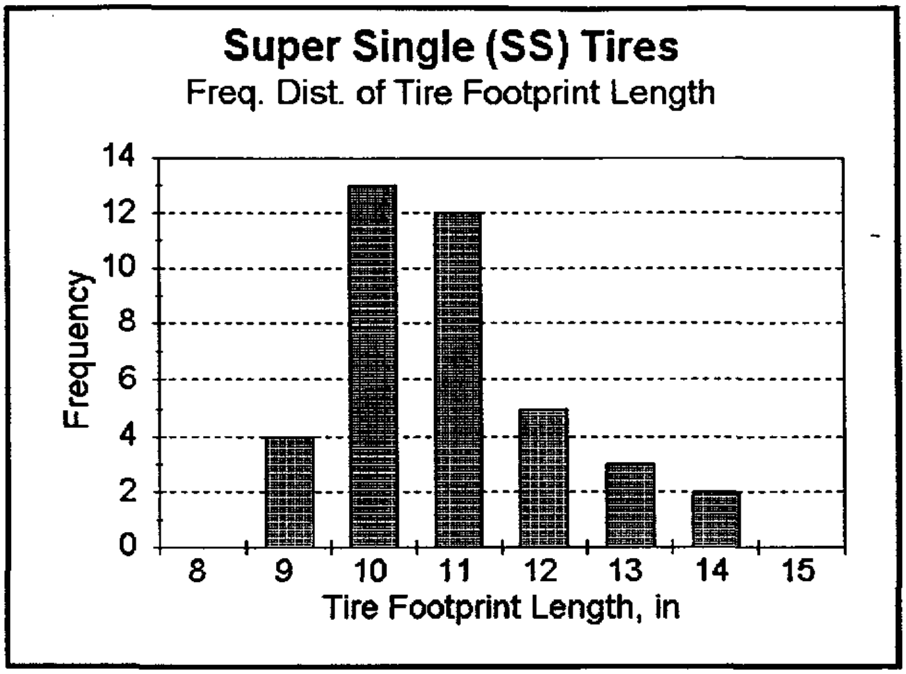

Figure 4.11. Frequency Distribution of Tire footprint Length for Super Single (SS) Tires

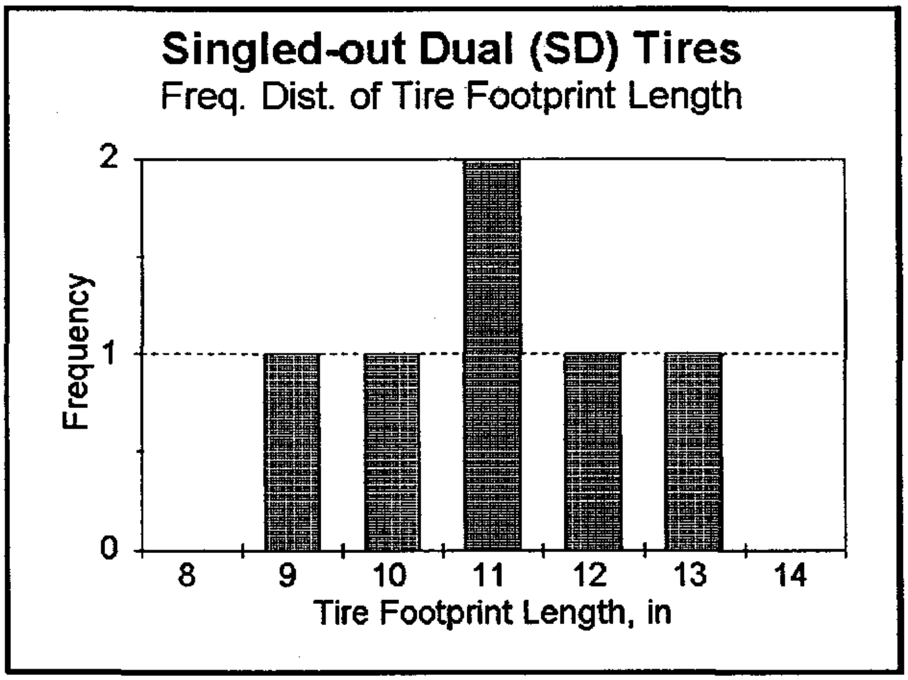

Figure 4.12. Frequency Distribution of Tire footprint Length for Singled-out Dual (SD) Tires

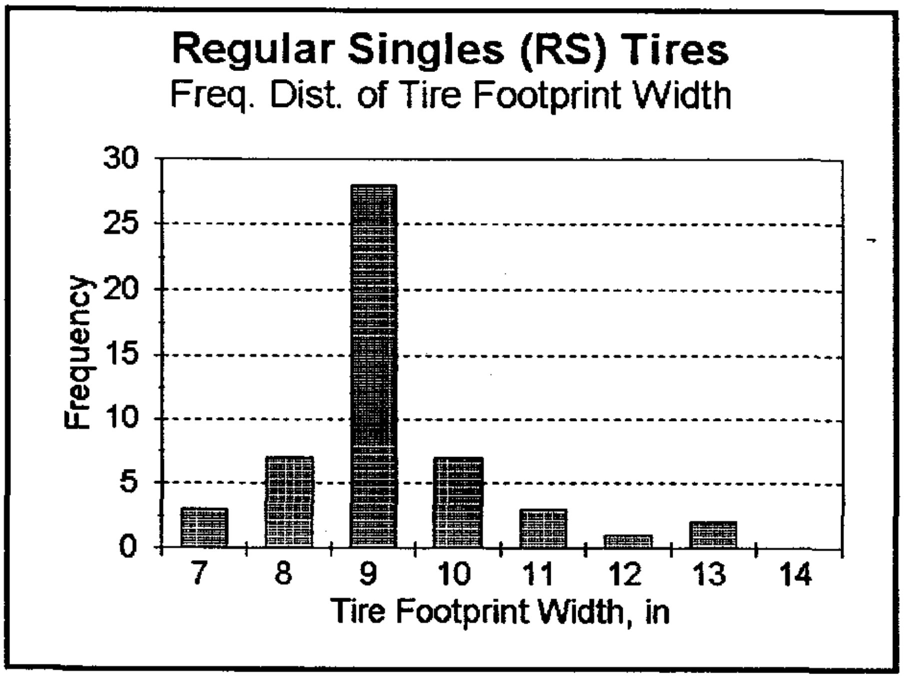

Figure 4.13. Frequency Distribution of Tire footprint Width for Regular Single (RS) Tires

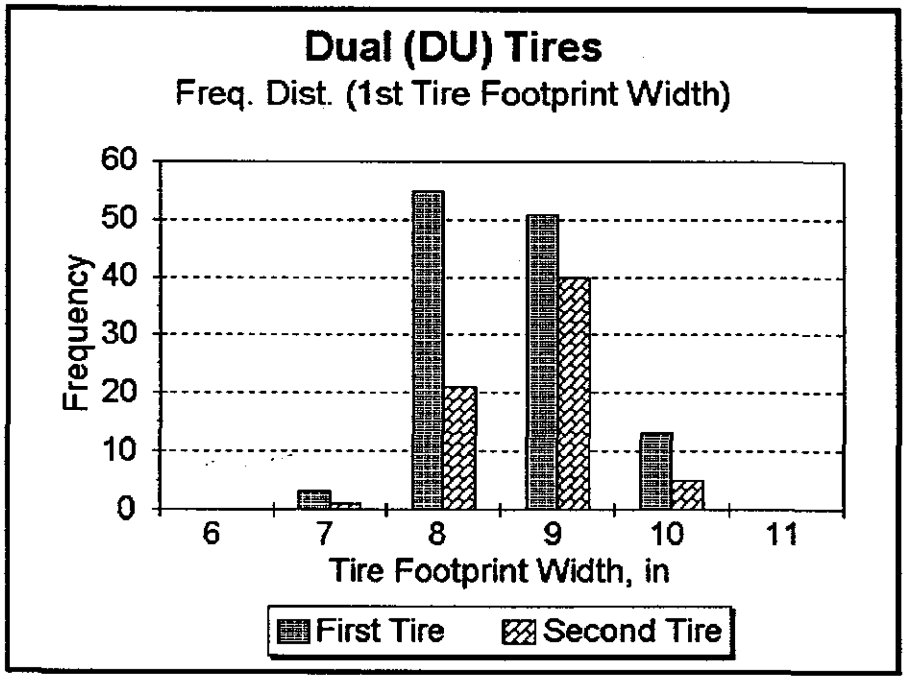

Figure 4.14. Frequency Distribution of Tire footprint Width for Dual (DU) Tires

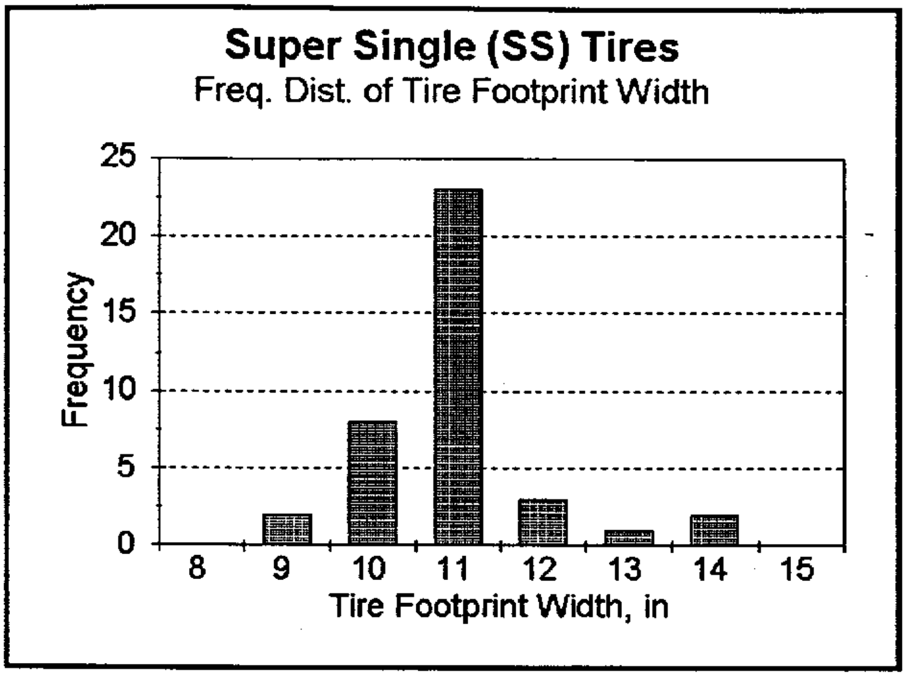

Figure 4.15. Frequency Distribution of Tire footprint Width for Super Single (SS) Tires

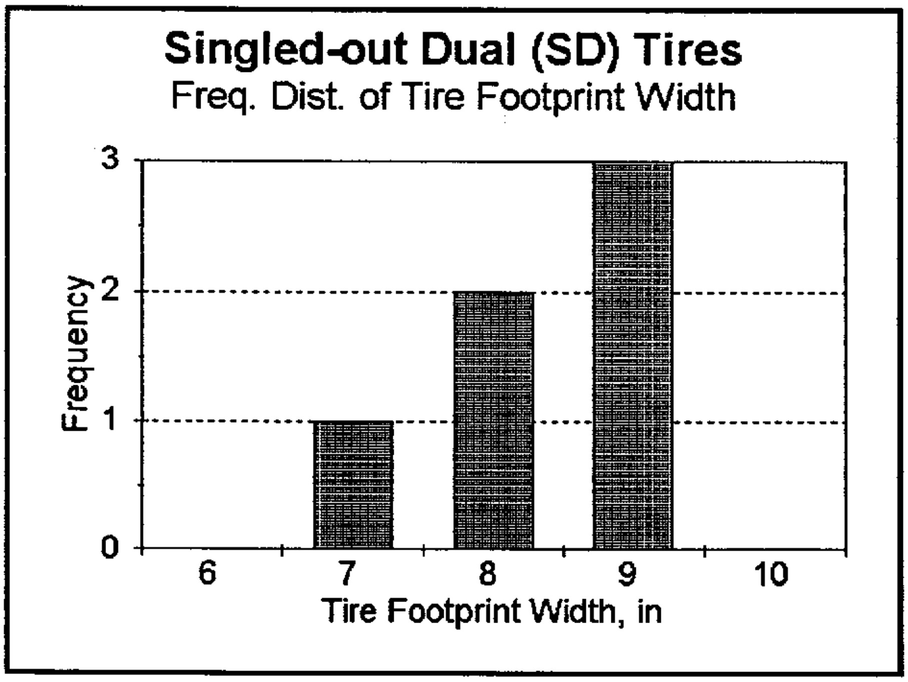

Figure 4.16. Frequency Distribution of tire footprint Width for Singled-out Dual (SD) Tires

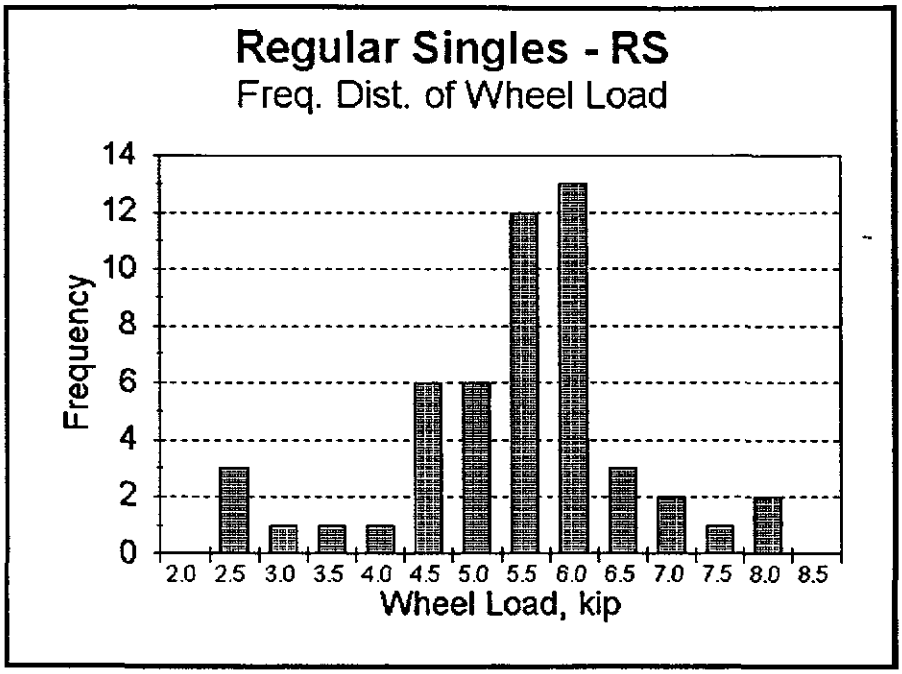

Figure 4.17. Frequency Distribution of Wheel Load for Regular Single (RS) Tires

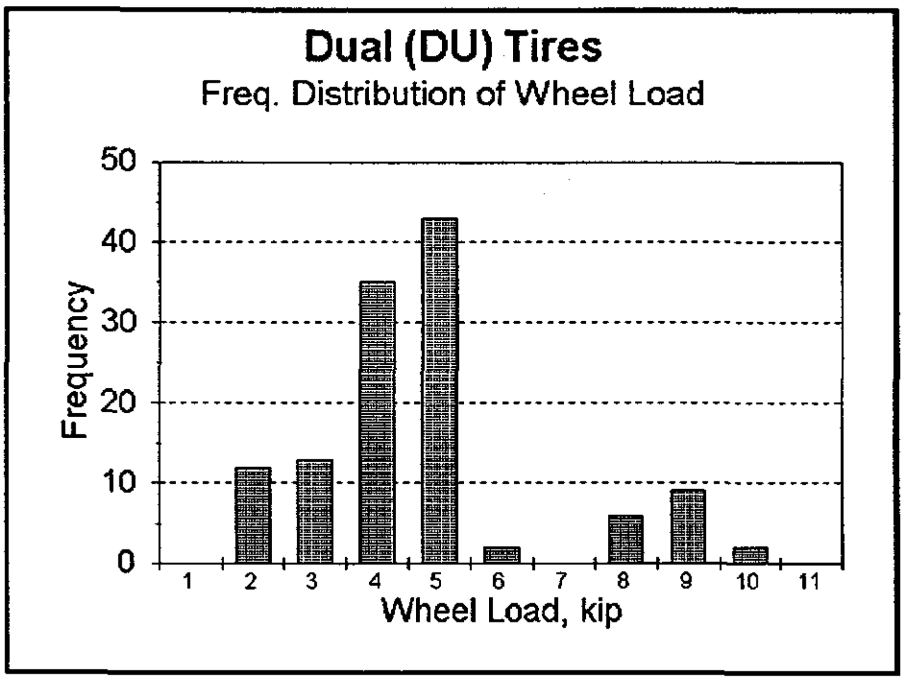

Figure 4.18. Frequency Distribution of Wheel Load for Dual (DU) Tires

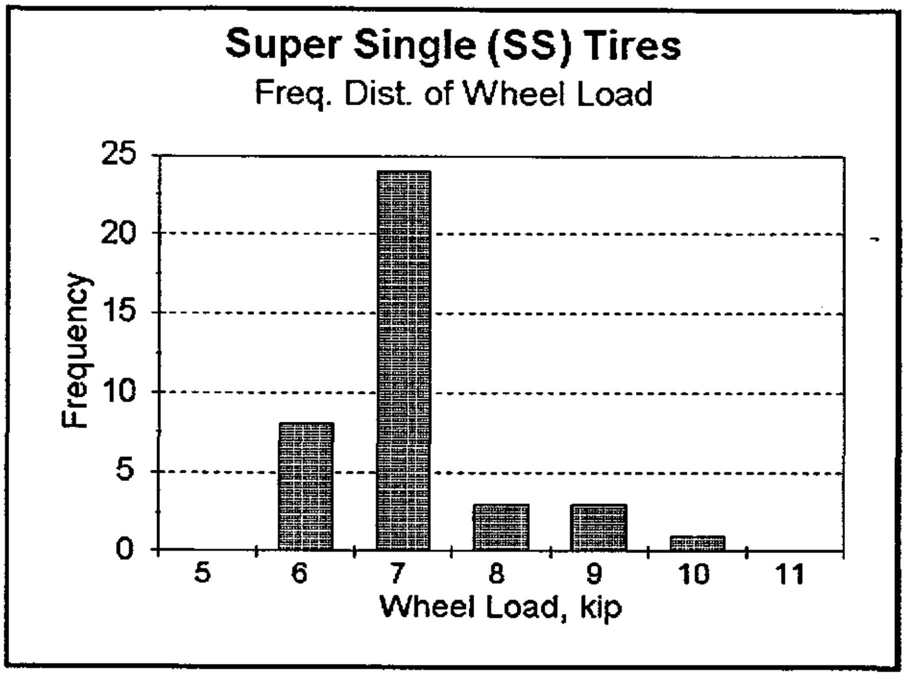

Figure 4.19. Frequency Distribution of Wheel Load for Super Single (SS) Tires

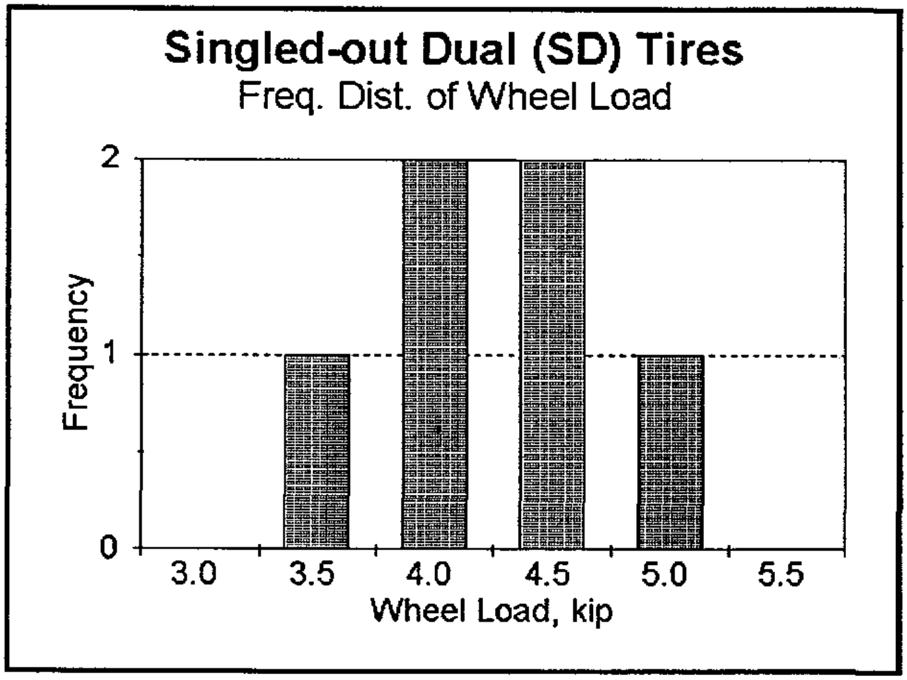

Figure 4.20. Frequency Distribution of Wheel Load for Singled-out Dual (SD) Tires

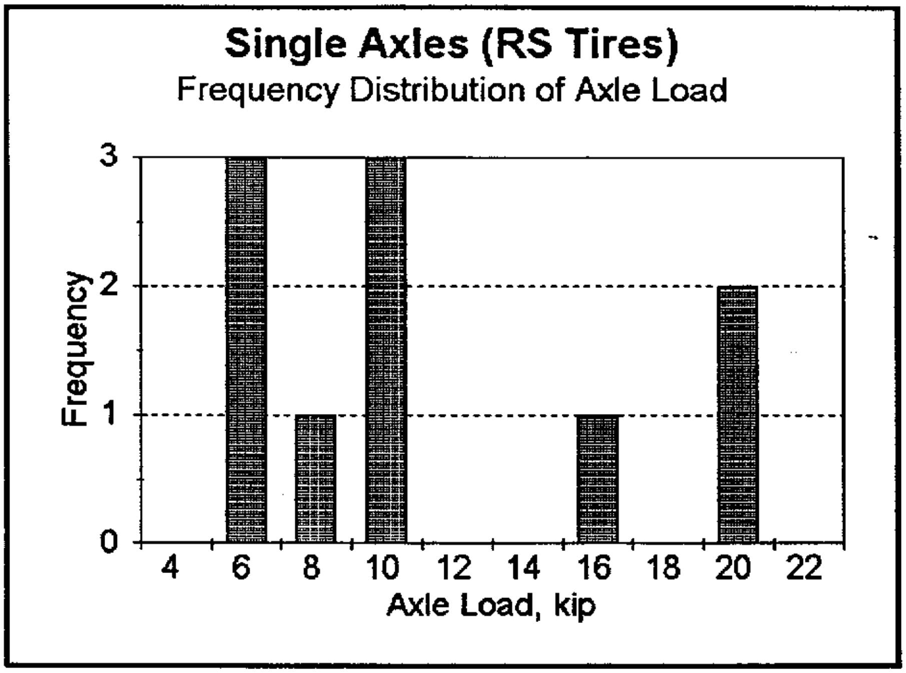

Figure 4.21. Frequency Distribution of Axle Load on Single Axles with Regular Single (RS) Tires

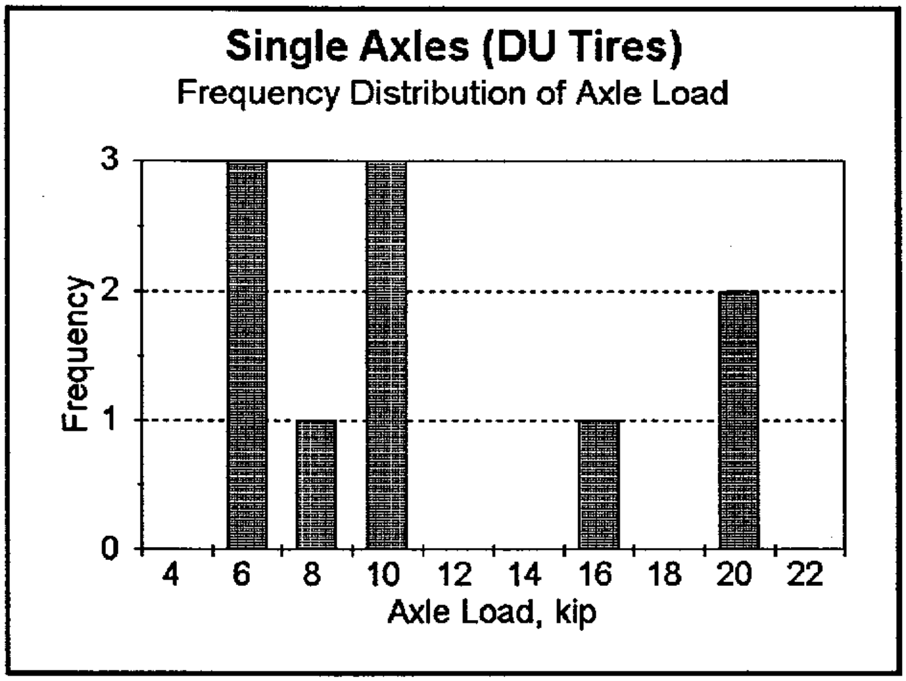

Figure 4.22. Frequency Distribution of Axle Load on Single Axles with Dual (DU) Tires

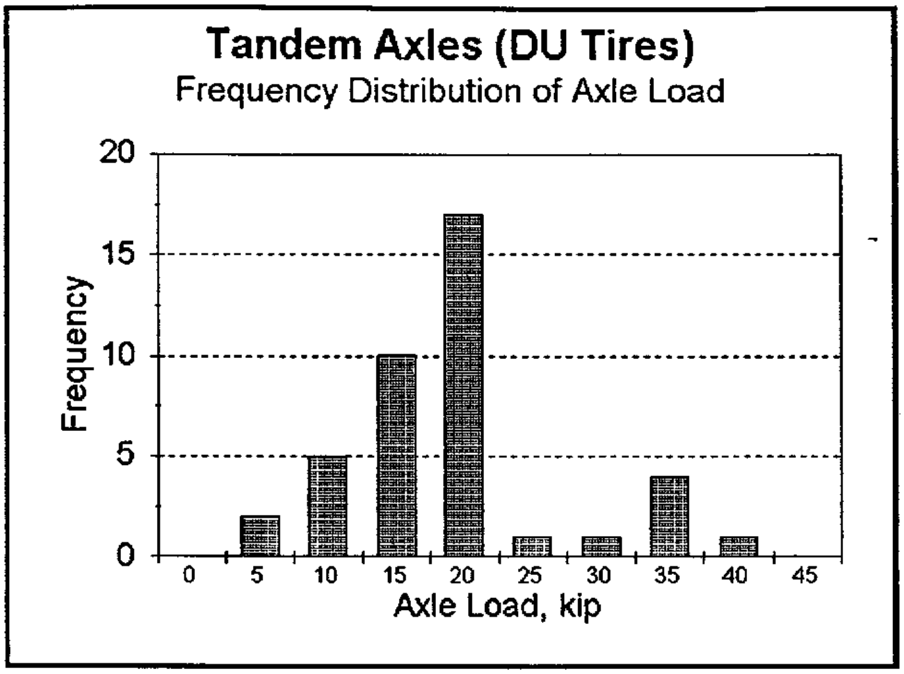

Figure 4.23. Frequency Distribution of Axle Load on Tandem Axles with Dual (DU) Tires

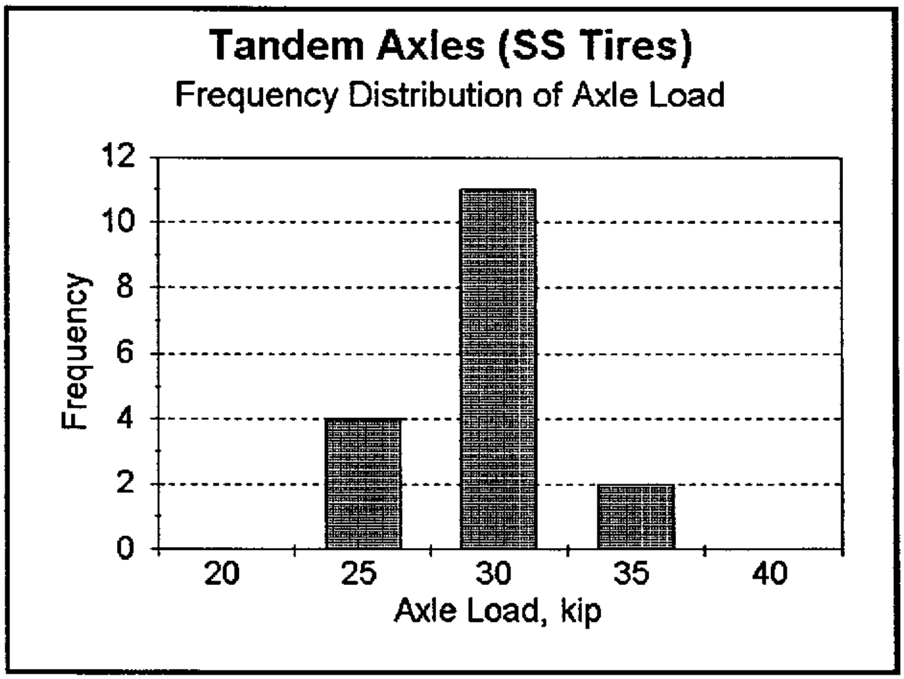

Figure 4.24. Frequency Distribution of Axle Load on Tandem Axles with Super Single (SS) Tires

CHAPTER 5
FIELD TESTING AND ANALYSIS OF FIELD DATA

This chapter reports the work completed under Tasks 5 and 6, namely, "Field Testing" and "Analysis of Field Data". In order to estimate the load equivalencies and pavement damage caused by Singled-out Dual (SD) and Super Single (SS) tires on South Dakota pavements, an instrumented site was set up during Task 3 of the study. The following paragraphs present details regarding the test section, the experimental design, the instrumentation used, the data collected, and the analyses performed.

FIELD TESTING

Test Section

The test section, which was reconstructed in 1991, was representative of a typical flexible pavement in South Dakota and was located near Howes corner on Highway 34 in Pierre, South Dakota. In addition to installing field instrumentation for monitoring pavement response, two cores were also secured from the pavement in case additional laboratory testing was needed.

The pavement structure consisted of approximately 5 in of asphalt concrete surface course (as measured from the cores) placed over 6 in of base course and 8 in of subbase course. The subgrade was reported to be some form of stiff clay.

Experimental Design

One of the main response parameters which describes the performance of a pavement structure under load is deflection. Hence, it was decided to obtain representative deflection readings at various loads caused by the different types of tires evaluated in this study.

Deflections in the field were obtained for two experimental matrices. The factors included in each matrix are as follows:

<u>Matrix 1</u>

Season	-	4 levels (Summer, Fall, Winter, Spring)
Wheel configuration (Tire)	-	3 levels (DU, SD, SS)
Tire Load (Load)	-	3 levels (400, 600, 800 ppi)
Channel	-	2 levels (1, 2)
Temperature	-	Covariate

Matrix 2

Season	-	4 levels (Summer, Fall, Winter, Spring)
Wheel configuration (Tire)	-	3 levels (DU, SD, SS)
Tire Load (Load)	-	3 levels (6000, 9000, 12000 lb)
Channel	-	2 levels (1, 2)
Temperature	-	Covariate

As can be seen, the only factor different in the two matrices is Load. For Matrix 1, tire loads were applied as pounds per inch (ppi) of tire width while for Matrix 2, these were applied as total load in pounds (lb) on the wheel assembly. Pavement temperature data was also collected in the field and treated as a covariate along with deflection.

NOTE: It is worthwhile mentioning that in the case of Loading Matrix 1, the total load on the SS and SD wheel configurations will be less than that on a DU tire because of their smaller overall tire widths as compared to that of the DU tires. This is true since the load is being applied as pounds per inch of tire width and being kept the same for all wheel configurations.

Since the load is applied a ppi, the total load on each of the various wheel configurations will be different and is as follows:

Wheel Configuration	Tire Width (in)	Load Intensity (ppi)	Total Wheel Load (lb)
DU	20	400	8,000
		600	12,000
		800	16,000
SD	10	400	4,000
		600	6,000
		800	8,000
SS	15	400	6,000
		600	9,000
		800	12,000

Field Instrumentation

The instrumentation installed in the field consisted of two in-pavement deflectometers as shown in Figure 5.1. The deflectometers were of the DC-DC LVDT type and were installed longitudinally in the outside wheel path as shown in Figure 5.1. This configuration allowed replicate deflection measurements for each pass of the test vehicle. A longitudinal section of the pavement with the deflectometers installed is shown in Figure 5.2 while Figure 5.3 depicts the deflection of a typical layering scheme under the action of a wheel load.

Data Collection

A number of replicate measurements were obtained in the field from both of the deflection gauges for each cell in the two test matrices. Lateral vehicle placement was monitored to accept readings only on runs that passed directly over the gauges. Lateral placement was monitored both visually by spotters as well as by spraying flour on the pavement before running a truck over it. An average of seven readings were collected for each cell in both test matrices. Pavement temperatures were also measured for each cell using a thermometer placed in a hole drilled at the edge of the pavement. Motor oil was used in the hole to transfer the actual pavement temperature to the thermometer. The pavement temperature was used as a covariate in the analysis. It was also used to estimate the stiffness of the asphalt concrete during the different seasons.

All testing was performed using a single-axle flat bed truck (supplied by the South Dakota Department of Transportation). The chosen truck was such that it could be easily loaded and fitted with various types of wheels involved in the study. Another truck was used to provide the 18,000 lb single-axle load used as the equivalency factor reference for all cells in the test matrices. Two deflection referencing assemblies were permanently placed in the test sections. The deflectometers and recording equipment were borrowed from the FHWA. While passing over the deflectometers, the truck speed was maintained at approximately 30 miles per hour.

Data Conversion and Organization

The data was collected using LVDTs that were anchored about 12 feet deep below the surface. The signals were received as voltages and were later converted to deflections using a calibration factor of 8.25 mils/volt. A two step procedure as described below was used to remove any erroneous measurements:

1. While collecting data in the field, lateral placement of the loaded wheel was monitored and it was indicated whether the wheel passed over the deflectometer or not. All readings with a status of 'N' (indicating that the wheel did not pass over the sensor) were discarded.

2. Following this elimination, the averages and standard deviations for the remaining data points in each cell were computed. The t-test was then used to eliminate any outliers in the data collected for each cell. The remaining observations in each cell were used in any subsequent analyses.

The data was subsequently organized for each of the experimental matrices. Load equivalency factors (LEF) were computed using Hutchinson's model for single axle loads:

$$LEF = \left[\frac{D_i}{D_s}\right]^{3.8} \tag{5-1}$$

where, D_i = Deflection under a given load, and
D_s = Deflection under the standard load.

Tables 5.1 and 5.2 report the average values of deflection and LEF for each experimental matrix. Separate values of D_s were used for each season and consisted of an average for the loading condition representing a 9,000 lb wheel load.

STATISTICAL ANALYSIS

The corrected deflection data and corresponding load equivalency factors (LEF) were then subjected to statistical analyses using the analysis of variance (ANOVA) procedures. Separate analyses were carried out on deflections and LEF to study the influence of the various factors included in the experimental design.

Initial analysis runs were performed on combined data for all seasons. Subsequent analysis runs were later carried out to determine the effects of the remaining factors within each season and isolate any problems or errors that may be related to any particular season. The results of these analysis runs are presented in the following paragraphs.

Deflections

Separate analyses were performed for each matrix. The factors included in each experimental matrix were discussed earlier. Temperature was treated as a covariate for both matrices. The number of observations for each cell varied thus rendering unbalanced designs for both matrices. All two-factor interactions were also included in the analyses; all significance tests were performed at a level of significance of $\alpha = 0.05$.

The ANOVA results for both matrices with all seasons combined are reported in Table A-1. The terms DF, SS, and MS, respectively, represent the degrees of freedom, sum of squares, and mean squares associated with a particular factor or interaction. The F value is computed as:

$$F_i = MS_i \; / \; MS_{Error} \tag{5-2}$$

and represents the variation in a response variable due to the effect of Factor "i" as compared to the random error associated with the process. A factor is said to be significantly affecting a response variable if its F value exceeds a certain critical value of F which is a function of: a) the level of significance, α, the degrees of freedom for that factor, and the error degrees of freedom.

All factors for both matrices are significant. The order of significance for main factors for both matrices is:

Matrix 1:	Load > Season > Tire > Channel
Matrix 2:	Load > Season > Tire > Channel > > Temperature

In the above expression, " > " indicates a change in the order of significance. Two " > "'s appearing together will imply a much larger change. For Matrix 1 then, it would mean that the most significant factor is Load, followed by Season, Tire, and then Channel. Temperature proves out not to be significant for Matrix 1 but for Matrix 2, it is significant. The level of significance (F = 22.7) is much smaller as compared to other factors though. All two-factor interactions except Tire x Channel and Load x Channel are found to be significant. It is interesting to note that a significant interaction exists between the factors Season and Channel. This means that the difference in deflections recorded by the two channels is not the same for all seasons.

ANOVA results for data within each season are reported in Table A-2. All factors are significant for both matrices, with the order of significance for the various seasons as follows:

Summer:	Load > Tire > > Channel
Fall:	Load > Tire > > Channel
Winter:	Channel > > Load > Tire
Spring:	Load > Tire > > Channel

Observing the above orders of significance and looking at the F values for each factor, it emerges out that there was something wrong with the Winter data. A review of the field data obtained for Winter reveals that the deflections obtained for Channel 1 were consistently higher than those for Channel 2.

In view of the above, it was decided to drop the Winter data and repeat the analysis with all seasons. The results of this analysis are reported in Table A-3. Again, all factors for both matrices are found to be significant. The order of significance for main factors for both matrices is:

Matrix 1: Load > Season > Tire > Channel >> Temperature
Matrix 2: Load > Season > Tire > Channel

Contrary to the previous case, Temperature proves out not to be significant for Matrix 2 but for Matrix 1, it is significant. The level of significance ($F = 7.25$) is much smaller as compared to other factors though. All two-factor interactions except Tire x Channel and Load x Channel for Matrix 2 are found to be significant.

Load Equivalency Factors

Load equivalency factors (LEF) were computed from the deflection data obtained in the field. The same experimental design as used for deflections was used for LEFs as well and the factors included in both the matrices were also the same as those for the case of deflections. Temperature was still included as a covariate. All two-factor interactions were included in the model for analysis and all significance tests were performed at a level of significance of $\alpha = 0.05$.

The ANOVA results for both matrices with all seasons combined are reported in Table A-4. For Matrix 1, all factors except Channel are significant, while for Matrix 2, only Load and Tire were found to be significant. The order of significance for main factors for each matrix is:

Matrix 1: Load > Tire >> Temperature > Season
Matrix 2: Load > Tire

Both Season and Temperature are only marginally significant for Matrix 1. It is interesting to know that although Season was the second most significant factor for deflections, it has very little, if any, effect on LEFs. This indicates that for the same layering scheme, testing in any season should yield the same conclusions about relative damage for different types of axle and loading configurations. All two-factor interactions except Load x Channel were found to be significant.

ANOVA results within each season are reported in Table A-5. All factors other than Temperature are significant for both matrices, with the order of significance for the various seasons as follows:

Summer: Load > Tire > Channel
Fall: Load > Tire > Channel
Winter: Channel > Load > Tire
Spring: Load > Tire > Channel

Once again, the Winter data emerges out as contradictory to the normal behavior. The analysis with all seasons was repeated after dropping the Winter data. These results are reported in Table A-6. Again, all factors for both matrices are found to be significant except for Temperature in Matrix 1. The order of significance for main factors for both matrices is:

Matrix 1: Load > Tire >> Channel >> Season
Matrix 2: Load > Tire >> Channel >> Season > Temperature

Season although found significant, has a much lower level of significance as compared to the other factors. Again, this indicates that for the same layering scheme, testing in any season should yield the same conclusions about relative damage for different types of axle and loading configurations. All two-factor interactions are also significant, some marginally though.

CONCLUSIONS

As a result of the statistical analysis of the deflection obtained in the field and the corresponding load equivalency factors computed, the following conclusions are in order:

1. All factors studied for both matrices significantly affect the surface deflection of the pavement. The order of significance for main factors for both matrices is:

   Matrix 1: Load > Season > Tire > Channel
   Matrix 2: Load > Season > Tire > Channel >> Temperature

2. Individual analyses and observation of the data summaries for the various seasons indicate that the Winter data does not follow normal behavior. Output values from one channel were found to be consistently lower than the other.

3. The analysis of LEFs indicates the following factors to be statistically significant with decreasing order of significance:

   Matrix 1: Load > Tire >> Temperature > Season
   Matrix 2: Load > Tire

   It is interesting to note that Season does not affect the LEFs as significantly as other factors. Also interesting to note is the fact that although the load in both the matrices was applied differently, the overall conclusions were essentially the same.

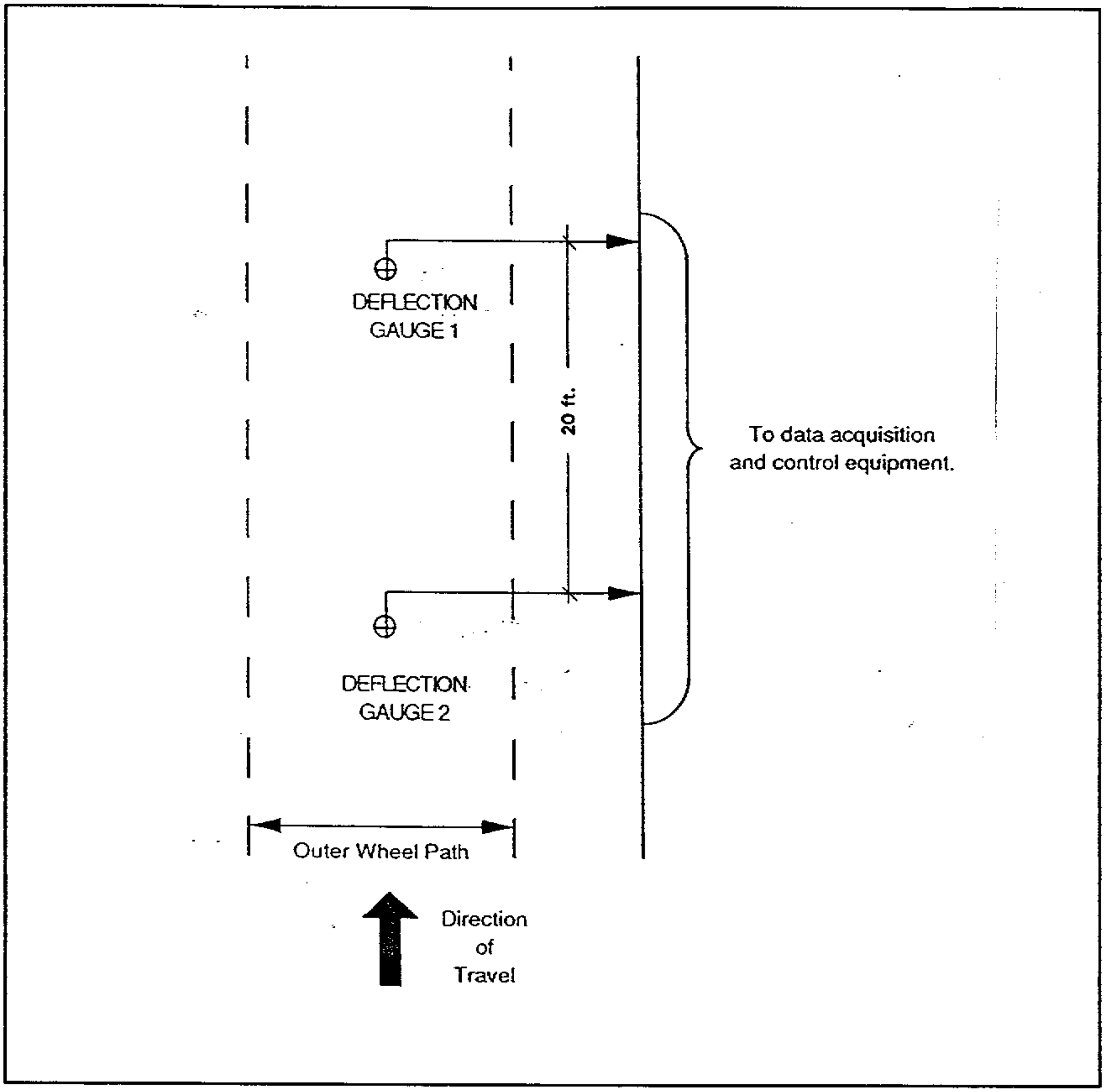

Figure 5.1 Instrumentation layout for the instrumented pavement section.

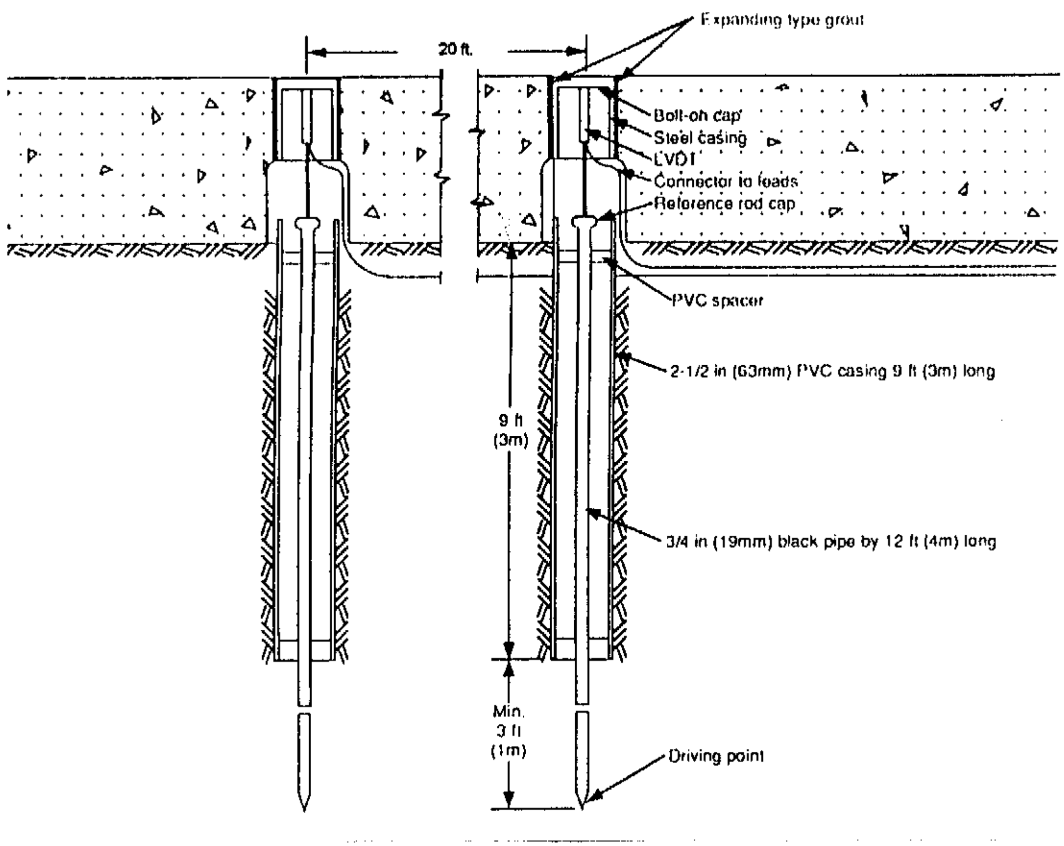

Figure 5.2 Longitudinal Section of the Instrumentation layout.

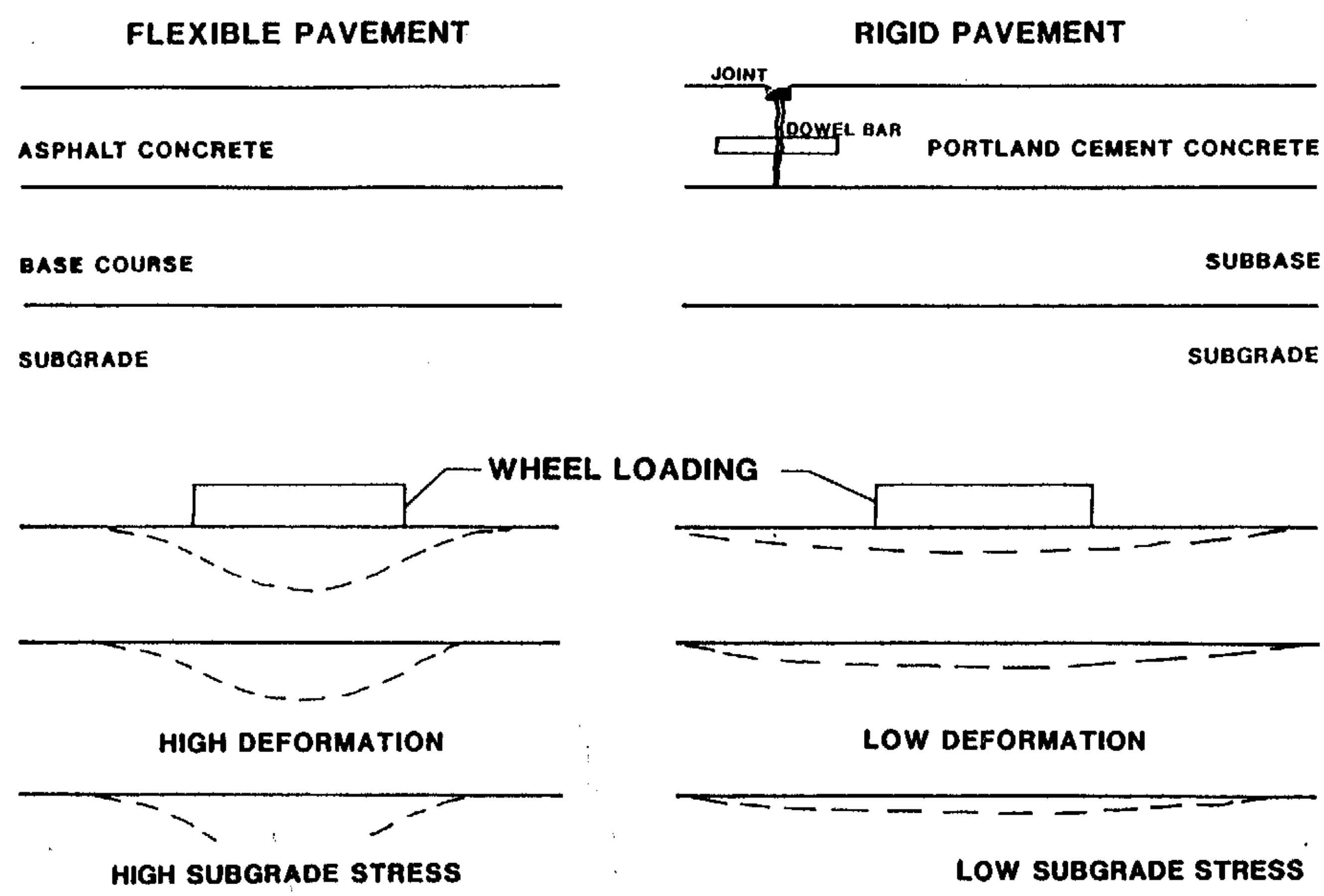

Figure 5.3 Typical Flexible and Rigid Pavement Deflection Basins.

Table 5.1. Summary of Deflection Data

a. Matrix 1 (Load in ppi)

Season	Wheel Configuration	Load = 400 ppi		Load = 600 ppi		Load = 800 ppi	
		Ch 1	Ch 2	Ch 1	Ch 2	Ch 1	Ch 2
Summer	DU	9.416	11.229	14.834	15.989	20.111	20.927
	SD	5.049	6.268	8.734	9.051	11.632	12.352
	SS	10.388	11.496	13.349	14.598	19.249	19.709
Fall	DU	7.911	7.835	11.803	11.932	14.321	14.707
	SD	6.087	5.144	7.743	7.698	10.479	9.451
	SS	7.050	6.592	11.083	10.479	13.626	13.549
Winter	DU	9.181	4.522	11.059	7.315	14.040	9.406
	SD	7.983	4.189	10.272	6.108	11.302	7.516
	SS	11.443	7.951	12.667	9.532	14.585	11.848
Spring	DU	9.748	12.891	17.785	18.424	22.604	22.465
	SD	9.562	10.096	12.845	13.938	16.703	16.939
	SS	13.245	14.718	18.611	18.339	24.789	23.520

Table 5.1. Summary of Deflection Data (Continued)

b. Matrix 2 (Load in lb)

Season	Wheel Configuration	Load = 6000		Load = 9000		Load = 12000	
		Ch 1	Ch 2	Ch 1	Ch 2	Ch 1	Ch 2
Summer	DU	8.520	9.069	10.942	12.755	14.834	15.989
	SD	8.734	9.051	15.156	15.071	19.341	20.957
	SS	10.388	11.496	13.349	14.598	19.249	19.709
Fall	DU	6.445	6.542	8.031	8.572	11.803	11.625
	SD	7.743	7.651	11.984	11.142	15.314	14.868
	SS	7.050	6.592	11.083	10.479	13.626	13.549
Winter	DU	7.583	4.024	10.747	6.017	11.059	7.315
	SD	10.272	6.108	11.815	8.364	14.382	10.519
	SS	11.443	7.951	12.667	9.532	14.585	11.848
Spring	DU	11.607	11.179	13.990	14.623	17.785	18.424
	SD	12.845	13.938	18.309	17.347	24.653	24.956
	SS	13.245	14.718	18.611	18.339	24.789	23.520

Table 5.2. Summary of Load Equivalency Factors

a. Matrix 1 (Load in ppi)

Season	Wheel Configuration	Load = 400 ppi		Load = 600 ppi		Load = 800 ppi	
		Ch 1	Ch 2	Ch 1	Ch 2	Ch 1	Ch 2
Summer	DU	0.566	0.617	3.188	2.365	10.111	6.573
	SD	0.053	0.068	0.426	0.274	1.268	0.888
	SS	0.827	0.679	2.170	1.697	8.570	5.229
Fall	DU	0.948	0.727	4.335	3.536	9.005	7.795
	SD	0.351	0.145	0.876	0.665	2.758	1.457
	SS	0.625	0.371	2.744	2.177	7.479	5.732
Winter	DU	0.553	0.341	1.116	2.112	2.768	5.534
	SD	0.324	0.254	0.844	1.061	1.211	2.362
	SS	1.298	2.941	1.872	5.759	3.192	13.172
Spring	DU	0.597	0.632	2.492	2.408	6.198	5.113
	SD	0.240	0.246	0.724	0.835	1.961	1.750
	SS	0.813	1.026	2.962	2.369	8.802	6.105

Table 5.2. Summary of Load Equivalency Factors (Continued)

b. Matrix 2 (Load in lb)

Season	Wheel Configuration	Load = 6000		Load = 9000		Load = 12000	
		Ch 1	Ch 2	Ch 1	Ch 2	Ch 1	Ch 2
Summer	DU	0.392	0.287	1.000	1.005	3.188	2.365
	SD	0.426	0.274	3.451	1.888	8.756	6.602
	SS	0.827	0.679	2.170	1.697	8.570	5.229
Fall	DU	0.434	0.359	1.107	1.002	4.335	3.536
	SD	0.876	0.665	4.579	2.514	11.621	8.076
	SS	0.625	0.371	2.744	2.177	7.479	5.732
Winter	DU	0.269	0.220	1.002	1.002	1.116	2.112
	SD	0.844	1.061	1.446	3.504	3.026	8.355
	SS	1.298	2.941	1.872	5.759	3.192	13.172
Spring	DU	0.494	0.361	1.014	1.004	2.492	2.408
	SD	0.724	0.835	2.781	1.917	8.617	7.630
	SS	0.813	1.026	2.962	2.369	8.802	6.105

CHAPTER 6
DAMAGE MODEL SELECTION AND COMPUTER SIMULATIONS

This chapter deals with the work completed under Task 3, namely, "Estimate of Highway Damage". The process of selecting a representative damage model and its application to generate load equivalency factors (LEF) through computer simulations using a modified version of ELSYM5 is described. Comparisons of the computer simulated deflections and LEFs are made with those obtained through field data collection and the AASHTO Design Guide [*4*].

The purpose of Task 3 was to select a damage model from the available deflection based models, develop evaluation criteria, and evaluate the selected model through computer simulations. The differences if any, in the damage caused by the three different wheel configurations (Dual - DU, Singled-out Dual - SD, and Super Single - SS) in use in South Dakota were also to be delineated.

BACKGROUND

Damage to a highway pavement is most commonly induced by traffic. Each pass of a vehicle causes the pavement layers to deflect under the applied load. The conversion of mixed traffic loadings to an equivalent number of standard load applications is often done through theoretical comparisons of the damage caused by any load to that caused by a standard load.

The 1986 AASHTO Guide for Pavement Design [*4*] defines a Load Equivalency Factor to be the ratio of the number of repetitions of any axle load and/or configuration necessary to cause the same reduction in present serviceability index (PSI) as one application of an 18-kip (1 kip = 1000 lb) single axle load. Defined in different terms, it is the damage caused by any one load or axle configuration relative to the damage caused by a standard load/axle (in our case, the 18-kip single axle load). This re-emphasizes the fact that axle type and weight are far more critical in determining the pavement performance than gross vehicle weight alone.

DAMAGE MODEL SELECTION

A comprehensive literature survey was performed to gather up to date information on the damage models currently available to compute load equivalency factors. The survey revealed that the most common mechanistic responses used to determine load equivalency factors are:

- Maximum surface vertical deflection
- Maximum vertical strain on the top of the subgrade

- Maximum tensile strain at the bottom of the surface layer
- Maximum tensile stress in a concrete pavement

As identified in the proposal, surface deflection was chosen as the primary response upon which to base the choice of a damage model. The most relevant surface deflection response-based equivalency factor methods identified through the survey were screened using a subjective evaluation as shown in Table 6.1.

As a result of this subjective evaluation, two pavement surface deflection based methods with an overall rating of 7 or more emerged. These methods were:

1. Christison et al [5]
2. Hutchinson et al [6]

A review of both the methods revealed that the same expression is used by both to predict the equivalency factors for single axle loads:

$$LEF=(D/D_b)^{3.8} \tag{6-1}$$

where,

$D/D_b=$ Ratio of the pavement surface deflections caused by a single axle load to that recorded under the standard 18-kip single axle-dual tire load of the Benkleman Beam.

Since both of these methods yield the same results when applied to single axle loads, it was decided to select the Hutchinson method for use in the subsequent computer simulations for estimating highway damage.

DEFLECTIONS AND LOAD EQUIVALENCY FACTORS

Experiment Design

In order to systematically evaluate the damage model selected above, it was decided to employ the same experimental matrices as used in Task 5 during field data collection (Refer Chapter 5). The factors included in each matrix and their levels are as shown below:

Loading Matrix 1

Seasons:	4 levels (Summer, Fall, Winter and Spring)
Wheel Configurations:	3 levels (DU, SD, and SS)
Tire Load:	3 levels (400, 600 and 800 lb/in of tire width)

Loading Matrix 2

Seasons:	4 levels (Summer, Fall, Winter and Spring)
Wheel Configurations:	3 levels (DU, SD, and SS)
Tire Load:	3 levels (6000, 9000 and 12000 lb)

The two matrices differ from each other only in the way the tire loads were defined. For Matrix 1, loads were applied as load per unit width of the tire, while for Matrix 2, loads were defined as the total load applied through a tire assembly. This was done in order to study the effect of both the total load on a tire assembly as well as the load intensity.

NOTE: It is worthwhile mentioning that in the case of Loading Matrix 1, the total load on the SS and SD wheel configurations will be less than that on a DU tire because of their smaller overall tire widths as compared to that of the DU tires. This is true since the load is being applied as pounds per inch of tire width and being kept the same for all wheel configurations.

Field Data

Pavement deflection is primarily affected by the traffic loading and the daily or seasonal changes in environmental conditions such as temperature and moisture, and consequently, changes in the stiffness of the layers and hence the support. Since the amount of deflection is largely due to the amount and kind of traffic traversing on the pavement, its measurement in the field is necessary to understand the effect of the different wheel configurations being addressed in this study.

Deflections were collected in the field during four different seasons (Summer, Fall, Winter and Spring). Two separate deflection gauges, referred to as channels and placed approximately 20 feet apart, were installed in the wheel path on the pavement test section. The raw voltage signals recorded by the gauges were converted to deflection through the use of calibration factors. The measured deflections were then inspected for poor measurements which were subsequently removed. These deflections were subjected to statistical evaluation using Student's t-test and any outliers removed. The resulting average deflections are reported in Table 6.2(a). Table 6.2(b) contains the corresponding LEFs.

Computer Simulations

A layered elastic program (a modified version of ELSYM5 [7]) was used for performing the computer simulations to assess the highway damage. ELSYM5 is a solution of the elastic layer theory which provides the means to determine the stresses, strains and deflections in a pavement system with up to 5 different materials. It was chosen because of its ability to model multiple wheel and/or axle configurations. This program also has the feature of inducing layer slip which may be useful in modeling material deficiencies in existing pavements.

The pavement structure used in these computer simulations is one from which cores were obtained, and was chosen because it meets the current SDDOT design standard for flexible pavements in South Dakota. Details of the pavement structure used are shown in Figure 6.1. Layer thicknesses were obtained from the cores. Various representative layer moduli sets for different seasons of the year were used in ELSYM5 and an attempt was made to match the deflections obtained in the field. The loading case used to arrive at these moduli for each season was DU at 9000 lb which is representative of an 18,000 lb equivalent single axle load. The final values of layer moduli selected for the various seasons are reported in Table 6.3. Modulus values for Winter and Summer were assumed to be the same since the maximum deflections observed in the field for the DU 9000 lb case were almost equal for these two seasons. The values in parentheses indicate the moduli suggested for use by the South Dakota Department of Transportation based on a regression analysis with the liquid limit.

With the values of backcalculated layer moduli finalized, ELSYM5 was used to estimate the deflections and corresponding load equivalency factors for various seasons, wheel configurations and load categories. A tire pressure of 90 psi was used for all tires except for DU at 9000 lb where the tire pressure was assumed to be 80 psi to match with the Benkleman beam. The tire pressures, along with load on each tire, were used to calculate the tire loading areas which were assumed to be circular in shape. All damage factors within a season were computed with respect to DU at 9000 lb (18 kip equivalent single axle load). Tables 6.4(a) and 6.4(b) show the deflections and LEFs obtained through computer simulations using ELSYM5.

AASHTO

LEFs were also determined using the AASHTO Guide for Pavement Design. The computation of LEFs for flexible pavements using the AASHTO procedure requires the use of a Structural Number (SN) and terminal serviceability (p_t). The various layer moduli obtained from computer simulations to match deflections were used to arrive at pavement layer coefficients and thus SNs for the pavement structure used in this study. The SN values obtained for various seasons are reported below:

Summer:	SN = 4.6
Fall/Winter:	SN = 5.1
Spring:	SN = 5.1

Since the SNs do not differ much with season, an average value of SN = 5.0 was used for all seasons. The terminal serviceability (p_t) was assumed at 2.5.

With the above assumptions, Table D.4 of the 1986 AASHTO Guide for Pavement Design, was employed to determine the LEFs for the various load categories, interpolating linearly between axle loads if necessary. These LEFs are reported in Table 6.5.

It is important to note that since different wheel configurations could not be accounted for using this procedure, same LEFs resulted for all the different wheel configurations for any given load while using the AASHTO guide. When the load was taken in ppi (pounds per inch), however, tire widths were used to calculate the total load. The resulting LEFs thus indirectly reflected the effect of different wheel configurations.

DISCUSSION OF RESULTS

Data regarding deflections were collected from the field for the two different loading matrices for the three different wheel configurations (DU, SD, SS) in use in South Dakota. Deflections were also generated for the same cases using ELSYM5 as described above. Corresponding LEFs were also calculated. The purpose of this exercise was to observe the trends of these responses for the different wheel configurations.

Deflections

Deflections collected from the field were compared with those obtained from ELSYM5 simulations for both loading matrices as is reported in Table 6.6(a). The deflections were then plotted for the different seasons and loading matrices and are included in Appendix B. Figures B-1 through B-4 are for Loading Matrix 1, and Figures B-5 through B-8 are for Loading Matrix 2.

The highest deflections were observed during the Spring season and can be explained by the fact that the pavement layers would be relatively soft during that part of the year due to spring thaw. The largest observed deflection was caused by the SS tire for the 800 lb/in case during Spring. The deflection caused by the SD tire for the same load in Spring was also high.

In the case of Loading Matrix 1, the DU and the SS tires produced the greatest deflections during the Summer and the Fall seasons. During Winter and Spring, the SS tires had the largest deflections. This observation may be explained by the fact that both DU and SS tires have a greater width (DU = 20 in and SS = 15 in) and will therefore carry a larger load, and thus induce larger deflections.

In the case of Loading Matrix 2, deflections during Spring were noticeably higher than those in any other season for all load categories and wheel configurations. Some of the following observations were made from the deflection comparison for this matrix:

1. In Summer, the SS tires produced higher deflections at lower tire loads; but the SD tires were more damaging at higher loads (9000 lb and 12000 lb) as can be seen from Figure B-5.

2. The SD tires produced the largest deflections during Fall; the SS tires produced the largest deflections in Winter.

3. The SS tires had the highest deflections during Spring, except at 12000 lb load where the SD tire was slightly higher than the SS.

Moreover, it was observed that there was good correlation between the field values and the ELSYM5 projections of the deflections especially in the case of the DU tires.

Load Equivalency Factors (LEFs)

Load equivalency factors were computed from the deflections collected in the field, as well as those generated from ELSYM5 simulations, using the Hutchinson's [6] deflection based damage model discussed above. The LEFs were also calculated using the AASHTO Guide. Table 6.6(b) provides a summary of the LEFs obtained. A graphical representation of the LEF comparisons for both loading matrices is included in Appendix C.

It is interesting to note that LEFs are not as strongly affected by season as was the case for deflections although differences do exist. For Loading Matrix 1, the highest LEF observed in the field was for the DU 800 lb/in case during Fall. The Summer LEFs for the same wheel configuration and load were also high followed by the SS tire for the same load in Winter. As in the case of the deflections, LEFs for DU were highest in the case of Summer and Fall, where as SS tires produced greater LEFs during Winter and Spring. This is understandable considering that for Matrix 1, DU tires carried the highest load, followed by the SS and SD tires, respectively.

In the case of Loading Matrix 2, the largest LEF was due to the SD wheel configuration at 12000 lb in Fall. The LEFs for the SS in Winter and the SD in Spring for the same load followed closely. The trends observed in the LEFs were similar to those observed for deflections as discussed in the section above.

There was good correlation between field, ELSYM5 and AASHTO values at the lower load level (6000 lb). It was also observed that the AASHTO LEFs were in proximity with those obtained from the field and ELSYM5 for the DU tires even in the case of higher load levels. However, at higher load levels, there was not much correlation between field data and ELSYM5. This may be attributed to two factors:

a. Inability of the available models to simulate wheel configurations, SS and SD.

b. Stress sensitivity of the granular base, subbase, and subgrade materials.

STATISTICAL ANALYSIS

A statistical comparison of the ELSYM5 projections and the field data was made using the GLM procedure of the SAS program. Since several factors like the Load, Wheel Configuration, Season, and the Source (field, ELSYM5) affect the deflections and the LEFs, an attempt was made to study which of the aforementioned was most significant. Table 6.7 reports the F-values for the various factors affecting deflections and LEFs for both matrices.

It was observed that the most significant factor affecting both deflections and LEFs is the Load. This was followed by Season in the case of deflections and Wheel configuration in the case of damage factors. In the case of LEFs for Matrix 2, Source was significant because there was no way of distinguishing between the different wheel configurations in AASHTO calculations and no way of distinguishing between singled-out duals and super single tires in the case of ELSYM5. The insignificance of Season for LEFs is evident from the very low values of F obtained for both matrices.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the traffic survey and subsequent analysis of data, the following conclusions can be drawn:

1. For Loading Matrix 1, Dual tires were found to be most damaging. This is understandable since the total load carried by the DU tires, as compared to the SS and SD, was the largest, for the same ppi of tire width.

2. For Loading Matrix 2, where all wheel configurations carried the same load, the Super-Single and the Singled-Out Dual tires were found to inflict the greatest damage to the pavement.

3. The LEFs obtained from the field for DU type tires were in reasonable agreement with those obtained through AASHTO procedures.

4. Available computer models do not facilitate differentiation of tire widths as in the case of SS and SD wheel configurations, although the models can differentiate between single and dual tire configurations. As suggested later, use of finite element models such as FLEXPASS or ILLIPAVE can be made to better model in these situations.

5. Season was not found to significantly affect LEFs for both loading matrices.

6. The damage factors obtained in this study were based on data from single axles only. Additional field tests must be performed to obtain LEFs for tandem and tridem axles.

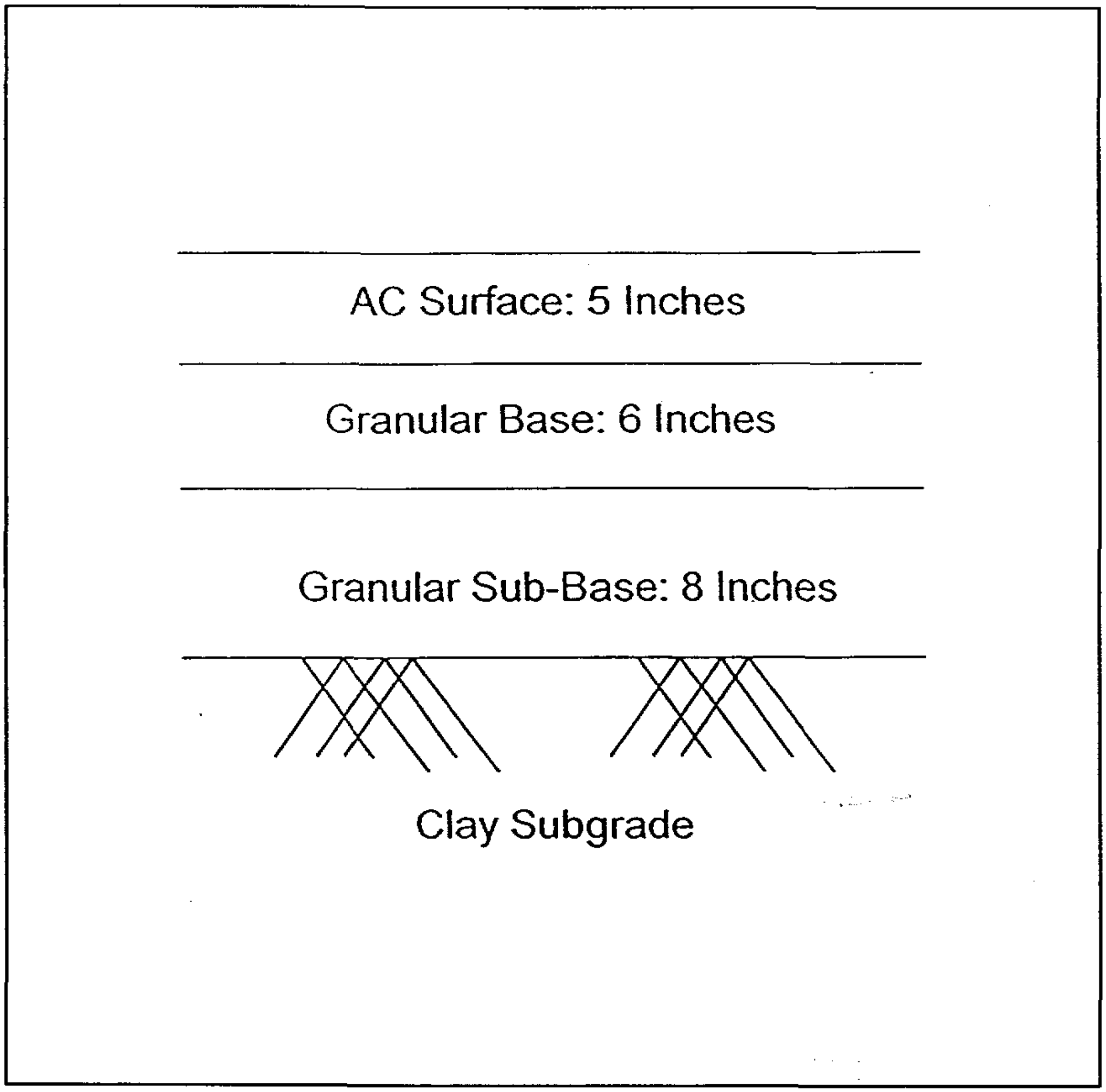

Figure 6.1 Cross-Section of typical flexible pavement section in South Dakota

Table 6.1. Subjective Evaluation of Deflection-based LEF Methods

Rating Criteria→	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	0=No 1=Yes	Score*
Screening Criteria→ / Method ↓	Is this a theoretical method?	Is the method based on *testing* results?	Are there explicit LEF equations in *terms of* pavement responses?	Are there load equivalency factors for tridems?	Is the method applicable to flexible pavements?	Are variables or parameters relatively easy to calculate or measure?	Is the method rigorous?	Do results have widespread applicability?	Is there enough information to implement the method?	
Zube [*8*]	0	1	0	0	1	1	1	0	1	5
Scala [*9*]	1	0	0	1	1	1	0	0	1	3
Gerard [*10*]	1	0	0	0	1	1	1	0	0	5
Treybig [*11*]	1	0	0	1	1	1	0/1	0	1	5
Christison [*5*]	0	1	1	0	1	1	0	1	1	4
Christison [*12*]	0	1	1	0	1	1	0	1	1	4
Sharp [*13*]	0	1	0	1	1	1	0	0	0	4
Christison [*5*]	0	1	1	1	1	1	1	1	1	8
Hutchinson [*6*]	0	1	1	1	1	1	1	1	1	8
Majidzadeh [*14*]	1	0	1	0	1	1	1	0	0	5

Score*: Between 7-9 may be used
Between 4-6 is a fair score
Between 0-3 is poor

Table 6.2(a). Summary of Average Deflections Obtained in the Field

Wheel Configuration	Load	Summer	Fall	Winter	Spring
Matrix 1: Load in PPI					
DU	400	10.32	7.873	6.851	11.32
	600	15.411	11.87	9.187	18.104
	800	20.52	14.514	11.72	22.534
SD	400	5.659	5.615	6.86	9.83
	600	8.893	7.72	8.19	13.39
	800	11.992	9.865	9.409	16.82
SS	400	10.942	6.821	9.697	13.98
	600	13.973	10.781	11.1	18.48
	800	19.479	13.587	13.216	24.15
Matrix 2: Load in pounds					
DU	6000	8.794	6.493	5.803	11.39
	9000	11.848	8.301	8.382	14.30
	12000	15.411	11.714	9.187	18.10
SD	6000	7.892	7.697	8.19	13.39
	9000	15.113	11.563	10.09	17.83
	12000	20.149	15.091	12.45	24.80
SS	6000	10.942	6.821	9.697	13.98
	9000	13.973	10.781	11.1	18.48
	12000	19.479	13.587	13.22	24.15

Table 6.2(b). Summary of Average LEFs Obtained from the Field

Wheel Configuration	Load	Summer	Fall	Winter	Spring	Average LEFs
Matrix 1: Load in PPI						
DU	400	0.59	0.84	0.45	0.61	0.62
	600	2.78	3.94	1.61	2.45	2.69
	800	8.34	8.4	4.15	5.66	6.64
SD	400	0.06	0.25	0.29	0.24	0.21
	600	0.35	0.77	0.95	0.78	0.71
	800	1.08	2.11	1.79	1.86	1.71
SS	400	0.75	0.5	2.12	0.92	1.07
	600	1.93	2.46	3.82	2.67	2.72
	800	6.9	6.61	8.18	7.45	7.29
Matrix 2: Load in Pounds						
DU	6000	0.34	0.4	0.24	0.43	0.35
	9000	1	1.05	1	1.01	1.01
	12000	2.78	3.94	1.61	2.45	2.70
SD	6000	0.35	0.77	0.95	0.78	0.71
	9000	2.67	3.55	2.48	2.35	2.76
	12000	7.68	9.85	5.69	8.12	7.84
SS	6000	0.75	0.5	2.12	0.92	1.07
	9000	1.93	2.46	3.82	2.65	2.71
	12000	6.9	6.61	8.18	7.45	7.29

Table 6.3. Layer Moduli used in Computer Simulations

Season	AC Modulus (psi)	Base Modulus (psi) (21,000)	Sub-base Modulus (psi) (13,600)	Subgrade Modulus (psi) (11,000)
Summer	300,000	50,000	35,000	22,500
Fall/Winter	800,000	60,000	46,000	28,000
Spring	500,000	40,000	28,000	15,000

Table 6.4. ELSYM5 Deflections and Load Equivalency Factors

Load (PPI)	Wheel configuration	Summer		Fall		Winter		Spring	
		Deflections	LEFs	Deflections	LEFs	Deflections	LEFs	Deflections	LEFs
MATRIX 1: Load in Pounds per inch									
400	DU	10.9	0.74	7.62	0.71	7.62	0.71	13	0.7
	SD	7.11	0.15	4.55	0.1	4.55	0.1	7.71	0.1
	SS	9.96	0.53	6.53	0.39	6.53	0.39	11.1	0.38
600	DU	15.3	2.68	10.9	2.75	10.9	2.75	18.7	2.77
	SD	9.96	0.53	6.53	0.39	6.53	0.39	11.1	0.38
	SS	14	1.91	9.37	1.55	9.37	1.55	15.9	1.5
800	DU	19.5	6.74	14	7.13	14	7.13	24.1	7.27
	SD	12.7	1.32	8.44	1.04	8.44	1.04	14.3	1
	SS	17.7	4.67	12.1	4.09	12.1	4.09	20.6	4
MATRIX 2: Load in pounds									
6000	DU	8.5	0.29	5.88	0.26	5.88	0.26	10	0.26
	SD	9.96	0.53	6.53	0.39	6.53	0.39	11.1	0.38
	SS	9.96	0.53	6.53	0.39	6.53	0.39	11.1	0.38
9000	DU	11.8	1	8.35	1	8.35	1	14.3	1
	SD	14	1.91	9.37	1.55	9.37	1.55	15.9	1.5
	SS	14	1.91	9.37	1.55	9.37	1.55	15.9	1.5
12000	DU	15.3	2.68	10.9	2.75	10.9	2.75	18.7	2.77
	SD	17.7	4.67	12.1	4.09	12.1	4.09	20.6	4
	SS	17.7	4.67	12.1	4.09	12.1	4.09	20.6	4

NOTE: ELSYM5 cannot differentiate between SS and SD wheel configurations.

Table 6.5. AASHTO Load Equivalency Factors

Load	Wheel configuration	Tire Width (in)	Axle Load (lb)	LEF
MATRIX 1:Load in PPI				
400	DU	20	16000	0.623
	SD	10	8000	0.034
	SS	15	12000	0.189
600	DU	20	24000	3.03
	SD	10	12000	0.189
	SS	15	18000	1
800	DU	20	32000	8.9
	SD	10	16000	0.623
	SS	15	24000	3.03
MATRIX 2:Load in Pounds				
6000	DU	-	12000	0.189
	SD	-	12000	0.189
	SS	-	12000	0.189
9000	DU	-	18000	1
	SD	-	18000	1
	SS	-	18000	1
12000	DU	-	24000	3.03
	SD	-	24000	3.03
	SS	-	24000	3.03

NOTE: AASHTO does not allow differentiation between any of the wheel configurations.

Table 6.6(a). Comparison of Deflections: Field vs. ELSYM5

Load (PPI)	Wheel configuration	Summer		Fall		Winter		Spring	
		Field	ELSYM5	Field	ELSYM5	Field	ELSYM5	Field	ELSYM5
MATRIX 1: Load in PPI									
400	DU	10.3	10.9	7.87	7.62	6.85	7.62	11.3	13
	SD	5.66	7.11	5.62	4.55	6.09	4.55	9.83	7.71
	SS	10.9	9.96	6.82	6.53	9.7	6.53	14	11.1
600	DU	15.4	15.3	11.9	10.9	9.19	10.9	18.1	18.7
	SD	8.89	9.96	7.72	6.53	8.15	6.53	13.4	11.1
	SS	14	14	10.8	9.37	11.1	9.37	18.5	15.9
800	DU	20.5	19.5	14.5	14	11.7	14	22.5	24.1
	SD	12	12.7	9.97	8.44	9.41	8.44	16.8	14.3
	SS	19.5	17.7	13.6	12.1	13.2	12.1	24.2	20.6
MATRIX 2: Load in pounds									
6000	DU	8.79	8.5	6.49	5.88	5.8	5.88	11.4	10
	SD	8.89	9.96	7.7	6.53	8.19	6.53	13.4	11.1
	SS	10.9	9.96	6.82	6.53	9.7	6.53	14	11.1
9000	DU	11.8	11.8	8.3	8.35	8.38	8.35	14.3	14.3
	SD	15.1	14	11.6	9.37	10.1	9.37	17.8	15.9
	SS	14	14	10.8	9.37	11.1	9.37	18.5	15.9
12000	DU	15.4	15.3	11.7	10.9	9.19	10.9	18.1	18.7
	SD	20.1	17.7	15.1	12.1	12.5	12.1	24.8	20.6
	SS	19.5	17.7	13.6	12.1	13.2	12.1	24.2	20.6

NOTE: ELSYM5 cannot differentiate between SS and SD wheel configurations.

Table 6.6(b). Comparisons of Load Equivalency Factors: Field vs. ELSYM5 and AASHTO

Load (PPI)	Wheel configuration	Summer			Fall			Winter			Spring		
		Field	ELSYM5	AASHTO	Field	ELSYM5	AASHTO	Field	ELSYM5	AASHTO	Field	ELSYM5	AASHTO
MATRIX 1: Load in Pounds per inch													
400	DU	0.59	0.74	0.623	0.84	0.71	0.623	0.45	0.71	0.623	0.61	0.7	0.623
	SD	0.06	0.15	0.034	0.25	0.1	0.034	0.29	0.1	0.034	0.24	0.1	0.034
	SS	0.75	0.53	0.189	0.5	0.39	0.189	2.12	0.39	0.189	0.92	0.38	0.189
600	DU	2.78	2.68	3.03	3.94	2.75	3.03	1.61	2.75	3.03	2.45	2.77	3.03
	SD	0.35	0.53	0.189	0.77	0.39	0.189	0.95	0.39	0.189	0.78	0.38	0.189
	SS	1.93	1.91	1	2.46	1.55	1	3.82	1.55	1	2.67	1.5	1
800	DU	8.34	6.74	8.9	8.4	7.13	8.9	4.15	7.13	8.9	5.66	7.27	8.9
	SD	1.08	1.32	0.623	2.11	1.04	0.623	1.79	1.04	0.623	1.86	1	0.623
	SS	6.9	4.67	3.03	6.61	4.09	3.03	8.18	4.09	3.03	7.45	4	3.03
MATRIX 2: Load in pounds													
6000	DU	0.34	0.29	0.189	0.4	0.26	0.189	0.24	0.26	0.189	0.43	0.26	0.189
	SD	0.35	0.53	0.189	0.77	0.39	0.189	0.95	0.39	0.189	0.78	0.38	0.189
	SS	0.75	0.53	0.189	0.5	0.39	0.189	2.12	0.39	0.189	0.92	0.38	0.189
9000	DU	1	1	1	1.05	1	1	1	1	1	1.01	1	1
	SD	2.67	1.91	1	3.55	1.55	1	2.48	1.55	1	2.35	1.5	1
	SS	1.93	1.91	1	2.46	1.55	1	3.82	1.55	1	2.65	1.5	1
12000	DU	2.78	2.68	3.03	3.94	2.75	3.03	1.61	2.75	3.03	2.45	2.77	3.03
	SD	7.68	4.67	3.03	9.85	4.09	3.03	5.69	4.09	3.03	8.12	4	3.03
	SS	6.9	4.67	3.03	6.61	4.09	3.03	8.18	4.09	3.03	7.45	4	3.03

NOTE: ELSYM5 cannot differentiate between SS and SD wheel configurations. AASHTO does not allow differentiation between any of the wheel configurations.

Table 6.7. ANOVA for Study of the Source of Deflections and LEF

Factor	F-Value (Deflections)		F-Value (LEFs)	
	Load Matrix	PPI Matrix	Load Matrix	PPI Matrix
Load	403.2	308.5	155.9	186.2
Wheel configuration	52.8	167.4	14.8	104.4
Season	277.6	201.9	0.1	0.1
Source	24.4	10.6	25.4	5.7

CHAPTER 7
PROJECT GROWTH AND HIGHWAY DAMAGE COST

The work discussed in this chapter was completed under Task 4, namely, "Project Growth and Highway Damage Cost under the Do Nothing Alternative". The economic impact of increased activity of Singled-out Dual (SD) and Super Single (SS) wheel configurations on the South Dakota highway network is evaluated through the use of AASHTO pavement design principles.

Task 4 was aimed at using the results from Tasks 2 and 3 (actual tire and load data, and damage estimates) to project the growth of increased tire loads and their economic impact on the SD DOT highway network. Only flexible pavements were considered during this economic evaluation since approximately 70 to 80 percent of the South Dakota highway network comprises of flexible pavements. Also, increased tire loads in this case were considered to imply an increased proportion of the Singled-out Dual (SD) and Super Single (SS) tires in the traffic stream.

The work performed under Task 4 was divided into two parts. Part I focused on the economic impact of the tire load increases on the pavement section monitored during Task 5. Part II on the other hand was directed at running a similar analysis for the entire South Dakota highway network.

ANALYSIS TECHNIQUE

The original request for proposal (RFP) for the study suggested the use of mechanistic models for projecting pavement life and the subsequent economic analysis. Our proposal had indicated the possible use of NAPCOM for performing the economic analysis. However, based on the results of the field study and subsequent discussions with the South Dakota Department of Transportation, it was decided to use the AASHTO procedures for evaluating the impact of increased tire loads on the pavement network in South Dakota. This selection was prompted by the fact that the LEFs determined in the field for Dual (DU) tires were found to be reasonably close to those obtained using the AASHTO procedures (refer to Chapter 6).

The AASHTO Guide for Pavement Design, 1986 [*4*] is based on mechanistic-empirical principles and has served as a beacon to highway engineers for several years. It employs the idea of assigning a Structural Number (SN) to a pavement section depending upon its layer thicknesses and moduli. The SN is consequently used in conjunction with other factors such as roadbed modulus and reliability to determine the Design Traffic. This represents the total number of 18-kip equivalent single axle load (ESAL) applications that the pavement structure will be able to carry before it fails. This design traffic can then be used along with an Initial

Year Traffic and a compound growth rate at which the traffic grows in the region through the following equation to determine the number of years the pavement will last:

$$W_d = W_i \left[\frac{(1+g)^n - 1}{g} \right] \tag{7-1}$$

where, W_d=design traffic

W_i	=	Initial year traffic
g	=	Annual percent growth rate of traffic, and
n	=	Design life of the pavement.

An increase in the initial year traffic due to a larger incidence of SS or SD types of tires would result in a decrease in the life of the said pavement. It is this principle that was used in Task 4 to compare the different scenarios of tire load increases.

ANALYSIS APPROACH

Several steps were involved in performing the economic analysis. These are explained as follows:

Determination of Design Traffic

Given the thicknesses and layer coefficients of each of the component layers in a pavement section, the Structural Number (SN) for the pavement section was determined. This SN was subsequently input into the AASHTO Pavement Design Equation (Equation 7-2 below) to determine the design number of 18-kip ESALs the pavement can endure before it fails.

$$\log_{10} w_{18} = Z_R * S_0 + 9.36 * \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\dfrac{\Delta PSI}{4.2-1.5}}{0.4+\dfrac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07 \tag{7-2}$$

where,

w_{18}	=	Design 18-kip ESALs
Z_R	=	Design reliability factor
S_0	=	Standard deviation
ΔPSI	=	Change in the present serviceability index, and
M_R	=	Resilient modulus of subgrade.

Initial Year Traffic

The computation of initial year traffic requires the use of ADT and the Average Daily Load (ADL). A typical traffic distribution was assumed for each functional class encountered based upon the W-1 and W-2 Tables of the 1989 Truck Weight Data from South Dakota [*15*]. Using a factor to adjust the ADT in the distribution to the observed ADT for the pavement section in consideration, an average daily load (ADL) is computed. A sample calculation is shown in Table 7.1. The initial year traffic can then be calculated using:

$$W_i = ADT \,.\, ADL \,.\, 365 \,.\, F_l \,.\, F_d \qquad \textbf{(7-3)}$$

where, W_i = Initial year traffic
F_l = Lane distribution factor, and
F_d = Directional distribution factor.

Life of a Pavement Section

Assuming an annual growth rate for traffic of 6 percent, Equation 7-1 was used to calculate the number of years that the said pavement will last. With the life of the pavement section and its initial construction and maintenance costs known (costs used were supplied by the South Dakota Department of Transportation' s Pavement Management section), the Present Worth of the option, and hence the EUAC (Equivalent Uniform Annual Cost per mile) as then computed using:

$$EUAC = PW\left(\frac{i}{1-(1+i)^{-n}}\right) \qquad \textbf{(7-4)}$$

where, *PW*: Present Worth of Cash flow
i : Discount rate
n: Life of the pavement in years

Present Worth: Life cycle costs may be expressed as a present worth (PW) or as an equivalent uniform annual cost (EUAC). Using the present worth method, all costs are adjusted to a present worth using a selected discount rate [*16*]. The costs incurred at any time in the future can be combined with the initial construction costs to give a total present worth over the analysis period.

$$PW = CASHFLOW\,\frac{1}{(1+i)^n} \qquad \textbf{(7-5)}$$

where the terms are the same as described above.

Discount Rate: The discount rate (commonly called the interest rate) represents the time value of money [*16*]. It is usually expressed as an annual compounded rate that represents the rate of interest money will earn over a future period. It has been suggested that the difference between the market rate of interest and the rate of inflation be used as the discount rate [*16*]. A technical paper from FHWA noted that the difference between interest rates and inflation rates does not remain constant over time [*17*]. It recommends the use of a discount rate in the range of 3 to 5 percent.

PART I - PAVEMENT SECTION MONITORED DURING TASK 5

A pavement section considered typical in the South Dakota flexible highway network was chosen to monitor deflections due to different wheel configurations and loads (see Chapter 5). The structural number of the pavement section was determined to be 5.0 through backcalculation. The SN from the original plans of the site was 3.3. Both SNs were used to determine life of the pavement section.

The design traffic for that particular section was determined using AASHTO Design Guide, 1986 for the following parameters:

Structural Number:	3.3/5.0
Resilient Modulus of Subgrade:	18,000 psi
Reliability:	90 percent
Standard Deviation:	0.49
Initial Serviceability:	4.0
Terminal Serviceability:	2.5

and comes out to be 7.5 million ESALs for an SN of 3.3 and as 99.3 million ESALs for an SN of 5.

An average daily traffic of 3,000 was assumed and initial traffic for one year determined using Equation 3 and assuming an ADL (Average Daily Load) equal to 1.0. This was assumed to be the base case where 100 percent of the traffic consisted of Dual tires. All tire assemblies were assumed to be loaded at 9,000 lbs. Since all wheel configurations are assumed to be carrying the same total load, the damage they inflict would be a function of wheel configuration only. This would afford a direct comparison of different scenarios where varying percentages of SS and SD configurations are introduced in the traffic stream.

Miner's hypothesis was then used to estimate the increased damage due to an increased activity of Super Single or Singled Out Dual tires in the South Dakota highway network. Initial traffic during the first year for the base case is:

Initial traffic = 3000*1.0*365/2*1.0*1.0 = 547,500 applications.

Assuming an annual growth rate of 6 percent, and a discount rate of 4 percent, the life of the said section for the above traffic levels using Equation 7-1 is determined. Using the Load Equivalency Factors (LEF) determined in the field, the total applications of 18k ESALs in one year for each of the following scenarios was determined. Using these initial year traffic values and the design traffic above, Equation 7-1 was used to determine the number of years the pavement will last for each of the scenarios considered. The following table summarizes the findings:

Scenario	Initial Year Traffic	SN of 5.0 (Backcalculated)		SN of 3.3 (Original Site Plans)	
		Life	% Decrease in Life	Life	% Decrease in Life
100% DU	547500	42.47	--	10.25	--
90% DU, 10% SS	621412	40.99	3.5	9.46	8.6
90% DU, 10% SD	649335	40.01	5.8	9.15	11.6
80% DU, 20% SS	695325	39.23	7.6	8.67	16.2
80% DU, 20% SD	751170	38.02	10.5	8.15	21.2

As can be seen from the above table, as the percent of Super Single or Singled-Out Dual tires in the traffic stream increases, the life of the pavement shortens. This will expedite the need for an overlay warranting extra costs than projected earlier; or the Equivalent Uniform Annual Costs would be higher in such a case.

PART II - ENTIRE SOUTH DAKOTA PAVEMENT NETWORK

The stepwise procedure used for performing the economic analysis for the entire South Dakota pavement network, and the results thus obtained, are explained as follows:

1. Pavement sections from the entire South Dakota flexible pavement network [*18*] were divided into representative sections based upon their functional classification and SN values.

2. Three functional classes were chosen for inclusion in the analysis based upon the observed frequency of their occurrence in the South Dakota flexible highway network. These were:

   a. 02 (Rural Principal Arterial) 32.0 percent
   b. 06 (Rural Minor Arterial) 49.4 percent
   c. 07 (Rural Major Collector) 16.0 percent

Other functional classes were not considered for analysis since they only comprised approximately 2.6% of the total miles in the South Dakota highway network.

3. Pavements in each functional classification were further categorized based on their SN values. The range of SN values considered for each functional class were:

   a. SN < 3.5
   b. SN = 3.5 - 5.5
   c. SN > 5.5

4. For each of the nine cells in the aforementioned matrix, the following parameters were computed:

   a. Average ADT
   b. Average Structural Number
   c. Total number of miles.

   Table 7.2 shows these values for each cell in the matrix.

5. For the average Structural Number under each cell, the Design Traffic or the number of applications that the pavement can receive before failure was determined using the DARWin [*18*] flexible pavement structural design system. Reliability was assumed to be 90 percent, the Standard Deviation was taken as 0.49, and the Roadbed Soil Modulus was assumed to 6000 psi. (based on typical conditions existing in South Dakota).

6. AASHTO Load Equivalency Factors were used for DU type tires.

7. Correlations of LEF for SS and SD type tires with those for DU type tires were established using field data. Certain discrepancies were found to occur in the Winter data as discussed in Chapter 5. These were attributed to random error and it was decided to ignore the Winter data for the rest of the Computations. This further evidenced by the fact that correlations between DU and SS type tires was poor when the Winter data was included. Regression analyses were carried out between the LEFs for DU tires and those for SS and SD tires and the following relationships were observed:

Wheel configuration	LEF Ratio	R^2
Singled-out Dual (SD)	2.776	0.95
Super Single (SS)	2.442	0.63

Consequently, regression analyses were carried out between the LEFs for DU tires and those for SS and SD tires for all season except Winter. The following relationships were observed.

Wheel configuration	LEF Ratio	R^2
Singled-out Dual (SD)	2.719	0.96
Super Single (SS)	2.183	0.86

The LEF for SS and SD type tires were then computed using the above relationships.

8. Based upon the functional classification, a typical traffic distribution was assumed from the W-1 and W-2 Tables of the Truck Weight Study data for South Dakota. Initial year traffic values were determined for the given ADT and functional class using the procedure outlined in the section on Initial Year Traffic discussed above.

9. Given the design traffic from 4 and the initial year traffic from 7 above, the life for the pavement section representing each cell in the matrix was determined using Equation 7-1 and a growth factor of 6 percent. This was designated as the base case where 100 percent of trucks were assumed to have Dual tires.

10. Different tire scenarios were then introduced in the traffic stream, and the total applications of 18-kip ESALs due to each in one year calculated. For this, the initial year traffic values computed in 7 above were used with the LEFs in 6 above in accordance with Miner's hypothesis to determine the new initial year traffic values. The following tire scenarios were considered:

    I. 100% DU
    II. 90% DU, 10% SS
    III. 90% DU, 10% SD
    IV. 80% DU, 20% SS
    V. 80% DU, 20% SD

The Design Traffic and the Initial Traffic for each of the scenarios above has been tabulated in Table 7.3.1.

11. Using the initial year traffic values in 9 above, and the design traffic from Equation 7-1, the number of years that the given pavement will last for the various scenarios in 10 above was determined. Table 7.3.2 summarizes the life for all the cells of the matrix. For Functional Class 07, the average Structural Number in the SN < 3.5 category was 1.94, and thus resulted in very short life span for the representative pavement sections. However, it could not be discarded as an anomaly because it contributed 162.2 miles which constitutes approximately 13 percent of the flexible highway network in South Dakota. It was observed that this category however comprised about 80% of the total EUAC costs. (Table 7.4)

    Figures 7.1 through 7.3 show the impact of increased use of SS and SD type wheel configurations on the life of the pavement. The reduced life of the pavement in turn means increased maintenance and rehabilitation costs to the state agencies. Figure 7.4 depicts the percent increase in costs for various percentages of SS and SD wheel configurations in the traffic stream.

12. Using estimated costs for initial pavement construction and maintenance typical of South Dakota conditions (supplied by the South Dakota Department of Transportation's Pavement Management Section), the equivalent uniform annual costs for each scenario were computed. A set of sample calculations is shown in Table 7.5.

13. The EUAC was multiplied by the miles in 3 above, and summed for all functional classes for each of the scenarios in 10 above. The EUAC of each option has been summarized in Table 7.4. The economic impact of the use of unconventional wheel configurations in the traffic stream was determined in terms of percent increase of EUAC. The percent increases have been outlined below:

a.	90% DU, 10% SS	6.16%
b.	90% DU, 10% SD	8.83%
c.	80% DU, 20% SS	12.18%
d.	80% DU, 20% SD	17.50%

14. The economic impact on the entire network was thus evaluated.

OPERATING COST RAMIFICATIONS

The use of SS and SD tire configurations instead of the conventional dual tires provides financial benefits to the trucking industry in two ways: 1) through increased fuel efficiency, assumed at 10%, and 2) through reduction in tare weight, and hence, increased haulage. However, the use of these tires also causes increased damage to the pavements, thereby increasing maintenance and rehabilitation costs to be incurred by the DOT. This analysis attempts to delineate the ratio of the cost to the DOT versus benefits to the trucking industry.

An analysis similar to that conducted by K-Tran [*3*] in 1991 was performed to determine the cost-benefit ratio of the use of SS and SD tire configurations. According to the South Dakota Motor Fuel Tax Division, the gallonage equivalence for diesel motor fuel tax receipts during fiscal year 1992 equalled approximately 970 million gallons. Since South Dakota is largely an agricultural state, it was assumed that 70 percent of the gallonage was consumed for non-commercial and agricultural purposes. This leaves 291 million gallons to be consumed by the trucking industry. This cost-benefit analysis considers all the alternative scenarios (strategies) discussed in the study.

Alternative Strategy 1 (90% DU, 10% SS)

The 10 percent of the tires converted to SS configuration, would consume 10 percent of the total gallonage consumed by trucks, i.e., 29.1 million gallons. Assuming that the average fuel consumption of each truck was 5 miles per gallon, the total number of miles travelled by trucks with SS tires would be 145.5 million.

As mentioned earlier, the use of SS/SD tires would increase fuel efficiency by 10 percent. If the average cost of motor fuel is assumed to be $1.00 per gallon, the total annual fuel savings to the trucking industry as a result of conversion to the SS tire configuration would be $1.00*0.1*29.1 million = $2.91 millions.

The reduction in tare weight is estimated at 1,600 lb (400/lb * 4 axles = 1,600 lb). Converting the tare weight to ton-miles, (1,600 lb / 2,000 lb/ton * 145.5 million miles) gives an increased haul capacity of 116.4 million ton-miles. If a value of $0.05 per ton-mile were assumed, the financial benefit of the reduced tare weight would be 116.4 * 0.05 = $5.82 millions.

The total annual benefit to the trucking industry is then computed as ($2.91 + $5.82) million = $8.73 million. From the values reported in Table 7.4, increased costs to the SD DOT for Alternative Strategy 1 was $18.7 million giving a cost-benefit ratio of 2.14.

The cost-benefit ratios for other alternative strategies are computed in a similar fashion and reported in Table 7.6.

CONCLUSIONS AND RECOMMENDATIONS

1. Super Single and Singed-Out Dual tires are highly damaging to the pavement, and result in lowering the lives of the pavements upon which they ply.

2. From the study and the field data collected, regression analyses showed that the Super Single tires were 2.18 times as damaging as the Dual tires. The Singled-Out Dual tires were found to be 2.72 times more damaging than the conventional Dual tires.

3. No relations are available for relating SS and SD wheel configurations to their tandem counterparts. Further study in this area is warranted.

4. Accelerated Load Studies have studied the impact of SS wheel configurations in the field; however, none have investigated the damaging effect of SD type tires. Such an investigation is required so that more light can be shed upon their effect on the fatigue life of pavements

5. Investigation of the effects on costs due to increased SS and SD activity revealed that costs went up by about 18 percent if 20 percent of the trucks converted to SD tires, and by 12 percent if the same percent conversion was made to SS tires.

6. The cost to the DOT versus benefits to the trucking industry ratios for the various scenarios evaluated in this study were:

a.	90% DU, 10% SS	2.14
b.	90% DU, 10% SD	3.33
c.	80% DU, 20% SS	2.12
d.	80% DU, 20% SD	3.30

Table 7.1 Sample Computations for ADL

Functional Class 02
SN Range 3.5 - 5.5
ADT 1,849

Using 1989 Truck Weight Study data for the P/M arterial system:
Total Vehicles counted 8,594
Factor (ADT/Vehicle Counted) 1849/8594 = 0.21515

Vehicle Type	Number Counted (N)	ADT (Factor*N)	18-kip Rate/1000[1]	ADL (ADT*18-kip Rate/1000)
Passenger Cars	5,461	1,174.9	0.8	0.94
Buses	48	10.3	257.0	2.65
Pickups				
Single Unit	2,123	456.8	3.9	1.78
2-Axle, 6-tire	270	58.1	362.1	21.04
3-Axle	84	18.1	615.0	11.11
4-Axle	20	4.3	458.0	1.97
Single Trailer Trucks				
4-Axle or less	127	27.3	558.4	15.26
5-Axle	379	81.5	1,115.5	90.96
6-Axle or More	27	5.8	881.9	5.12
Multi-Trailer Trucks				
5-Axle	14	3.0	845.0	2.55
6-Axle	1	0.2	1,121.0[2]	0.24
7-Axle	40	8.6	1,925.0	16.57
Total	**8,594**			**ADL = 170.19**

[1] Estimated values as per 1989 traffic data.

[2] Values for Interstate used since none was available for arterial.

Table 7.2. SN and ADT for each FC in the SD highway network

FC	CATEGORY	AVERAGE SN	AVERAGE ADT	MILES
2.000	SN <3.5	2.74	2,262.0	155.30
2.000	SN = 3.5 - 5.5	4.40	1,849.0	192.80
2.000	SN > 5.5	6.26	2,883.0	42.30
6.000	SN <3.5	2.52	834.0	324.90
6.000	SN = 3.5 - 5.5	4.21	939.0	255.70
6.000	SN > 5.5	6.48	2,183.0	27.30
7.000	SN <3.5	1.94	406.0	162.20
7.000	SN = 3.5 - 5.5	4.01	1,200.0	29.60
7.000	SN > 5.5	7.07	663.0	3.90

Table 7.3.1. Design and Initial traffic of each alternative

					INITIAL TRAFFIC				
FC	SN	MILES	ADL	DESIGN TRAFFIC	BASE CASE	CASE-II	CASE-III	CASE-IV	CASE-V
2.000	2.74	155.30	208.20	117,000.0	37,997.3	43,016.3	41,499.0	48,035.4	45,000.6
2.000	4.40	192.80	170.19	1,881,160.0	31,059.7	35,162.3	33,922.0	39,265.0	36,784.3
2.000	6.26	42.30	265.36	22,020,302.0	48,428.9	54,825.9	52,891.9	61,222.8	57,354.9
6.000	2.52	324.90	76.77	71,264.0	14,009.6	15,860.1	15,300.7	17,710.7	16,591.7
6.000	4.21	255.70	86.43	1,429,830.0	15,773.4	17,856.9	17,227.0	19,940.4	18,680.6
6.000	6.48	27.30	200.93	28,671,094.0	36,670.3	41,514.0	40,049.6	46,357.8	43,429.0
7.000	1.94	162.20	37.37	15,529.0	65,823.0	71,617.3	69,865.5	77,411.7	73,908.1
7.000	4.01	29.60	110.45	1,058,901.0	194,550.6	211,676.8	206,499.1	228,803.1	218,447.7
7.000	7.07	3.90	61.03	55,917,116.0	107,489.2	116,951.5	114,090.8	126,413.7	120,692.3

Table 7.3.2. Life of each alternative

FC	SN	MILES	ADL	DESIGN TRAFFIC	LIFE-I	LIFE-II	LIFE-III	LIFE-IV	LIFE-V
2.000	2.74	155.30	208.20	117,000.0	2.91	2.59	2.68	2.34	2.49
2.000	4.40	192.80	170.19	1,881,160.0	26.32	24.67	25.14	23.24	24.08
2.000	6.26	42.30	265.36	22,020,302.0	57.36	55.31	55.90	53.49	54.57
6.000	2.52	324.90	76.77	71,264.0	4.57	4.10	4.23	3.71	3.94
6.000	4.21	255.70	86.43	1,429,830.0	31.96	30.18	30.69	28.63	29.54
6.000	6.48	27.30	200.93	28,671,094.0	66.41	64.32	64.93	62.48	63.57
7.000	1.94	162.20	37.37	15,529.0	0.24	0.22	0.23	0.21	0.22
7.000	4.01	29.60	110.45	1,058,901.0	4.85	4.50	4.60	4.21	4.38
7.000	7.07	3.90	61.03	55,917,116.0	59.59	58.19	58.60	56.90	57.67

Table 7.4. Total Cost of each Alternative

FC	SN	MILES	COST-I	COST-II	COST-III	COST-IV	COST-V
2.000	2.74	155.30	20,427,334.0	22,061,826.0	22,770,001.0	23,696,026.0	25,112,151.0
2.000	4.40	192.80	4,662,186.0	4,764,933.0	4,818,492.0	4,888,262.0	4,969,280.0
2.000	6.26	42.30	765,007.0	769,288.0	771,566.0	774,518.0	777,818.0
6.000	2.52	324.90	28,417,035.0	30,515,610.0	31,424,705.0	32,224,926.0	34,020,727.0
6.000	4.21	255.70	5,616,838.0	5,733,746.0	5,784,011.0	5,826,434.0	5,925,411.0
6.000	6.48	27.30	479,543.0	481,397.0	482,377.0	483,162.0	485,074.0
7.000	1.94	162.20	241,152,163.0	255,790,550.0	262,133,523.0	270,426,606.0	283,113,241.0
7.000	4.01	29.60	2,453,170.0	2,572,308.0	2,623,921.0	2,691,406.0	2,794,596.0
7.000	7.07	3.90	69,936.0	70,228.0	70,355.0	70,432.0	70,682.0
TOTAL COST PER ALTERNATIVE			304,043,212.0	322,759,886.0	330,878,951.0	341,081,772.0	357,268,980.0
PERCENT INCREASE:				**6.16**	**8.83**	**12.18**	**17.51**

Note: Costs are EUAC (Equivalent Uniform Annual Costs)

Table 7.5. Sample Calculations for Initial Traffic, Life, and Costs

General Considerations

The following is an example computation based on the summary information reported in Table 7.2 where overall averages were computed for various pavement functional classes and structural number ranges. Consider the case of rural principal arterial roads (functional class = '02') and the structural number range of 'less than 3.5'. Table 7.2 provides the following information:

Average Structural Number:	2.74
Average ADT:	2,262

Design Traffic

To determine the design traffic for the pavement section under consideration, the following assumptions were made:

Initial Serviceability:	4.00
Terminal Serviceability:	2.50
Reliability:	90%
Standard Deviation:	0.49
Resilient Modulus of Subgrade:	6,000 psi

Use of the above parameters in DARWin 1.0 gives a design traffic of 117,000 18-kip Equivalent Single Axle Loads.

Average Daily Load (ADL)

Using the 1989 traffic data for P/M arterial system (refer Table 7.1), the average daily load for the section in consideration can be determined as follows:

Total vehicles counted:	8,594
ADT per vehicle counted:	2,262/8,594 = 0.2632
ADL for this particular case:	(170.19/0.21515)*0.2632 = 208.20

Design Life[3]: Base Strategy (100% DU)

Growth Rate:	6%
Directional Distribution:	50%

[3] The lives reported here are the remaining lives of the pavement sections and are based on their existing Structural Numbers.

Lane Distribution: 100%
Initial Traffic: 208.2*0.5*1.0*365 = 37,997.3

Using Equation 7-1, and substituting values,

$$117{,}000 = 37{,}997.3\ [(1+0.06)^n - 1] / 0.06$$

the design life is computed to be n = 2.91 years.

Design Life: Alternative Strategy 1 (90% DU, 10% SS)

Assuming that tire changes take effect only on Single Trailer and Multi-trailer trucks (assumption carried through all alternative strategies), and using the numbers reported in Table 7.1,

$$\textit{Initial Traffic} = \left[\left(\frac{(0.94+2.65)}{0.21515} + \frac{35.9}{0.21515}\right) + ((607.48)*0.2632*(0.9*1+0.1*2.72))\right]*0.5*$$

$$= 43{,}016.3$$

Substituting the initial traffic and other parameters in Equation (7-1) gives

$$117{,}000 = 43{,}016.3\ [(1+0.06)^n - 1]/0.06$$

which after solving results in a design life of n = 2.59 years.

The initial year traffic and design lives for other alternative strategies are obtained following the same methodology and are reported in Table 7.3.

Costs

The following costs which were supplied by the South Dakota Department of Transportation's Pavement Management Section were used to compute the Present Worth of the options as well as the Equivalent Uniform Annual Costs (EUAC).

Initial Construction Costs:	
Surface (Asphalt Concrete)-2 lane primary:	\$260,000
6" Gravel Base and Blotter:	\$90,000
Total Initial Construction Costs:	\$350,000
Average Maintenance Cost per mile:	\$5,000

All costs are converted to their Present Worth, using a Discount Rate of 4%, and the following formula:

$$Present\ Worth = Cash\ Flow\ \frac{1}{(1+i)^n}$$

Since the remaining life of the pavement for the base strategy is only 2.91 years, only one maintenance schedule is considered.

Therefore, present worth of the maintenance for the base strategy is:

$5{,}000*(1/(1+0.04)^2) = \$4{,}622.8$

Total present worth over the remaining life of the pavement is:

$350{,}000 + 4{,}622.8 = \$354{,}622.8$

Equivalent Uniform Annual Costs of the option per mile:

$354{,}622.8*(0.04/(1-(1.04)^{-2.91})) = \$131{,}512.2$

Total EUAC for 155.3 miles (total length of pavements in the Structural Number category 'less than 3.5', and functional class '02') = 131,512.2*155.3 ≈ $ 20,427,840.

Costs for all other options are calculated similarly and reported in Table 7.4.

Table 7.6. Cost-Benefit Ratio Summary

Scenario	Benefits to Trucking Industry: Fuel Cost Savings ($ million)	Increased Haulage ($ million)	Total ($ million)	Costs to DOT ($ million)	Cost-Benefit Ratio
90% DU, 10% SS	2.91	5.82	8.73	18.72	2.14
90% DU, 10% SD	2.91	5.15[1]	8.06	26.84	3.33
80% DU, 20% SS	5.82	11.64	17.46	37.04	2.12
80% DU, 20% SD	5.82	10.30	16.12	53.22	3.30

Note:

1. The reduction in tare weight for one side of an axle due to conversion to SD tire configuration has been assumed to be:

Tire	117 lb
Tire assembly (including rim)	60 lb
Total	177 lb

The total reduction in tare weight per truck will be:

177 * 2 side * 4 axles = 1,416 lb

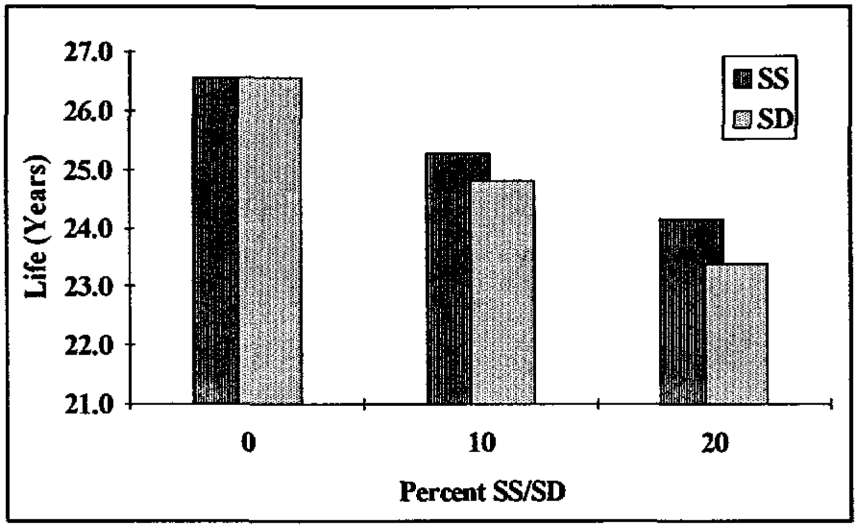

Figure 7.1. Design Life vs. Percent of SS/SD Wheel Configurations in the Traffic Mix (Functional Class = 02, SN Range = 3.5 - 5.5)

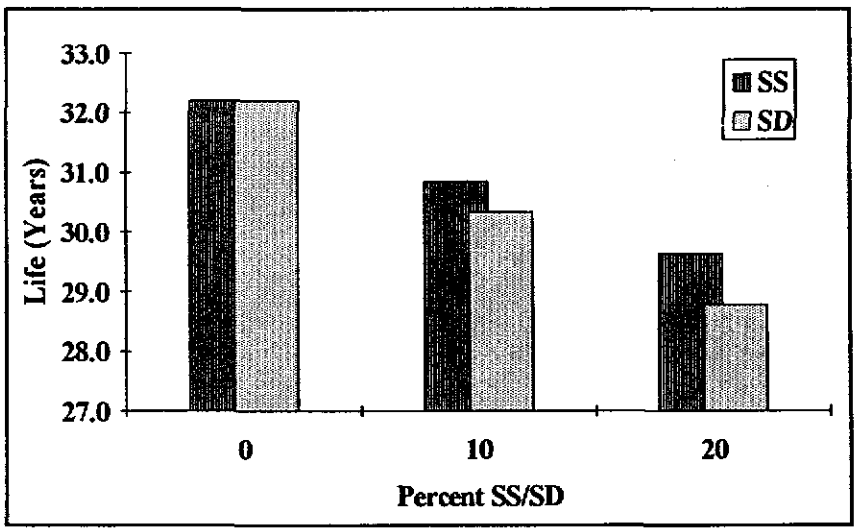

Figure 7.2. Design Life vs. Percent of SS/SD Wheel Configurations in the Traffic Mix (Functional Class = 06, SN Range = 3.5 - 5.5)

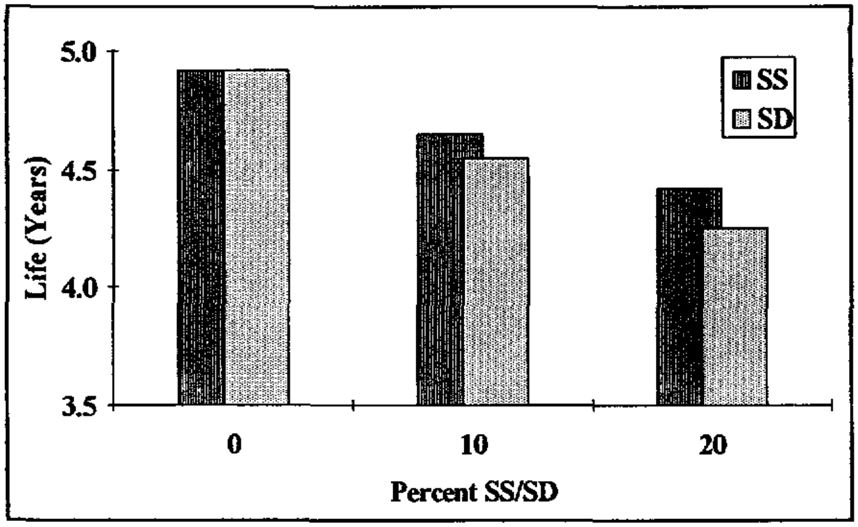

Figure 7.3. ***Design Life vs. Percent of SS/SD Wheel Configurations in the Traffic Mix (Functional Class = 07, SN Range = 3.5 - 5.5)***

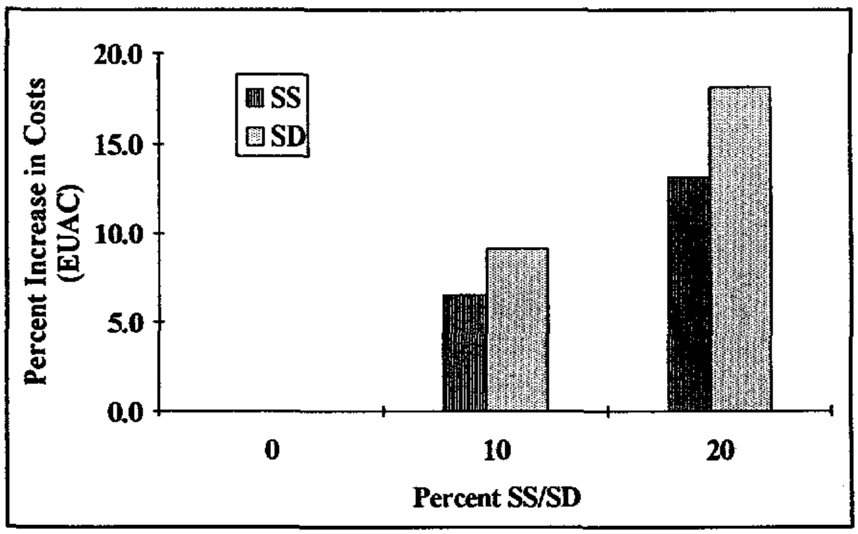

Figure 7.4. Percent Increase in EUAC vs. Percent of SS/SD Wheel Configurations in the Traffic Mix

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

The objective of this research was to evaluate the effect of increased tire loads on pavement service life. Increased tire loads due to truck owners replacing dual tire wheel configurations with super single tires or singled-out dual tires is expected to shorten a highway service life and increase maintenance requirements. Since additional information was needed to make decisions regarding such load increases, this research attempted to quantify the effects of these changes on the applicability of current flexible pavement design procedures and their effect on pavement performance as related to South Dakota highways.

CONCLUSIONS

The following paragraphs summarize the conclusions drawn from the study and the recommendations for future research.

1. The proportion of Super Single and Singled-Out dual tires in the sampled traffic is 17.9 and 2.8 respectively. Of all the tires in the sample, the Super single tires had the highest tire pressure and carried the highest load. Frequency distributions of various parameters including tire width, tire pressure, tire imprint dimensions, wheel load and axle load indicate that most of the data is normally distributed.

2. The results of the statistical analysis of the field deflection data and the corresponding load equivalency factors indicates that:

   - All factors included in the experimental matrices significantly affect the surface deflection of the pavement. The order of significance for main factors is:

     Matrix 1 (Load in ppi): Load > Season > Tire > Channel
     Matrix 2 (Load in lbs): Load > Season > Tire > Channel >>Temperature

   - Individual analyses and observation of the data summaries for the various seasons indicate that the Winter data does not follow normal behavior. Output values from one channel were found to be consistently lower than the other.

   - The analyses of LEFs indicate the following factors to be significant:

     Matrix 1 (Load in PPI): Load > Tire > > Temperature > Season
     Matrix 2 (Load in lbs): Load > Tire

   - Season does not affect LEFs as significantly as the other factors.

3. For the Matrix 1, the dual tires were found to be the most damaging. This is understandable since the total load carried by the DU tires as compared to the super single and singled-out dual tires was the largest. This was due to the fact that the load was applied as pounds per inch width of tire and DU configuration has the largest overall tire width.

4. For Matrix 2, where all wheel configurations carried the same total load, the Singled-Out Dual and the Super Single tires, in that order, were found to inflict the greatest damage to the pavement.

5. The LEFs obtained from the field for dual tires were in reasonable agreement with those obtained using AASHTO procedures.

6. Super single and singled-out dual tires are highly damaging to the pavement and result in lowering the pavement life. Regression analyses showed that the super single tires were 2.18 times as damaging as the dual tires. The SD tires were found to be 2.72 times more damaging than the conventional DU tires.

7. Investigation of the effects on costs due to increased SS and SD activity revealed that costs went up by about 18 percent if 20 percent of the trucks converted to SD tires, and by 12 percent if the same percent conversion was made to SS tires.

8. The cost to the DOT versus benefits to the trucking industry ratios for the various scenarios evaluated in this study were:

a.	90% DU, 10% SS	2.14
b.	90% DU, 10% SD	3.33
c.	80% DU, 20% SS	2.12
d.	80% DU, 20% SD	3.30

RECOMMENDATIONS

Based on the limited field and analytical studies performed during this project the following recommendations can be made:

1. The proportion of the different types of tires in the traffic stream as obtained through the traffic survey are:

Regular Singles:	23.4 percent
Duals:	56.0 percent
Super Singles:	17.9 percent
Singled-out Duals:	2.8 percent

However, realizing the limited nature of the survey performed it would be advisable to perform a detailed traffic survey to properly establish these percentages. If the above percentages are confirmed, it would be prudent to devise some legislative mechanism to limit the use of such tires in the stream, realizing their damaging effects.

2. The current limit of 600 ppi for different tire assemblies should either be maintained or reduced to a lower limit, such as 500 ppi as suggested by WASHTO (2), in order for the pavement to sustain minimal need for early rehabilitation.

3. The damage factors obtained in this study were based on data from single axles only. Additional tests must be performed to obtain LEFs for tandem and tridem axles, for the various wheel configurations investigated in this study.

4. Accelerated load studies by other agencies have evaluated the impact of SS tires in the field; however, none have investigated the damaging effect of SD tire assemblies. Further study in this area is warranted to shed light on their effect on the fatigue life of pavements.

5. Available computer models do not facilitate differentiation of tire widths as in the case of SS and SD wheel configurations, although the models can differentiate between single and dual tire configurations. Use of finite element models such as FLEXPASS or ILLIPAVE can be made to better model in these situations.

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APPENDICES

APPENDIX A - ANOVA TABLES

Table A-1. ANOVA for Deflections (All Seasons Combined)

a. Matrix 1 (Load in ppi)

Source	DF	SS	MS	F	Significant at α=0.05?
Total	302	6,721.867	-	-	-
Season	3	2,258.358	752.786	2,367.44	Yes
Tire	2	1,280.200	640.100	2,013.06	Yes
Season x Tire	6	256.536	42.756	134.46	Yes
Load	2	2,230.994	1,115.497	3,508.14	Yes
Season x Load	6	224.639	37.440	117.74	Yes
Tire x Load	4	89.796	22.449	70.60	Yes
Channel	1	35.655	35.665	112.13	Yes
Season x Channel	3	257.755	85.918	270.20	Yes
Tire x Channel	2	0.426	0.213	0.67	No
Load x Channel	2	1.552	0.776	2.44	No
Temperature	1	0.102	0.102	0.32	No
Residual	270	85.853	0.318	-	-

Table A-1. ANOVA for Deflections (All Seasons Combined) (Continued)

b. Matrix 2 (Load in lb)

Source	DF	SS	MS	F	Significant at $\alpha=0.05$?
Total	302	6,875.940	-	-	-
Season	3	2,933.438	977.813	2,396.64	Yes
Tire	2	579.026	289.513	709.60	Yes
Season x Tire	6	85.322	14.220	34.85	Yes
Load	2	2,496.617	1,248.308	3,059.63	Yes
Season x Load	6	303.178	50.530	123.85	Yes
Tire x Load	4	76.830	19.208	47.08	Yes
Channel	1	44.619	44.619	109.36	Yes
Season x Channel	3	235.778	78.593	192.63	Yes
Tire x Channel	2	1.322	0.661	1.62	No
Load x Channel	2	0.322	0.161	0.39	No
Temperature	1	9.328	9.328	22.86	Yes
Residual	270	110.158	0.408	-	-

Table A-2. ANOVA for Deflections (Individual Seasons)

a. Matrix 1 (Load in ppi), Season = Summer

Source	DF	SS	MS	F	Significant at α=0.05?
Total	76	1,701.887	-	-	-
Tire	2	781.633	390.816	1,913.63	Yes
Load	2	849.113	424.556	2,078.83	Yes
Tire x Load	4	37.254	9.314	45.60	Yes
Channel	1	18.611	18.611	91.13	Yes
Tire x Channel	2	0.801	0.400	1.96	No
Load x Channel	2	1.718	0.859	4.21	Yes
Temperature	1	0.095	0.095	0.46	No
Residual	62	12.662	0.204	-	-

b. Matrix 2 (Load in lb), Season = Summer

Source	DF	SS	MS	F	Significant at α=0.05?
Total	73	1,163.139	-	-	-
Tire	2	85.176	42.588	123.56	Yes
Load	2	984.178	492.089	1,427.72	Yes
Tire x Load	4	56.559	14.140	41.02	Yes
Channel	1	15.034	15.034	43.62	Yes
Tire x Channel	2	1.093	0.547	1.59	No
Load x Channel	2	0.680	0.340	0.99	No
Temperature	1	0.082	0.082	0.24	No
Residual	59	20.335	0.345	-	-

Table A-2. ANOVA for Deflections (Individual Seasons) (Continued)

c. Matrix 1 (Load in ppi), Season = Fall

Source	DF	SS	MS	F	Significant at α=0.05?
Total	77	673.225	-	-	-
Tire	2	207.822	103.911	621.87	Yes
Load	2	431.682	215.841	1,291.72	Yes
Tire x Load	4	18.552	4.638	27.76	Yes
Channel	1	1.857	1.857	11.11	Yes
Tire x Channel	2	2.129	1.065	6.37	Yes
Load x Channel	2	0.427	0.214	1.28	No
Temperature	1	0.228	0.228	1.37	No
Residual	63	10.527	0.167	-	-

b. Matrix 2 (Load in lb), Season = Fall

Source	DF	SS	MS	F	Significant at α=0.05?
Total	75	607.936	-	-	-
Tire	2	63.848	31.924	217.21	Yes
Load	2	515.605	257.802	1,754.04	Yes
Tire x Load	4	13.737	3.434	23.37	Yes
Channel	1	1.184	1.184	8.06	Yes
Tire x Channel	2	3.139	1.570	10.68	Yes
Load x Channel	2	0.143	0.072	0.49	No
Temperature	1	1.314	1.314	8.94	Yes
Residual	61	8.966	0.147	-	-

Table A-2. ANOVA for Deflections (Individual Seasons) (Continued)

e. Matrix 1 (Load in ppi), Season = Winter

Source	DF	SS	MS	F	Significant at α=0.05?
Total	76	656.879	-	-	-
Tire	2	165.620	82.810	494.73	Yes
Load	2	177.594	88.797	530.50	Yes
Tire x Load	4	31.506	7.877	47.06	Yes
Channel	1	266.165	266.165	1,590.15	Yes
Tire x Channel	2	5.033	2.517	15.03	Yes
Load x Channel	2	0.415	0.207	1.24	No
Temperature	0	0.000	-	-	-
Residual	63	10.545	0.167	-	-

f. Matrix 2 (Load in lb), Season = Winter

Source	DF	SS	MS	F	Significant at α=0.05?
Total	78	661.715	-	-	-
Tire	2	209.480	104.740	671.51	Yes
Load	2	167.148	83.574	535.81	Yes
Tire x Load	4	9.032	2.258	14.48	Yes
Channel	1	263.173	263.173	1,687.25	Yes
Tire x Channel	2	2.278	1.139	7.30	Yes
Load x Channel	2	0.467	0.233	1.50	No
Temperature	0	0.000	-	-	-
Residual	65	10.139	0.156	-	-

Table A-2. ANOVA for Deflections (Individual Seasons) (Continued)

g. Matrix 1 (Load in ppi), Season = Spring

Source	DF	SS	MS	F	Significant at α=0.05?
Total	70	1,431.518	-	-	-
Tire	2	381.662	190.831	732.44	Yes
Load	2	997.244	498.622	1,913.79	Yes
Tire x Load	4	28.927	7.232	27.76	Yes
Channel	1	2.239	2.239	8.59	Yes
Tire x Channel	2	1.149	0.575	2.21	No
Load x Channel	2	5.447	2.723	10.45	Yes
Temperature	0	0.000	-	-	-
Residual	57	14.851	0.261	-	-

h. Matrix 2 (Load in lb), Season = Spring

Source	DF	SS	MS	F	Significant at α=0.05?
Total	73	1,509.712	-	-	-
Tire	2	305.844	152.922	473.00	Yes
Load	2	1,132.864	566.432	1,752.03	Yes
Tire x Load	4	47.704	11.926	36.89	Yes
Channel	1	0.418	0.418	1.29	No
Tire x Channel	2	0.184	0.092	0.28	No
Load x Channel	2	3.300	1.650	5.10	Yes
Temperature	0	0.000	-	-	-
Residual	60	19.398	0.323	-	-

Table A-3. ANOVA for Deflections (All Seasons except Winter Combined)

a. Matrix 1 (Load in ppi)

Source	DF	SS	MS	F	Significant at α=0.05?
Total	225	5,517.884	-	-	-
Season	2	1,711.254	855.627	3,159.91	Yes
Tire	2	1,222.260	611.130	2,256.96	Yes
Season x Tire	4	148.857	37.214	137.44	Yes
Load	2	2,203.640	1,101.820	4,069.13	Yes
Season x Load	4	74.398	18.600	68.69	Yes
Tire x Load	4	73.438	18.359	67.80	Yes
Channel	1	6.772	6.772	25.01	Yes
Season x Channel	2	16.082	8.041	29.70	Yes
Tire x Channel	2	1.935	0.967	3.57	Yes
Load x Channel	2	3.400	1.700	6.28	Yes
Temperature	1	1.964	1.964	7.25	Yes
Residual	199	53.884	0.271	-	-

Table A-3. ANOVA for Deflections (All Seasons except Winter Combined) (Continued)

b. Matrix 2 (Load in lb)

Source	DF	SS	MS	F	Significant at α=0.05?
Total	223	5,351.053	-	-	-
Season	2	2,070.267	1,035.133	2,419.48	Yes
Tire	2	389.956	194.978	455.73	Yes
Season x Tire	4	64.913	16.228	37.93	Yes
Load	2	2,550.825	1,275.412	2,981.10	Yes
Season x Load	4	81.822	20.456	47.81	Yes
Tire x Load	4	89.010	22.252	52.01	Yes
Channel	1	3.577	3.577	8.36	Yes
Season x Channel	2	12.923	6.462	15.10	Yes
Tire x Channel	2	2.585	1.292	3.02	No
Load x Channel	2	0.369	0.185	0.43	No
Temperature	1	0.524	0.524	1.22	No
Residual	197	84.283	0.428	-	-

Table A-4. ANOVA for Load Equivalency Factors (All Seasons Combined)

a. Matrix 1 (Load in ppi)

Source	DF	SS	MS	F	Significant at α=0.05?
Total	302	2,280.781	-	-	-
Season	3	8.810	2.937	2.83	Yes
Tire	2	441.183	220.591	212.45	Yes
Season x Tire	6	110.637	18.440	17.76	Yes
Load	2	1,037.538	518.769	499.63	Yes
Season x Load	6	16.425	2.737	2.64	Yes
Tire x Load	4	228.716	57.179	55.07	Yes
Channel	1	0.821	0.821	0.79	No
Season x Channel	3	143.701	47.900	46.13	Yes
Tire x Channel	2	8.261	4.130	3.98	Yes
Load x Channel	2	0.116	0.058	0.06	No
Temperature	1	4.232	4.232	4.08	Yes
Residual	270	280.343	1.038	-	-

Table A-4. ANOVA for Load Equivalency Factors (All Seasons Combined) (Continued)

b. Matrix 2 (Load in lb)

Source	DF	SS	MS	F	Significant at α=0.05?
Total	302	2,541.005	-	-	-
Season	3	7.202	2.401	2.20	No
Tire	2	346.960	173.480	158.69	Yes
Season x Tire	6	59.919	9.987	9.14	Yes
Load	2	1,390.846	695.423	636.16	Yes
Season x Load	6	35.851	5.975	5.47	Yes
Tire x Load	4	224.208	56.052	51.28	Yes
Channel	1	0.380	0.380	0.35	No
Season x Channel	3	170.833	56.944	52.09	Yes
Tire x Channel	2	8.496	4.248	3.89	Yes
Load x Channel	2	0.465	0.232	0.21	No
Temperature	1	0.690	0.690	0.63	No
Residual	270	295.155	1.093	-	-

Table A-5. ANOVA for Load Equivalency Factors (Individual Seasons)

a. Matrix 1 (Load in ppi), Season = Summer

Source	DF	SS	MS	F	Significant at α=0.05?
Total	76	626.710	-	-	-
Tire	2	169.718	84.859	435.13	Yes
Load	2	294.226	147.113	754.35	Yes
Tire x Load	4	111.612	27.903	143.08	Yes
Channel	1	14.850	14.850	76.15	Yes
Tire x Channel	2	6.273	3.137	16.08	Yes
Load x Channel	2	17.926	8.963	45.96	Yes
Temperature	1	0.013	0.013	0.07	No
Residual	62	12.091	0.195	-	-

b. Matrix 2 (Load in lb), Season = Summer

Source	DF	SS	MS	F	Significant at α=0.05?
Total	73	508.178	-	-	-
Tire	2	51.597	25.799	117.31	Yes
Load	2	353.059	176.530	802.70	Yes
Tire x Load	4	59.991	14.998	68.20	Yes
Channel	1	15.328	15.328	69.70	Yes
Tire x Channel	2	3.220	1.610	7.32	Yes
Load x Channel	2	12.000	6.000	27.28	Yes
Temperature	1	0.008	0.008	0.04	No
Residual	59	12.975	0.220	-	-

Table A-5. ANOVA for Load Equivalency Factors (Individual Seasons) (Continued)

c. Matrix 1 (Load in ppi), Season = Fall

Source	DF	SS	MS	F	Significant at α=0.05?
Total	77	572.775	-	-	-
Tire	2	155.116	77.558	473.24	Yes
Load	2	318.122	159.061	970.56	Yes
Tire x Load	4	72.981	18.245	111.33	Yes
Channel	1	10.765	10.765	65.69	Yes
Tire x Channel	2	0.807	0.403	2.46	No
Load x Channel	2	4.289	2.144	13.08	Yes
Temperature	1	0.371	0.371	2.26	No
Residual	63	10.325	0.164	-	-

b. Matrix 2 (Load in lb), Season = Fall

Source	DF	SS	MS	F	Significant at α=0.05?
Total	75	667.019	-	-	-
Tire	2	79.330	39.665	147.86	Yes
Load	2	471.500	235.750	878.80	Yes
Tire x Load	4	65.235	16.309	60.79	Yes
Channel	1	18.304	18.304	68.23	Yes
Tire x Channel	2	6.580	3.290	12.26	Yes
Load x Channel	2	9.162	4.581	17.08	Yes
Temperature	1	0.543	0.543	2.03	No
Residual	61	16.364	0.268	-	-

Table A-5. ANOVA for Load Equivalency Factors (Individual Seasons) (Continued)

e. Matrix 1 (Load in ppi), Season = Winter

Source	DF	SS	MS	F	Significant at α=0.05?
Total	76	660.297	-	-	-
Tire	2	140.641	70.320	96.61	Yes
Load	2	189.895	94.947	130.44	Yes
Tire x Load	4	33.052	8.263	11.35	Yes
Channel	1	106.866	106.866	146.82	Yes
Tire x Channel	2	78.179	39.090	53.70	Yes
Load x Channel	2	65.808	32.904	45.21	Yes
Temperature	0	0.000	-	-	-
Residual	63	45.857	0.728	-	-

f. Matrix 2 (Load in lb), Season = Winter

Source	DF	SS	MS	F	Significant at α=0.05?
Total	78	761.551	-	-	-
Tire	2	171.058	85.529	127.77	Yes
Load	2	206.143	103.072	153.98	Yes
Tire x Load	4	47.938	11.984	17.90	Yes
Channel	1	133.875	133.875	200.00	Yes
Tire x Channel	2	78.570	39.285	58.69	Yes
Load x Channel	2	80.457	40.229	60.10	Yes
Temperature	0	0.000	-	-	-
Residual	65	43.509	0.669	-	-

Table A-5. ANOVA for Load Equivalency Factors (Individual Seasons) (Continued)

g. Matrix 1 (Load in ppi), Season = Spring

Source	DF	SS	MS	F	Significant at-α=0.05?
Total	70	412.190	-	-	-
Tire	2	86.345	43.173	343.84	Yes
Load	2	251.720	125.860	1,002.38	Yes
Tire x Load	4	53.310	13.327	106.14	Yes
Channel	1	3.789	3.789	30.17	Yes
Tire x Channel	2	2.867	1.434	11.42	Yes
Load x Channel	2	7.003	3.501	27.88	Yes
Temperature	0	0.000	-	-	-
Residual	57	7.157	0.126	-	-

h. Matrix 2 (Load in lb), Season = Spring

Source	DF	SS	MS	F	Significant at α=0.05?
Total	73	597.054	-	-	-
Tire	2	104.893	52.447	330.17	Yes
Load	2	395.993	197.996	1,246.46	Yes
Tire x Load	4	72.725	18.181	114.46	Yes
Channel	1	5.703	5.703	35.90	Yes
Tire x Channel	2	2.525	1.263	7.95	Yes
Load x Channel	2	5.683	2.842	17.89	Yes
Temperature	0	0.000	-	-	-
Residual	60	9.531	0.159	-	-

Table A-6. ANOVA for Load Equivalency Factors (All Seasons except Winter Combined)

a. Matrix 1 (Load in ppi)

Source	DF	SS	MS	F	Significant at α=0.05?
Total	225	1,619.330	-	-	-
Season	2	7.656	3.828	13.68	Yes
Tire	2	377.308	188.654	674.08	Yes
Season x Tire	4	33.871	8.468	30.26	Yes
Load	2	858.628	429.314	1,533.99	Yes
Season x Load	4	5.440	1.360	4.86	Yes
Tire x Load	4	218.923	54.731	195.56	Yes
Channel	1	26.784	26.784	95.70	Yes
Season x Channel	2	2.070	1.035	3.70	Yes
Tire x Channel	2	6.889	3.445	12.31	Yes
Load x Channel	2	26.059	13.029	46.56	Yes
Temperature	1	0.008	0.008	0.03	No
Residual	199	55.694	0.280	-	-

Table A-6. ANOVA for Load Equivalency Factors (All Seasons except Winter Combined) (Continued)

b. Matrix 2 (Load in lb)

Source	DF	SS	MS	F	Significant at $\alpha=0.05$?
Total	223	1,779.305	-	-	-
Season	2	7.054	3.527	13.43	Yes
Tire	2	227.828	113.914	433.78	Yes
Season x Tire	4	7.993	1.998	7.61	Yes
Load	2	1,216.449	608.225	2,316.07	Yes
Season x Load	4	4.103	1.026	3.91	Yes
Tire x Load	4	187.256	46.814	178.26	Yes
Channel	1	37.059	37.059	141.12	Yes
Season x Channel	2	1.770	0.885	3.37	Yes
Tire x Channel	2	9.735	4.868	18.54	Yes
Load x Channel	2	24.905	12.452	47.42	Yes
Temperature	1	3.419	3.419	13.02	Yes
Residual	197	51.734	0.263	-	-

APPENDIX B - FIELD VS. ELSYM5 COMPARISONS
(Deflections)

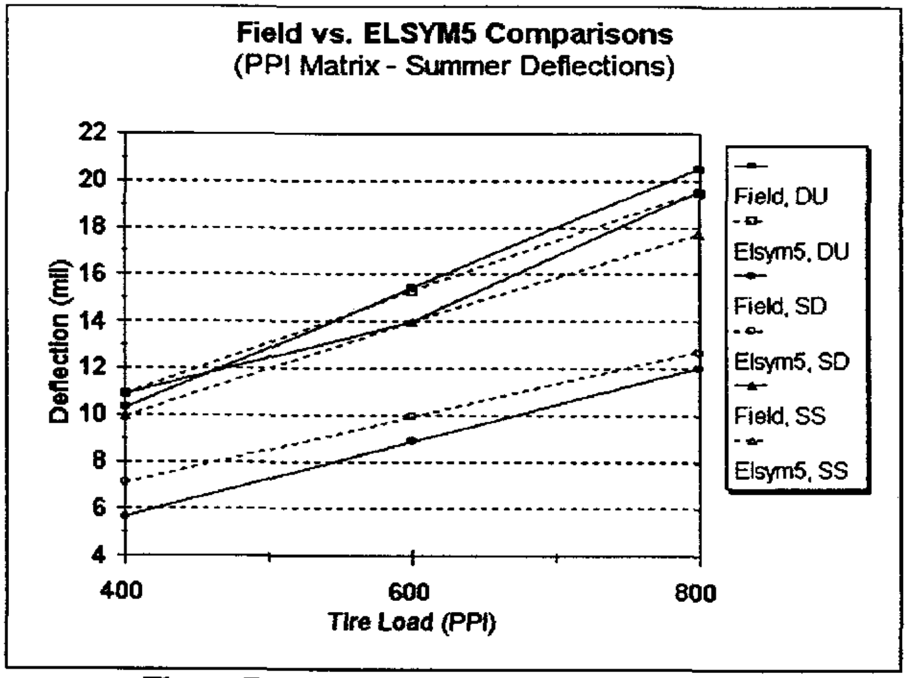

Figure B-1. Summer Deflections for Matrix 1

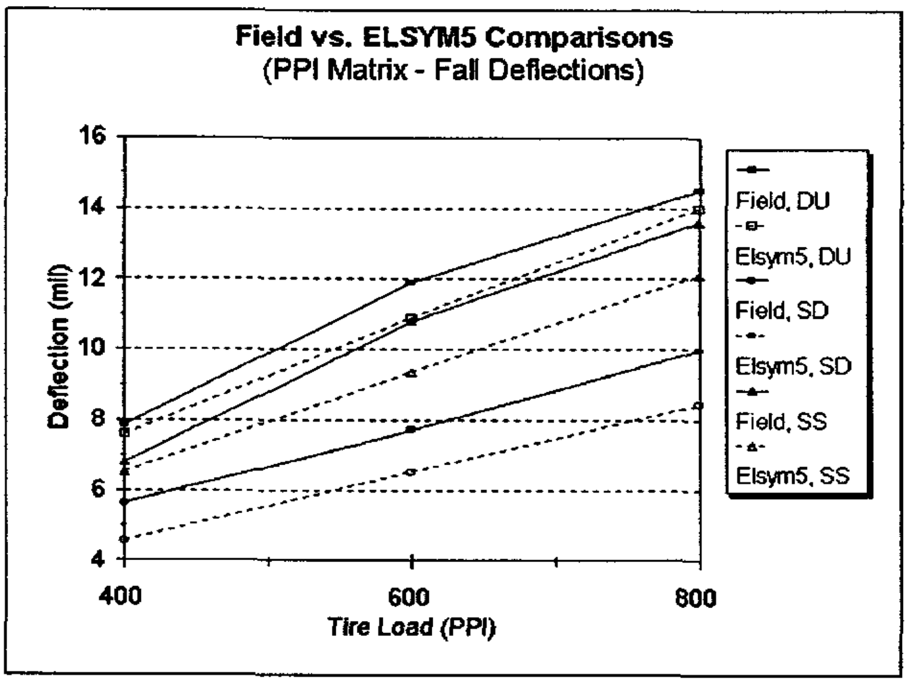

Figure B-2. Fall Deflections for Matrix 1

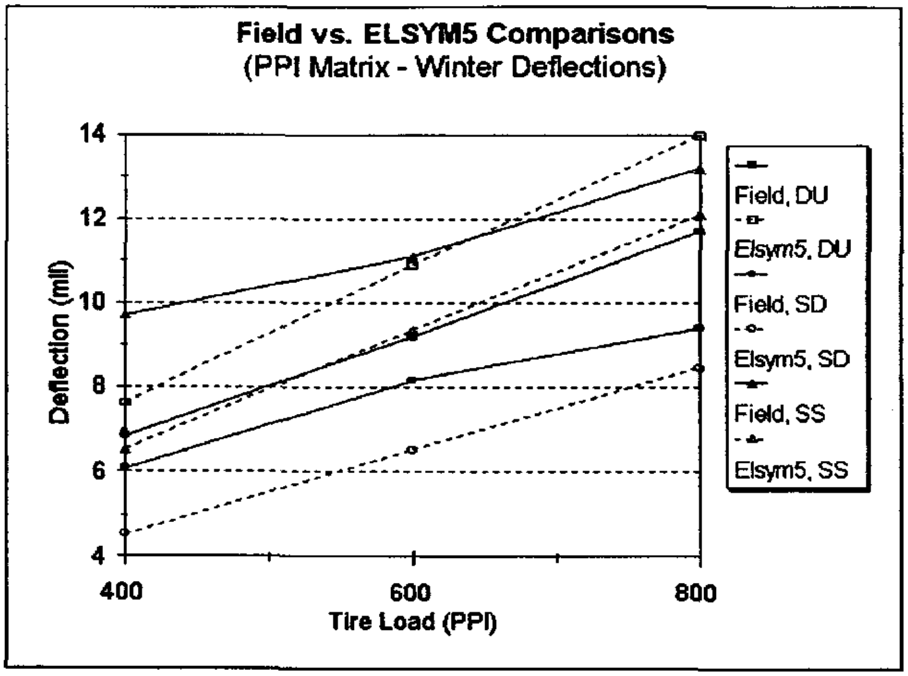

Figure B-3 Winter Deflections for Matrix 1

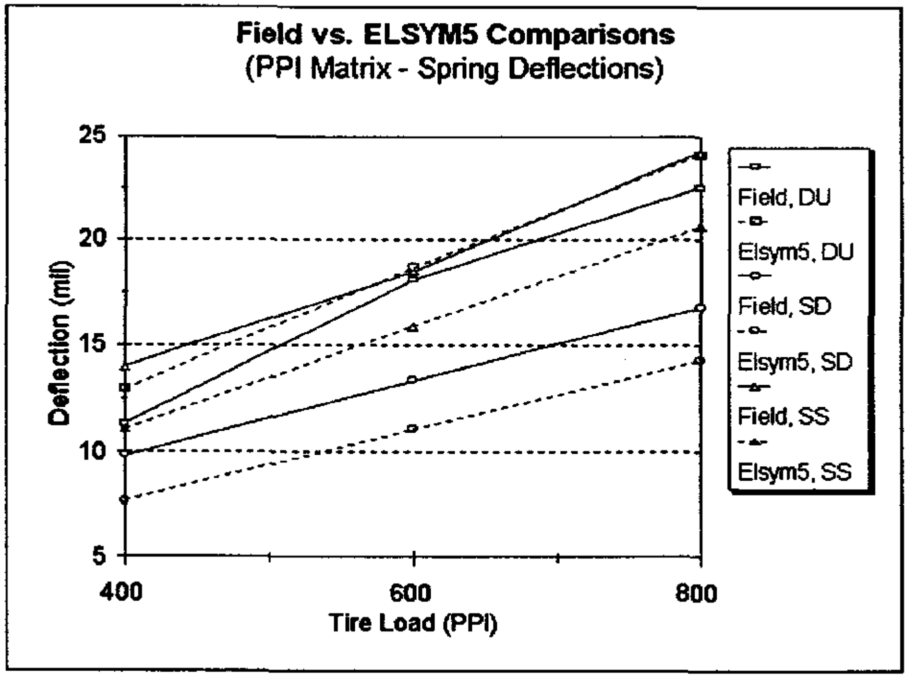

Figure B-4 Spring Deflections for Matrix 1

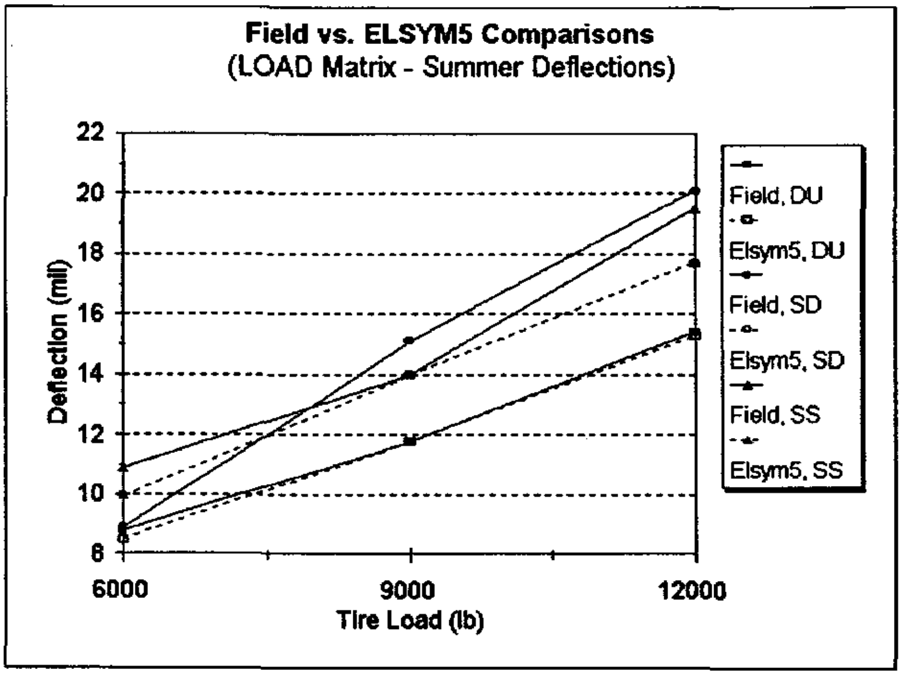

Figure B-5 Summer Deflections for Matrix 2

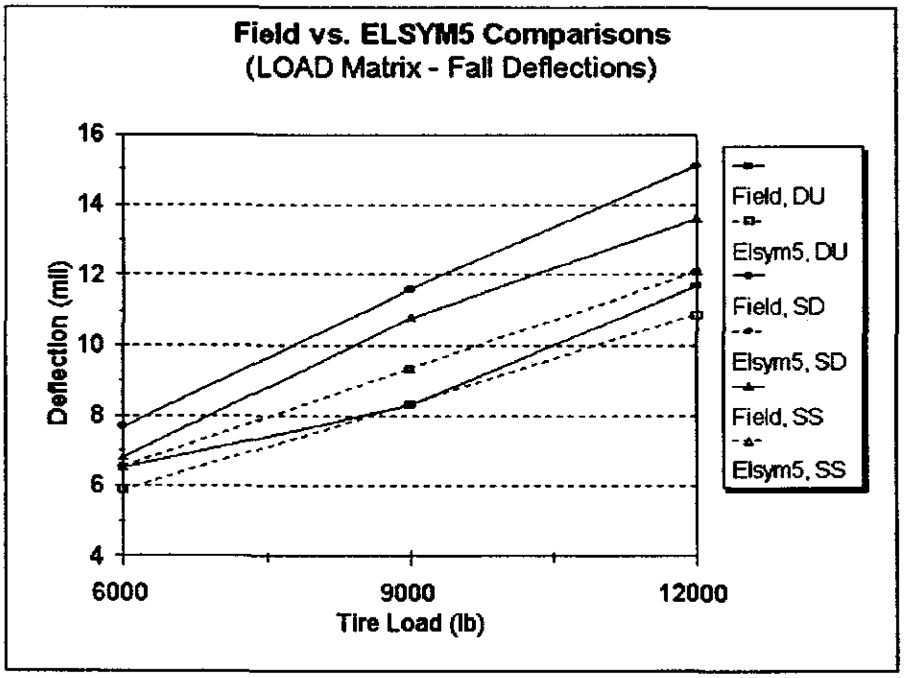

Figure B-6 Fall Deflections for Matrix 2

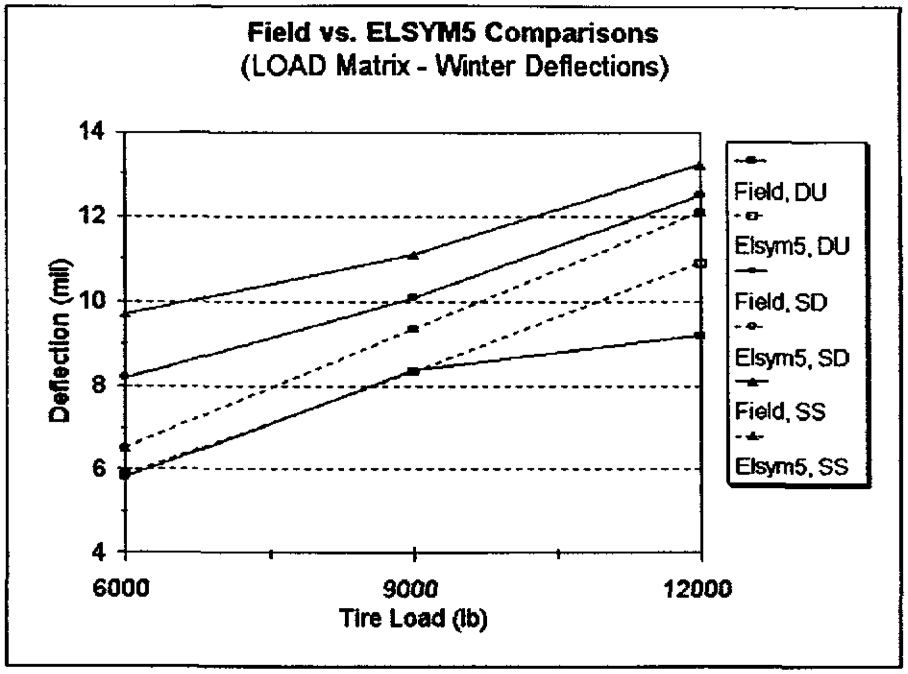

Figure B-7 Winter Deflections for Matrix 2

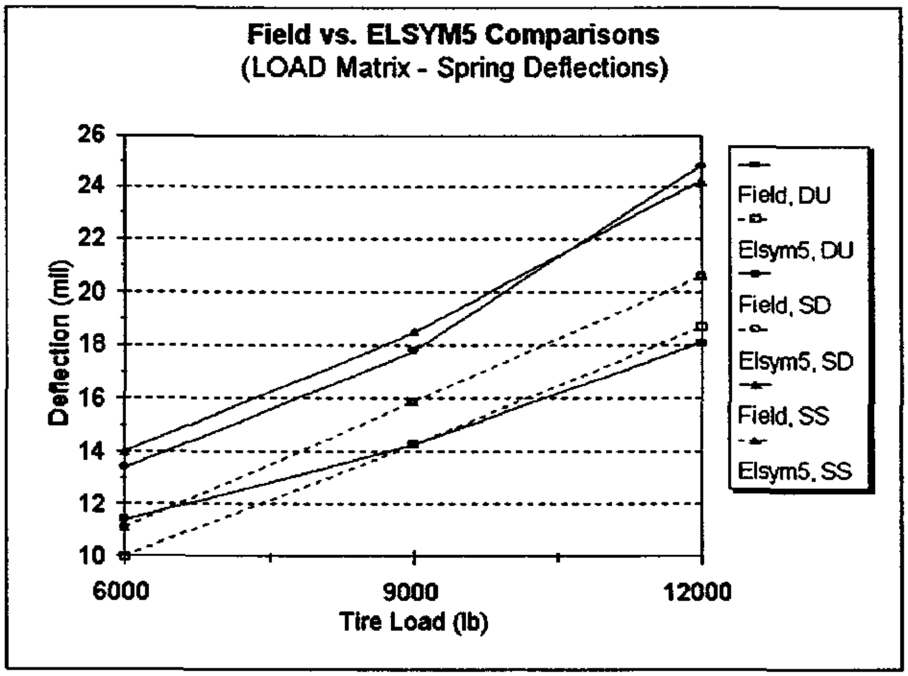

Figure B-8 Spring Deflections for Matrix 2

APPENDIX C - FIELD VS. ELSYM5 COMPARISONS
(Load Equivalency Factors)

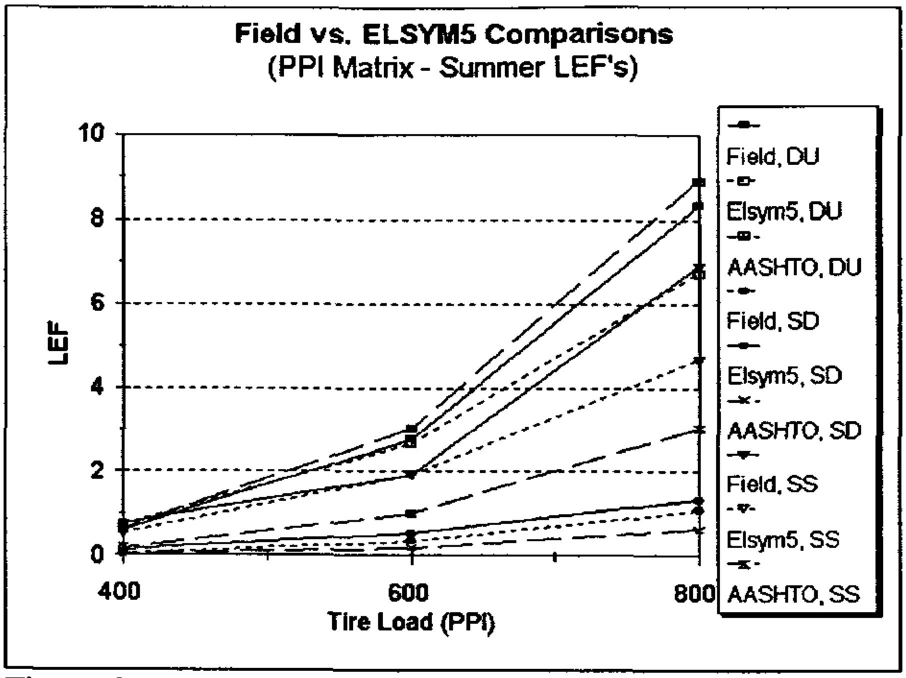

Figure C-1 Summer LEFs for Matrix 1

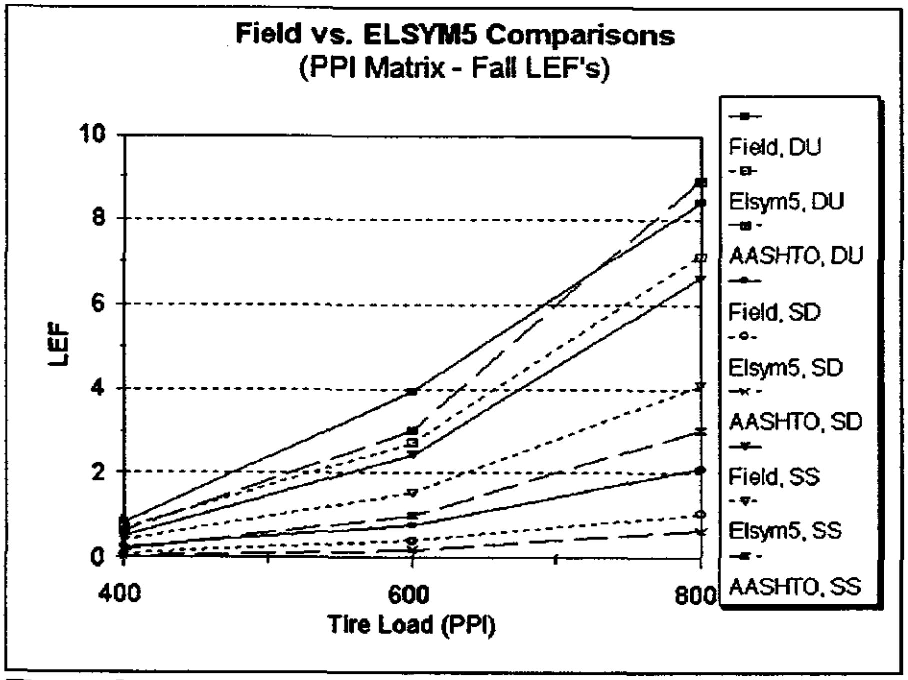

Figure C-2 Fall LEFs for Matrix 1

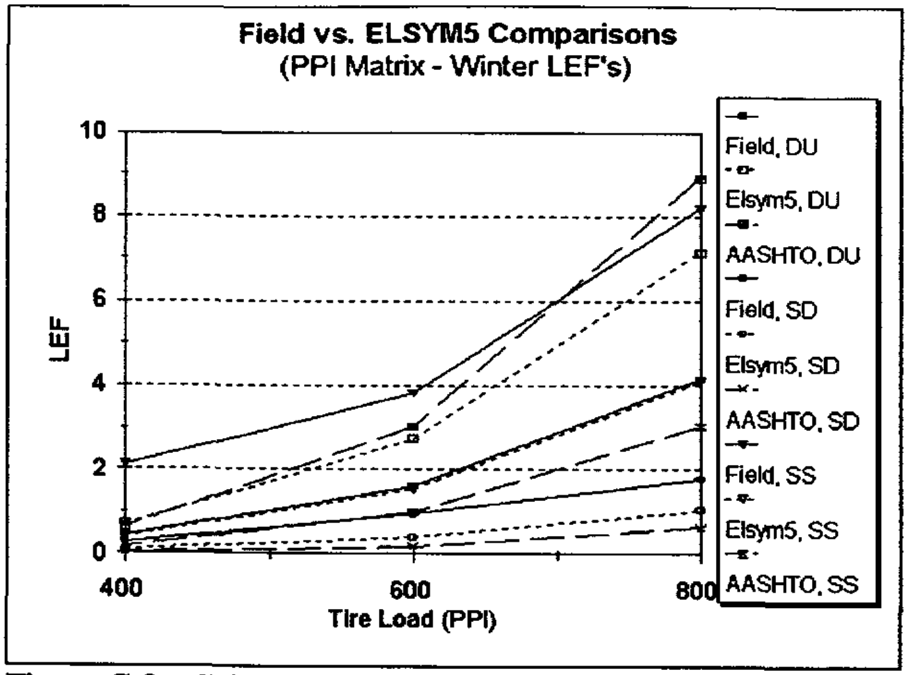

Figure C-3 Winter LEFs for Matrix 1

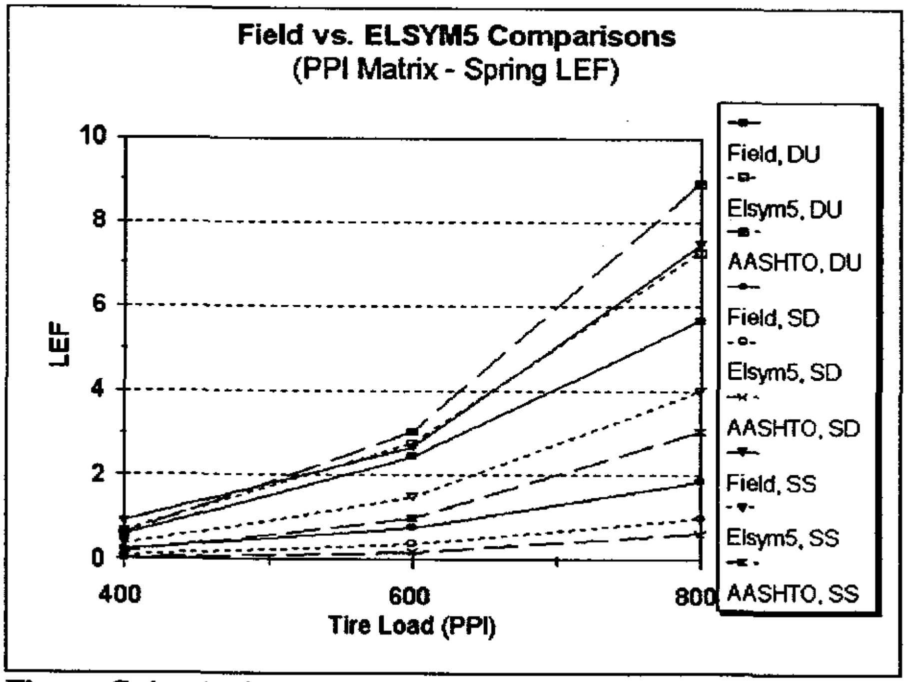

Figure C-4 Spring LEFs for Matrix 1

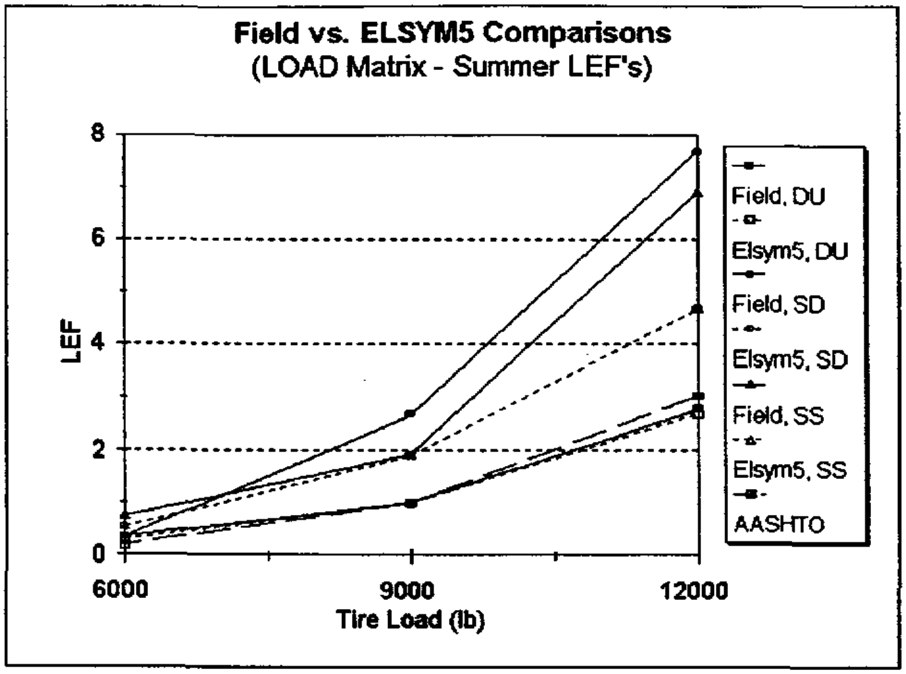

Figure C-5 Summer LEFs for Matrix 2

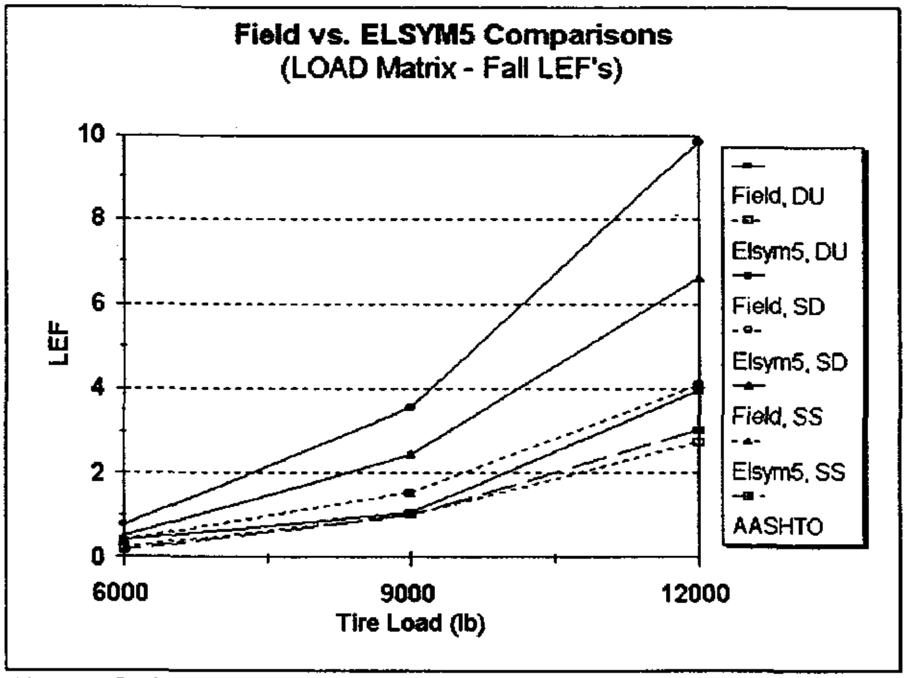

Figure C-6 Fall LEFs for Matrix 2

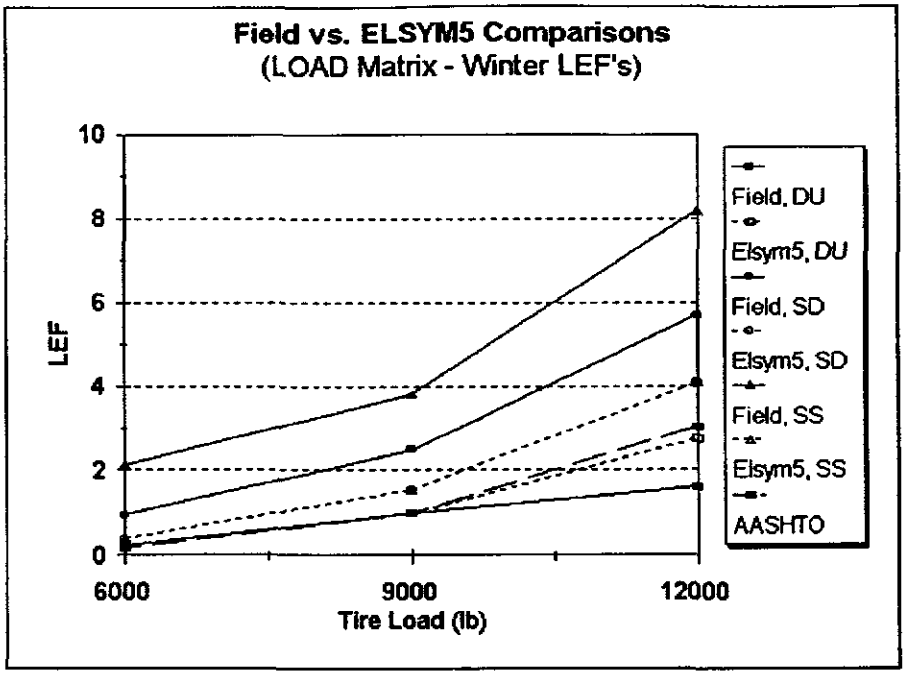

Figure C-7 Winter LEFs for Matrix 2

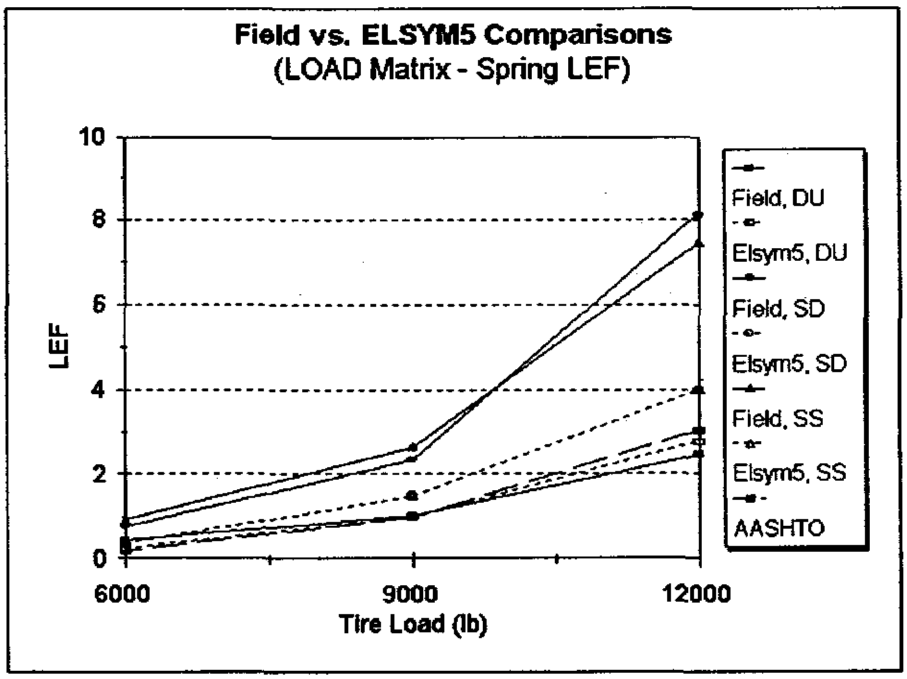

Figure C-8 Spring LEFs for Matrix 2